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Vinterkonferansen 2013
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Seismic volcanostratigraphy of the North Atlantic Igneous Province: New mapping of volcanic facies units

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The early continental breakup and initial seafloor spreading in the northeast Atlantic area was accompanied by widespread intrusive and extrusive volcanism. The increasing numbers of good quality of seismic reflection profiles allow us to distinguish and map distinct morphologies and seismic properties of the flood basalts. In the previous works, several distinct volcanic seismic facies units have been identified: (1) Landward Flows, (2) Lava Delta, (3) Inner Flows, (4) Inner Seaward Dipping Reflectors (Inner SDR), (5) Outer High, (6) Outer SDR. Such facies succession represents a typical volcanic rifted margin and defines the extent of the breakup extrusive complex landward of the first magnetic seafloor spreading anomaly. Seismic volcanostratigraphy provides important constrain on the pre-volcanic basin configuration, margin subsidence history, and the volume of igneous rocks. These constraints lead to a better understanding of the melt supply from the upper mantle and the relationship between tectonic setting and volcanism. We present an updated map of the volcanic seismic facies units in the northeast Atlantic area based on high-quality geophysical data combined with the newest published and unpublished data. The map gives key boundary conditions for understanding the processes forming volcanic margins and constraints on the thermal evolution of associated prospective volcanic basins.

Application of a Heavy Mineral Method in Exploration

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Heavy mineral method is used to study the amount and type of heavy minerals in the sample material. The results are easy to interpret when the transport history of the sample material is known. In glaciated areas, the optimal sample material is the basal till. Most important heavy minerals are gold, platinum group minerals (PGM’s), sulphides and accessory minerals such as scheelite and rutile. Other important indicator minerals for diamonds (kimberlites) are for example chromite, chromium diopside, picroilmenite and garnet (G10).

In the method used by Store Norske Gull AS (SNG), sample is typically taken from 70 to 100 cm depth and sieved (10 mm) in the field to remove the larger stones. Sample size is five litres (10-12 Kg) for the heavy mineral and 0.5 l for the subsample taken for geochemical analysis. Notes about position, depth, overburden and other possible observations are taken for every sample point. Sample density used in a regional style survey is 1-4/ Km². A sampling team of two persons can collect about four samples per day with a shovel and iron bar, if moving from sample point to another is done by foot. With an ATV or a car, up to 15 samples per day is possible.

The pre-concentration of the sample is done with a Knelson Concentrator, which uses centrifugal force and water pressure for the process. After the Knelson concentration the sample size is 0.6 dl. The pre-concentration starts by wet sieving the sample material through a 2 mm sieve with a pressure washer, which removes even the smallest fragments from the stones. After wet sieving, the sample slurry is fed to the device, which is able to concentrate > 90 % of the gold grains > 0.01 mm. The human eye can see > 0.1 mm grains, but only 7 % of all the studied grains in SNG dataset were in that size fraction. Most of the gold grains are 0.02-0.05 mm in their longest axis.

As a final concentration method, SNG uses micro panning, which is normal gold panning with a smaller pan. Other methods for the final concentration in heavy mineral studies are spiral concentrator, shaking table, heavy fluids and hydroseparator. Before the micro panning, the 0.6 dl sample is sieved under water to prevent the flotation of any gold grains. Furthermore,
some soap is added to the panning water to reduce the surface tension. By panning the sample is reduced to about half a tea spoon in volume. To be able to find the gold grains in the remaining heavy mineral mass, the gold grains have to be concentrated on a specific place on the pan. Otherwise, it would be very hard to find the gold out of the ‘million’ grains still left. Sample is then examined under a stereomicroscope to count the amount, size and shape of the gold grains. In addition, the other indicator heavy minerals are noted.

The heavy mineral and the geochemical results for the till samples in the Karasjok Greenstone Belt area show that the heavy mineral method is more sensitive for gold than the conventional geochemical analysis. Only 6 % of the 1074 samples had no gold grains while 57 % of gold assays of the subsamples were at or below detection limit (1 ppb). The main advantages of the micro panning compared to other final concentration methods are simplicity and much better recovery for the gold grains in the fine fraction. The reason for the good recovery is probably the heavy mineral matrix that shields the gold grains during panning and also acts like a heavy liquid, but has a viscosity close to water. On the other hand, reliable and repeatable micro panning depends on the operator and needs a lot of experience.

The occurrence of the gold and the style of the mineralization can be estimated with the heavy mineral and geochemical data. For example, pristine shaped gold grains suggest a source that is nearby. A gold grain is normally rounded after a kilometer in glacial transport. Other indicator minerals, such as PGM’s, together with gold grains could point to a Ni-Cu-PGM-mineralization associated with mafic and ultramafic rock types. Existence of sulphide minerals, such as sphalerite and chalcopyrite, could indicate a possible VMS-type mineralization. Relatively low gold grain count with a relatively high gold content in the geochemical sample could indicate that primary gold mineralization is refractory (invisible gold). Heavy mineral methods are useful for exploration together with geochemistry. They are highly sensitive and especially suitable for gold exploration, since gold occurs in detectable amounts in the sample material and it is easy to recognize. In addition, gold is easy to concentrate and it survives in glacial environment because of its physical and chemical properties.

Environmental monitoring: Can microfossils make a difference?

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According to the EU’s Water Framework Directive (WFD) member states and associated countries (like Norway) have to take action to improve the ecological quality of water bodies of degraded quality status due to human influence. The assessment of the quality status should be performed by comparison with ‘reference conditions’ which ‘is a description of the biological quality elements that exist, or would exist, at high status’. The problem is that, for most areas, traditional biological and instrumental monitoring data do not exist from pre-impact times so there are no data with which to compare the present-day situation.

A diversity-based classification system for soft-bottom macrofauna serves as a standard for describing the present-day ecological quality status (EcoQS) in Norwegian coastal waters. On the other hand, the fossil remains of benthic foraminifera in dated sediment cores allow tracing the record of environmental change over decades or centuries. Recently the NFR-funded PES project has, for the first time

1) shown that benthic foraminifera are as reliable to define present-day ecological status as the conventionally used macrofauna.

2) developed a new method to determine in situ reference conditions (i.e., habitat-specific) for soft-bottom habitats using palaeoecological approaches based on comparisons between macrofauna and benthic foraminifera.

The application of the method is illustrated with an example from the inner Oslofjord, Norway. Here, changes in EcoQS over the past century (i.e., palaeoEcoQS) is determined based on fossil foraminiferal assemblages in dated sediment cores. The results are supported by comparisons with available biological and hydrographical time-series.

Including the foraminifera method in standard bio-monitoring assessments, will allow reconstruction of in situ EcoQS from pre-
Late Quaternary evolution of the proximal Lofoten Basin Channel, Norwegian Sea - preliminary results

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The Lofoten Basin Channel system is the continuation of the Andøy Canyon, offshore northern Norway. It can be followed from the base of the continental slope at ~ 2200 meters water depth to the deepest part of the Lofoten Basin in the Norwegian Sea. We analysed high resolution geophysical data and nine sediment cores from the proximal part of the channel in order to investigate the spatial distribution and temporal deposition of sediments in this system. The high-resolution seismic data reveals several acoustically transparent units that are interpreted as debris flow deposits originating from slides on the nearby slope. The swath bathymetry shows several channel systems with some levee development. A shift in channel location and development of a second-order channel system is found in the upper most parts of the system. In the middle parts of the study area these channels form a rather complex braided system. The sediment cores contain mainly two facies: (I) muds and (II) fine – medium sands which constitutes part of Bouma sequences A - E. The core chronology based on radiocarbon dating of in situ foraminifera, indicates Holocene ages (8 – 2.2 ka BP) for the sandy turbidites. The area of the proximal Lofoten Basin Channel is thus characterized by the interplay of both turbidites and debris flow deposits, and the channel system has been active during the Holocene.

Rock-avalanche and societal response in Norway: A historical review


1: Åknes/Tafjord Beredskap IKS
2: The Geological Survey of Norway
3: The Norwegian Water Resources and Energy Directorate

Rock-avalanches have been responsible for many of the largest avalanche and landslide accidents in Norway, classified by the number of fatalities. The majority of these events took place in the counties Sogn & Fjordane (SF) and Møre & Romsdal (MR). The best known events occurred in Loen (SF), in 1905 and 1936, with respectively 61 and 74 fatalities; and in Tafjorden (MR, 1934) with 40 fatalities. In these events the victims lost their life due to rock-avalanche generated tsunamis with several tens of meters vertical run-up highs (73 meters in Loen, 1936). Other major tsunami related events took place at Skafjell (1731) and Tjelle (1756) in MR with 17 and 32 fatalities. Large rock-avalanche accidents have also occurred due to onshore events, for example in Arnafjord when 45 people perished in 1811. Outside these two counties, the largest accident took place in Lyngen in the county Troms (TR) when 14 persons died in the 1810 rock-avalanche generated tsunami.

Until the events of 1934 (Tafjorden) and 1936 (Loen), no risk management was carried out. Incidents were taken as nature given. After these events The Geological Survey of Norway (NGU) raised the issue of rock-avalanches and started registration and manual displacement measurements of unstable rock slopes in western Norway. These investigations were disrupted by the Second World War. The Norwegian Geotechnical Institute (NGI) did research on unstable rock slopes in the late fifties and in the sixties and summarized this in some important publications. In 2003 “International Center for Geohazards” (ICG - a Center of Excellence, 2003-2012) was founded by NGI (hosting organization), NGU, NORSAR, University of Oslo and Norwegian University of Science and Technology. Research on rock-avalanches, rock slope stability and tsunamis were important goals for ICG.

Recent attention on actual risk mitigation on rock avalanches started up in MR in the late 1990s when the county council and NGU started a pioneer mapping program for rock slope failures.
and related risk (published in 2011). 87 rock slope failures with potential to develop rock avalanches (volume > 100,000 m³) were identified, and three of these were classified as high risk objects. Similar mapping programs have started in the counties of SF and TR, and so far, one high risk object has been identified in TR. The municipalities in Norway have wide responsibilities for safety for their inhabitants and visitors. To handle the high risk of rock avalanches in MR, several municipalities and the county council established the Early Warning Center Åknes/Tafjord Beredskap IKS (ÅTB) in Stranda in 2008, with financial support from the government. Another center was established in TR in 2011 - Nordnorsk fjellovervåking IKS (NNFO), with geological support from ÅTB. However, it was widely admitted - including by the government - that the magnitude and complexity of the rock-avalanche scenarios requires risk treatment and management at a national level. Responsibility for avalanche and landslide risk at that time was fragmented on the national level. In 2009, The Norwegian Water Resource and Energy Directorate (NVE), already responsible for flood risk mitigation, were also assigned the main national mandate for avalanche and landslide risk mitigation. Since 2009 NVE has taken the overall responsibility for the mapping program, with NGU as the executor. A plan for further mapping, prioritizing between counties, was prepared in 2011. In 2012 the government decided that the early warning of rock-avalanches in Norway will be incorporated in NVE, with ÅTB as the major center. Implementation is dependent upon agreement with the municipalities.

For building permits, the building code of Norway has restrictive limits related to natural hazard. To avoid too heavy restrictions on development in the extensive hazard zones of tsunamis, the code was changed in 2010. The current code (TEK10) can allow new buildings, even if the hazard level is above the standard limits; prerequisite real-time monitoring, early warning, and some other terms (lack of alternatives etc.).

To handle the organizational, operative and practical issues of actual rock avalanche events, a "National rock avalanche emergency plan" is under work by several civil preparedness authorities (initiated by the County governor of MR). This plan will describe the responsibilities and the roles of the actors, the need for exercises, etc.

The detrital zircon record: Supercontinents, parallel evolution - or coincidence?

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The interpretation of detrital zircon data is facing some important and potentially damaging inconsistencies that are commonly overlooked: Combined U-Pb and Lu-Hf data from detrital zircon in sedimentary rocks have been used successfully to study global processes such as the extraction, growth and preservation of continental crust (e.g. Belousova et al. 2010), suggesting generally similar patterns of evolution of different continents. Yet at the same time, such data are increasingly used to identify the source-rocks of individual clastic deposits (e.g. Lahtinen et al. 2002), based on the implicit assumption that material from different source terranes carry distinct provenance signatures.

For example, Precambrian detrital zircon age-fractions from late Mesoproterozoic to Phanerozoic sedimentary rocks in Greenland have patterns of U-Pb ages and initial Hf isotope composition indistinguishable from that of zircon from granitoids in Fennoscandia. Although geological considerations suggest that detritus was almost certainly derived from sources within Greenland, the overlap suggests that detrital zircons cannot be used as a general tool to distinguish between sources east and west of the North Atlantic. This is perhaps not surprising, as Fennoscandia and Laurentia (including Greenland) have been near neighbours in three supercontinents (Columbia/Nuna, Rodinia, Pangea). Transport and homogenization of clastic material in intracontinental basins and along a common continental margin would smooth out differences, and the two neighbouring continents may have closely parallel histories of internal growth. It is stronger reason for concern that Precambrian age fractions in detrital zircon suites from areas as distant as Australia and Southern Africa also show distribution patterns that cannot be distinguished with confidence from sources in Fennoscandia. These continents have not been near neighbours in post-Archaean supercontinents. Since exchange of detritus between such distant blocks is improbable, one is left with the alternative explanations of pronounced parallel evolution (perhaps mainly related to the assembly of supercontinents in the...
geological past), or pure coincidence. Ruling out the unattractive possibility of coincidence requires larger sets of data and more rigorous statistical methods that are commonly applied in detrital zircon studies. Whatever the explanation: Exchange, parallelism or coincidence, observations such as these challenge one of the main assumptions underlying the use of zircon as an indicator of sedimentary provenance: That a given age and initial Hf isotopic pattern of a population of detrital zircons can be related to a specific first-generation source (e.g. Fedo et al. 2003).

References:

Origin of Solitary Mantle Peridotites and a new view on the tectonostratigraphy in the Scandinavian Caledonides

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Understanding the Scandinavian Caledonides is closely tied to the interpretation of the Tectonostratigraphic Map and its later revision as a map of Tectonostratigraphic Terranes (Roberts & Gee 1985, Gee & Stephens 1987). Lately, major improvements in the general understanding of processes in continental collision and post-orogenic extension have originated in the Caledonides. Many of these improvements are tightly linked to new quantitative methods, particularly improved analytical facilities, dating methods and numerical models, through which we have learned a lot about temperatures, pressures and fluids, strength, ages and rates as well as the global positions where important Caledonian events took place. Unless these new data are tightly linked to detailed understanding of field relationships, however, the basis for new interpretations may not be safely tied to reality. The importance of understanding both small- and large-scale field relationships can therefore rarely be underestimated. Until recently the large-scale implications of most of these modern studies have been tied to the accepted interpretations of the tectonostratigraphic and terrane maps. Perhaps the time has come to revise some of these regional interpretations? Among the most enigmatic rocks in the Caledonides (and in mountain belts world-wide) are occurrences of exposed mantle rocks. These rocks are often referred to as solitary, “Alpine-type” mantle peridotites and in the Caledonides they occur along large segments of the mountain belt. They are particularly common near the interface between undisputed Upper Allochthon (outboard terranes) and the Middle Allochthon assigned to an origin in Baltica. Mantle rocks, however, also occur at lower structural levels, below rocks assigned to the Middle Allochthon as well as within the Western Gneiss Region. Among the most enigmatic rocks are coarse to fine-grained detrital serpentinites uniquely derived from erosion of exposed mantle. Many of these mantle peridotites have not been properly accounted for by comparison with uniformitarian examples. Instead, these rocks have been described mostly as dismembered ophiolites, but many without containing the most characteristic elements of an oceanic- or back-arc magmatic spreading ridge, the sheeted dykes. Many are also intimately associated with coarse to fine-grained siliciclastic rocks and even slivers of attenuated felsic orthogneiss, and none of these peridotites have evidence of magmatic emplacement into their surrounding rocks. In a recent paper we suggested that these mantle rocks were exhumed and partly exposed by hyperextension of the continental crust in the pre-Caledonian passive margin of Baltica (Andersen et al. 2012). If this is correct the margin of Baltica must have had a very complicated 3-D geometry, which necessarily also must be reflected in the subsequent deformation and metamorphic history (closure and subduction events) as well as in the lateral variations seen along the present-day remnants of the mountain belt.

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Basin development and orogenesis in the North Atlantic-Barents Sea Region
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Field observations, combined with new geochronological data (ID-TIMS and LA-ICP-MS), from East Greenland, Svalbard and North Norway indicate that our present understanding regarding Neoproterozoic and Paleozoic basin development and orogenesis in the areas surrounding the North Atlantic need to be revised. New data from East Greenland indicate that the eclogite bearing southern part of Liverpool Land is a detached piece of Baltica (Western Gneiss Region) stranded on Laurentias eastern plate margin in the Early Devonian. It is furthermore argued that the large volumes of leuco-granites present in the East Greenland Caledonides are linked to westward subduction and development of a magmatic arc on continental crust along Laurentias eastern margin, 20-30 m.y. prior to westward thrust emplacement of these rocks to their present position. Remnants of a correlative continental arc have recently been identified in the Uppermost Allochthon in the Boda area. In the latter area Silurian intrusives penetrate a Late Mesoproterozoic to Early Neoproterozoic metasedimentary sequence (Heggmo Unit) and Grenvillian plutons, previously interpreted as being part of the c 1800 Ma autochthonous Baltic basement. Our field observations and geochronological data indicate that they are part of the Uppermost Allochthon.

Geochronological data from the autochthonous Baltic basement gneisses, their Neoproterozoic to Paleozoic cover sequences, and various Caledonian allochthons show several interesting features. Zircon age provenance data from the Neoproterozoic-Cambrian cover sequences demonstrate (i) a systematic variation from East to West, (ii) North to South, as well as with (iii) with stratigraphic position. Based on the observed changes in zircon provenance data, and comparison with nearby source areas, it is proposed that collision between Baltica and Arctida and creation of the Timanides in the late Neoproterozoic caused opening of an ocean (Iapetus?) west of Baltica. Zircon age data from the Dividal Group indicate that this unit was deposited in a foreland basin south of the Timanides. It is furthermore argued that the Kalak nappes are exotic terranes (with respect to Baltica) and derived from the Timanides. These terranes were accreted to Baltica during the subsequent Caledonian orogeny. Preliminary provenance data from metapsammitic units within the Upper and Uppermost Allochthons indicate a Laurentian affinity for these terranes.

Tracking the Triassic – early results of linking the Longyearbyen CO₂ reservoir across the northern Barents Shelf
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The Longyearbyen CO₂ Lab has identified a late Triassic reservoir with potential to sequester carbon dioxide generated by the local power-plant. The aim of this study is to provide a detailed regional understanding of Triassic sedimentation across the northern Barents Shelf. Study of the offshore development of the northern Barents Shelf is hampered by limited well-data and varying reflection seismic data quality. The ages of seismic sequence boundaries in the northern Barents Sea has been debated but by tying it to the geological development and previous studies we can identify and define the main seismic boundaries. The Triassic is delineated by the base Triassic (Top Permian) reflector and late Triassic/early Jurassic erosion and condensation forming a boundary to the overlying mid-Jurassic sediments. The Mesozoic sediments on the northwestern Barents Shelf form SW-NE elongated depocentres with units thinning toward the Edgøya Platform and Storfjorden.

Early-middle Triassic sediment influx sourced from the Uralian orogeny and Fennoscandian Shield prograded westward across the Barents Shelf and deposited large sandstone successions east of Svalbard. From seismic studies it is apparent that local highs such as the Gardarbanken High acted as obstacles to influx from the Uralian sourced sediments from the
southeast. Early interpretation suggests that subaerial exposure of highs in the northern Barents Sea were important controls on early Triassic deposition. Late Triassic sedimentation appears to have transgressed most Highs and the delta-front had moved toward the present exposed island of Edgeøya. The three main early Triassic progradational units offshore correlate partly to similar successions onshore, although the exposures on Svalbard represent far more silty and shaly intervals with limited sand representing deeper environments. How and where the eastern and western influence is linked is a chief objective of this study.

Correlation from the offshore regions across Storfjorden onshore Svalbard is difficult due to limited and generally poorer data quality, fold-and-thrust influence in the southern region and thin and subcropping Triassic sequences. Using well and seismic data from Adventdalen and Reindalen and the available seismic lines across Svalbard, we can provide a regional mapping of the base Triassic reflector and look at internal characteristics of the offshore Triassic successions and compare to onshore exposures, including new paleocurrent data. The study will provides a more accurate palaeogeographic understanding of the Triassic and links the extent of western and eastern source influences on Triassic sedimentation.

Assessing rock stiffness from Rock Physics to evaluate the sealing quality of North Sea shales for CO₂ storage plays

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Caprock quality is crucial when evaluating the storage potential of a reservoir. The objective of this study is to evaluate the quality of the primary and secondary seal in case of CO₂ storage in sandstones from the Mid to Late Jurassic in the Norwegian North Sea. These seals are composed of Lower Cretaceous - Upper Jurassic shales for the primary, and from the three Cenozoic groups (Nordland, Hordaland and Rogaland) for the secondary targets, respectively. The method consists in evaluating the thickness of the target seals, and then the possibility of seal breaching features like faults.

We have collected and analyzed well data from 60 wells in the Norwegian North Sea, of which 3 are from Central Graben, 2 are from the Norwegian-Danish Basin (Egersund) and 55 are from the Northern North Sea (Viking Graben and Horda Platform). In addition to the standardized composite logs (resistivity, gamma ray, Vp, density), Vs logs have been obtained. These data have been organized according to formation and location.

The stiffness of a rock is a measure of the brittleness of the rock and is widely used in the shale gas industry. The objective of this industry is to allow the extraction of gas in tight shale, by the fracturation (fracking) method: according to this method, only the brittle shales will allow for the development of cracks with conductive capacity and, hence, acceptable gas recovery rates. For this purpose, a number of methods have been used to evaluate the geomechanical (mainly brittle) properties of shales from classical geophysical data; utilizing wireline logging but also AVO analysis. In our case, evaluating the stiffness of a formation will allow for locating the areas where critically stressed faults would create pathways for CO₂ and breach the seal integrity. These areas would thus not be suitable for CO₂ storage.

The present analysis in the study area demonstrates that primary seal in general is of sufficient thickness, honouring the recommendations given by the Norwegian Petroleum Directorate (minimum 50 meters), except within a thin North-South-trending corridor to the West of the Horda Platform. Analysis shows that this seal is brittle in the entire study area, in consistence with a deep depth of burial. The only area where it could be ductile is to the North of the Utsira High, despite the elevated geothermal gradient found there. Since rocks of this rheology are brittle, the primary seal could be breached during fault movements. To ensure its integrity, it is thus important to evaluate the composition of the faults from this area that have a less than 30 degrees away from the regional maximum horizontal stress (ENE-WSW).

The secondary seal is much shallower and therefore has a ductile rheology, which makes it less affected by fault movements. This is due to the nature of ductile deformation which creates less conductive faults that have self-healing properties. The thickness of the seal is at least 500 meters close to the shore, but most commonly between 1000 and 2000 meters. These properties make it a very high quality secondary seal, as has been demonstrated by the successful Sleipner storage site in the Utsira sands that are sealed by Nordland shales.
Late Cenozoic erosion estimates on the Norwegian Barents Shelf from measured/modeled thermal maturity and sonic/seismic velocity data

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The Barents Sea is believed to have been influenced in most parts by Late Cenozoic uplift / erosion. This late exhumation of the Barents Sea had large effects on sediment properties and on hydrocarbon maturation and migration. The current study seeks to estimate exhumation from shale compaction and vitrinite reflectance trends in the Norwegian Barents Sea and discuss its implications for hydrocarbon exploration. Well logs and geochemical data from about 50 wells and seismic refraction velocities based on widely distributed shot gathers along long-offset seismic reflection lines have been used to determine the shale compaction in the uplifted Barents Sea. The vitrinite reflectance and velocities have been used to quantify exhumation in the area as these are indicative of maximum depth and temperature to which sediments were buried. Velocities from seismic refraction profiles were calculated by Herglotz – Wiechert method which assume continuous increase in velocity with depth. The likely transition zones between mechanical and chemical compaction zones in shales were identified from the rock physics templates and bottom hole temperature analyses in reference wells located in the west (Tromsø and Sørvestnaget basins). The reference velocity-depth trends for shales and composite lithology were established respectively from the sonic logs and seismic refraction data at locations where velocity was lowest, and relatively thick Cenozoic succession was present. The velocity-depth trends from the other areas were then calibrated and any deviation from the reference trend was measured as erosion/uplift. The vitrinite reflectance vs. depth data was plotted on a semi-logarithmic scale and best fit curves were drawn for each well and extrapolated to near surface vitrinite reflectance of 0.2%. The difference between zero and extrapolated depth at 0.2% was then estimated as erosion/uplift. The vitrinite reflectance was also computed from the present day geothermal gradients and lithology information. The predicted vitrinite reflectance results suggested notably lower values and were compensated by different amount of erosion to fit with the measured vitrinite reflectance. The exhumation estimates from different methods presented in this study were all data driven. The results were within the agreement limit of 80-90% to each other and follow more or less similar trends in the study area. The exhumation trends from all the methods suggest minimum or no erosion in the western margin of the SW Barents Sea whereas exhumation increases significantly towards the NE and slightly towards the East in the Hammerfest Basin and on the platform areas. By combining and averaging the results from these methods, a general picture of exhumation in the area is determined resolving the under/over-estimation problems associated with a particularly method. The results suggested approximately 500 – 2000 m of erosion within the study area depending on the location. The shale properties in the Barents Sea area are significantly affected by exhumation resulting in higher velocities and densities, and lower porosities at shallow depths than expected for normal compaction. The results from this study are useful input for modeling of maturation, generation, migration and trapping of hydrocarbons in the area.

Reservoir Characterization of Potential Triassic and Jurassic Reservoirs for CO₂ Storage in the Skagerrak-Kattegat Area

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Regional assessment studies for CO₂ storage plays have been carried out in the Norwegian-Danish Basin of the Central North Sea and in the Skagerrak-Kattegat area. The study shows that all the necessary premises for a safe, long term CO₂ storage, are present in the area. Two trap types for storage have been studied more closely: 1) large and gently inclined, unfaulted reservoirs (aquifers) in the northern Skagerrak area and 2) dome structures with three-way closures above salt pillows in the Norwegian Danish Basin.
have focused on the Upper Triassic–lowermost Jurassic Gassum Formation and the Middle Jurassic Haldager Sand Formation. The current study presents reservoir characteristics of the sandstones of the Gassum and Haldager formations, of the Fjerritslev Trough and on the Skagerrak-Kattegat Platform, and corresponding reservoir models. The Gassum and Haldager formations are mapped on regional 2D seismic data in the Norwegian-Danish Basin, the Fjerritslev Trough and at the Skagerrak – Kattegat Platform. The seismic data were tied to Danish hydrocarbon exploration and geothermal energy wells. The Gassum and Haldager formations are found at a depth range of 750 – 2050 and 550 – 1750 m below sea level, respectively. Both formations are affected by salt tectonics (salt pillows/diapirs) in the south but form gently dipping reservoir units (aquifers) in the north.

An approach of sequence stratigraphic analysis has been used to predict the reservoir facies/parameters for the sandstones of the Gassum and Haldager formations and to develop a likely geological model to include the area closer to Norwegian coast. A reservoir facies model for the Haldager Formation in the Skagerrak-Kattegat area based upon the shallow core (IKJ well 13/1-U-1) and shallow seismic data is developed. The reservoir facies for the Gassum Formation are predicted assuming a depositional model where the sediments are sourced from north. The thickness of the Gassum Formation is predicted using thicknesses from seismic data and a pseudo-well is generated about 50 km north of existing Danish well; A 50% thickness erosion of highstand sandstones is assumed at each cycle when sea level fell during a lowstand. The removed thickness was compensated by assuming deposition of fine-grained transgressive systems tracts sediments, which are not included in the reservoir thickness. Good reservoir porosities (~20%) were found in the reservoirs penetrated by wells in the southern part of the study area. The porosity values towards north are expected to be higher related to shallow burial depth. The sealing properties of the transgressive shales overlying the lowstand sandstones are crucial for local sealing and lateral distribution of injected CO2. Well-defined depositional models from the Danish part of the basin justify the assumption of internal seals. Furthermore, the potential intercalation of shaly units and permeability heterogeneities developed in prograding sand systems may provide additional trapping capacity to the reservoir; this has been shown from closely spaced wells in the Danish sections in the eastern central part of the basin.

This geologic model is one of several possible scenarios that favour Gassum and Haldager formations as the potential CO2 storage reservoirs in Skagerrak area. Therefore, an evaluation of the reservoir properties using other possible scenarios is necessary. The sandstones of the Gassum and Haldager formations with their high net/gross ratios and good porosity/permeability provide promising aquifers for storing CO2 in the Skagerrak area.

Synchronous inter-hemispheric alpine glacier advances during the Antarctic Cold Reversal

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The termination of the last glaciation in both hemispheres was a period of rapid climate oscillations superimposed on the overall warming trend, resulting from large-scale reorganizations of the atmospheric and oceanic circulation patterns in both hemispheres. Environmental changes during the deglaciation have been inferred from proxy records, as well as by model simulations. Several oscillations took place in both the northern and southern hemispheres caused by melt water releases such as during the Younger Dryas in the north and the Antarctic Cold Reversal in the south. However, a consensus on the hemispheric linkages through ocean and atmosphere are yet to be reached. Here we present a new multi-proxy reconstruction from a sub-annually resolved lake sediment record from lake Lusvatnet in arctic Norway suggesting inter-hemispheric climate linkages during the Bølling/Allerød time period. Our reconstruction of the Lusvatnet cirque glacier shows a synchronous glacier advance with the Birch-hill moraine complex in the Southern Alps, New Zealand, during the Intra Allerød
Cooling. We propose these inter-hemispheric climate oscillations to be forced by the northward migration of the southern Subtropical Front during the Antarctic Cold Reversal. Such a northward migration of the Subtropical Front is shown in model simulation and in palaeorecords to reduce the Agulhas leakage impacting the strength of the Atlantic meridional overturning circulation. The Bølling-Allerød time period was a warm interval in the North Atlantic with a strong Atlantic meridional overturning circulation setting the stage for the later fresh water forcing of the Younger Dryas cold reversal with reduced overturning. Two minor cold reversals, the Older Dryas and the Intra Allerød Cooling, took place during this time span and we suggest a reduction in the Agulhas leakage during peak cooling over Antarctica as the mechanism teleconnecting arctic rapid climate oscillations with rapid climate oscillations in Antarctica during the Bølling/Allerød. Our high-resolution reconstructions provide the basis for an enhanced understanding of the tiny balance between migration of the Subtropical Front in the Southern Ocean and the teleconnection to the northern hemisphere via the Agulhas leak.

Numerical analysis of a multi-proxy data set from distal glacier-fed lake, Sørsendalsvatnet, western Norway

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Here we present a Holocene record of glacier activity as documented in physical sediment properties analysed on sediments from the distal glacier-fed lake Nedre (Nedre=Lower) Sørsendalsvatnet (918m a.s.l.), located 35 km inland from the coast in Western Norway. In this study, we put special emphasis on comparing different sediment parameters by means of statistical methods and on transforming chronological uncertainties into uncertainties of the reconstructed glacier activity. A multi-proxy data set consisting of sedimentological, physical and geochemical data shows one main process, as extracted by means of principal component analysis (88% of the variance explained by the first PC), driving the sediment variability in Nedre Sørsendalsvatnet. The common signal extracted from the sediment data is indicative of glacial activity in the catchment and is interpreted to vary in concert with the changing glacier equilibrium-line altitude (ELA). The reconstruction of former glacier activity is in accordance with glacier variability reconstructed from other sites in western Norway, including the termination of the deglaciation around 10,000 cal BP, the 8.2ka (Finse) event, the Holocene thermal optimum between ~8000 cal BP and 5500 cal BP, the onset of the Neoglaciation at 5500 cal BP. The largest glacial extent during the Neoglaciation time period took place during the 'Little Ice Age'. The robust radiocarbon chronologies from three different sediment cores give insight into the duration of the 8.2 ka event in the terrestrial system. The maximum glacier activity around 8.2ka is the culmination of a glacier advance that started with a slight expansion around 9 ka cal BP and accelerated at 8.4 ka BP. The glacier advance ended abruptly at 8.0 ka BP. Rates of change in the sediment parameters were higher during glacier retreat than during glacier advance, which seems exclusive to glacier records and is not reflected in ice-core records.

Geophysical mapping of clay layers in Numedalen region, Norway

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The amount of helicopter borne geophysics at the Geological Survey of Norway (NGU) has increased during last couple of years especially for mineral exploration. Sometime we also measure over areas with thick soil cover and we get responses on the electromagnetic data. Our five frequency electromagnetic system is designed mainly for mineral prospecting, and it is not ideal for soil mapping. However, we can see electromagnetic responses in the valley fillings. Based on this, a project was established to evaluate what kind of soil information could be extracted from the data by using various available inversion codes. We selected Numedalen valley area, south of Kongsberg for our initial study where a small SkyTEM survey was done in 2005. In 2011, the same area was covered with standard NGU helicopter borne geophysics including Frequency Electro-Magnetic measurements (FEM).
Electric resistivity maps obtained from SkyTEM survey were in agreement with the thickness distribution that was previously developed from gravimetric measurements. Drilling in the valley suggests a filling of coarse-grained sand and gravel overlying marine clay. We found clay layers of approximately 20-150 m thickness at about 50 m above mean sea level from SkyTEM and FEM surveys. These findings were also supported by resistivity profiling and well-drilling results. The recent NGU helicopter borne FEM survey showed a good agreement with SKYTEM results. As expected, the SkyTEM survey can see deeper than the NGU FEM data. In the poster, we present different inversion results and compare detailed resistivity results of all the three geophysical methods.

Enigmatic breccia at Frøya (mid Norway) – Impact, fault or fluidization breccia?

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The Frøya islands of Mid Norway offer outcrops of breccias, which are especially well exposed on two headlands on the northeastern-most point of the islands. One of the two breccia outcrops in question, Skaget, has previously been interpreted as (1) part of a sedimentary basin or (2) as a result of a fluidization process formed during Tertiary crustal extension. The discovery of a second, comparable outcrop two km north of Skaget, at the Rottingen Island, suggests that the breccias may be part of a more aerially extensive unit, probably extending in N-S direction offshore. The breccias occur within a Caledonian (440 Ma) granite. They can be subdivided into two distinct units: a lower light green to white fine-grained breccia (unit 1) overlain by a coarse, granitic breccia (unit 2). Both units show indistinct layering dipping 20-60° towards the east. The host granite near the contact with the breccia units is severely faulted by thrusts, strike slip and extensional faults oriented N-S and NE-SW. In this granite, fault rocks are found as cataclasites along faults and as mm thick veins or slivers of microbreccia; the latter are without fault boundaries. Unit 1 is found in direct contact with the granite and consists of a 0.5 to 7 m thick zone of indistinctively layered white to light green polymict breccias. The contact zone with the granitic basement has an irregular character, in places as a diffuse transition from granite to breccia, with apophysical dikes of breccia fingerling into granite. In other places this contact is sharp. Texturally, the breccia is polymictic with clasts consisting of reworked microbreccia and granite. Apparent flow structures and pseudo lamination fingerling into fractures are present within zones of finer fragments. This indicates fluidization/mobilization of this breccia. The unit 2 breccia is separated from unit 1 by an irregular but sharp contact, bearing similarities to an unconformity. Thickness of unit 2 is unknown, as only part of the unit is exposed onshore. The unit 2 is a monomict breccia consisting of sub-rounded and angular cm- to decimeter-sized granite clasts surrounded by finer-grained granitic matrix. Bedding with variable grain composition makes it resemble typical alluvial fan deposit e.g. similar to Devonian deposits in the Norwegian Caledonides. We discuss two alternative explanations for the origin of these breccias: i) a tectonic origin; or ii) a meteoritic impact origin. Both models suggest the uppermost unit 2 breccia to be of sedimentary origin, whereas the lower unit 1 has an ambiguous origin. In the tectonic model, these outcrops represent a northernmost strand of the East Frøya Fault. This fault is a N-S trending strike-slip fault with approximately 2 km of dextral displacement. Extreme brecciation has taken place in fault bends; Rottingen represents a restraining bend as suggested by contractual faults, whereas Skaget represents a releasing bend with mainly extensional faults. The micro breccias were formed due to shear and become mobile due to overpressures in the fault zone – causing the breccia to fluidize and inject into voids and fractures in the granite. This fault activity may have been formed relatively shallow due to the low degree of recrystallization and presence of mostly brittle structures. In a meteoritic impact model the breccias may be a part of a deeper breccia system formed below a potential crater floor. Several textural observations are found similar to subcrater breccia veins in well-known craters; chaotic foliation and injection veins with no fault contact. However, so far no convincing Planar Deformation Features (PDFs) have been identified in quartz crystals; the impact hypothesis remains uncertain.
Geological Maps in the MAREANO programme


Geological Survey of Norway (NGU), Trondheim

The seabed mapping programme MAREANO aims to investigate the physical, biological and environmental status of the seabed in Norwegian offshore areas. Results are continuously published on www.mareano.no. Multibeam bathymetry and backscatter, seabed samples and video data have been continuously acquired since 2006.

One product of the MAREANO programme is geological maps. These maps are published both in digital format and as a series of pdf -maps in scale 1:100 000 on the NGU and MAREANO web sites. The maps can be downloaded and printed, or printed copies can be ordered from NGU. So far, 33 maps have been published. The maps can be found at:

- www.ngu.no/no/hm/Kart-og-data/
- www.mareano.no/datanedlasting/

The 1:100 000 maps present five different maps in one map product:

- Sediments (grain size). This is the main seabed sediment map showing the composition of sediments in the uppermost part of the seabed.
- Sediments (genesis). The map shows interpretations of processes that have been active in shaping the seabed as it is today.
- Sediments (sedimentary environment). The map shows present sedimentary environment and seabed processes, e.g. erosion and deposition areas.
- Landscapes and Landforms. The map shows interpreted large and small scale morphological elements.
- Acoustic backscatter. The map shows reflectivity data from multibeam echosounder.

The poster will present one map from the map series.

Salt tectonics of the Onion Creek Salt Diapir, SE Utah

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Salt structures are common structures in many evaporite-rich rift and continental margin basins, but relatively few are exposed at the surface. Where onshore exposures occur, such field areas provide valuable means of studying structures and structural relations at the subseismic scale. One such salt structure is the Onion Creek salt diapir in Utah, USA, and despite being an exposed and easily accessible salt diapir it has not previously been studied in detail.

The Onion Creek salt structure is located in the Pennsylvania-Permian Paradox Basin in SE Utah, and the salt-bearing unit is the Pennsylvania Paradox Formation. The salt movements commenced shortly after salt deposition and where further driven by sediments shedding from the Uncompahgre Uplift to the NE. The salt movements continued through the Permian and, for the most part, ceased during the Triassic. The Onion Creek salt diapir forms the eastern culmination of the Fisher Valley salt wall, the northernmost of the salt walls in the basin. Unlike the rest of the salt structures in the area the Onion Creek area has significant relief, which together with excellent exposures makes 3D mapping of the structure easier. Detailed mapping was carried out to address the following questions:

1) How did the caprock behave during salt movements?
2) How did the salt movement influence the immediate wallrock?

Preliminary results from the fieldwork indicate systematic folding of the immediate wallrock, with the formation of a major synclinal structure. Going northwards into the wallrock we see folding with an increase in wavelength away from the wallrock boundary. The fold axes are sub-horizontal and oriented sub-parallel with the diapir/wallrock boundary. The presence of a synform closest to the boundary is a feature commonly seen on seismic sections across salt structures, however the continued folding of the wallrock is not.

The structural expression of the caprock is rather chaotic. It comprises an insoluble residue of shale, dolostone and gypsum/anhydrite. Depending on lithology, the layers are folded, boudinaged or sheared. The fold axes of the caprock are plunging towards NE, E and SE. In conclusion, the study shows some of the complications that can be associated with salt...
diapirs on the subseismic scale, which may be of importance during seismic mapping and interpretation of such structures affected by salt structures such as the southern North Sea, the Gulf of Mexico or the Eastern South America-West African continental margins.

Robust EM model building - utilizing the full suite of data and knowledge

Bhuiyan, A. & Sakariassen, R.

Petroleum Geo-Services

Marine towed electromagnetic (EM) source-emitted signals are recorded by streamer-based EM sensors after having travelled through seawater, subsurface and air layers. The EM data recorded over the seafloor are used to detect subsurface resistors and rank hydrocarbon-bearing prospects initially identified from seismic data. Controlled source electromagnetic (CSEM) forward modeling plays an important role in sensitivity studies, survey design and data interpretation. A simplified earth model is often used in EM attribute analyses whereas in reality the subsurface geology is very complex and provides a major challenge in EM exploration. As the East Shetland Basin of the North Sea area has a very challenging geology in terms of EM surveying, it was selected as a test area. The heavy oil reservoirs of the Bentley, Bressay and Kraken discoveries are in close proximity to other highly resistive layers such as the regional Balder tuff that lies directly above the reservoirs, and a granite intrusion beneath the Bentley discovery. The weakness of the seismic resolution in the Kraken discovery also makes structural interpretation challenging. There are many benefits in making maximum use of all geophysical data and geophysical and geological knowledge as inputs into the Towed EM scenario model. Towed EM forward modeling comprises stepwise progressions from simple plane-layer through to complex scenario modeling (using realistic reservoirs and other structural units). Each step is evaluated in the context of EM sensitivity before moving to the next level of complexity. A very important aspect of the evaluation is the use of knowledge-based analysis in the acceptance or rejection of a model – in essence making constant reality checks. Seismic data from the East Shetland Basin were used to construct subsurface structural models including hydrocarbon-bearing reservoirs, the granite intrusion and the volcanic ash layer. Well log data are used to assign resistivity within the structural models.

This study focuses mainly on the EM target responses, the normalized E-field magnitudes or phase differences, referred to an off-target response. The target responses of the Bentley reservoir for a plane-layer (30 m thick and 75 Ωm resistivity) and 3D box model (areal extent of 4x12 km; 30 m thick and 75 Ωm resistivity) are unrealistically high (normalized E-field magnitudes, ~50%). Using a more realistic 3D reservoir model with the same resistivity gives weaker modeled responses (normalized E-filed magnitudes, ~20%). A response for a reservoir with uniform thickness (30 m) is high at the edge compared to a realistic 3D reservoir model of non-uniform thickness (varying between 10 and 60m). The introduction of non-hydrocarbon related high-resistivity elements (granite and volcanic ash) further improve the EM modeled responses, particularly at long offsets (granite ~1530 m below mud line). The granite beneath the Bentley discovery is generally interpreted as regionally persistent but recent, high quality seismic data provides a more precise definition of the lateral extent of the granite. Modeling using a plane-layer granite intrusion (corresponding to a wide lateral extent) reduces the overall target modeled responses (normalized E-field magnitudes, ~10%). However, the introduction of a finite granite body increases the target modeled responses significantly. The Kraken reservoir has a weak seismic anomaly response which makes it challenging to interpret if using only seismic but modeling indicates that the resistive structures could be interpreted with EM data.

Geology here and there and everywhere! Eight years with The Day of Geology in Norway

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The Day of Geology in Norway started out 8 years ago after an initiative from Halfdan Carstens in 2004, when he was the president of The Geological Society of Norway. The impulse for the initiative was to show the population of Norway the influence geology has in our land and society, both nature-wise and economically. This has been the red thread throughout the arrangements existence. Many countries have this kind of arrangement, and they vary from one country to another. In Norway it is supposed to be arranged on the
same day in September nationwide. However, 
due to convenience or size of the place it can be 
held on other days and for more days. For 
example, in Oslo we have several arrangements 
for 4-5 days. 
In Norway the Day of Geology is a joint-work 
among the geology amateur organizations, 
industry producing geological resources like 
sand, gravel and building materials, professional 
geologists in research institutes and industry. The 
group of people in these organizations reflects all 
the aspects of geology in our society; the love for 
geology in its own, geology as natural resources, 
its meaning with respect to jobs and economy, 
and technical and academic competence. 
It is The Day of Geology-arrangements from the 
southernmost tip of the country to the 
northernmost areas, from east to west. There has 
also been arrangements on Spitsbergen and on 
the off shore installations of the oil- and gas 
industry, but not in 2012. The arrangements 
include public visits to large mines like the huge 
titanium-deposit of the AS Titanium. Other 
examples are activities for schools children at 
museums, high-school students visiting research 
laboratories, geological excursions for everyone 
on foot, bicycle and boat. There has been a vast 
variety of activities offered to children, families, 
students and interested audience. 
The numbers of people involved and 
arrangement have varied from one year to 
another. In Oslo 2012 about 6000 people took 
part in a variety of activities. Throughout the 
country about 20 000 people took part in the Day 
of Geology. If this is multiplied with the 8 years of 
activity, about 160 000 people in Norway have 
had a geological experience due to this work.

Geology-education in 60 minutes! 
Teaching geology for pupils of 
primary and secondary school and 
high school at natural history 
museums

Birkeland, A.

Naturhistorisk museum, Universitetet i Oslo

A visit from groups of pupils from schools to a 
natural history museum is a special one and 
complex. It is special due to the kind of people a 
class comprises, their young age and level of 
maturity, the knowledge they have when they 
come, that they are in a situation of learning, the 
short time span of their visit and other factors. A 
lot of this differs from a leisure time-visit of the 
young people with their families or by their own. 
The obligation of a natural history museum to 
school children is to convey knowledge, to 
stimulate their appetite to investigate more, to 
make them want to go on and study natural 
sciences, to give them knowledge that is relevant 
in their lives, for example in political questions of 
environment and the exploitation of natural 
resources. This must be done in the framework of 
about 1 hour. 
The museum educators must know why teachers 
take their classes to us. This can be because they 
want their pupils to learn themes of natural 
science in an other way than in the framework 
given by the teacher and textbook, that the 
teachers want them to learn at an other arena 
and in the richness of objects from nature that a 
natural history museum can offer, that the 
teacher don’t have the competence her self to 
convey a subject. Another aspect is that our 
teaching must tie on to the curriculum of the 
schools. If not, very few teachers will find us 
adequate. On the other hand, there are factors 
influencing our teaching set by the museum 
educators, e.g. that we don’t want to do what 
might as well can be done at school facilitated by 
a schoolteacher. That we find it unnecessary to 
spend time showing pictures and films from the 
Internet that the children can see at home or at 
school. It is also that we don’t want the teachers 
to use us as entertainers on an amusing day out. 
A visit to a museum for a class is usually one of 
mainly three kinds: they walk around on their 
own watching the exhibition; they are guided 
through parts of the exhibitions by a museum 
educator who is explaining and telling the story 
of what they see, or it can be activities facilitated 
by a museum educator who is explaining and 
telling what they see and what happens. 
In the talk I will show some example of teaching 
at The Natural history museum in Oslo where 
mentioned aspects are taken into consideration. 
It will show methods where young children’s 
natural urge to be active and interact socially are 
being used as a positive element, activities in 
which their ability to be surprised and 
enthusiastic are used as a means to communicate, 
sessions were young adults need and wish to be 
intellectually stimulated, to see abroad textbooks 
and put knowledge into wider contexts are being 
acknowledged.
Structural analysis of the Leirdjupet Fault Complex in the southwestern Barents Sea

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The Leirdjupet Fault Complex is located in the southwestern Barents Sea and trends N-S from the Loppa High towards the Stappen High between 73°-73°55'N at 21°E. The fault complex divides the Bjørnøya Basin into a deep western part and a shallow eastern part, the latter formally known as the Fingerdjupet Subbasin. A set of 2D seismic lines have been interpreted in order to constrain timing of faulting and study the subsequent structuring the area has been subjected to. The fault complex has been divided up into three segments, each representing different structural settings. The study addresses the possibility of fault segmentation and linkage by examining variations in the fault throw along the Leirdjupet Fault Complex. The Leirdjupet Fault Complex has been affected by at least three tectonic extensional events and subordinate phases of contraction. The extension which occurred during Late Paleozoic may have comprised two discrete phases of tectonic movement, implying that the initial phase of fault movement rapidly was succeeded by renewed activity. The Leirdjupet Fault Complex is a deep seated structure and is assumed to represent a class 1 fault, separating areas of different tectonic outline. The fault complexes, including the Leirdjupet Fault Complex, present in the southwestern Barents Sea are likely to have developed due to deep-seated zones of weakness inherited from earlier periods of tectonic activity. Observations relating the study area to the regional development of the southwestern Barents Sea indicate that the Leirdjupet Fault Complex might bound a northern continuation of the relict structural high, the Selis Ridge, situated below the present day Loppa High.

Seismic velocities guiding geological interpretation in frontier areas: the Stappen High area, SW Barents Sea

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The Jurassic-Cretaceous basin fill of the deep Bjørnøya Basin in the SW Barents Sea shallows towards the Stappen High in the north. The high was uplifted in early Cenozoic times, most likely associated with rifting and volcanism at the central segment of the western Barents Sea continental margin. The uplift brought relatively well-consolidated Mesozoic strata to subcrop at the sea floor in an area also characterized by shallow water depths. The corresponding high acoustic impedance contrast and shallow water give rise to a series of strong and closely-spaced multiples in the seismic reflection data. In most seismic data acquired in the area up to recent years, these multiples have masked the structure and stratigraphy of the Stappen High. In new long-offset (up to 12 km) seismic lines, after successful removal of the multiples, we see very interesting structures in the northern flank of the Bjørnøya Basin up against the Stappen High, and also in the west at the down-faulted transition to the Vestbakken Volcanic Province. In addition to the south-dipping Jurassic and Early Cretaceous strata we now also see a thick succession of Triassic and Permian strata. These strata are faulted within the Stappen High causing challenges in the correlations across the faults. To guide the mapping and correlation across the major faults we have utilized the seismic reflection data in a rather unconventional way. We have analysed the refracted first-arrivals of individual shot gathers with a maximum offset of 12 km, which are usually classified as noise and muted away. By this we are able to determine the velocity-depth gradients in the upper 2-3 km. The velocity-depth gradients reflect the compaction history and maximum burial depth of the Mesozoic clastics, prior to the uplift and erosion. The shallow velocity structure is further
constrained by interval velocities from stacking velocities based on analysis of CMP gathers during the conventional processing of the seismic reflection data. The different structural domains, bounded by the major faults, reveal rather different velocities, which have to be interpreted in the context of differential vertical movements across the major faults, as well as the prominent Late Neogene uplift and erosion which affected the entire Barents Shelf.

In this presentation we will show how the shallow velocity distribution have guided our mapping and geological interpretation of this structurally complex area. We will also briefly discuss the implications for ongoing exploration activities in the area.

Subsurface monitoring of large and complex rockslides: A key requirement for early warning

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The risk from large rockslides in Norway is due to large run-out, the possibilities for river damming and the generation of disastrous tsunamis in fjords. The investigations, monitoring and early warning that have been designed and implemented for the Norwegian rockslides follows requirements guided in national codes and international standards for geotechnical design. In order to be able to have a good understanding of the landslide it is of vital importance to achieve subsurface geological data, including the depth of the instability and the related deformation. The newly ended EU project SAFELAND also concluded that early warning systems should not only be based on surface displacement data.

The subsurface monitoring systems at the monitored rockslides at Åknes and Mannen will be presented. Deep boreholes are instrumented with 100 to 120 m long DMS columns (Differential Monitoring of Stability) measuring the movements in 2D, which are linked to a fully real-time operational early-warning system. The DMS column is like a sensorized spiral cord or “snake” composed of a sequence of hard tabular modules connected to each other by special joints. The 120 m long columns consists of totally 245 sensors. The sensors include biaxial inclinometers, temperature sensors as well as piezometers and digital compasses in selected modules. These instruments are to be seen as laboratories inside the moving rocks and gives detailed knowledge about the deformation mechanisms. The system is very stable and gives continuous data with high resolution.

The displacement data from Mannen at Åknes clearly documents the sliding zones, which is also in accordance with core and borehole data. The subsurface instrumentation at Åknes gives also key information about the water-pressure, which is important for the driving mechanisms. In areas of permafrost, the system will also give temperature-depth information which is important in order to resolve the driving mechanisms.

Microseismic monitoring and analysis of injection data from the In Salah CO2 storage site, Krechba, Algeria

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1: Norwegian Geotechnical Institute
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At the industrial-scale CO2 capture and storage project at In Salah, microseismic monitoring has been tested and the injection data have been analyzed to understand the geomechanical behavior of the reservoir and sealing formations. Injection of CO2 was started in spring 2004 and continued up to the mid 2011 in three injection wells in Krechba, Algeria. A total amount of about 4 million tonnes of CO2 has been stored underground. The reservoir rock consists of a deep saline Carboniferous sandstone with a thickness of around 20 m which lies 1800 m underground. The porosity of the sandstone is between 13 and 20% and its permeability is about 10 mD. The reservoir is covered by 950 m of Carboniferous mudstones and tight siltstones which act as the seal for the storage complex. Another 900 m thick sequence of Cretaceous sandstone sand mudstones comprising the regional potable aquifer covers the sealing formations.

The analysis of pressure versus injection rate was carried out which allowed differentiation of periods of matrix and fracture injection in the three CO2 injection wells (KB-501, KB-502 and KB-503). The formation fracture pressure and maximum matrix injection rate can also be inferred. The maximum applied pressure in all three wells has most likely exceeded the fracture pressure of the...
injection horizon for periods of time. We have studied the injection history of the wells during 2010 to explore possible relationship between the microseismic and injectivity data assuming the microseismic events occur upon formation fracturing. Injection history of KB-502 showed fracturing of the reservoir about mid-year as injectivity of the reservoir increased significantly. Microseismic data have been recorded with three -component downhole geophones, deployed in a single vertical well. Waveform data from 6 levels have been recorded continuously since August 2009 and data acquisition is ongoing. More than 1500 events have been identified as occurring throughout 2010. The observed microseismic activity from 2010 appears to correlate well with CO₂ pressure and injection rates at the well head, showing an increase in seismicity observed mid-year. Typical peak activity of 20-40 microseismic events per day was observed. It can be inferred that increases in microseismic activity correlate with formation fracturing and thus microseismic monitoring is a good monitoring technique to manage reservoir fracture pressure. Interpretation of the microseismic data, i.e. the locations of the events and their source parameters in combination with the injection rate and pressure data at the well head, can provide valuable information about the CO₂ behavior and processes related to injectivity and fracturing within the reservoir.

10 Myr of ecological crisis in the Permian of Spitsbergen: timing, magnitude, and possible causes of the middle- and end-Permian extinctions

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Highlights:
• Discovery of Middle Permian extinction in Boreal Realm
• End-Permian extinction may have happened earliest in Spitsbergen
• Middle Permian extinction may have been more severe of the two
• Transition to "Mesozoic" character occurred in aftermath of Middle Permian event
The middle to end-Permian (260-250 Myr BP) witnessed two mass extinctions that changed the course of life on Earth. The first, a Capitanian extinction, lay for many years undiscovered in the shadow of the greatest crisis in Earth’s history, at the close of the Permian. The earlier of these events (occurring in the penultimate Stage of the Permian) wiped out >50% of marine invertebrate species and was first discovered in the record of fusulinacean foraminifers in South China, where it is seen to precisely coincide with the onset of Emeishan large igneous province volcanism. This Capitanian extinction may be temporally associated with terrestrial losses amongst plants and megafauna suggesting an event of global scale with a suitably large trigger in the form of volcanic and thermogenic emissions from Emeishan. The results of two seasons’ fieldwork in Isfjorden (Festningen) and Van Keulenfjord have revealed the Capitanian extinction event for the first time from a northern mid- to high-latitude (Boreal Realm) setting, confirming its global extent. The more famous and better studied end-Permian event resulted in the loss of 95% of marine species, and occurs close to the Permian-Triassic boundary (PTB) in many regions. This event likely also had a volcanic origin: the Siberian Traps. The timing of this extinction in Spitsbergen is examined here, where it appears to predate the lithologically and chemosтратigraphically defined PTB, raising the prospect that Siberian Traps volcanism affected the inherently less hospitable environments of the higher latitudes earlier than the tropics. Although of less significance globally, the Capitanian event may have seen more severe losses in the mid- to high latitudes of Spitsbergen than the latest Permian event. Thus, ranges of the superbly well-preserved and abundant brachiopod and bivalve faunas of Spitsbergen point to an abrupt and major extinction at a level that can be correlated with the Capitanian J. altudaensis conodont Zone in China (the level at which Emeishan volcanism initiated). Following a barren interval (also seen in China) an entirely new assemblage of brachiopods and bivalves radiated in the Late Permian. These faunas have a prominent "Mesozoic" character, suggesting that the transition from "Palaeozoic" to "Mesozoic" fauna may have occurred in the aftermath of the Capitanian event. The Late Permian assemblages in Spitsbergen never reached the levels of diversity seen in the Middle Permian, and were short-lived, disappearing entirely in the upper few metres of the Permian Kapp Starostin Formation.
New U-Pb LA-ICPMS zircon provenance age data on Triassic sandstones (Vilchekov, Vasilyev and Thegetthoff formations) from Franz Josef Land: Preliminary results

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Franz Josef Land represents the northern-most uplifted margin of the Barents Sea. The archipelago has a complex tectonic history that has been influenced by the tectonic developments of the Norwegian–Greenland Sea and the Arctic Ocean. Detrital zircon U-Pb LA-ICPMS age data from core samples of Triassic sandstones are used to investigate provenance changes over time and constrain potential source areas as well as compare with time equivalent successions on Svalbard. The Triassic sequence of Franz Josef Land is about four times thicker than the corresponding successions on Svalbard, which raises questions about the differences and similarities of the depositional environments and sediment sources for these areas. The core samples analyzed were provided by VNIIOkeangeologia, St. Petersburg. Samples collected from Alexandra, Hayes and Graham Bell islands represent depositional ages from Ladinian to Norian. The preliminary zircon age data suggest a dominating south-easterly (Uralides) Late Triassic source. Our preliminary results from Graham Bell Island show that Caledonian (c. 390-500 Ma) and Neo- and Mesoproterozoic zircon ages are well represented in the samples, whereas Paleoproterozoic and Archaean zircons are few or not detected. The Carnian (Vasilyev Fm.) and Norian (Thegetthoff Fm.) provenance signatures are similar to those of the De Geerdalen Formation and the Wilhelmøya Subgroup, respectively, on Svalbard.

