Structure and petrofabrics of quartzite and elongate pebbles at Sandviksfjell, Bergen, Norway

ARTHUR G. SYLVESTER AND DAVID R. JANECKY


Thrust slices of Precambrian gneiss and its thin cover of Lower Paleozoic (?) metasedimentary rocks were imbricated during the Caledonian orogeny and are now exposed at Sandviksfjellet on the northeast side of Bergen. Locally one of the main thrust faults between metasedimentary rocks and the overlying crystalline nappe is folded into a 50 m-high Z-fold whose axis is parallel to the main lineation and to the overall southeastward Caledonide transport direction. Pebbles in the hinges and mid-limb of the Z-fold are greatly elongated into prolate ellipsoids up to 1.25 m long. External to the fold, quartzite pebbles are oblate spheroids. Preferred orientation of c axes of quartz in both pebbles and associated meta-arkose is surprisingly weak and not clearly related to the mesoscopic fabric. Partitioning of strain along the thrust faults and compositional heterogeneity of the metasedimentary rocks are regarded as the main reasons why the quartz c axis subfabrics are so weak.

Most of the final shape of the greatly elongated prolate pebbles in the Z-fold is postulated to result from an extremely inhomogeneous strain distribution, however, little of the sequence of events resulting in pebble deformation is preserved in the quartz subfabric. In fact, considerable pebble strain may have been accomplished by pressure solution without intracrystalline plastic flow. Two deformation models are presented to explain the relations between the folded thrust and the prolate pebbles: one synkinematic and the other late- or post-kinematic. Synkinematic formation of the large Z-fold and elongation of the pebbles involved alternative extension and constriction of the metasedimentary sequence beneath the main nappe when it overrode a structural asperity. In the alternate two-stage model, emplacement of younger, higher nappes deformed the older, main thrust and part of its footwall of metasedimentary rocks. After the Ulriken Gneiss Nappe was emplaced above the metasedimentary rocks, with consequently increased load pressure and increased ductility in the lower plate, weak nearly orthorhombic preferred orientations of quartz c axes were imposed in all of the quartzose rocks, and pebbles were flattened even more.

A. G. Sylvester, Department of Geological Sciences, University of California, Santa Barbara, California 93106, USA; D. R. Janecky, University of California, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.

The relatively high degree of symmetry and frequent repetition of patterns of preferred orientation of various minerals in metamorphic tectonites have always seemed to promise a means of insight and interpretation into the stress and strain history of these rocks beyond what may be gained mesoscopically. Based largely on successful experimental studies, dynamic interpretations may now be made of most patterns of preferred orientation of calcite and dolomite (Wenk et al. 1973; Wenk & Shore 1975), and of some patterns of quartz (Sylvester & Christie 1968; Lister & Price 1978; Lister & Hobbs 1980; Law 1986; Law et al. 1986).

This study addresses two questions which may give insight to mechanisms of deformation accompanying overthrust faulting: (1) Does the process which causes pebbles to be greatly constricted impart a preferred orientation to quartz in those pebbles which, in and of itself, is unique to that particular deformation? (2) Do the mesoscopic fabrics, including those of the pebbles, and the preferred orientations of quartz provide insight to the mechanisms of deformation in a major thrust zone? The answers require knowledge of the mechanism of pebble deformation as well as the temporal and mechanistic relation of the quartz subfabric to the pebble deformation.

Deformed pebbles are not completely reliable indicators of strain in a rock mass, because they may deform very differently from their matrix both in bulk and individually, because their shape, size, and orientation vary in the original rock (Ramsay 1967), and because of stress solution (Mosher 1987). However, in those cases where
initial clast shape, axial orientation, deformation path, and deformation mechanism were known or confidently inferred, the pebble strain has been inferred correctly (Flinn 1956; Burns & Spry 1969; Mosher 1987), lending credence to interpretations of very strongly deformed pebble fabrics.

Undefomed clasts are not present in or near our study area, so we are unable to quantify the pebble strains, but we assume that the pebble shape reflects the symmetry of deformation. We also assume that both the mesoscopic and microscopic fabrics resulted primarily from deformation during the Caledonian orogeny, although we are aware that this assumption may not be valid as Evans and White (1984) learned in the Scottish part of the orogen.

Several investigators have attempted with variable degrees of success to determine principal strain axes by petrofabric studies of deformed pebbles and quartzites beneath Caledonian and Appalachian thrust sheets (Strand 1944; Oftedal 1948; Kvale 1945, 1953; Brace 1955; Flinn 1956; Koark 1961; Christie 1963; Hossack 1968; Ramsay & Sturt 1970; Kronenberg 1981). In nearly every published case, the pebble constriction may be regarded as the result of penetrative deformation during overthrust faulting, whereas the preferred orientation of quartz apparently represents a late-kinematic flattening attributable to the mass of the newly-emplaced, overlying nappe, just as Christie (1963) demonstrated for the main phase of deformation during movement of the Moine thrust in northwest Scotland. This is because quartz c axes readily ‘forget’ influences of earlier parts of the deformation history and thus record only the effects of late, comparatively slow, relatively homogeneous, and penetrative deformation (Lister & Price 1978; Brunel 1980).

