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The role of extensional tectonics in the Caledonides of south Norway: Discussion

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IN A recent paper in this journal, Fossen (1992) provides detailed structural data on the extensional structures from original middle and upper crustal levels in the orogenic crust from parts of the south Norwegian Caledonides. These crustal levels experienced greenschist to amphibolite facies metamorphism during the Silurian, Scandian Orogeny and the early stages of the extensional collapse of the thickened orogenic crust (Fossen in press). In agreement with studies in other parts of the southwest Norwegian Caledonides (Osmundsen 1990, Osmundsen & Andersen 1990), Fossen (1992) provides additional evidence for extensional top-to-the-west (west to northwest) re-activation of the large-scale top-to-the-southeast directed contractional fabrics and thrusts within the Caledonian allochthons. On the basis of the data from the middle and upper parts of the syn-orogenic crust, Fossen (1992) argues that the post-contractional extension of the South Norwegian Caledonides chiefly was driven by divergent plate motions between Baltica and Laurentia rather than by the internal body forces generated within the thickened lithosphere. Fossen's model is based mainly on the assumption that the extensional deformation he describes everywhere post-dates contractional deformation in the Scandinavian Caledonides. This, he argues, is in conflict with models of orogenic extensional collapse driven by body forces in a thickened orogenic lithosphere as envisaged by Dewey (1988) and England & Houseman (1988), that requires contractional deformation in the foreland contemporaneously with extensional deformation in the hinterland of the orogen.

The models for the extensional collapse of the South Norwegian Caledonides, outlined by the present author and co-workers (Andersen & Jamtveit 1990, Andersen *et al.* 1991, Dewey *et al.* in press, Andersen *et al.* in review), integrates studies in the exhumed high-*P* rocks as well as in the middle to upper parts of the orogenic crust. Without going into detail on the deep crustal fabric, here (the reader is referred to the original papers), our observations from the lower, middle and upper parts of the orogenic crust are consistent with the expected sequence of structural, metamorphic, magmatic and stratigraphic events inherent in the general model proposed by Dewey (1988). The widespread late-Caledonian high-*P* metamorphism (in parts coesite-bearing) in the Western Gneiss Region (Griffin 1987, Smith & Lappin 1989), which constitutes the lowermost structural level in the Norwegian Caledonides (Andersen & Jamtveit 1990), clearly demonstrates that the thickness of the orogenic crust must have been comparable or thicker than the present-day Himalayan–Tibetan crust and other orogens that undergo gravitational collapse, where the hinterland areas are characterized by extensional and wrench tectonics and thrusting occurs at lower topographic levels (<3 km) along the margins (Dewey *et al.* 1988). Thus, in addition to the available geological data, gravitational spreading of the syn-orogenic crust in the Norwegian Caledonides is likely to have taken place on the basis of its original extreme thickness, the analogy with present-day collision zones and the theoretical modelling of the strength of orogenic lithosphere (England & Houseman 1988).

A key point in this discussion is whether considerable extensional deformation in the hinterland of the Norwegian Caledonides was contemporaneous with the contractional deformation in the foreland; in other words, if the earliest extensional fabrics in the hinterland are of similar age to the formation of the foreland fold–thrust belt geometries in the Oslo area. Fossen's (1992) discussion of timing of the contractional and extensional events across the orogen to support his idea of divergent plate motions as a driving mechanism for the extension, and which he uses as the basis for refuting the previously published collapse models, is not adequate, in my view.