Zircon provenance data from Triassic sediments on Bjørnøya, the Urd and Skuld formations: new constraints on depositional models in the western Barents Sea

Bue, E.P., Andresen, A. & Nystuen, J.P.

Bjørnøya is situated on the Stappen High and is the southernmost island of the Svalbard Archipelago that represents the uplifted western margin of the Barents Sea. Models of the depositional history of the Barents Sea region based on seismic data, drill core and provenance studies indicate that this epicontinental sea was filled in towards the northwest and west during the Triassic. These models can be tested and refined by direct sampling and provenance analyses of sediments exposed on Bjørnøya. In this study, the provenance of Triassic sandstones on Bjørnøya was studied by zircon LA-MC-ICPMS U-Pb analyses. One sample from the Urd Formation and two from the Skuld Formation were collected at Miseryfjellet and analysed. The data show distinct differences in zircon age populations. The Urd Formation sediments reached Bjørnøya in the Olenekian and display a distinct Late Palaeozoic Uralide signature that demonstrates ultimate derivation from the east. The data also include Palaeozoic and Precambrian, mainly Meso- and Neoproterozoic, ages that most likely reflect derivation from continent Baltica in the south. These sediments are therefore interpreted to have originated in the Ural mountains and in Baltica. The zircon age data from the Skuld Formation lack the Late Palaeozoic Uralide signature and mainly Meso- and Neoproterozoic ages are present. This suggests a western Laurentian (North Greenland) source in the Middle and early Late Triassic, that most likely includes reworked sediments with proto-sources in Canada and Greenland. The data from the Urd and Skuld formations are distinct from their equivalents further north on Svalbard (e.g. on Spitsbergen). The data from Bjørnøya demonstrate changes in sediment provenance during the Early and Middle Triassic in the western Barents Sea and shows that the east derived sediments have a distinct and easily identified signature that is useful for constraining depositional models of the Mesozoic in the Barents Sea.

An analysis of Wilson Cycle plate margins: From suture to ocean?

Buiter, S. & Torsvik, T.

The Wilson Cycle theory of oceanic closure and opening along the same suture is a powerful concept in analyses of ancient plate tectonics. It
imply that collision zones can be extensionally reactivated long time after the collision has waned. However, some sutures are seemingly never reactivated and already Tuzo Wilson recognized that Atlantic break-up did not follow the precise line of previous junction. We have reviewed margin pairs around the Atlantic and Indian Oceans with the aim to evaluate the extent to which oceanic opening used former sutures, summarise delay times between collision and break-up, and analyse the role of mantle plumes in continental break-up. We aid our analyses with plate tectonic reconstructions using GPlates (www.gplates.org).

Although at first sight opening of the North Atlantic Ocean largely seems to follow the Iapetus and Rheic sutures, a closer look reveals deviations. For example, Atlantic opening did not utilise the Iapetus suture in Great Britain and rather than opening along the younger Rheic suture north of Florida, break-up occurred along the older Pan-African structures south of Florida. We find that today's oceanic Charlie Gibbs Fracture Zone, between Ireland and Newfoundland, is aligned with the Iapetus suture. We speculate therefore that the Iapetus suture was reactivated as a transform fault. As others before us, we find no correlation of suture and break-up age. Often continental break-up occurs some hundreds of Myrs after collision, but it may also take over 1000 Myr, as for example for Australia-Antarctica and Congo-São Francisco. This places serious constraints on potential collision zone weakening mechanisms.

Several studies have pointed to a link between continental break-up and large-scale mantle upwellings. It is, however, much debated whether plumes use existing rifts as a pathway, or whether plumes play an active role in causing rifting. We find a positive correlation between break-up age and plume age, which we interpret to indicate that plumes can aid the factual continental break-up. However, plumes may have been guided towards the rift for margins that experienced a long rift history (e.g., Norway-Greenland), to then trigger the break-up. This could offer a partial reconciliation in the debate of a passive or active role for mantle plumes in continental break-up.

Cenozoic exhumation in the Snøhvit area, Hammerfest Basin, Norwegian Barents Sea

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The Barents Sea is well known for its unusual basin evolution and complex uplift history which have resulted in the discovery of abundant gas and little oil. Several recent oil and gas discoveries in the southwestern Barents Sea are now triggering an increased interest in this huge, largely unexplored petroleum province. The complexities of the Hammerfest Basin necessitate the use of all available geological and geophysical information when undertaking regional interpretations, play fairway assessments and prospect definition. In order to study the petroleum system, it is also important to investigate exhumation effect on the rock properties and hydrocarbon prospectivity. This study focuses on estimation of Cenozoic exhumation in the Snøhvit area that comprises three discoveries Snøhvit, Albatross and Askeladd. An integrated approach, using well log data and published compaction curves, has been utilized to estimate exhumation based on transition zone between mechanical and chemical compactions. Bottom hole temperature has been used to infer the transition zone temperature. On the basis of transition zone, the estimation for exhumation is investigated. A suite of well logs from 15 exploration wells from the Snøhvit area, has been taken into account. The transition zone from mechanical to chemical compaction marked on the basis of grain framework stiffening due to the onset of quartz cementation as long as the surface area is available for precipitation of quartz and temperature is higher than 70°C. Compaction of sediments occurs due to effective vertical stress at a shallow depth (mechanical compaction) and dissolution of unstable minerals and precipitation of new and more stable minerals at a higher temperature corresponds to greater burial depth (chemical compaction). Due to the combine effect of mechanical and chemical compaction, the rock properties such as velocity, density and porosity alter continuously with increasing burial depth. Our analyses show that the present day transition zone temperature in the study area does not match with the actual temperature reflecting Hammerfest Basin as an exhumed basin. The compaction trends, particularly, velocity versus depth found in the studied wells have been used to investigate the transition from mechanical to chemical compaction. When Vp versus depth trends have been compared with published compaction curves, there was found a mismatch on the basis of which exhumation was calculated. The
calculated exhumation estimates differs for Snøhvit, Albatross and Askeladd discoveries depending upon the structural configuration. The exhumation for Snøhvit field is from 300 to 800 m increasing from west to east whereas in the Albatross discovery it increases in opposite direction ranging from 700 to 1000 m. In the Askeladd discovery it ranges from 300 to 1000 m and decreasing from south to north. This exhumation estimation is in accordance with the published literature.

It is clear from our investigation that a complex burial history of Hammerfest Basin involving uplift, erosion and renewed burial during Cenozoic time has influenced the distribution of hydrocarbon in the reservoirs and the position of fluid contacts.

Catastrophic fluid escape venting tunnels and related features associated with large submarine slides on the continental rise off Vesterålen-Troms, North Norway

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Video inspection of the seabed on the continental rise (ca. 2200 m water depth) off Vesterålen- Troms, North Norway has revealed several remarkable features, including large tunnels, small tunnels, chimney tunnels, carbonate crusts and bacterial mats. The structures occur in landslide areas with slide blocks up to 2 km long, 1 km wide and 100 m high.

There are several alternate and/or related explanations for the large seabed tunnels with opening diameters up to 1 m and inner diameters of 10-20 cm. We favour two causal hypotheses for the large tunnels: 1) they formed due to dewatering of fine-grained Lofoten Basin Channel levee deposits on which the slide masses accumulated and/or 2) they formed by sudden venting of underground gas accumulations due to loading by the slide masses. The tunnel formation probably occurred instantaneously, following sliding, possibly as explosive blowouts.

Numerous small tunnels with diameters up to a few centimetres occur in slide blocks of compacted sediments and in scarp edges in the continental slope. They are interpreted to have been formed by 1) fluid expulsion following off-loading as a result of submarine sliding, which exposes overpressured pore waters to ambient pressures and convergent flow immediately within the scarp edge/slide block margins with resultant blowout, and/or 2) destabilization and decomposition of gas hydrates as a result of sliding.

Cemented chimney tunnels up to 15 cm tall, and with inner diameters up to a few centimetres occur both in broken sediment blocks and on the present seabed. Chimney tunnels in broken blocks may have formed in the sediment prior to sliding, while overturned and upright chimney tunnels on the seafloor indicate that fluid release is a process that has been going on for a long time period, possibly from immediately after sliding up to the present.

Cemented chimney tunnels, bacterial mats and carbonate crusts indicate active leakage of subsurface fluids and methane through the seabed and the gas hydrate stability zone, either from thermogenic sources or from shallower reservoirs.

The data were collected by the MAREANO programme (www.mareano.no) which is a multidisciplinary marine mapping programme providing knowledge for sustainable ocean management.

Reference:

Mesozoic basins, sediments and structures onshore Norway and in the coastal zone

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Erratic blocks of Mesozoic sediments were found in Norway for the first time in 1845, on the
northwest shore of Beitstadfjorden, and in 1867, an outcrop of coal utilized by local farmers on Andøya was investigated. Subsequent mapping on Andøya and new finds of erratic blocks along the coast of Norway indicated that Mesozoic rocks could be present in several fjords and offshore the present coastline. Geophysical and geological mapping of the Norwegian continental margin started in the 1960’s. Mapping of the shelf was intensified after discovery of the Ekofisk oil field in the North Sea in 1969, but the first map of Mesozoic rocks in the coastal zone was not published before 1975. Later, shallow sampling and stratigraphic drilling was performed in many sub-cropping sedimentary units along the coast.

On the mainland of Norway, Mesozoic sedimentary rocks (Jurassic and Cretaceous) crop out on Andøya only. These are the youngest rocks on land in Norway. Triassic dykes occur in West Norway, while Mesozoic structures and fault products are common at major and minor fault zones in various parts of coastal Norway. Deep weathering products (saprolite) of Mesozoic (mainly Triassic) age occur also, mainly along major fault zones. Many of these fault zones represent reactivated Caledonian-Devonian structures. Sedimentary rocks are found in half-grabens in many fjords, especially in Mid Norway and northern Nordland. The majority are of Middle-Late Jurassic age and are interpreted to represent the remains of a much more extensive Jurassic-Cretaceous sedimentary succession that covered large parts of coastal Norway. The sedimentary rocks were downfaulted during tectonic activity in Late Jurassic-Early Cretaceous times, thus escaping late Tertiary-Quaternary erosion.

Detailed lithostratigraphic and sequence stratigraphic correlation of the Mesozoic successions in the coastal zone with age equivalent successions offshore have only been done for Andøya. Such detailed correlations remain to be published for other nearshore/inshore Mesozoic basins. Although most of the coastal area has now been investigated in search for Mesozoic basins, at least at a reconnaissance scale, none of the basins, except for the one at Andøya, has been drilled and properly documented. This is a future major task that would lead to a much more thorough understanding of the Mesozoic and Cenozoic geological development of the Norwegian coastal zone.

References:


Shallow gas, gas hydrates and pockmarks along the Norwegian offshore: Is there any relation to deglaciation?

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The MAREANO project, which started in 2005, has performed seabed mapping (hydrography, biology, geology and environmental studies) off Lofoten-Vesterålen and in the SW Barents Sea. Data collected show seafloor features such as fluid flow imprints, which can be assessed using gas hydrate modelling and shallow and deep seismic data. One of the issues looked into has been how to estimate the effect of the last glacial on the gas hydrate stability zone, and its relation to pockmarks at the seafloor, fluid flow anomalies, and gas hydrate bottom simulating reflectors (BSR) in the subsurface. The North Sea, Norwegian Sea and Barents Sea were strongly affected by glaciers during the glaciations. The study has shown a large change in the gas hydrate stability zone (GHSZ) since the last glacial maximum and resulting in release of gas trapped as gas hydrates within it. Due to melting of gas hydrates, which happened due to changes in bottom water temperature and unloading when glaciers lifted from the seabed, gas escaped through the seafloor creating pockmarks. Stratigraphic studies in the pockmark areas have provided good control on when the pockmarks formed. Restricted sediment infilling in pockmarks and their penetration of the marine-glaciomarine sediment boundary indicate that they formed after deposition of the glaciomarine sediments and that they were active to the very recent past. Fluids are also leaking along stratigraphic boundaries and open faults from deeper source rocks.
Characterization of magma batches and reconstruction of the evolution of plutons using trace element of rock-forming minerals: Sausfjellet pluton, Bindal batholith, Central Norway

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The size of magma batches, the nature and extent of their interactions, and whether or not large magmatic reservoirs are able to develop at mid-crustal level has been debated over the past decade. These questions have consequences for our understanding of the thermal structure of the crust, the relationship between magmatic and regional metamorphic events, and also for the volume of ore deposits resulting from extreme magma fractionation of magmatic systems. In this study we present a new approach to estimate the size and extent of interaction between magma batches that formed intrusive bodies through the use of the trace element record of rock-forming minerals. A previous study conducted on augite in the lower part of the Wooley Creek batholith, northern California concluded that this portion of the intrusion was emplaced as individual magma batches of basaltic andesite to andesite composition and that individual batches underwent fractional crystallization, because augite populations in individual samples plot along distinct fractionation trends. Interaction between the different batches was limited despite the fact that no sharp contacts were observed and that these batches can be considered coeval based on ID-TIMS data (Chamberlain, personal communication).

In order to test the validity of this method and better understand its potential for reconstruction of magma evolution through time, a similar study is being conducted on the Sausfjellet pluton, a part of the Bindal batholith, north-central Norway. Previous study (Barnes et al., 2004; Lithos (75) 389-412) suggested that stage 2 of this intrusion, which is asymmetrically zoned, results from the evolution of a single magma batch by fractional crystallization coupled with assimilation. Stage 2 rocks range from modally-layered biotite two pyroxene diorite in the east, to nearly massive biotite hornblende quartz monzodiorite in the west. Augite found in stage 2 has Mg# varying between 0.71 and 0.60 with the highest Mg# corresponding to augite found in the most mafic part if the unit. Augite from the layered part of the intrusion is normally zoned and displays lower total REE concentrations (100-180 ppm), smaller negative Eu anomalies (0.65-0.40), and lower Zr (40 to 150 ppm) than augite in the more evolved part of the unit (300-530 ppm, 0.6 to 0.1 and 80 to 300 ppm for REEtot, Eu anomaly and Zr respectively). These observations are consistent with evolution of at least a part of stage 2 by fractional crystallization of a single magma batch. However, augite from the most evolved stage 2 rocks does not plot on a simple fractionation trend. This distinction indicates that fractionation was not the only process involved in the genesis of this unit. Enrichment in Zr and depletion in Sr in augite associated with increased bulk-rock δ18O in these evolved rocks suggests that assimilation might be responsible for such chemical variations. These results indicate that use of trace element compositions of rock-forming minerals, combined with field work and bulk rock geochemical data represent a useful tool to understand the evolution of melt compositions through time and predict the behavior of various elements in individual magmatic systems.

Post-orogenic 1560 Ma pegmatite dykes in the Astridal metasupracrustal belt, West Troms Basement Complex: a distal effect of granite-forming processes and intracratonic deformation

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The West Troms Basement Complex consists of Neoarchean and Paleoproterozoic crust that likely represents the continuation of the Fennoscandian Shield beneath and across the Caledonian Nappes. The complex is transected by several ductile shear zones and consists of belts with mixed lithologies including abundant metasedimentary and metavolcanic rocks that record a polyphase deformation history. Late granite pegmatites in the Astridal belt of the Senja Shear Belt have been deformed and yield U-Pb ages of 1725 ±22 Ma and 1562 ± 2 Ma, with evidence of an overprint at about 400 Ma which formed or reset some, but not all, titanites. The ages indicate that formation of the pegmatites...
occurred very late, and in part after termination of the main Svecofennian orogeny (ca. 1750 Ma). Comparison within the larger scale context of the Fennoscandian Shield suggests that emplacement of these pegmatites may have been caused by late-stage reactivation of shear zones as a distal effect of deeper crustal processes, e.g. intrusion of the coeval aged Åland rapakivi granite suite in the central Baltic Sea region.

U-Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province

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The opening of the Arctic oceanic basins in the Mesozoic and Cenozoic proceeded in steps, with episodes of magmatism and sedimentation marking specific stages in this development. Besides the stratigraphic record provided by sediments and fossils, the intrusive and extrusive rocks yield important information on this evolution. This study has investigated the age of mafic sills and one felsic tuff in Svalbard and Franz Josef Land using the ID-TIMS U-Pb method on zircon, baddeleyite, titanite and rutile. The results indicate crystallization of the Diabasodden sill at 124.6 ± 0.3 Ma and the Linnévatn sill at 124.8 ±0.4 Ma, the latter also containing slightly younger secondary titanite with an age of 123.9 ± 0.3 Ma. A bentonite in the Helvetiafjellet Formation, also on Svalbard, yields an age of 123.3 ± 0.3 Ma. And, finally, a mafic sill in northeastern Franz Josef Land yields a baddeleyite age of 121.5± 0.3 Ma, which, because of the thin shape of these crystals, is likely to be 1 or 2 m.y. younger than the actual age. Data for two other sills intercepted in the Nagurskaya and Severnaya boreholes indicate preliminary zircon ages of 122-123 Ma. The new radiometric ages document that the magmatism in the northern Barents Sea was a short-lived event in Early Cretaceous, about 123-125 Ma.

A new valorization system for geological building materials of national, regional and local significance

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Our society depends completely upon access to mineral resources in order to function. Without such access, society becomes vulnerable. However, this issue is very seldom addressed by policy makers or land-use planners, neither on local nor regional scale. The Geological Survey of Norway provides information and decision support for the management agencies that addresses both the society's need for building materials as well as information on mineral resource quality, based on geological and mechanical parameters. We are now launching a system with a quantitative valorization of deposits, to be used by land-use planners. This system will, in turn be utilized by the Commissioner of Mines to supervise land-use planning on local and regional level around the country. The parameters will be presented in the lecture.

Thermodynamic constraints on the microbial ecology and biogeochemical cycling in deep-sea hydrothermal systems

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The Loki’s Castle and Jan Mayen hydrothermal systems on the Arctic Mid-Ocean Ridge (AMOR) are very different in terms of geological setting and chemical composition of venting hydrothermal fluids. Experimental data in combination with numerical models were used to evaluate the effect of these differences on the microbial ecology and biogeochemical cycling at the different sites. The modeling was done by in silico mixing of seawater and hydrothermal fluid at various mixing ratios followed by calculation of Gibbs free energy from selected redox reactions. Experimental data include high throughput
sequencing of amplified 16S rRNA genes and metatranscriptomic data from total RNA. Modeling suggests that the energy available from each kilogram of vent fluid from the sediment influenced Loki's Castle by far exceeds the energy of the basalt hosted Jan Mayen vent field. Sulfide oxidation dominates the energy landscape at the Jan Mayen field at low and moderate temperatures (<40°C). However, at Loki's Castle there is a shift from methane oxidation as the most energetic reaction at low temperatures (<15°C) to hydrogen and sulfide oxidation at moderate temperatures (<40°C). Consistent with this, biofilms dominated by sulfur oxidizing and hydrogen oxidizing Epsilonproteobacteria as well as biofilms dominated by methane oxidizing Methylo coccales are present on the Loki's Castle chimney walls. Metatranscriptomic analyses also revealed that Epsilonproteobacteria at Loki’s Castle have a high expression of denitrification genes, indicating that respiration with nitrate is important for primary production on chimney surfaces. Modeling, on the other hand, suggest that denitrification represents less than 10% of the energy available for Epsilonproteobacteria. At high temperatures (>50°C) anaerobic respiration with sulfate or CO₂ as electron acceptor gets more endergonic than aerobic respiration. This shift seems to be accompanied by a shift in functional groups of microorganisms, with high relative abundances of anaerobic methane oxidizers both at the Jan Mayen and Loki’s Castle vent fields at high temperatures. Our study illustrates how geochemical modeling and modern sequencing technology can be a useful combination for generating and testing hypothesis in the field of microbial ecology.

Thorium in the Fen Carbonatite Complex: More energy than in all Norwegian oil and gas resources combined

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The ankerite carbonatites and hematite-calcite carbonatite rocks ("rødberg") of the Fen carbonatite complex have for quite some time been known to contain a considerable amount of thorium minerals. These thorium resources have been quoted among the worlds largest deposits. Previous resource estimates given by USGS and IAEA are 180 and 132 thousand tons respectively. The background for these estimates is, however, not known. New estimates calculated on basis of 663 whole rock analyses form surface and drill core samples reveal that the thorium resources to a depth of only 100 meters is at least 56500 tons. Thorium resources estimated assuming an extent down to 500 meters depth, which is not unlikely, may be up to 675,000 tons. The thorium-bearing rocks may continue to an even greater depth, and thus the total thorium resources may be even higher. For comparison the energy of the Fen thorium resources amounts to somewhere between 10 and 120 times (or even more) the energy of ALL Norwegian oil and gas resources (produced, known and hypothetical) combined.

Thorium may become an important, efficient and CO₂-free energy source in the future. In fact energy-producing thorium-based scientific power-plants have formerly been in operation in the US, but were closed down because they "did not fit into the US nuclear strategy". As thorium is about 4 times more abundant than uranium in the upper continental crust thorium as an energy-source is virtually unlimited. There are, however, several general challenges in nuclear science that must be solved before thorium energy may be produced commercially.

At Fen the thorium mainly occurs as thorianite and in monazite, both intimately associated with the REE minerals bastnaesite, parsite and synchysite. All these minerals typically occur dispersed in the rocks as tiny grains, only a few microns large. This ultra-fine dispersal of the thorium-bearing minerals represents a major challenge for a potential future thorium extraction form the Fen ores.

Thorium may be extracted from many ore deposits throughout the world, and from several of these deposits thorium is more easily extracted than from the Fen ores. Today thorium merely represents a problem in mineral processing and in the industrial use of other components from thorium-bearing minerals.

The world’s future need of energy is, however, enormous, and if thorium power-plants become widespread globally the picture may change dramatically and the Fen thorium deposits may become exploitable. Thorium also may become a strategic resource, and thus Fen may become important for Europe. If exploited, thorium most likely will be extracted along with REE minerals also of great importance to modern industries. The use of Fen thorium resources eventually belongs to the future, possibly a few generations away. In the meantime we should map the thorium and REE resources in 3D, perform research projects on industrial thorium and REE extraction from the Fen ores and develop
Potential smart mining concepts that may allow environmentally acceptable mining operations in the area.

**Palynological studies of the upper Oppdalsåta Member and the Slottsmøya Member (Agardhfjellet Formation), Upper Jurassic-Lower Cretaceous in Janusfjellet and Knorringfjellet, central Spitsbergen**

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The Upper Jurassic-Lower Cretaceous in the Isfjorden area (central Spitsbergen), at localities Knorringfjellet and Janusfjellet, consists of dark siliciclastic rocks, mostly dark shales, and local carbonate seep bodies. Totally 37 samples from the silts and dark shales and three samples from the carbonate seep bodies are studied through palynological analysis. Two zones have been defined on the basis of dinoflagellate cyst assemblages. The lower boundary of Zone 1 is defined by the last abundant occurrence for *Valensiella cf. ovula* and the first abundant occurrence of *Sirmiodinium grossii*. The upper boundary (= base of Zone 2) is defined by the last abundant occurrence of *Paragonyaulacysta* sp. and the first common occurrence of *Tubotuberella apatela* and *Kallosphaeridium* sp. Zone 1 is also characterized by the highest frequencies of *S. grossii* and *Paragonyaulacysta* sp. The upper boundary of Zone 2 is defined by the last common occurrence of *Kallosphaeridium* sp. Zone 2 is also characterized by the highest frequencies of *Prolimosphaeridium anasillum* and *Escharispaheridia* sp. in the Knorringfjellet profile. The zones are correlated with foraminiferal zones and ammonite zones from the same area. The zones are also established with reference to δ¹³Corg curves presented by Hammer et al. (2012). The dinoflagellate cyst occurrences recorded from the Agardhfjellet Formation in central Spitsbergen, are compared to occurrences from other localities in the Boreal Region, and chronostratigraphic deviations are evident. Few stratigraphically diagnostic species are recorded in the assemblages in this study. The established zones are correlated with the foraminiferal assemblages presented in Hjálmarsdóttir (2012), as the material is from the same rock samples. Datings based on ammonites and agglutinated foraminifera suggest an Early Volgian to Late Ryazanian age for the Slottsmøya Member.

A *Leiosphaeridia* bloom at 45.62 m in the Janusfjellet profile is correlated with a *Leiosphaeridia* bloom on the western Barents shelf. This *Leiosphaeridia* bloom is assumed to have been induced by the Mjølnir meteorite impact at the Volgian-Ryazanian boundary. Palynofacies analysis has been carried out to interpret relative sea level changes. Occurrences of bisaccate/monosaccate pollen, regular pollen, spores, «plant debris», amorphous organic matter, dinoflagellate cysts, *Tasmanites, Leiosphaeridia*, wood and chitinous microforaminifer test linings are used in the sequence stratigraphic analysis. The palynomorphs and the palynodebris from the carbonate seep deposits show better preservation than the palynological contents in the shale deposits. This is due to early authigenic precipitation of carbonate, which led to a relatively rapid cementation of the sediments, preventing flattening of the fossils. This study is the first detailed report of palynomorphs and palynodebris from hydrocarbon seep bodies.

**References:**

**Extensive faulting and related fold evolution along the Oseberg Øst fault system, Norwegian North Sea**

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Interaction between normal faulting and associated propagation folding has implications for the understanding of hangingwall depocentre geometries and syn-rift sedimentary systems.
Three dimensional seismic and well data are used to understand the geometry and evolution of the Oseberg 9st normal fault system from the Jurassic North Sea rift. Integrated structural and stratigraphic analysis permits the reconstruction of initiation, growth, interaction and linkage of normal fault segments and highlights the role of fault-related folding in the development of a normal fault system. The 11 km long, planar normal fault system dips to the W, has up to 550 m displacement, and has a dominantly NNW-SSE strike, although prominent NNE-trending fault ‘jogs’ are present. Overall, displacement and associated drag increases towards the southern end of the fault system. Local displacement minima occur at the linkage point between incipient fault segments.

Analysis of sequential isopachs, stratal geometries and displacement distribution show that isolated fault-parallel synclinal depocentres formed in the hangingwall of the propagating fault segments during a Late Bajocian – Bathonian rift initiation stage. The depocentres were associated with fault-parallel monoclinal folds above buried normal fault tips and their lengths were related to the length of the underlying, blind fault segments. In contrast, fault-perpendicular hangingwall anticlines located adjacent to the present day fault jogs and local displacement minima separated the synclinal fault-parallel depocentres along strike. The individual fault segments subsequently linked along-strike by breaching of existing relay ramps to form a single laterally extensive hangingwall depocentre during the rift climax (Middle-Late Oxfordian). Resulting from the evolving fault system inferences can be made on geometries of hangingwall depocentres, the timing and origin of sediment sources and main sediment transport system(s): (I) the orientations and interactions of normal faults and folds define the location of the hangingwall depocentres, (II) displacement minima are areas of segment linkage (e.g. breached relay ramps) result in intra-basinal highs, and (III) the fault scarp-related sediment input and the associated relay ramps defined the local pathways for coarse grained clastic sediments that have been delivered into the adjacent fault-parallel hangingwall depocentres.

Relationship between glacial erosion and fluid flow inferred from 3D seismic data, SW Barents Sea

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This study investigates the relationship between glacial erosion, glaciotectonically displaced sediment blocks and indications of fluid flow and shallow gas accumulations in buried glacial sediments of the south-western Barents Sea margin. The study is based on two three-dimensional (3D) seismic datasets, NH98003 and EL0001, regional 2D seismic data and exploration well 7216/11-1. 3D seismic techniques have allowed mapping and visualizing of buried geomorphological features in great details within the study area. Large semi-circular depressions and fluid migration pathways are imaged, as well as glaciogenic sediment blocks and rafts. A glaciogenic origin is inferred for the megablocks and rafts indicating high glaciotectonic activity of the former ice streams. Six large-scale depressions are inferred to be sources for the removal of sediment mega-blocks and rafts at one particular stratigraphic level of the Plio-Pleistocene succession. Mapped fluid migration pathways and shallow gas accumulations show evidence of an active fluid migration system, and its spatial relationship with the erosional depressions is documented. Modeling of the gas hydrate stability zone has been performed for glacial and interglacial conditions and its effect on the sediment properties is discussed. A conceptual model is proposed for the formation of the depressions, where brittle glaciotectonic deformation along a weak layer at the base of gas-hydrate cementing sediments is inferred. Subsequent expulsion of gas-rich fluids is assumed to have followed deglaciation which might further have reworked the depressions.

Mapping and modelling seabed nature-types in the MAREANO programme

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Seabed nature-type (habitat) mapping is an important component of the MAREANO seabed mapping programme – www.mareano.no. Nature types are being mapped across a range of spatial scales from landscape to ecosystem level. Within the area mapped to date by MAREANO we find diverse physical landscapes exhibiting a wide range of variation in topography and sedimentary conditions at the seabed. This geological diversity gives rise to diverse habitats and spectacular benthic fauna including cold water corals, sponge...
Mineral reactions and structural evolution of shear zones transecting the layered sequence of the Leka Ophiolite Complex (LOC): Field relations and micro-textures

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Serpentinisation and chemical alteration of the oceanic mantle is fundamental to understanding processes observed at Mid-oceanic ridges. The process that alters the mantle lithosphere can be studied in exposed ophiolite complexes. The Leka Ophiolite Complex (LOC), Nord-Trøndelag, is considered to be a part of the Uppermost Allochton that was thrust up on Baltica during the Caledonian Orogeny. This makes the LOC, which is assumed to represent a unique cross-section through the oceanic crust and subjacent mantle, an excellent place to study the coupling between deformation, hydration and transport of elements, reflected in changes in mineralogy and textures.

LOC displays a penetrative NW-SE trending foliation that is transected by an EW trending conjugate set of deformation zones. Detail mapping reveal that the EW to NE-SW trending shear- and fracture zones show movement locally with a displacement of several meters. The deformation zones display textures and structures formed during granulation and cataclastic flow. These deformation zones function as conduits for fluids and facilitate transport of mobilized elements. Ca derived from serpentinisation of primary clinopyroxene is transported along such deformation zones and result in formation of secondary diopsidic pyroxene. Where the deformations zones transsect plagioclase bearing rocks rodolites are formed (Austrheim and Prestvik 2008). A number of replacement textures are present in the wall rock of the shear zones and allows the following reaction to be written:

Olivine → Clinopyroxene, Orthopyroxene → Clinopyroxene, Chromite → Chlorite → Clinopyroxene, Clinopyroxene → Serpentine.

We speculate that the described alteration occurred when the LOC was still part of the oceanic lithosphere. We present deformation textures and mineral chemistry from micro-scale shear zones in drill core samples obtained from two outcrops in dunites belonging to the layered cumulate section south of Kvaløya farms.

Reference:

som følger med et kommersielt marked som etterspør tjenester. Risikoen man står overfor i en slik situasjon er at innsats kan bli fragmentert og lite målrettet mot de løsningene som skal til for å realisere CCS i stor skala.

Som et forspøk på å bøte på denne situasjon har FOU miljøene sammen med CLIMIT utarbeidet en næringspolitisk visjon, som er ment å være retningsgivende for FOU innsatsen videre. Den lyder:

«Norske Forskningsmiljøer skal bidra til å utvikle kunnskap og teknologi som muliggjør etablering av et "sentrallager" på norsk sokkel som kan ta imot >10 Mt CO₂-pr år fra norske og europeiske kilder i 2018. CO₂ lagring skal sees i sammenheng med potensial for utvikling av EOR, åpne nye markeder for vår petroleumskompetanse og utnytte det forretningsmessige mulighetsvindu som forventes innen CO₂ lagring»

I løpet av høsten 2012 blir det gjennomført et forprosjekt for å avklare nærmere hvordan en slik visjon kan bidra til å identifisere de mest sentrale geofaglige og petroleumteknologiske gap som må lukkes for å realisere et generisk sentrallager. Dette innebærer at man må vurdere så vel geofaglige og reservoartekniske problemstillinger samt utbyggingsløsninger, logistikkproblemer, synergier med CO₂ til EOR med mer. Med dette ønsker man å få frem hvordan dette dekkes av pågående FOU, alternativt hvilke gap som finnes, samt hvordan vi bør innrette oss for å lukke gappene.

I forøvrig blir resultatet fra dette forprosjektet presentert.

**Status innen CCS ved årsskiftet 2012-13: hvor står vi og hvor går vi?**

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Utfordringer knyttet til teknologienes kostnader og modenhed samt svak prosjøen med hensyn på å utvikle rammebetingelser (lovgivning og internasjonale avtaler), manglende offentlig og industriell finansiering og til slutt motstand mot lagring på land på kontinentet har bidratt til å utsette beslutninger som vil føre til gjennomføring av de første fullskala demonstrasjonsanlegg.

På denne side gjentar det internasjonale energibyrået (IEA) årlig det samme budskapet om at 2 graders målet fortsatt er oppnåelig dersom man gjør de riktige valg og "kommer i gang" med en rekke tiltak slik som CCS. IEA's analyser viser videre med all tydelighet at CCS er et viktig, nødvendig og kostnadseffektivt tiltak i en verden der fossile brenseler fortsatt vil spille en dominerende rolle innen energiforsyning i mange tiår fremover.

Mens utviklingen i EU står i stampe pga manglende finansiering og politiske beslutninger, ser vi at CCS tas i bruk i Nord Amerika hvor motivet er økt selvforsyning av olje ved hjelp av CO₂ til EOR i USA og utnyttelse av tungolje i Canada. Ved å skape et marked for CO₂ og CCS ser vi at teknologien tas i bruk og man vil å et større incentiv for å bringe kostnadene ned.

I foredraget gis en status for hvor man står internasjonalt med hensyn på implementering av CCS samt noen mulige utviklingstrekk fremover.

**The Lower Miocene Skade Formation in the northern North Sea (Extent and thickness, age from fossil and strontium isotope correlations, lithology, paleobathymetry and regional correlation)**

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The deposition of the Skade Formation represents a southern shift in coarse clastic influx to the northern North Sea basin from the East Shetland Platform, relative to Oligocene time (Rundberg & Eidvin 2005). We have investigated the Skade Formation in six wells and in most wells the deposits are turbiditic in origin and were probably deposited in quite deep parts of the shelf. The Skade sections in well 25/2–10 S and 25/1–8 S contain common mullusc fragments and lignite coal, and have probably been deposited in shallower water close to or as parts of a delta (Eidvin et al. work in progress).

According to the mapping of Gregersen & Johannessen (2007) these are wells situated in the distal part of the Hutton sand area. Hutton sand is an informal term used in British sector by
several oil companies to describe all sands above the Lower Eocene Balder Formation in the Northern North Sea (British Geological Survey 2000). In some areas Hutton sand extends into the Norwegian sector and continues into the Skade Formation, but we prefer not to use the term Hutton sand in Norwegian waters (Eidvin et al. work in progress).

The Skade sands pinch out to the east. The sandy system has a maximum gross thickness in excess of 300 m. According to our investigations, the sands were deposited between approximately 23.5 and 15.5 Ma. It has been suggested that they are a result of uplift of the East Shetland Platform, possible associated with a renewed compressional tectonic phase along the possible associated with a renewed compressional tectonic phase along the northwest European margin (Lundin & Dore 2002, Boldreel & Andersen 1994). We suggest to down-grade the Skade Formation to member status (Eidvin et al. work in progress). The climate was probably warm temperate during the Early Miocene and culminated with a subtropical status (Eidvin et al. work in progress). The down-grade the Skade Formation to member status (Eidvin & Andersen 1994). We suggest to down-grade the Skade Formation to member status (Eidvin et al. work in progress). The climate was probably warm temperate during the Early Miocene and culminated with a subtropical climate in the early Middle Miocene (Zachos et al. 2001).

References:


Eidvin, T., Riis, F. & Rasmussen, E. S., work in progress. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, with correlation to the Norwegian Sea, Greenland, Svalbard, Denmark and their relation to the uplift of Pennoscandia.


The Upper Miocene-Lower Pliocene Utsira Formation in the northern North Sea (Extent and thickness, age from fossil and strontium isotope correlations, lithology, paleobathymetry and regional correlation)

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The Utsira Formation represents a huge sedimentary depositional system in the northern North Sea (about 450 km long and 90 km wide) comprising one large sandy depo-center (250-300 m in the southern Viking Graben) and one much smaller center (80-100 m thick in the northern Viking Graben). These areas are separated by a central area comprising an eastward prograding sandy coastal plain wedging out into mudstone-dominated facies to the east. Far to the north, in the Tampen area, the Utsira Formation is represented by a thin glauconitic unit overlying Oligocene strata and deposited close to the Miocene-Pliocene transition. This member is thought to cap the main Utsira Formation sands in the north-eastern part of the basin (Randberg & Eidvin 2005, Eidvin & Rundberg 2007, Eidvin et al. work in progress). Within the Tampen area the glauconitic member is locally absent and Upper Pliocene deposits lie unconformably on Paleogene sediments, e.g. in the Tordis Field area (Eidvin 2009, Eidvin & Øverland 2009). We suggest to divide the Utsira Formation into four members, viz. Southern Utsira Member, Central Utsira Member, Northern Utsira Member and a Glaucnitic Utsira Member in the northernmost part. In the same way as the Skade Formation, in the western part of the Norwegian sector block 30 and 25, the Utsira Formation merges with parts of Hutton sand. Rundberg & Eidvin (2005) pointed out an obvious correlation conflict between the Utsira and Skade formation in the type wells of Isaksen & Tonstad (1989) and showed the need for a revision of the base of the Utsira Formation. Eidvin & Rundberg (2007) suggested an adjustment of the base of the Utsira in the type well 16/1-1 from 1064 to 815 m, and noted also that after such a revision the well 16/1-1 is no longer the appropriate choice as the type well for the sandy system. It penetrates only thin sand and does not represent typical succession of the
sandstones of the Utsira Formation. Consequently, we suggest 24/12-1 from 730 to 495 m as the new well type section (also the well reference section for the Southern Utsira Member). We suggest 25/2-10 S from 520 to 480 m as the well reference section for the Central Utsira Member, 30/6-3 from 750 to 680 m as the well reference section for the Northern Utsira Member and 34/4-6 from 1250 to 1210 m as the well reference section for the Glauconitic Utsira Member. According to our investigations the Utsira Formation sands were laid down between approximately 12 to 4.5 Ma. In some areas the deposition started slightly earlier (Rundberg & Eidvin 2005).

References:

Eidvin, T., Rii, F. & Rasmussen, E. S., work in progress. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, with correlation to the Norwegian Sea, Greenland, Svalbard, Denmark and their relation to the uplift of Fennoscandia.

Eidvin, T., 2009: A biostratigraphic, strontium isotopic and lithostratigraphic study of the upper part of Hordaland Group and lower part of Nordland Group in well 34/7-2, 34/7-12 and 34/7-R-1 H from the Tordis Field in the Tampen area (northern North Sea). Available from the internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Tordis-biostr-rapp.pdf


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Middle Miocene sandy deposits of the Nordland Group, northern North Sea (Suggested called Eir member (informal), extent, age from fossil and strontium isotope correlations, lithology, paleobathymetry and regional correlation)

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Middle Miocene sediments in the northern North Sea represent the basal part of the Nordland Group and occur as an infilling unit within the Viking Graben. In most areas in the northern North Sea these are mainly fine grained sediments. Exceptions is the Middle Miocene units in well 15/9-13, 25/1-8 S, 25/2-10 S (southern Viking Graben) and 30/5-2 and 30/6-3 in the northern Viking Graben. The Middle Miocene in all these wells is sandy and is probably deposited in an inner to middle shelf environment. The age is to a large extent based on the occurrence of the index fossils B. badenensis and B. reticulata and Sr isotope analyses. The Middle Miocene section in well 25/1-8 S was probably deposited at a very shallow marine site and oceanic forms as Bolboforma did not enter the area. In this well the age is mainly based on correlation of benthic and planktonic foraminifera and a number of Sr analyses. It may be difficult to distinguish these sands from sands of Utsira above and Skade below. However, we tentatively like introduce the name Eir Member, after an Æsir in Norse mythology, for these sandy sections in the Norwegian sector as a new member in the Nordland Group. We suggest 25/2-10 S from 630 to 520 m as the well type section and 30/5-2 from 920 to 760 m as the well reference section. In the same way as the Skade and Utsira, this unit also merges with parts of Hutton sand in the western part of block 25. Well 25/1-8 S and 25/2-10 S are situated in the distal part of the Hutton
sand area according to Gregersen & Johannessen (2007). However, we suggest using the term Eir Member for this unit in Norwegian waters (Eidvin et al. work in progress).

References:
Eidvin, T., Riis, F. & Rasmussen, E. S., work in progress. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, with correlation to the Norwegian Sea, Greenland, Svalbard, Denmark and their relation to the uplift of Fennoscandia.


The Lower Oligocene-Lower Pliocene Molo Formation on the inner Norwegian Sea continental shelf (Extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation)

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The Molo Formation is a sand-dominated unit on the middle/inner part of the shelf extending from the coast off Møre (63°15'N) to Lofoten (67°50'N). It has a unique seismic signature, and represents a prograding system comprising fairly steep clinoforms. Eidvin et al. (1998) investigated sidewall cores of the Molo Formation in well 6610/3-1 (in its northern part) and gave an Early Oligocene age for the unit based on benthic foraminiferal and dinoflagellate cysts correlations and Sr isotope analyses. At a later date T. Eidvin and M. Smelror investigated sidewall cores of the same formation in well 6510/2-1 (in middle part of the formation). Based on the same kind of analyses they suggested an Early Miocene age for the formation in that well. Eidvin et al. (2007) investigated ditch cutting samples of the Molo Formation in well 6407/9-5, 6407/9-2 and 6407/9-1 (in its southern part) and based on the same kind of analyses they suggested a Late Miocene to Early Pliocene age for the unit in those wells.

Eidvin et al. (2007) interpreted the Oligocene fossils in well 6610/3-1 and the Early Miocene fossils in well 6510/2-1 to be reworked and suggested a post mid Miocene age for the whole of the Molo Formation. They interpreted the Molo Formation to be the proximal equivalent to the deeper marine Kai Formation. However, interpretation of new seismic data, for the current presentation, indicates the northern proximal part of the Molo Formation is as old as Early Oligocene and that the formation contains younger sediments towards west and south. We now believe that the recorded index fossils in well 6610/3-1 and 6510/2-1 are not reworked, and that the Molo Formation is the proximal equivalent to both the Brygge and Kai formations. Eidvin et al. (2007) suggested 6610/3-1 from 555 to approximately 349 m (the top is not sampled and logged) as the well type section and 6407/9-5 from 787 to 670 m as well reference section. For the current presentation we suggest well 6510/2-1 from 480 to 441 m (the top is not sampled and logged) also as well reference section.

References:


Using alternative bathymetry data to complement multibeam echo-sounder data in MAREANO mapping

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The MAREANO (Marine AREA database for NORwegian waters, www.mareano.no) seabed mapping programme generates a wide range of products, including landscape, landform, sediment and benthic biotope maps. Production of these maps relies heavily on full-coverage multibeam data (bathymetry and backscatter) which reveal the seabed in unprecedented detail, and which form the basis for geological
interpretations and the identification of seabed terrain of ecological relevance. The acquisition of multibeam data represents a significant proportion of the total annual MAREANO budget, and efforts to reduce this cost will help to maximize the cost-effectiveness of MAREANO in the future.

To evaluate the potential use of one alternative source of bathymetry data (accumulated singlebeam bathymetry compiled by the Trondheim-based navigation system manufacturer Olex AS), we simulate a future mapping approach where full-coverage multibeam data are not available. In an area of 15 000 km² offshore Lofoten-Vesterålen-Troms, where much singlebeam bathymetry exists, a simulation dataset is prepared by limiting multibeam coverage to four 10 km wide cross-shelf transects and complementing these with Olex bathymetry data gridded to a resolution of 50 m. This combined Olex/multibeam dataset is used as a basis for interpreting sediment distribution and modelling the distribution of benthic biotopes, following standard MAREANO procedures. This allows direct comparison of the simulated results with published MAREANO maps from the same area based on full-coverage multibeam data, and the value of Olex data in the production of MAREANO sediment and biotope maps can be assessed.

Despite the quality and resolution of Olex bathymetry being considerably lower than the multibeam bathymetry, landscape types and larger landforms are often easily distinguished in the Olex data. The simulation study shows that also sediment and biotope maps of acceptable quality can be produced at a regional scale (1:250 000 or coarser) using alternative bathymetry data sources combined with limited coverage multibeam data. Simulated and published maps display the same general trends in sediment and biotope distribution, and testing of modelled biotope distributions based on the two datasets shows little difference in model performance. There are however numerous limitations to be considered when using Olex bathymetry for MAREANO purposes. Among the most important are (1) that the quality of Olex data rarely allows for detection of smaller topographic features, e.g. coral reefs and pockmarks, and (2) that future cruise planning without access to the full-coverage backscatter data obtained through multibeam surveys may result in sampling stations not being optimally placed, thus adversely affecting the biotope maps that rely on this information.

Characterization of the effects of grain size to mine water quality and ARD production in Kinetic quality and ARD production in Kinetic Using Recsk Deep deposit waste rocks

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The quality of acid/neutral mine drainage from waste dumps is controlled by several factors. One of the most aggressive is grain size. Unlike coarser grain materials, finer grain materials expose greater surface area to weathering and sulphide oxidation. This textural variation also influences the hydraulic properties and oxygen circulation in a waste dump. These in turn, control the main driving mechanisms for an acid generating or neutralizing reaction to occur in the system. Depending on their rates and other intrinsic properties, leachate chemistry for a certain grain size can be characterized.

In this paper, kinetic test using humidity columns is performed on five different grain size ranges of waste rocks from Recsk Deep deposit in Hungary. Water leachate quality is analysed mainly for their pH, alkalinity, conductivity, anions, cations and dissolved metal concentrations. Results showed that finer grain size materials (Group I: 1-2 mm, 2-4 mm) produced neutral to near neutral pH of 6.4-7.2 while coarser size materials (Group II: 4-8 mm, 8-16 mm, 16-32 mm) have pH starting from 6.4 over time going down to 3.3. Meanwhile, there is a correlation of grain size and sulphate production rate opposite of expected. Group I yielded higher sulphate production rates starting at 0.026 mg/kg/min down to 0.008 mg/kg/min than coarser materials starting at 0.011 mg/kg/min down to 0.002 mg/kg/min. While some inconsistencies in the pH and corresponding Ca²⁺-SO₄²⁻ concentrations exists, a highly correlative relationship between the latter and TDS, conductivity and salinity is established. These results strongly suggest that the rate of sulphide oxidation and neutralization may be only partly controlled by available surface area of the material undergoing reaction as well as a number of interrelated factors.

It must be noted that while grain size variation is an important factor in leachate quality, it is
however, deeply rooted to the mineralogical composition of the waste rocks before, during and after the duration of a kinetic test. Likewise, variations in routine and some idiosyncratic procedures can also have a significant effect on the leachate chemistry.

Geochemical identification of black shales horizons in the Oslo graben – practical impact for area planning and project design

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Black shales in Norway are mainly from Cambro (542-488 my) to Early to Mid Ordovician (488-460 my) age. Some of these black shales horizons are rich in sulphides, and may lead to the generation of acidic leachates, the release of heavy metals and swelling potential, while some other horizons do not present any relevant risk to the environment. The stratigraphy of these Cambro-Silurian interbedded shales, calcareous rocks and black shales have been identified by palaeontologists, using trace fossils, and correlated worldwide. This method of characterization is however limited to expert palaeontologists and is not necessarily adapted to the construction needs. Because of this, excess masses from different construction sites have been deposited rather uncritically in hazardous waste deposit sites through the years, resulting in highly increased (and not always justified) costs. Being able to identify the shale lithology has a huge impact on project cost, design and demand for deposit areas. The goal of this study is consequently to propose a geochemical identification methodology to better and quicker characterize the different shales (included black shales) encountered, and to more precisely estimate their risk potential, preferably in an early phase of project planning.

Following a research program, partly financed by the Norwegian Research Council, several Norwegian consulting companies, the geological survey of Norway and the University of Oslo, the Norwegian Geotechnical Institute (NGI) has developed a geochemical method to identify the different black shale units. This geochemical characterization includes the calculation of the acidification and neutralization potentials, whole rock analysis and the comparison of several major and trace elements contents. This study was carried out using a systematic approach based on the analysis of drill cores (drilled through different black shale horizons), and samples obtained through consulting services in building projects in black shale formations. All the data gathered have been added to a database which has allowed the identification of the trends and characteristics of each black shale horizon. The most populated areas in Norway are in the south-eastern part around Oslo. It is now possible to identify the different shale (included black shale) horizons by their geochemical composition. This opens up for a new framework to which additional information about the different black shale units may be linked. This should also allow a quick, rather cheap and objective identification of the black shale horizons based on easily-obtainable characteristics. Representative sampling is still important, but as more geochemical samples are gathered and systemized, representative sampling is expected to be less critical for the identification of the black shale horizons in the Cambro-Ordovician shales.

Definition of a newly discovered granulite-facies domain in Bamble, S Norway: Petrology, P-T modeling and U-Pb geochronology

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New field work uncovered several occurrences of granulite north of Kragerø in the gneiss complex of the Bamble sector, generally assigned to an amphibolites-facies metamorphic domain. Here, we report preliminary data on two granulite localities. A garnet-bearing enderbitic-charnockitic gneiss is dominated by garnet (Alm59-67Prp12-28GrS6-20SpS1-2), orthopyroxene (En10-56Fs44-58, Mg#=0.41-0.56), plagioclase (An22-49Ab50-75) and quartz, with variable amounts of K-feldspar, clinopyroxene (En31Fs22-25, Mg#=0.55-0.58) and biotite (Mg#=0.57, Ti=0.29 p.f.u.). The gneiss occurs strongly foliated, with a microlayering characterized by alternating garnet-orthopyroxene- and quartz-feldspar-rich layers. The intense fabric is evident by orientation of pyroxene long crystal axis and quartz rods parallel to the layering. Clinopyroxene occurs only locally, where present usually as fine grains along orthopyroxene grain boundaries. Minor amount of biotite spreads as stable phase in the matrix mineralogy, as inclusions in garnet, or locally as reaction corona on orthopyroxene or garnet. Pargasitic-
hastingsitic amphibole occur secondary. Coarser domains with non-preferred crystal orientations are locally preserved in strain shadows. The garnet +orthopyroxene ±clinopyroxene +plagioclase +quartz-assemblage document medium-pressure granulite facies conditions. Pressure and temperature estimates were computed using Thermocalc and further constrain by P-T pseudosections by TheriaK-Domino software. The P-T calculations yield P up to 1.03 ±0.17 GPa and T = 838 ±112 °C. P-T pseudosections show a large stability field of garnet and orthopyroxene. Anatexis occur above ca. 810 °C and biotite starts breaking down above 820-850 °C. Clinopyroxene is stable at higher pressures. Together the information indicates that the granulite reached pressures of about 1.15 GPa around 800°C.

At the second locality, the assemblage garnet +orthopyroxene +clinopyroxene +plagioclase +quartz and minor biotite, yields slightly lower estimates of P = 0.82 ±0.20 GPa and T = 785 ±165°C. Zircon at the second locality shows characteristic rounded habit and concentric sector zoning typical for high-grade metamorphic crystallization. U-Pb SIMS dating defines a concordia age at 1144 ±6 Ma (±2σ) interpreted to date peak metamorphism. The discovered garnet-bearing enderbitic-charnockitic gneiss documents a Sveconorwegian medium-pressure granulite facies metamorphism in the Kragerø region. The new petrological and geochronological data illustrate an extension of the Sveconorwegian high-temperature metamorphism outside the previous well-known high-T dome of the Arendal area in the central part of the Bamble sector.

New landscape classification in Norway used for defining geo-input to landscape character assessment

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Geology is a major attribute in all landscapes. Rocks and rock structures have a large influence on landforms. Rocks, landforms and geoprosesses influence biodiversity and are the building stones in landscapes. The near relationship between geodiversity, biodiversity and landscapes are appreciated in the new environmental legislation in Norway (the Nature Diversity Act), were the aim "is to protect biological, geological and landscape diversity and ecological processes through conservation and sustainable use". Within this legislation the term "nature type (habitat) are defined as "a homogeneous environment, including all plant and animal life and environmental factors that operate there, or special types of natural features such as ponds, habitat islands in fields or the like, and special types of geological features".

The legislation has induced a need of a better end new system of classification of nature in Norway, developed by the Norwegian Biodiversity Centre (www.artsdatabanken.no). NiN (Nature types in Norway) has been in existence for some years and the work to update the system into a version 2.0 has started. The system is hierarchical going from a detailed substrate level up to a landscape level.

NiN landscape version 1.0 is based on large geomorphologic units. These units have been mapped automatically using a digital elevation model. The basic units are valleys, plains, the strandflat and various hills and mountain top landscapes and target scale of the classification is 1: 500 000. The 2.0 version will have a much more detailed target scale and will be based on more complex landscape gradients, although the basic geomorphic basis is maintained.

This work has been started with a full analysis and mapping in the county of Nordland. Data has been retrieved from 258 test areas selected by stratified random sampling. Landscape gradients have been used for criteria defining landscape types. They will also be used in a description system important for future analysis of landscape character. We have used this material for an analysis of landscape gradients used for specific criteria for landscape mapping. A preliminary analysis of the relationships between geo- and biodiversity has been performed serving as a pilot study for a work to establish a step-less model of abiotic nature variation on a 1x1 km scale for Norway.

Late Paleozoic basin configuration in the western and central Barents Sea

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The Late Paleozoic basin configurations in the western and central Barents Sea as outlined in previous studies (e.g. Faleide et al. 2008, 2010) have recently been challenged by Gernigon & Brönner (2012) based on new high-quality magnetic data covering most of the SW Barents Sea. Thus, both NE/NNE and WNW are now proposed as the dominant trend of the Late Paleozoic structures in the SW Barents Sea. We think that the magnetic data mainly reflect the Devonian basin configuration related to the collapse of the Caledonian Orogen. The magnetic data nicely detect structures which are interpreted as the frontal thrusts of the (main?) Caledonian Orogen. These thrusts turn from a NE to a NNW trend just off the coast of northern Norway. The thrusts were possibly reactivated (by back-sliding?) in Devonian time. Thick units of non-magnetic sediments were deposited in front of the orogen as reflected by the depth to magnetic basement estimated by Gernigon & Brönner (2012). The Carboniferous rift structures are, on the other hand, better revealed by seismic and gravity data. New high-quality long-offset seismic data show a horst and graben basin relief with a dominant NE to NNE trend, which also gives rise to lateral density variations reflected by the gravity anomalies. To what extent the NE/NNE-trending rift structures reflect an underlying structural grain, or only formed in response to a new regional stress regime, is still not sorted out by the ongoing study.

The Carboniferous horst and graben basin configuration also had impact on the depositional systems and facies distribution within the Permian succession. A better understanding of these structures is important for future exploration within the former disputed area between Norway and Russia in the central Barents Sea.

Quantification and restoration of pre-drift extension across NE Atlantic conjugate margins

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The sedimentary basins at the conjugate margins offshore mid-Norway and East Greenland formed in response to multiple phases of post-Caledonian rifting from Late Paleozoic time to final NE Atlantic crustal breakup at the Paleocene-Eocene transition. The >200 million years of repeated extension caused comprehensive crustal thinning and formation of deep sedimentary basins. The main rift phases span the following time intervals: Late Permian, late Middle Jurassic-earliest Cretaceous, Early-mid Cretaceous and Late Cretaceous-Paleocene.

To reconstruct the basin evolution and construct well-constrained paleogeographic-/tectonic maps we have to quantify the pre-drift extension through time and space. This is done using various techniques: The geometry of crustal thinning is compared to a reference thickness of the crystalline crust close to onshore areas which have experienced limited or no crustal extension. The corresponding thinning factors are compared to stretching factors derived from both back-stripping and forward modelling.

For this purpose we have constructed a set of conjugate crustal transects based on an integrated analysis of all relevant geophysical and geological data. In these transects the Cenozoic oceanic crust has been removed based on conventional plate reconstructions. In some of the conjugate transects there are uncertainties with respect to the exact location of the continent-ocean boundary and the contribution from breakup-related igneous intrusions to the observed crustal thicknesses.

The total (cumulative) pre-drift extension amounts to in the order of 300 km which correlates well with estimates from plate reconstructions based on paleomagnetic data. The implications for the regional basin evolution and provenance (source-to-sink) will be discussed.

Why measure resistivity before drilling? Case examples from the Barents Sea

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Controlled source electromagnetic (CSEM) measurements has for the last decade been used by the petroleum industry for exploration purposes, mostly for drill-drop decisions.
However, despite a very good statistical record in predicting the outcome of exploration drilling, the technology is not widely accepted as an important exploration tool. This is mainly due to the fact that the significance of EM results is not well understood within the asset teams; hence the confidence in the data is less than for instance for seismic.