Geologic setting

The quartzite and conglomerate studied in this investigation are considered to be part of a metasedimentary and metaigneous group of rocks of Lower Paleozoic (?) age (Kolderup & Kolderup 1940; Kvale 1960; Sturt & Thon 1978). Because the stratigraphic assignment is uncertain, this sequence of rocks is here informally called the Sandviksfjell group for exposures on the northeast flank of that mountain in the northeastern part of the city of Bergen. The Sandviksfjell group consists chiefly of arkosic quartzite and quartz schist, with lesser proportions of mica schist, conglomerate and greenstone. These rocks and the Precambrian gneisses with which they are associated are found in imbricate thrust slices of Caledonian age within the Inner Bergen Arc (Fig. 1).

The core of the Inner Arc consists of the Øygarden gneiss (Sturt & Thon 1978), which is part of the autochthonous Western Gneiss Group (Bryhni & Sturt 1985; Roberts & Gee 1985), overlain tectonically by Lower Paleozoic schist and metavolcanic rocks assigned to the Upper Allochthon of the Norwegian Caledonides (Bryhni & Sturt 1985). Above these rocks are several imbricate thrust slices assigned to the Middle Allochthon (Bryhni & Sturt 1985) involving Precambrian crystalline rocks as well as minor amounts of metasedimentary rocks lithologically similar to the Sandviksfjell group. All of the rocks of the Inner Arc are tectonically overlain by thrust sheets composed of Precambrian para- and orthogneisses of the Ulriken Gneiss Nappe together with plutonic rocks of the anorthosite-mangerite kindred of the Outer or Major Bergen arc (Kolderup & Kolderup 1940; Sturt & Thon 1978) in the Lindås Nappe (Bryhni & Sturt 1985). Overall Caledonide thrusting direction in the Bergen area is east- and southeastward, judging from the orientation of lineations, sheath folds, and branch lines (Kvale 1953, 1960; Hossack 1985). The distance of overthrusting is at least 400 km (Hossack 1985).

In order to characterize the structural relations of the Sandviksfjell group in more detail, we mapped a 10 km² area of imbricated gneiss and metasedimentary rocks at a scale of 1:5000. The study area, which extends from the center of Bergen, northwest to Hellneset, is bounded on the southwest by Byfjorden and on the northeast by a line trending approximately northwestward from Blåmansvatnet to Storediket to Kobbervika (Fig. 2). A suite of oriented specimens of quartzite and deformed pebbles was collected for petrofabric study from the central and best exposed part of the area near Munkebottsvatnet and Langevatnet (Fig. 3).

Lithology and structure

Øygarden and Ulriken gneisses

The Øygarden gneiss has a Rb/Sr isochron age of 1750 ± 60 Myr, and late stage anatectic dikes in
the Ulriken gneiss have a 1440 ± 100 Myr isochron (Sturt et al. 1975). Both gneisses are characterized regionally by mineral assemblages typical of the amphibolite facies, thought to have developed during polyphase deformation in Precambrian time (Sturt & Thon 1978).

The Øygarden gneiss is a strongly foliated, biotite-rich, pink, granitic gneiss with common porphyroblasts of potassium feldspar. It is intruded by dikes and irregular masses of mafic igneous rocks, now metamorphosed to amphibolite, which are boudinaged and also strongly foliated. Anatectic dikes and small masses of medium-grained, locally foliated gray granite and coarse pegmatite cut the gneiss and amphibolite and are locally associated with bending of the foliation of the gneiss.

The Ulriken gneiss in the study area is composed of migmatite gneiss intruded by foliated porphyritic granite. Locally, migmatite xenoliths in the granite preserve an older foliation that is cut by the granite and variably obliterated by a younger foliation. A zone of blastomylonite up to 10 m thick is present at the base of the Ulriken gneiss where it is in thrust contact with rocks of the Sandviksfjell group.

A strong foliation in both gneiss complexes dips
Fig. 2. Generalized geologic map of the area between Eidsvågfjellet and Fløyfjellet. Barbs on thrust faults are on the upper plate. The area in the polygons shown in Fig. 3.
Fig. 3. Detailed geologic map of the Langevatnet–Munkebottsvatnet area. Sample locations for microfabric studies are marked with x and a Qn or Pn sample number.
moderately northeastward, approximately parallel to the main layering in the metasedimentary rocks and the thrust faults. Locally, in the Lynghaugen and Himplane areas of Bergen (Fig. 2), the main foliation of the Øygarden gneiss is warped into broad, macroscopic folds that plunge gently northeastward (Fig. 4). A weakly developed lineation in the gneisses is parallel to the axes of these folds (Fig. 4). Macroscopic folds were not discerned in the Ulriken gneiss within the study area.

Most deformation of the Øygarden gneiss preceded the deposition of the Sandviksfjell group of rocks, so a comprehensive study of either of the gneiss complexes was not done except to determine qualitatively the extent to which deformation of the metasedimentary rocks was also imprinted on the gneiss. Within the Øygarden gneiss a thrust fault, which is well exposed in the canyon south of Håmanen, is inferred to extend northwest to Eidsvågfjellet (Fig. 2), based on the presence of a topographic lineament that separates strongly banded gneiss west of the fault from more homogeneous gneiss to the northeast.

Sandviksfjell metasedimentary rocks

The lower three-quarters of the Sandviksfjell group are predominantly arkosic metaquartzite, whereas muscovite-rich quartz-feldspar schist with interbedded lenses of conglomerate constitutes the upper quarter of the sequence near the main thrust fault (Figs. 2, 3). Layering in the metasedimentary rocks is generally parallel to the foliation in the bounding gneisses. Where not obliterated by deformation, graded bedding and cross stratification show that the sequence is upright. Quartz, mica, and porphyroclasts of K-feldspar constitute the typical mineral assemblage of the metasedimentary rocks and indicate conditions of greenschist facies metamorphism which, regionally, Sturt & Thon (1978) associate with polyphase Caledonide deformation.

