Lithostratigraphy of the Mesoproterozoic Telemark supracrustal rocks, South Norway: revision of the sub-Heddersvatnet unconformity and geochemistry of basalts in the Heddersvatnet Formation

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The Mesoproterozoic Rjukan Group represents the oldest part of the Telemark supracrustal rocks in southern Norway. Under the traditional nomenclature, the Rjukan Group contains the felsic volcanic Tuddal Formation (ca. 1.512 Ga) and the volcanic-sedimentary Vemork Formation (ca. ≤1.495 Ga), and is overlain by the Vindeggen Group. The Rjukan and Vindeggen Groups are separated by the sub-Heddersvatnet unconformity. The lowest component of the Vindeggen Group is the Heddersvatnet Formation, which is deposited directly above the Tuddal Formation.

The contact regions between the Tuddal and Heddersvatnet Formations, and the stratigraphic relationship between the two formations, are controversial and revisited here. New evidence from the sub-Heddersvatnet unconformity and basaltic lava interbeds in the northern flank of the Gaustatoppen suggests that the Heddersvatnet Formation interfingers laterally with the Vemork Formation. The deposition of the Heddersvatnet Formation started at a late stage of the Vemork Formation sedimentation. The geochemistry, sedimentology and lithostratigraphy indicate that the Vemork Formation represents the axial depocenter, whereas the Heddersvatnet Formation was deposited near uplifted flank(s) of the rift basin. The sub-Heddersvatnet unconformity continues under the Vemork Formation. Observations seem inconsistent with the traditional lithostratigraphic division of the Telemark supracrustals. This study argues that the term (Rjukan Group) should be abandoned, and that the Vemork Formation should be included as part of the Vindeggen Group.

The geochemistry of the basaltic lavas of the Heddersvatnet Formation basaltic lavas suggests deep intraplate melting combined with crustal contamination in a within-plate paleotectonic setting. The geochemical signature is similar to that of some continental flood basalts and the Vemork Formation basalt.

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Introduction

The Mesoproterozoic volcanic-sedimentary Telemark supracrustal rocks in southern Norway represent a succession of sedimentary and volcanic rocks that have been well-preserved, despite diverse tectonic and low-grade metamorphic processes. These supracrustal rocks are an important feature of the Fennoscandian Shield. The classical lithostratigraphic framework of the Telemark supracrustals was established by Wyckoff (1934) and Dons (1960a, 1960b), who subdivided the entire package into the Rjukan (oldest), Seljord and Bandak Groups, separated by major unconformities. Traditionally, the oldest Rjukan Group was subdivided into the lower Tuddal Formation and the upper Vemork Formation. This was later modified by Dahlgren et al. (1990a, 1990b), who suggested that the contact between the Vemork Formation and the Seljord Group was transitional, and therefore the former should be included in the latter. Laajoki et al. (2002) recommended abandoning the term Seljord Group, and. They divided this sequence into the older Vindeggen Group and the younger Lifjell Group. The overlying Vindeggen Group is separated from the Rjukan Group by the sub-Heddersvatnet unconformity (Laajoki, 2005). The Vindeggen Group starts with the Heddersvatnet Formation, but the contacts between the Tuddal, Vemork and Heddersvatnet Formations are considered problematic (see Wernerskold, 1910; Wyckoff, 1934; Dons, 1960a & 1960b; Falkum & Petersen, 1980; Brewer & Field, 1985; Dahlgren, 1990a, 1990b; Starmer, 1993; Richards, 1994; Menige & Brewer, 1996; Brewer & Menige, 1998; Sigmond, 1998; Laajoki, 2005; Laajoki & Corfu, 2007). The present study addresses this controversy with new field-based lithostratigraphic, sedimentological and geochemical evidence.

The main contributions of this study are (i) the revision of the sub-Heddersvatnet unconformity, (ii) the correlation between the Vemork and Heddersvatnet Formations, and (iii) the paleotectonic reconstruction of newly-discovered basaltic lavas in the Heddersvatnet Formation. This study concludes that the present lithostratigraphic subdivision and nomenclature of the Telemark supracrustals will require some adjustment.
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NORWEGIAN JOURNAL OF GEOLOGY

Geological setting

The Mesoproterozoic (ca. 1.5 – 1.0 Ga) volcanic-sedimentary Telemark supracrustal rocks or sequences (Sigmond et al., 1997) occupy the northern part of the Sveconorwegian Telemark sector (Bingen et al., 2005), or Telemark block (Andersen, 2005), of the Southwest Scandinavian Domain (Gaál & Gorbatschev, 1987) in the Fennoscandian (Baltic) Shield (Fig. 1). In contrast to most of the metamorphic Precambrian crust in South Norway, the Telemark supracrustal units are relatively well-preserved (Dons, 1960a; 1960b; Laajoki et al., 2002; Bingen et al., 2003, 2005). They form a supracrustal sequence approximately 10 km thick, metamorphosed under low-grade greenschist-amphibolite facies conditions (Brewer & Atkin, 1987; Atkin & Brewer, 1990).

The sub-Svinsaga unconformity is the most important unconformity within the Telemark supracrustal rocks, and separates the sequence into two major packages. The Vestfjorddalen Supergroup, deposited in the interval between ca. 1.512 and 1.347 Ga, and an upper succession of Sveconorwegian units, deposited between about ca. 1.169 and 1.019 Ga. The Vestfjorddalen Supergroup consists of two groups: (1) the older Rjukan Group, comprising continental felsic volcanics of the Tuddal Formation (ca. 1.512 Ga, Bingen et al., 2005), and the 2 km thick sequence of the volcanic-sedimentary Vemork Formation (ca. ≤1.495 Ga, Laajoki & Corfu, 2007), characterized mainly by mafic volcanism; and (2) the 5 km thick...
The Rjukan and Vindeggen Groups were previously mapped in the Rjukan area by Wyckoff (1934) and Dons (1960a, 1960b, 1961), and in the Ámotsdal and Frøystaul areas by Dons et al. (2003, 2004). Previously, Dons (1960a, 1960b, 1961) included the basal conglomerates and associated sandstones, which locally overlie the Rjukan Group, as part of the Gausta Formation, Vindeggen Group. Laajoki (2005) studied the areal distribution and the nature of the sub-Heddersvatnet unconformity and concluded that the basal conglomerates and associated sandstones form an important and clearly mappable unit and should be treated as a formation, which he named the Heddersvatnet Formation. More recently, Laajoki and Corfu (2007) subdivided the Vemork Formation into smaller lithostratigraphic units, and discussed its relationship with the Tuddal Formation and the Vindeggen Group.