The Barents Sea. Since the late 70’s, exploration has taken place in the Barents Sea. The first wells gave encouraging results with among others gas discoveries as the Askeladd and Albatross in the early 80’s. However, it is only the Snowhite Field (1984) that has been set in production so far. After these discoveries, no significant discovery was made until 2000, when Goliat was found. In 2011, new optimism emerged in the area following the discoveries of Skrugard, Norvarg and Havis. Despite the obvious lack of success apart from the mentioned discoveries, drilling has demonstrated the potential in the region through numerous minor discoveries and shows. This proves that there is indeed a working hydrocarbon system in the area, but also that the challenges of finding commercial volumes of hydrocarbons has not yet been solved for most of the area.

CSEM data. In this setting, it is obvious that new information could be essential in order to improve the chance of success (COS) in the area. Resistivity measurements before drilling will give valuable information regarding the possibility of a HC charged reservoir. However, as there could be several explanations to a resistive anomaly, it is important to include such data in the exploration workflow, and develop models which can explain the observed resistive responses.

The next step is to run the models through a risking procedure in order to establish the COS based on EM data. Combining that with EM based volume estimates will give an Expected Value (EV) of a specific target.

CSEM data should, however, not be treated as a stand-alone tool. Integration with seismic data will significantly reduce the uncertainties and improve the chance of success in an exploration region. This applies in particular in frontier areas, like large parts of the Barents Sea.

We will show data examples from various parts of the Barents Sea, including Triassic opportunities in the northeastern parts, Jurassic in central parts and Tertiary/Upper Cretaceous in the Bjørnøya Basin. The data examples will illustrate the value of EM data in a license round setting as well as drilling priority decisions and development of new play models.

The visual aspects of teaching geoscience

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Geology is by nature a quite visual subject in the sense that it is based on visual observations and descriptions, be it in the field or in the laboratory. Even numerical modeling relies on visual outputs that are to be compared with natural examples. Basically, if we are going to successfully communicate geology and convey geologic ideas, we need to employ visual methods and effects. When it comes to geology books, this fact calls for well-prepared figures that are consistent with regard to layout and style. Figures have several functions. First, they are there to attract attention, which means that they must be visually appealing. Second, they must be technically correct, and third, they must be simplified so as to emphasize the feature that is to be communicated to the reader and at the same time look realistic enough that the reader sees the link to the geologic setting(s) they relate to. Together, these points call for a close communication between the scientist and the artist, or ideally: the scientist should also be the artist.

Drawing skills are highly variable among students and some basic training in this field should probably be part of the geology curriculum at undergraduate university level and given more attention in class, particularly during field camps and in field trip-oriented courses. Many students struggle with 3D visualization. We believe that well-prepared illustrations where basic principles and aspects of 3D illustrations are implemented help. Furthermore, interactive block models and digital elevation-based models, including Google Earth, help students grasp 3D aspects of geology. In addition to being exciting and visually attractive, both physical experiments and animations add a valuable fourth dimension to this as they visualize geologic processes through time.

Creating animations is a time consuming process, hence a relatively simple application that has the ability to produce realistic 3D models of geologic structures and their development through time would be desirable. An ongoing attempt is made at the University of Bergen to create such a tool, and some aspects of this tool will be demonstrated and discussed.
Insights into the post-Caledonian tectonic history of W Norway using geochronology and thermochronology – recent results

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The post-Caledonian tectonothermal history of Norway has always been enigmatic, in contrast to the much better known history of the offshore Norwegian North Sea and continental shelf. Post-Devonian sediments are mostly absent onshore, but post-Caledonian faults and fractures criss-cross the bedrock, reflecting a history of brittle deformation and related cooling and uplift that is still poorly understood. Here we focus on K/Ar and Ar/Ar dating methods coupled with fission track analyses to shed some light on this development.

The most straightforward data come from direct dating of post-Caledonian dikes, which yield published ages around 260-250 and 230-220 Ma. As a more indirect dating method, multidomain K-feldspar thermochronometry has been utilized for samples from the alteration rims to fractures postdating W-directed Devonian extensional shearing in the Øygarden Gneiss Complex west of Bergen. Fracture opening was accompanied by recrystallization of K-feldspar in the adjacent wallrock, and the recrystallized K-feldspar yields a 40Ar/39Ar age spectrum with ages between ~290-230 Ma (Permian – Early Triassic), with a bulk age of 282 Ma. In contrast, the unrecrystallized, cryptoperthitic K-feldspar in the gneiss only a few cm away from the fractures preserves ages between ~430-280 Ma, with a bulk age of 391 Ma (Middle Devonian). The differences in age and texture between the gneissic and recrystallized K-feldspars are most readily explained by dissolution-reprecipitation of a portion of the original K-feldspar during recrystallization related to fracture formation.

The third approach involves K/Ar dating of illite from fault gouge. Illite from 10 faults from the Hardanger-Bergen-Sogn area was dated, and ages obtained for 2-6 µm, < 2 µm and < 0.2 µm grain-size fractions cluster to define periods of illite growth that we relate to tectonic activity in the early Carboniferous, Permian, Late Triassic-early Jurassic and Cretaceous-earliest Paleogene times.

All together, the data strongly suggest that faulting was periodic, with several periods of onshore tectonic activity in the Permo-Triassic, with additional evidence for latest Jurassic – Early Cretaceous and Carboniferous activity. Devonian faulting appears to be more difficult to capture with these methods, although reflected by U/Pb dating of sphene from fracture fill. The cooling history is constrained by a range of thermochronometers, including K-feldspar Ar/Ar data, apatite fission track analyses, (U-Th)/He data and limited stratigraphic constraints. The general pattern shows fast cooling in the Devonian and the Permian through the Triassic and Early Jurassic, followed by much slower cooling (< 1 °C/Ma) in the Late Jurassic and Cretaceous. The overall Permo-Triassic cooling can be explained in terms of rift-margin uplift and erosion, which in contrast to the late Jurassic North Sea rift phase was quite pronounced in the offshore Horda Platform area. In detail, however, cooling occurred diachronously over W Norway, which we suggest is linked in part to the aforementioned fault activity.

Silica cementation and silcrete formation of the Kilimatinde Cement, Central-Tanzania

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The Kilimatinde Cement is a Tertiary sedimentary unit located in the Bahi Basin, Central-Tanzania. It is well-cemented by silica, calcium carbonate or iron oxides. The sedimentation was tectonically controlled resulting in lacustrine, fluvial and alluvial deposition. The Kilimatinde Cement has been studied and sampled in the field and by mineralogical (thin section, SEM, XRD) and geochemical (main and trace elements) analyses. The studied section can be mineralogically subdivided into three parts: a lower part (quartz, opal, microcline, orthoclase, plagioclase), a middle part (quartz, opal, microcline, kaolinite), and an upper part (quartz, microcline, kaolinite). The geochemical analyses of the section revealed high concentrations of SiO2 (> 90 wt %); the sediments can be classified as silcrete. In addition high concentrations of uranium were detected (peak values from 94 to 394 ppm). None uranium bearing minerals have been identified, indicating uranium enrichments as most likely due to absorption on minerals e.g. clay minerals.
Silica cement dominates in the analyzed section. The cement in the lower and middle part is mainly opal and chalcedony, while microcrystalline quartz is the main cementing agent in the upper section. All opals are identified as opal-CT, occurring as spherical aggregates of both complete and composite lepispheres. Stratigraphically the structural ordering in these sections is decreasing up-section. Silica precipitated from groundwater in the lower part of the section, while silification in the middle and upper parts relates to pedogenesis, identified by soil-like features, such as illuviation and nodular textures. The earliest phase of silification is recognized as the pseudomorphic transformation and/or replacement of sedimentary clay minerals by opal, in thin sections observed as brown patches of isotropic character. Further recrystallization of the initial opal results in more ordered variety opal-CT. In the final cementing stage chalcedony is precipitated in residual cavities.

**REE-deposits: Business as usual or new methods?**

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Since China changed its policy on the export of REE (here used to only cover the Lanthanides) in 2009 the mining industry has experienced a boom in the search for REE deposits. Because of China’s monopoly on the REE marked research on these deposits and mineralogy has largely been ignored outside China. Many of the REE deposits currently being explored around the world are associated with continental rift systems, both in the form of carbonatites and syenite systems, hence alkaline rocks. So how do ore deposits in alkaline settings differ from more conventional ore deposits like porphyry deposits? and to what degree can knowledge be directly transferred, and to what extent must new approaches be developed? This presentation will discuss some of the challenges and approaches adopted for REE-deposits from exploration to extraction, and will be exemplified with a case study of the Kvanefjeld multi-element deposit in South Greenland. The Kvanefjeld deposit is situated in the northern part of the 1.16 Ga old Ilmaaussaq Alkaline Complex, and is hosted in a nepheline syenite called lujavrite. The Ilmaaussaq complex has been studied since the early 19th century, and is known to contain more than 220 different mineral species of which approximately 15% are true REE minerals, i.e. minerals where REE is a major component in the structure. The main ore mineral in Kvanefjeld is seenstrupine-(Ce), a complex phosphosilicate, and elsewhere in the complex eudialyte, a zirconosilicate, is being evaluated as a potential mine for REE and Nb.

**Geoscience in upper secondary school – Geoprogrammet the first four years**

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In the national curriculum “The Knowledge Promotion 2006”, geoscience was introduced as an optional course in upper secondary school at level 2 and 3. For the first time in Norway, geoscience was treated as an independent science subject and is now taught at a more advanced level and to a greater extent than earlier. Geoscience covers geology, geography and geophysics (meteorology, oceanography). The curriculum indicates that field work is central to the subject and students should be engaged in scientific activities in their local natural surroundings. The investigations should be conducted in a geotop which is defined by physical characteristics within a demarcated area. Teaching geoscience demands highly skilled teachers. They not only need theoretical knowledge of geology, geography and geophysics, they must also master fieldwork. Since this subject is new for upper secondary school we also had to develop teaching materials and acquire knowledge about how to teach this subject, in other words research in geoscience education. To meet this challenges, the Norwegian Centre of Science Education (Naturfagsenteret), established a 5-year Geoprogrammet supported by Statoil (2008-2013). Geoprogrammet is in its last year and we want to present what we have accomplished. We have studied how this new subject is working in schools and how newly developed teaching materials are used. Research results from the research program “Georoots and fieldboots” are part of a Ph.D. study by one of us (Remmen).

Fieldwork is an essential component of teaching and learning geoscience. However, research show that teachers – for various reasons - find the implementation of fieldwork challenging – despite the potential it has for enriching students learning. Our research focuses on how fieldwork
can be improved, from both the teachers’ and the students’ perspectives.
Together with the Institute of geosciences (UiO), Geoprogrammet has provided a professional development course for teacher. Experiences from this will be presented in a different talk by Thorsen and Frøyland.

Formation of intra-cratonic basins by lithospheric shortening and phase changes – a case study from the ultra-deep East Barents Sea Basin

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Very large subsidence, accommodating an up to 20 km thick sedimentary succession, is observed in the East Barents Sea Basin (EBB). Subsidence started in the Early Palaeozoic, with a significant acceleration of subsidence in Permian-Triassic times. The observed gravity signal suggests that the East Barents Sea is at present in isostatic balance and indicates that a mass excess is required in the lithosphere to compensate for the observed large subsidence. We propose that the formation of the EBB was initiated by shortening and buckling of the lithosphere, with the mass excess originating from metamorphism of hydrated mafic gabbroic lower crust. We use a forward thermo-mechanical finite element technique to evaluate this hypothesis and model shortening of continental lithosphere. The lower crust in the dynamic model is modeled with petrologic consistent densities for a wet mafic gabbroic composition, supposedly emplaced during a previous extensional episode, that depend on pressure and temperature taking into account de-hydration at high PT conditions. The model successfully explains the main characteristics of the Eastern Barents Sea Basin, notably the large anomalous and fast subsidence during the late Permian-Early Triassic, its present-day geometry and the absence of a significant gravity anomaly. A small initial asymmetric thermal anomaly in the mantle consistent with a slightly hotter Kara Sea lithosphere leads to asymmetric contractional basin formation with significantly more uplift on the east flank, consistent with uplift and inversion observed on Novaya Zemlya during Permian-Triassic times.

Radon - a geological problem for society – Radon - et samfunns-problem forankret i geologi

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Radon, a colourless and odourless gas, is the second largest cause of lung cancer after smoking and is estimated to cause around 300 deaths per year in Norway through lung cancer (WHO) - a death rate which is higher than that from road traffic accidents (Statistics Norway). Exposure to radon increases the likelihood of developing lung cancer. The risk is increased further - by a factor 20 - when radon exposure is combined with smoking (NRPA). The recommended upper level for indoor radon concentration is 100 Bq/m3, with an action threshold of 200 Bq/m3 (StrålevernInfo 25.9).

Radon (222Rn) is produced through the decay of uranium (238U), and has a radioactive half-life of ca. 4 days. This lifetime is long enough time for the gas to accumulate in dwellings, and for radon decay products to enter the lungs through inhalation, where alpha-producing isotopes of Polonium can lead to tissue damage... Uranium-238 is a naturally occurring radioisotope found in varying concentrations in bedrock and sediments. In Norway, bedrocks such as alum shale and some types of granite can contain high concentrations of 238U. Sediments with high permeability can facilitate the flow (transportation) of radon gas from the ground and into dwellings, even if the sediment itself does not contain large concentrations of uranium. An example of this phenomenon can be found at Kinsarvik in Ullensvang kommune.

NGU and NRPA are collaborating to produce a geologically controlled radon probability map that indicates areas in Norway, which may have increased likelihood of an indoor radon problem. This new national radon risk map is based on three datasets: indoor residential radon measurements, bedrock geology and drift geology, and is intended as a tool for area
resource management, and to assist in planning for future construction. Current airborne geophysics coverage in Norway is limited but more comprehensive coverage is anticipated in the coming years; future versions of these maps will incorporate equivalent Uranium levels from airborne geophysics.

References:
Norwegian Radiation Protection Agency (NRPA) - www.nrpa.no/radon/helsenisiko
Statistics Norway www.ssb.no/transport - 208 casualties due to traffic accidents in 2010

A shallow marine storm-dominated shelf: Sælabonn Formation, Oslo Region (Lower Silurian)

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The Sælabonn Formation belongs to the Bærum Group and is recognized in the western part of the Oslo Region, from Hadeland in the north, to Skien in the south (Worsley et al., 1983). The Sælabonn Formation is the lowermost unit of the Silurian succession in the Western Districts of the Oslo Region bound to an erosional surface; the Ordovician-Silurian boundary. In the Central Oslo Region, the Solvik Formation is the eastern equivalent, displaying deeper marine conditions. The Helgøya Formation in the Mjøsa area, located above the "Mjøsa hiatus", has been correlated with the upper parts of the Sælabonn Formation and is of early Aeronian age (Skjeseth, 1963; Dahlqvist & Bergström, 2005). The carbonate-dominated Rytteråker Formation is overlying the Sælabonn and Solvik formations. The Sælabonn Formation represents a shallow-shelf environment dominated by storm processes (Thomsen, 1982). Whether the Sælabonn Formation was situated in a foreland basin or in an epicontinental basin has previously been vaguely discussed, but will be further outlined in this presentation.

Outcrops in the Ringerike and Modum districts were logged during the summer and autumn of 2011. Samples of both siliciclastic and carbonate material were collected, and various laboratory and microscope techniques, including point counting analyses, were performed.

The sedimentary logs display three units of the Sælabonn Formation. The laterally equivalent lower units, the Store Svartøya and Sylling members, are dominated by mudstone occasionally interbedded by tempestites of sand and bioclastic material. The middle unit (Djupvarp Member) has the highest content of coarser-grained siliciclastic material, very fine sand, and represents isolated sand shoals in the Ringerike District and tempestites in the Modum District. The upper unit (Limovnstangen Member) has an upward decreasing content of siliciclastic material with mudstones interbedded with tempestites containing sand and bioclastic material, which occasionally appear as couplets. The sedimentary structures and lithology indicate a sedimentary environment dominated by storm processes where siliciclastic material is brought out into the basin and deposited together with winnowed bioclastic material. Indications of tidal processes have not been recorded.

Palaeocurrent measurements from the Djupvarp and Limovnstangen members suggest a stable palaeoshoreline, trending in a SW to NE direction. There is insufficient evidence to reach a conclusion on sediment transport direction into the basin; sedimentary structures only reveal intrabasinal reworking and transport directions by wave- and storm-induced bottom currents. Grain size of the tempestites ranges from silt to very fine sand, where the mineralogical composition suggests a quartz-rich source, which may have been the hypothetical "Telemark land" or frontal thrust sheets in the south-eastward moving Caledonian nappe pile. The development of the Sælabonn Formation represents an overall transgressive setting, where increasing water depth and accommodation space were created due to subsidence triggered by tectonic loading of the advancing Caledonian nappe. The Djupvarp Member represents an intermittent progradation which is caused by slowdown of thrusting and increased input of sediments to the foreland basin. The Sælabonn Formation is suggested to have been formed in the back-bulge depozone of the Caledonian foreland basin. Displacement of the peripheral bulge is considered the likely cause of the hiatus in the Ordovician-Silurian transitional interval in the Mjøsa area.

References:
of the Kalak nappe complex. We investigated an outcrop where an older, subvertical metamorphic fabric is preserved within a lens, which is surrounded and overgrown by the regionally dominant, younger, subhorizontal white mica-dominated metamorphic fabric. Thermobarometry shows that the subvertical fabric formed at >640°C (peak T from Ti in Biotite thermometry is 730°C) and ~6 kbar accompanied by partial melting, whereas the subhorizontal fabric formed at ~450°C and ~6 kbar, accompanied by top-SE shearing. U-rich zircons, which formed during partial melting and formation of the subvertical fabric, give a weighted mean 207Pb/206Pb age of 703±4 Ma (Nordsimion probe data), whereas titanites, which formed during shearing and formation of the subhorizontal fabric, give 206Pb/238U ages between 442±1 and 429±1 Ma (single grain TIMS data). Rutiles which crystallized parallel to the subvertical fabric, give 206Pb/238U ages of <440 Ma, indicating that the temperature during formation of the low-grade fabric was high enough to reset the U-Pb system of these rutiles. Together, these new data suggest that the high-grade metamorphic event observed in the north-eastern and central parts of the Kalak nappe complex at ~710-680 Ma (recorded in the NE part of the nappe by the migmatitization of the Eidvågeid paragneiss) affected the south-western part of the nappe complex (Eide lens) as well, and therefore extends over a distance of about 180 km along strike. No effect of the intrusion of the Seiland Igneous Complex at ~580-520 Ma has been observed in our data set. The main Caledonian shearing and thrusting probably occurred over a time span of about 10 m.y. at 440-430 Ma.

**Neoproterozoic partial melting and ca. 10 m.y. of Caledonian shearing in the south-western Kalak nappe complex, northern Norway**

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The Kalak nappe complex of the North-Norwegian Caledonides has in recent years become known for its protracted Neoproterozoic magmatic and deformational history. In the north-eastern and central parts of the Kalak nappe complex, there is evidence for ~980-960 Ma, ~880-820 Ma, ~710-680 Ma, ~580-520 Ma and ~440-400 Ma tectonometamorphic events. This history is considered to be atypical for the calm Neoproterozoic evolution of the passive continental Baltic margin from which the nappe complex was interpreted to be derived. Therefore, models involving an "exotic" origin for the entire nappe complex have been proposed. However, not much is known about the extent and geodynamic significance of these different tectonometamorphic events within the Kalak nappe complex, which at present does not allow for more evolved tectonic models to be proposed. A systematic study in the nappe interior and along the nappe sole thrust indicates that large parts of the Kalak nappe complex consist of lenses of high grade relicts embedded in a deformed matrix with a retrograde overprint. These lenses represent key localities to understanding the early evolution of the Kalak nappe complex, in that they preserve evidence for the pre-Caledonian tectonometamorphic events. In this contribution we present new field, petrological, and geochemical data from one of these key localities in the south-western part of the Kalak nappe complex. We investigated an outcrop where an older, subvertical metamorphic fabric is preserved within a lens, which is surrounded and overgrown by the regionally dominant, younger, subhorizontal white mica-dominated metamorphic fabric. Thermobarometry shows that the subvertical fabric formed at >640°C (peak T from Ti in Biotite thermometry is 730°C) and ~6 kbar accompanied by partial melting, whereas the subhorizontal fabric formed at ~450°C and ~6 kbar, accompanied by top-SE shearing. U-rich zircons, which formed during partial melting and formation of the subvertical fabric, give a weighted mean 207Pb/206Pb age of 703±4 Ma (Nordsimion probe data), whereas titanites, which formed during shearing and formation of the subhorizontal fabric, give 206Pb/238U ages between 442±1 and 429±1 Ma (single grain TIMS data). Rutiles which crystallized parallel to the subvertical fabric, give 206Pb/238U ages of <440 Ma, indicating that the temperature during formation of the low-grade fabric was high enough to reset the U-Pb system of these rutiles. Together, these new data suggest that the high-grade metamorphic event observed in the north-eastern and central parts of the Kalak nappe complex at ~710-680 Ma (recorded in the NE part of the nappe by the migmatitization of the Eidvågeid paragneiss) affected the south-western part of the nappe complex (Eide lens) as well, and therefore extends over a distance of about 180 km along strike. No effect of the intrusion of the Seiland Igneous Complex at ~580-520 Ma has been observed in our data set. The main Caledonian shearing and thrusting probably occurred over a time span of about 10 m.y. at 440-430 Ma.

**Variations in Depocentre Style under Mid-Late Jurassic Salt-Influenced Rifting: Norwegian Central Graben, North Sea**

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Recent studies suggest fault growth process and fault array evolution control many of the first order features of the sedimentology and stratigraphy of rift basins. Nevertheless, where weak mobile evaporite strata are present within the cover stratigraphy, the structural style and evolution of normal faults and their associated depocentres is more variable than in salt-free settings. For example in polyphasic rifts, fault
evolution beneath and above salt layers may be decoupled, thus the location, geometry and evolution of supra-salt depocentres are not directly controlled by sub-salt ("basement") faults. Existing models for structurally controlled depocentre evolution in rifts are mainly based on salt-free rifts and therefore do not address the full spectrum of basin settings. Using three-dimensional seismic and well data in the Norwegian Central Graben, we investigate the interaction between normal faulting, salt tectonics and depocentre evolution during the Jurassic rift phase. During Middle to Late Jurassic rifting mobility of evaporites within the Permian Zechstein Supergroup makes a significant contribution to accommodation creation/destruction and to the overall geometry and evolution of depocentres. Three main types of rift-related depocentre can be recognised based on the dominant factor(s) controlling space. **Type I** depocentres are mainly driven by salt mobilization (often, evacuation of salt), and any sub-salt, basement normal faults are effectively decoupled from the cover deformation. In the study area, these depocentres are tens of kilometers long and several kilometers wide and mainly located on the Sorvestland Arch above salt walls and salt ridges. **Type II** depocentres are mainly fault-controlled and have no significant salt involvement. These depocentres represent typical fault-bounded half-graben depocentres and are found along the axial zone of the Central Graben. **Type III** depocentres are hybrid-type depocentres in that both the basement normal faulting and evaporite mobility have worked in concert to generate accommodation space. Here, the Zechstein evaporites have not fully decoupled basement and cover faulting, but still has affected the stratigraphic architecture. These depocentres are asymmetric in the hanging wall of basement normal fault and typically extend from a few kilometers to tens of kilometers depending on the fault geometry and salt availability. They are usually located in areas between the Type I and Type II depocentres.

**Crustal and basin evolution of the southwestern Barents Sea: from Caledonian orogen to continental breakup**

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A new generation of aeromagnetic data documents the post-Caledonide tectonic evolution of the southwestern Barents Sea (SBS) up to the continent-ocean transition. Clear evidence of reactivation of Caledonian structures controlling both Late Palaeozoic and Mesozoic basins can be observed at the edge of the Hammerfest and Nordkapp basins where low-angle reactivated detachments are observed on seismics. North of the Finnmark Platform, deep Palaeozoic basins such as the Ottar and Maud basins have also earlier been identified on seismics but due to data limitation their architectures remain poorly constrained. The presence of deeply buried salt pillows (e.g., Samson and Norvarg domes) suggests nevertheless that the pre-Permian saliferous basins may also extend towards the north underneath the thick Triassic-Jurassic succession recognised on the Bjarmeland Platform. Our new aeromagnetic surveys confirm most of the previous structural elements but new features appear and illustrate the complexity of the pre-Permian and underlying basement architecture. We propose an updated tectonic scenario of the SBS in which the Caledonian nappes and thrust sheets, well constrained onshore, swing from a NE-SW trend close to the Varanger Peninsula to NW-SE across the Nordkapp Basin and the Bjarmeland Platform. On the Bjarmeland Platform, the dominant magnetic grain is clearly NNW-SSE. We show that this pattern reflects a regional pre-Permian system involving several Caledonian thrust sheets that possibly collapsed and controlled the post-Caledonian late Palaeozoic rift development of the SBS. Contrary to the previous models, we believe that the pre-Permian basins have a dominant NNW-SSE orientation in most of the Bjarmeland Platform. We also consider that this model can explain the later development of the southwestern Barents Sea. One specific case is the Bjørnøya Basin, located between the Loppa and Stappen highs, which are interpreted as a series of rigid continental ribbons poorly thinned as compared to the Hammerfest and Bjørnøya basins and the Vestbakken volcanic province that developed to the west as part of the sheared margin preceding the continental breakup. As part of this extensive complex system, the Bjørnøya Basin is interpreted as a highly-thinned and propagating system that aborted in Late Mesozoic time. This thick Cretaceous sag basin is characterised by a deep high-density body, interpreted as a combination of exhumed lower crust and/or serpentinitised mantle as suggested by potential field modelling. The abortion of this propagating (aulacogen) basin may be partly explained by its trend oblique to the regional, inherited, structural grain highlighted by the new aeromagnetic compilation. This abortion coincides with a migration and complete reorganisation of the
crustal extension towards the western sheared margin and proto-breakup axis.

**Lithospheric Structures of the Northern Norwegian Margin and their Comparison to Southern Norway and Northern Greenland**

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The northern, central and southern domains of the Scandinavian mountains exhibit distinctly different large-scale geophysical and geological characteristics. These include, for example, topography, Moho depth and gravity lows. Recent studies have revealed major lateral changes in lithospheric thickness and composition underneath southern Norway and southern Sweden. These can consistently explain the isostatic compensation of the topography, the gravity signal and the seismic velocities of the uppermost mantle. These changes as well as changes in the lower crustal architecture correlate with the boundary between the Sveconorwegian (Neoproterozoic) and Svecofennian (Palaeoproterozoic) domain.

In the study presented here, we trace this mantle boundary zone to the north, where it is obscured by the overlying nappes of the Caledonian orogen but likely follows the edge of the Svecofennian domain. We show that juxtaposition of lithospheric mantles of different composition can locally create positive buoyancy, thereby providing isostatic support for the topography of northern Norway. We furthermore investigate a prominent gravity and geoid low which lies just south of the Lofoten peninsula extending across onshore and offshore domains. A similar, yet larger anomaly is found on the conjugate margin in northeastern Greenland. We compare two possible origins of this anomaly: a low-density upper crust, representing the northward extension of the Transscandinavian Igneous Belt and thick, depleted lithospheric mantle of possibly Archean origin. In oceanic domains and in the transition to the continental shelves, the lithosphere thickness is primarily thermally controlled. In the North Atlantic region this is reflected in the long-wavelength gravity field and even more clearly in the geoid undulations. We perform combined geophysical-petrological forward modeling of the lithosphere and sublithospheric upper mantle using the interactive modeling program LitMod3D. For a proper comparison of the structures to the Greenland side, the ice-effects have been removed from the gravity and geoid data sets and are respectively considered in the isostatic calculations.

The existence of similar lithospheric structures (either shallow or deep) along both sides of the conjugate Atlantic margins, has important implications for the Cenozoic rifting history. To which degree can older, lithospheric structures (like the juxtaposition of Neo- and Palaeoproterozoic mantle) guide the location and extent of rifting? Did these structures already play a role in previous tectonic processes like the Caledonian orogeny? A number of ongoing geophysical studies aim to shed a better light on this part of the Norwegian margin in the coming years, including active and passive seismic arrays as well as magnetotelluric studies.

**Improving the Geologic Time Scale – Status 2012**

Gradstein, F.M. & Hammer, O.

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Arthur Holmes, the Father of the Geologic Time Scale once wrote: “To place all the scattered pages of earth history in their proper chronological order is by no means an easy task”. Ordering these scattered and torn pages, and understanding the processes that acted on these pages requires a detailed and accurate time scale. Geologic Time Scale 2012 (GTS2012) is more detailed and more accurate than GTS2004.

Calibration to linear time of the succession of events recorded in the rocks on Earth has three components: (1) the standard stratigraphic divisions and their correlation in the global rock record, (2) the means of measuring linear time or elapsed durations from the rock record, and (3) the methods of effectively joining the two scales, the stratigraphic one and the linear one. Over 65% of international stratigraphic divisions and their correlative events are now standardized, using the GSSP (Global Stratigraphic Section and Point) concept. The radiometric (U-Pb and 40Ar/39Ar) and orbital tuning methods are becoming better calibrated, and external error analysis improved. Existing 40Ar/39Ar ages become 0.64% older, and U/Pb ages stratigraphically more realistic, although often scaling uncertainty remains between the sedimentary levels of an age date and that of a stage boundary. Resolution of age dating exceeds that of biochronology, but not of orbital tuning. Although radiometric ages can be more precise than zonal or fossil event assignments, the uneven spacing and fluctuating accuracy and precision of both radiometric ages and zonal composite scales demands special statistical and
mathematical techniques to calculate the geologic time scale. Numbers to be accounted for include: Uncertainty in bio-magneto and other events correlation, uncertainty in relative scaling of stages, uncertainty in linking radiometric ages dates to stage boundary levels, uncertainty in radiometric age dates itself and uncertainty in orbital tuning. Relative to GTS2004, 26 of 100 stage or series boundaries have changed age in GTS2012, of which 14 have changed more than 4 myr, and 4 (in the Middle to Upper Triassic) between 6 and 12 myr.

Ages and durations of Neogene stages derived from orbital tuning are considered to be accurate to within a precession cycle (~20 kyr). Paleogene dating combines orbital tuning, radiometric and C -sequence splining; hence stage ages uncertainty is larger and varies between 0.2 and 0.5 myr. In Mesozoic and Late Paleozoic high-resolution orbital tuning is achieved between selected tiepoints.

Interactive Lithostratigraphic and Biostratigraphic Wallcharts for Offshore Norway

Gradstein, F.M.

Cooperative project between Norlex and Time Scale Creator

The Norwegian Offshore Stratigraphic Lexicon (NORLEX at http://www.nhm2.uio.no/norlex) and the Time Scale Creator Project (https://engineering.purdue.edu/Stratigraphy/tscreator) provide interactive relational stratigraphic databases for offshore Norway. Two practical and current products are

1. Interactive Lithostratigraphic (wall) Chart, and
2. Interactive Biostratigraphic (wall) charts for Mesozoic and Cenozoic.

The charts may be operated on and downloaded from above internet sites. Interactive means that through simple ‘mouse over’ clicking lithostratigraphic formation and member names link directly to their master definition, their age and in which wells they are observed. It also means that when one clicks on a fossil name its basic taxonomy and its picture are shown, and in which offshore well it is observed and how deep. NORLEX provides an (Petrobank and NPD sponsored) relational stratigraphic database for the North Sea, Norwegian Sea, Barents Sea and Svalbard. Mesozoic and Cenozoic members clarify the stratigraphic position and geographic extent of (reservoir) sand bodies. Core photographs, well logs, field outcrops, microfossil occurrences and other vital attributes are all relationally cross-linked. In addition, there are menus for instantly finding updated formation and member tops or microfossil events in all wells, plus a map contouring routine for unit thicknesses and depths. Time Scale Creator (TsC) and its TsC Pro counterpart enable you to explore and create charts of any portion of the geologic time scale from an extensive suite of global and regional events in Earth History. The internal database suite encompasses over 20,000 biologic, geomagnetic, sea-level, stable isotope, and other events. All ages are standardized to Geologic Time Scale 2012, and can be interpolated back to previous time scales, if so desired. The biostratigraphic datapacks for offshore Norway are part of a stratigraphic series that also includes petroleum basins in the Gulf of Mexico, Australia, New Zealand, China, Russia, Alaska and Arctic Canada.

The current offshore Norway charts have been compiled with assistance from many geoscientists and organisations. In particular are mentioned Mike Charnock, Harald Brunstad and Els van Wenum (Lundin), Terje Hellem (Idemitsu), Dirk Munsterman (TNO, Utrecht, The Netherlands), Erik Anthonissen (Chevron, USA), Felix Gradstein and Øyvind Hammer (Geology Museum, University of Oslo), Gabi Ogg (Geologic Time Scale Foundation) and James Ogg and students (Purdue University, USA).

Stability of heavy metals in submarine mine tailings: A geochemical and microbiological study

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Mining processing waste (tailings) has been deposited directly into Norwegian fjords. However, little is known about the stability of toxic elements in these tailing deposits in Norwegian waters and the environmental impact they may have. In this study we investigate geochemical and microbial processes in submarine tailing deposits in Ballangsjorden (Nordland). Here a nickel mine, Nikkel & Oliven AS
(1988 – 2002) produced more than a million tons of tailings of mainly olivine that was deposited in the fjord at Fornesodden, while tailings of mainly sulphotides and quartz from an older mine, Bjørkåsen Gruve (1909 – 1964), were deposited in the innermost part of the fjord at Ballangsleira. The oldest deposit site Ballangsleira, which is located on land, had historic problems with acid mine drainage (AMD) when dissolution and oxidation processes during weathering generated heavy metal runoff into the river and the sea. The study aims to document if the different tailing compositions have any effect on the submarine biogeochemical processes and the mobility of heavy metals compared to the surrounding sediment. Sediment cores from the two disposal sites and from one site outside the deposits were collected in 2011. Depth profiles of sediment and extracted porewater are analysed for major and trace elements, and extracted DNA for microbial diversity. Preliminary results reveal that the deposit at Fornesodden is relative rich in Ni and Cr, while the deposit at Ballangsleira is higher in Zn and Cu compared to the surrounding sediments. The exception is the top layer of the surrounding sediment, which is highly enriched in Zn and Cu together with Fe. The extracted porewater shows higher pH values in the deposit at Fornesodden and lower values in the deposit at Ballangsleira compared to the surrounding sediment and surface seawater, probably reflecting the different mineral composition. The porewater profiles furthermore document sulfate reduction with depth at the background site and to a lesser extent at Fornesodden. The analyses also show enrichment of Mn, Fe and several heavy metals in the porewaters. Pyrosequencing of amplified 16S rRNA genes reveal that all cores were dominated by Proteobacteria, Actinobacteria or Firmicutes. Archaea were most abundant in sediments outside the deposits (up to 33%) and present in the deposits at low abundances (<2.5%). Preliminary analysis using multivariate statistics did not reveal any clear connection between geochemical and microbiological variability between the deposits.

The outcrop and subsurface expression of shelf-margin clinoforms: the Eocene Battfjellet Formation, Spitsbergen

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Shelf-margin clinoforms (relief of 100's meters) are the main building block of many stratigraphic successions, and are commonly recognized in seismic reflection data. However, due to limitations related to seismic resolution, and the general lack of fully-cored clinoform successions, detailed subsurface characterization of their depositional architecture is problematic. Outcrops offer an opportunity to investigate clinoforms at both seismic and sub-seismic scale, and data integration therefore play a key role in understanding shelf-margin clinoforms.

In this study, a combined subsurface and outcrop dataset is used to investigate the depositional architecture and evolution of an Eocene clinoform succession on Spitsbergen, Arctic Norway. The shelf-margin clinoforms belongs to the Battfjellet Formation, and record the infill of a foreland basin by the progradation of a mixed-influenced, deltaic shoreline system (Steel & Olsen, 2002; Johannessen & Steel, 2005).

The dataset include more than 100 sedimentary logs, a fully-cored well (drilled for research purposes) and onshore well-tied 2D seismic (e.g. Johannessen et al., 2011). The dataset gives a unique opportunity to investigate the depositional architecture, including the internal facies distribution, of shelf-margin clinoforms.

The flat to low angle topset segment of the clinoforms consists of coastal plain deposits in its most landward reaches, and delta front to shoreface parasequences further basinward (Helland-Hansen, 2010). The parasequences are partly overlapping and record periods of delta lobe progradation, autogenic lobe switching and abandonment. The slope segment consists predominantly of heterolithic deposits in its stratigraphic upper part and mudstone in its lower part, and record deposition from various gravity-flow and suspension fallout processes in a pro-delta setting. Locally, sandstone-dominated wedges, up to 80 m thick, extend down from the shelf-edge onto the slope. The wedges consist of multiple-stacked turbidite lobes and channels that were fed by shelf-edge deltas (Johannessen & Steel, 2005). In some places, the slope wedges can be traced down-dip into turbidite lobe complexes on the basin floor (Steel & Olsen, 2002; Johannessen & Steel, 2005; Johannessen et al., 2011). These lobe complexes occur in several narrow (<10 km), depositional dip zones that typically extend across the entire length of the preserved basin (100 km), and record periods with increased coarse-grained sediment flux into
the basin. In general, however, the basin floor segment in most of the investigated clinoforms consists of finely laminated mudstone.

Acknowledgments
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References:

A review of Lower Cretaceous clastic wedges in Svalbard: a key to the prognosis of prolific sandstone units in the Barents Sea?

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Although the Lower Cretaceous on Svalbard has received considerable attention from both academia and industry, it remains among the least understood and most debated stratigraphic intervals on the archipelago. During the Early Cretaceous, Svalbard formed part of the epicontinental Boreal Sea, and was linked to basins in Greenland, Arctic Canada and Alaska. The basin infill was affected by tectonic and magmatic processes associated with the opening of the Amerasian Basin (e.g. Gjelberg & Steel, 1995). The Lower Cretaceous succession is divided into the Rurikfjellet-, Helvetiafjellet- and Carolinefjellet formations (Mørk et al., 1999). Together, they form a >1000 m thick R-T megasequence that reflects long-term shoreline progradation and retrogradation. The Rurikfjellet Formation (Berriasian-Hauterivian) is up to 400 m thick, and consists of the lower mudstone-dominated Wimanfjellet Member, and the upper sandstone-rich Klutodden Member. The formation is generally densely bioturbated, and the sandstones contain various wave- and storm-wave generated structures, indicative of deposition on a storm-influenced shelf (Dypvik et al., 1991). Recently, wells drilled in the Longyearbyen area have surprisingly encountered gravity deposits with rafted blocks of coastal plain facies, suggesting a hitherto unknown Valanginian to early Hauterivian shoreline progradation. The upper part of the Rurikfjellet Formation contains shoreface and delta-front deposits, and records an overall regressive trend (Edwards, 1976; Dypvik et al., 1991; Gjelberg & Steel, 1995; Midtkandal et al., 2007). The Rurikfjellet Formation is equivalent to the Knurr- and Kolje formations in the Barents Sea (Mørk et al., 1999).

The Helvetiafjellet Formation (Barremian-Aptian) is up to 155 m thick, and consists of the lower sandstone-dominated Festningen Member, and the upper heterolithic Glitrefjellet Member. The lower sandstone-dominated part was deposited in a braid-plain environment, whereas the upper heterolithic part was deposited in a marginal marine environment (e.g. Gjelberg & Steel, 1995; Nemec, 1992; Midtkandal et al., 2007). Both carnivorous and herbivorous dinosaurs lived on the coastal plain of this system, as evident from preserved foot prints at several localities (Hurum et al., 2006). The stratigraphic architecture of the formation indicates deposition during a long-term fall and subsequent rise in relative sea level (Gjelberg & Steel, 1995; Midtkandal & Nystuen, 2009).

The Carolinefjellet Formation (Aptian-Albian) is up to 850 m thick, and consists of five members (Dalkjøgla, Innkjøgla, Langstakken, Zillerberget and Schönrockfjellet) that are alternatingly sandstone and mudstone dominated. The sandstone-dominated units form extensive sheets that contain abundant hummocky cross-stratification. The formation is suggested to represent the transgressive, storm-reworked shelf segment of the underlying Helvetiafjellet Formation (Gjelberg & Steel, 1995), and correlates with the Kolmule Formation offshore (Mørk et al., 1999). The stratigraphic comparison between the offshore Barents Sea and onshore Svalbard is a challenging task. There are for example no equivalent offshore formations to the Helvetiafjellet Formation, although, both shallow marine clastic wedges and gravity flow deposits are present along basin margins and basinal highs (e.g. the Loppa High, and the northern and western margins of the Fennoscandian Shield). In addition, southeastward prograding shelf-margin clinoforms, visualized in offshore reflection
seismic data, suggest the presence of an Early Cretaceous depocentre in the Barents Sea.

References:


Sedimentology, paleontology and diagenesis of the Ordovician (Darriwilian) Svartodden Member (Huk Formation), Slemmestad, Oslo Region

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The Ordovician (Darriwilian) Svartodden Member of the Huk Formation in the village of Slemmestad in the Oslo Region, Norway, is characterized by large and abundant orthoconic endocerid cephalopods. *Proterovaginoceras incognitum* (Schröder) is the most dominant species recorded in the Svartodden Mbr. The Svartodden Mbr. is a 2 m thick limestone unit, corresponding to the lower part of the Baltoscandic Orthoceratite Limestone, characterized by several hard- and firmgrounds formed as a result of a very low net sedimentation rate and by early cementation. The main part of the fieldwork performed on behalf of the study was conducted at the well-known outcrop near the Slemmestad IF arena, a bedding surface measuring approximately 1500 m². The unit was carefully logged with a particular focus on detecting firm- and hardgrounds. The macrofauna was recorded and the different cephalopod species were quantified. Current directions based on orientations of cephalopod conchs show a preferential current in a N-S direction. Extensive bioturbation can be witnessed from abundant trace fossils on the main bedding surface. Tunneling asaphiid trilobites took advantage of the firmgrounds and produced most of the abundant *Thalassinoides* trace fossils contained in the unit. The main cause for this opportunistic behavior is linked to predation pressure from the abundant omnivorous nautiloid cephalopods. The tunnels are believed to have been inhabited by microrromatolites, forming microbial linings growing from the tunnel peripheries. Slabs were dissolved in acetic acid, and the acid resistant residue was analysed with respect to microfossils, authigenic minerals and microtektites. The recorded conodont species *Drepanodus arcautus* (Pander) and *Baltoniodus medius* (Dzik) are characteristic species of the *Ecoplagocnathus pseudoplatus* zone, also previously reported from the Svartodden Mbr. Brachiopods belonging to the genera *Conotreta* (Walcott) and *Myotreta* (Goryanskij), as well as bryozoans of the genera *Moyarella* (Nekhoroshev), *Chasmatopora* (Eichwald) and *Moorepheyloporina* (Bassler) have also been recorded. These new findings have shed light on the depositional environment and the fauna contained in the Svartodden Mbr. New records and interpretations of firm- and hardgrounds based on field observations and element analysis by x-ray fluorescence (XRF) of the bulk unit are presented. Element concentrations of Fe, S, Mn and P are used to recognize the hardgrounds. The diagenetic history of the unit based on studies of cements in cephalopod siphuncles, includes several stages of precipitation and dissolution of cements caused by alternating burial and uplift.
The application of Icelandic tephra layers to refine marine sediments chronology and the marine reservoir age in a Mid- and Late Holocene marine core from the E-Norwegian Sea

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The study and reconstruction of the marine reservoir age has been an important issue in Quaternary and paleoclimate science the last four to five decades. A major effort has been made to radiocarbon date marine shells and whale bones from museum archives, pre-industrially collected along the Norwegian coast and from sites in the Arctic area (Mangerud et al., 2006). Also, recent archeological studies from coastal sites in Ireland and neighboring coastal areas using macro fossils and shells to date the late Holocene marine reservoir age has generally resulted in the same conclusion as found at most Norwegian sites, i.e. a marine reservoir age around 400 yrs with some local variability in the delta R (Ascough et al., 2009). For the first time a high-resolution marine core, located in the E-Norwegian Sea underneath the Norwegian Atlantic current, has been dated with a large number of high precision radiocarbon dates utilizing planktonic foraminifera (Sejrup et al., 2010, 2011). The results of the radiocarbon dating have been used to construct calibrated chronology mainly based on lead and cesium dating in the top, supported by historical tephra layers and through a simple wiggle match with the INTCAL 14C tree-ring for the older record. The results show that for the last 1000 years the delta R for this open ocean site shows delta R values bracketed between 160-190 yrs. This is significantly higher than found at the coastal sites. Similar local delta R deviation of +175 yrs is also determined for the 3826 14C BP dated Hekla 4 regional tephra layer found at the core site. We will present results from the identification of both historical (last 1100 yrs) and some regional late- and mid Holocene tephra layers from Iceland that will contribute to better constraining and independently also refining of the delta R values at this site. The results will also be discussed in terms of other well dated and tephra rich archives from the Norwegian-Greenland Sea region.

References:


An experimental study on the formation of clay coatings (smectites, chlorites) and its implications in sedimentary environments

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The most important porosity reducing process in siliciclastic sandstone reservoirs is quartz cementation. Different types of clay minerals modify the quartz cementation process in different ways. The modifications can be either beneficial or harmful to the reservoir properties. Porosity reduction is inhibited by the formation of clay-overgrowths but the formation of clay minerals can also occlude porosity and reduce permeability. In this study hydrothermal experiments were performed in order to investigate the formation of clay coatings (smectites, chlorites) on feldspar and quartz surfaces. Observed experimentally grown clay overgrowths were compared to diagenetic overgrowths found in Upper Jurassic sandstones from the South Viking Graben.

The experiments were performed by varying the bulk solution chemistry at a temperature of 100 and 150 °C for 21 to 50 days using feldspar and quartz as substrates. The substrates were examined using scanning electron microscopy (SEM) and aqueous solutions were analyzed by ICP-MS. The initial bulk solution speciation and saturation index calculations were done using the computer code PHREEQC. The experiments showed that chlorite (clinochlore) formed on feldspar surfaces when the aqueous silica saturation was below quartz saturation. Upon adding quartz to the reactor, the silica saturation increased and smectite formed
instead. At low pH (~5 to 6), only kaolin formed (kaolinite at 100 °C and dickite at 150 °C). At increasing pH above 6–7, kaolin was replaced by chlorite or smectite. The major control on the clay formation was the aqueous silica saturation and pH. Both clay phases formed easily at Mg concentrations down to 0.01 mol/Kg. The effect of the substrates was two-fold: (1) Providing surface areas for nucleation of the clay particles; and (2) providing elements required for the clay growth (Al, Si, K). The low solubility of Al around neutral pH conditions suggest that local supply rates of Al and spatial diffusive transport control the clay growth in sedimentary rocks. The experimental clay overgrowths are analogous to preserved clay-rims originally formed on feldspar grains observed in Intra-Draupne Sandstones from the South Viking Graben. The study serves as a benchmark to obtain essential variables that could be related to the diagentic reactions affecting reservoir quality.

The magnetization history of the Early Cretaceous magmatic rocks from Svalbard shows primary magnetization and complete Late Cretaceous and/or Cenozoic remagnetization

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Early Cretaceous sills constituting the Diabasodden Suite (DBS), crop out all over Svalbard, Arctic Canada and Franz Josef Land. They have also been identified offshore on seismic in sedimentary basins in the North Western Barents Sea. Recent dating of the sills using U-Pb and Ar-Ar methods suggest a magmatic event around 125 Ma. The magnetization history of the DBS is rather complex. Sills from eastern Svalbard carry Early Cretaceous paleopoles (reverse polarity) concordant with those from North America after correction for sea-floor spreading. Demagnetization and magnetomineralogical studies on a new suite of samples from central Svalbard reveal two well defined clusters of paleomagnetic directions. The paleopoles of these two clusters are interpreted to represent the 125 Ma event and a complete post Early Cretaceous overprint. Sills collected in or near the Billefjorden fault zone in central Svalbard carrying steep magnetization directions (reverse polarity), are suggested to represent a post Early Cretaceous magnetization overprint that may be related to fault activity prior to and during the Eocene West Spitsbergen Fold-and-Thrust Belt. Steep magnetization directions (both polarities) are also found in sills outside the Billefjorden fault zone and in eastern Svalbard. A published paleopole from the lavas on Franz Josef land and preliminary results from the Kong Karl Land lavas, also show steep magnetization directions. Published paleomagnetic results of the Devonian, Permian and Triassic sedimentary rocks of Svalbard reveal persistent partial remagnetization.

Svalbard and the North Western Barents Sea have seen regional uplift in the late Cretaceous and flank uplift caused by the Paleocene-Early Eocene sea floor spreading. The entire Barents shelf was uplifted and eroded during Neogene time. The North Western Barents sea and Svalbard are characterized by high heat flow, young magmatism and a thin lithosphere. It is discussed if the extensive regional remagnetization found in magmatic and sedimentary rocks on Svalbard was due to uplift, erosion and tectonics in the Late Cretaceous or in the Neogene.

The Giant Claw of the North: Cephalopod arm hooks from the Boreal Upper Jurassic

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A number of unusually large (>4 cm) cephalopod arm hooks (onychites) have been found by our group in the Upper Jurassic of Spitsbergen, where they occur in Kimmeridgian-Volgian shales and seep carbonates of the Agardhjøellet Formation. Hooks of similar size and age have also been reported from Greenland, Andøya (northern Norway) and the North Sea. All these hooks belong to the same form species, Onychites quenstedti, and we suggest that they represent a single biological species or genus of belemnoid, possibly a belemnotheutid (belemnoid without rostrum), endemic to the Boreal and High Boreal realms. Large cephalopod arm hooks (mega‐onychites) are usually interpreted as an expression of sexual dimorphism, with disproportionately large hooks in the males. The hooks are therefore unlikely to belong to a cephalopod of unusually large body size. We suggest the use of logarithmic spirals as morphological descriptors for the distal part of onychites. The remarkable fit of our specimens to
such a shape model can be interpreted as a functional adaptation connected with particular mathematical properties of logarithmic spirals.

**Milankovitch in the Lower Palaeozoic of the Oslo Region?**

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It has long been noted by geologists that large parts of the Lower Palaeozoic succession of the Oslo Region have a rhythmic appearance, with limestone-shale or siltstone-shale alternations on decimetre to metre scales. Some examples are the Fossum, Steinvika, Vollen, Arnestad, Frognerkilen, Solvang and Grimsøya Formations in the Ordovician, and the Solvik Formation in the Silurian. The great success of cyclostratigraphy in recent years, not only in the Caenozoic but also in the Mesozoic and partly the Palaeozoic, prompts a thorough investigation of these lithological cycles in the light of possible astronomical forcing and using modern time series analysis techniques. We present preliminary results indicating Milankovitch signals in at least some of these formations. The analyses are based mainly on magnetic susceptibility measurements in the field, allowing high-resolution logging at low cost. In the Arnestad Formation, we observe several significant periodicities in the frequency ratios expected from cycles in the obliquity and long and short eccentricity bands. The sedimentation rate calculated from these possible Milankovitch cycles is consistent with new U-Pb ages obtained from the Arnestad (Kinnekulle) and upper Grimsøya tephras in Asker, south of Oslo. These results, together with the newly reported GICE carbon isotope excursion in the Frognerkilen Formation, indicate a substantially younger age for the Sandbian-Katian boundary than previously assumed. We also present magnetic susceptibility curves from several other Cambrian and Ordovician formations in the Oslo Region, some of them showing clear cyclicity. There are many uncertainties connected with the Milankovitch interpretation of these cycles, including the possibility of cycles produced by processes internal to the sedimentary or diagenetic systems, variation in sedimentation rate, the differential compaction of shales and carbonates, statistical issues, and the lack of accurate astronomical estimates for the orbital periodicities in the Palaeozoic. However, the prospect of an extremely precise chronology for the Lower Palaeozoic using cyclostratigraphy, as has been achieved for younger parts of the geological record, should encourage further work in this area.

**Role of Re-Os isotope geochemistry in building the next generation time scale**

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The much-welcomed arrival of GTS2012 [1] lifts the bar for geochronologists of all stripes . . . what new tools and clever innovations will deliver yet further refinements in the on-going effort to calibrate deep time? The rhenium-osmium (Re-Os) isotopic system is a relative new-comer to the arena, and like all of its long-tested cousins, has both strengths and weaknesses, and both appropriate and inappropriate applications. Here we summarize the opportunities and pitfalls offered by this new player. Earth’s time scale is constructed with two parallel approaches: (1) establishing relative time with biostratigraphy and magnetostratigraphy, correlating unique events with chemostratigraphy, and constructing cyclostratigraphy where possible, and (2) calibrating the relative time scales with time pins from radiometric ages and astrochronology. Magnetostratigraphy and astrochronology provide extraordinary age control for the last 250 m.y., but are only tentatively pushed back into the Palaeozoic. The Ediacaran fauna is the oldest reliable biostratigraphic marker known to date, and high-resolution biostratigraphy is really not possible before the Cambrian. $^{40}$Ar/$^{39}$Ar ages may be extraordinarily precise in pristine igneous rocks or fully recrystallized metamorphic rocks, but where thermal evolution is complex, argon loss may reduce geologic accuracy. Thus, the utility of $^{40}$Ar/$^{39}$Ar chronology tends to diminish in older systems. In the Precambrian, therefore, U-Pb and Re-Os geochronology, complemented by chemostratigraphy, are the only widely applicable methods for temporal correlations.

Re-Os geochemistry provides both radiometric dating and chemostratigraphy. Dating sulfide phases in igneous rocks and hydrothermal or metamorphic veins brackets ages of sedimentary sections; in particular, molybdenite (MoS$_2$) contains structurally bound parent Re, but essentially no initial daughter Os, thus constituting a single-mineral chronometer [2]. Additionally, Re and Os are sequestered in organic-rich sedimentary rocks (ORS), providing a robust chronometer for depositional ages in sediment-
ary sections. Further, the initial $^{187}$Os/$^{188}$Os ratio in seawater, like $^{87}$Sr/$^{86}$Sr, varies with time, placing chemostatigraphic footprints on unique events and evolving processes through Earth history. Notably, the Re-Os system provides both the age and seawater $^{187}$Os/$^{188}$Os ratio for deposition of ORS, commonly with C and S isotope analyses also available. Thus, details of seawater chemistry and paleoenvironment accompany the age. Re-Os geochronology of ORS may have relative analytical precision as good as 0.5% (e.g., ± 1 Ma for 200 Ma rocks). U-Pb ages, however, are commonly reported with much tighter analytical precision. Reported analytical precision, however, has different meanings for different analytical methods, and none provide a measure of geologic accuracy. High precision is acquired from multiple spot age determinations for a single mineral grain; higher "n" means better calculated precision. Re-Os ages for ORS, in contrast, are derived from isochrons which provide a single age determination. For each isotopic system, the reported analytical precision is correct, but it is not a measure of geologic accuracy – which is the ultimate goal. Re-Os chemostratigraphy is still in its infancy, as high-resolution data sets are few. Nevertheless, given the relatively short seawater residence time for Os, short-lived $^{187}$Os/$^{188}$Os excursions may be detected. The preserved $^{187}$Os/$^{188}$Os in ORS may not record contemporaneous seawater $^{187}$Os/$^{188}$Os in all cases, however. The geochemist must preclude detrital Os contributions with variable $^{187}$Os/$^{188}$Os, local variations in seawater $^{187}$Os/$^{188}$Os (e.g., restricted basins or near-shore environments), and post-depositional disturbances. Reliable temporal trends in seawater $^{187}$Os/$^{188}$Os ratios should be derived from isochrons and/or reproduced from two or more demonstrably correlative, geographically separated sections.


Earth system interactions in deep time

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Geological records provide an archive of geosphere-biosphere interactions in the deep past. Understanding their drive-response relationships is not trivial given the complexity of the system and data limitations. Here I discuss how such interactions may be inferred from incomplete records, highlighting two case studies: (1) The response of calcifying phytoplankton to climatic and environmental changes in the Cenozoic, and (2) linkages between the history of marine biodiversity and large-scale geological changes over the Phanerozoic.

Nickel exploration in the Hamn Layered Intrusion, northern Norway.

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Store Norske Gull AS

The Svecofennian Hamn intrusion is located on the island Senja in Northern Norway. The intrusion covers an area of ca. 15 km² and consists of two separate bodies divided by a mountain ridge. The Ni ore at Hamn was mined from 1872 to 1886, producing 105000 tons of ore with an average grade of 0.9% Ni. In addition to Ni, Co and Cu were also extracted from the ore. In 2006 the area was claimed by Store Norske Gull who carried out bedrock mapping, several geophysical surveys and drilled 6 holes with a total length of 1601.1 meters in the period 2007-2008. The southern body of the intrusion has been heavily deformed and has lost most of its primary textures. The main body of the intrusion has survived most of the regional deformation and much of the original textures and mineralogy is still intact. The intrusion consists mostly of rocks of gabbro-noritic composition. These rocks are found both as a massive, homogeneous type, and with visible rhythmic layering. Magmatic layering can be observed in outcrops throughout the whole main body and shows a strike from 300° to 320°, with dip of layering from 60° to vertical.

Along the western border of the intrusion the contact with the surrounding gneisses can be observed. The contact seems undeformed and a marginal series consisting of fine grained magnetite bearing melagabbro can be found in several outcrops. The eastern border towards the surrounding rocks is deformed and consists of sheared and partly mylonized rocks as the eastern contact of the intrusion have been cut off by the Svanfjellet Shear Zone.
Lenses containing ultramafic and/or troctolitic rock types follow a belt through the whole intrusion with a strike that mostly follows the main magmatic layering. Inside these lenses a multitude of lithologies are found, with magnetite bearing and/or potassium rich gabbronorites usually present, giving them a high magnetic anomaly. The most common ultramafic rock type is a herzolitic olivine chromite orthocumulate. Olivine is usually found fresh and the rocks only contain minor amounts of serpentinite and secondary magnetite.