The contact of the metasedimentary sequence with the underlying Øygarden gneiss is poorly exposed and discontinuous, but where observed it is generally a strongly sheared zone of mechanical detachment which follows a primary contact. Approximately 100 m west of Munkebottsvatnet (Fig. 3), however, the contact zone lacks sheared textures and grades upward from siliceous gneiss through a thin zone of muscovite-rich quartz-feldspar schist to arkosic quartzite, indicating a depositional contact.

The upper contact of the Sandviksfjell group is a major detachment zone of strongly sheared rocks and blastomylonitic Ulriken gneiss. Identified thrusts, primarily within the upper metasedimentary rocks, include slices of highly sheared gneiss assumed to be Ulriken gneiss (Fig. 3). The uppermost zone of sheared rock thickens northwestward to Kobbervika where the dip of
the thrust faults steepens and the metasedimentary rocks are thinner (Fig. 2). Layers of black ultramylonite up to 10 cm thick are present in the basal parts of the imbricate thrust faults between Langevatnet and Orretua (Fig. 3) and can be traced continuously for distances up to 100 m.

Near the thrust faults the metasedimentary rocks have a strong schistosity which is parallel to lithologic layering and is defined by subparallel orientations of mica and flattened quartz and feldspar grains. Schistosity is most strongly developed within 10 m of the faults and is virtually absent in the central and lower parts of the sequence except near the basal thrust fault.

A strong lineation, defined by the elongated growth of mica, elongation of quartz and feldspar, axes of minor folds, elongate pebbles, and crenulations in the axial surface cleavage, is well-developed in both the metasedimentary rocks and the mylonitic gneisses. The general orientation of the lineation is NW–SE, nearly horizontal (Figs. 3, 5).

**Conglomerate**: Conglomerate bodies are evidently lenticular, cannot be traced over very great distances, are parallel to non-tectonic lithologic

---

Fig. 5. Composite point diagrams (lower hemisphere, equal-area) of orientations of planar and linear structures in metasedimentary rocks of the Sandviksfjell area. A. 64 poles to foliation (dots) in mylonite and conglomerate along thrust fault at the base of the Ulriken gneiss. B. 38 lineations (dots) and 2 fold axes (x’s) in mylonite and conglomerate. C. 26 poles to foliation (dots), 4 lineations (x’s), and 13 fold axes (open circles), in quartzite in Blåmansvatnet area. D. 56 poles to foliation (dots), 17 lineations (x’s), and 9 fold axes (open circles) in quartzite, Langevatnet-Munkebottsvatnet area.
layering, and are not found in a consistent, relative, stratigraphic position in the metasedimentary sequence. For example, thin layers of conglomerate are present near the base of the sequence between Storevatnet and Storediket, whereas between Munkebottsvatnet and Langevatnet, conglomerate crops out almost continuously beneath each imbricate slice of the upper thrust (Fig. 3).

Conglomerate pebbles are chiefly white quartzite, but pale blue, gray green, and light pink varieties are also present. A few gneissic pebbles were found near Blåmansvatnet and as far northwest as Storediket (Fig. 2). K-feldspar is a minor component in the pebbles, but the conglomerate matrix is a mica-rich arkose with common porphyroclasts of potassium feldspar and about 5% calcite.

Pebble shapes range from oblate disks up to 30 cm in diameter with their shortest dimension normal to the foliation, to greatly prolate, nearly sword-shaped, triaxial ellipsoids more than one meter long. The latter are found only in the mid-limb and hinges of a 50 m-high Z-fold at Sandvikshytta (Figs. 3, 8). Suites of 30 stretched pebbles were measured at each of three exposures within that fold and yielded axial ratios (longest: intermediate: shortest) ranging from 10:2.5:1 to 20:2:1. The longest pebble we found measured 1.25 m. If recalculated to spheres of equivalent volume, then many of the pebbles must, in fact, have been boulders originally, concentrated in one area probably representing a channel in a braided stream complex. Oblate pebbles are smaller, sparsely distributed, and provide only a qualitative impression that their general shape is one of semi-equant disks.

Folds: Small folds with wavelength of approximately one meter are present in the metasedimentary rocks, chiefly in quartz-mica-feldspar schist between the imbricate thrusts. They are not common directly beneath the main thrust. Their axes are oriented NW–SE, parallel to the lineation, and they have an asymmetric, somewhat disharmonic style with variably dipping axial surfaces (Figs. 6, 7). A weak cleavage parallel to the axial surface is commonly crenulated, defining a lineation parallel to the hinges of the folds. Locally, some of the flattened quartzite pebbles are also folded parallel to the crenulated cleavage. All of the folds verge to the northeast and increase in abundance from northwest to southeast along the belt of outcrop (Fig. 3). In form and style, the
folds in the quartzite are similar to those described in many orogenic belts, for example, ‘Rillenfalten’ (Lindström 1961) in arkosic rocks along the east front of the Caledonide orogen in northern Sweden.

At Sandvikshytta the upper thrust fault between Ulriken gneiss and metasedimentary rocks is folded into a single, 100 m high, asymmetric, northeast-verging fold (Figs. 3, 7). Here is the principal location of strongly constricted quartzite pebble conglomerate in the study area, and it is defined by the outcrop of the conglomerate with a thick mid-limb and hinges and thin outer limbs. It is positioned structurally between two thrust faults, and two blind imbricate thrusts may terminate in it (Fig. 3, 7). The fact that the main thrust fault is folded with the conglomerate indicates to us that the fold formed during or after the principal local episode of thrusting.

