

Devonian, orogen-parallel, opposed extension in the Central Norwegian Caledonides

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ABSTRACT

Late orogenic, Early to Middle Devonian extension in the Scandinavian Caledonides was unidirectional in western Norway. New data from two detachment zones (Høybakken and Kollstraumen) north of the Møre-Trøndelag Fault Complex show that bidirectional, opposed, orogen-parallel extension dominated in this region. At this time, the fault complex acted as a transfer zone for the Høybakken detachment. Extension and uplift in central Norway triggered significant magmatic activity, in contrast to the lack of granite intrusions during exhumation of western Norway.

Keywords: Norway, Devonian, extension, detachment.

INTRODUCTION

The Scandinavian Caledonides consist of a stack of thrust sheets, which were amalgamated and thrust toward the east-southeast mainly as a result of Silurian-Devonian (Scandian) collision between Baltica and Laurentia (Roberts and Gee, 1985). Tectonothermal events of Late Cambrian–Early Ordovician (Finnmarkian) and Middle Ordovician (Taconic equivalent) age are also recorded at certain structural levels (e.g., Andréasson, 1994).

In the Early Devonian, the hinterland parts of the orogen were extended, in part because of orogenic collapse, as is well established in western Norway (reviewed by Andersen, 1998). The Møre-Trøndelag Fault Complex (Fig. 1A) played a major role in the Devonian scenario, acting as a ductile sinistral shear zone in a developing transtensional and/or transpressional strain regime in the surrounding regions (e.g., Roberts, 1983; Krabbendam and Dewey, 1998; Osmundsen et al., 1998; Braathen, 1999).

North of the Møre-Trøndelag Fault Complex, major antiforms and synforms deform the entire nappe package and the overlying Devonian deposits. Yet, the distribution of small-scale structures and lineaments of definite Devonian age remains debatable. Our intention is to fill this gap in the understanding of the Devonian geological effects on the Central Norwegian Caledonides and shelf area. Herein we present evidence of strike-parallel extension in central Norway and of bidirectional, opposed extensional movements; this scenario differs from the situation in western Norway. Hence, these observations have significant regional implications.

In western Norway, the Devonian extension is

manifested in a 3-km-thick mylonite zone, the Nordfjord-Sogn detachment (Norton, 1987), that truncates and juxtaposes lower-plate high- to ultrahigh-pressure rocks of the Western Gneiss Region against upper-plate Caledonian nappes. The upper-plate rocks are draped by Lower to Middle Devonian, supradetachment, partly fault-bounded basins (e.g., Osmundsen et al., 1998). At a late stage of extension, or postdating it, the extensional detachment and overlying and underlying rocks were deformed in regional east-west-trending folds. The entire area was subsequently modified by Permian and Mesozoic faulting (e.g., Eide et al., 1997; Braathen, 1999). Farther north, these folds gradually rotate into northeast-southwest trends (Roberts, 1983) and become progressively tighter. The onshore part of the Møre-Trøndelag Fault Complex comprises the steep Verran and Hitra-Snåsa faults, both characterized by ductile and later, superimposed brittle elements. Shear events along these faults include ductile sinistral movement in the Early Devonian, followed by several brittle dip-slip and dextral- to oblique-slip movements from the Late Devonian through early Tertiary time (e.g., Grønlie and Roberts, 1989).

North of the Møre-Trøndelag Fault Complex (Fig. 1B), the intense folding and Caledonian reworking of Paleoproterozoic(?) orthogneisses of the central Norway basement window and overlying supracrustal nappe rocks mimic areas farther south in the Western Gneiss Region. Supracrustal rocks occur as long lobes and tongues that were downfolded into the mainly granitoid gneisses during the Silurian-Devonian Scandian orogeny (Figs. 1B and 2; Solli et al., 1997; reviewed by Roberts, 1998a). Some of the

basement rocks reveal high-pressure, granulite-facies mineral assemblages. Younger structures include the Devonian Høybakken detachment (Séranne, 1992), a discrete mylonite zone that separates Devonian sedimentary rocks and their substrate from the footwall gneisses and that hosts thin granitic pegmatite dikes.