The parental magma(s) that produced the different rock types of the Hamn Intrusion is assumed to have been in equilibrium with the first ferromagnesian phases to crystallize, i.e olivine. The Mg# number of olivine in the earliest cumulates should then reflect the primitiveness of the parental magma. Highest Mg# content in olivine have been measured to 85.6 and the MgO content of the parental magma have been calculated to 12.4 wt%. This indicates a parental magma of basaltic composition, which usually has a nickel content of approx. 300 ppm, enough to produce economically interesting Ni-Cu mineralizations. The whole-rock analyses from the Hamn intrusion show clear indications of nickel depletion. With the exception of some few distinct areas, all samples show comprehensive nickel depletion in almost all lithologies. The amount of sulphides found in outcrops and drill cores are far too insufficient to account for the major chalcophile depletion observed both in mineral and whole-rock chemistry. This suggests that there has been an early sulphide phase in the magma that has depleted the residual magma of nickel and copper.

**Inversion of fault-slip data from Northern Norway: challenges and new development**

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Coastal areas in Northern Norway preserve brittle fault zones with abundant slickensided or striated fault planes. Some of these fault zones link up with prominent basin-bounding faults offshore. Using fault-slip analysis to invert for stress, strain or strain rate may therefore contribute to the understanding of offshore rift-basin development and to the general understanding of the tectonic history of Norway. However, inverting fault-slip datasets from these areas offer several challenges. As the faults are often exposed in crystalline basement rocks, offset markers are rare and the correct assessment of slip sense can be difficult. This poses a major problem when using fault-slip inversion routines which are 'slip sensitive'. In addition, the datasets are often heterogeneous, representing e.g. multiple fault generations and/or mixed states of stress that may cause large errors if the dataset in question is not correctly separated into homogenous subsets. Recent development in the field of fault-slip analysis can tackle the challenges posed by such datasets. By using direct linear inversion methods operating in stress-space in combination with clustering algorithms it is possible to automatically separate heterogeneous data into homogenous subsets and evaluate the principal axes and shape ratios of the stress, strain or strain rate tensor representing each subset. The orientation and magnitude of vorticity, if present, can also be constrained by expanding the 'stress space' method to a nine dimensional parameter space. These new inversion routines are robust and insensitive to the correct assessment of slip sense. They may consequently contribute to the understanding of the tectonic evolution of fault zones in Northern Norway and other areas where heterogeneity and slip-sense complicates fault-slip analysis.

**Late Mesozoic to Mid Cenozoic structural alignments and stresses in the Arctic and North Atlantic**

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Here we present a new reconstruction fitting microcontinents og major plate in the North Atlantic applying particular focus to the Northwards drift of Greenland during the Early Cenozoic. Fitting Greenland southwards backwards in time give: 1) due space along the west Barents Sea margin, including fitting microcontinents (Hovgård and Grønlandsryggen,
Conjugate margin exploration: What can we learn from comparing the sub-basalt geology at East Greenland, Jan Mayen Micro-continent and the Mid-Norwegian margin?

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The fjords of East Greenland boost spectacular exposure of Carboniferous to Cenomanian sediments cut and capped by ca. 55 Ma mafic intrusives and basalts. These rocks are formed and deformed through several tectonothermal events, some of which are of regional importance: (1) Late Jurassic to Early Cretaceous rifting, (2) pre-break-up rifting and erosion, and (3) subsequent break-up volcanism, (4) mid Cenozoic magmatism and translation of Jan Mayen from the Greenland to European plate, and finally (5) Late Cenozoic uplift and deep erosion. The mountains display exhumed oil traps, but standard basin models do not explain how these fields formed or were exhumed. Accordingly tectonothermal models must consider the effects of the break-up and associated magmatism, and particularly the thermal effects of rocks now eroded both within the section (the sub-basalt unconformity) and above presently exposed sections (Eocene and younger rocks). Considering the sub-basalt setting of the Norwegian Sea Margin we face almost the opposite challenges. Combined well and seismic data represent good control down to the 55 Ma basalts. Below the basalts, seismic horizons can be tied to Turonian (perhaps Cenomanian with good will), and thus the age and tectonothermal history of potential plays on the marginal high is at best speculative. This represents a challenge, but also opportunity to exchange the missing, or unknown, sections across the rifted Northeast Atlantic margins. We played a “what-if-game”, where Norwegian Turonian and younger geology is inferred into the missing section of East Greenland, and reversely substitute sub-Turonian geology on the mid-Norwegian margin with well-documented East Greenland settings. Similar games were played with the Jan Mayen Micro-continent.

Combined field, geophysical and modeling efforts from the broken margins suggest that:
(1) The East Greenland evolution can be understood only if sections below and above the basalts are included in models, even though these sections may be eroded now. Maturation stopped in the Mid Cenozoic, due to both erosion and diffusion of break-up heat. Had East Greenland been buried under the Norwegian post-basalt setting then its prospects would have been extraordinary. Furthermore it is crucial to understand processes leading to uplift of the Mesozoic marine sediments exposed in the mountains of East Greenland.
The Rendalen-Grejsdalen transect of the North-East Greenland Caledonides: New field observations from NE-dipping normal faults bounding a migmatite complex

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Dramatic topography combined with excellent exposures of the bedrock make the North-East Greenland Caledonides an ideal field laboratory to study tectonic processes related to the formation and disintegration of large-scale continent-continent collision zones. The structure of the North-East Greenland Caledonides is characterized by thrusting of tectonic units over the foreland in the W, accompanied by widespread extensional shearing of the same units in the hinterland in the E. The relative contributions of thrusting vs. normal faulting to the current architecture of the orogen is a matter of debate, and many of the important fault zones shaping the orogen have so far not been described in any detail.

In this contribution we present new structural field observations from a transect which crosses three important tectonic units of the North-East Greenland Caledonides. These are from west to east: the Niggli Spids, Hagar Bjerg and Franz Joseph allochthons, respectively. The first two units consist of variably metamorphosed metasedimentary rocks of the Latest Mesoproterozoic Krummedal succession, whereas the third unit consists of Neoproterozoic metasedimentary rocks of the Eleonore Bay Supergroup. All three units show evidence for complex, polyphase deformation. We present a structural cross section through the entire region as well as field evidence for the nature of the tectonic boundaries between the three units:

(1) the Niggli Spids allochthon is separated from the Hagar Bjerg allochthon by a well-exposed, gently north-east-dipping ductile to brittle normal fault, the Rendalen fault. Interestingly, the Niggli Spids rocks in the footwall of this normal fault seem to be of lower metamorphic grade than the migmatitic rocks of the Hagar Bjerg allochthon located in the hanging wall of this fault. (2) The Hagar Bjerg allochthon is separated from the Franz Joseph allochthon by an inferred steep, brittle normal fault, which juxtaposes the migmatites of the Hagar Bjerg allochthon with biotite-garnet-grade rocks of the Franz Joseph allochthon. Metamorphic PT work is ongoing in order to characterize in detail the metamorphic evolution of each unit and the tectonic and metamorphic breaks between them.

Outcropping Middle Triassic deltaic sandstone bodies from Sørkapp, Svalbard as an analogue to the main reservoir section in the Goliat Field, Hammerfest Basin, south-western Barents Sea

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The Goliat Field is situated on a giant four-way rollover down-faulted structure in the south-eastern margin of the Hammerfest Basin and banked against the Troms-Finnmark Fault Complex. Two major oil pools are seen in the field; an upper accumulation in the Fruholmen and Tubåen formations, while the main accumulation is found in the estuarine, fluvial to deltaic Middle Triassic Kobbe Formation. Hitherto Middle Triassic proximal facies and prolific reservoir sandstones facies are only reported close to basin margins in the Barents Sea.
Near similar described depositional settings to the Kobbe Formation in the Goliat Field were reported at Karentoppen, Sørkapp, Spitsbergen. The Middle Triassic section here was subdivided into a member, the Karentoppen Member within the Anisian Ladinian Bravaisberget Formation. The reported deltaic facies become a candidate for comparative sedimentological and sequence stratigraphical studies, with the purpose of improving the understanding of depositional processes and sand body geometry in the Goliat Field. Outcrop studies in 2011 on the Karentoppen Member and core studies on the reservoir section in the Goliat Field were conducted to better define thicknesses, lateral continuity, and vertical stacking patterns of the sandstone bodies in a proximal mid-Triassic unit. A refined facies analysis of the Kobbe Formation in Goliat reveals a proximal deltaic facies including estuarine, tidal-fluvial channel environment. The Karentoppen Member reveals near similar facies associations as delta front, shallow marine environment with amalgamated distributary channels, but with less tidal influence. Both vertical and lateral facies patterns from the outcrops give a better understanding of the geometry of the sandstone bodies and might be used to give better reservoir characterisation of the “Kobbe reservoir” in the Goliat Field. Based on this study, a westerly provenance area for the Karentoppen Member is consistent with previous study. This is in contrast to the proposed eastern drainage area for the Kobbe Formation in the Goliat area. Due to the proximal facies distribution in both areas these clastic wedges might define the northwest and south margins of the Middle Triassic basin in the Barents Sea. The facies distribution in both areas also suggests a more point sourced drainage as opposed to the more distal facies distribution in the familiar north-west prograding clinoforms in the Lower Middle Triassic in the Greater Barents Sea and on Svalbard elsewhere. The poster will demonstrate some of the findings in the Karentoppen outcrop and the core description and interpretation of the Kobbe Formation in the Goliat Field. A conceptual depositional model is given for the two areas.

Looking back to the future - Norwegian geoscience and the global quest for mineral resources

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The last decade has shown an increasing demand for mineral commodities, resulting in growing prices. Although the financial crisis in 2009 caused a temporary decline, and the present crisis in Europe may have consequences on prices not yet known, there are reasons to believe that demand and prices will continue to increase in the long run. The main engine behind this is growing wealth in highly populated areas in the world, combined with high- and green-tech revolutions. New discoveries of economic sustainable resources have so far not contributed in improving the rather disturbing long term prognoses of a serious gap between supply and demand for important commodities. A scenario where raw materials become scarce or even inaccessible of political or economic reasons, led many nations (including Norway) to develop strategies on how to face such situations. EU launched the Raw Material Initiative, addressing 'fair play' in the raw materials markets, recycling and substitution of raw materials and the need for increasing raw material exploitation in Europe. The latter is a challenge for the geoscience community. After many years of re-orientation towards other disciplines, an ore geologist is perhaps more scarce at the present time than any of the raw materials. The impact may be that our community fails to meet the challenge given by EU and national policies. On the other hand, investments in prospecting and new mines seems to delay, particularly in countries where the mining sector did not survive the large decline in the 80's and 90's. The number of new jobs does not reflect the political focus on raw material supply. Nevertheless, the Norwegian government has launched several programs for improving the knowledge base of Norwegian deposits, resulting in a significant step forward. EU have started the implementation of the Raw Material Initiative through an increasing number of calls and tenders related to raw materials, and collaborative actions between geological surveys and universities across borders are stronger and more numerous than ever. Thus, there is a climate of opportunities for re-vitalizing economic geology research and education. In Norway, the government programs provide genuine new geophysical, geochemical and geological data sets that can feed prospecting activities as well as more fundamental research. This activity may act as a centre of gravity for new and ground-breaking research on ore genesis, new ore types and re-interpretation of metallogenic provinces. In the near future, several financial tools may be available for supporting such research: EU programs, Nordic cooperation actions and Norwegian research programs. Moreover, the geological survey may
play an important role through financial support to MSc/PhD students and other research cooperation.

On the kinetics of diageneric reactions – Diffusion/transport limitations on the K-feldspar to illite conversion during burial diagenesis

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Aqueous activity diagrams show that at diageneric conditions, the K-feldspar-kaolinite mineral pair resides at a pseudo equilibrium inside the illite stability field. The K-feldspar-kaolinite pair is therefore thermodynamically unstable if illite is allowed to form. From diageneric sandstone systems, it is well known that the conversion from kaolinite and K-feldspar to illite (KK->I) starts at temperatures above about 120 °C. At these temperatures the energy barrier for illite nucleation is sufficient lowered to drive the overall reaction forward. This conversion will proceed spontaneously until either K-feldspar or kaolinite is exhausted, and the amount of illite that may potentially form depends generally on the amount of the reaction-limiting source phase. This is because burial diagenesis takes place in a chemically closed system with only locally derived reactants. More seldom are occurrences of the three-mineral assemblage in deeply buried sandstones at temperatures >140 °C. In such systems, K-feldspar and kaolinite occur in the same sediment volume, but the two are prevented to interact through the pore space by transport (diffusion) barriers. One such example is from well 2/7-31 in the Central Graben where the Rotliegend Formation sandstones buried at more than 4700m/170°C contain pockets of kaolinite engulfed in illite with K-feldspar close by. To model KK->I, we defined a diffusion-reaction simulation with kaolinite and K-feldspar initially separated at each side of a 1D column. The kinetics of kaolinite and K-feldspar dissolution and illite nucleation and growth, were estimated according to a rate law taking into account the distance from equilibrium. Initially ion-diffusivities were the same for the whole column. In cells with illite growth, the diffusivity was reduced according to the volume fraction of illite in the pore space, and the sensitivity of KK->I on the reduced diffusivities was explored. Preliminary calculations show that KK->I depends on the fraction of illite in the pore space forming a diffusivity barrier between the K-feldspar and kaolinite. The aluminium for illite growth was sourced from kaolinite because of the low solubility of aluminium, and illite growth therefore occurred close to/at the kaolinite-solution interface. The results are in accordance with the above mentioned observations from the Rotliegend sandstone from the Central Graben.

Structural analysis of the Kautokeino Greenstone Belt from geophysical and field studies: Towards a refined understanding of its gold mineralisation

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The Palaeoproterozoic Kautokeino Greenstone Belt (KGB) is a linear, steeply-dipping, NNW-SSE striking belt of meta-supracrustals (mostly shallow marine sediments and volcanics) between the Reiseatnu gneiss complex to the west and the more flat-lying jergol gneissic dome to the east. The KGB has traditionally been interpreted as an early Proterozoic rift basin inverted during shortening associated with the Svecofennian orogeny (1.9-1.7 Ga). Despite extensive bedrock mapping during the 1980’s the structural geology and tectonic development of the KGB remain poorly understood. We present new geophysical and preliminary structural data, which help refine our understanding of the tectonic architecture and evolution of the KGB. We also suggest a possible tectonic framework for the belt mineralisation, particularly that observed at Bidjovagge. Our work forms part of the wider government investment Mineralising i Nord Norge (MINN) program focusing on improving our knowledge of the geological environment in which mineral deposits are found, thereby increasing the interest of exploration companies in northern Norway.

The new airborne potential field geophysical data discloses several key features, which suggest the KGB to be a ca. 30 km wide ductile sinistral transpressive belt. A network of, what we assume for the moment, to be Svecofennian ductile shear zones, transpose locally an earlier foliation which is otherwise only preserved within lower strain, asymmetric lenses in the KGB. In the jergol gneissic dome to the east of the KGB we observe a distinct NE-SW foliation which is truncated by the presumably later KGB, which deflects this earlier foliation with a sinistral geometry. In addition,
structures in the easternmost Jergol gneiss complex display a different evolution from those in the KGB. In the Jergol, the NE-SW fabric is cut by shear zones which appear to have a dextral kinematic component. These are also deflected into the KGB suggesting that they are older than the sinistral shear accommodated by the KGB. A comparison of the gneissic complexes of the Jergol and Reiseatnu, which are juxtaposed against the KGB, indicates that the aeromagnetic signature for these two domains is different and none of the interpreted dextral structures are present in the Reiseatnu. This tentatively suggests that these two complexes have a different tectonic evolution and may represent different terranes juxtaposed along the KGB.

Preliminary structural work carried out in 2012 generally supports the geophysical interpretation although the kinematics are more complex than what can be deduced from the analysis of the geophysical datasets. Although outcrop is sparse and of general poor quality, the sinistral structures interpreted from the geophysics show predominantly oblique sinistral movement with an obvious top-to-the-NW thrusting in the western part of the KGB. In the central part of the KGB, where these structures are steeper, both oblique structures and lateral strike-slip movements (both sinistral and dextral) are observed. The mineralisation at Bidjovagge appears to be associated with such strike-slip structures.

**Middle to Late Pleistocene stratigraphy on the eastern Pechora Lowland, Arctic Russia — a stratigraphic record spanning 200 000 years**

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Located 50 km west of Vorkuta in northeastern European Russia is the key section Seyda 1. This river bluff together with neighbouring sections reveals the terrain-forming deposits and valley-infill spanning in time from MIS 7 to MIS2.

Sediments of the penultimate interglacial-glacial cycle are found at Seyda 1, overlying an older till of unknown age. The interglacial unit is dated to around 200 ka (MIS 7) by OSL and U/Th (Murray et al. 2008), and consists of an up to 1 m thick peat, as well as sand and silt interpreted as fluval and floodplain deposits. Pollen analyses suggest conditions warmer than today. Above is a 20 m thick matrix-supported till from early MIS 6 (Saalian), sandier than the lower till and less boulder-rich. On top of the till is glaciectonized fluval gravel and sand. The glacial event causing this deformation is likely of late MIS 6 age.

Measurements of fabric and glaciectonict structures suggest ice dispersal from the Kara Sea except for the lower part of the 20 m thick till indicating ice from Novaya Zemlya or eastern Barents Sea. The next major event is a large-scale fluval incision of the landscape. At Seyda 1 the down-cutting was approximately 45 m. This might have occurred during the last interglacial period (Eemian) when south-flowing rivers got steeper gradient due to post-glacial uplift. However, OSL dates can only bracket the fluval incision between 160 and 100 ka. During the Early and Middle Weichselian the Barents-Kara ice sheet inundated the northern part of the area while the valleys to the south were occupied by ice-dammed lake with deposition of deltaic and glaciolacustrine sediments. Two ice-dammed lake events are recorded along the Seyda valley, around 90-80 ka and at 60 ka. Intervening with these are fluvial deposits showing that the rivers were active throughout large parts of the Weichselian.

Reference:

**Lower Cretaceous Evolution of the Vesterdjupet Fault Zone, Lofoten Margin, North Norway**

Henstra, G., Rotevatn, A., Gawthorpe, R., Helland-Hansen, W., Bastesen, E. & Ravnås, R.

The Lofoten-Vesterålen segment of the middle Norwegian margin consists of a series of late Paleozoic to early Cenozoic half grabens that exhibit a similar yet distinct structural style and basin-fill. As part of the Atlantic system, the area experienced recurring episodes of rifting alternated with periods of tectonic quiescence or uplift prior to continental break-up and formation of oceanic crust by the Early Eocene. As shown by previous work, the Vesterdjupet Fault Zone is a composite, segmented fault that
extends for 100 km along the Lofoten-Vesterålen margin. The present day geometry of the Vesterdjupet fault zone consists of N-S- and ENE-WSW-trending segments. It dips to the NW and forms the SE border to the North Træna Basin half graben. Traditionally, the Vesterdjupet Fault Zone is interpreted to be composed Jurassic fault segments that linked up as relay ramps were breached during renewed rifting in Early Cretaceous times. More recent, however, it has been suggested that the lower Cretaceous instead resembles a post-rift infill where fine-grained marine sediments onlap fault scarp and filled in a submerged half-graben landscape which was inherited from Jurassic rifting. This introduces a contradicting interpretation of the nature of the lower Cretaceous. We have re-mapped the Vesterdjupet fault zone in detail, from where it truncates the Bivrost lineament in the SW to where it peters out in the NE, using Shells in-house seismic database that consists of a dense grid of (reprocessed) 2D and 3D seismic surveys, including the recently released NPD dataset over the margin. By mapping the various intra lower Cretaceous seismic events as recognized from shallow drilling we aim at a higher resolution of displacement distribution through time. Rather than treating the Early Cretaceous as one rifting event, this allows more subtle transitions between rift and post-rift within this time span to be recognized.

**Benthic foraminiferal assemblages in Early Jurassic deposits of the south-western Barents Sea**

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The Lower Jurassic sections of two commercial wells (7119/12-1 and 7119/12-2), drilled in the Hammerfest Basin (south-western Barents Sea), were analyzed for foraminiferal assemblages in order to reconstruct paleoenvironmental changes. Quantitative foraminiferal assemblage analyses are integrated with sedimentological data to assess depositional conditions, transgressive-regressive developments and stratigraphic relations of the delta-influenced, marginal marine succession forming the upper part of the paralic Kapp Toscana Group. This sand-dominated
We will present our effort to implement the new northern Barents Sea Ice sheet. Atlantic root in the disintegration of the western and northern Barents Sea Ice sheet.

We present a series of new time-slice reconstructions from the DATED Project documenting the changing limits of the Eurasian Ice Sheet during the last glaciation (40-10 ka BP). Reconstructions are based on a compiled chronology of over 3000 dates representing the accumulated sum of knowledge on the timing of advance and retreat of the Scandinavian-British-Irish-Barents-Kara Sea Ice Sheets. The timing of both maximum extent and retreat were spatially variable across the ice sheet complex likely reflecting regional contrasts in forcing mechanisms and geographical setting. For example, maximum ice extent in the west occurs ~3000 years earlier than in the northeast sector. We expect the time-slices and derived area and volume estimates to be particularly useful for numerical and isostatic modelling requiring regional scale empirical constraints on past ice sheet extent, and design the reconstructions for this purpose. The ice sheet margin is delineated every 1000 years for the reconstructions for this purpose.
the last 25 ka BP. Additional intervening snapshots are reconstructed when necessary to capture significant rapid changes in the ice margin. We also present some reconstructions at uneven intervals for earlier periods, reflecting the preservation bias of the chronological record. Uncertainty estimates (represented by maximum, minimum, preferred positions) are given for each time-slice. The ice sheet scale approach highlights instances of conflicting evidence and gaps in the ice sheet chronology. Greatest gaps are found along the western marine margins, in the Barents Sea and western Russia, and the inland areas glaciated during the Younger Dryas.

The database and reconstructions will be updated as new information is published and made publically available via the project webpages. Future versions will extend the spatial coverage to include the Icelandic Ice Sheet and additionally include landform evidence to constrain ice sheet geometry (e.g. ice stream locations and thickness) and retreat patterns. In the database, each date is classified on the basis of stratigraphic information to facilitate interpretation of the ice sheet evolution, attributed to the source publication, fully documented with information relevant to its interpretation and searchable by: location, dated material, dating technique, stratigraphic position or setting, derived age and associated errors, pertinent comments from the source publication and sample elevation or depth, core name, laboratory id and/or sample name as applicable. For internal consistency all radiocarbon ages have been recalibrated using the most recent calibration curve (INTCAL09) and all terrestrial cosmogenic nuclide (TCN) exposure ages are reported using the same production rate and scaling model. The uncalibrated $^{14}$C and TCN ages as reported in the source publications are also given. TCN results are additionally reported with all the necessary details required to re-calculate the ages with different production rate and scaling models.

Factors Controlling Symmetry, Width, and Degree of Magmatism at Passive Margins

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Contrasting end members of volcanic and non-volcanic passive margin formation show a large variability in structural style and associated subsidence history that imply strong variability in the underlying thermo-mechanical conditions at the time of rifting. For instance the Iberia-

Newfoundland non-volcanic conjugate margin system has evolved from initial wide to late stage narrow, most probably asymmetric rift, leading to exhumation of mantle lithosphere and sub-lithospheric mantle in a wide ocean-continent transition zone under essentially cold conditions. In contrast rifting in for instance the South China Sea or the Central South Atlantic conjugate passive margins resulted in very wide (> 250 km) strongly thinned crustal conjugates. Volcanic rifted margins such as in the North and South Atlantic show excess magmatic activity and shallow water conditions at the rift-drift transition implying even higher geothermal gradients. Here thermo-mechanical finite element model experiments are used to investigate factors that are potentially important controls during volcanic and non-volcanic passive margin formation, which may explain these characteristic differences. Focus is on factors that control the degree of magmatism and structural style during lithosphere extension and passive margin formation.

Quaternary landscape evolution in Norway – to what degree is Norway sculpted by glaciers?

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Sediment volume estimates from offshore Norway suggest that extensive deposition occurred in the Quaternary, implying a significant amount of erosion onshore Norway during this time period (e.g. Steer et al., Nature Geoscience 2012). It appears that the total sediment volume far exceeds the amounts expected from fjord erosion suggesting a considerable amount of erosion of higher elevation low relief surfaces. These new views on the topographic evolution of Norway question the classical understanding of Norwegian morphology: that a low-relief peneplain was uplifted and dissected in the Cenozoic. Here we investigate how the Norwegian topography and morphology may be explained by glacial erosion processes modifying a preglacial topography, constrained to a first order by the present-day topography and estimates of erosion using the offshore sediment budget. We use a numerical surface process model, including a higher-order ice sheet model, in order to constrain landscape evolution for a climatic forcing similar to what may have prevailed throughout the Quaternary. We find that glacial erosion processes may be
responsible for the characteristic morphological features found in the Norwegian topography and may explain the bimodal distribution of glacial erosion of both fjords and regions at higher elevations, respectively. Furthermore, our results suggest two distinct phases of erosion, with a first phase of extensive erosion at high elevations early in the Quaternary, followed by a second phase of main valley deepening (fjord formation) as a consequence of the extensive glaciations following the mid-Pleistocene transition. This two-phase glacial erosion history results in both high elevation low relief surfaces and deep fjords as observed in Norway.

**Outreach – why bother?**

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Outreach is something few geologists ever bother to do. If a scientists do outreach at all it is often only to impress his colleagues, not to tell the public about his research. Why should we do outreach? It takes time away from research, you have to answer questions from a lay audience, and you have to stop using your tribe language. The common term for outreach in many institutions are “vulgarization” and “dumbing down”. We all know researchers that appeared in media and are later called “media horny”.

On the institutional level outreach are praised with empty words in every annual report or speech by the institutional leaders. It is politically correct to mention the magic word “outreach – formidling” but when push comes to show no institution takes it seriously and backs it with a proper amount of money or approval. Today scientific publications are rewarded in many institutions, but few have any form of rewards for the scientists doing outreach. Outreach takes time just like research and is a skill that needs to be trained. If institutions want to praise scientists doing outreach they should take them seriously, if not they should take the consequence and declare their institution outreach free and ban the use of paid time to do it. But why do some of us do outreach anyway? My rewards are the meetings with enthusiastic children, getting letters and e-mails from all over the World and see schools do projects generated from my research. Other smaller but important byproducts of this is the branding of me and my science; public awareness of how science works; being able to influence political decisions in publishing policy (Open access); attract sponsors to projects; and trying to change the attitude in academia towards outreach.

I do not believe every scientist should do outreach, many are not shaped for it. They can be eminent researchers anyway and should be praised for their work, and left alone. But if any institution wants to take outreach seriously a few positions among the scientists should be hired not only on the amount of scientific publications but also partly on the outreach documented in a CV.

**Spitsbergen Jurassic Research Group**

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Paleontological fieldwork at Spitsbergen 2004-2012 has revealed the presence of abundant plesiosaur and ichthyosaur remains, a series of 15 seep carbonate bodies, as well as a rich invertebrate fauna from the Upper Jurassic – Lower Cretaceous Slottsmøya Member of the Agardhfjellet Formation, a 70-100 meter-thick unit of dark grey to black shale and paper shale. Deposition of the Slottsmøya Member occurred at high paleolatitudes, at or near the Arctic Circle, and molluscan and foraminiferal biostratigraphy indicates an Early Volgian – Ryazanian age for the unit.

The Spitsbergen Jurassic Research Group has performed a multidisciplinary study of the Slottsmøya Member and aspects from chemostratigraphy, cyclostratigraphy, lithostratigraphy, sedimentology, carbonate methane seep deposits, fluid inclusions, microfossils, invertebrate fossils to the gigantic marine reptiles have been studied. Comparative analyses of the marine reptile material found in the Slottsmøya Member indicate a diverse assemblage of new plesiosaurians (two new genera and three new species of plesiosauroid and one new species of pliosaurid have recently been described) and ichthyosaurians (two new genera and species have recently been described). Placed within a high resolution stratigraphic framework, the diverse invertebrate and vertebrate assemblage of the Slottsmøya Lagerstätte provide an unparalleled opportunity to study the evolution and paleoecology of a high latitude Mesozoic marine ecosystem.

The SJRG project has played an important role in graduate student training. Since 2008 eight
master’s students have joined the team that have contributed to the geology and vertebrate and invertebrate paleontology. Two doctoral students studying the plesiosaurs and seep carbonates joined SJRG in 2008 and 2010, respectively. One new is in hiring to study ichthyosaur evolution. The outreach is on a scale never seen for a single research project in Norway, with two International Documentaries (History Channel and National Geographic), Livefeed of digs, blogging on National Geographic main website, Web Pages in Norwegian and English, front page of New Scientist and several hundred national and international media appearances. Further challenges of the project are the enormous work it is to prepare all the skeletons collected. An optimistic time estimate is 10 years of preparation before we see the end of what we have collected so far (37 skeletons). But the material is unique and no effort like this will be undertaken in the Arctic again in the foreseeable future. This collection will be the biggest collection of latest Jurassic marine vertebrates anywhere in the World and will be studied for many years to come. The same is true for the seep carbonates, which are some of the best Mesozoic seep carbonates Worldwide.

Three-dimensional heterogeneities in tidally influenced Triassic strata; new data to condition reservoir prediction performance of local CO₂ storage on Svalbard

Husteli, B., Midtkandal, I., Jensen M., Olaussen, S., Helland-Hansen, W. & Tveranger, J.

Beneath Longyearbyen, in Central Western Svalbard, an Upper Triassic to Lower Jurassic reservoir is targeted for sub-surface sequestration of CO₂ emitted by the local coal-fueled power plant. The goal of the Longyearbyen CO₂ Lab is to capture CO₂ post-combustion and iteratively develop the necessary technology, integrating research and education. Detailed modelling, of the fluids future behaviour is desirable to ensure the success and safety for future storage. The reservoir consists of the mudstones and sandstone units of the DeGeerdalen Formation, Wilhelmøya Subgroup. Matrix permeability and porosity of the reservoir is low and the effective reservoir properties are dominated by extensive fracturing which appears to be linked to the stratigraphy. This relation implies that mapping and forecasting of depositional architectures in the reservoir is beneficial for predictive modeling of reservoir properties. Although secondary porosity is expected to account for the majority of available storage space and fluid flow, the matrix porosity and permeability is crucial for the long-term perspective of CO₂ storage and migration, potentially providing additional space for injection through the fracture system. Previous studies of the target reservoir show that the reservoir largely consists of marginal marine clastic deposits that are tidally influenced, settled in the framework of the westwards prograding deltaic Carnian coastline. Individual units resolved from seismic analysis exhibit lateral continuity on a scale of kilometers to tens of kilometers. However stratigraphic variations beyond seismic resolution can be expected in tidally influenced environments, and, reservoir behavior inconsistencies could result from a sub-seismic diversity in facies distribution. Spatial facies distribution is therefore important to resolve in order to decipher the depositional architecture in the area of the intended CO₂ sequestration site in particular, and as input to understanding stacking patterns in tidally influenced reservoirs in general. Heterolithic intervals are a challenge in current practice of reservoir modeling. For reservoir modeling purposes it is of key relevance to identify the scale of the elements and evaluate how they are organized in a vertical and lateral sense. A meticulous study of scales, grain size variations and stacking patterns allows populating the model with predictive configurations extrapolated from our observations. Several deposits exhibiting characteristics of tidal influence are investigated on Svalbard. For now, the related reservoir outcrops 6 kilometers north of the proposed point of injection have been studied. The rocks are exposed in a coastal cliff, stretching for 15 kilometres, allowing studies of lateral changes, limited by the dipping strata, which is continually younger from west to east, due to a regional dip towards southwest. Edgeøya, east of Svalbard is a key locality for Triassic and Jurassic sediments and may therefore also be of interest for the reservoir. Kvalpynten south on Edgeøya, east of Spitsbergen was the focus of fieldwork in time equivalent strata in August 2012. The study is part of the project Geological input to Carbon Storage (GeC) and Longyearbyen CO₂ Lab. CLIMIT funds the study. The results will be presented in publications as part of a PhD, terminating in March 2015.
Method for estimating CO₂ storage volume in saline aquifers
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Gassnova

Gassnova is a State owned enterprise which executes the interests of the State in Carbon Capture and Storage projects and provides advice to the Norwegian Ministry of Petroleum and Energy. The objective of this effort was to identify a site and document safe storage for the CO₂, captured at the gas power station at Mongstad. This qualification was done in accordance with the EU Directive for underground storage of CO₂. During the qualification work on sites in the Norwegian North Sea a procedure for calculation of storage capacity was established. Uncertainties of input parameters and the data basis were considered and the result is presented as a probability distribution of the storage capacity. The method requires close alignment between geologists and reservoir engineers and integrates communicating pore volume, pressure build-up and safe pressure estimation. In this presentation the calculation of the Johansen site is used as example. The procedure starts with assessment of the data base and the geological interpretation. Here is presence and quality of storage formation divided into risk areas and risked based on factors like well control, analogues, depositional process and regional geology. Different depositional models are considered for the various areas. Uncertainty in depth conversion is included. In the next step communication across faults and barriers, between areas internal in the storage complex as well as communication to volumes outside the complex is assessed in respect of probability and quality. Thickness, porosity and permeability is mapped and modelled mainly based on seismic inversion, attribute analyses and depositional interpretation. Uncertainties in the parameters are studied and probability distributions developed. The result of this part is a total pore volume distribution.
The next step is the dynamic assessment. The pressure development with various assumptions is predicted by simulation exercises which in the end give a probability distributed pressure development. This pressure development is compared with the fracture pressures of the formation, which also is assigned a probability distribution, based on laboratory analyses and experience.
By simulating all these distribution a distribution of the storage capacity becomes the final result. This is comparable to reserve distribution of oil fields.

Formation of potentially porosity preserving grain coats in Brent and Dunlin age sandstones from the northeastern North Sea Area - A combined petrographic and hydrothermal synthesis study of samples from the Gjøa and Agat Areas
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Development of grain coatings in sandstones potentially preserves porosity during burial since coatings occlude detrital quartz surfaces reducing quartz cementation. The most effective grain coatings preserving porosity are chlorite, micro-quartz and illite. Chlorite forms from a smectite or berthierine precursor between 80-100 °C, micro-quartz form from Opal CT at around 60-65 °C and illite forms from smectite around 70-80 °C (already formed illitic grain coatings can also grow further during the kaolinite to illite reaction above about 130 °C.
For coatings to be effective in a reservoir from a reservoir property perspective there must be an original porosity (mainly facies and provenance controlled) worth preserving at the transition between mechanical and chemical compaction (70-80 °C or around 2000-2500 m burial). This study concentrate on the Middle and Lower Jurassic sandstones in the northeastern part of the North Sea where not much is known about eventual porosity preserving coatings. Samples from two areas were chosen covering both shallow burial (Gjøa area – wells 35/9-1 and 35/9-2, six samples each with burial depths between 2200 and 2800m) and Deep Burial (Agat area – well 35/3-2, three samples with burial depth around 4000m). Petrographic description was performed on thin sections (optical microscopy and scanning electron microscopy (SEM) and SEM of unreacted and hydrothermally reacted stubs (small core samples). The twelve samples from the low temperature Gjøa field was hydrothermally reacted at 180 °C for two weeks to test the potential for coating formation during deeper burial. The results show several possible porosity preserving coatings both in Brent age samples and Dunlin age samples. The samples investigated from the Agat area was fine grained
high matrix sandstones with some traces of chlorite coating but no reservoir potential at deep burial. Some of the more clean sandstone samples from the Gjøa area on the other hand showed good porosity preserving potential due to coatings. Two samples one from a Brent age sandstone and one from a Dunlin Age sandstone were particularly interesting. The Brent Age Sandstone contained substantial amounts of grain coating micro-quartz and the Dunlin age sample was clay coated. The hydrothermally reacted Dunlin aged Gjøa sample showed massive formation of chloritic grain coats from the original clay coats indicating good porosity preservation potential in some of the Dunlin aged sands. The Brent age sandstone was coated with micro-quartz. The existence of porosity preserving grain coating micro-quartz in Brent aged Middle Jurassic sediments in the northern North Sea area has to our knowledge not been reported before. The challenge from an exploration point of view is to predict the existence of grain coatings and link the coatings to laterally mappable sandstones.

Physics of Geological Processes (PGP)

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Centre for Physics of Geological Processes (PGP) was established as a Norwegian Centre of Excellence on February 1st, 2003. Its mission is to obtain a more fundamental and quantitative understanding of the complex patterns and processes of the Earth. Our strategy has been to establish a new cross-disciplinary science centre at the interface between physics and geology where geological processes are approached by integrated field-, experimental-, theoretical-, and computer modelling studies. Since the start, PGP has produced some 450 articles in international journals. Among 50 students graduated from PGP, ca. 40% works in academia, and ca. 40% in petroleum related business. 10 out of 34 postdocs work at research institutions abroad. PGP has also contributed to 10 art-science exhibits, 3 books on popular geoscience, ca. 250 articles in newspapers and magazines as well as more than 200 radio and TV programs. During this presentation I will present highlights of the research carried out in PGP with focus on fluid-rock interactions, pattern formation in fluid-rock systems, and implications for the evolution of the Earth’s crust.

Seismic stratigraphic sub-division of the Triassic succession in the central North Sea – integrating seismic reflections and well data


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The Triassic succession in the southern parts of the Norwegian North Sea has traditionally been discarded in the context of hydrocarbon exploration and consequently little effort has been invested in understanding the Triassic stratigraphy. The success in the UK J-block (Judy, Jade, Jasmine fields) has however recently led to increasing interest in the Triassic stratigraphy also on Norwegian sector. Several attempts of sub-dividing the Triassic succession into second order sequences have been published, although due to the transparent nature of the Triassic on seismic data, regional, published sub-divisions are based on well data only. Most wells in the area have been intended for post-Triassic targets and the wells that do reach the Triassic usually terminate in the topmost few 100 meters. Consequently, very few wells penetrating the entire preserved Triassic sequence are available. The Triassic depositional environment was semi-arid and characterized by terminal fluvial systems that grade into playa- or floodbasin mudstones. These sequences are generally barren and lack regional marker beds complicating correlation based on well data further. To enquire a better understanding of the petroleum system involving Triassic sediments in the Norwegian North Sea, a more complete and accurate correlation of the various sequences are needed between wells. This is also crucial for the understanding of the sedimentary environment(s) across the region at the time of deposition. This study focuses on the southern parts of the Norwegian North Sea, northeast of the Central Graben, and integrates geophysics with geology by comparing seismic amplitude maps with well data. A complete set of regional, long offset reflection seismic data (NSR) has enabled the mapping of five second-order seismic successions (tss-1 – tss-5). The focus of this study has been to map seismic reflections which appear as amplitude anomalies and/or sedimentary successions with a similar reflection seismic response. These are then correlated to wells available in the study area. This has given a unique lateral time control of the Triassic succession, and the depositional environments throughout the Triassic, including timing of halokinesis.

All succession tops has been correlated to wells
indicating either climate changes, with increased/reduced input of siliciclastics from the hinterlands, or regional markers, such as potential maximum flooding surfaces or playa lakes. Also, succession tops are often correlated to unconformities and onlap surfaces related to salt structures. A complete Triassic succession is only observed in the northern and eastern parts of the study area. Accommodation space was controlled by relief inherited from Permian rifting during deposition of succession tss-1 in the Early Triassic. However, thickness distributions indicate that the same graben structures acted as the main accommodation spaces throughout early Middle Triassic. Salt remobilization initiated in early middle Triassic, during deposition of succession tss-2, mainly in the western and central parts of the study area. Halokinesis influenced the sedimentation throughout the Triassic and controlled the drainage systems and relief in parts of the study area. Halokinesis is mainly seen in the eastern part of the study area during Late Triassic (successions tss-4 and tss-5).

MAREANO – Geochemical results from surface and subsurface sediments

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More than 150 sediment sampling stations from the western part of the Barents Sea and the Norwegian Sea reveal low levels of heavy metals, arsenic and organic pollutants in recently deposited sediments as well as changes during the past 100 – 150 years. Sediment cores have been retrieved from the shelf, slope and deep-sea plains off Lofoten, Vesterålen, Troms and Finnmark. The depositional settings vary significantly from deeper basins within the shelf, typically marine valleys between more shallow banks to the deeper areas with fine-grained sediment accumulation including pockmark areas. Several sampling stations are located on the slope, where there are varying depositional conditions, depending on ocean currents and stability of the slope sediments. Application of Pb210 and C14 dating techniques show that underneath a relatively thin layer of sediments (mostly < 10 cm) the sediments are several thousand years old. Sedimentation rates on the deep sea plain are significantly lower compared to the shelf as well as the slope.

The general picture shows that pollution levels are low, with most heavy metal concentrations close to background levels in the surface sediments according to the climate and pollution authorityless (Klif) classes for coastal and fjord sediments. Several heavy metal concentrations are quite constant deeper in many sediment cores, implying constant deposition of these heavy metals during the past 100 – 150 years. The exceptions are mercury (Hg) and lead (Pb), which both show increasing trends over a period of several decades in several analysed sediment cores. Despite up to a 3-fold increase in Hg concentrations, the concentrations are still low, i.e. < 0,05 mg/kg sediment. Pb shows a comparable development over time, i.e. a 2 to 3 fold increase over a period of several decades, with a minor decreasing trend in the top layers of the sediment cores, going from approx. 10 mg/kg to 20 – 30 mg/kg in the upper parts of the sediment cores. The Hg and Pb increased concentrations suggest anthropogenic sources being responsible for the increases. An important Hg-source is probably the use of coal for power production, leading to emissions of Hg to the atmosphere. An important source for Pb is probably the use of leaded gasoline up to the late 1970’ies, when production of leaded gasoline was prohibited in western industrialized countries. The levels of organic pollutants including total hydrocarbons (THC) and polycyclic aromatic hydrocarbons (PAH) are low in surface sediments at most locations, close to background everywhere in the studied area except the fjord areas and areas with fine-grained sediments to the west of Lofoten and Vesterålen Islands according to the Klif classification for coastal and fjord sediments. Also in these areas the levels are relatively low as compared to other areas of the Barents Sea, and do not exceed 1800 µg/kg dry weight for the sum of 48 PAH compounds. One does observe increasing trends in PAH levels towards the surface in the sediment cores at many locations. The increase is typically observed in sediments from between ca. 100-50 years ago, with a leveling-off or a slight decrease in the levels in the last decades at some locations. The increase is generally due to pyrogenic PAH and may be explained by wood- and coal-burning, traffic exhaust and other sources related to incomplete combustion. The levels of petrogenic PAH are low at all places but are increased in deepest sediment layers from a few locations with migration of hydrocarbons, including PAHs from reservoirs below.

There are major regional variations in heavy metal, THC and PAH concentrations depending on
where in the Barents Sea the sediments have been sampled. The concentrations of most metals and organic compounds from Storfjordrenna south of Svalbard are generally higher compared to most other stations. Erosion from land sources comprising of organic-rich sedimentary rocks in Svalbard contribute to the sediments in Storfjordrenna, giving significantly higher concentrations of e.g. arsenic, THC and PAH compared to other parts of the Barents Sea and the Norwegian Sea. Therefore variations in levels of heavy metals and organic compounds in the sediments can be attributed to differences in sources on regional scale. In the case of arsenic (As) the levels in Storfjordrenna are equivalent to class III pollution level according to the Norwegian classification system for sediments in fjords and coastal waters.

**Thermal rock conductivity prediction from petrophysical well log data – A study of wells on Svalbard and the North Sea wells.**

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1: IRIS
2: Information Strategies
3: Tectonor

Thermal history is an important control on generation of gas and oil in source rocks. Therefore, good measurements and a realistic treatment of thermal conductivity in rocks are essential for hydrocarbon generation modelling in sedimentary basins. In the recent few years there has been an increasing interest for the application of geothermal energy for heating and power production as seen from the establishing of the Centre for Deep Geothermal Energy (CGER). Various techniques have been used to estimate thermal conductivity of rocks over the years. (Fjeldskaar et al., 2009) compared results from two different approaches 1) simple upscaling, based on arithmetic, geometrical and harmonic mean values of averaged conductivity from anticipated mineral composition and 2) more advanced models based on infometric regression of thermal conductivity and anisotropy from measurements of rocks with known porosity and mineral composition. Despite the both accurate and precise prediction obtained from the latter it may be a difficult task to select a realistic and representative mineral composition and porosity that characterises large rock volumes in basin modelling. To overcome this problem we have developed a model based on infometric regression thermal conductivity from selected petrophysical well log types. The well log data contain latent information on mineralogy and porosity and have proved a suitable replacement for true mineral composition and porosity.

Reference:

The Eidfjord area revised: New thermochronological constraints on the exhumation history of central southern Norway

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The origin of the mountainous topography in southern Norway is at present unresolved. Post-Devonian sediments are absent onshore, making quantification of crustal uplift and fault displacements difficult. Low-temperature thermochronological techniques can be employed to constrain the timing of vertical movements through the uppermost few kilometres of the crust and are at present the most effective means of obtaining information about the topographic evolution prior to the Quaternary glaciations. This study aims to delineate the post-Caledonian morphotectonic evolution of the inner Hardangerfjord region by the means of apatite fission track and (U-Th)/He thermochronology, in combination with inverse thermal history modelling. Thirty-two samples derived from the steep flanks of the inner segments of the Hardangerfjord were analysed by the apatite fission track method. The resulting cooling ages range from Late Triassic to Late Cretaceous. A general positive age-elevation trend is evident, with abundant Early Cretaceous ages close to sea level and Jurassic ages on the Hardangervidda plateau. Four samples from the Eidfjord and Ulvik districts were analysed by the (U-Th)/He method, giving dominantly Cretaceous single grain ages. Fission track age-elevation gradients and combined data from the apatite fission track and (U-Th)/He thermochronometers


reveal low Jurassic-Cretaceous cooling rates in the order of ~1 °C/Ma. Large age jumps over limited horizontal distances suggest post-Middle Jurassic offset across both small-scale faults and regional structures. Offset age-elevation gradients indicate local displacements in the order of several 100 to more than 1000 metres. Thermal history modelling reveals two distinct episodes of accelerated cooling, which can be linked to documented pulses of tectonic activity onshore southern Norway and in adjacent offshore areas. Rapid cooling (2-6 °C) is inferred for the Permo-Triassic and is consistent with rift flank uplift and accelerated denudation in connection to the development of the North Sea Basin. The Jurassic and Cretaceous periods were characterised by low cooling rates (≤ 1 °C/Ma) and relatively minor regional exhumation, suggesting that the effects of the second North Sea rift phase were not pronounced in inland areas. Localized, periodically increased exhumation rates associated with fault displacement and footwall uplift are inferred from the fission track age distribution, but are not resolved by the thermal history models. The second episode of rapid cooling (~2 °C/Ma) is constrained to the late Cretaceous-Eocene and may have been attributed to tectonic activity in relation to the North Atlantic breakup or enhanced topographic relief following thermally induced uplift triggered by the Iceland mantle plume. Distinctly different Paleogene cooling paths for adjacent structural blocks suggest that fault activity may have continued into the Cenozoic. Considering the fission track age distribution patterns and thermal history models reported from southwestern Norway in general, it is suggested that extensive fault activity has exerted a significant control on the overall morphology of the passive margin. Pre-Eocene peneplanation and domal tectonic uplift, as has been proposed in previous studies, cannot fully account for the thermochronological data obtained in the current work.

Correlating microbial community structure with geochemical data in sediments from the Arctic Mid-Ocean Ridge

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På jakt etter sjeldne jordarter i Tørdalgranitten

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Det har vært gruvedrift og malmtekt i Telemark siden Middelalderen. Sølvgruvene på Kongsberg kom i gang i 1624. Bergseminaret, som det andre siden Middelalderen. Sølvgruvene på Kongsberg har vært gruvedrift og malmtekt i Telemark for Norge og verden.


U/Pb analyses of detrital zircons from tectonostratigraphic terranes of the west Norwegian Caledonides. Towards an onshore-offshore correlation

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Provenance methods are important tools in investigating offshore sedimentary successions. Provenance results can constrain the lateral...
distribution of reservoir bodies, the reservoir quality and the correlation of the reservoir strata. The U/Pb dating of detrital zircons is a well-established provenance method where the age of detrital zircons reflects the source of the analyzed sedimentary rock. To interpret the offshore U/Pb ages in provenance studies, the ages of the surrounding landmass need to be established. The ages of the Norwegian landmass are generally well constrained, but there are also numerous units within the landmass that have yet not been studied.

In the first phase of this Sognefjorden onshore–offshore study we report U/Pb zircon ages from eleven meta-sedimentary rocks representing the Caledonian terranes. The U/Pb zircon ages were obtained at the Bergen Geoanalytical Facility (UiB) using a single detector ICP-MS coupled to a laser ablation system. The analyzed meta-sedimentary rocks represent autochthon, lower allochthon, middle allochthon, and upper allochthon terranes of the West Norwegian Caledonides. Phase one of this study is a contribution to building up knowledge of ages present within the west Norwegian landmass, an important framework for the interpretation of U/Pb zircon analyses of offshore sedimentary rocks. In the follow-up study more U/Pb zircon ages will be obtained from 10-20 offshore samples. The sedimentary rocks in will be obtained from drill cores and cuttings from fields in the vicinity of Sognefjorden that represent stratigraphic units from Jurassic to Paleocene in age.

Most of the detrital zircon results reported here show predominantly two dominant age groups expected from the Norwegian landmass (900-1250 Ma and 1450-1800 Ma). One of the samples shows age peaks that are not usually recognized as being from the west Norwegian landmass. The sample is from quartzite lenses interfolded in the Western Gneiss Region (WGR) and contains age groups resembling sedimentary rocks usually interpreted to be derived from the Laurentian landmass. The detrital zircon ages that are present in the quartzite lenses within the WGR are constrained to 1750-2000 Ma and 2500-2900 Ma time intervals.

Compaction involves sediment and/or rock volume reduction due to effective stress and chemical dissolution and precipitation of particles. This results in notable changes in mineralogy, texture and pore fluid chemistry. Transition from mechanical to chemical compaction results in mineralogical changes and a stiffer rock which consequently result in log derived physical properties that deviate from empirical trend lines. Compaction processes result from stress changes due to subsidence and exhumation of sediments (mechanical compaction) and temperature and time (chemical compaction). Chemical compaction processes will continue in basins undergoing uplift as long as the temperature is above about 70°C. Compaction of sediments plays a significant role in petroleum systems at different scales. To fulfill a petroleum exploration and/or development plan, understanding the compaction is a crucial part of the investigations; from basin scale modeling to micro-scale properties of the sediment constituents. Fine grained dominated sedimentary rocks have however, received less attention than reservoir rocks despite their critical role in generation and sealing of petroleum.

In this work an integrated approach using well log data, XRD bulk and clay mineralogy, SEM microscopy as well as organic geochemistry data were utilized to understand compaction in the Egersund Basin. In this basin two adjacent exploration blocks, 9/2 and 9/4, show a very different post-depositional history although the sediments have the same provenance. Results suggest that well log data, particularly Vp, can be used to infer the transition from mechanical to chemical compaction. The Vp results is consistent with XRD mineralogical observations where decrease of smectites and/or smectite rich illite-smectites content with depth increase P-wave velocity, corresponds to increase of illite and micro-quartz content take place in the same depth zone. SEM microscopy analyses provided direct evidences of chemical compaction initiation seen as micro-crystalline quartz precipitated in association with authigenic illites. Similar compaction trends are seen in both study blocks. Nevertheless, in block 9/2 larger vertical displacement due to a deeper burial and a higher exhumation (around 750 m) notably contributed to higher maximum temperatures and kerogen maturation during maximum burial. This resulted in an increased consolidation in non-organic intervals in this block compared to the neighboring block 9/4. Compaction retardation due to kerogen content and maturation in organic

Compaction and rock properties of Upper Jurassic-Lower Cretaceous mudrocks, Egersund basin, Northern North Sea

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carbon rich intervals is also more pronounced in block 9/2. The Egersund Basin case study allows comparison of compaction in uplifted and normally subsided basins and hence has direct implications for compaction in complex tectonic regimes.

**Velocity and resistivity relationships in organic carbon rich shale and mudstone intervals, implications for compaction**

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Shales and mudstones include more than 70% of the whole sedimentary record and play an inevitable role in generation and entrapment of petroleum. Furthermore, progressively increasing environmental concerns and consequent CO₂ storage plans make shales and mudstones the most important top seal candidates at many proposed injection sites. Compaction results in changes in mineralogy, texture and pore fluid chemistry. Sonic velocity and bulk density log data have been proved as efficient tools to infer these changes particularly mineralogical and textural ones. Nevertheless, compaction has also direct effect on formation resistivity data which is more sensitive to fluid chemistry and clay minerals. The objective of this study is to use resistivity data to model P-wave velocity (Vp) and understand the effect of compaction on the modeled and measured P-wave velocity values.

We utilized log data from ten wells drilled in the Egersund Basin located to East of the Central Graben, northern North Sea (blocks 9/2 and 9/4). The Mesozoic narrow marginal Egersund Basin with a NW-SE trend contains proven petroleum resources in the Yme oil field. The screening investigations also showed that the basin could be a good candidate as a CO₂ storage site. The thick Upper Jurassic-Lower Cretaceous shales and mudstones intervals overlay the Middle Jurassic reservoir units where the available Vp data allowed a direct comparison with modeled values. Previous authors empirically related Vp to the formation resistivity factor and depth. In this work Vp was modeled in fine grained organic carbon rich sediments of Upper Jurassic-Lower Cretaceous intervals, according to established relationships. Constants values in the formulations were tuned to obtain the highest possible correlation of predicted and log derived Vp values. Comparison between modeled Vp and log derived Vp values have implications for compaction of fine grained sediments. Large deviations of modeled Vp from the measured values in organic carbon rich intervals can be attributed to reverse compaction trends. Occurrences of kerogen and suggested kerogen maturation-related microcracks and hydrocarbon generation may play key roles in compaction retardation. Proof for the organic carbon occurrence and maturation were provided by geochemical and SEM microscopy analyses as well as high gamma-ray and resistivity response. Similar trends prevail in both studied blocks. Nevertheless, due to a shallower burial level and a less pronounced exhumation history in block 9/4, generally lower resistivity values and higher velocities are observed. This resulted in less deviation between modeled and log derived Vp values in the block 9/4 compared to the block 9/2. Results suggest that the Vp modeling from formation resistivity can be incorporated in compaction investigations of organic rich fine grained dominated intervals.

**High-resolution C-O stable isotope analyses on Pliensbachian belemnites from the Rodiles Formation (northern Spain)**

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The Jurassic basin in western and northern Europe was a large intracratonic sea characterised by several palaeohighs predating the opening of the Atlantic ocean. In coastal environments of the Lower Jurassic, like the modern northern coast of Spain, sediments record sea-level changes on cm-scale. We studied a Lower Jurassic succession to the east of Gijón at the locality Playa de Vega (N 43°28'53" W 5° 7'55"") where the Rodiles Formation is exposed. The latter can be divided in the limestone-rich Buerres Member and the Santa Mera Member, which comprises intercalations of strongly carbonaceous fossil-rich shales and marls, and limestones. The Buerres Member lies conformably on the Gijón Formation, which represents a mainly continental environment, while the clastic Vega Formation erodes into the top of the Santa Mera Member indicating a strong
regression. The quality of the exposures together with the abundant fossils facilitates a sequence stratigraphic approach towards the understanding of the successions. This, combined with chronostratigraphic data and biostratigraphy enables to correlate exposures along the Asturian coastline. C-isotopes and ⁸⁷Sr/⁸⁶Sr isotopes in the Santa Mera Member rocks do reflect secular seawater trends and allow in interpreting several climatic changes during the Pliensbachian until the early Toarcian. The fluctuation in water temperatures, with amplitudes up to 10°C in these 10 Ma during the Lower Jurassic, can be explained manifold including by the eruption of massive flood basalts in the southern hemisphere initiating the opening of the southern Atlantic (during the thouarsense and dispansum biochrons; c. 178.5–180.5 Ma), mass extinctions (during the middle of the Lower Toarcian; semicelatum ammonite subzone) and eustatic sea-level changes. These processes resulted in lithologies deposited under anoxic conditions during sea-level rise, which produced S-rich black shales, and shallow water carbonates during sea-level falls. However, continental facies were not established until as late as the Early Bathonian (c. 168 Ma). Preliminary studies showed that whole-rock δ¹⁸O isotope analyses are disturbed while δ¹³C isotope excursions are typical for the Lower Jurassic. When sampling belemnite it was possible to gain primary δ¹⁸O reflecting the paleoecology of the Lower Jurassic. However, not every belemnite sample hosted an original isotope ratio.

The study therefore concentrates on belemnites from 5 layers of the Santa Mera Member of know age to compare C-O isotopes of the fossils with brachiopode shells from the same bed and values known from the literature.

Preliminary results on liquid petroleum occurring as fluid inclusions in intracellular mineral precipitates in the vertebrae of Pliosaurus funkei

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Two samples of a vertebra and a jawbone from two specimens of the Upper Jurassic Pliosaurus funkei from Spitsbergen have been described with respect to findings of fluorescing inclusions of liquid petroleum hosted in mineral precipitates representing a former primary skeletal porosity. Analyses were undertaken to elucidate potential animal and/or petroleum derivation(s) of the fluid(s) and possibly the timing of infilling with respect to the burial history of the hosting pliosaurus. The fluid inclusion temperatures of homogenization range from 47 to 117 °C. The earliest trapped fluids are primary aqueous inclusions occurring in calcite and barite close to the boundary to the skeletal matrix, followed by (or penecontemporaneously with) isolated, bluish-fluorescing, primary petroleum inclusions in vicinity of the aqueous fluid inclusions in barite. These inclusions homogenize at the highest measured temperatures. Subsequently trapped hydrocarbons homogenize at lower temperatures as their density increases. Such observations of decreasing API (increasing density) with decreasing temperature may be related to secondary changes in migrated petroleum during earlier documented uplift at Spitsbergen. Biomarkers reflect a depositional condition for the Upper Jurassic shales, i.e., the source rock expelling petroleum was potentially the rock occurring just below the Pliosaurus-bearing strata. In addition to inclusions validating a petroleum origin, a few low-viscosity, reddish-brown colored inclusions, not likely to represent a bituminous liquid, are observed, potentially of an animal origin.