Structural petrology

Sandviksfjell metasedimentary rocks

Five oriented specimens of quartz-rich metasedimentary rocks were collected in the Munkebottsvatnet–Langevatnet area stratigraphically upward from the base of the metasedimentary sequence to the basal thrust fault of the Ulriken gneiss (Fig. 3) to investigate penetrative and/or progressive influence of shear deformation on the quartz c axis subfabric. A sixth sample of highly sheared micaceous quartzite was collected 20 cm below the uppermost thrust fault, 100 m west of Orretua (Fig. 3). Orientations of c axes in 150 grains were measured optically in each of two mutually perpendicular thin sections on a universal stage and were combined into composite lower hemisphere, equal area projections (Fig. 9). Each projection is oriented relative to the foliation and lineation of the mesoscopic fabric.

Petrography: The metasedimentary rocks are composed of quartz (40–50%), K-feldspar (30–40%), muscovite and biotite (10–20%), albite (5–10%), and trace amounts of zircon and garnet. Texture ranges from granular to lepidoblastic granular, depending on the mica content. Quartz grains range in size from 0.1 mm to 0.5 mm and in shape from equant with regular boundaries to strongly flattened or stretched ribbons. These may be referred to as alpha and beta quartz grains, respectively, in the terminology of Lister & Price (1978). Within 1 m of the thrust faults, quartz grains are increasingly flattened or constricted, and small, new, strain-free grains increase in abundance along preexisting grain boundaries. The large quartz grains generally exhibit strong undulatory extinction. Deformation lamellae are notably sparse; they were observed in fewer than six per 300 grains. Muscovite is fine-grained in sheets parallel to the foliation, and in ultra fine-grained, sericitic, felted mats within thrust zones. The micas are bent in all rock samples and kinked in many. Large muscovite grains wrap around quartz grains in the least deformed rocks. K-feldspar ranges from small (0.1 mm), irregular-shaped grains between quartz grains to broken porphyroclasts up to 3 mm in maximum dimension with oriented inclusions of albite and biotite in the least deformed rocks. The proportions of major minerals, the presence of zircon and twinned feldspar, and the presence of oriented biotite and plagioclase inclusions in the K-feldspar indicates that these rocks were derived from a granitic terrain. The overall texture is typical of a protomylonite.

Microfabrics: Preferred orientation patterns in all specimens are very weak except for a tendency toward a pole-free area around the mesoscopic lineation (Fig. 9). In distribution and strength, the fabric patterns of individual samples resemble microfabrics typical of undeformed, unrecrystallized orthoquartzites (Sylvester & Christie 1968, their specimens Q1 and Q2).

In view of folding, thrust faulting and mesoscopic deformation which have affected these rocks, the lack of preferred orientation of
quartz is surprising, because stronger quartz subfabrics have previously been observed in mesoscopically undeformed quartzite many tens of meters from thrust faults in New England (Balk 1952) and Scotland (Law et al. 1986). The lack of preferred orientation may be regarded as evidence for deformation by grain-boundary mechanisms rather than dislocation creep and reorientation of quartz c axes (Edington et al. 1976; Etheridge & Wilkie 1979; Etheridge & Vernon 1981), but it is clear that strain was concentrated along the mica-rich layers which partition domains of quartz into microlithons of little or no strain. However, other factors including the heterogeneous mineralogy of the rocks (Price 1978), the superposition of late-stage deformation (Lister & Price 1978; Brunel 1980), a non-coaxial strain history (Oertel 1983), and intensification of deformation only close to the thrust itself (Gretener 1977; Law et al. 1984) may also explain the relative weakness of the quartz subfabric, as discussed below.

**Conglomerate**

Five oriented samples of deformed pebbles and one sample of associated arkosic matrix were collected from the lenticular conglomerate below the basal thrust fault of the Ulriken gneiss (Fig. 3) to investigate the relationships between mesoscopic and microscopic deformation features. These samples include a range of pebble shapes associated with the Z-fold at Sandvikshytta (Fig. 7), including disks (P1, P2), elongate pebbles from the upper and lower fold limbs (P4 and P3, respectively), and an elongated pebble from the upper fold hinge zone (P5). The samples from oblate pebbles vary in distance from the basal thrust (1 m above P1 versus 5 cm above P2), and in composition with P1 containing significant K-feldspar. Quartz c axis subfabric (Fig. 10) was determined in the same fashion as for metasedimentary rocks described above.

**Petrography:** The pebbles are composed of quartz (90%), K-feldspar (<5%), muscovite (<5%),
Fig. 9. Contoured lower hemisphere, equal-area stereographic projection plots of quartz c axis subfabric in quartzite. Each diagram represents 300 data points. Contours are in percent per 1% area. S1 (equator) and L1 (projection center) show orientations of foliation and lineation, respectively. Dashed great circle represents the horizontal plane. Sample locations are shown in Fig. 3.