The age of the thrusting in the Oslo area (foreland) is admittedly not well constrained since the syn-orogenic clastic wedge in the foreland is deeply eroded by as much as 3 km (Bjørlykke 1983, personal communication 1993). The thrusting, however, clearly post-dates the late Silurian continental Ringerike sandstone for which an upper age is unknown due to lack of fossils. As the thrust-related deformation of the youngest sedimentary rocks show no record of syn-sedimentary or early-diagenetic deformational fabrics, it is however likely that the main contractional deformation of the foreland deposits occurred in the Lower Devonian and possibly even later. By comparison with the most recent calibration of the time scale by McKerrow (written communication 1992) this corresponds to an age of the main thrusting event in the foreland at around, or more likely later than, 410 Ma. The youngest supracrustal rocks affected by contractional deformation in the hinterland are of Llandoverian or possibly Wenlockian age (Andersen *et al.* 1990), corresponding to 430–425 Ma on the same time scale. At this time the deposition in the foreland was still characterized by carbonates.

The Devonian sedimentary rocks in the hanging wall of the extensional detachments in the Sogn–Sunnfjord region of western Norway contain Lower (?) to Middle Devonian (base Eifelian at 387 Ma, time scale after McKerrow written communication 1992) flora and fauna at high stratigraphic levels in the Kvamshesten and Hornelen basins. Detailed structural studies (Osmundsen 1990, Osmundsen & Andersen 1992, in revision, Hartz *et al.* in press) adjacent to these basins shows that the principal extensional unroofing of the Caledonian nappes that comprise the basement of the Devonian sediments occurred prior the deposition of these basins. The top-to-the-west extensional structures that are unconformably overlain by the Devonian red beds, were initially formed at the same metamorphic conditions as the latest contractional (top-to-the-east) structures. The extensional structures became increasingly semi-ductile to brittle prior to the deposition of the Old Red sediments, and most of the upper-plate extension that was rooted in the large-scale extensional detachments had terminated prior to the deposition of the Devonian sediments. Thus the Silurian (top-southeast) thrusting was immediately succeeded by extension (top-west) which unroofed the greenschist to amphibolite facies basement of the Devonian rocks over a period of approximately 25–30 Ma in the late Silurian–early Devonian. This suggests that the extensional unroofing in the hinterland at least partly was contemporaneous with deposition of the red beds and the subsequent thrusting of the rocks in the foreland.

Furthermore, the basal 'Old Red' facies in the hanging-wall of the Møre–Trøndelag fault zone (MTFZ), contain a fauna that apparently straddles the Siluro-Devonian boundary (Reusch 1914). These deposits are considerably older than the Devonian rocks discussed above, and of comparable age as the Ringerike sandstone in the Oslo area. Consequently these rocks in the hinterland are older than the thrusting in the foreland (Oslo area). Both the sedimentary facies and the structural studies shows that the deposition of the 'Old Red' along the MTFZ is related to extensional tectonics during the orogenic collapse (Bøe 1989, Séranne 1992), hence demonstrating even more convincingly that extension occurred in the hinterland contemporaneously with contraction in the foreland. Thus, Fossen's (1992) suggestion that the extensional structures post-date all of the contractional structures in the Scandinavian Caledonides is not supported by the available regional stratigraphic information.

Without going into a long discussion of the combined radiometric, structural and metamorphic evolution of the deepest exhumed level of the SW Norwegian Caledonides, and leaving the discussion to the stratigraphical arguments, it is concluded that the temporal relationships between contractional and extensional deformation in the foreland and hinterland, respectively, most likely can be attributed to gravitational instability and collapse of the syn-orogenic lithosphere as suggested previously (Andersen & Jamtveit 1990, Andersen *et al.* 1991). The data presented by Fossen (1992) do not require plate divergence between Baltica and Laurentia in the Late Silurian to Lower Devonian as an underlying driving mechanism for the extensional structures, but can be explained by orogenic extensional collapse as previously suggested.

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The role of extensional tectonics in the Caledonides of south Norway: Reply

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I WELCOME Andersen's interest in my paper, and appreciate the opportunity to discuss the extensional deformation in the Caledonides of southern Norway, further.