In the northeast, the central Norway basement window terminates in a shear zone, herein named the Kollstraumen detachment zone, which is close to the base of the Caledonian thrust stack. Previously, the intense deformation in this zone has been largely considered to relate to Scandian east-directed thrusting. However, abundant Devonian pegmatite dikes, some of which are severely deformed, demonstrate that there was also a component of Devonian extensional movement along the detachment.

OBSERVATIONS

A northeastern and southwestern Devonian detachment bounding the central Norway basement window is consistent with the notion that the gneiss dome formed beneath oppositely directed Devonian extensional shear zones, the Høybakken and Kollstraumen detachments. The geometry of this system is in many ways akin to that of the metamorphic and/or extensional core complexes described from the United States (e.g., Davis and Lister, 1988). In order to convince the reader of the validity of this new model for extension in the Central Norwegian Caledonides, we address four critical observations.

Devonian Basins

The late Scandian extension in the Norwegian Caledonides is recorded by several Devonian

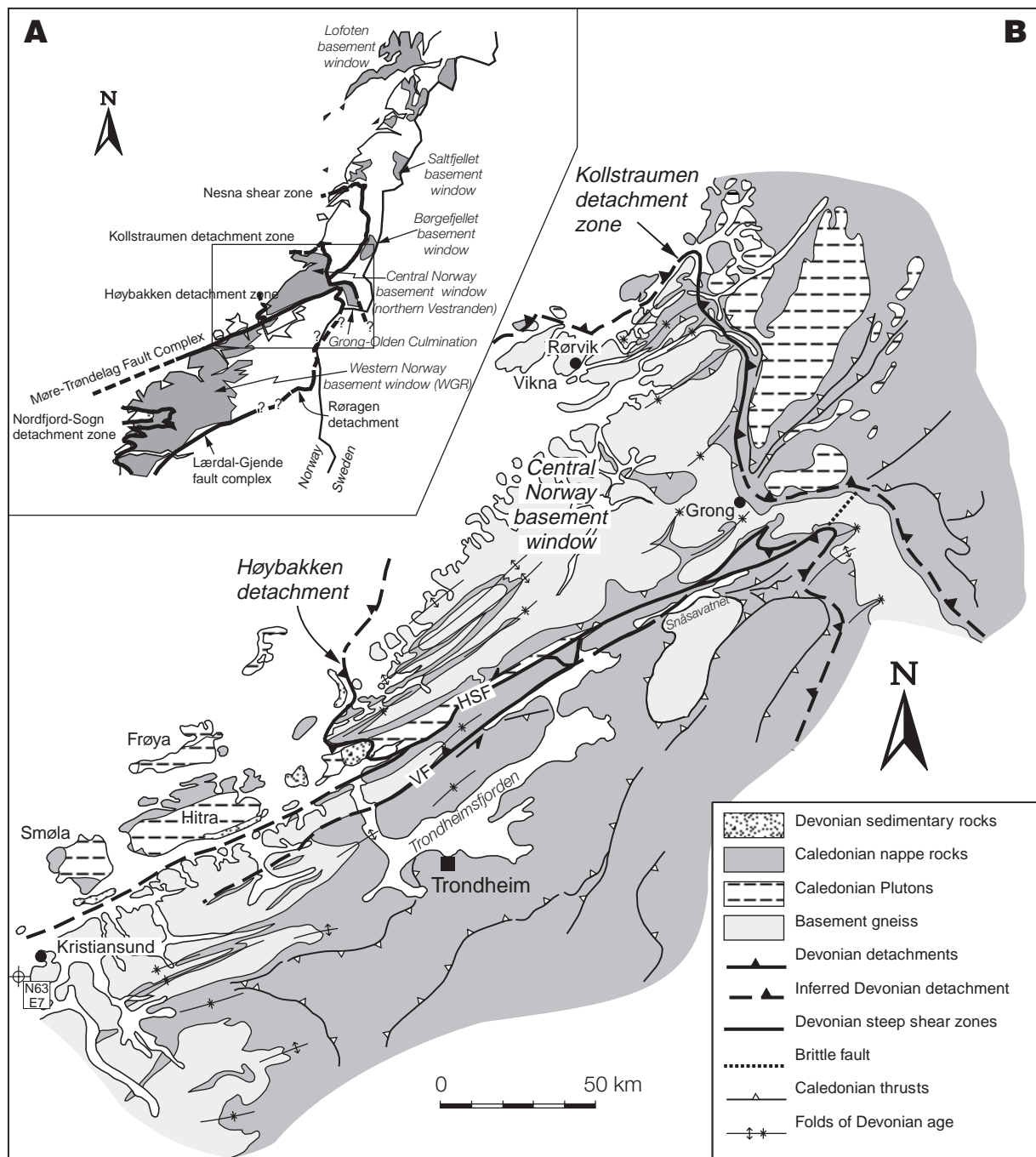


Figure 1. A: Sketch map of central parts of Scandinavian Caledonides, highlighting basement windows and Early-Middle Devonian faults and shear zones. B: Tectonic map (located in A) of Trondheimsfjord region, locating Møre-Trøndelag Fault Complex and Høybakken and Kollstraumen detachment zones. HSF—Hitra-Snåsa fault, VF—Verran fault.