Q1. Quartzite collected 100 m west of Munkebottsvatnet near base of metasedimentary sequence. Q2. Quartzite collected 10 m north of Munkebottsvatnet near base of metasedimentary sequence. Q3. Cross-stratified quartzite collected 120 m northeast of Munkebottsvatnet near middle of metasedimentary sequence. This sample is probably the least deformed of all the quartzite samples. Q4. Quartzite collected 200 m northeast of Munkebottsvatnet near the top of the metasedimentary sequence. Q5. Quartzite collected 260 m northeast of Munkebottsvatnet, 4 m beneath thrust fault. Q6. Quartz-feldspar-mica schist collected 100 m northwest of Orretua, 20 cm above quartzite but about 1 m beneath the thrust fault itself.
and small amounts of zircon, garnet, chlorite, muscovite, and biotite. Oblate pebble P1 has less quartz (60%) and more K-feldspar (35%) and muscovite (5%) than all others. Average grain size ranges between 0.1 mm to 0.5 mm. The quartzite texture is interlocking granular with grains somewhat flattened in the foliation in the oblate pebbles and elongated parallel to the lineation in prolate pebbles. Most grains are irregularly-shaped with highly serrated boundaries and with development of small, new, strain-free grains along preexisting grain boundaries, along intra-crystalline defects, and at junctions of several grains. Internally, the quartz has strong undulatory extinction, and many grains are mosaics of another. Some of the feldspars in the K-feldspar-rich pebble appear to be subgrains of once larger crystals that have been mechanically broken.

Muscovite laths are short, isolated, and commonly bent or kinked.

Quartz subfabric: Orientation patterns of the oblate, K-feldspar-rich pebble (P1) and the matrix sample (P3A) are weak, although like the meta-sedimentary samples (Fig. 9), they show a tendency toward a pole-free area about the lineation (Fig. 10). Prolate pebbles and an oblate pebble nearest the thrust contact show especially well-developed pole-free area patterns (Fig. 10). In pebbles from the upper fold limb and hinge (P4 and P5), the peripheral girdle is cleft slightly from the primitive as if tending toward a cross-girdle pattern (Fig. 10). However, the overall symmetry of these prolate pebble patterns is orthorhombic. Patterns for some prolate pebbles have weak maxima disposed perpendicularly and symmetrically in a peripheral girdle with respect to the main lineation (P4, P5), whereas others have distinctly asymmetric patterns (P3) (Fig. 10). In oblate pebble P2, a single maximum in a peripheral girdle is perpendicular to the lineation, but at an angle to the plane of the pebble containing the greatest and intermediate axes and to the foliation in the surrounding rock. In this case, the quartz subfabric is orthorhombic, but the overall fabric is monoclinic.

Muscovite subfabric: Preferred orientation of muscovite (001) in a prolate pebble (P3) was measured by Steve Lipshie using X-ray transmission on a modified pole-figure goniometer (Oertel 1970; Oertel & Curtis 1972; and Lipshie et al. 1976). Principal strains calculated from the resulting projection (Fig. 11) are (Lipshie, written communication, 1980):

Preferred orientation: \( (p_i) = (0.251 \quad 0.53 \quad 7.56) \)
March 'strain': \( (E_i) = (0.59 \quad 0.24 \quad -0.49) \)
Pebble strain: \( (p_{E_i}) = (5.21 \quad -0.37 \quad -0.74) \)

The March 'strain' (March 1932; Lipshie et al. 1976) for this pebble indicates an orthorhombic flattening in contrast to the constrictional pebble strain. However, the relation between March 'strain' and actual strain suffered by the rocks may not be straightforward, because even if the March 'strain' is real strain, it probably represents only a late part of the total deformation (Lipshie, pers. comm.). In addition, the March 'strain' calculations are normalized to constant volume and assume an 'original' or uniform distribution of marker orientations. Lipshie calculated the pebble strain by assuming both constancy of volume and original spherical strain. The discrepancy between the pebble strain and the March 'strain' may be reconciled by postulating that the pebble elongation and formation of the quartz subfabric were synkinematic, and that the mica subfabric represents late minor flattening of the pebbles after they were elongated. Thus, the final strain was well recorded by mica but only weakly by quartz.

Discussion

Quartz subfabric: Overall deformation features and the orientation of the short axis of oblate pebbles are normal to the thrust fault, suggesting that deformation of the pebbles and meta-sedimentary rocks occurred contemporaneously, and we would expect that the deformation would be recorded by the quartz subfabric. However, the weak or random microfabrics in Sandviksfjell metasedimentary rocks are surprising for rocks so near a major zone of deformation, and they contrast greatly with microfabrics in rocks associated with deep-seated thrust faults elsewhere (e.g., Kvale 1945; Balk 1952; Christie 1963). The general pattern of quartz preferred orientation in the Sandviksfjell rocks, a c axis maximum in a peripheral girdle normal to the lineation, the Type II fabric in the classification of Lister (1979), is a
Fig. 10. Lower hemisphere, equal-area projection plots of quartz c axis subfabric in pebbles, Sandviksfjell area. Each diagram represents 300 data points and is contoured in percent per 1% area. S1 and L1 give orientations of the foliation and lineation, respectively. Dashed circle represents the horizontal plane. Sample locations are shown in Figure 3. P1. Oblate pebble collected 1 m beneath thrust fault, 100 m southwest of Orretua. P2. Oblate pebble collected 5 cm beneath thrust fault, 120 m south of Orretua. P3. Prolate pebble collected in lower hinge of Z-fold 300 m northeast of Munkebottsvatnet near Sandvikshytta. P3A. Arkosic matrix at prolate pebble locality P3, 300 m northeast of Munkebottsvatnet near Sandvikshytta. A is fold axis, and A. P. is axial surface of Z-fold at Sandvikshytta where sample was collected. P4. Prolate pebble collected in upper limb of Z-fold 360 m northeast of Munkebottsvatnet near Sandvikshytta. P5. Prolate pebble collected in upper hinge of Z-fold 360 m northeast of Munkebottsvatnet.
Fig. 11. Preferred orientation diagram for muscovite in pebble P3 determined by transmission X-ray measurement of (002) reflection from the mica (001) plane (Lipshie, pers. comm.) Contours are in multiples of population density for a uniform distribution of grain orientations: 0.5, 1, 2, 4, and 6 times uniform distribution density. Principal directions of preferred orientation distribution are indicated by p. Foliation approximately coincides with the plane containing p1 and p2; greatest pebble length is approximately parallel to p1. Orientation of the diagram is the same as for prolate pebble P3, Figure 10.

