Abstracts

Basin inversion in a strike-slip regime: the Tornquist Zone, southern Baltic Sea

N. R. DEEKS & S. A. THOMAS

The southern section of the deep seismic reflection profile BABEL (Baltic and Bothnian Echoes from the Lithosphere) crosses the Tornquist Zone between the mainland of southern Sweden (Scania) and the island of Bornholm. This marks the boundary between the Sorgenfrei Tornquist Zone to the NW and the Teisseyre Tornquist Zone to the SE. The region represents a large-scale releasing bend in the dextral strike-slip system of Tornquist and has led to the development of pull-apart basins such as the Rønne, Arnager and Hollviken grabens, from the Carboniferous to the late Jurassic.

The area around BABEL is covered by proprietary surveys (courtesy of JEBCO Seismic Ltd., BGR Germany and the Swedish Geological Survey) which allow the three-dimensional interpretation of sediment/structural interactions within these basins. Within the area various classical (positive) inversion structures are seen on seismic sections, including 'arrowheads', inversion monoclines and flower structures. These features are found in association with both basin-bounding and intra-basinal faults. There is also evidence of inversion of basement blocks within the upper crust. Inversion took place between the late Cretaceous and early Tertiary, probably as a response to Carpathian/Alpine movements to the south. Strike-slip structures indicate that movements were dominantly dextral with rigid blocks such as Bornholm channeling deformation around them. At the same time, progradational sequences of sediment are seen to build off these blocks.

The BABEL section images a number of features believed to have resulted from the post-Carboniferous strike-slip movements of the Tornquist fault system. Structures imaged within the upper part of the section are consistent with those interpreted in three dimensions from the JEBCO survey, as a brittle response within the upper crust. Below these, between 6 and 10 seconds TWT, a zone of high reflectivity is observed. This is similar in character to regions of lower crust imaged on either side to the NE and SW, but is shallower below the Tornquist Zone. This is interpreted as a region of lower crust in which deformation is transferred in a more ductile fashion. Below this again there are coherent reflectors that may represent a more brittle transfer of the deformation into the upper mantle. The extent of upper crustal deformation imaged on the profile is around 40 km in width whilst in the lower crust it is at least 90 km.

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Shear tectonics in the Bjørnøyrenna Fault Complex, southwest Barents Sea

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The main geometry of the NE-striking Bjørnøyrenna Fault Complex evolved during a Late Jurassic–Early Cretaceous NW–SE directed extensional phase. This phase caused large-scale faulting and rotation of blocks sliding on listric faults. The result was a steep relief across the fault complex from the elevated Loppa High to the SE into the deep Bjørnøya Basin.

In Early Cretaceous times many of the major fault complexes in the SW Barents Sea were reactivated by shear movements. In the Bjørnøyrenna Fault Complex this was taken up by SSW–NNE directed dextral shear from Early Aptian time, which led to a differentiated stress regime along the fault complex according to the direction of the different segments of the main faults. Some local areas show clear signs of inversion due to transpression while other areas were affected by continuous extensional stress. In post-Cenomanian time the shear stress relaxed and the area was subject to slow subsidence through Late Cretaceous times.

Along the northwestern crest of the Loppa High a series of narrow grabens, appearing as positive and negative flower structures, can be found. Because of later uplift and erosion of the area, they cannot be dated more exactly than post–late Triassic.

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Finite element modelling of pull-apart basin formation

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This finite element modelling study is pursued in order to investigate the formation of pull-apart basins. A purely elastic rheology and a plane stress situation is assumed. Slip along the faults due to an external loading (i.e. compression) applied to one boundary of the model is controlled by the Byerlee Law. Variable modelling parameters are the fault geometry (i.e. fault overlap and fault separation), the coefficient of friction of the faults, the elastic material properties (i.e. Young's modulus, Poisson ratio) and the magnitude of the external loading.

