The concealed Kopperå fault: A half-graben bounding structure located along the eastern flank of the Trøndelag depression, mid-Norway

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Seismic-reflection data acquired along a traverse from Stjørdal, east of Trondheim, to Storlien in Jämtland, Sweden, clearly indicate the presence of a concealed, moderately steep-dipping fault which we have named the *Kopperå fault*. The fault is located along the eastern flank of the 8-10 km deep *Trøndelag depression*, and effectively delimits a half-graben in its hanging-wall. The Kopperå fault truncates the westward extension of the lower-angle, extensionally reactivated, Steinfjell thrust that marks the base of the Caledonian Upper Allochthon in this area. The top-to-the-WNW reactivation is considered to relate to late-Scandian, Devonian extension, but no robust dating of the Steinfjell fault is yet available. Although the timing of generation of the blind Kopperå fault is clearly speculative, some comparable, steep, normal faults transecting low-angle, ductile, Mid Devonian, detachment faults elsewhere in the Mid-Norwegian Caledonides have radiometrically dated Early Carboniferous ages. The Kopperå fault may thus conceivably fall into this age category.

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Introduction

The Caledonides of Scandinavia originated as an assemblage of stacked thrust sheets and nappes mostly in Siluro-Devonian time during the oblique convergence of the plates Baltica and Laurentia, which culminated in a collision involving subduction of the Baltoscandian margin of Baltica beneath Laurentia. This accretionary and dominantly top-to-the-ESE thrusting and coeval metamorphic event is generally known as the Scandian phase of the Caledonian orogeny (Gee 1975). As well as telescoping the platformal and continental rise successions flanking Baltica, the Scandian collision also involved outboard, oceanic and volcanic arc terranes and, farther out, even more exotic rock successions and granitoid batholiths from the eastern margin and offshore insular arcs of Laurentia (Stephens and Gee 1989, Roberts et al. 2002, 2007). This scenario provides the framework of an established tectonostratigraphy of Lower, Middle, Upper and Uppermost allochthons, a subjacent Parautochthon and a thin autochthonous sedimentary cover lying unconformably upon older Precambrian crystalline basement (Roberts and Gee 1985).

A topic of some considerable debate has been the extent to which the Paleoproterozoic rocks are incorporated as tectonic slices in the basal parts of some thrust sheets (Zwaan and Roberts 1978, Bryhni and Sturt 1985, Gee et al. 1985, Ramsay et al. 1985), and also appear in internally imbricated, antiformal window structures within the Lower Allochthon (Kulling 1964, Sjöström and Talbot 1987, Greiling et al. 1993, 1998). Seismic-reflection studies initiated in the 1980s included a c. E-W profile in the Mid-Norden region from Jämtland in Sweden to coastal Trøndelag, Norway, the first results of which, from eastern areas, pointed to a more considerable involvement of the basement in Scandian thrusting than had hitherto been anticipated (Hurich et al. 1988, 1989, Palm et al. 1991, Hurich and Roberts 1997). In this brief contribution we discuss one particular late normal fault – which we have named the *Kopperå fault* – that is clearly visible on the seismics east of Meråker, in Trøndelag, and which appears to define a major half-graben structure. We show how this fault, which does not seem to penetrate the surface and is thus a blind structure, may have initiated, and how it may relate to other half-graben bounding faults elsewhere in southern Norway.

Geological setting

The geology along the valley Stjørdalen is dominated by volcanosedimentary rocks in three separate nappes of the Trondheim Nappe Complex, part of the Upper Allochthon (Fig. 1). Both the Meråker Nappe in the east and the Støren Nappe in the west are composed mainly of greenschist-facies metasedimentary successions with significant components of magmatic rocks (including ophiolites and immature arc products) at lowermost stratigraphic levels (Gale and Roberts 1974, Wolff 1979, Gee et al. 1985, Grenne and Lagerblad 1985, Nilsson et al. 2005, Slagstad et al. 2014, Gromet and Roberts 2016). The central and structurally lower Gula Complex, or Nappe, is a heterogeneous unit of generally higher metamorphic grade, in places with gneisses and migmatites (Olesen et al. 1973, Nilsen 1978, Wolff 1979, Roberts and Stephens 2000). The Meråker Nappe extends eastwards to just beyond the Swedish border where it is floored by the mylonitic *Steinfjell thrust* (Hurich et al. 1988), first recognised well over a century ago by Törnebohm (1896) and later referred to informally as the 'Grense thrust' (Border thrust) (Roberts 1967) before acquiring its current formal name. Subsequently, the amphibolite-facies thrust zone was reactivated as a top-to-the-WNW normal fault during late-Scandian extensional deformation (Sjöström and Bergman 1989), coeval with an interpreted gravitational collapse of the orogen (Roberts 1967, 1969). Directly below the Steinfjell thrust we find a comparatively thin unit of strongly retrogressed rocks of the Seve Nappe Complex (Middle Allochthon), known as the Essandsjø Nappe in eastern Norway. Below this we encounter foliated felsic volcanites, quartzites and phyllonites of the Lower Allochthon in the core of the Skardøra Antiform (Hurich et al. 1988).