basins, including one elongate basin along the Møre-Trøndelag Fault Complex (Fig. 1B; e.g., Bøe et al., 1989; Osmundsen et al., 1998). Characteristics of the basins include (1) their long, narrow shape, compared to their impressive stratigraphic thicknesses; (2) margins evident either as faults or as unconformities; (3) coarse clastic input, which can be attributed to proximal to distal alluvial-fan and flood-plain environments; and (4) abundant synsedimentary faults.

The basin situated along the Møre-Trøndelag Fault Complex contains a latest Silurian(?) to

Middle Devonian fill (Bøe et al., 1989). Conglomerates predominate in the east-northeast, whereas sandstones and marls make up the bulk of the succession in the west-southwest. There, the basin is folded into a tight, southeast-verging syncline with associated cleavage. Phengite along this cleavage is believed to be of Late Devonian to earliest Carboniferous age (Bøe et al., 1989). The link between deposition in this particular basin and movement on the underlying detachment is not well established. However, the basin is folded around axes that correspond with

the folded detachment, and the basin axis is parallel to the transport direction of the underlying Høybakken detachment (Séranne, 1992).

Devonian Pegmatite Dikes as Time and Strain Markers

Granitic pegmatite dikes are common in both the Høybakken and Kollstraumen detachment zones. They constitute important time markers, especially in the northeast, where Devonian sedimentary rocks are lacking. Even more important, they reveal strain markers that distin-