The results obtained demonstrate that the formation of pull-apart basins is largely controlled and determined by the fault geometry. For instance, if the fault separation is about 50% of the fault overlap, several small pronounced depocentres develop, connecting both fault tips. However, in the case of a 10% fault separation, a single long extended and deep basin develops. If the fault overlap varies, small sub-basins may develop, being separated by a local sill.

Changing the elastic properties of the model, for instance, by increasing the Poisson ratio and reducing the Young's modulus, intensifies the subsidence, whereas the overall shape of the basin remains constant. The developed mechanical model, coupled with the bulk rheological properties and the thermo-mechanical evolution of the thinned lithosphere, allows us to refine predictions of subsidence in pull-apart basins.

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Late to post-Caledonian fault systems in the northeastern part of the Møre–Trøndelag Fault Zone (Snåsa–Sandøla area), Central Norway

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Detailed field investigations in the northern part of the Grong–Olden Culmination (GOC) and surrounding areas have revealed a complicated pattern of folds, faults and shear zones affecting and transecting structures and tectonostratigraphy established during the Scandian orogeny. The main tectonic units are (from the bottom): (1) Olden Nappe; (2) Formofoss Nappe Complex; (3) Gula and Skjøtingen Nappes (Seve nappes); and (4) Snåsa and Gjersvik Nappes (Köli nappes).

The observed structures show a polyphase history starting with semi-ductile folding and shearing, followed by fault formation. Fault-related rocks in granitic lithologies show transition from microlaminated mylonites to dominating flinty cataclasites and locally late fault gouge. Syntectonic hydrothermal activity leads to widespread silicification and local epidotization of brecciated rocks. Lithologies rich in phyllosilicate gave rise to phyllonitic fault products.

In the mainly granitic units (1) and (2), good examples of fault systems are found, formed in connection with general north–south compression and east–west extension:

- The Kleiva–Bergfossen fault, a main branch of the Hitra–Snåsa Fault, crosses the GOC and shows a sinistral net slip of the order of 2.5 km. An associated set of dextral faults, probably formed as transcurrent faults, allowed anticlockwise block rotation, adding another 2.5 km of sinistral shear.
- In western Sanddøla, a system of syn- and antithetic Riedel wrench faults is well developed in unit (2) along the northerly dipping border of the GOC. Lateral net slip up to 1 km along single faults is observed.

Units (3) and (4) do not show similar, well-developed fault systems. One reason is that 'weak' lithologies absorb most of the shear movement in anastomosing zones of phyllonites which are controlled by earlier anisotropy (e.g. foliation). Another reason is that regional crustal stresses might not have been homogeneously transferred to the higher tectonic units, but were compensated by local accommodation along established Caledonian thrust planes.

A possible last response to regional east–west extension is the downfaulting (detachment?) of the area east and north of the first order Kongsmoen–Gartland–Sanddøla normal fault. This fault is possibly the most important of several similar structures along the northwestern side of the Møre–Trøndelag Fault Zone.

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Structural diversity of the Trollfjorden–Komagelva Fault Zone, northern Norway and western Kola Peninsula

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The *Trollfjorden–Komagelva Fault Zone* (TKFZ) is a regionally penetrative structural feature extending from the southwestern Barents Sea to the northern coast of the Kola Peninsula. In the latter area it is currently seismically active. Although it has been considered as a major fault zone with a significant strike-slip component, there have been very few detailed field studies focusing on the structural and deformation characteristics along the fault zone. The present work employs integrated data sets to delineate the structural characteristics of TKFZ. This included the following data sets: (1) Remote sensing; (2) geophysics; (3) digital topography; (4) detailed and regional fieldwork; and (5) thin-section studies.