Formation of parting in quartz – Combined EBSD, SEM-CL and optical study

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This paper presents hydrothermal quartz with macroscopic planar partings from the Mesoproterozoic Modum complex in Southern Norway. Similar macroscopic parting in quartz has only been described from two localities in the world; Madagascar (Flörke et al., 1981) and Southern California (Murdoch et al., 1938). The study area consists of well foliated and banded sillimanite-garnet-amphibolite-mica gneiss that is cut at high angle by hydrothermal veins containing albite, clinoclase, hornblende, hydroxyl apatite (Nordrum et al., 2010) and quartz. The rim of the veins is generally made up of almost pure end-member euhedral albite. Inside, vugs are partially filled with euhedral hornblende (10-25cm long) and euhedral hydroxyl apatite ranging in size from mm’s to several cm’s. Locally
apatite and hornblende is completely enclosed in quartz. The quartz is anhedral, inequigranular and has undulose extinction bordering sub-grain rotation (Passchier, C.W. et al., 2005). It generally has large planar penetrative faces with pearly luster, which continue throughout the specimen with a few mm spacing. Thin sections oriented perpendicular to the most pronounced planar structure show lamellas that extinguishes at small angles (2 degrees) to each other.

EBSD mapping of the planar faces shows two orientations \(\{0-11\}\) and \(\{1-101\}\), corresponding to the \(r\) - and \(z\)-faces respectively, separated by irregular boundaries. The misorientation between these two crystallographic orientations on the parting is a 60 degree rotation on \(\{001\}\), in accordance with the Dauphiné twin law.

SEM-CL imaging documents three generations of quartz and two, possibly three, planar structures; two evident, one more obscure. The most prominent of the three appears to cut across the recrystallization causing an apparent displacement. Similar textures have been described as impact structures and further studies on this feature may reveal whether these also relate to impact.

References:

The Upper Triassic Paralic Deposits of the De Geerdalen Formation on Hopen: analogy to the subsurface Snadd Formation

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The De Geerdalen Formation of Hopen is time-equivalent to the upper part of the Snadd Formation of the Barents Sea, a formation that has received interest as a possible hydrocarbon reservoir in addition to having source rock potential. The De Geerdalen Formation on Hopen has previously only been superficially described in a regional context and has been suggested to be a fluvial coastal plain depositional system. Recent sedimentological investigations add to this understanding and explain subtle but important variability in sedimentary architecture pointing to different depositional processes. Tidal channel sandstone belts of equal size and geometry as fluvial channel sandstone belts reveal distinguishable but characteristic internal heterogeneities and structures separating them form their fluvial counterparts. Lateral correlation along the island suggests that the channel sandstone belts are positioned at different stratigraphic levels.

The scale of depositional architectures at the Hopen Island is directly relatable to subsurface seismic data in the Barents Sea. Additionally some of the depositional features demonstrated at Hopen are also of comparable in size and geometry to plan-view sedimentary systems extracted from seismic attribute mapping. Further, detailed sedimentological descriptions carried out for the present study explains these depositional features in more detail than that which can be resolved in subsurface data. The present study shows how the seismic scale depositional elements vary temporally and spatially on the island, and place them in context with the heterolithic deposits encasing them. Together these results provide a valuable backdrop for the investigation of time-equivalent upper Snadd Formation deposits in the Barents Sea.

Water chemistry in the Bahi-Manyoni basin in Tanzania

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In the Bahi-Manyoni basin in Central Tanzania the geology and climate of the area are the main factors influencing the water chemistry and quality. There is an excess amount of sodium compared to chloride. Cluster analysis showed that sodium was correlated with alkalinity and together with the activity diagrams weathering of albite was found to be the most likely source. Potassium is weakly correlated with sodium so other factors like biological uptake may also affect the amount of potassium. The activity diagrams indicated that the system was in equilibrium with respect to K-feldspar and muscovite, so weathering of these minerals where also limited. Both cations were upconcentrated with increasing EC. The water samples are saturated with respect to dolomite, calcite and talc and precipitation of these minerals, together with dissolution of gypsum, controls the concentration of calcium, magnesium and sulphate in the shallow wells. In
the deeper wells upconcentration with increasing EC seem to occur. The concentration of arsenic in the water samples seems to be mainly governed by increasing amount of arsenic with increasing EC. Arsenic can also be sorbed onto iron-hydroxides and then desorbed if an increase of pH occur. The large amount of arsenic found in the water sample from Chipanga B deep well is most likely due to desorption because if increase in pH and anarobe conditions facilitating dissolution of iron-hydroxides. Uranium is weathered from the granitic basement in the area and transported by water, probably sorbed onto apatite or clay minerals suspended in the water. When the speed of the water decreases enough or the ephemeral rivers disappear underground, deposition of the colloids can occur. The enrichments are clearly seen in radiometric maps over the area, with little uranium found in the main river channels, but onto the plains before Bahi Swamp local, surficial deposits are seen. Aeromagnetic maps have indicated a correlation placement of deep wells with high uranium content and uranium elevated dykes in the area.

**Exhumation history along the Hardangerfjord Shear Zone – new insights from combined (U-Th)/He and fission track analysis**

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The Hardangerfjord Shear Zone (HSZ) is a major extensional NW-dipping crustal-scale structure that formed during Devonian extension shortly after the Caledonian orogeny. It might be part of an even larger zone of crustal deformation stretching across the North Sea into the Highland Boundary Fault in Scotland. The Shear Zone itself may have been reactivated several times since its formation, and one main aim of this study is to determine these episodes. The Hardangerfjord follows the trend of the HSZ and reaches up to 150 km inland. This deep incision into the Norwegian hinterland together with its steep and high cliffs makes the Hardangerfjord an ideal target for low-temperature thermochronological studies. The Hardangerfjord system also acted as one of the largest sediment pathways in the area during the last major erosion cycles. The amount of inland erosion and the corresponding depositional patterns are strongly affected by onshore uplift tectonics.

This project aims to constrain the amount and timing of post-Caledonian uplift of the footwall and the hanging wall of this shear zone, combining Apatite Fission Track (AFT) analysis with (U-Th)/He dating of zircons and apatites. Apatite fission track ages range from Late Triassic to Early Cretaceous and reflect rifting events offshore. The youngest AFT ages appear on the footwall of the HSZ and might be explained as a Triassic-Jurassic isostatic response of the thicker crust in the south to increased denudation. Zircon (U-Th)/He ages are Late Triassic to Late Permian and reflect an earlier rifting phase than the AFT data. Inverse thermal history models of AFT and (U-Th)/He data show that the last major reactivation of the HSZ which has affected the whole area must have happened between Triassic and Jurassic times. Younger fault ages e.g. from the Lærdal-Gjende Fault just north of the study area suggest even more recent reactivations, which are unfortunately out of the sensitive range of the applied thermochronometers. These reactivations have also triggered movements along smaller faults which are parallel to the main shear zone of the HSZ, and we were able to constrain the vertical fault offset across one of these faults to 450 m by AFT analysis. First estimations for maximum denudation since Late Triassic based on inverse thermal history models using a palaeo thermal gradient of 10-20°C/km indicate a total denudation of around 12 km.

**On the Paleoproterozoic Andean-type volcano-sedimentary setting of the Rombak basement window in northern Norway, and the relevance for gold deposits**

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The Paleoproterozoic Rombak Window (or inlier), surrounded by allochthonous Caledonian nappes, is situated near the southern margin of the Archean domain of the Precambrian Baltic Shield. A distinct feature is predominantly north-trending substrate intruded and surrounded by plutonic rocks. The substrate consists of metamorphosed volcanic rocks, schist, greywacke, and minor amounts of carbonate and quartzite. The volcanic suite continuously
progresses from mafic to felsic rocks including large volumes of andesite. The geochemistry in these rocks is characteristic of magmatism formed in a destructive plate margin. The plutonic rocks are predominantly granitic batholith, with basic intrusions commonly present in eastern part of the inlier. The deformation of the area is characterised by transpressive folding, thrusting, and sheared meta-sedimentary rocks intruded by syn- and post tectonic granitic associated with plumes of Svecofennian age. The geochemistry, age relations and structural features suggest a progressive development of an accretional belt in an Andean-type setting. Gold has been identified in a variety of structurally controlled sites that have developed in the volcanic substrate and is prior to synchronous with the plutonism. Although the gold occurrences are limited in size and extend, their presence shows that the area is prospective for undiscovered mineral resources. This is highlighted by the presence of anomalous stream sediment occurrences that were discovered in the inlier during the 1980s, but the source of the detrital gold has not yet been delineated. The present understanding of the tectonic evolution of the Rombak Window and its prospectivity for orogenic gold mineralisation illustrates that the inlier is underexplored.

Revised rockslide scenarios for the Åknes instability, based on in-situ instruments and ground based InSAR

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The Åknes rockslide, Western Norway, was recognized as unstable since the 60s, where locals observed year to year widening and eastward elongation of the upper tension fracture. The fracture was instrumented with extensometers from the 80s. It was realized that the rockslide was a high risk object with the potential to create a tsunami in Storfjorden, and in 2004 a detailed investigation and monitoring program was initiated, which included geological and geophysical surveys, borehole drilling and extensive instrumentation. From the investigations and measurements, a geological model was proposed, which link the structural geology to the observed geomorphology/deformation of the slope, as well as measurements of active displacement on various parts of the slope. The model and measured differences in displacement rates were used to draw different rockslide scenarios. The nominal annual probability of a failure was partly estimated from the frequency of major rockslides in the Storfjorden area. The rockslide has now been monitored continuously for several years, which has greatly increased the knowledge of the dynamics and factors influencing the displacement rate. In particular we have a better understanding of the displacement in different part of the rockslide. The distributed displacement data are from in situ instruments such a Differential GPS network of 9 antennas and 28 prisms, measured by a total station. These instruments record the 3D movement of different parts of the instability in detail. A ground based InSAR system has measured distributed displacement of the rockslide for several years and this year we have obtained overlapping measurements from two directions. Here we present an analysis of several years of displacement of different parts of the Åknes instability. We use the InSAR data and in situ measurements from the surface and in boreholes to redraw and adjust the failure scenarios for the Åknes rockslide.

FRAM-2012: Exploring the Arctic Ocean crust using a hovercraft research platform

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Basement geology in the Arctic Ocean is virtually unexplored except for the active Gakkel spreading center investigated by the AMORE expedition in 2001. The objective of the FRAM-2012 expedition using a hovercraft as research platform, was to sample bedrock on the slopes of Lomonosov Ridge, one of the few places in the Arctic Ocean and its surrounding continental margins where there is no or minimal overburden. To get there, the hovercraft had to drive over 1000 km from the ice edge north of Svalbard. Halfway at 85° N, a short period of earthquake monitoring on Gakkel Ridge was to be carried out. The hovercraft proceeded to 85° N, and fuel was obtained by rendezvous with icebreaker ODEN. However, continued northward progress was halted by persistent white-out conditions and also difficult ice. The situation forced a change of plan which resulted in a 5
week extended stay at Gakkel Ridge. The Gakkel Ridge is part of the diverging boundary between the European and the North American plate, yet the globally recorded seismic activity along the ridge varies from abundant to none. Three deployments of prototype seismic recorders were made in triangular arrays over the rift valley at a section of the Gakkel Ridge where no seismic events appear to have been recorded by the global seismograph network. An average of 10 small earthquakes per day was recorded during 25 days of operation within this zone. The new data set will help shed more light on extension processes in this part of the Gakkel spreading center where the sea bed petrology is dominated by ultra-mafic rocks rather than basalt.

The first documentation of pre-Elster glacial sediments in NW-Europe.

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It is almost 200 years ago the theory about an ice age was proposed by Swiss geologists and soon after indications of three ice ages were recognized. In Denmark Johnstrup in 1882 realised from studying the Cyprina clay that there had been more than one glacial episode in Denmark. In 1895 the geologist Victor Madsen recognized that there had been three ice ages in Denmark. In the book from 1979 (Danmarks Natur bind 1, Gyldendal, ISBN 87-567-3260-0) about the geology of Denmark the number of Quaternary ice ages had increased to 6 and the oldest glacial deposits present in Denmark were assumed to be from the Elster ice age in Mid Pleistocene. In the latest comprehensive book from 2006 about Danmarks Geologi (Naturen i Danmark - Geologien, Gyldendal ISBN 87-02-03027-6) there is a proposed larger number of ice ages but the oldest glacial deposits are still referred to the Elster ice age approximately 450 000 years ago.

The present study is moving this age considerably back in time. A 22m thick sequence of glacial sediments in the central Jylland south of Silkeborg has been described and analysed. The sediment is comprised by rhythmic bedding of lake sediments deposited during a glacial period. Below the rhythmic bedded sequence a deltaic deposit is present presumably deposited by a river bringing meltwater to the lake. Several characteristic, e.g. the presence of detrital coal in the lowermost part of the profile, and an unusual clay-mineralogy indicated that this could be a very old sequence. To investigate whether this sequence could have been deposited before the last reversal of the geomagnetic field, a palaeomagnetic study was carried out. It showed that the magnetic inclination of the sediments is negative throughout the profile thus referring the deposit to the Matuyama Chron. The sequence is therefore older than 781 000 years, the age of the Brunhes-Matuyama boundary. The result confirms studies made by Kronborg and Nielsen of three well cores also from Jylland which were previously analysed for magnetic inclinations showing some intervals of possibly reversed polarity, with some uncertainty due to the disturbances caused when coring in soft sediments and the missing declination data. The present study of an outcrop, however, removes these uncertainties and proves the presence of glacial deposits considerably older than hitherto thought. The implications for the Quaternary stratigraphy are significant. Apparently the number of glaciations from which deposits exist reach much further back in time than hitherto thought and glacial and interglacial units may have to be reinterpreted with respect to age and mutual correlation.

The basement of the Utsira High: U/Pb, (U-Th)/He and fission track thermochronology

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The Utsira High is a basement horst in the northern North Sea, ca. 160 km offshore southern Norway. Since the recent discovery of the large Johan Sverdrup hydrocarbon field on the Utsira High, the area has become the focus of intense research. The basement is composed of Caledonian granitic and gabbric rocks with arc-related geochemical signatures. U/Pb zircon dating on three samples gave Middle-Late Ordovician and middle Silurian crystallisation ages. These ages are equivalent to Caledonian intrusive rocks onshore Norway which are assigned to the Upper Allochthon. Though the magmatic rocks most likely crystallised in a volcanic arc, the presence of Proterozoic and
Archean xenocrystic cores testifies to the presence of much older rocks in the source regions of the melts. This observation is consistent with previously published isotopic and geochemical data from arc-related Caledonian rocks, including samples from the Utsira High, which also indicate the involvement of Proterozoic crust (Slagstad et al., 2011).

The younger history of the Utsira High basement block is recorded by fission track and (U-Th)/He thermochronology. Apatite fission track ages of three samples range from late Permian to Late Triassic. The samples, although from similar depths, currently reside at significantly different temperatures. This diversity is also recorded in the (U-Th)/He ages: One sample from the southern part of the Utsira High at a depth of 1930 m gave late Cretaceous (U-Th)/He ages, and the recorded bottom hole temperature for the well is low (44 °C). Another sample close to the western margin of the Utsira High at a depth of 1936 m gave (U-Th)/He age of 20-0 Ma, indicative of temperatures close to or exceeding the (U-Th)/He closure temperature in apatite (75 °C). Correspondingly, the bottom hole temperature in this well is high (80 °C). Time-temperature modelling based on apatite fission track data indicates fast cooling in the Permo-Carboniferous and residence at or near the surface during the Triassic to Early Cretaceous followed by reburial and consequently reheating to present-day temperatures. Surface exposure in the Triassic is consistent with Triassic clay formation in saprolites on the Utsira High (Fredin et al., 2012).

The time-temperature models further show differences between samples in the exact timing of rapid uplift, surface exposure and residence time at the surface, which indicates differential movement across faults that must have been active during the late Palaeozoic and Mesozoic.

References:

Metasomatic alteration of 2.2 Ga mafic and intermediate intrusive rocks at Vannøya, West Troms Basement Complex, North Norway

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The island of Vannøya, which is part of the West Troms Basement Complex, North Norway, is composed of Archean and Paleoproterozoic rocks, including a unit of 2200 Ma mafic/intermediate intrusive rocks. These intrusive rocks have undergone several stages of deformation and metamorphism associated with metasomatism. Most of the samples that were collected for this study are undeformed, however, they show different degree of alteration. Samples that in hand specimens look unaltered are dominated by albite, hornblende/actinolite and magnetite; no pyroxene or plagioclase has been observed. This suggests that the rock underwent extensive hydration at an early stage.

One type of altered rock is characterized by spheroidal green and black aggregates that commonly are 1-2 cm in diameter. The green aggregates are dominated by epidote, while the black domains are dominated by biotite. In hand specimen, the matrix separating the green and black aggregates resembles the unaltered igneous protolith, however, microscope studies show that the primary plagioclase has broken down to form albite and epidote. It is inferred that the green and black aggregates formed during an episode when the mineral grain boundaries were saturated by a hydrous fluid. Most likely, the epidote dominated aggregates formed when Ca that was liberated during plagioclase breakdown was transported toward sites of epidote growth. In a similar way, K was transported towards sites of biotite growth. The epidote dominated aggregates are enriched in REE, Sr and Pb, suggesting that these elements were transported in the same direction as Ca. High concentrations of Cs, Rb, Ba and Li of the biotite dominated aggregates may suggest that these components were derived from an external source together with K. Both the biotite dominated aggregates, and the matrix between the aggregates is enriched in Na relative to Ca, and can be classified as spilites.

At some localities, the rock described above has undergone an additional stage of metasomatism. The metasomatizing fluid appears to have been introduced along a network of fractures, and subsequently reacted with the rock in 10-50 cm wide zones along the fractures. Within these zones, two distinctly different rock types can be distinguished: the central part (adjacent to the fractures) the rock is white and consists of nearly pure albite, while the rock in the marginal part (further away from the fractures) is brown on weathered surfaces and consists of albite and carbonate, in addition to minor amounts of rutile and quartz. At some outcrops a brecciated rock occurs, with clasts of albite in a matrix of an albite and carbonate dominated rock. Whole rock compositional data shows that the central albite dominated parts are depleted in Fe2O3, TiO2, MgO, P2O5 and REE relative to the protolith. The marginal carbonate rich parts, however, were
only depleted in Fe$_2$O$_3$ compared to the protolith. Further, this rock type shows a slight enrichment in HREE and U.

Vegetation history through periods of extreme environmental changes

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The Phanerozoic fossil record shows 5 periods with major biodiversity loss among marine faunas, which are also known as the big five mass extinctions: the end – Ordovician (446 Ma), Late Devonian (371 Ma) end-Permian (251 Ma) end Triassic (200 Ma) and the Cretaceous Palaeogene boundary (65 Ma). These events reset the evolutionary lines among marine families and genera and resulted in the collapse and reorganization of entire ecosystems. Although the scenarios of these mass extinctions are controversially discussed, all of them were associated with extreme environmental changes. In the current review I will focus on the role of terrestrial land plants as known from palaeobotanical and from the palynological records. At first hand diversity trends of land plants appear to be very different from those known for marine biota leading Alfred Traverse to the challenging statement that "plant evolution dances to a different beat". I will review recently published data on extinctions and radiations of land plants including 2 critical intervals, the End-Permian and the Late Triassic mass extinctions. I will discuss the present knowledge and future challenges to improve our understanding of their role during these major mass extinction events.


Volcanic materials for construction purposes in cold regions

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Volcanic materials may serve as a natural resource for construction purpose – as light weight aggregate, as building blocks and even (when it comes to the ashes) as pozzolanic material. To be able to benefit from the properties of these materials, especially relating to use in cold regions, knowledge of their thermal properties will be of vital importance.

A comprehensive study has been performed for volcanic materials at Kamchatka in East Russia and Iceland. Generally, existing data were received mostly for volcanic solid rocks or for thawed state, but for use in cold regions it is also very important to know the thermal properties in frozen state and the phase composition of water (unfrozen water content).

It was observed that thermal conductivity and thermal diffusivity are very low both in thawed and frozen state and these materials therefore can serve as isolation materials. In dry state thermal conductivity is 0.14-0.18 W/(m·K) and thermal diffusivity – 0.13-0.16 m$^2$/s. On condition that the density ($\rho_d$) and humidity (W) are changing from 0.7 to 1.65 g/sm$^3$ and from 10 to 80 % respectively the thermal conductivity ($\lambda$) increases from 0.37 to 1.0 W/(m·K) in a thawed and from 0.41 to 1.27 W/(m·K) in a frozen state. The dependence on humidity degree ($S_r$) showed that these coefficients also depend on glass composition (andesitic, rhyolitic and basaltic types) and secondary minerals (opal, palagonite and allophane) that occurred after volcanic glass alteration. The higher values were found for volcanic material containing rhyolitic glass and opal, the lowest values for materials with andesitic and basaltic glass as well as with allophane and palagonite. Unfrozen water content also depends on the mineral and chemical compositions. For example, for the first group $W_w$ can change from 0 to 2-3%, for the second group it can vary from 3 to 11% under temperature below -2°C.

Marine tailings deposits, can they be rehabilitated rapidly? Results from the ImpTail project

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We show preliminary results from ImpTail, a project partially funded by the Norwegian
Submarine landslides affecting the Jan Mayen micro-continent, Norwegian-Greenland Sea

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The Jan Mayen micro-continent is located in the Norwegian-Greenland Sea. It forms an up to 30 km wide and relatively flat-topped submarine ridge which narrows and deepens towards the south. The ridge rises 1500 – 2000 m above the surrounding sea-floor and has a length of some 250 km. Its northern termination is defined by the Jan Mayen Fracture Zone that is part of the mid-Atlantic spreading ridge system. Here, both submarine and sub-aerial (on the island Jan Mayen) volcanism occur. Based on newly acquired swath bathymetry data covering most of the ridge, the eastern and western slope morphologies were studied. Preliminary analyses show that the slope includes a number of smaller slide scars (up to some km wide) as well as one up to 50 km wide scar located on the eastern slope. The morphology of the larger slide scar is “fresh” and includes an irregular headwall area and channels that can be followed from the headwall at about 800 m water depth and downslope to at least 2500 m water depth. This morphology is distinctly different from that of the large slide scars along the Norwegian continental margin and in the paper factors that may explain this difference will be discussed.

Provenance of the Mesoproterozoic (Jotnian) Dala Sandstone Formation: implications for correlation of supracrustal units and origin of Archaean zircons in SW Norway

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Zircon U-Pb SIMS data are used to constrain the age and tectonic setting of the Dala Sandstone, and to address large scale sediment routing in the Mesoproterozoic. The youngest ca. 1.61 Ga age peak constrains the maximum deposition age of the lower Dala sandstone. A lack of ages from the underlying and immediately adjacent Transscandinavian Igneous Belt basement, and structural relations, indicates that slow and limited stretching of the craton formed a sag basin. The ca. 1.46 Ga Oje basalt, which separates the lower and the upper Dala sandstone, places sedimentation in the context of the Danopolitan orogeny. However, absence of Danopolitan ages in the sediments demonstrates that the drainage system did not tap the evolving orogen. Instead, the important c. 1.61 Ga zircon population suggests input from the Gothian realm; the remaining detrital zircons in the Dala Sandstone are attributed to sources in the Transscandinavian Igneous Belt and the Svecofennian domain. The low amount of Archaean grains and the lack of <1.6 Ga grains in the Dala Sandstone, and the inferred lack of active rifting, do not support previously proposed correlations with the roughly coeval Telemark volcanosedimentary rift-successions in SW Norway. The data further suggest that the important Archaean components in Mesoproterozoic sediments in SW Norway reflect sediment input from sources to the north, e.g. Lofoten, or sources outside the Fennoscandian Shield, such as the Lewisian basement of Scotland and its correlatives. The difference between the
Dala Sandstone and the Telemark successions are most easily explained if SW Norway was emplaced in its current position after the formation of the basins.

Transport of CO₂ along possible migration pathways - how CO₂ or natural gasses may reach the surface

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The most important requirement for CO₂ storage to be secure for the intended time periods of at least 100 years and up to 1000 years is the presence of a tight seal preventing migration out of the storage reservoir. The currently ongoing CO₂ storage projects are based on the assumption that the forming CO₂ plume will stay in areas where the caprock is assumed to have good sealing properties, i.e. having no open fractures or high permeable geological bodies that can act as fluid pathways. Notwithstanding the widely accepted thesis that there are many suitable places to store CO₂ safely, the geology may be more complex than taken into account so far. Since a leakage would spoil the intended aim of CO₂ storage the leakage risk has to be evaluated based on geologically likely scenarios.

Here, some geologically plausible scenarios are presented and linked to recent findings in the European project ECO₂ (Sub-seabed CO₂ Storage: Impact on Marine Ecosystems). These scenarios will serve as base for numerical modelling of CO₂ migration from a subsurface reservoir to the surface.

Recognition of Svecofennian sulphide bearing crust in the Rombak region, northern Norway

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The Palaeoproterozoic Rombaken Tectonic Window (RTW) of northern Norway consists of sulphide-bearing metasedimentary units that can be followed for 55 km along a N-S trending strike length. The metasedimentary units consist of conglomerate at the base, quartzite, turbiditic sequences, graphitic shale, and marble. These units are strongly deformed and have been cut by mafic dykes and granites prior to the Caledonian event. The depositional age of the metasedimentary units has been assumed to be Paleoproterozoic, mainly based on the ages of granitic intrusions, while the deformation may have been Svecofennian. The metamorphic grade is amphibolite facies, with retrogression to greenschist facies along major ductile shear zones. Several sulphide deposits have been explored in the supracrustal metasedimentary units, in particular Zn-Pb at Sildvika, Zn-Pb-Cu-As-Au at Haugfjellet and As-Au at Gautelis. However, no comprehensive studies, combining the structural, geochronological and metallogenetic relationships have so far been carried out in the region.

The structures of RTW are dominated by an early upright east-verging fold-thrust belt, which is subsequently cut by steeply-dipping, N-S trending anastomosing sinistral strike-slip shear zones, which are parallel to the orientation of the fold limbs. Later, dextral sub-vertical NE-trending shear zones diagonally cross-cut, displace, and fold both the fold-thrust belt strata and the sinistral shear zones. The dextral shear zones have a late-stage brittle component. The highly segmented and tectonized supracrustal belt in the southern part of the RTW was cut by monzogranite with SHRIMP Zircon U-Pb ages of ca. 1790 Ma (i.e. between 1786 ± 8 and 1790 ± 8 Ma). Lead isotope systematics of galena from stratiform Zn-Pb mineralization at Sildvika and Haug-fjellet indicate an original Svecofennian signature (206Pb/204Pb ratios as low as 15.14), but also indicate disturbance by later Caledonian thrusting (206Pb/204Pb > 16) further to the east at Cunojavri close to the Swedish border. The original ore lead signature is comparable to stratiform Svecofennian Zn-Pb mineralization at Tjämotis (Sweden) and Vihanti (Finland), both in 1.92 Ga successions in the Svecofennian Domain of the Fennoscandian Shield. Based on the structural model, age relationships and the Pb isotope signatures, we are able to construct a metallogenic model with four episodes of sulphide mineralization: 1) stratiform Zn-Pb deposits in turbidites; 2) Au-As-Fe-Cu skarn deposits related to shear zone parallel intrusions cutting marble and turbiditic sequences; 3) Orogenic Au-As deposits along the strike-slip shear zones; and 4) Au-Cu deposits in brittle quartz veins. In a regional perspective, this model can be correlated with similar structures and ore-bearing supracrustal rocks in the Svecofennian Domain of Sweden, Tjämotis (120 km south and along strike of the extension of the supracrustal slivers in RTW), and the gold-line...
province in the Lycksele-Storuman area (350 km south of RTW).
In summary, based on structural, metallogenetic and lead isotope studies on sulphide mineralizations, as well as SHRIMP U-Pb zircon dating, we present the first detailed tectono-metallogenetic study of Svecofennian crust at the complex interface between the Achaean, Svekokarelian and Svecofennian terrane boundaries in Norway.

Recent mapping and studies in marine abrasion caves in Torghatten, Brønnøy.

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In addition to Torghatthulet, a tunnel cave in Torghatten, Brønnøy municipality, several smaller caves were investigated through accurate surveying, morphological and mineralogical documentation. Torghatthulet (198 m long), Svartholene 1 & 2 (165 m and 225 m length) with few exceptions display block-covered floors around 115 m a.s.l. and ceilings reaching 140 m a.s.l. Morphology is generally dominated by frost action and breakdown where the largest blocks located at or near the entrances. In places, rounded weathering forms, like tafoni occur, also in the entrance areas. The deepest parts of Svartholene display polished rock surfaces, similar to P-forms, indicating wave action, although the typical pear-shaped cross-sections are absent or buried beneath sediments. Sediment mineralogy indicates advanced, probably pre-glacial deep weathering as a primary speleogenetic process, later exploited and “exhumed” by erosion at a former high seastand.

Volcanic vents and onset of modern-style phosphogenesis 2 billion years ago

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Early Paleoproterozoic time (2.5-2.0 Ga) marks the period in Earth history when modern-style aerobic conditions were established worldwide, as archived in a suite of interlinked mineralogical, geochemical and isotopic anomalies in the rock record. The appearance of the oldest significant phosphorites at c. 2.0 Ga is a consequence of those processes, albeit its underlying causes remain speculative and a subject of much study. Phosphorite intervals in organic-rich rocks from volcanic-vent-influenced settings of the c. 2.0 Ga Zaonega Formation, NW Russia preserve a fossilized consortium giant sulfur-oxidising bacteria and methanotrophic archaea. Such sulfur bacteria, commonly in association with methanotrophic archaea, inhabit the (sub)oxic-sulfidic redoxcline in sediments of venting areas and upwelling zones, and mediate modern phosphogenesis. The Zaonega findings suggest that Paleoproterozoic phosphorites track the establishment of new redox conditions in sediments providing a habitat for giant sulfur-oxidising bacteria in response to the oxygenation of Earth.

Dans&drama or natural science – what do we need?

Lervik, K.S.

Objective: RING (Realfag – Inspirasjon – Næringslivet – Glede) will contribute to point out the connection between competence goals in different scientific subjects, and the activities of the industry. The goal is to visualize future university/college education and career choice. Scope: The RING project will take basis in the curricula of natural science. To experience the subject’s practical aspects and utility value, will hopefully stimulate, motivate and rise interest in the scientific studies. "RING kunnskapsdagene" was in January 2011 arranged as a pilot-project together with 5 high schools in Rogaland (Stavanger katedralskole, St. Olav vgs., Hetland vgs., Randaberg vgs., Sola vgs.) with nearly 900 students attending. It was repeated in 2012 with 1665 students from all VG1 high schools of southern Rogaland. In parallel there has been an event each autumn for junior high schools together with Stavanger kommune, where 200 students have visited oil industry related companies, to have an insight into the industry. The programs will be repeated in 2013. FORCE in cooperation with Rogaland fylkeskommune have organized a work shop, “RING kunnskapsdag”, where the students can participate in practical activities related to natural science and also witness technical demonstrations. This will hopefully contribute to
the students receiving information about what study opportunities the scientific studies can give them. “RING kunnskapsdag” shall contribute to increase understanding about general business conditions’ demands for knowledge and competence, and to create a foundation for reflection and future career decisions.

The initiative origins at FORCE, and it is now called upon a project group who will carry the responsibility to lead the project. The responsibility includes involving representatives from oil related industry, Rogaland fylkeskommune, Stavanger commune, Norsk olje&gass, NH0, Teknologiforum Rogaland, Universitetet i Stavanger and Vitesenteret. The project group can expand if needed.

Over time, the RING-project will expand to also include practical activities to all schools (junior high schools, high schools and the transition to higher school levels). The purpose is to provide goal-oriented information to scientific related studies, and suggest different opportunities within these subjects and also provide information about different career choices.

Bygningstein i Nordland – historisk og i dag

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I to påfølgende EU-prosjekter (PNASTINA OG NIBA) innenfor Nordland har kartlegging av bygningstein og mulig utnyttelse av denne vært tema. Lokalisering av historiske brudd, større eller mindre aktive brudd og steintyper som tidligere er testet og vurdert av industrien eller NGU er gjennomført. De eldste bruddene er fra vikingtid; brudd på kleberstein, kvernstein og brynest. Nordland er marmorbygget i Norge og Ankerske på Fauske er hovedsenteret for marmor som bygningstein. Bruddet som i dag er i driftshvile er drevet mer eller mindre kontinuerlig i 130 år. Ankerske sikret mange rettigheter på marmor i Nordland og hadde også andre marmorbrudd, og dreiv også brudd på andre steintyper.


A bonebed in the Hørbyebreen Formation (Famennian-Viséan) on Spitsbergen

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Fieldwork at the mountain Triungen (Dickson Land) on Spitsbergen during the summer of 2010 has led to the discovery of a fish- and tetrapod bonebed in the basal strata of the Triungen Member (Hørbyebreen Formation). The Triungen Member is the lowermost unit in the Billefjorden Group (Hørbyebreen and Mumien Formations), a sequence of fluvial sandstones and conglomerates, lacustrine and flood-basin shales, coal seams and plant-bearing horizons. The fossils were found primarily in the soft sandstones directly overlying the basal conglomerates, but also in the conglomerates themselves. Apart from numerous plant fragments, only vertebrate remains have been found. The material is very fragmentary and mainly composed of teeth and scales, but it also includes cranial, mandibular and postcranial elements. Prominent components are sarcopterygian (onychodontaiform) teeth, including a parasymphyseal tooth whorl. Unquestionable tetrapod remains include ribs carrying uncinate processes. Probable tetrapod elements include a tabular horn and mandibular fragments.

At Triungen, the strata of the Triungen Member rest with an angular unconformity on the folded redbeds of the Early Devonian Wood Bay Formation. As the oldest post-deformational unit above the Old Red Sandstone (ORS) sequence, the member is decisive for dating the Svalbardian orogenic event. Originally dated as Tournaisian, the Triungen Member was later thought to be entirely of Famennian age. Palynomorphs from a coal seam 60-65 metres above the base have since been dated as Viséan, while a reliable dating of the basal part of the member has until now been impossible due to the lack of miospores. Therefore, we initially concluded that the discovered bonebed probably was Tournaisian in age, a time known for its near absence of tetrapod fossils. Subsequently, however, one of our samples collected from immediately above the basal conglomerate, proved to contain a rich spore assemblage, indicating a mid- to late
Famennian age. A late Famennian onset of the post-Svalbardian sedimentation as recently reported for the Lomfjorden trough, could thus also be true for the Dickson Land area. The bonebed at Triungen contains the first Palaeozoic tetrapod remains recorded for Spitsbergen. If our age determination is correct, these tetrapods are roughly contemporaneous with Ichthyostega and Acanthostega from Greenland. A further implication from this new dating would be that the Svalbardian orogenetic event must have been completed by late Famennian time, and that the uppermost ORS-, and thereby youngest pre-deformational unit, the Plantekløfta Formation (not present at the Triungen locality) is probably not younger than Frasnian. Furthermore, with the Hørybreen Formation ranging from the Famennian to the Viséan, the Triungen site - given there is no major hiatus in the sequence – would still stand as a good candidate for searching for tetrapods from the Tournaisian.

Digital Advantages in Permanent Monitoring of CO₂ storage sites

Lindgård, J.E.

CO₂ capture and storage have been a focus area of the Norwegian government, and in 2011 the CO₂ storage atlas was published, mapping out suitable areas of significant storage potential instead of emission of the gas to the atmosphere. Octio is currently working on a CLIMIT sponsored research project related to new technology in order to monitor marine CO₂ storage sites as well as explore the potential of passive seismic methods. The project focuses on integrating multiple sensor technologies in one monitoring system. This will significantly reduce the interpretation uncertainty of the subsurface as independent physical measurements are used to commonly evaluate the reservoir properties in a similar manner as what is done in the borehole logging industry today.

From a rock physics point of view it is common knowledge that physical properties of a rock are connected by non-linear relationships that make interpretation of the seismic response an important and challenging task. Some examples of the properties making interpretation difficult are grain sorting, mineralogy, pressure effects, chemical/dissolution effects, fluid and fluid distribution. Rock physical analyses are aided by borehole logging and core measurements, but it is still challenging to determine the heterogeneities in the reservoir over a lateral extent of the reservoir. The potential of Octio’s technology is to significantly reduce the risk of misinterpretation caused by the complexity in the rock as more independent physical measurements will limit the interpretation scenarios.

The new integrated system under development in the project is focusing on 4C acoustic sensors (hydrophone + 3 broadband accelerometers), EM sensors, gravity meters, environmental sensors and tiltmeters as the key sensor technologies. From a geophysical perspective this basically means that the system will have high bandwidth seismic data together with a resistivity measurement from the EM sensors as well as indication of potential reservoir compaction/pore pressure effects from the gravity meter and tiltmeter. A feature of the geophysical technology used is that all sensors can all (independently) be used for inverting for fluid movement in the reservoir and also map out saturation to a significantly higher degree than before. On the environmental side, the sensors are operating in the water-column, continuously measuring current speed and direction as well as oxygen, CO₂, turbidity, conductivity, velocity and temperature. This will provide a good basis for detecting anomalies in the water-column that can originate from top side operation, leakage from the injection or natural gas seeps in the overburden. The challenges connected with implementing such a system are not insignificant in terms of i.e. new workflows needed, data management issues and comprehensive multidisciplinary teams. However in order for conducting a safe operation during injection and storage of CO₂ for meeting the regulations from the government it is an absolute necessity to closely monitor fluid movement and avoid leakage back to the seafloor. The result of this project will be a concept design and a cost benefit analysis of this system referred to existing sensor system technology. The project have a clear goal of testing out the system at a relevant field in order to have it ready to meet the requirements when offshore CO₂ storage is commercialized on the Norwegian continental shelf.

Dating of landforms and Quaternary landscape evolution

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Numerical dating techniques used for establishing chronologies for the Quaternary Period (0-2.588 Ma) have more or less been synonymous with radiocarbon dating.
Radiocarbon dating at its best can be used back to c. 50 cal. ka, and since onshore Quaternary deposits commonly are from the end of the last glacial period, it is not surprising that the majority of dating efforts for a long time focussed on the most recent part of the Quaternary Period. There are, however, Quaternary deposits and landforms in Scandinavia which cannot be dated by radiocarbon dating, because of their age and/or lack of organic material. Earlier, these could only be used for constructing relative chronologies until they perhaps became test sites for new numerical dating techniques. The past two decades have seen a rapid development of dating methods of continuously improving precision, and today methods based on in situ cosmogenic nuclides and luminescence signals are widely used on terrestrial material. Despite this, it is rare to find studies reporting ages older than the last glacial period. 100 ka could be close to the upper range of luminescence-based methods, but is still far from the limit for cosmogenic nuclide-based methods. This gives the impression that deposits and/or landforms older than c. 100 ka hardly exist, but is that the case? Most geological material can provide apparent chronological information, but it is still up to the geologists to collect the ‘right’ material from ‘meaningful’ geological settings in order to obtain chronological information that actually represent answers to the questions asked. Nature rarely provides us with what we want: 1) suitable material for 2) the method of the desired dating range at 3) the perfect geological situation. In landform evolution studies we must therefore use multiple approaches (material and methods) to better constrain the ages of Quaternary features. Some examples of apparent ages of landforms will be presented, discussed and interpreted in the light of geological processes. This is due to the relatively poor reservoir quality of the Triassic sandstones present in outcrop and in the subsurface of Svalbard.

This study maps the variations in fracture patterns in the Triassic De Geerdalen Formation regionally throughout Svalbard with the intent of extrapolating fracture data in to the Longyearbyen CO₂ storage project and also the Barents Sea hydrocarbon province. Fractures have been measured in select outcrops throughout Svalbard, from locations in western-central and eastern Spitsbergen to Edgeøya and also Hopen. The study focusses on relating the fracture origin and type to varying regional tectonic zones and the fracture patterns and densities to differing lithologies and finally facies and their associations. Through data analysis it has been deduced that fracture orientations and types are relatively uniform throughout the De Geerdalen Formation of Svalbard, with prominent conjugate sets striking NW-SE and NE-SW throughout the regions of central Spitsbergen and Edgeøya, with only a subtle change in orientation being present at Hopen. Facies in the De Geerdalen Formation vary significantly regionally, following north westwards prograding delta trend. With this, fracture densities also vary greatly with regards to their interactions with individual lithologies, facies, their thickness and extent. Fracture densities are observed to be widely variable in south eastern and eastern Svalbard and more uniform throughout central Spitsbergen where lithologies remain variable, yet facies and bed thickness appear to take greater control. Due to the relative uniformity of fracture orientations and the importance of density changes with regards to lithology, bed thickness and facies types, the overall aim of the study is to produce a workable dataset showing the characteristics of fractures in the De Geerdalen Formation. This database may be implemented into geological models of the Barents Sea subsurface. This is to allow for more precise reservoir modelling of future exploration targets, in order to support mechano-stratigraphic studies typically based solely on core data, which tend to underestimate the abundance of vertical and horizontal fractures present in a particular unit.

Regional fracture orientations, patterns and distributions throughout the Carnian (Triassic) succession of Svalbard; An emphasis on fracture types and their lithological relationships

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Current understandings based on tests conducted from the Longyearbyen CO₂ storage wells show that fractures play a key role in affecting reservoir properties with regards to perme-
Active debris flows in Nes, Hallingdal, Southern Norway; detailed field mapping and susceptibility modeling revealing past and present activity

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North of Nesbyen, a c. 6 km long part of the western valleyside has been investigated as a part of the speaker’s master work at the University of Oslo, to map debris flow activity and to identify buildings that could be hit by debris flows in the future, a work which is performed by the Norwegian Energy and Water Directorate, NVE. This area shows relatively high debris flow activity, and in 2007 and 2011 four debris-flows happened during periods of intense rainfall. A hotel and several homes were strucked by debris and a garage was destroyed. The Hallingdal valley is oriented in c. S-N direction, which was slightly oblique to the main NW-SE ice-flow direction in the area. Consequently, the studied valleyside was located in a lee-side position relative to the ice flow direction. Large quantities of till was deposited beneath the ice, and overconsolidation of the till has taken place in the area, except for areas with exposed bedrock. The till cover is generally 4-5 m, occasionally 10-15 m thick. Most of the till area is cut by a large amount of ravines (debris flow channels) that occasionally have exposed the bedrock. On the valley bottom, where the river Hallingdalselva is running, a large amount of alluvial fans are located, and they are located just outside the ravines. The volume of these fans are much less than the amount of till that are eroded from the ravines, which means that material are removed by river erosion, which consequently mean that the ravines are not all of recent age; they may be as old as the deglaciation (stratigraphical work and dating is not yet performed). The investigations in this work were based on intense field mapping, resulting in a detailed map of existing debris flow channels and deposition fans of old events. The detailed field mapping of runout channels and deposition fans was compared then with debris flow susceptibility mapping on a national scale that is going on at the Geological Survey of Norway, NGU. The modelling uses a GIS-based approach which incorporates the detection of the starting zones and a simple assessment of the debris flow runout using the Flow-R model (IGAR, University of Lausanne). The discrimination of starting zones is based on an index approach including the topographic parameters slope angle and curvature extracted from a digital terrain model (DTM) and the hydrological setting based on the upslope contributing area (also derived from DTM). A combined probabilistic and energetic approach is used for the assessment of the maximum run out distances. The modelling results proved to fit quite well with the field mapping results. However, some discrepancies between the observations in field and model could be found. Therefore, the detailed field mapping was subsequently used for further parameter adjustments to improve the debris flow runout modelling.

New zircon U-Pb and Lu-Hf constraints from granitoids in the offshore Caledonides on the Utsira High, North Sea

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The age and tectonic significance of two basement granitoids cored on the Utsira High, North Sea, are constrained by zircon LA-ICPMS U-Pb and Lu-Hf isotopic analyses. Syenite in well 25/10-2R is dated to 482 ± 2 Ma, and hydrocarbon bearing weathered and fractured granite in well 16/1-12 yields an age of 436 ± 3 Ma. The 16/1-12 discovery is located just south of the Edvard Grieg discovery. The Edvard Grieg discovery was made by Lundin Norway in October 2007 in well 16/1-8, PL 338. Evolved Hf signatures demonstrate reworking of Proterozoic and/or Archaean crustal rocks, suggesting the presence of (a Laurentian?) microcontinent beneath the Utsira High. The offshore granitoids are coeval with tectonomagmatic events in the onshore Upper and Uppermost Allochthons in the Scandinavian Caledonides recording collisional events along the Laurentian margin, and the final closing of the Iapetus Ocean. With previously
published data a complex Caledonian tectonomagmatic history is revealed in the ca. 50 km x 50 km field area that is most easily explained if the basement represents an amalgamation of thrust sheets comparable to the onshore Upper and Uppermost Allochthons. The results of this study thus emphasise the relevance of onshore Caledonian structures for the understanding of the offshore Norwegian margin.

Quartz cementation – the role of grain to grain pressure solution in sandstones

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In this study 20 Late Precambrian quartzite samples from the Hanglecærro Formation located on the Varanger Peninsula in Finnmark, Norway was investigated petrographically with special emphasis on quartz cement volume and intergranular volume. The Hanglecærro Formation is an orthoquartzite (>95% quartz). Two samples investigated contained around 10% authigenic clays. The rest of the samples where clay free or contained only minor amounts of clays. Micro stylolites were observed in two samples only. The fact that cementation in the Hanglecærro Formation has gone to completion makes the formation suitable for studying the end results of quartz cementation in detail. Stylolitisation is the accepted process producing dissolved SiO₂ where the dissolved SiO₂ is subsequently transported by diffusion into the region between the stylolites where precipitation of quartz cement takes place. This process will not affect the intergranular volume (IGV). The low amount of clays in the Hanglecærro Formation makes it possible to test the hypothesis that grain-to-grain pressure solution might be a significant contributor to quartz cement in sandstones essentially devoid of clays and clay laminae limiting stylolitisation. Grain-to-grain pressure solution will reduce the IGV during cementation since it brings the grains closer together. Therefore the relation between IGV and the amount of quartz cement in the Hanglecærro Formation indicate the nature of the SiO₂ dissolution process. Quartz cementation commence after mechanical compaction has lowered the initial depositional porosity to about 25-30%. This will be the IGV at the start of cementation. The results of the study show an average quartz cement content of 23% (24.7% if the clay rich samples are excluded) and an average IGV of 25.4 %. This result indicates that the source of the cement even in this very clean quartzite is from stylolites. It also indicates that enough quartz cement is produced at stylolites to stabilize the grain framework before crushing or grain to grain dissolution can occur. These results therefore support the current models for quartz cementation that state that pressure solution at grain-to-grain contacts is a negligible source of quartz cement in sandstones.

The potential for preservation of deep reservoir quality in Jurassic sandstones of the Central Graben, North Sea

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Syn-rift sandstones in the Central Graben are frequently buried to great depth (>4km) and display large variations in reservoir quality. In the present study petrophysical, petrographic and basin modelling methods have been employed in an integrated study to evaluate these variations. Porosities in the range of 20-30% are commonly encountered even below 4 km depth in Jurassic sandstones of the Central Graben. Quartz cementation will be the main porosity reducing process at this depth and porosity preservation is therefore dependent upon factors slowing down the cementation process. It is well established that the rate of quartz cementation is linked to temperature, and that overpressure and hydrocarbon porefluids have a negligible impact on the rate of cementation. On a regional scale the Central Graben is charaterized by sediments somewhat less cemented than expected from the present day burial temperature. This is due to increased subsidence rates during the Cenozoic, especially Quarternay. Modelling of quartz cementation indicate that this will have caused about 10 vol.% less quartz cement to precipitate at 4500 meters compared to more continuously subsiding basins, such as the Viking Graben, and may be an important reason for the differences in porosity-depth gradients in these two regions. In addition previous studies have shown that porosities are preserved in sequences containing grain coating microquartz in the Ula and Gyda fields. In the present study data from the Tambar and Freja areas are evaluated petrographically with respect to reservoir quality. The results show that the Tambar field Jurassic sandstones
show bimodal porosity distributions in texturally very similar sandstones. Petrographic investigations show these results to be due to grain coating microquartz preserving porosity. In the Freja discovery however microquartz is absent. Still porosities are high (avg. 18%) and fairly constant in an approximately 30 meter cored Jurassic sandstone interval. Though porosities and facies are constant throughout the interval permeabilities are better in the uppermost 15 meters of the cored section. Petrographic evaluation show that this is due to textural variations in the illite content of the sandstone. In the upper high perm interval the illite preferentially occur as pore-lining clays. Hence macro porosity and permeability are higher in this interval. Petrophysical data from several wells without Jurassic sandstone cores indicate high porosities (> 20%) and normalised porosity distributions that may indicate absence of grain coatings. The low amount of quartz cement indicated by this data is likely caused by the overall low time temperature integral (TTI) in these sediments due to late rapid subsidence and heating that occurred during the Quaternary.

Collapse of marine-based outlet Glaciers from the Scandinavian Ice Sheet

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We reconstruct >2000 m thick Younger Dryas outlet glaciers in Hardangerfjorden and Sognefjorden, western Norway, using 10Be exposure ages from lateral moraines. We then demonstrate that the margin of these outlet glaciers retreated up the 120–170 km long fjords at rates of 250–350 m/year. The topography of the fjords and the ice-surface profiles are very similar to the present day Jakobshavn Isbræ on Greenland, the fastest flowing glacier on Earth, and also to glaciers in Antarctica that are considered as “key players” for sea level rise on a warming Earth.

We further show that a southwestern sector of the Scandinavian Ice Sheet collapsed in two distinct steps lasting 1000 and 500 years respectively, and that these steps are separated by about 7000 years without net retreat. The first step, between 19.5–18.5 ka ago, was the break-up of the Norwegian Channel Ice Stream and the second was the rapid retreat up the fjords 11.6–11.1 ka ago, mentioned above. This stepwise ice-margin retreat strongly contrasts with the more monotonic decay that has been recorded elsewhere.

On the longevity and preservation of antecedent landscapes: impact for onshore-offshore correlations

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A new development in earth sciences is the ability to semi-quantitatively link onshore catchments with correlative offshore stratigraphy in shelf, slope and deep-water basin settings. The technique, termed source-to-sink analysis (S2S), allows for prediction in both modern and ancient settings, albeit that uncertainty increases with age of the S2S system. A key element of a complete S2S analysis is the geomorphological analysis of onshore catchments. The results drawn from this analysis is improved prediction of sediment entry points to basins, sediment volume and quality and timing of sediment supply. In ancient systems, preservation of onshore catchments is apparently very uncertain in deep time. However, our analyses and examples show the contrary; in many instances there is substantial evidence for geomorphic patterns created by or related to onshore catchments, despite overprinting by other, later geological processes. Nonetheless, preservation will vary with tectonic setting and is less likely on active margins and in thrust belts than on relatively stable, passive-margin cratons. In the latter examples, it seems impossible to get rid of for instance deeply incised valleys once formed. In effect, later geological processes
Fracture analysis in the western Bergen region and consequences for geothermal exploitation and tunnel construction

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The present study aims to investigate fractured bedrock in the western Bergen region. The study is twofold, one objective is to understand how fractured and deformed bedrock inflicts with subsurface tunnel construction and the second is to investigate if the fractured bedrock is suitable for a subsurface geothermal reservoir. Overlapping field area and data collection makes collaboration of the two projects beneficial. Permeability in such rocks is linked to the presence of fractures, faults and permeable layers or zones. In order to obtain an overall understanding of the permeable fracture systems we have mapped and analyzed fracture systems along scan lines in vertical road sections and on horizontal outcrops focusing on fracture aperture, length and connectivity. In addition, detailed scan lines have been generated in an SE-NW oriented tunnel transecting the contact between the Minor Bergen arc (MiBA) and the Øygarden Complex. The combined data set provides a good 3D and lateral understanding of the fracture systems. Especially the tunnel data provides a good opportunity to compare subsurface fracture characteristics to the weathered and eroded surface outcrops. Samples of fracture fillings are systematically collected, with particular focus on clay composition, age and swell tests. The most common fracture trend in the area is composed of NNW-SSE striking fractures and fracture corridors. The NNW-SSE trending fracture set is characterized by isolated fractures and fracture corridors of around 5-20 m length. Fractures are commonly filled with cement (quartz, calcite and gypsum) and clay (gouge). In the tunnel, clay filling fractures are observed to form up to 0.5 m thick zones. The clay consists of mica, chlorite and smectite. Water-bearing structures have been systematically investigated, and we have found that the NNW-SSE trending fracture systems observed in the tunnel are the most water-bearing (permeable) fracture sets. Close and around the minor Bergen arc shear zone increased fracturing is observed both in inner Bergen arc rocks and in the Øygarden Complex. Microtectonic studies show an increase in the degree of recrystallization and alteration of minerals towards the tectonic contact between the Minor Bergen Arc and the Øygarden Complex. It is well known that the granitic gneisses in the western Bergen region are radioactive and for that reason a hypothesis has been postulated that the area can be a suitable location for a geothermal facility. However, to be able to extract substantial heat from the underground, high rock permeability is crucial, in particular when considering a hot wet rocks system. Gamma spectrometry is also conducted in the area, firstly to detect the heat generation potential, secondly to investigate the sources and distribution of radioactivity in the area. Radioactivity has a general high value in the entire western Bergen area consistent with previous reports, however values are highly variable. The general radiation in the granitic gneiss is highest in the western part of the area, related mostly to high Uranium concentrations (20-250 ppm). In fault zones an increased gamma count has been recorded, particularly related to higher Thorium concentration (50-150 ppm).

The structural analysis indicates that the NNW-SSE trending fractures are the far most permeable structure in the area. These fractures represent challenges considering subsurface construction as they are water bearing and should therefore be considered in the planning.
process and placement of the tunnel. In terms of geothermal exploration this fracture systems will generate the highest permeability. Such facility should therefore direct fluid in a N-S direction.

Deep structural features of the northern North Sea area based on results of regional-scale 3D density and thermal modelling

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In order to understand the regional configuration of the crystalline crust within the northern North Sea and adjacent areas of the continent, a lithosphere-scale 3D structural model has been constructed in frame of the Crustal Onshore-Offshore Project (COOP project). Construction of the 3D model has been done by use of recently published/released structural data. For upper part of the model, all available data sets were gridded and compiled in terms of thickness maps for the following intervals: sea water, the Cenozoic, the Upper Cretaceous, the Lower Cretaceous, the Jurassic, the Triassic, the Permian salt and, finally, Zechstein clastics and carbonates. Furthermore, the depth to the top of crystalline basement has been used to assess the configuration of Lower Permian and pre-Permian sediments. Thickness of Lower Permian and pre-Permian sediments has been calculated as the difference between the base of Upper Permian-Meso-Cenozoic sediments and the top of the crystalline basement. Configuration of the crystalline crust and the Moho topography has been constrained by the published interpretations of deep seismic lines. The lithosphere-asthenosphere boundary has been compiled from previously published data.

In order to validate the deep structure of the study area, the initial 3D geometry was used as a starting point for 3D density modelling which has been performed by use of the software IGMA$^+$ (the Interactive Gravity and Magnetic Application System). The 3D density modelling demonstrates that the obtained gravity response of the final 3D model is in a good agreement with the regional component of the observed gravity field. During 3D density modeling, the crystalline crust of the study area has been subdivided into several layers. Within the uppermost crystalline crust, gabbro to anorthositic rocks have been included into the 3D model. In addition, a low-density (2627 kg/m$^3$) upper crustal layer is modelled beneath the Horda Platform. This layer can correspond to metasediments or granite. The next upper crustal layer is characterized by regional distribution and has a density of 2670 kg/m$^3$. The modelled middle crust of the study area contains four layers with similar densities around 2700 kg/m$^3$. The largest middle crustal layer is the middle crust of Baltica. The modelled lower crust consists of three layers. Upper layer is the lower crust of Baltica and the deepest crustal layer is the high-density lower crustal layer (3060 kg/m$^3$) which corresponds to the high-velocity layer. This layer thickens strongly beneath the Norwegian-Danish Basin and the eastern part of the East-Shetland platform. In addition to high-density lower crust, the high-density zone (2930 kg/m$^3$) within the continental crystalline crust has been modelled to fit the observed and calculated gravity.

The obtained Moho topography and depth to the base of lithosphere are deeply located beneath the continent. Furthermore, Moho is strongly uplifted beneath the Central and Viking grabens whereas the lithosphere-asthenosphere boundary is relatively shallow beneath the western part of the model area.

The next step of the analysis was the 3D thermal modelling. Results of thermal modelling within the upper part of the 3D model indicate that the mainland is generally colder than the basin areas. This regional trend of temperature is related to the low thermal conductivity of sediments which increases heat storage within the areas covered by thick sediments. Thick low-conductive sediments reduce the rate of heat transfer, acting as a thermal insulation. This thermal effect is especially pronounced within the Central and Viking grabens, the East Shetland and Norwegian-Danish basins where the thickness of the sedimentary cover is highest. At great depths (70-100 km) the temperature distribution roughly reflects the configuration of the lower thermal boundary which is represented by the base of the lithosphere.