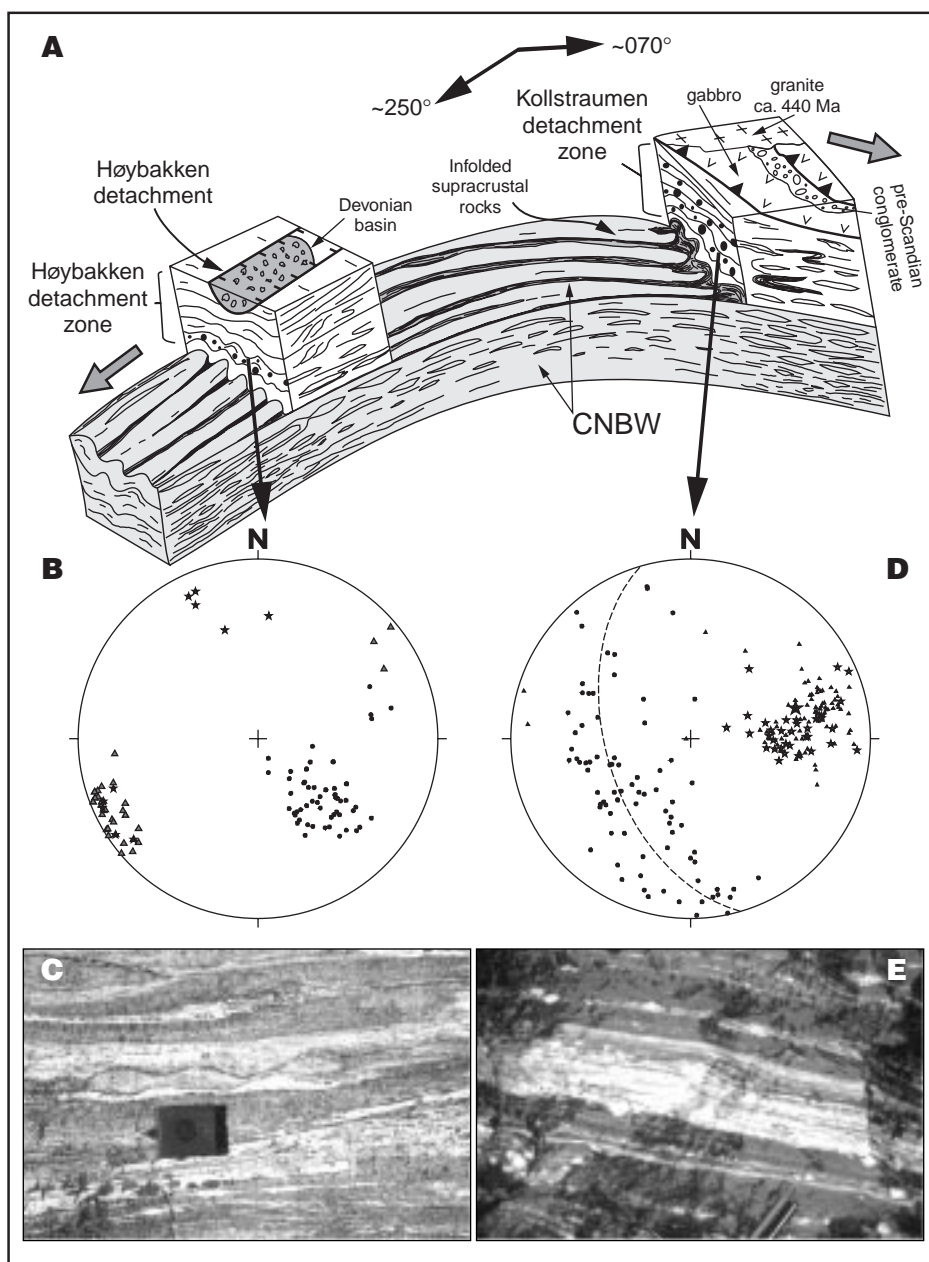


Figure 2. A: Block diagram illustrating position and geometry of detachment surfaces and detachment zones around central Norway basement window (CNBW). B: Stereoplot (lower hemisphere, equal area) of structural data from Høybakken detachment zone; poles to mylonitic foliation (dots; $n = 58$), fold axis (stars; $n = 10$), and stretching lineation (triangles; $n = 38$) are indicated. C: Photograph of top-to-west-southwest shear bands and sheared granitic lenses from Høybakken detachment zone. The compass is ~ 10 cm long. D: Stereoplot of structural data recorded around sheared pegmatite dikes in Kollstraumen detachment zone; poles to mylonitic foliation (dots; $n = 81$), fold axis (small stars; $n = 34$), average fold axis (big star), and stretching lineation (triangles; $n = 95$) are indicated. E: Photograph of mylonitic pegmatite dike from Kollstraumen detachment zone. Note top of pencil for scale.