commonly observed pattern, particularly in rocks near thrust faults (Christie 1963; Eisbacher 1970; Evans & White 1984; Law et al. 1984, 1986; Law 1986). Combined with the mesoscopic fabric elements of foliation and lineation, the symmetry of the fabric is nearly orthorhombic, consistent with a flattening deformation in pure shear (Sylvester & Christie 1968).

Quartz c axes in the prolate pebbles are oriented only slightly more strongly than those in the oblate pebbles, and the coincidence of the pole-free area with the maximum elongation direction of the pebbles is consistent with earlier interpretations by other investigators that, in syntectonic deformation, c axes of quartz tend to be oriented perpendicular to the direction of greatest stretching (Sylvester & Christie 1968; Eisbacher 1970; Lister & Price 1978). The slight asymmetry in type I girdles (Lister 1979) exhibited by some of the Sandviksfjell rocks has been used with increasing frequency to determine sense of shear (e.g., Gaudemer & Tapponier 1987; Postlethwaite & Jacobson 1987), but ambiguous results may be obtained (Passchier 1983), and the method should not be the sole basis for the interpretation of shear sense (Simpson & Schmid 1983). Because of the weakness of the preferred orientations in our case, we prefer not to use their asymmetry for a statement about sense of shear.

Lister (1979) also postulated that the positions of maxima are significant in a quartz subfabric diagram, but the weakness of the maxima in all diagrams for the Sandviksfjell microfabrics makes their interpretation very speculative. A maximum of 5% for a sample of N = 300 may be generated from random numbers.

The weakness of the preferred orientations may be explained in several ways: (a) obliteration of an older fabric by superposition of a younger one; (b) inhibition of fabric development by the presence of other mineral phases; and (c) strain partitioning.

An initially strong preferred orientation may have been obliterated by annealing after thrusting or by selective superposition of a later fabric, because quartz c axes rapidly forget the influences of earlier parts of a deformation history and record only the latest one (Lister & Price 1978). The provenance and pre-elongation microfabric of the Sandviksfjell pebbles are not known, however, so it is idle to speculate that the pebbles were derived from quartzites already having a strong microfabric, or that such a microfabric was modified considerably in the deformation accompanying thrusting, folding, and flattening.

It is also generally expected that the presence of other mineral phases will inhibit the development of quartz preferred orientation (Hobbs et al. 1976; Malavielle & Etchecopar 1981). Indeed, several writers have appealed to this explanation for naturally deformed quartzo-feldspathic rocks (Price 1978; Starkey & Cutforth 1978; Lister & Price 1978; Wilson 1980; White et al. 1982). But the evidence is contradictory, as discussed by Dell’Angelo & Tullis (1986), whose experiments showed that ‘the presence of feldspar has little or no effect on the operative slip systems in adjacent quartz grains in quartzo-feldspathic rocks’ and that ‘quartz c axis preferred orientations in aplite and quartzite at equivalent deformation conditions and quartz grains strains are essentially identical in pattern and strength’. The observations on naturally deformed micaceous rocks are equally conflicting when it is generally observed that the strength of quartz preferred orientation decreases with increasing mica con-
tent (Sylvester & Christie 1968; Kronenberg 1981) in contrast to White et al. 1982) who found no difference in $c$ axis orientations of recrystallized quartz grains between pure quartzite and quartz-mica layers of quartz-rich rocks associated with the Moine thrust. On the other hand, fault rocks and ductile shear zones are weaker than the adjacent rocks from which they are derived, so deformation may be preferentially concentrated or partitioned into fault and shear zones with little relation to that in the country rocks (Watterson 1975; White 1976, 1977; White et al. 1980; Lister & Williams 1984; Evans & White 1984; Law et al. 1984).

The presence of discrete zones of high strain, from thrust faults at the macroscopic scale to microfaults which bound microlithons of relatively unstrained grains at the microscopic scale, indicates to us that deformation in the meta-sedimentary rocks was partitioned at all scales. Thus deformation was not completely penetrative nor sufficiently effective to recrystallize or reorient quartz to a strong and distinctive pattern. To be sure, quartz did not get away scot free as shown by the strong undulatory extinction and ragged grain boundaries decorated with small, new grains.

**Origin of the prolate pebbles:** Several writers (Hobbs et al. 1976; Roy & Færseth 1981; Mosher 1987) have discussed the problems of prolate pebbles elongated parallel to the axis of a fold, and Ramsay (1967) offers three ways to accomplish such a feature:

1. The greatest principal extension is simply parallel to the fold hinges, and when the folds are tightened in constrictive deformation, elongation occurs parallel to the fold axis as in ‘dough rolling’ (Flinn 1956; Borradaile 1972; Lister & Price 1978), and thus, pebbles are relatively faithful recorders of the strain;
2. Already prolate pebbles are reoriented by rotation in simple shear. Once rotated into the principal direction of shear, they may be further deformed and elongated;
3. Two-stage deformation with a unique coincidence of tectonic and pre-tectonic fabrics. Following the first deformation, the short axes of oblate spheroid pebbles are nearly parallel to the maximum extension direction of a subsequent plane strain. Thus, the final shape of the pebbles is influenced by their initial shape even though the maximum elongation of the pebbles may not be parallel to the corresponding principal extension axis of the mean strain ellipsoid in the second deformation.