Andersen and co-workers have been studying a relatively small area of SW Norway near the Nordfjord–Sogn detachment (NSD), and have suggested that the model involving gravity-driven extensional collapse due to a detaching and descending cold orogenic root of the lithospheric mantle may apply to this area. In my paper I presented data from a much larger part of the Caledonides in south Norway, and particularly from the décollement zone which extends from the hinterland to the foreland. This regional approach is essential when large-scale orogenic models are to be discussed and evaluated. It appears that Andersen accepts the main thesis of my paper; i.e. that the contractional fabrics were consistently reworked by W- to NW-directed nappe translations and W-dipping shear zones related to horizontal extension of the Caledonian crust. It is not an *assumption*, however, that the contractional fabrics everywhere pre-date the extensional deformation, but a conclusion that was based on detailed and systematic field work and data analysis. The age relationship between the SE-directed (contractional) and WNW-directed (extensional) kinematic structures is surprisingly consistent. This conclusion is supported by much recent work in various parts of the Caledonides (Kvale 1960, Naterstad *et al.* 1973, Andresen, 1974, Brewer & Smythe 1984, Milnes & Koestler 1985, McClay *et al.* 1986, Olesen 1986, Milnes *et al.* 1988, Fossen & Rykkelid 1988, Holdsworth 1989, Powell & Glendinning 1990, Fossen 1991, 1992a,b, in press, Fossen & Rykkelid 1992a,b, Rykkelid 1992, Rykkelid & Andresen in press) and one would have to disregard the usefulness of almost any kind of kinematic indicators to argue against this conclusion.

Some of my statements are somewhat incorrectly quoted by Andersen, so the interested reader is urged to read the original paper carefully. In particular, I did not claim that the extension "chiefly was driven by divergent plate motions between Baltica and Laurentia rather than internal body forces generated within the thickened lithosphere". I wrote that the extension "was closely related to post-collisional, Lower to Middle Devonian plate divergence", and that "the exact reason for the plate divergence is unknown, but may possibly have been triggered or enhanced by the push exerted on the plates by an earlier (pre-D_2) extensional collapse in the central parts of the orogen. The back movement would in this case take place after, rather than during an extensional collapse of the central parts". Hence, there is room in my model for the general extensional collapse model envisaged by Dewey (1988), but kinematic indicators and overprinting relationships show that this must have occurred prior to the top-to-the-west movement recorded in the décollement zone east of the area where Andersen recently has been working.

In other words, extensional deformation may have been going on in the central part of the orogen as gravity-driven top-to-the-ESE thrusting was still being recorded in the décollement zone under the Jotun and other nappes (see fig. 14b in my original paper and Fig. 1a in this paper). Perhaps the coaxial fabrics described from the basement by Andersen and co-workers formed during this stage (?), together with normal faults and shear zones in the overlying orogenic edifice (now mostly removed by erosion) and thrust motion along the décollement zone towards the foreland. But the reversal of the shear sense along the décollement zone clearly *post-dates* this deformation, as does the extension along the NSD. As pointed out before (Milnes *et al.* 1988, Fossen 1992a, in press), although neglected by Andersen, the rotation of the décollement zone by the HFSZ and the NSD must have caused the back movement of Caledonian nappes to have ceased, while the NSD continued to be active, transecting and cutting out the entire overlying orogenic wedge (a displacement of 30–45 km if the NSD were dipping 20–30° to the west).

I am surprised that Andersen does not realize the necessity of plate divergence in the light of the kinematic data presented in my paper. It is simply not possible for the orogenic wedge to move back into the central and thickened part of the collision zone unless 'space' is simultaneously being provided by some sort of divergent motion. Extensional collapse of the central part of an orogenic belt can perhaps thin the crust in this area almost to normal thickness, provided that rock volumes may flow freely toward the foreland (by thrust motion along the basal décollement zone, Fig. 1a). However, since this deformation is gravity driven, the central part