guish Devonian deformation from early Scandian and older episodes. The pegmatite dikes in the detachment zones (0.1–1 m thick) may conveniently be separated into three groups: (1) dikes that are well preserved but slightly deformed and discordant to the foliation, (2) dikes that are folded and partly sheared or foliated with a low angle to the foliation, and (3) dikes that are highly strained and concordant with a mylonitic texture. Commonly, one type can be

traced into another. Diffuse dike boundaries and pods of pegmatitic granite indicate that the melt for the dikes was, at least partly, generated within the mylonite zones. Dated dikes have revealed ages of 404 and 401 Ma (U-Pb zircon; Schouenborg, 1988; Schouenborg et al., 1991), and ca. 390–380 Ma (Rb-Sr; Piasecki and Cliff, 1988), i.e., a time span that partly coincides with biotite and muscovite cooling ages, which are in the range 410–395 Ma (Solli et al., 1997).

Høybakken Detachment

The 2–3-km-thick mylonitic Høybakken detachment zone dips $\sim 20^\circ$ southwest (Séranne, 1992). Together with the overlying Devonian deposits, it is folded into tight, southwest-plunging folds. Internally, the zone is characterized by mainly LS- to L- and SL-tectonized diorite, marble, phyllonite, and mylonite and the pegmatitic dikes. Some banded cataclasites have also been encountered, especially near the top of the detachment zone. The mineral assemblage of the ductile fabric in mica schists, with prekinematic to synkinematic garnet and local prekinematic(?) albeit stable kyanite, is consistent with upper-greenschist- to amphibolite-facies metamorphic conditions. Similar mineral assemblages are also present within the Kollstraumen detachment zone.

The west-southwest-plunging stretching lineation (Fig. 2) is revealed as oriented minerals, stretched-out layers and quartz rods, and locally lobe-shaped pegmatite dikes. There are also prominent grooves on the brittle detachment fault surface(s), plunging west-southwest, with wavelengths in the range 0.3–2 m. Such mullion-like corrugations are well known from detachment faults in extensional core complexes in the western United States (e.g., Davis and Lister, 1988).

Within the Høybakken detachment zone, shear-sense indicators are common in the SL- to LS-tectonized rocks, but hardly ever observed in L tectonites. They include porphyroclasts in mylonites, diverse shear bands and minor folds, and shear fractures in more competent units. In late, semibrittle shear zones (<1 m) with cataclasite, separation is established through displacement of lithological markers. Consistent shear-sense indicators reveal mainly top-to-the-west-southwest transport, as also reported by Séranne (1992). In some parts, the effect of vertical shortening is significant, as indicated by boudinage and the lack of asymmetry.

Kollstraumen Detachment

The 1–2-km-thick, northwest-southeast-striking and moderately northeast-dipping Kollstraumen detachment zone delineates the northeast termination of the central Norway basement window (Fig. 1). The shear zone consists of more or less mylonitized marble, calc-silicate rock, schist, and orthogneiss. Structures of the hanging wall, which root in the detachment, stem from at least two Caledonian events: (1) an early phase of inferred Ordovician ophiolite obduction, with associated structures that are truncated by granitic plutons with an age of ca. 440 Ma; and (2) the Scandian east-directed thrusting, which also affected the granitic plutons (e.g., Nordgulen et al., 1993). The appearance of pegmatite dikes in the detachment zone is consistent with strain compartmentalization: (1) the lower and upper parts of the zone host weakly deformed dikes in SL tectonites, whereas (2) the central, high-strain part of the zone is characterized by partly foliated

to mylonitized dikes that are almost or fully concordant with the LS to L mylonites.