Palaeoenvironmental and floral disturbances during the end-Triassic mass extinction

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The end of Triassic (201.6 million years ago) was marked by one of the biggest mass extinctions of the past 600 million years. Up to about 50% percent of all marine and terrestrial species went extinct at the end of the Triassic (Benton, 1995). During this time the Northern Calcareous Alps
demonstrate the robustness of the model by total elevation of the Norwegian mountains. We as dominant, it is a significant contribution to the regional flow of the (sub)tropic Pangean landsmasses including the western Tethys region (Bonis, 2010). We assessed composition of organic microfossils from the marginal Restental section (NCA) in Austria and present valuable information about paleoenvironmental and vegetational disturbances at the Triassic/Jurassic boundary.

Influence of glacial erosion on vertical motions of Southern Norway and Eastern Greenland

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Norway and Eastern Greenland, separated during Early Cenozoic, remain mainly in tectonically inactive since. Yet significant mountain chains characterize their landscapes. The mechanism responsible for the vertical motions of these regions remains chiefly enigmatic. To understand the influence of the glacial carving, one of the dominant features of these mountains, we perform series of numerical experiments. Assuming that the lithosphere behaves as an elastic plate, we quantify the vertical motion associated with weight loss due to erosion by glaciers. Our numerical experiments show that localized glacial erosion combined with long wave-length response of the flexing lithosphere may result in local uplifts. That model, applied to Eastern Greenland, shows that glacial erosion has negligible effect on the main mountain chain. The effect, however, is significant in the area of the largest fjord of Eastern Greenland. The local uplift here is of a kilometer scale and can explain Cenozoic uplift of marine sediments. Application of the model to Southern Norwegian realm also shows significant vertical motions, up to 0.6 km. Although this mechanism cannot be considered as dominant, it is a significant contribution to the total elevation of the Norwegian mountains. We demonstrate the robustness of the model by presenting good correlation between amount of the eroded material and AFT data.
fit into the Barremian and Aptian secular seawater curves in the literature, while stronger negative values are reported form the Albian. However, negative δ13C are by far too low for the same geological time. This might be explainable by the depositional depth or the specific microclimate in the depositional embayment; factors which can affect δ13C as reported from elsewhere. Geochemical data of the limestones show a very typical composition for sea-water carbonates. Clastic input, monitored by Rb and Zr, amount to a maximum of 3% non-carbonate material. Silica is less abundant than 1.26%, Al2O3 less than 0.26%, Fe2O3 below 0.18% and MgO under 0.38%, while all other elements are extremely depleted, besides Sr (around 150-200 ppm). Rare earth element (REE) pattern show a typical sea-water shape distribution. However, Y/Ho ratios vary between 33 and 55. The higher value points to an environment unaffected by terrestrial water, while the lower value is typical for freshwater and abundant in coastal-near carbonates. Our complete data set will be able to control the effect of diagenesis on the isotope values and the amount of clastic material in the samples, which might have affected the REE. Based on these data we will be able to constrain the paleoenvironment and can argue for a depositional model for the chalk-chaert succession.

References:

Pyrite oxidation changes in Bolivian sulphidic mine wastes

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Bolivia was until late 1980’s a major producer of tin from poly-metallic vein deposits commonly high in sulphide minerals. The mines were often clustered in districts around favourable volcanic centers. These districts had earlier been large producers of silver from the late 1500’s, districts like San Jose-Oruro, Potosi and Huanuni. A large number of tailings and waste rock dumps from the more than 10,000 registered mines in the Altiplano of which many are producing acid drainage due to iron sulphide oxidation. Although acidity in mine drainage commonly requires most of the attention, the primary sources of toxicity are dissolved trace metals. Elevated levels of metal leaching are associated with acidic drainage because metal solubilities and the rates of sulphide weathering increase under acidic conditions.

The Itos mine is a polymetallic vein deposit within the San Jose mining district, had been mined for silver and tin until 1990, leaving behind large tailings and mine waste heaps. Quite often the pyrite content of the waste exceeds 10 wt.%. Serious ARD effects take place in the mine waste heaps. These processes can be well characterized with the pH 1 and 2 of the seepage water, which forms serious alteration in the waste itself and the neighbouring rocks.

In four consecutive years the pyrite oxidation rate was investigated on the same 7 samples by column test. 5-8 months pauses were left between the column test periods, that allow mimicking the alternation of wet and dry periods, typical for the place. Thus the results give much more information, than the oxidation rate in the individual column test periods, showing the changes by time. This applied method gave good result to characterize the behaviour of the waste in long-term.

Column tests were complemented with mineralogical analyses, such as electron probe microanalysis. The mineralogical and column test analyses show, that the changes of the pyrite oxidation rate split the samples into three different groups, one where the oxidation rate decreases, second where it increases with time and the third where oxidation rate is maximal and stays stable for several years.

Palynofacies and palynology of the Upper Triassic deposits at the Juvdalskampen section (central Spitsbergen)

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We present preliminary data from a palynofacies and palynological study of Upper Triassic sediments at the Juvdalskampen section on Spitsbergen. The aim is to establish a palynostratigraphic scheme and characterize their depositional environment. This study makes part of a major research initiative “NORSTRAT” funded by the RCN – FRINATEK program on environmental changes in association with Late Triassic mass extinctions.

In total 13 samples from the Upper Triassic De Geerdalen and Knorringfjellet Formations of the
Kapp Toscana Group yield diverse and well preserved assemblages of palynofacies and terrestrial and marine palynomorphs of a deltaic depositional environment. The sedimentary organic matter is dominated by palynodebris, such as wood or cuticle phytoclasts or by semi-transparent structureless amorphous material while palynomorph abundance is low (circa 10%). An overall trend from samples dominated by structureless amorphous matter at the base to samples dominated by terrestrial phytoclasts in the central part of the De Geerdalen Fm. is observable. This is subsequently followed by an interval with a decrease of phytoclast abundance and increase in structureless amorphous matter towards the top with an increase in palynomorphs for the uppermost part.

Samples of the lower part of the De Geerdalen Fm. (11 samples) are dominated by cuticles whereas the central and upper part is mainly dominated by woody tissue. Palynomorph assemblages are dominated by spores (e.g., Kryptomisporites spp., Leptolepidites sp., Carnisporites sp., Porcellispora sp., Taurocuspores sp.) and to a minor extent by (bisaccate and saccate) pollen suggesting a terrestrial environment for the whole formation. The overlying Knorningfjellet Fm. (2 samples) contains the highest amount of palynomorphs (about 20%) and is dominated by amorphous matter. Terrestrial forms dominate but marine algae remains, which were absent in the De Geerdalen Fm., are present. Marine forms are mainly represented by acritarchs (Veryhachium spp.) and prasinophytes (Cymatiosphaera) and rare dinoflagellate cysts (Heibergella sp., cf. Helbecysta sp.). An increase in marine palynomorph taxa from the De Geerdalen Fm. to the Knorningfjellet Fm. suggests a sea-level rise towards the top.

CO2FieldLab: Field experience with monitoring and safety assessment of CO2 migration in shallow subsurface.

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The potential for storing CO2 for environmental reasons in the subsurface in Norway is limited to submarine sedimentary formations. However, systematic testing and development of monitoring techniques and protocols for CO2 detection is resource-demanding in these environments. The CO2FieldLab project thus aims at determining the sensitivity of monitoring systems to detect shallow CO2 migration and seepage at the surface by means of injecting small amounts of CO2 onshore into permeable sediments in the shallow (approx. 100 m) and very shallow (20 m) subsurface.

The field laboratory is located at the Svelvik ridge about 50 km south of Oslo. This site was chosen as a field laboratory site based on the assumption that the sand ridge contains relatively homogeneous, unconsolidated, highly permeable sand, which offers well constrained conditions for controlled gas injection experiments. The upper part of the Svelvik ridge consists of heterogeneous fluvioglacial sand and gravel, that was deposited in water near the ice contact towards the very end of the Weichselian glaciation (around 7500 ybp in this area). The original height of the fluvioglacial deposit was about 70 m above present sea level, but much of the ridge above sea level has been quarried since 1915. The traditional geological model for the Svelvik Ridge postulates a proximal ice contact (glaciofluvial) type of deposit resting on basement at ca. 300 mbsl (Sørensen 1981; Sørensen et al. 1990). However, our characterization efforts show that the base of the fluvioglacial deposit is ca. 30 m below sea level, while the depth to granitic bedrock exceeds 330 m, as indicated by seismic surveys, drilling and well logging results. The section from 30 mbsl to more than 330 mbsl consists of heterogeneous, (possibly varved) alternating layers of sand, silt and clay, indicating a low saline and distal depositional environment. A proximal deposit overlying a distal deposit can be explained in terms of a significant but temporary advance of the Weichselian ice sheet in this area. In light of the above findings, the traditional model with highly permeable sand and gravel all the way to basement will have to be replaced with a more heterogeneous, anisotropic and less permeable formation. The question then arises whether this formation is considered suitable for the intended CO2 laboratory purposes. Based on well logs and sampling, a number of sandy intervals have been identified as promising target zones for CO2 injection. A controlled release of CO2 at 20 m below present quarry surface was conducted in September 2011. The sediment in these upper 20 m was assumed to be relatively homogenous sand and a simple model for CO2 migration to the surface was made. The CO2 displacement in the subsurface and at the surface was monitored with an extensive set of techniques deployed by the different project partners. The various subsurface
Diagenesis and quartz cement distribution of low permeability
Upper Triassic–Middle Jurassic sandstones of a naturally fractured reservoir, UNIS CO₂ Laboratory well site in Adventdalen, Svalbard, Norway

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Reservoir quality of Upper Triassic – Middle Jurassic sandstones of the Kapp Toscana Group, Spitsbergen, was studied in core samples as part of a pilot project for CO₂ storage in the Longyearbyen area. The reservoir is comprised by the De Geerdalen and Knorringfjellet formations, which show considerable variation in lithofacies and sandstone composition. The reservoir quality has been strongly reduced by various degrees of eogenesis and burial diagenetic compaction and cementation. Quartz cementation is particularly abundant in the fine-grained sandstone facies, and it is interpreted to have been sourced from diagenetic dissolution of labile rock fragments (e.g. chert) and feldspar in combination with clay mineral reactions in the De Geerdalen Formation. In contrast, silica sourced from dissolution at microstylolites seems to be important for quartz cementation in the mineralogically mature sandstones of the Knorringfjellet Formation, suggesting a microstructural and compositional control on the mechanism of quartz cementation. Phosphatic beds of the Knorringfjellet Formation were strongly influenced by iron-rich eogenetic minerals.

Low permeability of the sandstones, in spite of moderate porosity values, reflects that the porosity is dominantly secondary dissolution porosity associated with authigenic clay minerals (illite and Fe-chlorite). Considering the overall properties, the more promising zones for CO₂ injection in the studied reservoir may be in beds with enhanced dissolution porosity in both formations, and in a sand-supported conglomerate with chloride-coated grains. Water injection tests showed good injectivity in the relatively tight sandstones, suggesting that fractures are important conduits to fluid flow. On basis of detailed fracture mapping of outcrops (>7000 individual fracture measurements along >50 scanlines) a predominant WSW-ENE regional trend has been identified, which is inferred to be associated with Tertiary compression (Braathen et al. 2012, Ogata et al. 2012). Subordinate fracture sets related to local tectonism in the Triassic, emplacement of igneous intrusions and decompression during recent uplift are also identified and will be addressed through further study.

References:
Sequence stratigraphic application of foraminiferal facies patterns: Triassic and Jurassic examples

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Main features of foraminiferal facies are portrayed in a transgressive-regressive sequence model, which includes depositional conditions ranging from deltaic and coastal settings to offshore marine shelf conditions. The biofacies proxies include species diversity and frequency of normal marine (contra restricted) taxa. In the sequence stratigraphic framework, biofacies trends are outlined as faunal expansion and reduction separated by a trend change. Faunal expansion means upward increase in diversity and frequency of normal marine taxa leading to well-oxygenated offshore shelf conditions. Faunal reduction means upward decrease in diversity and increase in restricted taxa leading to hypersaline or hypoxic conditions. The model based on these facies patterns is supported by modern analogues, showing foraminiferal distribution along transects from shallow to deep water. Application of the model is illustrated by the following Triassic and Jurassic sections. The Flexurfjellet section is located in central Spitsbergen and comprises Bathonian to Kimmeridgian deposits. The section forms a transgressive-regressive sequence containing a low-diversity entirely agglutinated foraminiferal succession of restricted nature. With increasing depth, the transgressive systems tract shows a faunal expansion suggesting increasing salinity. This is followed by a trend change to faunal reduction suggesting that oxygen depletion becomes the dominant restricting factor. It culminates in a trend change zone containing the maximum flooding surface with minimum diversity and peak TOC (14%) signalling severe oxygen depletion. The regressive systems tract reveals a faunal expansion with decreasing water depth and improving oxygenation. The Janusfjellet section (central Spitsbergen) covers the same Bathonian to Kimmeridgian sequence, as the Flexurfjellet section. The distance between the two sites is 40 km. The biofacies trends of the sequence reveal local differences but also show essential similarities. Thus the sequence stratigraphic development of biofacies trends has a large regional, probably basin-wide extent and applicability.

The Brora section of Callovian age contains a foraminiferal succession of agglutinated and calcareous taxa with high to low diversities reflecting restricted to normal marine conditions. The transgressive systems tract includes normal marine conditions suggested by common calcareous taxa (Lagenina). A trend change from faunal expansion to reduction suggests upward-decreasing oxygenation. This leads to a wide, oxygen-depleted maximum flooding zone, with extreme dominance of agglutinated taxa and diversity minima associated with high TOC values (10%). The regressive systems tract is typified by a faunal expansion reflecting enhanced oxygenation.

The Juvdalskampen section of central Spitsbergen comprises a Carnian to Norian succession containing high to low diversity foraminiferal assemblages of calcareous and agglutinated taxa reflecting normal marine to brackish conditions. The transgressive systems tract reveals a faunal expansion, which culminates at the maximum flooding surface with normal marine shelf conditions. The regressive systems tract shows faunal reduction signaling decreasing salinity from prodelta through delta front to delta plain conditions. The study demonstrates that biofacies trend changes reflect major environmental alterations, which are localised to discrete stratigraphic levels or involve wider stratigraphic intervals. These changes are useful indicators of sequence boundaries and maximum flooding surfaces, but also occur within individual system tracts where a dominance change takes place between two environmental factors.

Micro and macro-fauna in the Jurassic-Cretaceous Slottsmøya Mbr. (Agardhfjellet Fm.), Central Spitsbergen


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Extensive field work in the Janusfjellet – Knorringfjellet area, Isfjorden, north of Longyearbyen, during the years 2004-2012 has revealed rich micro and invertebrate macro-fossils in the...
 Experimental insight into uplift effects on seismic velocities and petrophysical properties of sandstones: Implication for the Barents Sea area

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We present P- and S-wave velocities and corresponding petrophysical properties (total porosity and bulk density) of eight laboratory tested unconsolidated natural sands with different mineralogical compositions and textural variations. The samples were tested at effective stresses from 0.2 up to 30 MPa corresponding to approximately 3000 m subsidence in a sedimentary basin at hydrostatic pore pressure. Three loading cycles were applied to study the influence of pressure reduction on seismic velocities and rock physical properties simulating episodes of uplift in a complex burial history. The results show significant differences in rock physical properties between uplifted (unloaded) and reburied (reloaded) sediments compared to normally compacted sediments. Total porosity, bulk density, P- and S-wave velocities deviate from normal compaction trends during stress release. This can be explained by considering that compaction process is primarily inelastic and that release of stress will release the elastic part of the deformation. The degree of deviation is dependent on the maximum stress that the sediments previously experienced. Moreover, the magnitude of total porosity and bulk density rebound compared to P- and S-wave velocities is less during unloading/uplift. This can be explained by the fact that porosity and density are bulk properties, while velocities are wave propagation phenomena and more sensitive to the changes in microfabric during the release of stress. The results also show that the degree of velocity reduction and porosity increase is a function of uplift for sediments previously buried to the same burial depth. On the other hand, if the sediments experienced the same degree of uplift, porosity loss and velocity increase as a function of past maximum burial depth. This means that empirical P- and S-wave velocity relations for different uplift settings can be established. Such relationships can be used for Vs prediction for sandstones that have experienced uplift/reburial if the burial history is known. The experimental results obtained in this study

Slottsmøya Member, Agardhfjellet Formation. The age of the investigated intervals is Late Jurassic – Early Cretaceous based on previous published material, as well as refined from new date of the current project. For vertebrates; see Hurum et al. (this volume).

Three MSc projects are finished. One (by Rousseau) is a study of echinoderms in the dark shales and siltslimes. Five species are recognized and a depositional environment model reconciling autecologic, taphonomic and sedimentary evidence is presented. The echinoderm layer was formed by a single, rapid burial event during a storm, entombing together autochthonous and allochtonous species on a dysoxic muddy seafloor. Hjálmarðóttir’s MSc revealed extraordinarily well preserved agglutinated foraminifera from both shales and seaep carbonates as well as unique calcareous foraminifera previously undocumented from Spitsbergen. Palynological results are separately presented (Dalseg et al.; this volume) Radiolarians are for the first time systematically described from petrographic thin sections (shale samples) (Kiessling), a fauna characterized by an abundance of spongy spumellarians and a dominance of parvicingulids among the nassellarians. The fauna shows all characteristics of the Northern Boreal Province.

The hydrocarbon seep bodies are previously described by us, but new work is in progress as part of a PhD study (see Hryniewicz et al., this volume). That study is based on fifteen carbonate bodies from the upper part of the Slottsmøya Member. The carbonate bodies show complex and heterogeneous structures typical of hydrocarbon seeps, including zoned (botryoidal) cement textures and fissure-infilling sparite. A presentation of the microfacies of nine of the 15 seep bodies is presented herein (Hryniewicz et al.). During the field work large amounts of well preserved ammonite specimens from the hydrocarbon seep carbonates were collected and used as a basis for a chronostratigraphic interpretation of the seep deposits. The ammonites range in age from the Late Volgian through the Late Ryazanian, and include several genera and species that have not previously been reported from Spitsbergen. Acid preparation of seep samples reveal well preserved lingulid brachiopods, previously unknown from this unit, including Lingularia providing the first critical ultrastructural information for this important extinct member of the extant Lingulidae (Holmer).

Research results are documented in Norwegian Journal of Geology, volume 92 (2-3) from 2012.
significantly improve the understanding of velocity anomalies found in sandstones in uplifted basins like those in the Barents Sea area.

**Determination of the Biot’s coefficient for the permeability of DeGeerdalen and Knorringsfjellet Sandstones, two considered formations for CO₂ sequestration in Svalbard area**

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Subsurface storage of anthropogenic CO₂ emissions has been considered as an efficient option for reducing the amount of the released CO₂ to the surrounding environment. The subsurface injected CO₂ should remain inside the target reservoir formation, otherwise moving back of buoyant CO₂ to the atmosphere or surrounding formations may put serious questions to successful operation of CO₂ storage. Permeability is one of the most important petrophysical and dynamic properties of reservoir rocks that controls the amount of fluid flow throughout the rock. During the subsurface CO₂ storage, permeability plays an important role both in controlling the injectivity, and the fluid transport of the injected CO₂ through the reservoir. The importance of rock permeability will also be crucial, if the considered formation rock for the CO₂ sequestration is fractured and displays dual porosity. At the outset, one would foresee that the absolute permeability would remain constant for the same effective stress by applying simultaneous equal change in pore pressure and confining pressure. This concept has been stated as the ordinary effective pressure law by \( P_{\text{eff}} = P_c - P_p \) in which \( P_c \) and \( P_p \) are the confining pressure and pore pressure respectively. However, it has been shown that this law does not always hold, and should be rewritten as \( P_{\text{eff}} = P_c - \alpha P_p \) in which \( \alpha \) is the Biot’s coefficient that depends on mineralogy, texture and pore geometry of the rock constituents. In this study, we have planned to investigate two sandstone core samples from the wells DH4 and DH5 at Longyearbyen, Svalbard area, in the pilot that recently has been considered as a potential site for the CO₂ storage operation. The core samples belong to Triassic-Lower Jurassic.

DeGeerdalen and Knorringsfjellet formations that are considered the main reservoir formations in Svalbard area. The selected core samples are cemented, consolidated sandstone from the depth 782 to 783 m and 672 to 673 m and are uplifted up to 3 km. By measuring the rock absolute permeability at different applied pore and confining pressures, the Biot’s coefficient for the mentioned sandstone samples in case of applying deionized water as injecting fluid will be determined and the variation of rock permeability versus applied pressures for 2 core samples will be compared. The main purpose of performing this study is to analyze the stress dependent permeability of the rock and also the possibility of rock permeability increase due to pore pressure build up in case of CO₂ injection. Also by exact determination of the Biot’s coefficient, the applied pressures on the rock can be uniquely stated as the effective stress \( (P_{\text{eff}}) \) parameter and the expected permeability values can be uniquely calculated at each specific effective pressure.

**Out of the ice - The climatic significance of artefacts related to prehistoric reindeer hunting melting out of ice patches in Jotunheimen, central southern Norway**

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In the early years of the 21st century, prevailing negative net mass balance of glaciers and ice patches has caused marginal retreat of ice patches in Jotunheimen, central southern Norway. As a result, prehistoric remains lost and/or left by past reindeer hunters have appeared at melting ice patches. In the warm summer and autumn of 2006 the number of artefact recoveries at ice...
patches increased significantly due to melting of snow and ice patches and more than 100 objects were recovered in Jotunheimen.

In frozen state, organic objects may be extraordinarily well preserved through millennia. The archaeological potential is perhaps best known from the ‘Ice Man’ Ötzi found in the Alps, from equipment left behind at the Schnidejoch site in Switzerland, from mummies in Greenland and the Andes Mountains, and from objects at retreating ice patches in Yukon (Canada) and Alaska. In 2009, detailed multi-disciplinary investigations were initiated at the Juvfonne ice patch in Jotunheimen c. 1850 m a.s.l. A well-preserved Iron Age hunting field was discovered and a total approximately 600 artefacts have been documented at the Juvfonne site alone. Most of the objects were registered and brought to the Museum of Cultural History at the University of Oslo for conservation, exhibition and storing. Thirteen so called ‘scaring/guiding sticks’ recovered from the recently exposed foreland of Juvfonne were radiocarbon dated, yielding ages that group in two separate time intervals, AD 246-534 and AD 804-898. By putting the temporal distribution of the radiocarbon-dated artefacts in Jotunheimen into the context of late Holocene glacier-size variations in southern Norway, the most extensive reindeer hunting and trapping associated with snow/ice patches was apparently related to periods with prevailing warm summers when the reindeer herds gathered on high-altitude, contracted glaciers and ice patches most likely to avoid insect plagues. The ‘freshness’ of fragile organic finds suggests that most of the artefacts were rapidly covered by snow and ice and that they have been continuously covered by snow and ice since they were first buried. The age and context of the artefacts indicates that the ice patches have not been smaller than at present during the last millennium. A radiocarbon dated organic-rich layer exposed in the inner and basal part of a ~70 m long ice tunnel excavated into Juvfonne in the spring of 2012 show that the oldest ice in Juvfonne is about 6000 years old. This is in agreement with the age of initial formation of glaciers in Jotunheimen subsequent to the Holocene thermal optimum.

**Turspor - communicating the science of weather, climate and geology in the field**

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“Turspor” is a novel concept aimed at bringing the classroom out into nature and train university students in the communication and disseminat-
gion of geosciences to laypersons, high-school students and their teachers. The focus is inter-disciplinary with a focus on meteorology, climate science and quaternary geology, but the approach can in principle be applied to all geosciences.

The defining concept of “Turspor” is to inspire participants to seek in-depth knowledge relating to observations of features made in the field (glacial moraines, active permafrost, clouds, winds etc). By engaging master and PhD students in the process we create a platform where students can improve their teaching and communicative skills.

The concept was tested on 35 high school students during the summer of 2012 in the vicinity of the Norwegian Trekking Association’s (DNT) cabin Snøheim on Dovre. Before the arrival of the high school students, the university students prepared one page written summaries describing relevant geological or meteorological features and trained on how to best disseminate a basic scientific understanding of these. Specific examples were patterned ground caused by permafrost, glacier flour, katabatic winds, and equilibrium line altitude of glaciers.

Based on the success of the program, we are currently in the process of developing the concept to be offered as a course at the master and PhD level, including a week of training in didactics applied to topics in the geosciences. This will be followed by practical training in collaboration with local schools. The university students who complete the training will be in charge of one day with guiding of high school students in the field (e.g. at Finse, Southern Norway), as well as follow up on the topics discussed in collaboration with the high-school teachers during a subsequent visit to the classroom. By participating in the program, high-school students will experience inquiry-based learning, adding to their understanding of the scientific process.

The sites developed in the vicinity of Snøheim and Finsehytta will be further documented with a GPS tag, detailed description, background and pictures in collaboration with the Norwegian Broadcasting Corporation (NRK) and DNT using the web site: ut.no as well as the associated app. This integrated approach will make it possible for teachers, students and others interested to visit the localities chosen for teaching purposes and learn more about earth sciences while observing the features in the field.
Relationship between compaction, textural variation, cementation and intergranular rock volume in sandstones of the South-western Barents Sea

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The relationship between textural variation, intergranular rock volume (IGV) and chemical compaction (cementation) were studied in Triassic to Lower-Middle Jurassic reservoir sandstones of eight stratigraphic horizons (Stø, Nordmela, Tubåen, Fruholmen, Snadd, Kobbe, Klappmyss and Havert Formations) of the SW Barents Sea. In order to understand the inter-relationship between chemical compaction, texture, intergranular rock volume, an interdisciplinary approach that included sedimentological, petrographical and petrophysical data was used. A total of sixty-six (66) thin sections were analysed using x-ray diffraction, scanning electron microscopy and optical microscopy for IGV and cement volumes. These parameters were then compared to log-estimated properties such as porosities and velocities. IGV and cement volumes were also compared to published data and temperature/depth trends in order to estimate the most important factors affecting porosity loss within the chemical compaction zone. Core and cutting samples analysed were obtained from five wells (7121/7-1, 7122/7-3, 7122/7-4, 7122/7-5 and 7119/12-1) from the Snøhvit and Goliat fields of the Hammerfest Basin and from the Troms 1 area, a transition zone between the Hammerfest Basin and the Tromsø Basin. Features revealing an internal source for cementation were observed in samples as microstylolitization or as indications of grain-to-grain dissolution. These features did not change the IGV significantly. Rock physics templates were also used for an estimation of cementation in the studied wells. Cementation trends were observed to be consistent with temperature trends with the highest temperature zones having highest cementation while the lowest temperature zones had the least cementation. Well 7119/12-1 of the Troms 1 area showed the highest cementation volumes and lowest porosities both from well logs and from the thin section analysis. The cementation process found in this section agrees reasonably well with the rock physics constant cement model indicating that the quartz cement grow into the pore spaces. Knowledge of the interplay between mineralogy, cementation, IGV, and porosity on velocity can help better understand and identify different reservoir scenarios during analyses of well logs and may also be viewed on seismic amplitude anomalies. It can also help to better evaluate the risks involved with exploration targets.

Au-As-mineralization in the St. Jonsfjorden, West Spitsbergen: Implications for a sedimentary source

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Scree geochemical surveys in the 1980’s which were conducted by Norges geologiske undersøkelse (NGU), Store Norske Spitsbergen Kulkompani AS and Norsk Hydro revealed Au anomalies in the West Spitsbergen Fold Belt, including the St. Jonsfjorden region. Follow up sampling in 1991 located Au-anomalous scree in the Holmeslettfjella, Copper-Camp, Motalafjella, Løvliejellet and Bulltinden areas. In addition, it was recognized that the Au mineralization was structurally controlled with highest Au values (up to 14 ppm) along thrust faults. The area was resampled by Store Norske Gull AS geologists in 2008 and 2009 and the Au-anomalies were confirmed. Furthermore, a several meters wide, outcropping pyrite-arsenopyrite-mineralized zone, with Au values up to 55 ppm in the grab samples, was located at Holmeslettfjella along a thrust between the Vestgøtabreen High-Pressure Metamorphic Complex and Bullbreen Group. In the other locations, Au-anomalous samples were subcrop, boulder or scree samples. In the Copper Camp and Løvliejellet areas, the gold mineralization is related to the same thrust zone as in Holmeslettfjella with grab samples having Au values up to 25 ppm. In the Motalafjella and Bulltinden areas, the hosting thrust is the next major thrust SW from Holmeslettfjella. In addition, in the Bulltinden area, the location of the mineralized samples suggests that a normal fault to the SW side of the Bulltinden-Motalafjella thrust may also be gold mineralized. These results gave the foundation for a drilling program conducted in the spring of 2010. Bureaucracy in 2011 blocked further work so that no fieldwork or drilling has been done since. Continued field work in the region is planned for 2013.
In the Holmeslettjella area, the gold mineralization is located along a NW-SE striking, about 45° SW dipping thrust. Gold mineralization is hosted by the Holmslettjella and Motalafjella Formation shales and carbonate rocks and is related to quartz-carbonate-sericite- pyrite-arsenopyrite alteration and gold is refractory (5-20% cyanide leachable). Laser ablation study of arsenopyrite and pyrite confirmed the refractory nature of the gold. Based on the laser ablation study, the Au content of the fine grained arsenopyrite varies from a few g/t up to 1000 ppm with an average about 300 ppm. The rocks are strongly deformed and the samples with quartz-carbonate-sulphide fracture veins have the highest gold grades. In addition to Au and As, mineralized zones are variably enriched in, Bi, Cu, Hg, Tl, Sb, and Te.

The ages of the rocks in the area range from Mesoproterozoic to Middle Silurian. Rocks have been deformed during the mid-Paleozoic Caledonian orogeny, and in mid-Paleogene (Eocene). The age of the gold mineralization is not yet known, but gold mineralization cuts Silurian conglomerates and mineralized thrust structures have been active during Eocene deformation and NE directed thrusting, which are related to dextral transpression.

Geochemistry of host rocks in combination with the geological history suggests that the Holmslettjella Formation and the Ultramafic Vestgötabreen Complex to have been altered by CO2 rich fluids migrating through the rocks during the Caledonian orogeny. Gold and As in these fluids were potentially sourced from carbonaceous shales ("VAMSNAZ-shale": rich also in V, As, Mo, Se, Ni, Ag and Zn). At the same time as the fluids were migrating the serpentinites of the Ultramafic Vestgötabreen Complex underwent listwanite alteration that resulted in partial alteration of the serpentinites into listwanites.

You learn so long as you drill: some unexpected results from the UNIS CO₂ Lab drilling and testing venture in Adventdalen, Svalbard

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The Longyearbyen CO₂ Lab pilot project in Svalbard, Norwegian Arctic, has drilled eight slim hole wells in the Adventdalen area of central Spitsbergen to assess the geological conditions for an underground storage of the CO₂ greenhouse gas generated by the local coal driven power plant in Longyearbyen – the main city of this Arctic archipelago. An extensive seismic survey, borehole wireline logging and a range of core-sample laboratory analyses, along with the water-injection well tests, have been conducted to verify the injectivity potential and storage capacity of the selected reservoir sandstone succession and the sealing capacity of its shaley cap rock. The targeted reservoir is an unconventional ‘tight’ sandstone succession of the Late Triassic to Middle Jurassic Kapp Toscana Group. The depth of the top and base of the reservoir succession has been correctly predicted by the survey. As expected, the majority of the reservoir sandstone units have a low porosity and permeability, but within an acceptable range. The water-injection tests in well Dh4 have shown good injectivity at the depth of 870–970 m, which is attributed mainly to rock fractures. Three leak-off tests (LOT) in the upper, middle and lower parts of the Late Jurassic–Early Cretaceous Janusfjellet Subgroup have verified the sealing capacity of this shaley cap-rock succession. However, some unexpected results have also been obtained, which are worth discussing, as they may also have implications for the hydrocarbon exploration and production in the adjacent large offshore area of the Barents Sea Shelf. The most relevant observations are as follows:

- The sandstones of the Kapp Toscana Group drilled in Adventdalen area show an underpressure of more than 50 bar at a depth of 870 m (860 m below the mean sea level), which is a rather puzzling fact – still requiring explanation.
- The water injection tests indicate both an important role of reservoir open fractures and a pronounced compartmentalization of the reservoir sandstone units, although it still
remains to be assessed if the apparent bedding-parallel permeability are permanent or will gradually yield with the increasing reservoir pressure.

- The Norian–Bajocian Knorringsjellet Formation consists of some highly porous conglomeratic sandstone units (up to 20% porosity) with a very low permeability.

- There is a technical gas discovery in the Knorringsjellet Formation, indicating a wet-gas accumulation of thermogenic origin.

- Two of the wells (western drill site) in Adventdalen have encountered gravelly sediment gravity-flow deposits in presumed delta-slope facies association of the Rurikfjellet Formation, which has direct palaeogeographic implications for the location of the Valanginian/Hauterivian shoreline.

- The cap rock succession in its middle part includes the highly permeable sandstones of the Festningen Member of the Barremian Helvetiafjellet Formation, with an effective cross-well flow of 7500 mD×m

- The occurrence of bentonite layers, 10–20 cm thick, in the middle part of the Helvetiafjellet Formation in some of the wells supports the earlier notion of a Hauterivian–Barremian volcanism to the northeast.

- The organic-rich shales in well cores confirm the notion of an early Aptian marine anoxic event in the Barents Sea region.

The wells have been cored over their entire depth, with ~4.5 km of core samples recovered, including a 70-m thick surficial permafrost layer (preserved frozen). The multidisciplinary pilot project, which presently continues its programme, has involved experts from a wide range of Norwegian research institutions and has greatly improved our geological knowledge of the central Spitsbergen – with direct implications for the adjacent Barents Sea Shelf.

The importance of deep weathering to mineral exploration in Norway

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The Geological Survey of Norway and the Norwegian Petroleum Directorate carried out a joint study on deep weathering in Norway in 2009-2011 (TWIN Project - Tropical Weathering In Norway) to improve the understanding of deep weathering on mainland Norway as well as offshore. All known reports of deep weathering in Norway were reviewed and registered in a GIS database. The weathering in southeastern Norway and eastern Finnmark seems to occur in a stable and more distal part relative to the Mesozoic rift basins whilst the deep weathering in the Lofoten-Vesterålen and Hamarøya occur most likely on the basement surface of rotated fault blocks. The remnants of deeply weathered basement on the mainland of Norway occur as accumulations of clay minerals and grus aggregates along structurally defined weakness zones and locally as up to c. 100 m thick continuous saprolite layers. Weathering extending down to more than 200 m depth is observed in fracture zones. Deep weathering produces often negative magnetic anomalies because ferromagnetic minerals such as magnetite are altered to less magnetic hematite and iron-hydroxide minerals. Modelling of the observed magnetic field on the mainland suggests that some low-magnetic zones caused by deep weathering continue to a depth of c. 300 metres below surface.

Deeply weathered basement rocks on the Utsira High offshore southwestern Norway have recently been dated to Mid Triassic. K/Ar dating in the 1970ies of assumed hydrothermal clay alteration associated with Permian fluorite and sulphide vein deposits, as well as fault zones in eastern and southern Norway (e.g. at Lassedalen, Gjerpen, Heskestad, Skreia and Feiring) yielded Mid and Late Triassic ages. These ages most likely represent the same phase of deep weathering as observed offshore and not hydrothermal alternation associated with the formation of the mineral deposits. K/Ar dating of clay minerals in regional fault zones provided also a Late Triassic age. NGU has within the Coop Project (Crustal Onshore-Offshore Project) compiled new and existing aeromagnetic surveys on the mainland and offshore to provide a comprehensive and state-of-the-art aeromagnetic grid. Mapping of the deep weathering using the Amager method (Aeromagnetic and Geomorphological Relations) reveal that the deep weathering occurs regionally from the central eastern Norway to the strandflat in western Norway.

XRF analysis and mass balance calculations (degree of leaching) within the TWIN project commonly show a high degree of mineral alteration with bulk leaching of main elements (Si, Al, Na and K) in the range of 30 - 65%. The pervasive alteration of large volumes of bedrock is indicative of chemical weathering caused by percolating acidic groundwater in a warm climate, possibly during tropical to sub-tropical conditions in the Mesozoic. The weathering penetrated deeper into the fracture zones and was preserved below Late Jurassic and Cretaceous sediments. Subsequent erosion and denudation have largely removed the evidence of
the deep weathering on the mainland, however clay zones occurring at depths of 200-300 metres were preserved. The deep weathering process can also explain some of the enhanced concentrations of heavy metals and REE in some Norwegian tills.

The landscape of southeastern Norway and eastern Finnmark is dominated by palaeosurfaces (paleic surfaces) with glacially eroded inselbergs consisting of competent rocks such as quartzite and gabbro. Some of the alpine terrains in Norway such as Jotunheimen, Rondane, Dovre fjell, Lyngen and Øksfjord-Stjernøy-Seiland most likely represent glacially eroded inselbergs. We conclude that the Quaternary overburden in large tracts of Norway represent to a large degree a glacially reworked saprolite. The observed anomalous high concentrations of REEs and heavy metals such as Cr, Ni, Mo, Zn and Pb in (e.g. results from the MINN project in the coastal area of Finnmark) can be partly caused by a weathering process where main elements such as K, Na and Ca have been partly removed my leaching. Similar geochemical patterns with reduced concentrations of main elements and increased concentrations of heavy metals and REEs in till relative to the adjacent bedrock have also been reported in southeastern Norway (e.g. in the Numedal project in the 1970s and the GEOS project in 2002-2007). Besides those in southern Norway deep weathering has also been observed to be superimposed on several copper-gold deposits in Finnmark (e.g. in Sádgejohka (Sargejokk), Riednjajav'ri and Čierä). Chalcopyrite and bornite are frequently replaced by supergene minerals such as chalcocite, covellite, malachite, native copper, chrysocolla and limonite. Kaolinite deposits occur on the Varanger Peninsula in the Quaternary overburden as well as in the highly fractured bedrock. We conclude that the understanding of deep weathering processes and their timing in Norway is a key to a successful mineral exploration programme in Norway. Thus, a research project is needed to improve present geophysical and geochemical exploration techniques.

**Onshore-offshore neotectonics in Nordland, northern Norway – implications for petroleum exploration**

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The coastal area of Nordland, northern Norway, is a region with increased seismic activity relative to other parts of Fennoscandia. There is a parallel and shallow zone of increased seismicity along the coast largely reflecting extensional stress conditions. Below the Pleistocene wedge along the continental edge to the west there is another seismic zone with deeper compressional events. The amount of sediments deposited along the continental margin within the Pleistocene Naust Formation has recently been estimated by Dowdeswell et al. (2010) to be ~0.24 m ky⁻¹ over the ice age, with bedrock lowering of ~500 m in the ice-sheet catchment. The mean sediment delivery is 2–3 times higher for the most recent 600 ky than for the period 0.6-2.7 My. The coinciding patterns of sediment loading/unloading and compressional/extensional earthquakes indicate that there is a causal relationship between the two phenomena.

Pleistocene sedimentary wedges on oceanic crust in the Lofoten basin are also co-located with seismic activity (M=6+ earthquakes). Considering that the Pleistocene loading on the relatively stiff oceanic crust causes seismicity in the Norwegian Sea, it is also likely that a comparable unloading of the coastal areas in western and northern Norway may induce extension and accompanying earthquake activity.

One of the most significant exploration problems in the Helgeland and Ribban basins relates to the severe uplift and erosion of the area that occurred during the Cenozoic. An improved understanding of present-day deformation in terms of stress, fluid pressure, gas expansion and transient thermal states will therefore be crucial for the evaluation of the petroleum potential.

Several independent datasets in the outer Rana fjorden region indicate that the area is under WNW-ESE present day extension. A six-station seismic network established by NORSAR in this region detected during a two-year period (1997-1999) c. 300 earthquakes, often occurring as swarms. Fault plane solutions indicate E-W extensional faulting. The outer Rana fjorden district is also the location for the largest earthquake recorded in Fennoscandia in historical times, i.e. the c. 5.8 magnitude in 1819. Liquefaction structures in the postglacial overburden points to the likely occurrence of large, prehistoric earthquakes in this area. Three measurements of uplift of acorn barnacle and bladder wrack marks on the islands of Hugla and Tomma in the outer Rana fjorden area (Fig. 2) show anomalous low land uplift from 1894 to 1990 (0.0-0.07m) compared with the uplift recorded to the north and south (0.23-0.30 m). An irregular subsidence pattern in the order of c. 1 mm/year is also observed on...
DInSAR permanent scatterer data in the same area. The relatively low seismicity occurring at a depth of 2-12 km could therefore create the observed irregular subsidence pattern at the surface. We have established a network of benchmarks to measure the active strain in the Ranafjorden area by use of the Global Positioning System (GPS). Three 15-20 km-long profiles were established across outer, central and inner Ranafjorden. GPS campaign measurements in 1999 and 2008 indicate that the bench marks along the western profile have moved c. 1 mm/year to the NW and W relative to the stations along the two eastern profiles (Fig. 2).

Deeply weathered basement rocks occur locally on either side of Vestfjorden and farther south along the Nordland coast to the Ranafjorden area. The weathered bedrock can be found up to an altitude of c. 500 m above sea level and is most likely exhumed during Pleistocene erosion. The present day large scale topography is mainly an inheritance from the Mesozoic.

The unloading of the crust along the coastal areas of Nordland resulted most likely in flexuring and accompanying fracture extension and seismicity. We propose to establish a research project to monitor the present stress and strain in the Nordland region and to study how these phenomena can relate to the loading/unloading process along the coast. The pressure decrease associated with removal of sedimentary overburden may have caused expansion of gas and resulted in expulsion of oil from the offshore traps. Where uplift and tilting result in local extension, seal breaching and spillage may also occur. The cooling of the source rocks owing to vertical movement may also cause hydrocarbon generation to decrease. An improved understanding of the processes of uplift and erosion in time and space will therefore be an important piece of information in the petroleum exploration of the northeastern Nordland area.

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Scandinavian landscapes, the passive margin and the quest for a lost age

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Offshore Scandinavia, the time interval between 380 and 3 million years ago was characterized by well-documented phases of rifting in Permo-Triassic and Jurassic-Cretaceous times, the magmatic breakup of the NE Atlantic passive margin in the Eocene and Neogene phases of doming and warping. Onshore, we know very little. Scandinavia and Greenland were the sources for very substantial amounts of sediments from the Mesozoic to present day, but our understanding of how Scandinavia’s topography and landscape evolved through this time is poorly known and much debated. The suggested ages of formation for the spectacular relic geomorphic (‘paleic’) surfaces in Scandinavia are not well constrained, and range from the Triassic to the Quaternary.

New concepts have recently emerged that have greatly improved our understanding of how rifts and passive margins evolve through time. Coupled with knowledge of onshore topography, geomorphology and structural geology, new ideas are also developing with respect to the onshore evolution. The crustal thinning gradient, or taper, appears to control the topographic evolution of the margin’s hinterland, the reactivation of inherited structures and the long-term landscape evolution to a degree that we have just started to grasp. The taper is proxied by the apparent taper length, which is measured between the first crustal thickness minimum where the crustal thickness is reduced to 10 km or less to the highest point on the adjacent onshore escarpment. A first-order relationship appears to be that the sharper the taper, the higher the topography in the coastal regions and the higher degrees of asymmetry for the onshore topography. This relationship appears as valid for many passive margins, glaciated as well as non-glaciated. At the sharply tapering Møre margin, ENE-WSW-trending faults developed into the very large normal faults that created the crustal taper in Late Jurassic-Early Cretaceous times.

Here, very significant magnitudes of crustal thinning were accommodated by gently dipping normal faults that experienced 20-30 kilometres of displacement and that resulted in tectonic excision of 3/4 or more of the crystalline crust. Erosion into the footwalls of some of these faults in the Cretaceous created offshore erosional surfaces that may be candidates for correlation with onshore geomorphic features. Incision by the Quaternary strandflat and lack of good age-control on relic landscapes hampers precise correlation. Onshore, reactivation of faults in the Møre-Trøndelag Fault Complex generated a topographic envelope that achieves 2 km and that is consistent with a normal fault displacement.
gradient. The displacement gradient also scales to the crustal taper.
In Scandinavia, the larger river valleys became incised along trends that record topographic gradients with a very consistent NNW-SSE orientation, that is, parallel to the slip direction recorded along a very distinct population of reactivated faults along the margin. In Norway, reactivated faults bound high topography inboard of the most sharply tapered crustal sections and linear alpine ranges are bordered by strands of the Møre-Trøndelag Fault Complex and important faults in the Lofoten-Troms regions. Apatite fission-track age-jumps and K-Ar ages on fault gouges document activity through Jurassic and Cretaceous times, with tectonic juxtaposition occurring in or later than the Late Cretaceous in some cases. This indicates that these faults were active after the main phase of Late Jurassic-Early Cretaceous faulting observed in the offshore proximal margin, and that the topography associated with them is not merely an exhumed rift topography but represents late or post-rift topographic rejuvenation. Post-rift onshore normal faulting is a phenomenon that Scandinavia shares with other passive margins, such as the non-glaciated Brazilian margin, where normal faults bound inland Cenozoic half-graben basins and a low-relief peneplain was tilted and uplifted to high elevations. In Scandinavia, the patterns of topography and drainage related to formation and rejuvenation of the margin were modified and in some cases enhanced during the Quaternary glaciations, sometimes producing dramatic landscape contrasts across the reactivated faults. Time-constraints need to be improved considerably before we can arrive at consistent models for passive margins where onshore-offshore correlation can be substantiated by independent age-constraints from the onshore areas. Therefore, the dating of young events onshore is of utmost importance, including tectonic as well as landscape-forming processes.

Structural comparison of key Atlantic rifted margins: a review of observations and concepts

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In the last decade, a number of new geological and numerical models have been proposed to explain intriguing observations from deep margin settings that were previously not well understood. These new models, together with the increasing amount of high-quality geophysical data, now allow us to compare observations from different margins. Key areas are the Iberia-Newfoundland conjugates, the North-East and South Atlantic systems. A first-order structural similarity appears between the architectures of these rifted margins, including magma-poor as well as magma-rich ones. Typical is the seawards arrangement of characteristic entities such as platforms, necking zones, ocean-continent transitions and marginal/outer highs. The arrangement appears to reflect a commonality with respect to the tectonic processes involved in rifted margin formation. The study of magma-poor and magma-rich margins notably suggests that hyper-extension does not preclude a magmatic breakup.

We propose to clarify the definition of a number of terms typically used in rifted margin studies. Then we will present a review of available information from the Angola-Gabon, Iberia-Newfoundland and Norway-Greenland margins, usually referred to as the archetypes of hyper-extended, magma-poor or volcanic margins. We will discuss their similarities and differences and review the related deformation modes. We will finally propose to characterize the typical life cycle of rifted margins.

Opportunities for geohazard mapping and monitoring using geophysics and remote sensing - two Norwegian case histories

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NGI

Geohazards such as rock- and landslides, pose a significant risk to life and infrastructure in Norway, motivating research initiatives throughout various geoscience disciplines. NGI has lately focused significant research on the assessment and development of methods in the fields of geophysics and remote sensing to assist geologists and geotechnical engineers investigating potentially unstable areas. These may include rock instabilities from rockfall to large rock slides, debris slides, instability in
sensitive clays, as well as snow avalanches. Geophysical and remote sensing methods have been greatly refined over the last few years, both regarding equipment and field methods, but also in processing, interpretation and inversion techniques. This makes the methods valuable tools for both local and regional geohazard investigations. Although ground truth is usually needed, the use of geophysics may limit the need for costly boreholes and provide detailed information from large areas.

In this presentation, we highlight developments within airborne electromagnetic mapping and long range laser scanning, based on two case histories from western- and northern Norway. Airborne electromagnetic methods originate from mineral exploration developed more than 60 years ago mainly in Finland and Canada. The last two decades saw a leap in development towards both stronger and more accurate systems. The Danish SkyTEM system was originally developed at Århus University for accurate ground water mapping and opened up the use of AEM for high resolution surveys. In 2010 NGL, Århus Univ. and SkyTEM Aps formed a research cooperation to map an unstable area composed of highly fractured phyllitic rocks in West Norway. As potential sliding planes may contain significant amounts of water saturated clay (an ideal target for AEM), we choose this site for the survey. An integrated interpretation based on AEM, ground resistivity data, dGPS stations, hydro geology, engineering geology stability calculations and more indicates the existence of several sliding and/or fault planes in the area. Laser scanners provide an efficient means for remote mapping of terrain features and consequently stability assessment especially of rock slopes. Advanced parallel computing solutions developed at NGL enable us to carry out semiautomatic data analysis. This greatly improves efficiency when aiming at geomorphological parameters. Joint sets can be classified directly from 3D point clouds. For creeping slides with movements in the cm range lidar can track and monitor movements, while for smaller scale slides fallen blocks can be accurately mapped. The presented case is an unstable permafrost slope in northern Norway investigated with various terrestrial and space borne remote sensing methods within a consortium of Norwegian and international partners. Repeated 3D laser scanning, using a long range Optech Iliris LR system, provides an assessment of ongoing movements and has mapped areas with minor rock falls in the one year period between scans.

Marine Base Maps - examples from the Asta fjord project, North Norway

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The Astafjord project benefits from the fact that twelve coastal municipalities in Troms County, northern Norway, have joined forces to make better plans for the management of their marine areas. As part of the Astafjord project the Geological Survey of Norway (NGU) has developed a series of Marine Base Maps (MBMs). The map series include geological maps plus derived thematic maps which are directly targeted to the needs of coastal managers. Data contributing to the maps includes swath bathymetry and backscatter, together with ground truth data from video and grab sampling. Benthic fauna and content of pollutants in the sediments have also been mapped by project partners. The MBM series provides information on sediment grain size, anchoring conditions, trenching conditions (diggability), sedimentation basins, slope, slide hazard, average current velocity and habitat maps. The project is defined and run by the local management in cooperation with end users including fish farmers and the fishing community. Special dedicated efforts have been made to ensure effective transfer of project results, maps and scientific knowledge to coastal managers and other end users. All data have been incorporated in a GIS system for office use by local managers. The MBMs are made into electronic charts for use on working vessels, and they are published on www.mareano.no and www.ngu.no.

Through the MBM initiative the municipalities in the Astafjord area have gained tools for knowledge based management of their marine areas. The maps will provide a scientific basis for management tasks related to fish farming, fisheries, biological diversity (e.g. protecting spawning areas), environmental monitoring, and planning of infrastructure to optimize use of the marine areas. The MBM initiative under the Astafjord project has been well received by local managers and seems to offer a good basis for effective knowledge delivery and one that could be extended to other coastal areas.
Seafloor sampling offshore Greenland and Jan Mayen for stratigraphic tie and detection of active hydrocarbon systems

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One of the last frontier areas for oil and gas exploration with a large potential of hydrocarbon accumulations are located in the Arctic. Here little geological information is available due to rough weather and heavy sea-ice conditions. Due to lack of well control, the geological understanding in these challenging regions relies on correlating onshore geology to offshore seismic reflections, and on assuming a geological continuity of conjugate margins. Between 2008 and 2012, VBPR and TGS surveyed several under-explored areas around Greenland (Baffin Bay, Nuuk West, Ammassalik Basin, and Northeast Greenland shelf) and the southern Jan Mayen Ridge. The aim of these surveys were two-fold: (1) sample subcropping strata interpreted from seismic in order to identify the geological nature and properties of truncated reflections on the seafloor, and (2) to detect and document active hydrocarbon systems. The sampling was done using gravity coring for point sampling and dredging along steep escarpments for collection of a wider variety of near in-situ rocks that is difficult to sample by gravity coring. The subcrop gravity core samples are used to generate a pseudo-well, and the results provide a direct geology-seismic tie. Dated dredge samples complement the gravity cores and fill the gaps between sampling stations. Collected sediment samples are dated using biostratigraphy, and further analyzed for source and reservoir rock properties. Biostratigraphy results show that gravity core samples are dominantly in the correct age sequence in relation to the sampled localities. Potential seepage sites, such as shallow amplitude anomalies, depressions on the seafloor, terminations of deep-seated faults, salt diapirs, and piercement structures in general are targeted for hydrocarbon seep studies. The lowermost part of the gravity cores are sampled and analyzed for headspace gas, GCMS, and biomarkers. Our results are the first to document active hydrocarbon systems in the Baffin Bay, the NE Greenland shelf, and on the southern Jan Mayen Ridge. The analyses suggest the presence of Cretaceous and Jurassic oil sources locally within the peak-oil window. In conclusion, this robust sampling and analytical method provides results that can be integrated with geological and geophysical data in frontier basins to increase exploration confidence and reduce risks.

Ore potential of an ultramafic rock at the Kvaløya Island, West Troms Basement Complex

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The studied ultramafic rock occurs at the Kvaløya Island west of Tromsø, North Norway. The rock occurs in layers or lens-shaped bodies, sometimes more than 10 m wide and several hundreds of meters long within Archean gneisses belonging to the West Troms Basement Complex (WTBC). The WTBC is considered to be the northwesternmost exposed part of the Precambrian basement of the Fennoscandian shield. The mineral assemblage of the ultramafic rock is dominated by serpentinite, amphibole, talc, and chlorite, corresponding to green schist or lower amphibolite facies metamorphic conditions. Olivine and pyroxene have not been observed in the investigated samples. The whole-rock composition is comparable to garnet or spinel lherzolite, or to products derived from these rock types through a high degree of partial melting, e.g. komatite. XRF whole rock chemical analyses show that the Ni content in most samples exceeds the average crustal abundance (clarke value), at least by a factor of 20. Two samples (KV 660 and KV 662) show Ni content of 5640 and 5632 ppm (i.e. > 0.5 wt %), which is 70 times higher than the clarke value. For comparison, it should be mentioned that for industrial exploitation nowadays, Ni sulfide ores with Ni content of 2-5 wt % are considered as high-grade ores, while ores with Ni content of 0.3-1 wt % are considered as low-grade ores. The Co content of the analyzed samples also exceeds its clarke value, while Zn and Pb commonly show concentrations below their clarke values. The Cr content of the rock ranges up to 4000 ppm. Reflected light microscopy and back-scatter electron imaging show the presence of the following opaque minerals: magnetite, ilmenite, pyrrhotite, pentlandite, pyrite, and an
unidentified Fe-Ni-Co-sulfide, in addition to small quantities of millerite, chalcopyrite, sphalerite and galena. Electron microprobe analyses show that Cr is associated with magnetite, while Ni occurs in several sulfide phases. The unidentified Ni-Fe-Co-sulfide, according to its spatial relationship with pentlandite, could possibly be a member of the pentlandite–Co-pentlandite solid solutions series. However, the (Ni+Fe+Co)/S-ratio of the mineral (=5/8) is significantly different from that of pentlandite (=9/8), suggesting that it is a different mineral. To our knowledge, the chemical composition of the unidentified Ni-Fe-Co-sulfide is not similar to any other known Ni sulfides. It should be noted that the modal ratio of the two most abundant sulfide minerals, pentlandite and pyrrhotite is 1.5/1, which suggests that the rock is very rich in Ni relative to S compared to many other Ni-ores. The observation of two generations of pyrite indicates several stages of sulfide mineral formation. Our working hypothesis is that pentlandite and pyrrhotite formed during an early stage, while millerite formed at a later stage during decomposition of pentlandite. The high content of Ni (> 5,000 ppm), and the simultaneously low content of S, suggests that the rock may be of economic importance.

Hydrothermal circulation, oil and gas seepage and methanotrophy in 2.0 Ga oil field

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Organic-rich rocks in the c. 2.0 Ga Zaonega Formation (ZF), Karelia, Russia preserve isotopic characteristics of a Paleoproterozoic ecosystem. Isotopic results derived from drill cores obtained during the International Continental Scientific Drilling Program’s (ICDP) Fennoscandian Arctis Russia – Drilling Early Earth Project (FAR-DEEP) show a shift in δ13Corg from c. -25‰ in the lower part of the succession to c. -40‰ in the upper part. This shift is a primary feature and cannot be explained by secondary overprints. A possible explanation for this shift is a global forcing triggered by a change in δ13C of atmospheric CO2 due to episodic weathering of organic-rich rocks that accumulated during the preceding Lomagundi-Jatuli Cearb isotopic excursion. Considering however that the shift towards δ13C-depleted organic matter broadly coincides with lithological evidence for the generation of oil and gas and seeping to the sea floor, we propose that the availability of thermogenic CH4 triggered the activity of methanotrophic organisms, resulting in production of δ13C-depleted biomass. The stratigraphic shift in δ13Corg may record the change from a CO2-fixing autotrophic biomass to biomass containing a significant contribution from methanotrophy. A lithologic indication for thermogenic CH4, sourced within the oil field, is consistent with basinal methanotrophy, and indicates that the δ13Corg negative isotopic excursion observed in the ZF can be explained by regional/basinal processes.

Reservoir quality of Stø Formation in the Snøhvit field, SW Barents Sea

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This study investigates the reservoir quality of Stø formation in the Snøhvit field, SW Barents Sea by applying rock physics technique. The Snøhvit Field is located in the central part of the Hammerfest basin, at a water depth of 310-340 m. The area is highly faulted due to tectonic resulted several stages of uplift and erosion. The reservoir sandstones contain gas, condensate and oil in Lower to Middle Jurassic Stø formations. The Stø sandstones are moderate to well sorted and mineralogically mature. Thin units of shale and siltstone are also present. Stø formation is thickest in the southwestern part of the Hammerfest basin and gradually thinning eastward. The sands were deposited in a prograding coastal regime whereas shale/siltstone intervals represent regional transgressive pulses. Three wells (7121/5-1, 7121/4-1 and 7120/6-2S) from the Snøhvit area aligned from east to west were used in this study to investigate rock properties change within the Stø reservoir sandstone as a function of mechanical and chemical compaction processes. Since, the province of the Stø formation in Hammerfest Basin was in the south-east, well sorted and more coarse grain sediments were deposited in the east compared to the west. These mineralogical and textural variations affect rock
properties significantly during compaction processes. Gamma ray log response in the Stø Formation showed relatively high values in the west compared to the eastern wells indicate the difference in grain size and sorting variation within Stø Formation. Stress dependent mechanical compaction varies because of mineralogy and textural difference from east to west though the Stø Formation experienced similar effective stresses during burial (almost similar overburden). Well sorted Stø sandstone has lower velocity compared to shaly sandstone under the same effective stress.