In most previous studies, the most controversial problems have been associated with the nature and significance of the lithostratigraphic contacts between the Rjukan and Vindeggen Groups, and between the Tuddal, Vemork and Heddersvatnet Formations (for a review, see Laajoki, 2005 and his Table 1). Wyckoff (1934) and Dons (1960a, 1960b) stated that a regionally large angular unconformity exists between the Rjukan and the Vindeggen (previously Seljord) Groups, but this conclusion was subsequently called into question by Starmer (1993), Menuge & Brewer (1996) and Brewer & Menuge (1998). Dahlgren et al. (1990a) stated that the Vemork Formation represents initial volcanism and sedimentation of the Vindeggen Group, whereas Brewer & Menuge (1998) considered the Rjukan and Vindeggen Groups as one package, within which the discordance of individual units is a function of the mode of deposition in the context of important tectonic changes in the evolution of the Rjukan Rift Basin (see Brewer & Menuge, 1998; Laajoki & Corfu, 2007).

The Tuddal Formation was most likely deformed and deeply eroded before deposition of the Heddersvatnet Formation (Sigmund et al., 1997; Sigmund, 1998; Richards, 1994, 1998). This led Laajoki (2005) to recognize the sub-Heddersvatnet unconformity. In addition, Laajoki (2005) and Laajoki & Corfu (2007) suggested that the Vemork and Heddersvatnet Formations might interdigitate, which would indicate that the sub-Heddersvatnet unconformity continues beneath the Vemork Formation.

This study focuses on the area around Lake Heddersvatnet, on the southern flank of the Heddersfjell, Svineore, in the northern flank of the Gaustatoppen, and the Diplanut, where the contacts between the Tuddal, Vemork and Heddersvatnet Formations are well-exposed (Fig. 2).
the Diplanut area, the Vemork Formation continues laterally east to the Gausdalen fault and interfingers with the Heddersvatnet Formation (Fig. 2). Around the Lake Heddersvatnet area and on the Heddersfjell, the Vemork Formation is absent. The Heddersvatnet Formation lies directly over the Tuddal Formation, but is separated from it by the sub-Heddersvatnet unconformity (Fig. 2).

**Structural features**

Although all the rocks in our study area have been metamorphosed into low-grade greenschist facies, the meta-prefix is not used in some of the lithological names. The sandstone nomenclature used here was proposed by Folk (1980) and Pettijohn et al. (1987) and is based on the relative percentages of the major components in the relevant sandstones. The term volcanoclastic is used for any rock with a preponderance of fragments of volcanic origin and derived by weathering or by processes such as those in the Gausta Formation. The axial-plane cleavage dips at about 35° – 45° to the east-southeast. The general trend of the bedding and the axial-plane cleavage is parallel to that in the Vemork Formation, west of the Gausdalen fault zone (Fig. 2). This trend is a result of the E-W oriented folding phase preceding the Sveconorwegian orogeny, which deformed the Rjukan and Videggen Groups. Some of the beds near Svínøe are overturned due to this deformation (Fig. 2).

The structural observations around the Vemork and Heddersvatnet Formations are summarized here. Although the Tuddal Formation serves as the basement for both formations, the structural features of the Tuddal Formation are difficult to establish. The main reason is that the Tuddal Formation porphyre is massive, and the contacts with the individual lava beds are unexposed. In addition, the commonly observed flow banding is significantly distorted due to deformation. The only reliable bedding observation in the Tuddal Formation involves the lapilli tuffs on the southern shore of Lake Heddersvatnet (Fig. 2). These tuffs trend northeast, with variable dips to the southeast/northwest, or have been steeply folded (cf. Wyckoff, 1934; Laajoki, 2005). Around Lake Heddersvatnet, the flow banding is steeply-dipping and is limited by the sub-Heddersvatnet unconformity. Laajoki & Corfu (2007) structurally subdivided the Tuddal Formation into the Våerskarven, Dalsnuten, Kovvatnet, Heidalsnuten and Hortenuten domes, which are cut by several faults (Fig. 1). The domes represent primary volcanic complexes folded as a result of the Sveconorwegian deformations. To the east of the Gausdalen fault, the Tuddal Formation is over lain by the Heddersvatnet Formation, whereas to the west of the fault, it is overlain by the Vemork Formation (Figs. 1 & 2).

**Vemork Formation**

The Vemork Formation is exposed along a ca. 50 km long northeast-trending area extending from Rjukan to Trovasshøvet (Fig. 1). Due to strong deformation, most of the Vemork Formation contacts are sheared, unexposed or disturbed by other faults. The lowermost units of the Vemork Formation are best preserved along the southeast limb of the Midtfjell anticline, although these are cut by the Gausdalen fault (see Laajoki & Corfu, 2007 and Fig. 2). The Midtfjell anticline plunges 60° – 80° to the south-southwest. The Vemork Formation forms an asymmetrical syncline, the Vigfíðhova syncline, north-west of the Midtfjell anticline. The lithological asymmetry and the strongly sheared conglomerates adjacent to the Hortenuten dome (Fig. 1) indicate that the lower parts of the Vemork Formation have been truncated tonally along the northwest margin of the exposure (Laajoki & Corfu, 2007).