The observed shear-sense indicators and the pronounced stretching lineation (east-northeast plunging) in the Kollstraumen detachment zone are similar to those found within the Høybakken detachment zone. However, in this case they reveal top-to-the-east-northeast shear (Fig. 2D), i.e., opposite to that in the Høybakken detachment zone. Brittle fault products in the zone are not common, albeit Roberts (1998b) reported cataclastic east-northeast-directed, extensional shear structures from one particular traverse. Our structural studies have revealed that the Kollstraumen detachment zone is a major, regional, mainly ductile, late orogenic extensional shear zone.

REGIONAL IMPLICATIONS

The Devonian pegmatite dikes are an important temporal key for reconstruction of the polyphase regional deformation. Most likely, the west-southwest-directed transport along the Høybakken detachment zone occurred contemporaneously with top-to-the-east-northeast shear along the Kollstraumen detachment. The net effect of this bidirectional and opposed, orogen-parallel transport was the uplift of the high-grade central Norway basement window by tectonic denudation.

This scenario shows similarities to metamorphic core complexes. For example, Malavieille (1993, p. 1119) concluded on the basis of comparative studies, that “two low-angle shear zones with opposite vergence develop along the flanks of roughly symmetrical core complexes (often, one system dominates over the other).” Around the central Norway basement window, a slight asymmetry is observed, with a lower angle detachment in the southwest compared to that in the northeast. Thus, it is likely that the breakaway zone was located above the northeastern part of the basement window.

The LS to L tectonites of the detachment zones indicate localized constrictional strain, which on a regional scale may have enhanced the previously downfolded tongues of supracrustal rocks in the basement window. Such a northeast-southwest stretching axis is almost perpendicular to the main Scandian southeast-directed thrust direction; hence, the stretching is orogen subparallel.

A bidirectional, opposed extension model has important implications for the interpretation of the subvertical, ductile Hitra-Snåsa and Verran faults. At this stage, they probably acted as transfer faults, transferring the Høybakken detachment zone from a coastal position in the west, to an interior location in the east. The Grong-Olden Culmination, the narrow southeast arm of the basement window (Fig. 1), hence may be bound by the southeastward continuation of the Kollstraumen detachment zone on its northeast flank and the transferred Høybakken detachment zone on its southwest side; the latter may link with the northward extension of the Røragen detachment

(Norton, 1987; Fig. 1A). One particular observation fits well with this picture; the ductile element along the two steep faults of the Møre-Trøndelag Fault Complex terminates southwest of the Grong-Olden Culmination, whereas the younger, brittle fault structure transects it (e.g., Roberts, 1998b). The reduced width of the basement window to the east may imply that (1) the extent of deformation and displacement diminishes eastward or (2) the southwestern detachment has a steeper dip east-southeast of the Hitra-Snåsa and Verran faults than in the west.

The regional pattern thus suggests that the Møre-Trøndelag Fault Complex acted as a boundary zone between Devonian, westward unidirectional extension in western Norway and bidirectional opposed extension farther north. In western Norway, the Devonian detachment (mainly greenschist facies) is rooted in the middle to lower crust, and brought high- to ultrahigh-pressure rocks to high levels. Around the central Norway basement window, medium-grade conditions prevailed during extension, hence the metamorphic break (amphibolite vs. granulite facies) is less significant between the upper and lower plates. Such differences may be explained in several ways for central Norway, e.g., (1) less movement along, or a lower angle of, the detachment(s) and thereby less vertical throw or (2) total movement and vertical throw divided into two detachments instead of one, as in western Norway.

Another intriguing observation with significant implications for the tectonic denudation and uplift history is the distribution of extension-related magmatism; pegmatite dikes are common north of the Møre-Trøndelag Fault Complex, whereas no magmatic activity has been reported from areas south of the Møre-Trøndelag Fault Complex. This could imply that a warmer crustal root (granulite facies) existed in the north compared to a cold crustal root (eclogite facies) in western Norway during extension of the Caledonides.

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