As well as showing a variety of minor structures, e.g., shear bands, strain-slip cleavages, indicative of top-WNW, late-Scandian extension, the ductile mylonites of the Steinfjell thrust are also cut by more steeply dipping, comparatively brittle normal faults trending between N-S and NE-SW, with downthrows to the 'west'. By comparison with similarly trending late faults offsetting reactivated thrust zones elsewhere in Norway (e.g., Braathen et al. 2002, Osmundsen et al. 2003), it has been suggested that these steep, late faults could conceivably be of Carboniferous (Eide et al. 2002), Permo-Triassic or younger age (Fossen 2000, Mosar 2000, 2003). Such post-Caledonian, steep faults have been classified as 'Mode II extension' structures by Fossen (2000).

The local geology in the vicinity of Meråker and Kopperå is based on bedrock mapping by Chaloupsky and Fediuk (1967) and in part by Siedlecka (1967), and forms the basis for a compilation and editing of the 1:50 000 bedrock map-sheet 'Meråker' (Wolff 1972) (Fig. 2). A description of the geology in the area of this map-sheet and the adjacent sheet 'Færen' was given by Wolff (1973).

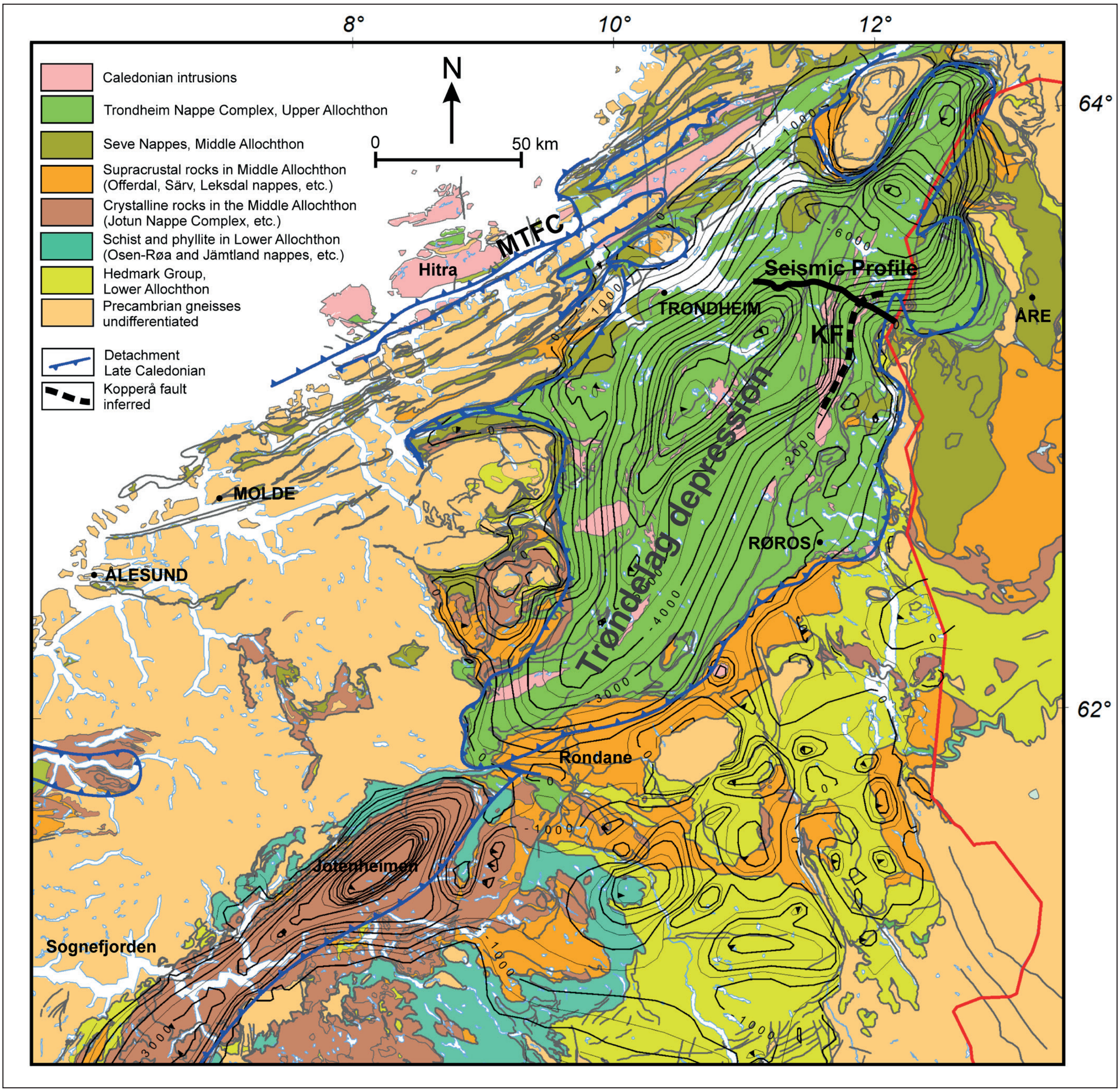

Figure 1. Tectonostratigraphic map of the Mid-Norwegian Caledonides showing the locations of the seismic profile, the Kopperå fault and the Trøndelag depression. The bedrock map has been adapted from Koistinen et al. (2001) and the interpreted depths to the Precambrian basement were compiled from Nystuen (1981), Skilbrei (1990) and Mekonnen (2004) based on aeromagnetic and gravity data. The detachment faults shown in dark blue are mostly observed structures, but some are inferred. KF – Kopperå fault; MTFC – Møre-Trøndelag Fault Complex. The map has been modified from a figure prepared by Bjørlykke & Olesen (in press).