The primary upper contact of the Vemork Formation is preserved only in the Diplanut area, between the Grassjell shear zone and the Gausdalen fault (Figs. 1 & 2). In other areas, the contact is highly sheared and represents the folded and faulted extensions of the shear zones. The bedding orientations are similar in both the Vemork and Gausta Formations (Fig. 2).

**Heddersvatnet Formation**

The Heddersvatnet Formation is best exposed around Lake Heddersvatnet, along the southern flank of the Heddersfjell, or Svínøe, and along the northern flank of the Gaustatoppen (Fig. 2). The formation is defined by the broad Vindsjá syncline, plunging to the north-northeast on Heddersfjell and to the southwest on Gaustaråen (Fig. 2). The Vindsjá syncline was formed during the Sveconorwegian deformation, and was later refolded along the Jonnbu anticline (Fig. 2). The bedding directions in the Heddersvatnet Formation are the same as those in the Gausta Formation. The axial-plane cleavage dips at about 35° – 45° to the east-southeast. The general trend of the bedding and the axial-plane cleavage is parallel to that in the Vemork Formation, west of the Gausdalen fault zone (Fig. 2). This trend is a result of the E-W oriented folding phase preceding the Sveconorwegian orogeny, which deformed the Rjukan and Videggen Groups. Some of the beds near Svínøe are overturned due to this deformation (Fig. 2).

**Sub-Heddersvatnet unconformity**

The sub-Heddersvatnet unconformity separates the Tuddal Formation of the Rjukan Group from the Videggen Group (Figs. 1 & 2). It is named after the lowermost formation of the Videggen Group (Laajoki, 2005), and its nature varies from one locality to another.

*Contact between the Tuddal Formation and the Vemork Formation*

Laajoki & Corfu (2007) placed the lower contact of the Vemork Formation against coherent Tuddal domes, made up of felsic volcanic rocks (Fig. 1). These boundaries can be mapped regionally. These authors noticed, however, that the change from felsic Tuddal volcanism to basaltic Vemork volcanism is of interbedded character, with felsic lava units in the lower part of the Vemork Formation. The primary contact between the formations is, however, not exposed in the Vemork-Diplanut area.
The massive conglomerate member (Maristi member) represents the first evidence of the Vemork Formation in the Vemork-Diplanut area, but the exact contact with the Tuddal Formation porphyre cannot be ascertained established. According to Laajoki & Corfu (2007), the conglomeratic member is most likely underlain by a thin sequence of Vemork-type basalts and sediments.

In the Frøystaul area, the Vemork Formation starts with a sandstone deposited directly upon above homogenous massive and foliated porphyry-homogenous of the Tuddal Formation massive and foliated porphyre, forming a sharp and slightly sheared erosional contact. The sandstone contains well-rounded epiclastic volcanic pebbles (<6.0 cm) from the Tuddal Formation, bluish quartz-phenoocryst clasts, and partly or completely altered plagioclase clasts in a sericite-rich matrix. According to Laajoki & Corfu (2007), this suggests significant erosion of the Tuddal Formation porphyre before the extrusion of the first Vemork Formation basaltic flow.

In localities where the lowermost Vemork Formation sandstone lies directly above the Tuddal Formation flow-banded rhyolite lava, it is greenish and rich in sericite, and contains plagioclase-phenoocryst clasts and glomerophyric plagioclase clasts, and sericite schist (op. cit.). The nature of the unconformity cannot be established due to the small size of individual outcrops and lack of regional-scale mapping. However, the unconformity cuts both the massive porphyre and the flow-banded rhyolite. The existence of an angular unconformity under the Vemork Formation is therefore possible. Temporally, its significance seems to be modest, because the time gap is minimal between the Tuddal Formation felsic lavas (ca. 1.512 Ga, Bingen et al., 2005) and the Skardfoss member rhyolite (<6.0 cm) from the Tuddal Formation, bluish quartz-phenoocryst clasts, partly altered feldspar clasts, variable amounts of feldspar phenocrysts, partly altered feldspar clasts, and sericite schist (op. cit.). The nature of the unconformity cannot be established due to the small size of individual outcrops and lack of regional-scale mapping. However, the unconformity cuts both the massive porphyre and the flow-banded rhyolite. The existence of an angular unconformity under the Vemork Formation is therefore possible. Temporally, its significance seems to be modest, because the time gap is minimal between the Tuddal Formation felsic lavas (ca. 1.512 Ga, Bingen et al., 2005) and the Skardfoss member rhyolite (ca. ≤1.495 Ga, Laajoki & Corfu, 2007) in the lower part of the Vemork Formation.

Contact between the Tuddal Formation and the Heddersvatnet Formation

The sub-Heddersvatnet unconformity is well-exposed around Lake Heddersvatnet, along the southern flank of the Heddersfjell, and along the northern flank of the Gaustatoppen (Fig. 2). Along the southern shore of Lake Heddersvatnet, near Nutan, and on the southern flank of the Heddersfjell (Fig. 2), the Heddersvatnet Formation has been deposited directly above the in situ weathered and brecciated Tuddal Formation porphyre (Fig. 3A) and lithophysae. The Heddersvatnet Formation erodes the Tuddal Formation volcanoclastic conglomerate, porphyre and associated lithophysae. The Tuddal Formation lithophysae have are spherulite growths formed around expanding vesicles in rhyolitic lava, with fibrous quartz-feldspar needles radiating from the nucleus. These kinds of vesicles of this type can be formed in a flowing melt, i.e., before solidification (Cash & Wright, 1988). The Tuddal Formation lapilli tuff bed-

The Heddersvatnet Formation volcanoclastic conglomerate along the northern shore of Lake Heddersvatnet lies directly over the Tuddal Formation flow banded lava, and forms a sharp and deeply erosional contact between the two formations. The flow banding in the Tuddal Formation rhyolite is a result of the mixing of different cooling layers, indicating slow internal movement of the lava.