On the other hand, chemical compaction depends on the dissolution of quartz grains at stylolites and available specific surface area to precipitate quartz cement. Some other factors like stylolites spacing, precipitation distance from stylolites also control the volume of quartz precipitation. Stylolites are the only internal source of quartz cement within a clay-free unit which evolved from clay-rich and rarely micaceous or organic matter rich laminae. More stylolites generate in poorly sorted sediments compared to well sorted sediments suggest high cementation in western well compared to the east. It can be concluded that both compaction processes (mechanical and chemical) result rock property variations in a same reservoir rock controlled primarily by mineralogical composition and textural variations. This should be kept in mind when analyzing a potential reservoir though it has considerable vertical thickness and lateral extent.

Art in nature – communicating geoscience through observations and art techniques

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In Gea Norvegica Geopark in Southeastern Norway we communicate a long and vivid geological story. The oldest rocks, more than 1100 million years old, have been shaped through mountain buildings cycles and several ice-ages, the boundaries between the Precambrian rocks, the Cambro-Silurian and the Permian Oslo Rift offers a unique travel through earth’s history. Signs of different geological processes are easily observed, the rocks tell their stories just like an illustrated book. Traditionally, connected to the mountains and rocks of Norway we can find a lot of myths, about origin, appearance and maybe strange looking forms. Different natural phenomena like structures, landforms, boulders and erratics used to be explained by and connected to mythological creatures and their activities. Intangible memories found in fairytales and myths are parts of Norwegian folklore and cultural heritage and might be used as an entrance to geological knowledge. In society, now and in the future, there is and will be a need for people with knowledge of natural science. Geology is part of this, management of natural resources, protection against floods, slides and other natural hazards and construction are just few examples of areas where geoscientific knowledge is important. But what we experience is that a lot of young students opt out natural science, even though the possibilities for future work are obvious and these subjects bring a lot of interesting studies. Based upon this and inspired by Norwegian history and literature from Sweden and Finland, we started a project called “Geologist meets artist” where we combined old mythology, geological features and materials and professional artists, to create a link between nature and art. The material itself used in different art forms may be of geological origin (rocks, clay, and sand) and structures and landforms can give way for great art. The aim was to test new models of interdisciplinary subjects into teaching and investigate the possibility of combining mythological stories, the material (clay, rocks), artistic techniques and earth science.

We have so far been carrying out three test projects with children of different ages. Together with professional artist we have focused upon art and geology and implemented different activities. Art types were ceramics, drawing and painting. In close cooperation with the artists we focused upon strengthening their geological background and prepare for a different art experience. Both geologists and artists attended all activities and took active part in the lectures.

Our conclusion indicates that this can be a successful interdisciplinary way of teaching nature science and we have got some ideas for further work. Feedback, in form of personal interviews of the participants and artists, shows that the learning outcome was positive; they got new perspectives on the rocks and the landscape and it was great fun. In the continuation of this project it might be interesting to work closer to the teachers and we might choose to work more with landscape observations and different structures than continue to work with geological materials.
Subbasalt Exploration Geophysics: Unlocking the Door

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Exploration of the subbasalt plays in the North Atlantic has been an ongoing effort since the 1980's. Numerous geophysical technologies were developed and tested in this environment. Many of the geophysical techniques have evolved into today's "broad bandwidth" solutions. Although significant progress has been made in imaging of, and through, the basalts, consistent imaging success in this play is still elusive. This paper will briefly review the evolution of geophysical technology for this play and the fundamental physics impacting the seismic wavefield. This phenomenon can be directly translated into specific factors impacting both seismic acquisition and processing. Over the last four years ExxonMobil and its affiliates have collected geophysical data over licenses in the North Atlantic subbasalt province. This includes areas of pervasive basalts, basal delta edges, inner flows and sill dominated environments.

Recent seismic experiments conducted over this acreage include multi-azimuth 3D streamer acquisition, enhanced seismic sources and deep streamer tow, and on bottom nodes for both conventional reflection and wide angle tomographic inversion. The uplift from multi-azimuth 3D seismic acquisition over 3D narrow azimuth can be clearly demonstrated but this is only realizable if combined with an appropriate processing sequence which includes advanced depth migration methods. Appropriate source and streamer design, focused on maximizing the low frequency content in the survey, are also critical components. In the processing realm, comparison between conventional, broad bandwidth and focused bandwidth seismic processing techniques has demonstrated the importance of maximizing the useable seismic signal. The On Bottom Nodes (OBN) experiment was found to produce the best noise-free data (compared to streamer); although work to date indicates that it appears to be more limited in its ability to suppress free surface multiples. However, these same data can be utilized for long offset tomographic inversion in order to determine rock velocities in regions where surface seismic does not have the ability to produce meaningful results. The results of industry’s first fully 3D magnetotelluric survey for imaging beneath basalts using full-wave anisotropic inversion of impedance tensors has demonstrated an ability to image the extent and orientation of intrusions into the sedimentary sequence. In addition, it has been utilized to demonstrate the deficiencies of equivalent 2D experiments. Existing potential field data was utilized to model the location of potential igneous feeder stocks and to validate the orientation of sub-seismic resolution dike systems modeled from the magnetotelluric data.

Clearly defined future opportunities still exist for enhancing both acquisition and processing technology, as well as the integration with non-seismic methods and geologic models.

Saprolitization and formation of sedimentary particles on the southern Utsira High (Edvard Grieg and Johan Sverdrup discoveries) and onshore analogues (Bornholm and Scania)

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The weathering of exposed crystalline rocks represents the first stage in the sedimentary cycle. Given preferable climatic conditions, time and only confined erosion, deep weathering profiles exceeding hundreds of meters have been reported.

The presence of deep weathered basement rocks in the Norwegian North Sea has been known for decades. Following the renewed interest in recent years on and around the Utsira High, an intrasabasinal structural high forming the eastern flank of the Viking Graben, good reservoir conditions and commercial hydrocarbon deposits were discovered by Lundin Norway in well 16/1-15 in the weathered and fractured granitic basement in May 2011 (as a part of the Edvard Grieg discovery made in October 2007).

The Johan Sverdrup discovery was made by Lundin Norway in August 2010 in well 16/2-6, PL 501. This discovery is defined as a fault-bounded trap against the Southern Utsira Basement High and overlain by Jurassic shales and/or Cretaceous
Âsgard marls. The main reservoirs consist of a sequence of Middle and Upper Jurassic sandstones of excellent reservoir quality. Saprrolites are believed to be the main source for the Upper Jurassic sandstones.

These recent discoveries have led to increased interest into the process of saprolitization both from the petroleum industry and academia. Observing weathering profiles in drill cores yield great vertical resolution but little or no information concerning lateral variations. While this is true for all core investigations, it’s particularly important for saprolites where the horizontal development can vary severely and be just as significant as the vertical.

Hence, studies of outcrops are necessary in order to get the full 3-dimensional impression of the weathering processes.

In Scandinavia, Mesozoic and Cenozoic sediments are scarce as a result of glacial erosion, and preserved deposits are restricted to only a few areas. In this project two onshore analogues have been studied. Both are located within the dextral strike-slip system of the Sorgenfrei-Tornquist zone separating the Danish basin from the Fennoscandian shield, resulting in a number of NW-SE trending horsts and grabens.

On the Danish island, Bornholm, the Precambrian Rønne Granite has undergone intense weathering resulting in transformation of K-feldspar to kaolinite. Overlaying the weathered basement is the Carbonaceous claystone of the Rabekke Formation.

The studied section is located in a former kaolinite quarry outside Rønne, Nygård, and represents a 12 m wide and 5 meter thick profile through the saprolite.

A second weathering section has been studied in the Kristianstad basin in Scania, Southern Sweden on the small island Ivö situated in the lake Ivösjön. The studied profile (in the Ivö Klack quarry) measures a 200 m wide and 22 m thick section of the kaolinitized Vånga Granite, with overlying fossiliferous Cretaceous carbonates.

Both sections bear similarities to the profiles observed from the Utsira High and will be vital when reconstructing the processes responsible for the saprolitization observed in drill cores.

**Geomorphology of buried glacial surfaces in the southern Barents Sea from 3D seismic data, indicating glaictectonic subglacial deformation**

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The geomorphology of ice sheet beds and the internal structure of tills can provide important information about subglacial conditions and ice sheet dynamics. Here we present observations from one three-dimensional (3D) seismic data set (ST0828) and regional 2D seismic data from the Nordkappbanken-Djuprenna area in the southern Barents Sea. The geomorphology of a buried horizon, imaged in detail using the 3D seismic data, reveals several semi-circular depressions around 40 m deep and 2 to 6 km wide. The occurrence of sediment accumulations immediately north-north-west of the depressions with the approximately same shapes and volumes as these suggests that the sediment accumulations and depressions are hill-hole pairs, eroded and deposited by glaictectonic deformation. Mega-scale linear furrows with a SSE-NNW orientation appear on the same buried surface and are interpreted to be mega-scale glacial lineations formed by a fast-flowing ice stream. The inferred hill-hole pairs and mega-scale glacial lineations indicate deformation by an ice stream flowing from SSE towards NNW, draining the Fennoscandian Ice Sheet during the last glaciation or deglaciation. Preliminary mapping of deeper faults and indications of fluid flow and shallow gas suggests that formation of the inferred hill-hole pairs may be associated with fluid flow from a deeper reservoir.

**Submarine slides and mass movements along the continental margin off North Norway**

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The MAREANO programme has performed detailed mapping (topography, shallow geology, biology and environmental studies) off Lofoten-Vesterålen and in the SW Barents Sea (www.mareano.no). High-resolution multibeam bathymetry and seafloor reflectivity data acquired by the Norwegian Hydrographic Service as part of MAREANO were used to plan cruises by the Institute of Marine Research (IMR) and the Geological Survey of Norway (NGU), focusing on seafloor video inspection, shallow sampling and high-resolution reflection seismic. The morphology of the continental slope from the Trænadjupet Slide, southwest of Lofoten (c. 67°N
Slide as previously suggested for the area north of We do not see evidence for one single huge Andøya rise beyond the mouth of the canyons. The headwalls of the slide complex occur in the mid slope area, being most well-defined in the south. It is evident that the Lofoten Contourite, located in the north, has been affected by slides. Some slide scars are more fresh-looking than others, suggesting that they are of different age.

The slope gradient outside Lofoten-Vesterålen is among the steepest on the North-European margin (4°-10°), and 15 canyons occur. Bleiksdjupet northwest of Andøya is the largest, but several others are incised 600-1000 m below their shoulder flanks. Amphitheatre-shaped headwalls and sidewalls strongly indicate that repeated sliding has been an important process in the retrogressive development of the canyons. Minor slide scars and mass movements are observed both inside the canyons and in the slope areas between the canyons. Bathymetry and seismic data on the continental rise show evidence of accumulation of slide debris and submarine fans on the continental rise beyond the mouth of the canyons.

We do not see evidence for one single huge Andøya Slide as previously suggested for the area north of Andøya. There is rather a complex topography with some large sides and several minor ones. Slide blocks up to 180 m high have been detected. In the same area, downslope-trending erosive channels occur.

Off northern Troms and Tromsøflaket some shallow seated slides occur, with headwalls at 550-700 m water depth. West of Tromsøflaket (c. 71°-71°30’) deep downslope-trending channels occur. The channels start at the shelf edge, and the features are probably related to meltwater erosion when the last ice sheet extended to the shelf edge. The present morphology of the pre-Weichselian Bear Island Slide is nicely imaged by the data.

### Products of pre-glacial weathering onshore Norway

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This presentation includes a brief review of how our understanding of the weathering conditions that prevailed in Norway before the Quaternary glaciations, gradually has developed. Despite the effects of the glaciations are important features in the landscape, the preglacial topography has scarcely been destroyed to such an extent that it is unrecognizable. This view was already ascertained by Reusch and Brøgger in 1878, and supported by others (i.e. Nansen 1922,1927). Their successors neglected this view without any further investigations, and interpreted the pockets and smaller areas of weathered rocks to be of Quaternary origin, and the kaolinite occurrences to be of hydrothermal origin. Even V. M. Goldschmidt (1954) advocated that the fine-sediments in Scandinavia represented unweathered, mechanically crushed-up bedrock. He analyzed samples of these sediments in order to obtain an average analysis of the underlying bedrock. In the 1970-ies several studies of glacial sediments, bulk and fractions, and of underlying bedrock in the Numedal area, documented that mineralogical and chemical changes had occurred. Not until then was it realized that the glacial deposits was composed of glacially abraded material intermixed with older, preglacial weathered material. Compared to the bedrock, the heavy mineral content of the silt fractions of tills is reduced by approximately 50 %, and maghaemite, not at all observed in the crystalline rocks, but frequently occurring in tropical and sub-tropical lateritic soils, is a common heavy mineral. Other indications of intense weathering are quartz enrichments, amount of elements adsorbed on clays, occurrences of kaolinite and gibbsite, boulders of same kind as underlying bedrock.

Conditions favourable for formation of maghaemite in soils have not persisted in Northern Europe since Tertiary (Miocene), while the weathering to gibbsite may be considerably older. Information sought outside the Norwegian mainland, i.e. the North Sea, and Northern Europe (including Southern Sweden), indicates several warm and humid periods through the Paleozoic and Mesozoic Eras. An interesting question is to which extent the weathered remnants have been protected against erosion by overlying sediments. Signs of compaction and early diagenesis can be traced. Further detailed mineralogical investigations may shed light on this.
Characterization of a new Ophthalmosaurid ichthyosaur from the Upper Jurassic of Spitsbergen

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Ichthyosaurs were a group of marine reptiles that ruled the Mesozoic seas. They evolved to be highly specialized marine predators, and were the first reptilian group to be entirely aquatic. This ongoing project’s goal is to describe a new Ophthalmosaurid ichthyosaur from the Slottsmøya Member of the Agardhfjellet Formation, from the Upper Jurassic of Spitsbergen. The Slottsmøya Member is the uppermost of four members in the Agardhfjellet Formation. It is overlain by the Myklegardfjellet Bed, the base of the Rurikfjellet Formation. The Slottsmøya Member consists of 55-60 meters of dark-grey to black silty mudstone, often weathered into paper shale. The preparation of the specimen PMO 222.654 is complete, and the species description is nearing completion. 3D scans have been taken of the specimen, which will be used in the description. The anatomy of PMO 222.654 will be compared to other ophthalmosaurid ichthyosaurs from the United Kingdom, Russia, Germany, South America and the other specimens from Svalbard. The shoulder girdle and pelvic girdle show extraordinary preservation and are three dimensionally preserved, which is rare for Upper Jurassic ichthyosaurs. Preliminary results based on morphology such as the three facets on the humeri, with the third facet being for an anterior preaxial accessory element, the shoulder girdle and elements of the skull indicate that PMO 222.654, should be included in the family Ophthalmosauridae. The basiooccipital from the occipital arch is well preserved and was removed from the skull. The occipital condyle is similar in size to Ophthalmosaurus icenicus and Brachypterygius sp., with little extracondylar area, but considerably more mediolaterally wider than tall. The humeri are small and robust with a distinct deltopectoral crest and a long dorsal process, unlike previously described humeri of Ophthalmosaurus icenicus. The specimen also bears an unusual proximal ridge, which is prominent from the dorsal process to the anterior edge. This proximal ridge has also been identified in another of the Upper Jurassic Svalbard specimens. Considering this, these results indicate that the specimen is a new species and represents a new genus in this family.

How long is a fault? The implications of (not) understanding fault dimensions from seismic data in exploration and production

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It is easy to fall for the temptation to believe that the seismically mapped tipline of a fault represents the line where displacement is zero and the fault actually ends. Yet, all faults in the subsurface have portions that fall below the resolution of any seismic dataset. In this contribution we explore the effects of this sub-seismic fault domain and discuss the implications of appreciating or ignoring it in exploration and production settings. This is done by the use of two examples:

First, we look at an outcrop example, where we study the length and character of the tip zone. We use reservoir modeling and fluid flow simulation to quantify the effect fault tip zone on fluid flow and reservoir compartmentalization. The studied fault exemplifies that the fault tip zone may extend several hundred meters beyond the seismically mapped tip line of a fault and reservoir fluid flow. As such, the sub-seismic continuity of seismically mapped faults should not be ignored in production.

Second, we discuss the implications of understanding (or not understanding) fault dimensions in an exploration setting. We do so by applying the lessons of the outcrop and flow simulation example to a real subsurface example where we discuss how this may affect the delineation of fault-controlled prospects. We demonstrate how small adjustments in fault interpretations in the sub-seismic domain may significantly affect trap definition, prospect volumes, project economics and the selection of exploration well locations.

Overall, the results and examples of our contribution highlight the importance of...
accounting for the fact that faults do indeed continue past the seismically mappable fault tip. Therefore, and finally, we discuss a very simple method for the estimation of sub-seismic fault continuity past the seismically mapped tip.

**Timing of brittle deformation associated with the Nordfjord-Sogn Detachment Zone: preliminary results from K/Ar illite dating**


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Cast in the cauldron of the collapsing late Caledonides, the Nordfjord-Sogn Detachment Zone (NSDZ) is an extremely large, long-lived extensional detachment that bounds Devonian aged sedimentary basins of western Norway. In its footwall, this major ductile shear zone exhumed ultrahigh-pressure rocks from the depths of the orogen, while its subsiding hanging wall accommodated Devonian clastic sediments shedding off the waning Caledonian terrain. It is known that in Permian and Jurassic-Cretaceous times, the NSDZ was reactivated by brittle faulting (Torsvik et al., 1992; Eide et al., 1997). Nevertheless, the timing of brittle faulting along the NSDZ and in its footwall is far from well constrained. This motivated an ongoing study where unraveling the history of brittle deformation along the NSDZ, and in particular its northern parts, is the primary goal. To do this, we use K/Ar analysis of illite from fault gouges from brittle faults within and outside the NSDZ. The same method has been successfully applied south of the Sognefjord. There, four periods of fault activity were identified: early Carboniferous, Permian, late Triassic-Early Jurassic and Cretaceous-early Palaeogene (Ksienzyk, 2012). One preliminary NSDZ sample collected from the east of the Hornelen Basin contained illites as old as Late Devonian, indicating illite growth during brittle fault activity at an earlier stage than in the faults studied in Hordaland. The fault was most likely reactivated in the Permian, as indicated by Permian illite ages of the smaller grain size fractions. Illite crystallinity values indicate that the illite in this sample grew under anchizonal conditions (ca. 300-150 °C) in the Devonian, and under diagenetic conditions (< 150 °C) in the Permian. This is different from south of the Sognefjord, where illite grew in several faults during the early Carboniferous under epizonal conditions (around or above 300 °C). We speculate, admittedly based on a single data point only, that exhumation of the study area through the brittle-ductile transition may have occurred in the late Devonian and that cooling below 150 °C was accomplished by Permian time. Clearly, additional data are needed to test these ideas. Therefore, 15 additional faults have been sampled and are currently being processed. The sample locations span the NSDZ from the Solund Basin in the south to the Hornelen Basin in the north, as well as the footwall of the NSDZ in the Nordfjord/Sunnmøre area. Sampling sites include the Dalsfjord Fault on Atløya and northwest of Askvoll, where Torsvik et al. (1992) and Eide et al. (1997) speculated that the fault gouges post-date the Permian and Late Jurassic-Early Cretaceous cataclasites and breccias. Completion of analysis permitting, new results will be presented at the conference.

References:

**Effects of lime treatment of AMD waters from Africa reservoir in the Muskau Arch near Łęknica, W Poland**

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The Muskau Arc is a large horseshoe-shaped glaciogenic belt formed during the Mid Polish Glaciation. Neogene lignite deposits containing pyrite were excavated there till the 1980s. The abandoned mining pits filled with water forming set of reservoirs called “anthropogenic lakeland”. Oxidation of sulfide-containing lignite, exposed to atmospheric oxygen and water leads to formation of acidic waters. The waters are characterized by high Fe and SO₄²⁻ content. This chemical
association with low pH waters represent main environmental waste problem in this region, which is typical for most Acid Mine Drainage (AMD) environments.

The objective of this study is comparison of the effects of lime neutralization treatments potentially applied to one of the largest reservoirs called Africa. This is a meromictic lake with permanent stratification: the mixolimnion at the top (down to ca. 10 m depth), in which the water is well mixed and saturated with oxygen, and the monimolimnion in the deeper part, which is poor in oxygen and which did not mix with upper water. The pH and concentration of major ions is strongly controlled by the stratification, lower pH (pH = 2.75) and ion concentrations (average TDS amount 1400 mg/L) in upper layer and higher pH equal 4.75 and salinity (average TDS reach 5500 mg/L) in the bottom one. In the set of model experiments, the lake water was mixed with different sample weights of lacustrine limestone and hydrated lime - materials commonly used for neutralization of AMD water. The treatment results in rapid increase of pH to about neutral (6-7) or even alkaline (11-12 in the case of large sample weight of lime) and precipitation of various secondary phases, mostly gypsum and iron hydroxides. These results in removal of ferric and ferrous ions and reduction of sulphates content less than 50%. The effect of the precipitates on the hydrochemical equilibrium of the lake is still to be determined.

Helicopter-borne ElectroMagnetic measurements for graphite mapping in the Skaland area at Senja

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In 2011, The Geological Survey of Norway (NGU) got extra funding for mineral exploration in the northern part of Norway (MINN). The annual budget for the years 2011 to 2014 was NOK 25 mill., and 75 percent of this was allocated airborne geophysical measurements. Both magnetic and radiometric measurements using fixed wing aircrafts and helicopter-borne magnetic, electromagnetic and radiometric survey were planned. Due to high marked prices for helicopter-borne geophysics, the NGU decided to use its own equipment for the helicopter measurements. NGU’s standard equipment for helicopter-borne geophysics consists of a Geotech Hummingbird five frequency electromagnetic system, Scintrex optical pumped Cesium magnetometer and a 1024 channel gamma-ray spectrometer (Radiation Solutions RXS-5). In addition, temperature, pressure and radar altitude are recorded. The in-house navigation system provides GPS data to the acquisition system and information to the helicopter pilot on position related to pre programmed flight lines. Standard operating parameters are: line spacing 200 meters, helicopter height above ground 60 meters and nominal speed 100 km/h.

One of the areas for the 2012 surveys was the northern part of the Senja island in Troms County. In this region, the operating "Skaland Graphite as" is located. As a cooperation with this company, a more detailed survey was performed in the area from the old Skaland mine to the operating Trælen mine. Line spacing was 100 meters, and due to rough terrain, average helicopter altitude was 90 meters and average speed as low as 65 km/h. Low speed resulted in high density of data along the lines but not better resolution due to higher measuring height. Electromagnetic data were inverted using a code from University of British Colombia, Canada (UBC 2000a, UBC 2000b). Results from the study will be presented.

References:
UBC 2000a: Background for Program "EM1DFM" Version 1. Developed under the consortium research project Inversion and modeling of applied geophysiscal electromagnetic data.
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UBC 2000b: Manual for the program "EM1DFM". Geophysical Inversion Faculty, University of British Colombia, Vancouver, Canada.

Salt tectonics in the Norwegian-Danish Basin: implications on trap formation and depositional systems.


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The Norwegian-Danish Basin, located in the central part of the North Sea, contains a thick evaporite succession that was deposited during
the late Permian. The Permian salt was subjected to intense salt tectonics that was initiated during the Triassic and was reactivated episodically until the Miocene according to previous studies. Salt tectonics in this area is characterized by a variety of structures such as pillows and diapirs that have strongly affected sediment deposition. In the context of CO₂ storage, we investigate the distribution and the quality of potential reservoirs and seals. We first need to determine whether the full thickness of the potential reservoirs and seals are involved in three-dimensional structural closures or whether they were thinned and eroded during salt movements.

It requires a good understanding of salt structures repartition and timing of salt movements. Secondly, we need to analyze and assess the faults and fractures associated with salt structures in order to evaluate the salt integrity. We have interpreted 2D seismic reflection profiles tied to wells to map (1) the distribution of salt structures, (2) key geological formations of the overburden, (3) pre-existing faults in order to evaluate their role (topography or movement) in the initiation of salt movement and distribution of salt structures and (4) faults over selected salt structures. Salt thickness map exhibits three domains with different pattern of salt structures: in the northern part of the basin, salt diapirs are aligned in a NW-SE trend whereas their repartition is more chaotic in the south-western part, at the border with the Central Graben, where the base salt is deeper and the salt layer is thicker. The last domain in the eastern part of the basin contains less diapirs with no specific distribution. On selected cross-sections, we constrained the timing of the salt movement initiation, its duration and reactivations by analyzing the sediments geometry and the unconformities around and over the salt structures. In the eastern part of the basin, analyzed salt structures were simultaneously triggered during the Middle Triassic, whereas initial salt movements started earlier in the western part of the basin. Salt tectonic reactivations occurred in the Middle Jurassic, Paleogene, and prior to the Quaternary for some salt structures. The start of these salt movements correlates with main regional tectonic events. From these selected cross-sections, we reconstructed the evolution of the Permian salt and Mesozoic depositional systems through time.
changes in the North Atlantic surface circulation to variations in Pacific to Atlantic throughflow via the Central American Seaway.

**Late Neogene palynostratigraphy of the Vøring Plateau – towards a framework for dating the Utsira Formation**

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Based on several studies with calcareous microfossils, the Utsira Formation was dated to be Middle Miocene to Early Pliocene (e.g. Piasecki et al. 2002, Eidvin & Rundberg 2007). Sandy units near the Tordis and Visund oil fields have been interpreted as the Utsira Formation, but a few incidents where water and drill cuttings injected into this 'Utsira Formation' caused leaks at the sea-floor (Eidvin & Øverland 2009). These events and the increasing use of the Utsira Formation as a carbon dioxide storage has re-emphasised the need for a better understanding of the stratigraphical distribution of the Utsira Formation, both spatially and in time. In this study, dinoflagellate cysts and acritarchs are used because of their better preservation, higher diversity and excellent potential for stratigraphic correlation in the higher latitude oceans in comparison to calcareous microfossils.

In a first phase, the palynology of ODP Site 642 on the Vøring Plateau is investigated to establish a Miocene–Pliocene biostratigraphic framework for the Norwegian Sea/North Sea region. Together with the already available palynological zonations in the North Atlantic, Iceland Sea and North Sea, ODP Site 642 will form a cornerstone for a mid- to high-latitude North Atlantic biozonation for the late Neogene. Preliminary results from ODP Site 642 have identified several Late Miocene and Pliocene biostratigraphic markers previously unknown (Mudie 1989) from the Vøring Plateau. These include the dinoflagellate cysts *Ataxiodinium confusum*, *Cerebryocysta poulensis*, *Corrudinium devernaliae*, *Operculodinium tegillatum*, *Operculodinium? erikianum*, and *Reticulatosphaera actinocoronata* and the acritarchs of the genus *Lavradosphaera* and *Cymatosphasera*. In the second phase of the project, we will investigate the palynology of the Utsira Formation from several North Sea industry wells in the Sleipner area – the type area of this formation – and the Tampen area.

References:


**The petrogenesis and potential sources of the Be- and HFSE- multi element mineralization of Høgtuva (Nordland, Northern Norway)**

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The Høgtuva tectonic window forms part of the regional structure of the Transscandinavian Igneous Belt (TIB) and is situated in the county of Nordland in Northern Norway. As such, Høgtuva is a granitic body that was emplaced about 1.7 Ga ago and metamorphosed under amphibolite-facies conditions. In lenses and spatially restricted zones in the south eastern part of this gneissenized granite, phenakite is the volumetrically most important of several beryllium minerals that are found in such quantities that the respective parts of Høgtuva are considered a major European Beryllium deposit that hosts 350000 tons @ 0.18 wt% Be. Parts of the beryllium ore zone display anomalously high concentrations of Zr, Nb, Th, U, REE and Zn. Fieldwork and detailed petrographic investigations revealed that late-stage (presumably hydrothermal) zircon and other HFSE-incorporating minerals are not cogenetic with the beryllium minerals even though they occur locally in close spatial association. In this respect, pseudomorphic replacement textures of late-stage zircon after e.g. högtuvaite (a beryllian sapphire-group mineral) provide evidence that the late-stage zircon post-dates at least some beryllium minerals. Beside of the occurrence of late-stage zircon, hydrothermal activity is indicated by the compositions of major rock-forming minerals in the mineralized gneisses: albitic feldspar and magnetite are of pure end member composition, biotite displays elevated Zn-contents and rare clinopyroxene is nearly pure aegirine in composition. Contrastingly, feldspar and magnetite form higher degrees of solid-solution series, Zn-contents are significantly lower in biotite and clinopyroxene is absent in parts of
the gneisses outside the mineralization that are free of beryllium minerals.
In order to identify cogenetic minerals and to decipher the temporal relationships of the beryllium-incorporating minerals as well as primary and late-stage HFSE phases, we present results on the in-situ U-Pb age determination of primary and late-stage zircons and selected beryllium minerals in petrographic thick sections using the LA ICP-MS technique. In addition to age determinations of the above minerals, rare earth and trace element compositions of beryllium and HFSE-incorporating minerals from the mineralized gneisses are compared to rare earth and trace element characteristics of adjacent lithologies in order to identify potential sources for beryllium and HFSE. With respect to distributions of the rare earth elements, all beryllium and HFSE minerals found in the mineralized and surrounding areas of the gneisses are characterized by pronounced negative europium anomalies, indicating a common internal source for the mineralization. A potential source for beryllium and the HFSE may be represented by numerous deformed phenakite-, beryl- and primary zircon-bearing aplites which are found in the vicinity of the mineralized gneisses.

Oslo Meteorite


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It is not often that the capital of a country experiences a meteorite fall or that buildings are hit. A meteorite fell through the roof of a cottage house, situated at Rodeløkka, in the centre of Oslo. The meteorite was found on March 12th 2012, and probably fell a few days earlier. Later several more pieces have been found.

Rodeløkka 550 g, 59°55'47.666" N - 10°45'17.960" E
ekkeberg Gletta 700+25 g, 59°53'46.20N - 10°46'17.960" E
Ekeberg kindergarten several pieces 150 g, 59°53'46.20N - 10°46'17.960" E

Nordre Grefsen several pieces total of 4.6 kg
With a total of more than 6.1 kg this is the third largest meteorite found in Norway. Only the Finmarken (Alten) and the Tysnes meteorites are bigger.

In general all the pieces of this meteorite were found more or less along a line from south to north, with the biggest pieces in the northern part of the city.

The meteorite is a breccia with well-defined chondrules up to 2 mm with. The matrix has a light white to grey colour while the chondrules in general are dark grey and consist mainly of opx and ol. Metallic and sulphide minerals are found as small grains up to 1 mm.

Mineral composition of the major silicates is olivine Fa1-34 with an average of Fa18, opx Fs2-18 but with the majority of analyses being Fs17-18. Small amounts of cpx occur on the margin of opx. In addition, there are small amounts of Al-Cr spinel and glass. Metals and sulphides like Kamacite, Trolite and Taenite are relative abundant (>20%), but the distribution in the sample is relatively heterogeneous. ol and py are strongly unequilibrated so a type H5 classification can be excluded.

Mineral composition and preliminary petrophysical data shows that this meteorite most likely is an H3. Raman analysis will give an additional insight into the composition of the meteorite.

Microstructure of ultramafic pseudotachylyte from Alpine Corsica – insights into earthquakes in mantle lithosphere

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Present-day subduction zones exhibit intense seismic activity in the descending oceanic lithosphere. The mechanism behind shallow earthquakes is generally well-understood and related to frictional stick-slip on fault planes.
Earthquakes originating deeper, at intermediate- (50-300 km) or at even greater depths (up to ~700 km) can generally only be studied by the seismic energies released from the earthquakes in subduction zones. The mechanism(s) responsible for nucleating seismic failure at such depths are not fully understood, and their investigation by direct observation of the deformation products formed by seismic faulting at depth is restricted by a general lack of exposed examples. In Alpine Corsica, paleoseismicity is recorded by pseudotachylites in the high-pressure and low-temperature, blueschist- to eclogite facies subduction complex. These rocks provide a direct insight to the nature and characteristics of deep-seated earthquakes formed at ambient conditions up to 1.8-2.6 GPa and ~450°C. Mafic and ultramafic pseudotachylite occur in Ligurian ophiolite gabbro and mantle peridotite respectively, within the Schistes Lustrés unit at Cape Corse. Ultramafic pseudotachylites are found at and beneath the paleo-MOHO within variably hydrated but commonly well-preserved lenses of peridotites enveloped by serpentinites, which crop out on the southern mountainside of Cima di Gratera. Numerous fault- and associated damage zones record crosscutting relationships where individual fault-veins vary in thickness from a few millimetres to more than ten centimetres. An angular relationship between two characteristic sets of fault veins is present; one set is subparallel to the gently dipping foliation in the gabbro and the gabbro-peridotite contact, whereas a steeper set of fault veins is commonly found to offset the gently dipping faults. Evidence of reactivation along both sets, however, suggests a conjugate system in which multiple generations of seismic failure have occurred. Affiliated injection-vein networks are commonly wider than the fault veins and take on several patterns suggesting large amounts of melt, re-injection and at times an 'explosive' nature with fragmentation within multiple sets of parallel fault-planes. The ongoing microstructural investigations using scanning microscopy (SEM), electron microprobe (EMP) and electron backscatter diffraction (EBSD) provide insight into the microstructure, mineralogy and grain-size, which can be used to characterise the rheological behaviour from domains within and adjacent to fault-veins and host-rock peridotite at the time of- and after seismic failure. Ultimately, our goal is to assign mechanical constraints on the these paleoseismic events, which in turn may provide insight into the nucleation and fault dynamics of deep-seated regions in subduction zones in which these rarely preserved rocks have originated.

Provenance, age and tectonic setting of the Lower Paleozoic Oville and San Pedro Formations (northern Spain)

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Lower Paleozoic clastic sedimentary rocks in northern Spain are well exposed and have commonly a large catchment area. They therefore are ideal rock successions to evaluate the provenance of northeast Gondwana and monitor possible changes in the source composition. We selected therefore two successions of different ages to identify those changes. The older succession is the Late Middle Cambrian to Lower Ordovician Oville Formation. The Oville Formation is composed of shales and friable sandstones to siltstones. The rocks have been deposited in shallow marine environments and the shales are rich in trilobites, which allowed in dating the base of the formation precisely. The top is macrofossil barren but hosts acritarchs which point to a depositional age at the boundary of the Cambrian to Ordovician. The matrix-rich rocks (wackes) gradually change, at the top of the section, into clean quartz-arenites of the Lower Ordovician Barrios Formation. The rocks of the Oville Formation match geochemically typical unrecycled upper continental crust (UCC) with Th/Sc ratios above 1-1.5 and Zr/Sc ratios around 10-20. Influence of mafic detritus is negligible as the rocks have typical UCC concentrations of Cr, Sc, V, Ni and Ti or show even lower values. The chemical index of alteration is high with values between 70 and 80.

The younger sampled formation is called San Pedro Formation and characterised by its intensive red coloration caused by a FeOx-rich matrix of the sandstones and shales. The San Pedro Formation is even mined in some exposures because of its high Fe-content. The rocks have an abundant matrix (10-20%) and have been deposited in a shallow marine environment controlled by tides and affected by storm events. The grain-sizes change from very coarse-grained sandstones to siltstones intercalated with shales. The age of the San Pedro Formation is poorly constrained and bracketed by the underlying Llandoveryan Formigoso Formation and the Lower Devonian age of the overlying La Vid Group. The rocks are geochemically slightly more mature with higher ranges of Th/Sc (0.6-1.2) and Zr/Sc (9.5-40).
New sedimentological investigations in Mesozoic strata of Peary Land on Northern Greenland: Scope of study, preliminary results and significance for the southwestern margin of the Barents Shelf

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The NPD is currently carrying out a palaeogeography project meant to focus specifically on the southwestern margin of the Barents Sea and its geo-historic link to the basins and the tectonics of North Greenland. Plate Tectonic reconstructions indicate a very tight pre-spreadling link between Peary Land and the shelf margin between Sørkapp and Bjørnøya, as well as between Holm Land/Peary Land and the southernmost shelf margin between Bjørnøya and Troms. The Post-Caledonian/Post-Ellesmerian sedimentary succession of the Wandel Sea Basin of North Greenland bears significant resemblance to its stratigraphic counterparts in the western Barents Sea and the Archipelago of Svalbard, and the two regions were probably parts of the same depositional systems during certain episodes of the geological past. Careful and detailed sedimentological studies of sedimentary strata of the Wandel Sea Basin are therefore considered to be vital in the process of improving the understanding of the geological history of the western margin of the Barents Shelf.

In the light of these acknowledgements the NPD is taking part in GEUS’ 2012-2014 geological field campaign to North Greenland. The Wandel Sea Basin comprises strata ranging in age from Visean to Paleogene. During the first field season during summer 2012, the NPD elected to pay specific attention towards the Late Permian Midnatfjeld Formation, the two Triassic formations Parish Bjerg and Dunken, and the Late Cretaceous Herlufsholm Strand Formation. These priorities were made due to the assumed palaeogeographic significance as well as outcrop distance from the elected camp-site.

Sedimentological descriptions and field logging with special emphasis on ichnology and sedimentary structures were carried out. The formations were sampled for thin sections and micropaleontology. This poster communication is limited to deal with the Triassic formations, and presents preliminary results and suggestions regarding reinterpretations of depositional environments. The Triassic Parish Bjerg Formation (upper two-thirds) and Dunken Formation, have in the past been broadly interpreted as shallow marine in origin. Findings from this study suggest that there are basis for more specific designations regarding depositional environments. For the investigated part of the Parish Bjerg Formation, an upward shallowing system from storm and wave dominated offshore transitional environments towards tidally influenced marginal marine environments are suggested. For the Dunken formation, predominantly marginal marine to fluvio-deltaic environments are proposed. Palaeoflow measurements in investigated strata suggest predominant sediment transport directions towards the east, south and north. Hence, the investigated Triassic sedimentary systems of Peary Land may have influenced the rock record of the southwestern margin of the Barents Shelf.

New U-Pb ages from the late Sveconorwegian intrusions in the southern part of the Western Gneiss Region, Norway

Skår, Ø.

Geological Survey of Norway

The plutonic intrusions constitute ~20 % of the present erosion level of southern part of the Western Gneiss Region (WGR). The intrusions are mainly composite, consisting of a major component of felsic rocks and minor proportions
of mafic and intermediate rocks. They were emplaced into a basement generated during the Gothian orogeny (1750–1500 Ma).

Only two of the intrusions in this area have earlier been dated by the U-Pb method. Six other intrusion have been dated by the more imprecisely Rb-Sr whole rock method.

In this study more than 11 of the Sveconorwegian intrusions have been dated by the U-Pb method in zircons by Laser-ablation ICP-MS. Some of the intrusions were earlier dated by the Rb-Sr whole rock method other intrusions are new. The new data confirm the previously age data. However, the new data suggest that most intrusion were emplaced in a more narrow time period between 950 and 990 Ma.

U-Pb data from inherited zircons in the intrusions and new dated rocks, confirms that the age of the surrounding gneisses and migmatites are of Middle to Late Gothian Age (1660 – 1500 Ma). The data further suggests that the time period between 1550 Ma and 1500 Ma was a more active magmatic period in the southern part of the Western Gneiss Region than previously discovered.

**Geoheritage in Europe and its conservation**

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The European Association for the Conservation of the Geological Heritage (ProGEO) works to promote the conservation of Europe’s rich heritage of landscapes, rocks, fossils and mineral sites by involving all countries in Europe, exchanging ideas and information in an open forum, and taking a full part in conservation in a global setting, including the formulation of conventions and legislation. The book is a part of this work and gives an overview of geoconservation in Europe with specific contributions from 37 countries. For the first time conservation of our geological heritage in Europe is put together in a book. The book, GEOHERITAGE IN EUROPE AND ITS CONSERVATION is published by ProGEO.

Europe is diverse both with respect to geology, landscape, countries and history. Geoconservation strategies and geoconservation practices and legislations varies between the countries, but also the mutual basis that geoconservation has throughout the continent. The book gives an updated overview of this variation. It describes how the management of geodiversity and the geological heritage is established in the different countries and gives also comments on lack of management and other challenges for geoconservation.

The idea of making such a book dates several years back to the early years of ProGEO. Gerard Gonggrijp from The Netherlands came up with the idea as a tool to meet the ProGEO aims of sharing information and create inspiration for geoconservation. Gerard, who passed away all too early, was the main founder of “The Working Group for Earth Science Conservation” as ProGEO was called in the early days, and was the first executive secretary in ProGEO. This book is dedicated to him.

The book is available through the ProGEO websites: www.progeo.se. On this website it will also be possible to find updated and supplementary information on geoconservation in Europe.

**Onshore-offshore examples of Upper Carboniferous and Triassic growth faults; Svalbard and NW Barents Shelf**

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Growth-basins develop in extensional regimes as a response to faulting, affecting the sedimentary architecture of the basin fill both spatially and temporally. The effects of fault growth encompass variable displacement and segment linkage, controlling positions of highs and lows along and across faults during their development. The impact of variable relief is recorded by erosion and deposition, with temporal accommodation creation influencing facies and facies belt distributions. These interlinked impacts and responses are important in a generic and HC/groundwater exploitation sense, but are still poorly understood. Our case studies of growth-basins are from Svalbard, an uplifted part of Barents Shelf, offering high-quality exposures that can be compared with seismic data. Outcrops in the Carboniferous Billefjorden and the Middle-Late Triassic Edgeøya are analysed as cases of comparative growth-basins.

The Upper Carboniferous Billefjorden Trough is dominated by thick sabkha deposits interfinger ing with thin units of shallow marine carbonate and mainly margin-bound siliciclastic deposits in a low-relief, arid basin. The Sabkha domains of the basin with low-shear strength evaporites promoted the development of major fault-tip monoclines with sharp hinges and steep fold-
limbs (Braathen et al., 2011), which during growth forced fold-parallel drainage and basin deposits to onlap tilted strata. Monocline back limbs were also uplifted above base level, experiencing surface dissolution and erosion, with local drainage incisions likely bypassing the growing monoclines as suggested by restricted siliciclastic sinks.

In the world class examples of Triassic growth-basin systems of Edgeøya, faulting interacts with typical prodelta to delta-front deposits, as reported by Edwards (1976). Wedge-shaped syntectonic basin fill covers prodelta shales grading into tidal flat sandstones, with some nearly massive mass-flow sandstones. Most of the basins and bounding faults terminates in a common erosive upper boundary, overlain by tidal flat deposits followed by marine shales of a major flooding event. In the fault-bound basins, striking examples of sedimentary facies distribution can be liked to accommodation creation, mimicking faulting events interplaying with sediment supply.

In this study, fundamental observations of the Carboniferous Billefjorden Trough and the Middle-Late Triassic Edgeøya growth-basins are compared. Derived understanding of complex onshore growth-basin characteristics with associated sedimentary facies associations are utilized in detailed study of similar basins in offshore seismic data.

References:

3D-model of Hopen. A digital 3D model improve our understanding of the geometry, heterogeneity and distribution of sandstone bodies in the Upper Triassic succession at Hopen, Svalbard

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A digital 3D model of Hopen has been created by using high-resolution photos taken along the coastline of the entire island. By merging these photos together in Photo Modeler software it has been possible to produce a workable 3D model of the island. Importing the model and the geological data into Petrel makes it possible to generate a geological model that can display the geological interpretations done on the island. Detailed sedimentological logs, from many different geologists, are representative of specific locations, mostly along the eastern side of the island. All the sediments at Hopen are part of the Upper Triassic succession and include the De Geerdalen, Flatsalen and Svenskøya formations. Large fluvial channels, up to 36 m thick, are observed in the steep, near vertical cliffs of the island. The model makes it possible to map seismic scale channels, as well as smaller sandstone bodies, and interpret them with measured sedimentological logs. Based on position of exposed sandstones visible on both sides of the island, the three-dimensional development of the river system can be suggested. The most suitable river path and sandstone thickness will be estimated by applying geological principles. The Petrel model can also allow for interpretations as analogue for large areas of the Barents Sea where correlative geological units form major reservoirs.

Sea-floor geomorphology of the southern Barents Sea, revealing dynamics of previous ice streams

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Ice streams, long corridors where ice is moving much faster than the surrounding parts of the ice sheet drain the majority of ice and sediment from contemporary ice sheets, and they play a key role in the dynamic behaviour and stability of ice sheets. As fast flow of ice streams takes place by deformation of soft subglacial sediments or basal sliding, dominant processes involved in ice stream behaviour are likely to be reflected in the geomorphology of ice stream beds and the character of underlying subglacial sediments. The beds of former ice streams (palaeo-ice streams) provide a more accessible source of information on the spatial variability of sub-ice stream processes than those of contemporary ice streams and may also reveal changes over longer time scales. Here we focus on major palaeo-ice streams that drained the former Fennoscandian Ice Sheet during the last deglaciation. The results are based on analyses of several marine geophysical datasets, including geomorphological
mapping from three-dimensional (3D) seismic data and multibeam swath bathymetry as well as analyses of seismic and acoustic stratigraphy. The results provide new insights into the configuration and dynamics of former ice streams in the southern Barents Sea during the deglaciation.

Pleistocene and Neoproterozoic glaciotectonics: the Great Breccia of the Port Askaig Formation, Scotland compared to Pleistocene glaciotectonic features of Norfolk

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The Port Askaig Formation in the Dalradian of Argyll is 750m thick and contains 47 diamictites separated by siltstone, sandstone, conglomerate and dolomite interbeds. Individual diamictites are up to 60m thick and normally contain stones up to 1-2m in size, but one – the ‘Great Breccia’ - is exceptional in also containing huge rafts, the largest measuring 320x64x45m. The rafts are of bedded dolomite (like the underlying Islay Limestone), of dolomitic diamictite (like the underlying diamictites) and of interbedded siltstones and dolomites. One raft contains within it a huge recumbent anticline. In the Garvellachs, the Great Breccia can be traced at the same stratigraphic level for 6km along strike across four islands. A horizontal section chart from there shows that there are at least 13 rafts with one diameter greater than 20m.

The origin of this remarkable bed has been debated. Shackleton was the first to propose a glaciotectonic origin (in Kilburn et al. 1965), making comparison with the Pleistocene glaciotectonic folds in the Chalk of Rügen in north Germany. I supported this interpretation – fitting with my ice-sheet explanation for most of the other diamictites – and drawing an analogy to the North Norfolk Pleistocene glaciotectonic features (Spencer 1971). This suggestion found favour with Benn & Prave (2006), but not with Arnaud & Eyles (2002) who proposed a submarine mass-flow hypothesis - as breccias derived from contemporaneous fault scarp failures - but gave no new supporting evidence and omitted opposing evidence. The poster illustrates aspects of the Great Breccia and compares, at the same scales, the horizontal section chart of the Garvellachs with a profile of the cliffs at Sheringham on the North Norfolk coast, which show glaciotectonic structures involving rafts of Chalk (Phillips et al. 2011).

Somebody else’s oil is in my beds – Triassic mudstones (Gråklint Beds), Jameson Land, East Greenland

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In petroleum geology there are source rocks and reservoir rocks. These roles are traditionally played by hydrocarbon-generating organic-rich mudstones and hydrocarbon-receiving sedimentary rocks with opportunistic porosity and structure. Conventional petroleum geology teaches us that source and reservoir are separated in time and space, as also are the processes of maturation and migration. But for unconventional hydrocarbon, locally generated oil and/or gas are retained in their own source rock, and are recovered by inducing fracturing of the shale with its dual source and reservoir roles. The logical assumption is that the in situ hydrocarbons belong to their hosting shale. Here we examine organic material in a lacustrine source rock, the Middle-Upper Triassic Gråklint Beds in northern Jameson Land, East Greenland. Three intervals of organic-rich mudstone with fine-grained silty intervals were acquired from the 10-meter-thick Gråklint section at Buch Bjerg. Sampling for Re-Os analyses followed AIRIE’s detailed stratigraphic approach: each data point on an isochron is derived from a few grams of material extracted from carefully targeted mm-scale laminae occurring within a few cm of each other. In this way, we use small-scale chemical variations to produce meaningful isochrons from very limited stratigraphic intervals. The practice of homogenizing up to 100 grams of shale from larger intervals to acquire an isochron blurs resolvable chemical variations and invites geologic misinterpretation.

Knowledge of source rock, timing of maturation, direction of migration, and layout of reservoir rock are essential to optimize exploration success. Biomarkers are an essential tool for linking migrated hydrocarbon to potential source rocks, but this approach may be compromised if the source rock hydrocarbon is modified. Our results for the Gråklint Beds show that source rocks can be reservoirs for others’ oil. Based on our Re-Os data, we conclude:

1) Hydrocarbon was introduced into Triassic rocks at about 130 Ma with a $^{187}$Os/$^{188}$Os ratio that is lower than any known ratios for Permian

2) Jurassic shales are the only known source rock in the region with \(^{187}\text{Os}/^{188}\text{Os}\) ratios (\textit{e.g.} Troms III, Norwegian shelf) low enough to serve as a hydrocarbon source at 130 Ma.

3) External hydrocarbon was again introduced into the Triassic Gråklint mudstones in one interval at about 85 Ma. Re-Os systematically relates both the 130 Ma and 85 Ma hydrocarbon events to the same source (Os in-growth precisely matches time lapsed).

4) A third migration event at about 15-20 Ma is captured in a clearly oil-stained interval.

5) 130 Ma and 85 Ma ages for hydrocarbon coincidence with changes in plate motions recorded by paleomagnetic data in the North Atlantic Ocean region. Co-supported by AIRIE Program, CASP, and Petromaks (NFR 180015/S30).

**Dissolved CH\(_4\) and H\(_2\) in hydrothermal plumes at Arctic vent systems**

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Recent discoveries of active vent fields at slow and ultraslow spreading ridges have revealed that hydrothermal activity in these areas is more common than previously assumed. In the Norwegian-Greenland sea two such vent fields are found, the Jan Mayen vent fields (71°N and 6°E) and Loki’s Castle (73°30’N and 8°E). Both these systems are located on the ultraslow spreading Mohrs Ridge, but they differ profoundly in the geochemical fluid and gas composition. The Jan Mayen vent fields show a fluid and gas chemistry representing a basaltic vent system, whereas the fluid circulation at Loki’s Castle is strongly influenced by sediments buried under the volcanic ridge. Analyzing the dissolved gas content in the corresponding hydrothermal plume provides insight into the composition of the vent systems host rock. Here we present an overview of dissolved hydrogen and methane concentrations in the water column above the two vent fields. The dissolved gas concentrations were determined shipboard by gas chromatography during 6 expeditions from 2007 to 2012. Thereby, significant differences in dissolved gas composition were observed. The water column above the Loki’s Castle high temperature vents was characterized by considerable amounts of both methane and hydrogen, whereas at the Jan Mayen vent fields the high rising plume was dominated by hydrogen. Elevated methane concentrations obtained close to the seafloor point to additional venting areas with diffusive fluid flow at the Jan Mayen vent fields. Water column investigations are a vital tool used to increase the knowledge on the prevailing fluid rock interactions in hydrothermal systems.

**Palaeosols and eogenesis of Triassic sediments from shallow cores at the Bjarmeland Platform and in the Nordkapp Basin, southwestern Barents Sea**

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Upper Triassic sediments of the Snadd Formation have been studied in three shallow drill-cores in the Bjarmeland Platform and Nordkapp Basin areas as part of former SINTEF drilling project and recently by independent master thesis work. Bugge et al. (2002) documented red beds and palaeosols in the uppermost part of the formation in two cores from the Nordkapp Basin. The sediments in core 7430/07-U-01 at the Bjarmeland Platform consists of coarsening up sandstone units capped by coal layers overlain by silty deposits containing various palaeosols in the lower part, and in the upper part, fining upwards sandstones grading to shales with thin coal beds, soils and root horizons. The red beds are characterised by colour-mottled horizons with grey, red, purple and ochre pigments, characteristic of ferruginous palaeosols. Several micro-textures typical of pedogenic profiles, \textit{e.g.} carbonate-coated grains, alveolar textures, circumgranular cracking and Microcodium have been identified in the polarization microscope. Coal beds are often associated with dark grey to black carbonaceous mudrocks reflecting high water table and reducing conditions during pedogenesis. The alternations between oxidised ferruginous palaeosols with carbonate
concretions and carbonaceous palaeosols most likely reflects variation in ground-water level. Oxidized palaeosols probably formed during low-water table while carbonaceous palaeosols were formed during high ground-water table perhaps in small pools on the delta plains. A coastal deltaic environment has been interpreted. The repetitive pattern of the successions is suggested to have formed as a consequence of autocyclic switching of lobes on the delta plain. A lower delta plain environment has been suggested for the coarsening upward units in the lower part of the core. The change to dominantly fining upward units combined with the lack of tidal influence in the upper part of the cored section may suggest a shift in depositional environments from lower delta plain to mid/upper delta plain.

Reference:

Provenance, age and tectonic setting of the Barrios Formation and Hirnantian glacial diamictites from northern Spain

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The Ordovician stratigraphy of the Cantabrian Mountain (northern Spain) hosts key-succession to understand climate changes during the Lower Paleozoic hothouse. Massive quartz-arenites are deposited during the lower Ordovician interpreted as rifted margin and passive margin deposits. At the top of these quartz-arenite, the Barrios Formation, volcanic ash appears. These thin beds are correlated with other deposits in northern Spain and dated into the Arenig. Our geochemical data point to volcanism related to extensional tectonic setting. These rock types are covered by diamictites, interpreted to be glacial deposits related to the Hirnantian ice age. Two different facies covering the quartz-pebble dominated diamictites: (i) quartz-arenites and (ii) thin dark shales. The latter are not enriched in TOC (< 0.4%) and deposited in oxygenated water. However, some authors argue for tectonic contacts between the quartz-arenites interlayered with the ashes and the topmost quartz-arenites.

The current interpretation of the basin evolution for the Ordovician deposits in northern Spain describes a mature passive margin after drifting away from northern Gondwana although the time of extension is debated. The interpretation of the diamictites as Hirnantian glacial deposits is also not beyond doubt and doubt the younger age of the uppermost quartz-arenites.

Therefore, this study likes to add new geochemical data for the succession and test if the diamictite shows trends to an-oxic depositional conditions monitored by geochemistry (see Young et al., 2000). We also will show U-Pb ages of detrital zircons to resolve the stratigraphic debate.

Reference:

Geologic controls on CO₂ injectivity and distribution in the Johansen Formation, northern North Sea

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In later years there has been broad attention towards finding permanent storage options for CO₂. The potential for storage in subsurface saline aquifers offshore the Norwegian coast is large, but common for many of these reservoir candidates is that geological data are sparse. The use of scenario models provides an efficient means of estimating the range of reservoir performances for a potential CO₂ storage site and for testing various injection strategies. This approach is particularly useful when there are uncertainties related to reservoir geometry, porosity and permeability distribution. Intra reservoir porosity and permeability are highly facies dependent, and the geological interpretation and subsequent interpolation of reservoir properties will be of crucial importance. In this study we have tested the effect of geological heterogeneities in the Johansen Formation, a sandstone aquifer underlying the Troll field some 30 kilometers offshore western
Norway. It is thereby located within fair proximity of the onshore gas power plants Mongstad and Kårstø, and has been suggested as a suitable candidate for CO2 storage by Norwegian authorities. In the case of Johansen Formation, a potential CO2 injection well should be located at a safe distance from the operating gas fields, which consequently implies areas without well control. From 3D seismic data predicting the existence and spatial extent of sandstone is possible to a certain degree, while intra-reservoir flow baffles such as draping mudstone layers and calcite cemented layers typically observed within the Johansen Formation are below seismic resolution. The number and lateral extent of potential reservoir flow baffles are dependent on the initial depositional setting, as is the facies distribution and thereby the porosity and permeability.

Based on interpretations of seismic data, wire line logs, core and cuttings samples, we have established a suite of scenario models for a potential injection area south of the Troll field, where top Johansen is found at 3 km burial depth. Using Eclipse 300 the distribution of CO2 is modeled for different geological settings; with and without the presence of pervasive draping mudstone layers, and with varying lateral extent of potential calcite cemented layers. The modeled area covers 10 x 15.8 km, with a thickness of 110 m at the injection point. Simulations were run with an injection phase of 30 years plus 200 years of migration. The results show that the presence of flow baffles not necessarily is a disadvantage as long as sufficient injectivity is maintained within individual sandstone bodies. In each scenario we aim to adapt a suitable injection strategy with respect to utilizing local effects such as the delimitation of gravitational flow, in order to distribute the plume within a larger volume and maximize the effect of trapping mechanisms (i.e. residual, stratigraphic, mineral and dissolution) as well as preventing unacceptable pressure buildup.