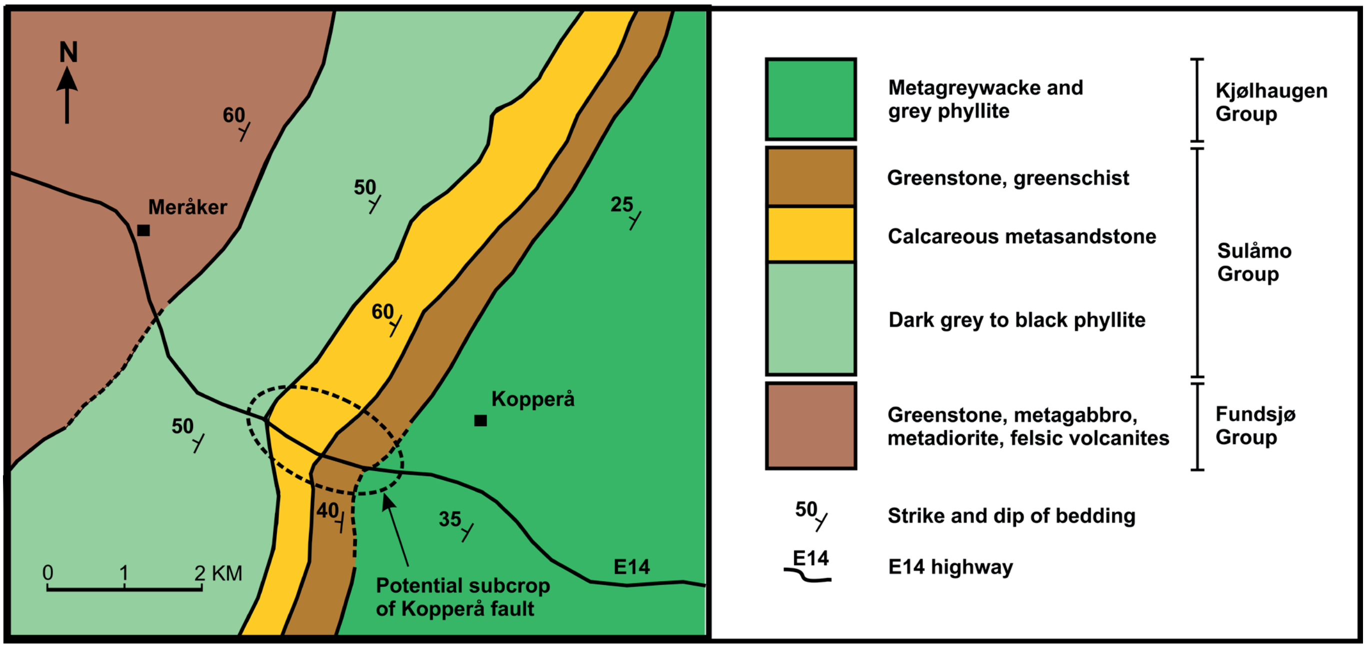

Figure 2. Simplified geological map of the area around Meråker and Kopperå; based on the work of Chaloupsky and Fediuk (1967) and, in part, Siedlecka (1967), and the 1:50,000 bedrock map-sheet 'Meråker' compiled by Wolff (1972).

Table 1. *Summary of the acquisition parameters for the seismic profile along the Stjørdalen valley.*

	WESTERN HALF	*EASTERN HALF*
source	Vibroseis, 10-60Hz sweep, 5-6 sweeps/shot station	1-3kg explosive
shot spacing	40m	200m
receiver spacing	40m	25m
geophone type	6-fold array	single 28Hz
CMP spacing	20m	12.5m

Seismic-reflection profiling

The seismic-reflection data were acquired in a multi-year (1987-1989) project with the aim of producing a semi-continuous profile from the Swedish border to the coast, west of Trondheim. The data addressed in this paper were mostly acquired along the main highway (E14) in Stjørdalen resulting in discontinuous coverage in the area of Meråker and crooked acquisition line geometries (Fig. 3a). A summary of the acquisition parameters is given in Table 1. Changes in acquisition parameters reflect available acquisition resources and changing geographical conditions along the profile. The seismic data were processed using standard, crooked line processing workflows. The final displays are coherency filtered to enhance display at small scale.

The interpreted seismic data are shown in Figure 3b. The data are presented at approximately 1:1 (H:V) with a time-depth conversion assuming a velocity of 6.0 km/s. The interpretation is consistent with that in Hurich and Roberts (1997). The Steinfjell thrust (ST) which marks the base of the Upper Allochthon occurs at the top of an interpreted culmination resulting from stacking of multiple thrust slices, presumably containing slices of the Middle and Lower allochthons. We interpret the basement/cover contact (B/C) at about 9 km depth at Steinfjell (Fig. 3b). The base of the Upper Allochthon is traced to a depth of 7 km west of Steinfjell and we suggest that the contact is truncated about 20 km to the west by the Kopperå fault (KF). We further suggest that, based on the downward disappearance of the reflection package at the 50 km mark, the base of the Upper Allochthon is offset down to the west by about 5 km by the Kopperå fault. If this is the case, about 12 km of the Upper Allochthon is preserved adjacent to the Kopperå fault and the basement/cover contact may potentially occur at 13+ km. However, we are not able to identify the basement/cover contact in the western portion of the profile.