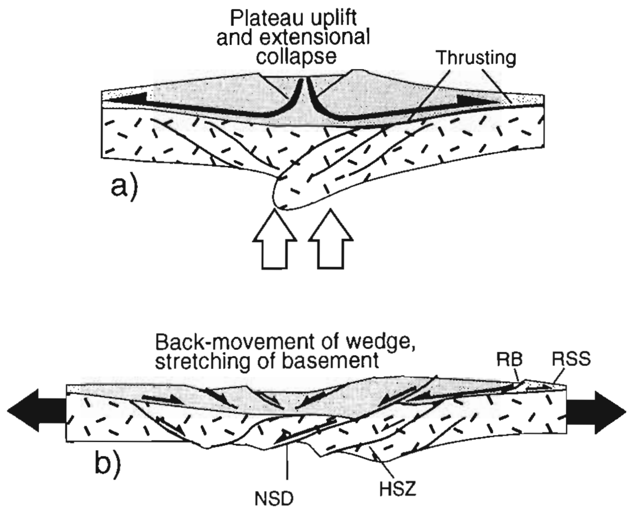

Fig. 1. Illustration of particle displacement pattern during (a) extensional collapse without plate divergence (as suggested by Andersen) and (b) the extensional deformation actually observed in the field. (a) corresponds to fig. 14(b) in my original paper (Fossen 1992a), and (b) is a modified version of fig. 14(c). NSD = Nordfjord–Sogn Detachment, HSZ = Hardangerfjord shear zone, RB = Røragen Basin, RSS = Ringerike sandstone.

can never be thinned more than to the thickness of the surrounding crust, and a gravitational collapse process alone therefore cannot cause the well documented backsliding of the orogenic wedge towards the hinterland. The only realistic explanation for this is that Baltoscandia and Laurentia experienced divergent motions at the time, possibly during, and certainly after, a possible gravitational collapse. Hence an extensional collapse model that does not take into account divergent plate motions, fails to explain the unequivocal kinematic data from the décollement zone.

It is interesting to note that Andersen himself insists on horizontal extension in the order of 180 km (Andersen *et al.* 1991). If this undocumented estimate should turn out to be correct, and if one disregards plate divergence, then this implies 180 km of gravity driven nappe translations (thrusting) towards the foreland while the central parts of the orogen experienced extension. In addition to being geologically and mechanically unsound, this would be incompatible with clear-cut kinematic data from the décollement zone, as emphasized above. Furthermore, the kinematics in Andersen's 'collapse-without-divergence' model is also incompatible with available data from the area where Andersen has been working. Somewhat simplified, one may say that Andersen's model implies a flow of particles from the elevated central zone towards the foreland (Fig. 1a). However, most of the extension is reported to have been taken up along a several kilometers wide low-angle, W-dipping shear zone (Norton 1986, Séranne & Séguret 1987, Chauvet & Séranne 1988), resulting in a displacement path in a significant part of the orogen which is opposite to that predicted by Andersen's 'collapse-without-divergence' model (Fig. 1b).

Andersen avoids discussing the discrepancies between his model and the kinematic data presented in my original paper, and instead argues that stratigraphic data support contemporaneous thrusting in the Oslo region (foreland) and extension in western Norway. The stratigraphic control in the Devonian basins is, however, not very well constrained, nor is the calibration of the Devonian time scale (cf. Gale *et al.* 1980). In fact, given the uncertainties involved, stratigraphic and geochronological data do *not* exclude the possibility that thrusting and extension were separated in time (Fig. 2). This requires a very rapid switch from contraction to extension, as well as rapid extensional deformation, as supported by new geochronological data (Chauvet & Dallmeyer 1992). It is, however, possible that extension actually started in the collapsing internal part of the collision zone as thrusting was still going on near Oslo, as suggested by Andersen and indicated in my original paper (cf. fig. 14b). A third possibility is that the extensional deformation in the décollement zone cut up-section somewhere southeast of the Jotun Nappe, leaving an unstable orogenic ridge that subsequently collapsed to form the large, open folds and the small-scale thrust structures observed in the late Silurian Ringerike sandstone (Fig. 1b). The latter explanation would account for the small difference in age between the gentle deformation of the Ringerike sandstone and the deposition of Lowermost Devonian sediments along the MTFZ north of the study area.