The sub-Heddersvatnet unconformity on the northern flank of the Gaustatoppen can be traced from the Gaudalen fault in the west to the Svineroe in the east (Fig. 2). The Heddersvatnet Formation epiclastic sandstone is deposited directly above the homogenous, massive to foliated porphyre of the Tuddal Formation, forming a sharp erosional and slightly sheared contact between the formations (Figs. 3B & C). The Tuddal Formation has an in situ weathering crust a few meters thick, enriched with sericite. Due to the nature of the Tuddal Formation porphyre, the angular unconformity cannot be established with certainty at these localities. The Heddersvatnet Formation coarse-grained sandstone contains quartz phenocrysts, partly altered feldspar clasts, variable amounts of lithic volcanoclasts from the Tuddal Formation, and a few granitoid or coarse gneiss clasts in a sericite-rich matrix. Some of the well-rounded epiclastic volcanic pebbles are up to 5.0 cm in diameter (Fig. 3D). In other localities, the contact represents a sharp erosional surface with irregular paleorelief or in situ weathering crust.

Lithostratigraphy of the Vemork Formation

The general descriptions of the Frøystaul and Vemork-Diplanut areas to date have been primarily based on studies by Laajoki & Corfu (2007). The Frøystaul area is the only place where the lower regions of the Vemork Formation are exposed. In most areas, the Vemork-type basaltic lavas have lost all of their primary features, and the interbedded sedimentary beds cannot be traced laterally for great distances. Although the volcanic-sedimentary beds are not well exposed, at least laterally, the Vemork-Diplanut area presents an important section for lateral stratigraphic correlation with the Heddersvatnet Formation. This is the only place where the upper contact of the Vemork Formation is exposed. Other areas exist, but are beyond the scope of this paper.
graphic pattern in this section is that mass-flow conglomerates and pebbly sandstones occur in the lower part of the formation, while sedimentary units in the middle and upper parts consist mainly of immature, cross-bedded or parallel-laminated sandstones. The sandstone beds are relatively rich in epidote and consist of abundant rock and mineral clasts from felsic and mafic sources. Petrographically, the detrital framework of the Vemork Formation sandstones classifies them as arkoses or lithic arkoses in all areas, with a variable prevalence of lithic volcanic clasts.

**Frøystaul area**

The volcanic-sedimentary sequence is about 2.2 km thick and consists mostly of subaerial basaltic lavas and some interbedded sandstone units. The main unit of the Vemork Formation starts with a 10 m thick pebbly sandstone containing well-rounded felsic volcanic clasts, quartz phenocrysts and altered plagioclase grains in a sericite-rich matrix. This is followed by alternate basaltic lava and sandstone beds with variable thicknesses. According to Laajoki & Corfu (2007), all the basaltic lavas are monotonous, consisting of massive greenstone or amygdaloidal lavas. They concluded that the ubiquitous amygdales and lack of pillow structures in the basalts indicates that the lavas probably erupted subaerially. The general strati-
the lower part of the Vemork Formation contains two important members, namely the Maristi and the Skardfoss members (Figs. 2 & 4A). The Maristi conglomerate member is a few tens of meters thick, containing up to a few meters of matrix-supported conglomerate beds capped and separated by thin, poorly-laminated sandstone units. The sizes of the conglomerate clasts ranges from a few cm up to 1.5 m. The bed thickness and clast sizes in the conglomerate beds decrease upwards, and the poorly-laminated and cross-bedded sandstone beds are common in the upper part of the member. The Maristi conglomerate member may represent indicate a mass flow deposit (Dons et al., 2004; Laajoki & Corfu, 2007).

The Maristi member passes upwards into the ca. 20-50 m thick Skardfoss member, which consists solely of flow-banded rhyolite. It and slightly erodes the underlying sandstone-mica schist. The most important feature of this member is that it consists of two types of volcaniclastic breccia occur in its the upper contact. of the member. The first type has a jigsaw-like texture and the fragments are free of quenching features, which indicates an autotrachytic breccia. The second type contains larger rhyolite fragments with roundish or curvilinear margins. The groups of clasts with jigsaw textures are supported in a matrix of smaller rhyolite fragments embedded in a granoblastic orthoquartzite, without any evidence of clastic origin (Laajoki & Corfu, 2007). The presence of autotrachytic and hyaloclastic breccias indicates that the Skardfoss rhyolite was extruded under subaerial conditions, and probably flowed into water.

Thin tuffitic schist, followed by alternating basaltic lava and sedimentary beds, overlies the Skardfoss member (Fig. 4A). However, these beds are poorly-exposed, and their real thickness and lateral continuity cannot be precisely measured. The porphyric basaltic lava beds contain mostly rounded or partly elliptical amygdales <7.0 cm in diameter, infilled with silica-rich material and some individual lithic fragments derived from pre-existing volcanic rocks. The primary textures have been mostly destroyed due to metamorphism, but some samples exhibit weak signs of intergranular to trachytic texture. The large and angular plagioclase grains are transformed into carbonate, and clinopyroxene grains are either leached or altered. Dark, iron-rich opaque minerals (magnetite) in a fine-grained groundmass are usually abundant.

The intermediate sedimentary sandstone interbeds are mostly low-angle or trough cross-bedded, medium to coarse-grained, and feature occasional well-rounded volcanic pebbles in a sericite-rich matrix. These cross-bedded units are usually capped with ca. 5-20 cm thick mudstone beds. In addition, the moderately-sorted sandstones contain some sub-rounded to angular poly- and monocrystalline quartz phenocrysts and abundant altered feldspar clasts that have been replaced with sericite. The topmost trough cross-bedded sandstone bed contains dark, angular mudstone rip-ups. The size of these rip-ups varies from a few cm up to 15 cm.