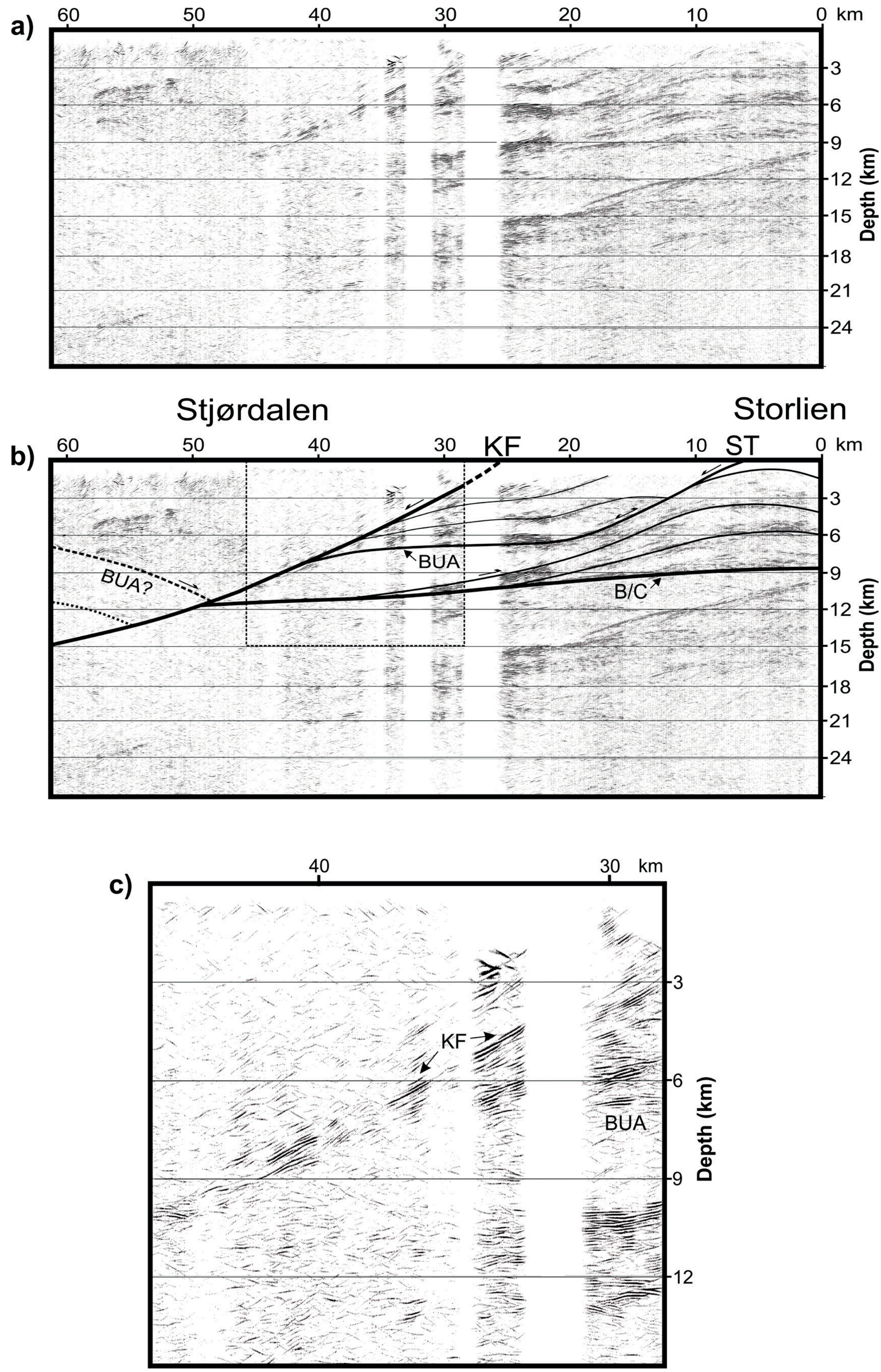

Figure 3. (a) Uninterpreted seismic data. (b) Interpreted seismic data. KF – Kopperå fault; ST – Steinfjell thrust (modified by extensional reactivation); BUA – base of the Upper Allochthon; B/C – basement-cover contact. (b) Seismic data showing the details of the reflection package interpreted as the Kopperå fault. Location is identified in (b) by the stippled box.

The Kopperå fault is identified by a consistent west-dipping set of reflections that cross-cut the nearly horizontal reflections in the Upper Allochthon to the east (Fig. 3b, c). However, confident projection of the Kopperå fault to the surface is hindered by the gaps in the seismic data in the Meråker area so our projection follows the trend of the deeper (1-1.5 km) reflections. The fact that the Kopperå fault cannot be identified at the surface indicates that the fault is either concealed or the seismic interpretation is not correct. The clarity of the reflections that define the interpreted fault and coincidence of the fault with the eastern edge of a major low in the basement as inferred from gravity and aeromagnetic data (Bjørlykke & Olesen, submitted) do, however, support the seismic interpretation.