The first of these mechanisms may be visualized as extrusion flow normal to the direction of fold transport, parallel to the hinge of a tightening fold. Cloos (1948) suggested that stretching and shortening on a regional scale may alternate along the trend of the fold axis just as the folds show culminations and depressions perpendicular to the trend of the fold axis. Where the fold axis is parallel to the regional transport direction, as is quite common near major thrust faults, especially in the Caledonian and Appalachian orogens, a classic paradox is raised: How and when were folds formed with axes parallel to the movement direction of the thrusts? We are not persuaded that a completely satisfactory explanation exists for this commonly observed relation (see reviews by Eisbacher 1970; Williams 1978), although we do acknowledge that local shortening and crumpling transverse to the regional transport associated with thrusts may be expected where horizontal compressive stress perpendicular to the direction of movement exceeds the near-vertical compressive stress due to the overburden. Analogous vertical folds are common on the margins of salt domes and granitic diapirs (Balk 1953; Sylvester 1964; Talbot & Jackson 1987).

An alternate explanation for linear structures, especially folds, associated with thrusts, holds that such features readily rotate into parallelism with the principal direction of shear and that once rotated, those linear structures may be stretched further (Lindström 1961; Bryant & Reed 1969; Sanderson 1973; Escher & Watterson 1974; Williams 1978; Carreras et al. 1977; Quinquis et al. 1978; Bell 1978; Cobbold & Quinquis 1980; Berthé & Brun 1980; Skjernaa 1980; Roy & Færseth 1981; Williams et al. 1984; Shackleton & Reis 1984; Ridley 1986). If this is a viable explanation for the constriction of quartzite pebbles, then at Sandviksfjell all pebbles should be strongly prolate with consistent axial directions, and regionally transitional orientations and shapes between unrotated and fully rotated pebbles should be observed, as has been found in allegedly rotated folds in the Caledonian and Appalachian thrust belts (Lindström 1961; Bryant & Reed 1969). However, in the study area, strongly prolate pebbles are found only in the core of the Sandvikshytta fold.
Ramsay (1967: 220) showed that a strain of 4:3:1 could be imposed on a general pebble shape having axial ratios 5:2:1 to yield pebbles stretched in Y of the second deformation to as much as 15:4:2. This approaches the deformation of 20:2:1 observed in the Sandvikshytta Z-fold. Unfortunately we lack an independent measure of the pebble shapes, or their shapes after elongation but before flattening, and there is no measure of the magnitude and orientation of a second deformation to give a quantitative solution to the problem.

These general mechanisms require constancy of rock volume in the thrust fault zone, but volume losses up to 55% may occur during deformation (Ramsay & Wood 1973; Mosher 1987), chiefly by diffusive mass transport aided by the presence of water at grain boundaries (Rutter 1976; McEwen 1978) if significant gradients of pressure obtain (Rutter 1978). Because faults are zones of weakness, large amounts of fluids may be channeled through them at some stage, possibly resulting in significant mass fluxes. Where large scale flattening has taken place between rather rigid, or at least much less plastic thrust plates, local and inhomogeneous creep in final stages of deformation may lead to strain softening and large strains along narrow zones at low deviatoric stresses (Mitra 1984). At temperatures in the greenschist facies range (200°C–350°C), effective diffusivities in the aqueous phase may be nearly equal to solid state diffusivities at very much higher temperatures (Rutter 1976). Indeed, textures thought to be characteristic of diffusive mass transfer by stress solution are common in rocks deformed at temperatures up to about 350°C, whereas crystal plastic flow textures dominate at higher temperatures.

Deformation of water saturated rock, under the nearly axially symmetric stress due to a newly imposed thrust sheet, would be expected to proceed anisotropically, and grain boundaries that are most compressively stressed should dissolve preferentially just as the most compressively stressed pebble surfaces do on the mesoscopic scale (Mosher 1987). Hence, nearly axially sym-

---

**Fig. 12.** Block diagrams showing sequence of events using the contemporaneous deformation model which could lead to formation of prolate pebbles parallel to the hinge of the Sandvikshytta fold and thrusting direction: A. Emplacement of nappe complex including Ulriken gneiss on Øygarden gneiss and overlying metasedimentary sequence of Sandviksfjell. Asperity on lower plate causes the basal part of the upper plate to dome and stretch transversely to the transport direction. B. After the asperity is passed, the base of the upper plate constricts by folding to its original width, and the fold axis is parallel to the transport direction. Pebbles only in the hinge and mid-limb of the fold are constricted by one or combinations of several mechanisms, including 'dough rolling', superposition of a plane strain on the partially deformed pebbles, and diffusion creep.
metric flattening strain with volume loss will occur with the short axis approximately normal to the thrust surface due to the load of the thrust sheet, without compensating stretching parallel to that surface. The geometry of such a strain may be the one recorded by the oblate pebbles at Sandviksfjell.

The prolate pebbles and associated Z-fold, however, require a more complex process to account for their origins. Two possibilities exist: (1) synkinematic deformation with ongoing thrust movement and (2) deformation associated with at least local cessation of thrusting or even with somewhat later events. For the first model, stretching of thrust sheets transversely to the transport direction occurs as a result of traversing an asperity in the underlying rocks (Fig. 12A). After passage of the asperity, folding and minor imbricate thrusting of the sheets may occur when they again constrict to their original width. With such a history, fold axes will be approximately parallel to the overall transport direction (Fig. 12B).