**Contact between the Vemork Formation and the Gausta Formation**

The contact between the Vemork and the Gausta Formations is either mostly unexposed or intensely sheared along the Grassfjell shear zone (Fig. 2). The Vemork Formation Aamygdaloidal lava in the Vemork Formation in the northern flank of the Diplanuten is in primary contact with a quartz-feldspar wacke followed by the cross-bedded sandstone and Gausta Formation quartz sandstone, which is free of feldspar and volcanic clasts. It starts with a polymictic conglomerate consisting of well-rounded orthoquartzite and felsic volcanic pebbles and minor jaspis clasts (Laajoki & Corfu, 2007).

Laajoki & Corfu (2007) considered that the sandstone and lava beds between the Grassfjell shear zone and the Gausdalen fault belong to the Heddersvatnet Formation (Fig. 2). However, our study shows considers that the Gausdalen fault separates and represents the boundary marker between the Vemork Formation and the Heddersvatnet Formation. This is because the sandstone and basaltic lava beds are disturbed by diabase (Fig. 2) and cannot be laterally traced from the northern flank of the Gaustatoppen to the Diplanut.

**Lithostratigraphy of the Heddersvatnet Formation**

The lithostratigraphy of the Heddersvatnet Formation is described from the northern flank of the Gaustatoppen, Svineroe and the southern flank of the Heddersfjell, where the outcrops and the contacts of different beds are exposed (Fig. 2).

**Northern flank of the Gaustatoppen**

Previously, the bedrock in the northern flank of the Gaustatoppen was mapped as an orthoquartzite intruded by metadiabasic sills (see Wyckoff, 1934; Dons, 1961). However, remapping proved that many of the latter were in fact bedding-parallel amygdauloidal basaltic lavas. In total, six different basaltic lava units have been identified (Fig. 4B), including the one reported byin Anderson & Laajoki (2003). The Heddersvatnet Formation in this area is ca. 400 m thick (Fig. 4B). It starts with a ca. 70 m thick epiclastic sandstone deposited directly above the Tuddal Formation in situ weathered porphyre in the Tuddal Formation (Fig. 4B). The coarse-grained epilastic sandstone is massive, with a lack of visible sedimentary structures. It contains well-rounded Tuddal Formation porphyre and silica-rich lithophysae fragments in a sericite-rich matrix (Fig. 3D). The detrital framework of the Heddersvatnet Formation sandstones classify them as arkoses or lithic arkoses in all areas, with variable dis-
tributions of lithic volcanic clasts. The lack of any visible structures, together with the pebbles at the bottom part of the unit, probably indicate rapid deposition from a sediment -gravity flow deposit.

The epiclastic sandstone is overlain by a ca. 70 m thick, medium to coarse-grained trough cross-bedded sandstone unit with mudstone interbeds. These trough cross-bedded sandstone beds are 1.5 to 2.0 m high and 3.0 to 5.0 m wide. The thicknesses of the mudstone interbeds vary from 2.0 to 50 cm. The cross-bedded sandstone bed also contains occasional angular, dark, mudstone rip-ups, which are usually less than 20 cm in diameter. Paleoflow measurements indicate flow direction from the present east-northeast to west-southwest (Fig. 4B). The angularity of the mudstone rip-ups indicates a short transport distance, or at least no intensive re-working. This unit provides evidence for the existence of sinuous-crested and linguoid (3-D) dunes under unidirectional flow conditions.

The lithostratigraphy of the Heddersvatnet Formation in the Svineroe area is slightly different from that in other localities. It features ripple-marked and laminated mudstone, ripple-marked sandstone with desiccation cracks and pillow lava structures. The area displays only small, discontinuous outcrops, making lithostratigraphic correlation between individual outcrops difficult.

The thicknesses of the mudstone interbeds vary from 10 to 30 cm. Although no hyaloclastite breccias can be found in this area, the nature of other basaltic lavas, subaerial debris flows, paleoflow and the associated structures of the sandstones indicate subaerial eruption and flow into water. The development of basaltic pillows does not necessarily require under-water eruption (Cas & Wright, 1987).

The epiclastic sandstone is overlain by a ca. 10 m thick basaltic lava bed (Fig. 4B), containing mostly rounded or partly elliptical amygdales <2.0 cm in size. The amygdales are former vesicles and are completely infilled with silica or talc-rich material, representing the flow tops. The elliptical amygdales and the mineral assemblage with heteroblastic intergrowths indicate even later regional metamorphism. The basaltic lava also contains a few angular lithic fragments that are <6.0 cm in diameter, derived from pre-existing volcanic rocks. Some of the larger, unrounded fragments may also represent previous vesicles that were deformed during flowage and later infilled with silica-rich material. This basaltic lava bed is again overlain by similar trough cross-bedded sandstones, followed by interbedded basaltic lavas and sandstones of variable thickness. The common feature of the basaltic lavas is that the primary structures and textures are almost completely destroyed due to metamorphism, but they show no signs of notable epidotization.

The lithostratigraphy is disturbed by a ca. 400 m thick medium to coarse-grained diabase, which is parallel to the planar structure of the surrounding rock, and forming a massive sill in the northern flank of the Gaustatoppen (Fig. 2). The topmost mappable unit in this area is a basaltic lava bed at least 5.0-10 m thick (Fig. 4B), which can be laterally correlated with the basaltic pillow lavas in the Svineroe area (Fig. 2). The primary features of this basaltic lava bed are trachytic textures resulting from migmatic flow, which have been well preserved in many cases. The original glassy groundmass material between the feldspars has been replaced by chlorite. Weakly-developed alignment of the feldspars due to magma flow indicates a gradational texture between the intergranular and the trachytic textures. It should be noted that the term trachytic texture is not restricted to rocks of trachyte chemical composition (Mackenzie et al., 1982). It can also exist in basaltic rocks, which tend to have a more intergranular texture.