Discussion

The reflection seismic imagery presented here shows that the concealed Kopperå fault is a c. WNW-dipping bounding structure to what we infer to be a half-graben in its hanging-wall. Unlike several, similar, sediment-filled, half-graben basins of pre-Mid Triassic age revealed by long-offset seismic lines beneath the Trøndelag Platform offshore Mid Norway (Osmundsen et al. 2002, 2005), there is no preserved evidence of late- or post-Caledonian deposits flanking the Kopperå fault in this part of the Meråker profile. Assuming that the 'Kopperå half-graben' did at one stage accommodate a sedimentary infill, then this has evidently been removed during denudation accompanying likely Cenozoic uplift which produced the Scandes mountains of today (Riis 1996, Lidmar-Bergström et al. 2000, Redfield et al. 2005).

From work in different parts of Norway, it is now well documented that several phases of extensional deformation are known to have followed the main Caledonian (Scandian), Siluro-Devonian collisional event (Fossen and Dunlap 1998, Andersen et al. 1999, Fossen 2000, 2010, Mosar 2003, Osmundsen et al. 2002, 2003, 2006, Kendrick et al. 2004, Fossen et al. 2016). In particular, the late-Scandian Devonian extension had a profound influence on the Caledonide orogen, reactivating major thrust zones, creating extensional allochthons and generating Devonian basins. In Mid Norway, a ubiquitous, late-stage, flat-lying cleavage axial planar to folds that consistently verge down dip, and also west-verging shear bands postdating ductile mylonites, were early on ascribed to a gravitational collapse of the high mountain range that resulted from the overthickened Scandian nappe pile (Roberts 1967, 1969). Later work in this region (e.g., Sjöström and Bergman 1989, Nordgulen et al. 2002, Osmundsen et al. 2002, Nilsson et al. 2005) has supported this notion, and in western Norway investigations have revealed a complex pattern of major extensional shear zones and some steeper faults (Hossack 1984, Norton 1987, Fossen 1992, Andersen 1998, Fossen and Hurich 2005, Ksienzyk et al. 2016). Several of these relatively low-angle shear zones can be followed into the offshore domain of the northern North Sea region (Færseth et al. 1995, Ksienzyk et al. 2014, Gabrielsen et al. 2015, Fossen et al. 2016). Inland, the Hardangerfjord Shear Zone (HSZ) (Hurich and Kristoffersen 1988) can be traced northeastwards across Jotunheimen via the Lærdal-Gjende fault (Milnes and Koestler 1985) into the Røragen detachment just east of Røros (Norton 1987, Gee et al. 1994). The extensional detachment is then inferred to extend north-northeastwards towards the Meråker-Storlien area, linking with either the extensionally reactivated Steinfjell thrust (Sjöström and Bergman 1989) or possibly the Kopperå fault. Interestingly, the HSZ follows a narrow but tight basement depression across Jotunheimen and its inferred extension north of Røragen coincides with the eastern flank of the *Trøndelag depression*, the deepest basement depression in the Norwegian Caledonides located beneath the Trondheim Nappe Complex (Fig. 1) (Wolff 1984, Skilbrei and Sindre 1991, Skilbrei et al. 2002). The Kopperå fault, in particular, appears to be situated along the southeastern shoulder of the steep slope marking the eastern flank of this NE-SW-trending, 8-10 km-deep Trøndelag depression. This steep slope is also the northwestern limb of the complementary Skardöra Antiform, which exposes the Lower Allochthon and Proterozoic crystalline basement rocks in its core (Hurich et al. 1988, Sjöström and Bergman 1989). In an extensional regime, this location, on the common slope between a major antiform and a synformal depression, would seemingly be an ideal situation for the generation of a graben or half-graben basin.

The precise age of generation of the blind Kopperå fault is open to speculation. From the above discussion, an association with the regional, Devonian, extensional deformation is implied. As yet there are no geochronological data on mineral growth during the extensional deformation along the nearby, reactivated, Steinfjell thrust, but an Ar/Ar study is in progress (M. Ganerød, pers. comm. 2018). In western Trøndelag, however, along the Møre-Trøndelag Fault Complex (MTFC), there are several radiometric dates indicating that ductile deformation along the major, low-angle, Høybakken detachment, which links to a principal strand of the MTFC, occurred between 401 and 381 Ma (Kendrick et al. 2004, Osmundsen et al. 2006). In the footwall to this detachment fault, Late Devonian to Early Carboniferous K-feldspar ages of 371-356 Ma are also recorded (Kendrick et al. 2004).

