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A computer model of sheath-nappes formed during crustal shear in the Western Gneiss Region, central Norwegian Caledonides: Discussion

JOHN M. BARTLEY

Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112, U.S.A.

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VOLLMER (1988) has presented an insightful re-interpretation of Caledonian fold-nappes in the Oppdal district as large-scale sheath-folds. However, his statement contrasting basement–cover relations at Oppdal with those in northern Norway (citing my 1982 paper) is not entirely correct. It may be true that basement involvement in the Caledonian nappes is volumetrically greater at Oppdal than in the Lofoten-Tysfjord area where I worked, but the difference is probably one of magnitude only and not of process. Basement deformation in the Lofoten-Tysfjord area certainly is not "more brittle" than at Oppdal. As summarized below, relations along the basement–cover contact are quite similar in the two areas. When placed in the context of regional relations in north Norway, this fact has important implications for the nature of Caledonian A-type subduction. In the interests of clearing up any misunderstanding, I briefly recapitulate the main points of my work on this problem and add some new remarks in the light of more recent data and ideas.

Maps and cross-sections from the Lofoten-Tysfjord area in Bartley (1982, 1984) and Steltenpohl & Bartley (1988) show km-scale recumbent folds that interdigitate basement and cover and isoclinally fold cover-nappe boundaries. The folds resemble those at Oppdal in style and in their timing relative to stacking of cover nappes and to metamorphism, though the folds are somewhat smaller in size. At Tysfjord and probably elsewhere, the folds have sheath-like forms (e.g. Steltenpohl & Bartley 1988, fig. 5). Fabric analysis and pelite thermobarometry indicate that the folds formed at kyanite-grade conditions (about 550°C and 8 kb; Hodges & Royden 1984, Steltenpohl & Bartley 1987), similar to metamorphic conditions at Oppdal according to Vollmer (1988). In thin section, the mylonitic basement rocks in the folds show intense uniform grain-size reduction and thorough recovery and recrystallization, consistent with deformation at high temperature. In short, basement involvement in Caledonian nappes at Lofoten-Tysfjord closely resembles that at Oppdal.

If there is a major difference between the areas, it is the regionally continuous exposures in Lofoten of parautochthonous Precambrian basement rocks that underlie the Pennine-like nappe complex (Bartley 1982). The Lofoten basement is composed of medium-pressure granulites that represent a westward continuation of the Baltic craton (Griffin *et al.* 1978). The granulite-grade mineralogy of the basement formed in the early Proterozoic, and in the field, in thin section and in moderately resistant isotopic systems (e.g. Rb–Sr whole-rock), the rocks show a general lack of Caledonian structural or metamorphic overprinting, although Rb–Sr and K–Ar mineral systems were partially or wholly reset (Hakkinen 1977, Griffin *et al.* 1978, Malm & Ormaasen 1978, Bartley 1981, 1982). The downward disappearance of Caledonian strain is spectacularly exposed on a regional scale and is completely gradational. The mylonitic basement rocks in Caledonian fold-nappes are geochemically identical to the mangerites that predominate in the underlying Lofoten basement complex (Bartley & Schubert unpublished data). These relations indicate conclusively that a high degree of ductile strain localization in the basement near the basement–cover contact was responsible for the detachment-like style of nappe transport in the Lofoten-Tysfjord area. Although the actual deformation mechanisms were highly ductile, the large-scale kinematics of this system, in which the cover and sheets of subjacent basement were sheared off a relatively undeformed deeper basement, strikingly resemble foreland thrust systems.

Because the undeformed basement probably reached temperatures in excess of 500°C during the Caledonian (Bartley 1984), the downward disappearance of Caledonian deformation probably cannot be attributed to an inverted temperature gradient caused by thrusting. The basement rocks that record large Caledonian strains appear to be somewhat hydrated compared to their undeformed counterparts (amphibolite instead of granulite facies), leading me to propose (Bartley 1982) that strain localization primarily was caused by hydrolytic weakening and reaction softening in the basement adjacent to the cover. I hypothesized that the requisite water was derived from synkinematic metamorphic dehydration of the cover, and was introduced downward into the basement by a mechanism similar to that recently proposed in more detail by McCaig (1988). This led to the further suggestion that the distribution of water (and not, for example, the thermally activated brittle–ductile transition) may have controlled the detachment of basement thrust sheets in the Scandinavian Caledonides (Bartley 1982).