The mineral assemblages, without such as lack of garnet, biotite and amphibole minerals, indicate that the metamorphic grade was no higher than low-grade green-schist facies. The entire topmost unit is interpreted to represent a waning flow conditions with traction current deposition, followed by pebbly mass flow deposits, and calmer flowing conditions, and overlain by subaerial basaltic lava flows.

Southern flank of the Heddersfjell

Along the southern flank of the Heddersfjell (Fig. 2), the Heddersvatnet Formation lies directly above the in situ weathered and brecciated lithophysae of the Tuddal Formation, which is here a few meters thick. The Heddersvatnet Formation in this area is ca. 250 m thick and starts with a matrix-supported massive breccia a few meters thick, lying above the felsic lava of the Tuddal Formation felsic lava (Fig. 4C). It is overlain by a ca. 10 m thick clast-supported breccia with an erosional contact. These poorly-sorted breccia beds shows no signs of grading or internal structure. The clast size of the sub-rounded to angular volcanoclastic breccia fragments varies from a few cm up to 50 cm. The matrix between the fragments is sericite-rich medium to coarse-grained arkosic sandstone. These beds represent subaerial plastic and pseudoplastic debris flows, in which the epiclastic material is derived from the intensively weathered Tuddal Formation porphyre and lithophysae.
The clast-supported volcanoclastic conglomerate beds overlie the breccia beds (Fig. 4C). The bed thickness varies from 2.0 to 10 m. The common feature among all the clast-supported conglomerate beds is that the topmost part of the beds contains stratified cross-bedded sandstone or siltstone with volcanic pebbles. The texture and fabric of the beds vary from ungraded and disorganized to crudely imbricated and normally-graded. The clast size of the rounded-angular epiclastic fragments varies from a few cm up to 50 cm. The matrix between the fragments varies from silt-size material to medium-grained arkosic sandstone. The contacts of the beds are mostly sharp, erosional, and unchannelized, although some more channelized contacts also exist. The bottom parts of the beds indicate subaerial pseudoblastic debris flow with an inertial bedload, or a more fluidal and turbulent sediment flow. The top parts indicate a waning current and traction in the context of a stream flow.

These beds are overlain by a matrix-supported volcanoclastic conglomerate unit several meters thick (<20 m), and interbedded, medium-coarse grained sandstone...
with trough cross-bedding and minor pebbles (Fig. 4C). The clast size of the conglomerate beds varies from a few cm up to 20 cm. The matrix-supported conglomerate beds represent a subaerial plastic debris flows with a high viscous strength. The interbedded sandstone may suggest scour-fills or antidunes in a channelized stream flow.

Lithostratigraphically, the topmost part of the Heddersfjell area comprises a medium-grained trough cross-bedded sandstone unit at least 80 m thick, with mudstone interbeds and minor volcanic pebbles (Fig. 4C). The thickness of the mudstone interbeds varies from 15 cm up to 50 cm and these occur in the upper part of the bed, i.e., before the transition to the Gausta Formation. The paleoflow measurements indicate flow directions from present day northeast to south-southwest. This topmost bed represents sinuous-crested linguoid (3-D) dunes.

**Contact between the Heddersvatnet Formation and the Gausta Formation**

The primary upper contact between the Heddersvatnet Formation and the Gausta Formation is best exposed in the Heddersfjell area (Fig. 2), where the trough cross-bedded sandstone becomes more mature and free of feldspar and volcanic material. The contact is transitional, with an arkosic sandstone texture in the contact rock, which contains up to 15 % sericite-rich pseudomatrix between the grains. This contact rock still contains a few volcanic pebbles and some slate fragments, but these are totally missing from the subarkose – quartz arenite of the Gausta Formation.

**Paleoenvironmental depositional model**

The paleoflow directions and genetically related lithofacies assemblages indicate that the Heddersvatnet Formation represents alluvial fan sedimentation during the syn-rift phase of the sedimentary basin (Fig. 5 & Köykkä, submitted). Subaerial debris flows, stream-flows and sheet flood deposits mostly characterize the proximal part of the Heddersvatnet Formation, whereas the distal part contains shallow water channel-fill dunes and continental flood basalts (Fig. 5). The laterally quite extensive mudstone bed in the Svinere area suggests a sub-basin development and intra-rift faulting inside the Heddersvatnet Formation.

The volcanic-sedimentary Vemork Formation is the main component that gradually filled the rift basin, whereas the Heddersvatnet Formation was deposited near uplifted flank(s) i.e. rift shoulder(s) of the basin. The uplifted flank was dominated by intensive erosion of the Tuddal Formation porphyre, leading to the accumulation of thick volcanoclastic debris flow deposits in the lower and proximal part of the Heddersvatnet Formation (Fig. 4C) and followed by alluvial stream sedimentation in the distal parts (Fig. 5).
Geochemistry of the basaltic lavas

According to Brewer & Atkin (1989) and Menage & Brewer (1996), basaltic lavas of the Vemork Formation may have formed by partial melting of depleted mantle. These feature within-plate chemical signatures, with trace element patterns similar to Phanerzoic continental flood basalts. Brewer & Atkin (1989) argued that low-grade metamorphic events may have caused disturbances to the entire rock geochemical systems, a situation which may result in misleading tectonic reconstructions. They suggested that the Vemork Formation basalts have passed through (i) early burial-type metamorphism, (ii) regional metamorphism and (iii) thermal metamorphism. According to these researchers, burial-type metamorphism resulted in the presence of hornblende, biotite, scapolite and opaque porphyroblasts, together with the following characteristic geochemical signatures: TiO$_2$ >2.5 wt. %, P$_2$O$_5$ >0.40 wt. %, K$_2$O (>1.0 wt %). Thermal metamorphism resulted in the development and occurrence of hornblende, biotite, scapolite and opaque porphyroblasts, together with the following characteristic geochemical signatures: TiO$_2$ >2.5 wt. %, P$_2$O$_5$ >0.40 wt. %, Zr >200 ppm, and Cr <80 ppm.