A second possible explanation involves parasitic folding associated with formation of the Bergen Arcs structure and emplacement of the anorthosite complex of the higher and younger Upper Allochthon (Fig. 1). All folds observed in the study area have a northeast vergence consistent with such an interpretation and thus could have been formed at the end of, or after, emplacement of the Middle Allochthon. In either case, the process of folding may not introduce any remarkably large strains into the total sequence of folded rocks as Oertel (1974) showed elsewhere.

The large contrasts in mesoscopic deformation between flattened oblate pebbles just outside the Sandvikshytta Z-fold and the significantly more intensive straining of all pebbles within the fold hinges and mid-limb to prolate shapes may be explained by focused deformation in the fold. Thus, the fold mid-limb and hinge zones may have been a zone of ductile flow where some late stage transport was taken up, correlating with movement on the blind thrusts observed in the metasedimentary rocks (Figs. 2, 3, 7). Such movement is in a direction consistent with regional patterns.

Summary and conclusions

The Ulriken Gneiss Nappe was thrust upon the Sandviksfjell group of metasedimentary rocks parallel to lithologic layering and generally at a stratigraphic level just above discontinuous thin beds of conglomerate. Only close to the main thrust and its associated imbrications is the metasedimentary sequence strongly deformed. Elsewhere it is characterized by a weak schistosity, by very weak quartz subfabrics in the quartzites, and by a lack of folds. Conglomerate pebbles are typically flattened into oblate ellipsoids whose short axis is perpendicular to the thrust surface and to the layering of the metasedimentary rocks. At one location only, in the mid-limb of a 100 m high Z-fold which folds the main thrust, are found greatly constricted pebbles, and their longest axis is parallel to the hinge of the fold and to the main direction of thrusting. The weak preferred orientations of quartz c axes in both oblate and prolate pebbles is similar in that they are characterized by a pole free area about the lineation, a feature in rocks evincing stronger overall quartz subfabric patterns denotes the principal direction of elongation in the rocks.

Differences in deformation style and extent between the Sandvikshytta Z-fold and the remainder of the study area imply the existence of strong rheological contrasts together with localization of folding and transport in the large conglomerate body during the final stages of tectonic activity, whether related to formation of the Bergen Arcs or to preexisting irregularities in the autochthon. Whichever regional deformation is appropriate for the origin of the Sandvikshytta Z-fold, we believe that the folding was followed by flattening of the thrust complex, as recorded by nearly axially symmetric oblate pebbles next to the major fold, and by the quartz and mica subfabrics. Flattening was most likely caused by the load of the emplaced thrust complex for which abundant evidence has been assembled throughout the Norwegian Caledonides (Roberts & Gee 1985). These events probably occurred continuously, rather than stepwise, and may have become locally more intense as the overburden pressure permanently increased and as temperatures increased due to increased insulation by the nappe and thrusting related generation of heat and fluids.

Acknowledgements. – This paper is dedicated to Professor Anders Kvale, who took a great interest in this study and helped us to understand his views of pebble deformation and Caledonide thrusting during excursions to the field together. Gerhard Oertel, John Christie, and an anonymous reviewer offered constructive criticism on earlier versions of the manu-
script that greatly improved its form and content. Stuart Gordon, Taz Tally, and Jerry Nichols assisted in collection of quartz microfabric data. Steve Lipshie kindly made available Gordon, Taz Tally, and Jerry Nichols assisted in collection of results and interpretations of strain analysis for one of theport provided by the Geological Institute, University of Bergen, and to Professor Brian Sturt and Asbjørn Thon of that institute for their interest and discussions. David Crouch and Dean Kubani drafted the maps and some of the figures. This research was partly supported by a grant from the General Research Committee, University of California, Santa Barbara.

Manuscript received February 1985

References

Brunel, M. 1980: Quartz fabrics in shear-zone mylonites: evidence for a major imprint due to late strain increments. Tectonophysics 64, T33–T44.
Law, R. D., Casey, M. & Knipe, R. J. 1986: Kinematic and tectonic significance of microstructures and crystallographic fabrics within quartz mylonites from the Assynt and Eriboll regions of the Moine thrust zone, NW Scotland.


Sanderson, D. J. 1973: The development of fold axes oblique to the regional trend. Tectonophysics 16, 55–70.


Talbot, C. J. & Jackson, M. P. A. 1987: Internal kinematics of


**NOTE ADDED IN PRESS**

Just before this manuscript went to press, Holst & Fossen (1987) published a quantitative analysis of pebble strains in the Sandvikshyttta Z-fold. They showed that the nature of the strains is the same as our qualitative observations herein: Oblate pebbles define domains of flattening strain, and highly prolate pebbles that represent extreme constrictional strain are found only in the Z-fold. They concluded, as we do here, that the Z-fold developed passively as a result of flow perturbation in a zone of ductile simple shear.

We also learned from that publication that Fossen (1986) subdivided what we informally call the Sandviksfjell group of rocks into several formations, and he tentatively correlated them with Eocambrian (Vendian) sparagmites in southern Norway. If this correlation and age are correct, it disproves Anders Kvale's suspicion that the Sandviksfjell group of rocks correlates with the Ulven conglomerate south of Bergen or with the Moberg conglomerate of upper Ordovician, also south of Bergen.