A very important fact which has been omitted by Andersen is that the Lower Devonian sediments of the Røragen basin also contain plant fossils that denote an early Devonian age (Høeg 1936); i.e. a quite similar age to the basins associated with the MTFZ and older than the Devonian sediments of SW Norway. The extensional Røragen basin is also of the same age as the age of the thrusting of the Ringerike sandstone suggested by Andersen. This casts additional doubt on Andersen's idea that most or all of the extension in the hinterland

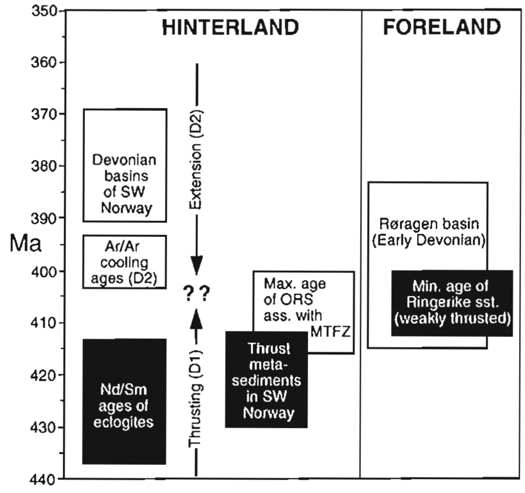

Fig. 2. Black boxes represent minimum age of youngest sediments involved in D_1 thrusting, and Nd/Sm ages dating the D_1 continent–continent collision. White boxes represent radiometric ages or lower age of sediments related to D_2. The height of the boxes represents uncertainties from calibration of the time scale (cf. Gale *et al.* 1980), uncertainties related to fossil evidence (see Steel *et al.* 1985 and references therein for the ORS), or error limits/spread in radiometric ages. MTFZ = Møre–Trøndelag fault zone. See text for discussion.

was accompanied by thrusting in the foreland, since the extensional Røragen basin is situated close to the foreland.

One should also keep in mind that the MTFZ acted as a strike-slip zone both during the late stages of contraction and during the Devonian extension. The geotectonic implication of the related Devonian basins is therefore less obvious, since extensional basins tend to develop in conjunction with strike slip faults whether they are situated in an extensional or contractional regional setting. Perhaps a key point in this discussion is to be aware of the fact that extensional deformation must have been an active internal process within the upper plate (orogenic wedge) during the Scandian contraction as well as during the later extension, and extensional basins formed on the upper part of an orogenic wedge can therefore not be taken as evidence of large-scale extensional tectonics (e.g. Platt 1986). It is therefore possible that some of the Devonian sediments are older than the extensional deformation recorded in the deeper part of the Caledonian crust, and presently preserved in the hangingwall of a later extensional detachment that is not directly related to the basin formation. It is very important to be aware of the difference in significance between kinematic data from the upper plate and those from the basal décollement between the basement and the orogenic wedge. The basal décollement recorded the bulk direction of displacement of the wedge, and therefore contains the critical information about the general kinematic and tectonic history of the orogen.

This discussion emphasizes the need and usefulness, but also the complexities involved in integrating kinematic, geochronologic, tectonic and stratigraphic data on a regional as well as local scale to recognize and constrain the evolution of orogenic belts. In the Caledonides, the switch from contractional to extensional tectonics happened so quickly that both stratigraphy and geochronology are on the edge of resolution, and the kinematic-structural evidence seems most convincing. We are lucky to have a significant part of the décollement zone with its kinematic indicators preserved more or less continuously from the foreland to the hinterland, and should acknowledge the significance of data obtainable from this zone. I feel that the best way to better constrain some of the issues discussed here may be to try and date the D_1 and D_2 deformation fabrics in this zone using various modern high-precision analytical methods.

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