Fourteen basaltic lava samples were collected from the Heddersvatnet Formation, and were crushed and milled for geochemical analysis to characterize their geochemical signatures. Major and trace elements were analyzed at the University of Oulu’s Institute of Electron Optics, using a Siemens SRS 303AS X-ray fluorescence spectrometer with pressed powders (Table I). All samples that exhibited petrographic evidence of effective burial metamorphism or complete metamorphic recrystallization were excluded. The petrographic and geochemical evidence related to the Heddersvatnet Formation basalistic lavas suggest that none of the selected samples showed metamorphic disturbance imprints that were similar to those described by Brewer & Atkin (1989). Accordingly, the selected samples represent a reliable data source for inferring the paleotectonic setting. Geochemical data on mafic volcanic rocks in the Heddersvatnet Formation are presented in Figs. 6A-F and are compared to published data on probable correlative rocks of the Vemork Formation (Menage & Brewer, 1996).

The Heddersvatnet Formation basaltic lavas are characterized by relatively high Al$_2$O$_3$ (16 – 18 wt. %) and K$_2$O contents (1.73 – 3.44 wt. %), a low MgO/FeO ratio (<1.0), high Ti/Y ratio (>285), and very low Cr and Ni contents (<50 ppm). Analyzed samples generally have 45 – 50 wt. % SiO$_2$ and ~4.0 wt. % total alkali content, and can consequently be classified as basalts (Fig. 6A). The scatter of the Vemork Formation samples suggests that mobility of SiO$_2$ and alkali elements took place during the regional metamorphism (Menage & Brewer, 1996). By eliminating these elements using the Zr/TiO$_2$ vs. Nb/Y discrimination diagram, a more clustered plot can be obtained for the Vemork Formation (Fig. 6B). In this diagram, the Heddersvatnet and Vemork Formation samples are characterized by relatively low Zr/TiO$_2$ and Nb/Y ratios, and also classify as basalts (Fig. 6B).

The multi-element spider diagram shows that the Heddersvatnet Formation basaltic lavas are generally enriched in light rare earth elements (LREE) and high field strength elements (HFSE), relative to primitive mantle and N-MORB, except for Sr (Fig. 6C). The clustered data for Nb, P, Zr and Ti suggest that HFSE were relatively immobile during the regional metamorphism (Fig. 6C). The scatter for Rb, Ba, Th, U, Sr, Hf and Dy may suggest that these elements were mobile during metamorphism (Fig. 6C). The minor variations in U and Zr may reflect analytical biasing, and those in Sr and Ba may indicate fractional crystallization of plagioclase, and variable plagioclase phenocryst abundance in the samples (Menage & Brewer, 1996). In general, the Heddersvatnet Formation basalts express a geochemical signature similar to that of some continental flood basalts and to the Vemork Formation basalts. Low Ni (<49 ppm) and Cr (<42 ppm) values suggest substantial crystal fractionation prior to eruption, which is also a general feature of continental flood basalts. The high concentrations of some of the LILE elements (e.g., Rb, Ba and K), which is also a characteristic feature of continental flood basalts, suggest crustal contamination. However, these elements may have been disturbed by metasomatism and/or regional metamorphism.

The K$_2$O vs. Na$_2$O values and the low FeO/MgO ratios indicate a high-K alkaline series, a conclusion that is also supported by the relatively high Al$_2$O$_3$ content association. The negative Nb anomaly, together with enrichment in Nb and Zr compared to primitive mantle and N-MORB, may suggest a mantle source for the Heddersvatnet Formation basalts (Fig. 6C). However, supplemental isotopic geochemical data may be needed for reliable interpretation. The negative Nb anomaly relative to Th and Ce is a general feature of volcanic arc basalts (Pearce, 1996), but the enrichment in Nb, Zr, Ti and Y compared to N-MORB argues against this origin (Fig. 6C). In addition, the relatively high Ti/Y ratios suggest deep intraplate melting, which is a characteristic feature of within-plate basalts (op. cit.). Melting at plate boundaries (MORB or VAB) is generally shallow and results in lower Ti/Y ratios. Compared to the middle and upper continental crusts, there is a slight enrichment in P, Ti and Y, and a depletion of Th and Sr (Fig. 6C). However, the general trend suggests at least some contamination of the Heddersvatnet Formation basaltic lavas by continental crust (Fig. 6C).

Only HFSE (e.g. Ti, Zr, Y, Nb, V) were used for the paleotectonic reconstruction. These elements are known to be comparatively immobile and stable under low-grade metamorphic conditions. The Ti vs. Zr and Zr/Y vs. Zr tectonic discrimination diagrams by Pearce (1982) and Pearce & Norry (1979) were used to separate the within-
## Table 1. Geochemical whole-rock analyses of the Heddersvatnet Formation basaltic lavas.

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Major elements wt.%; Trace elements ppm.; nd = Below detection limit.
plate tectonic setting from other settings (Figs. 6D & E). These simple diagrams are probably more accurate than, for example, the Ti/100-Zr-Yx3 ternary diagram, especially in the case of transitional tectonic settings or non-primary magmas (cf. Pearce, 1996, Fig. 9). The composition of the Heddersvatnet and Vemork Formation basaltic lavas is compatible with a continental within-plate paleotectonic setting (Fig. 6D & E). In the V vs. Ti discrimination diagram, the Heddersvatnet Formation basaltic lavas plot within the field of continental flood basalts and alkali basalts + OIB, whereas the Vemork Formation basaltic lavas cluster near the alkali basalt + OIB field (Fig. 6F).