The TKFZ can be mapped as a composite lineament zone consisting of tonal and geomorphological anomalies. Digitally processed and enhanced Bouguer and aeromagnetic data depict the fault zone as a geophysical dislocation zone which is characterized by steep gradients and elongate anomalies. These data sets indicate that the fault zone is a deep-seated structural element extending into the crystalline basement underlying both the Late Proterozoic to Early Cambrian sediments on the Varanger Peninsula and the Palaeozoic to Cenozoic sediments in the offshore Barents Sea. Deformation features observed along the fault zone show variation from semiductile to brittle. Fieldwork has been concentrated in the central and southeastern segments of the fault zone on the Varanger Peninsula and along the part of the fault zone exposed between the Rybachi and Sredni Peninsulas. Field studies have revealed the presence of significant contractional structures along and adjacent to the fault zones in some areas. There is also widespread evidence of both dip-slip and strike-slip movements along the TKFZ. On Sredni/Rybachi, dextral strike-slip or oblique slip structures prevail, post-dating a phase of SW-directed inversion tectonics. It is evident that the SW-directed shortening appears to play a significant role in the tectonic development of the TKFZ, in addition to the dextral and some sinistral strike-slip movements. Later tectonic events were characterized by extensional to transtensional structural regimes in Mesozoic and Cenozoic times.

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Oblique slip at links and terminations of normal faults

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Extensional faults exist in a large range of scales and in a variety of geometrical patterns. In filling the information gap between the seismically resolvable faults in extensional regimes and subseismic structural features, special interest has been paid to the understanding of links and terminations of extensional faults. For hydrocarbon exploration and production an understanding of fault networks, in terms of quantitative

description, is vital for improvements in reservoir models. Here, special focus will be on links and terminations, with reference to reservoir settings and their influence on reservoir behaviour. To do this, the slip movements at fault terminations and fault links have been studied at different locations.

An overview of the critical parameters for description of the structural settings mentioned above will be presented, but also field examples (Utah, Gulf of Suez) will be used to illustrate the complexity of fault interrelationships. The transition of pure dip-slip segments of an extensional fault to oblique slip segments reveals a number of interesting implications for the near-field deformation which are relevant for reservoir description. Extensional fault networks are composed of structures with different orientations directly implying segments with different slip orientations. Often confusion arises in terminology when talking about strike-slip movements and oblique slip movements in extensional settings. Examples will be presented from purely extensional regions where almost horizontal oblique slip directions have been observed indicating the termination of a large normal fault.

The analysis of slip directions at different locations of a fault network gives important indications on the near-field deformation and the overall bulk deformation in rotated extensional fault blocks.

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Transfer zone in the Stord Basin, offshore southwest Norway

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The Stord Basin/Åsta Graben system off the west coast of southern Norway (58–60°N, 3–5°E) consists of two conjugate graben segments formed during Triassic rifting and only slightly modified by mild episodes of late Jurassic–early Cretaceous rifting and early Tertiary inversion.

The eastern margin of the Stord Basin (Øygarden Fault) and the western margin of the Åsta Graben are the major graben-bounding structures in each case and are more or less colinear. The transfer zone is represented by a complex zone of NW-trending extensional faulting between 58°45′N and 59°15′N, in particular by a central NW-trending horst separating the two graben segments. The overall displacement on the transfer zone is one of oblique dextral shear.

The WNW-trending transfer zone between the two grabens is crossed by the projected continuation of the NE-trending Hardanger–Ling Graben 'lineament', a basement-controlled structural trend which onshore in western Norway marks the boundary between the Caledonian nappes and the basement of the Baltic Shield. The structure has also been recognized offshore on deep seismic data by N- to NW-dipping reflectors in the basement and can be traced on gravity and magnetic anomaly maps. It thus seems possible that the location of the transfer zone during Triassic rifting was controlled by the underlying basement structure.

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The evolution of the Scandinavian part of the Tornquist Zone

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The interpretation of newly released commercial 2D reflection seismic data in the Kattegat area, Denmark, has provided us with a better understanding of the early Palaeozoic to late Cretaceous tectonic processes along the Tornquist strike-slip fault zone.