**A helvite - Nb,Y, As, rich amazonite pegmatite at Øvre Eiker**

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An exotic amazonite pegmatite is currently being studied, sitting in the Fossum Formation about 1 km west of the Eikeren Ekerite batholith. Ekerite is an alkali feldspar, quartz and arfvedsonite-rich rock. This amazonite pegmatite occurs parallel to the sedimentary stratigraphy and differs from other surrounding pegmatites and diabase dikes that cuts the stratigraphy in the area (Hurum et al. 1997). The pegmatite is only 6 meter long and up to half a meter thick, and show a zonation in grain size from the margin to the center. There are several fragments of metamorphic cambro-silurian rocks within the pegmatite. The Ekerite is dated to 217 ± 1 Ma by Rb-Sr isotopes (Rasmussen et al. 1988). The Fossum Formation surrounding the pegmatite is described as feldspar-cordierite hornfels related to the heating from intrusion of the Ekerite batholith. The pegmatite consists of a coarse-grained, subhedral, green microcline feldspar (amazonite), quartz and helvite. In addition tourmaline, løllingite danburite, phenakite, biotite, zircon, fluorite and Nb-Y-silicates occur. The largest amazonite and helvite mineral group crystals are up to 1 cm in diameter, the texture also show a zonation of grain size and is possibly related to migration of fluids. The mineralogy indicates that the residue melt has been sufficiently rich in B, As, Be, S, Nb. Thin sections and hand specimen show different generations of amazonite with varying degrees of bleaching, and especially a zonation next to the helvite and løllingite vein structures. Classification of the pegmatite within the system proposed by Cerny (2005) has not been successful due to unusual mineral composition. The high amount of arsenic and lack of lithium, as well as low p-T conditions puts this pegmatite outside currently established classification schemes.

A likely source for the pegmatite is from a fluid rich residual melt of the Ekerite. The amazonite is probably related to a late hydrothermal alteration of an ekerite-pegmatite with microcline.

References:


Eolian sandstones feature excellent reservoir properties, though the significance of structural and sedimentological heterogeneities in such rocks is not fully understood. In the current work we attempt to elucidate the role of such heterogeneities for the overall permeability structure and fluid flow properties of eolian sandstone reservoirs. To achieve this, we study eolian deposits of the Entrada- and Curtis formations of the Jurassic San Rafael Group in Utah, USA. Probe permeameter measurements of dune and interdune units show sedimentological permeability variations at a range of scales: between units, between dunes, between strata and also down-dip strata. Statistical analysis, using a three-way ANOVA test, of the data sampled from undeformed Entrada Sandstone shows that 55% of the total permeability variance is due to the down-dip permeability within foreset strata, 31% is due to variation between grainflow and grainfall strata, 12% is due to variation in permeability between dunes, and as little as 2% is due to instrumental error. Distribution and complexity of deformation structures at different scales in porous sandstones affects reservoir performance, and this study aims to integrate subseismic structures such as deformation bands in a reservoir model. The Moab Fault, an extensional fault with maximum displacement of approximately 200 m and a strike length of 45 km affects the studied units. In the damage zone of this fault, deformation bands are abundant, and we investigate the role of the deformation bands as reservoir heterogeneities. Structural- and permeability data were recorded in the footwall damage zone of the Barlett segment of the Moab Fault. In general deformation band frequencies are highest, and therefore have the highest effect on fluid flow close to the fault core. In detail, however, lithologic changes in the vertical direction within the Entrada Sandstone are the main source of variance for the deformation band frequency. The effects of the structural and sedimentological heterogeneities on fluid flow in the Entrada Sandstone are being explored by means of reservoir modeling, and results are here.

GENINO - database for geological units in Norway

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GENINO is the NGU database for geological units in Norway, build up in cooperation with the Norwegian Polare Institute and Norwegian Petroleum Directorate. The database contains information of more than 5000 geological units. It contains references to publications where the units are featured, and is therefore a literature database as well. Genino is publically available, and is developed and updated continuously. The database will contain all names on geological units and structures which is published in maps and scientific papers. It is a tool to maintain an overview over unit names in Norwegian geology, included Svalbard and the Norwegian shelf, and to obtain information about the registered geological units and structures. According to the Norwegian Stratigraphic Committee, geographical names that are already in use in geological publications should not be used on new units. Through GENINO it is possible to find reference to all maps and publications where the unit or structure has been defined, used or mentioned. Access the Genino database through the NGU homepage (www.ngu.no). Click on “Geology” → “Bedrock geology” → “Database for geologiske enheter i Norge” → “Databasen Genino” (below “Visit”, right side of the page). The form that appears may be used in different ways: it is possible to search by one or more of the listed attributes. A click on the maps attribute will provide a list with all available maps. A search on a specific map will give an overview of all geological units registered in the map area. A click on the unit name gives information about that specific unit. If the unit name is known, it is possible to search directly by using name only. The information that will appear below a unit or structure includes: 1) The different ways of spelling the name found in publications (including the English name), 2) References of the current definition and description of the unit, 3) First usage in the geological literature, 4) Geographical location, 5) Localities (type localities, and the link “punktmarkering”, which show the location of the unit on a geographical map) 6) Regional geological location, 7) Description of the unit, 8) The age of the unit, 9) Relations, 10) List of references.
Through GENINO, it is possible to check if a name is already in use. If the answer on a search for a specific name is "O geologiske enheter oppfyller det aktuelle søkerkravet", it means the name is not in use, and it is free to be used as a name on a new geological unit.

Evidences for syn-sedimentary faulting and folding at low stratigraphic levels in the Devonian Kvamshesten basin, western Norway

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Sedimentary units mapped in the northwestern part of the Middle Devonian alluvial-fluvial Kvamshesten basin display systematic thickness variations in the vicinity of folds and faults, showing that they were active during basin sedimentation. The syn-sedimentary growth can be demonstrated for both extensional- and contractional structures, pointing towards a complex basin evolution.

The SW-NE striking Grunnevatnet fault, which terminates against the extensional Nordfjord-Sogn Detachment, has an offset of 2 km at the southwestern basin-margin, and a few tens of meters along the northwestern margin. In southwestern parts of the basin, the thickness of conglomeratic units decreases towards the Grunnevatnet fault, which may indicate that the Grunnevatnet fault was a blind normal fault during deposition of sediments at low stratigraphic levels. Along the northwestern part of the basin margin, reverse faults are associated with fault-propagation folds and with an increase in stratigraphic thickness from hangingwall to footwall and internally in the footwall towards the fault. We have thus documented for the first time syn-sedimentary contraction in the basin at low stratigraphic levels. Combined with earlier work, this work gives a more detailed understanding of the internal tectono-sedimentary evolution of the hangingwall of the Nordfjord Sogn Detachment. Shortening of the basin seems to be more important for the geometry of sedimentary units than recognized previously. The growth of normal as well as reverse faults in the hanging wall of a regional detachment fault illustrates some of the complex interaction between active tectonics and deposition in the Devonian supradetachment basins in western Norway. These results support the interpretations that argue for the basin development during contemporaneous (S)E-(N)W extension and N(E)-S(V) compression.

Glacial and vegetation history of the Polar Ural Mountains in Northern Russia during the last Ice Age, marine isotope stages 5-2

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We here present a new reconstruction of the environmental and glacial history of the Polar Ural Mountains in northern Russia during the last glacial cycle. The reconstruction is based on sediment records retrieved from lakes, geomorphological mapping, cosmogenic nuclide (CN) dating and studies of sediment exposures. In particular, we attach much importance to stratigraphic data that were obtained from Lake Gerdizty, situated on the eastern foothills of the Polar Urals. Sediment cores from this lake basin contain two till beds below lacustrine sediments that according to a series of optically stimulated luminescence (OSL) dates accumulate during the last 65 ka. This record has been compared with OSL dated moraine lobes on both sides of the mountain chain as well as glaciolacustrine sediments on the lowland. We conclude that the mountain chain was covered by an ice cap complex during Marine Isotope Stage (MIS) 4 (78–60 ka) whereas small glaciers existed during the Last Glacial Maximum (LGM). During MIS 4 the northern part of the ice cap probably merged with the adjacent Barents-Kara Ice Sheet that reached onto the lowland areas on both sides of the mountain chain during this glaciation. During this glaciation the equilibrium line altitude (ELA) during was then at least 1200 m
lower than at present. The pollen stratigraphy indicates that the surrounding landscape was covered by an open tundra and steppe-like vegetation throughout MIS 3–2 (65–12 ka). The first significant change in the vegetation, shown by an increase of dwarf-shrub communities of *Salix* and *Betula*, took place at the beginning of the late glacial Bølling-Allerød interstadial at around 15 ka. A reconstruction of the climate and environmental changes suggest a very cold summer climate during MIS 4 and probably also during the earlier MIS 5b (95-85 ka) glaciation, presumably amplified by the existence of the large ice dammed lakes. A milder climate appears to have prevailed during MIS 3 (65–30 ka), but a treeless vegetation nevertheless suggest that mean summer temperatures did not exceed 10-12 °C.

**The Future's So Bright, I Gotta Wear Shades**

Svensen, H.

*Physics of Geological Processes, University of Oslo*

**Statement 1:** Geoscience is under-communicated to the Norwegian public.

**Statement 2:** Geoscience is the natural science that should be the easiest to communicate

**Statement 3:** We can do a lot better

In this presentation, I will go through these statements in light of my experience of writing non-fiction for a general audience since 1999. I will discuss some of the myths and challenges of popular science outreach, and how we as geologists can share our knowledge about Earth past, present, and future.

**The PETM and the role of NE Atlantic volcanism: New sediment data and thermal models for the Vøring Basin aureoles**

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The Paleocene-Eocene Thermal Maximum (PETM) is characterized by rapid global warming and ocean acidification correlated in time with the initiation of volcanism in the NE Atlantic at about 56 Ma. Both timely aspects (tuff and sill dating) and studies of degassing mechanisms and volumes support that the volcanism and associated contact metamorphism of intruded basins (such as the Vøring and Møre basins) can explain the initiation of the PETM. However, some publications the recent 3-4 years have focused on the role of astronomical pacing of the marine and terrestrial gas hydrate reservoir as the key mechanism behind methane release and hence the PETM. Here we present new borehole and modeling data from the Vøring and Møre basins that highlight the importance of sill heating in generating CH₄ and CO₂. We have compiled TOC and vitrinite data from more than 10 boreholes in the two basins and compare the values with new data from the Utgard aureoles (6607/5–2). The Utgard sill complex is a god representative of sills emplaced in Cretaceous sediments. We use a thermal model coupled with vitrinite reflectivity and methane generation from organic matter, and show that the sill emplacement had a major effect on the sediments. In the Utgard case, the thermal input from the sills led to over-mature conditions of significant sediment volumes (1.5 km stratigraphically) and widespread methane generation. We estimate the total gas produced around the Utgard sill complex and extrapolative this to basin scale. The new data and results stress that volcanic basins are still a main player for understanding the PETM, and may also have relevance for understanding other Eocene warming events (hyperthermals).

**Tectonic and depositional evolution of the Loppa High area, Norwegian Barents Sea**

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The Loppa High is a distinct structural element with the crest striking in a general north-south direction. The eastern flank is dipping towards the deeper areas of the Bjarmeland Platform / Ottar Basin. The mid-Carboniferous and younger sedimentary cover unconformably overlies a basement of folded and fractured strata over parts of the Loppa High and its northeastern extension towards the Maud Basin (herein informally called the Aurelia High). In well 7220/6-1 these basement rocks are dominated by quartzitic metasandstones of uncertain age. A correlation to comparable facies in the Late Precambrian Sørhamna Formation on Bjørnøya is suggested. Seismic examples illustrate how the tectonic events have left their depositional footprints in the sedimentary cover. The first event that is
discussed in more detail deals with how differential subsidence has determined the geometry of the carbonate platform that was established in the Loppa High area in Moscovian time. In the surrounding basinial areas thick deposits of salt and associated evaporites and carbonates accumulated. Seismic and well data suggest that the two main evaporitic events occurred in Moscovian and Asselian time respectively. The salt onlaps the flanks of the Loppa and Aurelia highs. Lateral to the salt pinch-out, several Barents Sea wells show that thick anhydrite beds were deposited. The salt has acted as a detachment for later tectonism, including large scale gravity gliding of the overlying sedimentary package. Close to the pinch-out area of the salt, the combined effects of rifting and uplift of the Loppa / Aurelia highs have caused this gliding to form distinct graben structures. Along the northern margin of the Aurelia High, this applies to the western extension of the Hoop Fault Complex (situated southwest of the Svalis Dome / Maud Basin). And along the Aurelia High’s southern margin the same mechanisms resulted in formation of the Swen Graben and its continuation along the eastern flank of the Loppa High. The tectonic events that triggered this gravity gliding and graben formation were most active in Late Jurassic and Earliest Cretaceous time. The rotated fault blocks with the Skrugard and Havis hydrocarbon discoveries were formed by the same tectonic event. West of the Loppa High continued and rapid subsidence led to accumulation of thick Cretaceous and Cenozoic sedimentary packages.

Importance of onshore-offshore relationships for regional stratigraphic development – examples from the Norwegian margin

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Recent methodological advances in landscape analysis, seismic acquisition, absolute dating of sediments and thermochronology has led to an increased interest in regional studies attempting to bridge the gap between landscape evolution and filling of sedimentary basins. The fundamental control on longterm landscape and seascape evolution is gravity, which dictates river gradients, transport efficiencies and grain-size filtering en-route to the offshore basins. On margin scale, rift-related topography may control regional distribution of drainage divides and sediment transport routes for several tens of millions of years after initial rifting and basin formation. More locally, basement structures such as faults and other basement weakness zones have the potential to focus sediments on similar timescales, thereby strongly influencing the lateral distribution of sediment along the margin. A good understanding of these controls may thus help making forward predictions on the temporal and spatial distribution of sedimentary facies in nearby basins.

The link between landscape evolution and basin fill can also be studied by analyzing the offshore stratigraphic record in a “backward” approach. The onshore-offshore link can be investigated by comparing offshore sediment volumes to expected or assumed areas of denudation, such as datable surfaces or other landscape elements. Such “backfilling” techniques have been attempted on timescales ranging from thousands to millions of years. A different approach is to apply scaling relationships derived from modern landscapes to the ancient sedimentary record in order to determine which type of landscape and topography that best explain the observed offshore stratigraphy. All methods are associated with uncertainties, most of which are related to basic assumptions that have to be made with respect to closure of sediment budgets and estimating areas of denudation and deposition.

Here we will show examples of some of the different techniques that have been applied to the Norwegian margin in order to better understand the onshore-offshore link in sedimentary systems. We will also demonstrate how stratigraphic analysis of seismic and well data offers direct clues to the late Mesozoic topographic evolution of southern Norway.

From orogenic collapse to Cenozoic uplift: the history of the Hornelen basin

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The Hornelen basin is the largest of the Devonian ‘Old Red’ sandstone basins in Norway, comprising 25 km of alluvial-fluvial deposits which are organized into basin-wide, coarsening-upward
megacycles. Hornelen sits with several smaller basins in the hanging wall of the Nordfjord-Sogn Detachment (NSD), a major extensional shear zone along which the deeply-subducted Western Gneiss Region was exhumed, following (ultra-) high pressure-Scandian metamorphism. These Devonian basins are interpreted to have been formed as supradetachment basins in the hanging wall of brittle detachment faults which are the upper-crustal expression of large-scale extension and deep-crustal exhumation along the NSD. The timing of the rise of the UHP WGR to upper crustal levels corresponds closely with the timing of the basins, which are constrained only by sparse trace-fossil assemblages to a mid-Devonian age, roughly 390 Ma.

The most general goal of this study is to obtain information about the rock units that were at the surface in the middle Devonian. Of particular interest is determining whether rocks of the WGR were exposed at the time, which would imply that the WGR core complex was already established as such. Information about which other tectonic units were at the surface at the time would also give a feel for the level of exhumation in the middle Devonian. More specifically to the Hornelen basin development, the study aims at testing the supradetachment model using a sediment provenance approach in conjunction with available geochronological data from the WGR. The supradetachment model implies a direct link between movement on the brittle detachment fault (and thus basin filling) and exhumation of the metamorphic rocks of the WGR. Again, being able to document a unique WGR detrital signature with a combination of zircon, titanite and white mica geochronology would have important implications for the basin development. Preliminary detrital zircon provenance data from Hornelen show a dominant population of Caledonian ages, with a probability peak at 436 Ma and a secondary peak at 423 Ma. These ages suggest a large contribution from late Silurian plutonic sources, but the youngest ages (409-430 Ma) are younger than any known plutonism and may represent partial melting of the WGR, or late Silurian-early Devonian plutonism from tectonic units that have since been removed by erosion. Initial 40Ar/39Ar detrital white mica data from the Hornelen basin mostly reflect known cooling ages from the overlying nappes (> 400 Ma), but a group of younger ages (392-398 Ma) match WGR cooling ages and represent the best evidence to date that parts of the WGR had reached the surface by the time of Devonian basin-filling.

An additional goal is to use low-temperature thermochronology (fission track and U-Th/He analysis) to constrain the burial/uplift history of the basin and to detect and constrain vertical movements on the northern and southern basin-bounding faults (which continue offshore into the northern North Sea).

Why is it so difficult to create a microcontinent?

Tetreault, J., & Buiter, S.

Advancements in geophysical and geological studies of passive margins have led to a drastic revision in nomenclature, structural architecture, and kinematic evolution of passive margins. The structural architecture of passive margins includes variably deformed regions of continental crust: microcontinents, continental fragments, extensional allochthons, and outer highs, separated by extremely thinned crust (Péron-Pinvidic and Manatschal, 2010). The smaller blocks (extensional allochthons, outer highs, and H-blocks) are a fundamental part of many passive margins, but the larger crustal blocks (microcontinents and continental fragments) are not ubiquitous with all passive margins. Microcontinents are rifted fragments of continental crust surrounded by oceanic crust, whereas continental fragments are flanked by oceanic crust and highly thinned continental crust. Microcontinents and continental fragments have continental crustal thicknesses that reflect very little thinning, as opposed to the surrounding regions or the smaller blocks. This variable crustal thinning observed in passive margin architecture can be easily explained with different structural kinematic models, but mechanical models (analog and numerical) of extension and rifting often result in uniform thinning in a single area. Previous mechanical modelling studies (analog and numerical) have successfully reproduced large scale features of passive margins such as general margin shape and initial rifting structure, as well as many crustal scale features including initial rifting structure, detachment faults, and rolling hinge faults. But the variable thinning and kinematic evolution of passive margins that produce continental fragments and microcontinents is not easily replicated. Numerical geodynamic models that produce relatively undeformed continental fragments during rifting need to include various a priori conditions (e.g. inherited weaknesses or plume interaction) in order to isolate these crustal blocks from regional thinning. Why is it so difficult to reproduce what is created naturally by nature? We will review the physical conundrums presented by the existence of microcontinents in thinned margins and present mechanical models.
that include structural inheritance, serpentinization, mantle underplating, and plume interaction in the context of microcontinent formation.

**Giving the geosciences teachers the tools to teach geosciences**

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Geosciences was introduced as a new specialization in the curriculum of the Norwegian high schools through “Kunnskapsløftet” in 2007. As for the other natural sciences as physics, chemistry and biology, high school students can now specialize in geosciences in their 2nd and/or 3rd year. Although it is optional for the high schools to offer this specialization, 1/3 of about 300 do so. Although some of the teachers have a major in one of its disciplines as geography, geology or meteorology, few if any, have their major in geosciences. Therefore at the time of introduction there were lacks of competence among the teachers as well as a lack of traditions in teaching this subject. How should geosciences be taught? Should it be taught in the classroom along with the traditions of other subjects, or could the high school premises be utilized more in this subject? Should the students be evaluated by traditional exams? Or, could one use other ways to evaluate their competence in geosciences? How could this new specialization draw the students’ attention to how natural processes are related to society through natural hazards and resource exploitation?

To strengthen the competence among the teachers in geosciences and through this motivate them to teach the subject, Naturfagsenteret started the “Geoprogrammet” in 2007. The goal of Geoprogrammet is to ensure a good reputation for geosciences among both teachers and students in such a way that teachers become confident enough to teach the subject and many students specialize in it. Department of Geosciences was invited to contribute to a part-time study program for geosciences teachers with four one-year courses at bachelor level with 60 credits. The courses address equal parts of geosciences as well as ways to teach and evaluate the students. The uniqueness of geosciences is often best experienced in the field. Nevertheless, within the daily high school tasks both time and expenses are limited. This is often used as excuses for not utilizing the possible outdoor activities. It is therefore important to give the teachers educational skills and tools so that they are able to acknowledge the different local geoscience specialties, geotope. Done right, this will give the students solid experiences in recognition of different processes in the field as well as important working strategy in studying geosciences. However, themes of more general geosciences character as the use of field diary and mapping are also covered in the syllabus in combination with other educational strategies as evaluation, debate and role play.

The last of the four one-year courses for high school teachers is being held now. And it is time to evaluate the program. Should it be given on a regular basis? What changes should be made? In the first two courses there were about 12 participants and in the third 20. Prior to these three quite some effort were put into recruitment whereas this last one reached the limit of 30 participants easily. The feedback received directly from the participants and through evaluation reports are splendid. The words of mouths are now announcing the courses leaving an easy recruitment job left to us. And in the fall of 2013 the first course will be given for the second time. This way we will keep up the momentum of making geosciences a part of the common knowledge and form a tradition in teaching geosciences in the Norwegian high schools based on educational skills and tools.

More about Naturfagsenteret (The Norwegian Centre for Science Education) and Geoprogrammet at www.naturfagsenteret.no and about the study program at www.mn.uio.no/geo/studier/evu/

**Formation of barite chimneys at low-temperature hydrothermal venting: evidence for complex geobio-interactions**


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A low-temperature (20°C) venting area with active and extinct barite chimneys are located on the flank of the hydrothermal mound of Loki’s Castle black smoker field at the Mohns-Knippovich
bend in the Norwegian-Greenland Sea. The active barite chimneys are covered by white mats of abundant microbial cells and extracellular material together with small barite crystals. Within the chimneys microbial cells are partially embedded in barite and crystals are covered by extracellular material. These observations indicate that the microbial biomass serve as a substrate for nucleation and precipitation of barite with the potential of playing an important control on the construction of the chimneys. In addition, the presence of framboidal pyrite in black interior flow channels and in underlying hydrothermal sediment suggests that the chimney formation is linked to microbial sulphate reduction (MSR).

To further investigate the relationship between chimney growth and microbial activity we used a combination of biomolecular and isotope analyses. Pyrosequencing of amplified 16S rRNA genes followed by taxonomic classification reveal that sulphide oxidizers (Sulfurimonas) within the Epsilonproteobacteria dominate the microbial mats and the barite chimney wall. In the black interior flow channel a more diverse microbial community was observed indicating methane, sulphur and ammonia oxidation as well as heterotrophic processes. Multiple isotope analyses ($\delta^{18}O$, $\delta^{34}S$, $\Delta^{33}S$) reveal that the barite chimneys precipitated from a fluid that was modified by subseafloor MSR in the sulphide mound. This is supported by the sulphur isotope signature of the framboidal pyrite, pore water, and mono- and disulphides extracted from the hydrothermal sediment as well as the biomolecular data. We suggest that the MSR was triggered by mixing of the $H_2$ and $CH_4$ rich high-temperature ($320^\circ C$) fluids and percolating seawater, which resulted in remobilization of hydrothermal barium deposited as debris and plume fall out in the mound. The combined results strongly suggest that the formation of the barite chimneys is a result of complex seafloor and subseafloor geobio-interactions.

Ecosystem based management of the oceans requires sound knowledge on the geographic distribution of the benthic habitats and ecosystems. Bathymetric and geological data are important sources of information for characterisation and spatial delimitation of the boundaries for these habitats. Geology (including geomorphology) and oceanography are the two most important abiotic factors defining the benthic ecosystems. Spatial documentation of geology and oceanography is therefore a requirement for ecosystem based management.

The MAREANO programme started in 2005, and is funded by the Norwegian government (86.4 mill. NOK in 2012). It has so far documented 90,000 km$^2$ of seabed by mapping bathymetry, sediment types, habitats and biotopes, biodiversity, as well as seabed pollution in Norwegian coastal and offshore regions. The work in MAREANO is done by the Institute of Marine Research (marine biology), the Geological Survey of Norway and the Norwegian Hydrographic Service. The results from the programme feed directly into documents and reports which contribute to decision support for the government.

The area studied in 2005-2012 encompasses continental shelf, slope and deep water areas and includes many extreme habitats including shelf-edge canyons and submarine slide scars. Some of the world’s largest cold water coral complexes occur in this area. Geological features include a narrow, glacially shaped continental shelf outside Lofoten-Vesterålen, a wide continental shelf in the Southern Barents Sea, a continental slope extensively eroded by canyons and submarine slides, and a continental rise with large submarine fans. Cold seeps and gas flares occur locally; high geodiversity forms the basis for a rich biodiversity. Ship-borne multibeam data (including bathymetry, backscatter and water column data), is a major source of information for MAREANO, but recently Autonomous Underwater Vehicles (AUVs) equipped with Synthetic Aperture Sonar (SAS) have been tested in related projects an offer a promising new method for wide area detailed mapping. These data have shown very interesting results and the possibilities for wider use of these new techniques will be discussed.

**Growth and linkage of a salt-influenced extensional fault array:**

**Egersund Basin, Norwegian North Sea**


Geological Survey of Norway (NGU), P.O. Box 6315 Sluppen, 7491 Trondheim, Norway

The oceans are major sources of wealth.

**The MAREANO programme in Norway – the role of geology in integrated mapping for ocean management – from deep sea corals to giant submarine slides**


Geological Survey of Norway (NGU), P.O. Box 6315 Sluppen, 7491 Trondheim, Norway

The oceans are major sources of wealth.
In this study, we illustrate the structural style and growth history of a fault array in response to salt-mobilization by the use of 3D seismic reflection and well data from the Egersund Basin, Norwegian North Sea. The studied thin-skinned NE-SW striking normal fault array (c. 16 km long and approximately 6 km wide) developed in response to the growth of a low-relief salt pillow. General mapping, geometric analysis and fault displacement analysis reveal differences between the fault evolution in the southern part of the area where salt is thick, and the northern part, where salt is thin or depleted, in terms of geometry, timing and fault linkage or coupling between faults in the subsalt section and the cover. Present-day throw distributions suggest both lateral and vertical growth and linkage. Furthermore, the intricate but systematic style of displacement and growth suggests a staged evolution of: (1) initial syn-sedimentary fault growth during the late Triassic-middle Jurassic contemporaneous with growth of a salt pillow to the west, and (2) subsequent fault initiation at a shallower level contemporaneous with remobilization of the salt, with downward fault propagation and linkage with pre-existing stage 1 faults, resulting in reactivated fault surfaces in the late Cretaceous-early Tertiary. Based on the three-dimensional displacement analyses we conclude that salt mobilization controls the development of the fault array, where reactivation only occurs where salt is not depleted. A close connection is observed between pre-salt (sub-salt) fault occurrence and the localization of shallower faults formed during salt mobilization, showing that strain was largely transferred through the salt layer during the fault development.

Three-dimensional seismic data has provided important insights into the development of salt-influenced normal fault arrays; in particular we will highlight the lateral growth and linkage and the importance of dip linkage and blind fault reactivation. Comprehensive three-dimensional fault displacement analysis is therefore important, capturing a level of detail in displacement distribution and fault history that would otherwise be lost.

Garn Formation Depositional Model: Implications on Exploration and Development of the Zidane discovery and the outer Norwegian Sea area

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RWE Dea Norge AS

The Zidane gas discovery in PL435 is located between the Victoria discovery and Heidrun Field on the Halten Terrace, Norwegian Sea. The Zidane structure consists of two closures divided by a salt collapse graben. In 2010, the 6507/7-14S discovery well targeted the eastern structure, proving a 160m gross gas column in a Jurassic tilted fault block. The 6507/7-15S discovery drilled in 2012 targeted the western structure and proved a 180m gross gas column in a horst block. The hydrocarbons occur within the Garn and Ile Fms.

The Garn Fm is the primary reservoir in Zidane. It's generally considered to consist of tidally influenced upper shoreface sediments. However, recent sedimentological findings suggest a more fan-delta influence. Mineralogical studies indicate that the Garn Fm provenance is from a western, Greenlandian source area. Several extensional pulses affected the area during the Middle to Late Jurassic. Before the opening of the Atlantic Sea, Greenland was closer to Norway and sand provenance from the west was as likely as from Baltica in the east. The landscape, and hence the depositional environment, must have been more complex than only a narrow strait between the Greenlandian and Baltician hinterlands. Local highs and valleys, of significant size, may have acted as both sediment sources as well as barriers for deposition. Interestingly, the development of the Jurassic succession at East Greenland is remarkably similar to the Jurassic of the Norwegian Sea.

A change in thickness, depositional style and grain-size is recognized within the Garn Fm. The formation is particularly thick in some NW wells, and it also contains some rather coarse intervals that might represent a pebbly beachface. These observations, together with a slight change in overall depositional environments from beach and upper shoreface with subtidal channels in the west (including the Zidane area) to more sand wave and sand bar dominated in the east, indicates a western sand source. This is also supported by more marine incursions in eastern locations. From image logs, a steep and uniform eastern dip is observed in the wells, indicating a clinoform-shaped deposit from west to east. Hence, the Garn Fm, at least in the Zidane...
area, might be more of a fan-delta than a broad shoreface shelf.
The lowermost, coarsening-upward, part of the Garn Fm displays some pronounced high-gamma peaks derived from heavy minerals like garnet and zircon, probably deposited as a result of storm surges. Mapping the magnitude of these high-gamma peaks creates a pattern of lobes that reduces in magnitude towards the SE, indicating a W/NW source. Combined geochemical and isotopic data on samples from the Garn Fm result in similar provenance signatures, further supporting a common Greenlandian western source for these sands.
Combining sedimentological observations and sand provenance suggests that the Jurassic Garn Fm in the greater Zidane area must have been sourced from the west, rather than from the east, when Greenland was closer to Norway. For further exploration, this implies higher potential for reservoir sand in western areas e.g. the Utgardhøgda and Møre West.

Quantitative analysis of the erosional shapes of the high latitude margins

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Spatial relations are abstractions that help us to understand how the objects are related to each other in a real world. Within the geographic/geologic context, geometry and topology are crucial concepts in the spatial data analysis and in the determination of spatial relationships between objects. In this study we investigate types and forms of the relief along the shelves of North America, Ireland and North-West Norway. We use methodologies that relate spatial distribution of seascape features by integrating computational geometry and quantitative geomorphology. Differences in canyon morphology are related to properties of the land-to-sea connection, shape, curvature and gradient of the margins, as well as the competence of the sediment transport mechanism with distance from source. We discuss the classification of slope morphology and consequent erosional and depositional processes which contribute to the formation of typical features of the high latitude submarine systems.

Sunnfjord Geo Consulting AS – a company that delivers geohazard assessments and disseminates geology

Vie, E., Alsaker, E., Alsaker, S.L., Queck, O. & Nesje, A.

For a geologist, the Sogn og Fjordane region is like an open textbook of Caledonian metamorphic rocks, Devonian basins, Tertiary valleys, Quaternary deltas and the work of past and modern glaciers. The county is also so close to the Mesozoic oil and gas rich formations on the Norwegian continental shelf that some drilling installations are observable from land. Despite this, the geoscience environment in this part of Norway is more-or-less absent. In this regard we established Sunnfjord Geo Consulting (SGC) in 2012. Our vision is to become a central disseminator of knowledge in the region, with strong links to the academic environment, primarily the University of Bergen. Already, we are actively arranging excursions to localities in the area close to our office in Stongfjorden in Sunnfjord, Sogn og Fjordane. Among them, the most famous excursion site is the mountain Brurastakken, where it is possible, within a few hundred metres, to walk through 1.1 billion years of geological history.
SGC is also a company with commercial ambitions, aiming to become a leading operator in the market of geohazard evaluation in Western Norway. We are regularly producing risk assessments/evaluations of rock falls, debris flows, and snow/slush avalanches in Western Norway. Our customers are both governmental and private. [This is a growing industry in a region with wilder climate and public focus on the mighty forces of nature.]
On a longer term, we will use our competence and contact network to expand the business to deliver consultants for the petroleum exploration industry, and hopefully also the CO2-storage industry. The aim is to employ geologists with a broad spectrum of geological experience.
Exploration Success: A Consequence of Access at Scale and Leading Capabilities

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In recent years, there has been a surge of new hydrocarbon discoveries of substantial size on the Norwegian Continental Shelf as well as internationally. The new discoveries, including Skrugard and Havis in the Barents Sea, Johan Sverdrup in the North Sea, as well as offshore East Africa, have come as a response to two key factors: (i) ability to access new offshore acreage with high potential early, and (ii) possession of leading capabilities in terms of technology and knowledge in terms of successful analysis of petroleum systems. Early access of new prospective acreage is critical to future exploration success of substance. On the Norwegian Continental Shelf, access possibilities are limited in a global perspective, yet many new opportunities exist. New and improved geophysical technology is a driver to exploit existing accessed acreage better, but opening of remaining areas with potentially prospective sedimentary successions is a driver for sustainable growth of resources and reserves of hydrocarbons. Internationally, many such regions and basins with potential for high-impact discoveries remain untested, but access to such acreage is extremely competitive and also dependent on cooperation with national oil companies. Leading capabilities in terms of having the best geophysical technology as well as the best geological knowledge are essential for exploration and exploitation of hydrocarbons. Seismic imaging and interpretation remain critical geophysical success factors, but to an increasing degree other technologies such as leading drilling and production capabilities are vital to both access, explore and exploit new areas in a safe and sustainable way, not least in Arctic regions. Furthermore, companies to larger degree access acreage on generic and specific geological knowledge and insight of petroleum systems. The race of acreage is extremely competitive, and several companies access new territory before high-quality seismic has been collected to benefit from lower cost requirements.

CO₂-mineral sequestration and the potential for economic by-products

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There has been a lot of research development in recent years of different types of leaching techniques (acid leach, alkaline leaching, hydrobio leaching etc.). Most of this research has focused on leaching of sulfides and oxides for metal extraction. At the same time, there has been a lot of research taking place on CO₂-mineral sequestration, which has enhanced the understanding of mineral leaching in general. CO₂-mineral sequestration focuses on silicate minerals that release elements that can form (Ca, Mg, Fe) carbonate minerals for permanent CO₂-storage. Silicate minerals show a very large range of reaction rates, where olivine is one of the most reactive silicate minerals. The reaction rate of olivine is quite high. However, a common obstacle is that secondary minerals form on the surface of the olivine and inhibit a continuation of the high reaction rate. To maintain a high reaction rate, therefore, high pressure and temperature is implied. The release of CO₂ from combustion of fossil fuels and from industrial processes such as cement production, roasting of ores, and steel production has gained much interest in recent years due to the influence of CO₂ on the environment and effects such as global warming. Many of the sources of CO₂ such as emissions from power plants comprise only a few percent CO₂ and accordingly huge emissions volumes have to be managed to separate the CO₂ formed during combustion. Much focus has been on methods for CO₂ capture using liquid absorbents. These processes, so far, have had a high energy demand and have resulted in a CO₂ stream for which permanent storage or reuse has to be secured in a secondary process. However, the increasing focus on CO₂ emission as a tradable commodity opens opportunities for utilizing the emission gases for mineral leaching not only for CO₂-mineral sequestration, but also for element extraction. The natural sequestration of atmospheric CO₂ in mine wastes has been studied with the focus to document the sequestration with respect to the total carbon dioxide impact of the mining process. The natural occurring passive reaction
between atmospheric CO₂ and mine tailings may result in a reduction in the overall CO₂ impact of the mining. Natural sequestration of CO₂ is facilitated by silicate mineral weathering and carbonate precipitation, taking place *in-situ* in soils and rocks e.g. caliche, and *ex-situ* in oceans in soils e.g. limestone formations. It is necessary, as described above, to dissolve (or alter with element release) minerals in order to achieve mineral CO₂ sequestration. When these mineral dissolve, there may be elements released that can form economically valuable products, e.g. calcite (CaCO₃), magnesite (MgCO₃), silica (SiO₂), and nickel. Different rock types will have different leaching potentials depending upon both the reaction rate of the minerals and the mineral chemistry. Carbon dioxide is then used to precipitate Ca, Mg, Fe carbonate minerals. Olivine rich rocks (dunite) may be iron or magnesium rich with little or no calcium, but with potentially high concentrations of nickel. Pyroxene and amphibole rich rocks have lower reaction rates than olivine, but may have relatively high calcium content in addition to iron and magnesium. Anorthite rich rocks (anorthosite) have high calcium and aluminum content but little or no magnesium and iron. Carbonic acid has been shown to be effective for long-term leaching for actinolite and carbonate minerals and with electric pulse aided reactions under low temperature and pressure. Further research is necessary for developing economically viable methods or processes for using CO₂ as a leaching agent at atmospheric conditions.

**Characterization of the hydrogeological and geochemical processes in waste rocks are essential for effective reclamation**

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Tailings and waste rocks are the end products of a waste stream from sulfide containing ore deposits that can generate acid/neutral rock drainage (A/NRD) in considerable quantities. Fine-grained tailings have a large surface area available for mineral reactions. The fine grained materials, however, tend to have low conductivities and correspondingly low oxygen and water flow rates which reduces the availability of reactants and transport of products. Waste rocks are generally coarse grained and have less surface area available for mineral reactions than tailings. On the other hand, waste rocks have high conductivities, which results in greater availability of oxygen throughout the waste rock pile and easy transport of products to the toe/bottom of the piles. In a semiarid climate, where the waste rocks are typically unsaturated, there are three flow systems that should be evaluated: 1) matrix flow, which occurs within the fine grained matrix located between the larger particles; 2) micro flow, which is flow in and out of particles due to wetting and drying cycles and oxygen diffusion due to sulfide oxidation consumption; and 3) macro flow, which occurs between the larger particles (gravels and boulders) and through channels in the piles. These three flow systems play different roles in the mineral reactions and transport of constituents to the base of the pile. Mineral reactions in the matrix are comparable to those in tailings except the quantities associated with the matrix are relatively small. Depending upon the mineral makeup, neutralizing reactions by silicates may take place within the matrix within the micro system because of longer water residence time than for the macro system. Within the micro system, due to capillary forces, constituents can be transported to the surface of the larger particles. These constituents can then be transported within the macro flow system, often in response to rainfall, and arrive at the base within hours. However, only a fraction of the rainfall will arrive at the base of the waste rock as much can be retained by the matrix. The knowledge about the flow system within the waste rock piles can be utilized for remediation/reclamation of the piles. For example, a finer grained cover on top of coarse waste rocks can act as a capillary barrier, with high moisture content in the cover compared with the underlying waste rock. If water moves through the cover, most of this water will be retained by the waste rock matrix. This will result in relatively stable moisture content within the waste rock pile and constituent transport by wetting and drying cycles will be reduced, hence a reduced mass loading to the base of the waste rocks piles. These results will be compared to the Norwegian wet climate and waste rocks from massive sulfide deposits.

**The search of on-shore equivalents for reservoir chalk in the North Sea: Rare Earth Elements, δ¹³C and δ¹⁸O isotopes as indicators?**

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In the search of an on-shore equivalent of reservoir rocks for hydrocarbon deposits of the North Sea we studied 5 chalks successions of similar ages (Campanian-Maastrichtian) using trace element geochemistry and C-O stable isotopes. The on-shore chalk (n=45) has been sampled in Kansas (USA), Liège and Mons (Belgium), Aalborg and Stevns Klint (Denmark) selected by comparable porosities to reservoir chalk. Earlier studies based on petrography, petrophyics and mineralogy (XRD) argued for Liège (Hjuler and Fabricius, 2009) as the most comparable chalk. Off-shore chalk was sampled from the Tor and Hod Formations at Ekoﬁsk, Brynhild, Enoch, Sleipner and Jotun ﬁelds. Off-shore samples show δ13C values (n=42) mainly between -3.5 and -6 and are therefore more negative than secular values, while δ18O are in the range of the values for primary Upper Cretaceous seawater. The latter accounts as well for sampled on-shore chalk. In contrast, all on-shore samples, but some from Kansas, show primary δ13C values. However, clay minerals found in the chalk of Kansas display signiﬁcant higher diagenetic grades than those in the chalk of Liège, hence point to a different diagenetic history, which might have affected the O-isotope composition.

Rare earth element concentrations (REE) in on-shore chalk show ranges of Y/Ho ratios between 34 and 52 or even as high as 60 (Mons). REE pattern are similar to typical seawater. The clastic input (measured by Zr and Rb concentrations) is the lowest at Mons and Stevns Klint (≤1%), while samples from Kansas are very variable (≤1-3%), and the highest in chalk from Aalborg, which may have disturbedREE pattern and decreased Y/Ho ratios. Clastic input in off-shore chalk is comparable besides very few samples. But Y/Ho ratios are generally lower in the latter with only few samples higher than 40 and REE patterns are enriched in middle REE in comparison to typical seawater, and the on-shore samples. Combining C-O isotope analyses and trace element geochemistry, we can state that off-shore chalk has been affected by either higher diagenetic overprint than the European comparable chalk deposits or/and by a different secondary ﬂuid ﬂow, which disturbed REE concentrations and δ18O values, but not by a higher clastic input. This shows that further geological studies are necessary to understand reservoir chalk when testing on-shore chalk.

References:


Norwegian geology as a predictor of indoor radon concentrations

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Exposure to radon is estimated to be responsible for several hundred lung cancer cases each year in Norway; it is therefore important to identify areas prone to enhanced indoor radon concentrations, and to understand the geological factors influencing these increased exposure levels. An earlier study by Smethurst et al. (2008) in south-east Norway used a database of indoor radon measurements to investigate the relationships between high indoor radon concentrations, bedrock, drift geology, and airborne gamma ray spectrometer survey data. The work resulted in the production of radon hazard maps which showed where each data set suggested elevated radon levels and gave a very broad indication of the areas most prone to radon contamination. The statistical signiﬁcances of the relationships between geoscience data and radon measurements were not tested and therefore the maps were speculative in areas where indoor measurements were few or absent, thus limiting the usefulness of the hazard map as a tool for informed decision making.

This presentation describes an active study attempting to better constrain the relationships between geological phenomena and indoor radon concentrations by utilising Norway’s newly enlarged database of georeferenced radon measurements. The database contains measurements from all of mainland Norway and of these 26887 are georeferenced and from living rooms or bedrooms on the lower ﬂoors of residential buildings. We are relating these to a national digital bedrock geology map at 1:250,000 scale and digital drift geology maps at 1:50,000 and 1:250,000 as
available. The use of geological factors as indicators of radon hazard is particularly important in Norway because of the wide dispersal of its population and irregular distribution of comparatively few available indoor radon measurements. We apply statistical tests to investigate the power of mapped bedrock and drift geology as indicators of increased probability of elevated indoor radon levels. Simple classification schemes are used to study the potential of using geological factors alone as predictors of elevated radon levels in areas where little or no indoor radon data are available, and we use these classification schemes to produce a national geologically-controlled radon probability map for Norway. We attempt to quantify the confidence levels of our radon probability map, and we discuss the applicability of our approach to practical radon protection.

References:

A New Deformable Plate Model for the North Atlantic Provides a New Perspective on the Hyper-extended Basins of the Norwegian Margin

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A new deformable plate model for the North Atlantic between Norway and Greenland provides us with fresh insights into the geological evolution and hyper-extended basins of the Norwegian margin. This project was focussed on the development of the Norwegian margin using seismic and well data provided by Idemitsu Petroleum Norge.

The final breakup of Norway and Greenland appears to have taken place at about 20 Ma (Early Miocene). The relative movement of Greenland to the Barents Shelf can be modelled accurately during this period of major transtension on the De Geer Megashear. Our deformable plate modelling provides evidence for very high beta factors along the NE Greenland – Barents Sea margin in the period Early Eocene to Early Miocene when large areas of the outer margin have beta values of greater than 2 just for this period. These high levels of extension were superimposed on earlier extension in the Mesozoic and Carboniferous, resulting in the hyper-extended margin we see today.

Paleocene magnetic anomalies in the North Atlantic and Labrador Sea (chrons C27-C24) provide reasonable control for calculation of Euler poles of rotation defining the relative movement of Greenland and Norway. Using these Euler poles to model the plate movement of Greenland relative to the Voring-Lofoten margin in combination with maps of total crustal thinning from 2D flexural backstripping and gravity inversion modelling, we have estimated the amount of mid-late Paleocene pre-breakup extension (~57 to 54 Ma) that occurred across the margin. With the subsequent removal of the effects of this late-stage extension and the restoration of the pre-volcanic basin geometry, the 57 Ma plate tectonic reconstruction in our study provides us with a more accurate picture of the margin at that time. The mid-Paleocene reconstruction clearly shows for the first time the relative position of the Danmarkshavn Ridge on trend with the NE part of the Voring Marginal High. The amount and direction of earlier Paleocene and Mesozoic stretching has also been calculated and the effects incrementally removed to produce a series of reconstructions to 150 Ma. The deformable model shows that the axis of stretching migrates towards the COB, from rifting to continental break-up, with large amounts of stretching at the continental margin immediately prior to breakup. In the deepest part of the Bjørnøya Basin beta factors of over 3 are produced by a Late Jurassic (150 Ma) rift event. This contrasts with beta factors of about 2 in the Hammerfest and Nordkapp basins to the east which are typical of a normal rift basin. The high beta values in the axis of the Bjørnøya Basin are therefore interpreted to be a hyper-extended basin that formed in the Late Jurassic - Early Cretaceous. The hyper-extension basins stretch from the West Orphan Basin in Newfoundland to the Bjørnøya Basin, passing through the Voring Basin and Thetis Basin in NE Greenland. The Late Jurassic reconstruction shows the relative position of the Barents Sea and NE Greenland margins prior to the basins being hyper-extended. The Veslemøy High and Danmarkshavn Ridge are aligned in the Late Jurassic which leads us to believe that they have a shared tectonic evolution. The extent of the Upper Palaeozoic salt basin can also be mapped prior to hyper-extension. The Palaeozoic basin extends SW to NE from the Danmarkshavn Basin to the Nordkapp Basin in the Barents Sea, with the apparent offset seen in rigid plate models being removed in the deformable plate model.

Hyper-extension must have resulted in removal and erosion of much of the potential pre-rift...
source rocks in these basins although preservation should still be possible locally and on the basin flanks. Deformable plates modelling helps to predict the likelihood of source rock preservation and location of likely reservoir fairways. It has also provided information on beta factors and crustal thinning for the major tectonic events in the Late Jurassic and early Cenozoic which can be used to estimate heat flow.

Sedimentary basin formation and evolution along the SW Barents Sea margin

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The SW Barents Sea margin hosts several deep sedimentary basins which formed in response to various episodes/regions of lithospheric deformation. During several phases of rifting from the Late Jurassic to Early Cretaceous, deep sedimentary basins like the Bjørnøya, Tromsø and Sørvestsnaget basins developed. As typical syn-rift wedges are generally absent in most of the deep basins, it is believed that extension here was not accommodated by rotation of fault blocks. Instead, our data infer rapid differential subsidence centered on the basin axes. Locally, the subsidence was further enhanced by salt diapirism. The Harstad Basin, on the other hand, accommodated Cretaceous sediments with space created by westward tilting of the Jurassic strata. The Harstad and Sørvestsnaget basins were then overprinted by a Late Cretaceous megashear zone which extended through the Vestbakken Volcanic Province to the Wandel Sea Basin located in NE Greenland.

This megashear was finally torn apart during the continental break-up and initial sea floor spreading in Eocene, shaping the region into what we now regard as the mainly sheared SW Barents Sea margin. Rifting and volcanism at a releasing bend in the margin SW of Bjørnøya gave rise to the Vestbakken Volcanic Province (VVP). To the south of VVP is the Sørvestsnaget Basin that is bounded on its west by a prominent marginal high. Detailed mapping reveals that this basin can be further divided into three parts: (1) the northern part composed of Eocene pull-apart structures, (2) the central part which is similar to its northern counterpart but disturbed by almost coeval salt diapirism and, (3) the southern part which shows very subtle evidence of break-up relative extension but strong folding of pre-Eocene strata.

Our structural map also demonstrates strong along-strike variation of the continent-ocean transition associated with the Senja Fracture Zone. From 71°20’ to the north, the amount of uplift and width of eroded zone of the marginal high gradually diminishes with increase of latitude. To the south, the marginal high maintains a relative uniform geometry until it reaches a jump at 70°38’. The area south of this point is characterized by break-up related intrusions and a more landward position of the margin. Around 69°50’, the marginal high fades away and gives way to structures related to the oblique rifting which dominated the Lofoten-Vesterålen margin.

Further studies are needed to resolve the origin of such strong margin segmentation and the complex interplay between shear and rift structures, as well as the nature of the contractional deformation along some of the margin segments. These studies will also provide updated constraints for plate reconstructions and correlations to the conjugate margin offshore NE Greenland.

Compaction and rock properties evaluation of sedimentary rocks situated in the Southern Viking Graben based on well log data

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Physical rock properties such as total porosity, bulk density and velocity change with depth as a result of compaction processes. Investigating compaction trends with depth can yield valuable information about rock properties in sedimentary basins which can be applied for exploration and production purposes. In addition, rock physics analysis can link between geological characteristics and geophysical observations of the medium. It provides distinguishing variations in static and dynamic geological parameters from changes observable in acoustic properties obtained from seismic or well log data. The seismic properties are influenced by mineralogy and textural properties of rocks such as grain size, grain shape and sorting. Furthermore, cementation may take place in sediments at higher temperatures. It stiffens the rock and usually changes the rock physical properties substantially. The objective of
this paper is to diagnose the rock properties and studying their changes as a result of textural variations using well log data.

A normally subsiding basin where no major uplift and erosion of sediments has occurred is a suitable candidate to study compaction trends. The area of study covers the southern part of the Viking Graben basin located in the northern North Sea area. This basin was developed in the Middle to Late Jurassic time. This was followed by thermal subsidence and sediment infill since the Cretaceous. The dataset includes well log data of 53 wells located in Quadrant 15. The well logs were evaluated petrophysically to calculate porosity, clay volume and fluid saturation. Sedimentary facies were categorized based on estimated shale volume where a shale volume less than 25% were assumed to be clean sandstones while, facies with shale volumes above 75% were assumed to be pure shales. The results show a direct relationship between lithology and velocity where an increasing trend of velocity corresponds to decrease in clay content. Furthermore, rock physics templates reveal that changes in physical properties of the deeply buried reservoir rocks located in the southern part of the investigated area are more related to textural variation in the sediments, whereas, in northern part of the study area cementation is the key factor explaining the pronounced variation found in rock properties especially P-wave velocity. In addition, the impact of textural parameters like grain size on the rate of cementation can be evaluated since the cement distribution is a function of the present day thermal gradient distribution and rock textural variation in the study area.

An experimental study of the formation of H2, CH4 and N-species during low temperature alteration of ultramafic rocks

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H2, CH4 and NH4 are chemical species utilized as electron donors by chemolithothrophic microorganisms that may be important for subsurface endolithic communities. Production of H2 through serpentinization of olivine and pyroxene in ultramafic rocks, followed by reduction of CO2 to CH4, are well known to occur at higher temperatures. The knowledge of these reactions at low temperature conditions, and the effect of Fe(II)-containing secondary minerals such as brucite and serpentine, are however limited. In this experimental study we explore the formation of these species during low temperature (25°C) reactions between deionized water and dunite from different continental sites that vary from 1) unaltered, to 2) medium altered dunite, and 3) highly altered dunite.

The results reveal that H2, CH4 and NH4 were formed in all three setups. The highly altered rock gave the highest H2 concentration and the medium altered dunite the highest CH4 concentrations. We suggest that formation of H2 is the result of reduction and splitting of water due to oxidation of Fe(II) released from 1) olivine in the unaltered dunite, 2) a combination of brucite, olivine and possible serpentine in the medium altered dunite, and 3) brucite and serpentine in the highly altered rock. The detected CH4 have the following possible sources 1) Fischer-Tropsch type (FFT) reaction where dissolved inorganic carbon is reduced to CH4 in the presence of a catalyst, and 2) dissolution of CH4-containing fluid inclusions. Detection of NH4, NO3 and NO2 indicate that N-species absorbed at the seafloor-alteration stage are leached out from the altered dunite during the experiment. For the unaltered dunite the source of N-species is most likely the explosives used in the mining process. The results indicate that water-rock reactions in moderately to highly altered ultramafic rocks may provide reduced species that can be utilized as electron donors by microbial communities in subsurface environments. These low temperature processes could play an important role particularly in ophiolites and near seafloor parts of the ultramafic oceanic lithosphere.

40 years use of model tanks in teaching exogene geology at Geo, University of Bergen

Aarseth, I.

50 years ago Professor Hans Holtedahl made a large tank for demonstration of turbidity currents. It was built inside a small room in the basement of the old institute. In 1972 the tank was used in experiments for mine tailing deposition of "red mud" from Mongstad in a project in cooperation with Norsk Hydro. Lars Myhre (later NPD and NOPEF) was engaged in this project. Hydro dropped the plans for
aluminium production because of the market situation as well as of environmental reasons. In 1977 the tank was moved to "Realfagbygget" and has since served as a demonstration tool for students in G101 (now Geov102) in a variety of exogenic processes like rivers with delta s or fans and shores. The tank is hinged at one end and can thus demonstrate isostasy and in combination with draining (eustatic) it is well suited for transgression and regression. This large tank is 3.0 m x 1.2 m x 0.6 m and holds 2000 litres. Professor Ron Steel bought a "Flume" ("Mobile bed model tank") that was integrated in the introductory teaching. This 5.5 m long tank (4 m active) is supplied with pumps. Here we can demonstrate "meandering rivers" with levees, oxbow lakes, "crevasse splay" or "shoestring sands". By using sand of different colour (density) one can demonstrate sorting and cross lamination. It is also excellent to demonstrate the difference between wave ripples and current ripples. Experiments in the tanks are popular parts when school classes visit the institute. In 2005 Professor Sven Maaløe made a separate tank (2.4 m) for demonstration of tsunamis in connection with the 100 year jubilee for "jordskjelvstasjonen". The large tank is used for demonstration of the capacity and competence of rivers as well as Hjulstrøm's diagram with the use of the five sand fractions. The lowering of base level produce backward erosion of rivers and formation of river valleys with erosion along the bottom and mass movement from the river banks (v-shaped valleys). Blocks of ice floating in the tank makes students think of Archimedes, and blocks of ice with stones at the base show the difference to glacier ice. By scouring large stones with these blocks both rock flour and melt water are produced and contribute to the suspended matter in the tank.

These tanks are now an important part of the practical course in geology (Geov102) were 80 students each spring gets 42 hours exercise and 8 days of field work. Because of the large number of students in geology in Bergen the three groups have to be divided in two when visiting the sedimentation laboratory. The other half is occupied with theoretical problems connecting to the actual subjects. All students get three full hours in the lab: fluviatial-, glacial- and shore processes. Petroleum related environments are dealt with both in fluviatial ("shoestring sands") and shore environments such as barrier islands (reservoir), lagoons (source rock) and transgression (clay as seal).

Geohazards is only one of the many subjects that can be demonstrated in these tanks. The hurricane Katarina in New Orleans is an excellent example. Experiments in depositing mine tailings in Dalsfjorden from the planned extracting of rutil from Engebøfjellet has been undertaken in the large tank by Dr. Astri Kvassnes, NIVA.

**Eclogite facies pseudotachylytes in the Lindås Nappe, Bergen Arcs: field observations, textures and fault dynamics**

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The localities Ådnefjell, Hundkjeften and Husebøvatnet on the island of Holsnøy expose Proterozoic granulite and Caledonian eclogite facies rocks belonging to the Lindås Nappe in the Bergen Arcs. During the collision between Baltica and Laurentia, these rocks were brought deep down into the root zone of what once was an orogen comparable in size to the present-day Himalayas. The main structures at the investigated outcrops are shear zones and faults. The different types of deformation can be linked to differences in rock composition. The brittle faults seems to be restricted to the anorthositic-gabbric granulite, while the shear zones are developed in the eclogite. Pseudotachylyte is observed both on the fault planes, and as injection veins into the wall rock. The pseudotachylyte veins are often branched, or they split up and enclose lenses of wallrock. One of the faults can be traced continuously for 9.4 meters, before it dies out at both ends adjacent to two eclogite shear zones. In one end it also makes a horsetail splay. The amount of pseudotachylyte preserved on the faults varies considerably along the fault plane. In some places no pseudotachylyte is present, whereas in other places the veins may be several centimeters in thickness. Most commonly the thickness is in the order of a few millimeters to 1 centimeter. The faults in the area are in most cases parallel to the NNW-SSE trending defined by the granulite facies foliation and therefore difficult to see, but occasionally they are sharply crosscutting and oblique to it. In such cases the garnet-pyroxene rich layers oriented parallel to the foliation acts as markers, and occasionally minimum displacements on faults can be determined. The observed minimum displacements range from a few
centimeters to 0.6 meter. As is already shown in several previous studies by Austrheim and co-workers, the pseudotachylytes have eclogite facies mineralogy. The textures including dendritic garnets suggest that the eclogite facies minerals crystallized by fast quenching from a melt, and therefore that the ambient conditions during solidification corresponds to eclogite facies conditions. Most of the energy (>95%) produced during an earthquake breaking solid crystalline rocks is released as heat. Thus, if melting occurs, the amount of melted material produced on the fault plane can be used to make a minimum estimate of the energy released. If it is possible to measure the amount of material that was molten (by thickness of vein and specific gravity of the rock), and the displacement on the fault, it is possible to estimate the stresses acting on the fault plane where the earthquake released according to the equation: 
\[ \sigma = \rho \left( C_p \Delta T + H \right) \gamma^{-1}, \]
where \( \sigma \) is stress, \( \rho \) is density, \( C_p \) is heat capacity, \( \Delta T \) is minimum temperature increase, \( H \) is the latent heat of melting and \( \gamma \) is shear strain. The preliminary stress estimates suggest minimum stresses of 11 to 12 MPa for two of the faults at Holsnøy.