**Discussion**

This study supports the idea that the sub-Heddersvatnet unconformity continues under the Vemork Formation, and that the Vemork Formation interfingers with the Heddersvatnet Formation. The term interfinger is used here to denote a time-equivalent stratum of volcanic-sedimentary rocks, which change laterally from one type to another within a zone that comprises two distinct types of formations. Although it is a matter of definition, the boundary between these formations can be localized to the Gausdalen fault (Figs. 1 & 2).

The key problem seems to be the contact between the Tuddal and Vemork Formations, which has recently been considered to be more or less conformable (see Laajoki & Corfu, 2007 and references therein). The same contact is an angular unconformity between the Tuddal and Heddersvatnet Formations. However, the contact between the Tuddal and Vemork Formations is only observable locally in areas where the Vemork Formation overlies and cuts a homogeneous Tuddal Formation porphyre. This means that the angular unconformity may exist but is may not be visible. The contact should be mapped in more detail at both local and regional scales. At present, an angular unconformity cannot be ruled out. In addition, as stated in Laajoki & Corfu (2007), the regional tectonic synthesis of the Rjukan Rift Basin should be studied properly before the nature and the causes of the different unit boundaries can be understood. The extrusion of abundant mafic lavas of the Vemork Formation reflects a change in the magmatic regime in the rift basin, possibly coeval with a syn-rift tectonic phase. Thus, it is possible that the lower members of the Vemork Formation represent post-folding felsic volcanism, i.e., the late stage and final inputs of the felsic magma chamber(s).

The Vemork Formation is mostly unexposed, and the different sedimentary units cannot be followed for any great distance laterally (see Laajoki & Corfu, 2007). It is therefore difficult to directly correlate directly smaller individual volcanic-sedimentary units between the Vemork and the Heddersvatnet Formations. The lateral correlation is also hindered by the Gausdalen fault line (Fig. 2). The deposits on the west side of the fault zone are basaltic lava flows dominated by minor arkosic sandstone interbeds, whereas deposits on the east side of the fault zone are arkosic sandstones and conglomerates with minor basaltic lava beds (Figs. 2 & 4A-C). The thickness of the formations also varies greatly on the two sides of the Gausdalen fault zone. The Vemork Formation is about 2 km thick, whereas the Heddersvatnet Formation is about 400 m thick.

The open question today is the lithostratigraphic division and nomenclature of the lowerbottom part of the Telemark supracrustals, i.e. whether the Vemork Formation should be included in the Rjukan Group or not (see Laajoki et al, 2002). The sub-Heddersvatnet unconformity subdivides the Rjukan and Vindeggen Groups into two different packages. However, this study supports the idea that the sub-Heddersvatnet unconformity continues under the Vemork Formation. This means that the position of the Vemork Formation as part of the Rjukan Group is not logical. The Vemork Formation should be included as part of the Vindeggen Group, and the Tuddal Formation should be separate, as proposed by Dahlgren (1990a, 1990b). It is evident that more detailed geochemical and fieldwork studies need to be carried out to clarify the stratigraphic framework of the Telemark supracrustals.

According to Laajoki & Corfu (2007) & Corfu & Laajoki (2008), the deposition and sedimentation of the Vemork Formation started at around 1495 ± 2 Ma, whereas the felsic magmatism age of the Tuddal Formation is ca. 1512 ± 10 Ma (Bingen et al., 2005). This age difference would not allow much time for the formation of an angular unconformity between the formations. However, it is possible that the formation and the nature of the sub-Heddersvatnet unconformity may be rather explained by rotation of fault blocks inside the rift basin rather than by orogenic deformation. Fault block rotation or movement perhaps requires less does not require much time.

The magmatic and tectonic evolution of the Heddersvatnet Formation may be explained by continued rifting and possible development of intra-rift faulting following the late stage deposition of the Vemork Formation. This was accompanied by more evolved magma, with some crustal contamination during the deposition of the Heddersvatnet Formation. The termination of the volcanism suggests a gradual change from the syn-rifting to the post-rifting stage, probably in the late stage of sedimentation, and deposition of marine-dominated sediments of the Gausta Formation. The end of volcanism, and the input of extrabasinal epiclastic conglomerates, indicate tectonic evolution prior to deposition of the Gausta Formation. This is also supported by the whole-rock geochemistry and the difference in detrital framework between the Heddersvatnet and Gausta Formations (Köykkä, submitted).
Conclusions

New sedimentological observations and geochemical data reported in this study show that the Heddersvatnet Formation and the Vemork Formation interfinger with each other. This suggests that the sub-Heddersvatnet unconformity continues under the Vemork Formation and represents a likely angular unconformity above the Tuddal Formation. The stratigraphic position of the Vemork Formation as part of the Rjukan Group is thus brought into question; the Vemork Formation would be better treated as part of the Vindeggen Group.

The geochemistry of the Heddersvatnet Formation basaltic lavas are characterized by a geochemical signature similar to that of some continental flood basalts and the Vemork Formation basalt. The composition is compatible with a continental within-plate paleotectonic setting.

The Heddersvatnet Formation is interpreted as representing alluvial fan sedimentation during the syn-rift phase of the sedimentary basin (Fig. 5 & Köykka, submitted). The volcanic-sedimentary Vemork Formation gradually filled the rift, whereas the Heddersvatnet Formation was deposited in or near uplifted flank(s) of the rift basin. The magmatic and tectonic evolution of the Heddersvatnet Formation is characterized by more evolved magma, with some crustal contamination during deposition. The termination of the volcanism and sedimentary lithofacies assemblages suggests a gradual change from the syn-rifting to the post-rifting stage, and deposition of marine-dominated sediments of the Gausta Formation.

Acknowledgements

This study is based on fieldwork and geochemical laboratory work that was carried out in the years 2007-2008 and . This work was supported in part by the Finnish National Graduate School of Geology and the Faculty of Science at the University of Oulu. The author would like to thank B. Bingen and A. Solli for constructive reviews and emeritus professor K. Laajoki for guidance.

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