During the early Palaeozoic the Kattegat area seems to have been part of a foreland basin to the approaching Caledonides, and the Tornquist Zone was probably inactive. A Base Palaeozoic time structure map and a late Palaeozoic synrift isopach map outline the late Palaeozoic rifting. The isopach map, in combination with the time equivalent opening of the Skagerrak Graben at a right angle to the Tornquist Zone in the Kattegat, indicates that this extensional tectonic event had a dextral component of a minimum 10 km right lateral displacement.

The footwall blocks were deeply eroded during the Permian and at the beginning of the Triassic the area had become a peneplain. The regional Triassic subsidence gives seismic onlap and the youngest Triassic sediments are found to the east, supercropping the Precambrian basement. The Lower Triassic, in particular, shows indications of dextral movements, probably of the order of 3–4 km.

The Triassic subsidence was a regional subsidence, while the Jurassic–early Cretaceous subsidence was primarily restricted to the area between the two main faults in the Tornquist Zone, the Grenå–Helsingborg Fault and the Børglum Fault. Based on the regional stress field, minor dextral movements, of the order of 1–2 km, seem to have taken place along the Tornquist Zone during this period.

Late Cretaceous–early Tertiary compressional tectonics caused inversion of the zone between the main faults. This tectonic phase had a dextral strike-slip component, which is indicated by the 'push-up' and 'pull-down' structures formed along major curvatures in the Børglum Fault. An apparent dextral displacement along the Börglum Fault of the order of 5–7 km since the beginning of the Triassic, based on the displacement of early Permian depocentres, seems reasonable, which leaves 1–2 km right lateral displacement to the inversion events.

The continuous tectonic episodes along the Tornquist Zone throughout most of the Phanerozoic, with a total of 15–18 km dextral displacement, indicates that the zone with its old, easily reactivated, underlying basement faults can be seen as a 'buffer zone' in more coherent surroundings, whenever changes in the regional stress field are induced.

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The role of strike-slip faulting in the Tertiary tectonics of Britain

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For much of the late Palaeogene, zones of concentrated deformation passed through and around the British Isles. Of particular note is the contemporary coexistence of narrow deep rifted extensional basins with reverse faults and basin inversion; the total vertical relief represented by these structures is at least 3 km. All these structures can be shown to be related to major transcurrent (generally dextral NW–SE) fault systems that passed through the region during this period, with overall displacements of several kilometres. However, the pattern of these fault systems showed marked variation with time, with shifts in the specific faults that controlled the deformation. This episode was initiated in the Eocene as a broad shear zone passing off the Pyreno–Provencal plate boundary and linking with the Charlie Gibb Fracture Zone. However, after the Eocene this deformation linked with the Iceland–Faeroes Fracture Zone and reflects accommodation along the continental margin to the change of North Atlantic spreading directions and the rotation of the Jan Mayen microplate. The late Oligocene deformation that can be traced in western Britain involved sinistral transtensional strike-slip faulting on NE–SW-oriented structures along the line of the weak lithosphere of the Palaeocene 'Hebridian' volcanic province. This was almost a mirror image of the deformation encountered along the Norwegian continental margin at the same period. However, in contrast with the Tertiary strike-slip deformation encountered around the Norwegian continental margin, a number of the British fault systems can be mapped and viewed onland.

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Strike-slip movement along the eastern margin of Forlandsundet Graben, Spitsbergen

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The Paleogene graben along the west coast of Middle Spitsbergen is a distinct tectonic feature related to the opening of the North Atlantic. Three different approaches have been made to prove strike-slip movement along the eastern margin of the graben:

(1) A surface magnetic anomaly survey was carried out on the strand flats from Sarsøyra to Daudmannsflya. Narrow linear high anomaly zones are well detected and are arranged *en echelon* along

some belts. The most distinct high shows a left-stepping *en echelon* pattern, indicating a dextral strike-slip movement.

(2) Observations of fault slickensides reveal several stages of movement along the fault plane and the earliest ones show almost horizontal movement.