However, regardless of the mechanism of strain localization, the large-scale geometry of the Lofoten-Tysfjord area implies that Caledonian A-type subduction occurred by *en bloc* underthrusting of an effectively rigid Baltic lower crust and subjacent mantle beneath the nappe complex (Bartley 1982, Hodges *et al.* 1982). The effective rigidity of the Lofoten basement probably was not because it was particularly strong (compared to cold upper crust or underlying upper mantle), but rather because the high-strain zone in which the sheath-nappes formed was extraordinarily weak. The result is that the A-type subduction zone was still in effect thin-skinned to a depth of at least 30 km and far into the 'metamorphic core' of the orogen, even though deformation along and above the detachment in this position was under conditions far into the ductile field.

These considerations lead me to suggest that the sheath-nappes at Oppdal may well be larger examples of precisely the same process recorded at Lofoten-Tysfjord. As the lower boundary of the main Caledonian shear zone migrated downward with time (following an infiltration front of metamorphic water?), basement rocks were sheared ductilely into fold-nappes that refolded thrusts in the cover. This process had the result, certainly at Lofoten-Tysfjord and quite possibly at Oppdal, that the entire Pennine-type nappe complex is underlain by lower continental crust that scarcely participated in Caledonian nappe tectonics.

A computer model of sheath-nappes formed during crustal shear in the Western Gneiss Region, central Norwegian Caledonides: Reply

FREDERICK W. VOLLMER

Department of Geological Sciences, State University of New York, The College at New Paltz, NY 12561, U.S.A.

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I thank Dr Bartley for his comments and for his lucid summary of the relationships between basement and cover in the Lofoten-Tysfjord area. Bartley has pointed out many important similarities between the interpretations I made for the Oppdal area (Vollmer 1988), and the interpretations made for the Lofoten-Tysfjord area (Bartley 1982, Steltenpohl & Bartley 1988). I believe this emphasizes the importance of these interpretations for the deformational histories of the Caledonian and other collisional orogens. The major differences between the two areas appear to be the presence of the rigid basement exposed in Lofoten, and the scale of the basement-cored nappes.

Bartley refers to a sentence in my paper (Vollmer 1988) that compares the style of deformation in the Oppdal district with the style of deformation described by Bartley (1982) on east Hinnøy, north Norway. In that sentence I stated that the deformation in the northern Norwegian Caledonides appeared to be a "more brittle detachment-style deformation" (Vollmer 1988, p. 742). This referred to Bartley's (1982) observation that ductile fold-nappes in the Lofoten-Tysfjord area appear to be essentially detached from the lower, rigid basement gneisses. As clarified by Bartley in his Discussion, the detachment is a gradational mylonite zone, which he does not believe is a major structural discontinuity between two genetically distinct basement blocks.

I am not aware of any similar evidence from the Oppdal area to suggest that a rigid basement block exists below the fold-nappes there, although it may be possible. It seems that within the Oppdal district the deformation began as thin-skinned thrust tectonics, resulting in the formation of the regional tectonostratigraphic framework (Krill 1985), followed by the downward migration of increasingly ductile deformation into the basement gneisses (Vollmer 1988). This appears to be similar to what Bartley has described for the Lofoten-Tysfjord area. However, much of the basement in the western portion of the Oppdal district appears to have been migmatized during Caledonian deformation (Krill 1985), suggesting ductile deformation extends well down into the basement gneisses. It is possible that the deformation within the Oppdal area represents a later stage in the progressive development of these basement-cored nappes. Further mapping within these problematic lower gneisses will be required to clarify their deformational histories.

Steltenpohl & Bartley's paper (1988), which had not been published when my manuscript (Vollmer 1988) was prepared, illustrates many of the similarities Bartley refers to in his present Discussion, including the apparent presence of a refolded sheath-nappe in the Tysfjord area. In terms of regional deformation processes, it is notable that they interpreted gneiss domes in that area to be the result of crustal shortening and fold interference rather than diapirism. This is similar to the sugges-