Quite conceivably, the main reactivation along the Steinfjell thrust may also fall within the age range of the ductile deformation along and adjacent to the MTFC. The Kopperå fault, however, does appear to offset the westward extension of the reactivated Steinfjell thrust at depth (Fig. 2), signifying that it may be younger than the inferred Emsian to Early Frasnian, ductile extensional deformation recorded elsewhere in the region. This would allow for either a Late Devonian-Early

Carboniferous or an even younger age for the steeper Kopperå fault.

Work in Nordland county, to the north of Trøndelag, has in fact shown that Mid Devonian, top-WSW, ductile deformation there, along the Nesna shear zone (Braathen et al. 2000, Eide et al. 2002, Osmundsen et al. 2003), was superceded by ductile-to-brittle deformation on steeper, down-to-the-NW, extensional faults associated with Early Carboniferous unroofing and generation of gneiss-cored, elongated, antiformal domes (Eide et al. 2002). Thus, the Kopperå fault appears to fit readily into this category of Early Carboniferous, ductile-to-brittle, steeper normal faults, and most likely developing coevally with the complementary Trøndelag depression and Skardøra Antiform.

Yet another possibility is that the Kopperå fault was associated in some way, even during a younger reactivation, with the Permo-Carboniferous to Triassic rifting that characterises the Trøndelag Platform and adjacent offshore areas (Mosar 2000, 2003, Osmundsen et al. 2002). Mosar (op. cit.) in particular has defined an '*innermost boundary fault system*' (IBF) that is inferred to have involved reactivation of several Devonian-Carboniferous extensional faults in Mid Norway and Sweden. The IBF is in effect an innermost expression of the major Permian rifting phase that dominates the North Atlantic's eastern passive margin. In Mid Norway, radiometric evidence of Permian fault movement is so far restricted to a dating of pseudotachylite along the MTFC (Sherlock et al. 2004), but more data are available from areas in southern and western Norway (Eide et al. 1997, Andersen et al. 1999, Fossen and Dunlap 1998, Fossen et al. 2016, Ksienzyk et al. 2016). In northern Norway, the Lofoten Ridge is considered to have developed as a domal core complex in Permian time, flanked by moderately steep Permian faults (Steltenpohl et al. 2004). Permian faulting has also been documented by Davids et al. (2018). In this same region, low-angle, ductile, extensional faulting has been dated to Early Devonian (Emsian) time (Steltenpohl et al. 2011).

A second major phase of rifting in the Norwegian Sea and northern North Sea occurred in Mid to Late Jurassic time, locally extending into the Early Cretaceous. At this time, older faults were reactivated in a dip-slip normal sense, leading to the development of several horst and half-graben structures in both offshore and near-coastal areas of the Trøndelag Platform and Mid Norway (Gabrielsen et al. 1999, Osmundsen et al. 2002, Sommaruga and Bøe 2002, Bøe et al. 2010). Several such Jurassic half-graben basins are associated with strands of the MTFC, the nearest to our Stjørdalen valley area being the Beitstadfjorden Basin in innermost Trondheimsfjord (Bøe and Bjerkli 1989, Sommaruga and Bøe 2002). Thus, it cannot be discounted that the concealed half-graben flanking the Kopperå fault may have been generated during this particular period of Jurassic extension. In spite of this possibility, we suspect that an earlier age of generation of the Kopperå fault and its adjacent half-graben may be the more likely case, flanking the major c. NE-SW-trending antiforms and basement depressions that characterise the regional geology of this part of the Scandinavian Caledonides.

Conclusions

The seismic data clearly indicate that the Kopperå fault truncates the westward extension of the Steinfjell thrust that marks the base of the Upper Allochthon. The Steinfjell thrust was reactivated as a top-to-the-WNW normal fault presumably during late-Scanadian extension but so far lacks geochronological data. The timing of the Kopperå fault is not well constrained but data from Nordland documents Early Carboniferous, ductile-to-brittle deformation on steep, down-to-the-NW, extensional faults that supersede Mid Devonian, top-WSW, ductile deformation on low-angle detachment faults. Geometrically, the Kopperå fault thus falls readily into the Early Carboniferous set of structures that cross-cut earlier, lower angle, ductile extensional faults. The association of the Kopperå fault with the eastern flank of the *Trøndelag depression*, supports the interpretation that the fault is directly associated with the depression and bounds a half-graben that preserves 9-10 km of the Upper Allochthon at its thickest point.

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