(3) Total amount of horizontal displacement has been estimated by the comparison of geological units on both sides of the graben. A unit of high-grade metamorphic rocks, up to lower–middle amphibolite facies, contrasting to the surrounding low-grade phyllites, can be correlated across the graben and gives ca. 30 km dextral displacement.

The eastern marginal zone of the graben is underlain by a thrust sheet of Caledonian high-pressure metamorphic rocks in its northern half for about 50 km.

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Use of a GPS network to measure active strain along the postglacial Båsmoen fault in the Ranafjord area

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The postglacial Båsmoen Fault (BF) lies within the regional Ranafjord lineament, which is an area of increased seismicity and anomalous land uplift. It consists of south–southeasterly dipping reverse fault segments and can be traced for 50 km from the head of Sjona Fjord to the east along the Ranafjord and further into the valley of Dunderlandsdalen. The locations Utskarpen and Båsmoen at the northern shore of Ranafjord are situated at the fault. Some 1–2-cm-thick layers of fault gouge were identified in the fault escarpments representing the actual fault surfaces. The appearance of the fault is similar to the postglacial faults reported from the Lapland area in northern Fennoscandia. The height of the escarpment is 8–40 m. Several eastward dipping slickensides indicate a dextral component to the faulting. Two swarms of north–south trending normal faults were observed in the Nesna and Langvatn areas and may be Riedel shears to the reverse fault.

There is evidence of present-day movements along the fault: (1) A total of 0.89 m uplift of a bladder wrack mark from 1894 to 1990 (Bakkelid 1990) in Hamnesberget situated in the hanging wall block 7 km to the south of the escarpment; (2) Associated with the 1819 magnitude 5.8–6.2 earthquake (Muir-Wood 1989) in the Hemnesberget–Lurøy area, Helzen (1834) reported an uplift of the shallow sea floor above sea level during an aftershock in the bay at Utskarpen. During the main earthquake a major landslide occurred at the same location; (3) An uplift of approximately 1 m of a farmhouse in the 1890s at Båsmoen (Grønlie 1923). This observation was made relative to the neighbouring mountains Snøfjellet and Høgtuva; (4) A report of 2800 ± 90 year-old fossils within the postglacial fault breccia (Grønlie 1978) in the Bossmo Mine. These four observations may be related to movements along the Båsmoen Fault, but originally they were attributed to other causes, such as (1) changing marine conditions in the Ranafjord (Bakkelid 1990); (2) piling up of material behind a rotational slump in the marine clay (Muir-Wood 1989); (3) uplift of the mountain Høgtuva, as opposed to the farm (Grønlie 1923); and (4) water transport (Grønlie 1978).

There are consequently indications of both present-day reverse and normal faulting in the Ranafjord area. Possible strike-slip movements are difficult to detect in the morphology; however, published fault plane solutions of earthquakes in the area indicate strike-slip movements. By using differential static GPS it is possible to achieve a relative positioning between two stations, better than to a few millimetres over distances of tens to hundreds of kilometres (depending on the type of receivers used). A group of geodesists, geophysicists and geologists are therefore planning to establish a GPS network designed to measure the active geological strain in the Ranafjord area. The network is assumed to give an accuracy of 5–10 mm in the horizontal plane and 5–20 mm in height. If the Båsmoen Faults are presently active, as indicated by previously published observations, this could consequently be visible on the GPS in less than a decade.

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Transtensional graben formation above a basement lineament: examples from seismic interpretation and plaster cast modelling

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Structural elements with strike-slip deformation have recently been reported to occur above, or in between, deep crustal features offshore Norway. Such features are the Tornquist–Fjerritslev, the Møre–Trøndelag and Trollfjord–Komagelv fault zones. During the Mesozoic and Cenozoic, activity along the deep part of these lineaments caused reactivation and deformation of the overlying sedimentary cover.

The Swaen Graben, a transtensional, semi-regional structure on the Loppa High in the Barents Sea has been mapped by use of reflection seismic data, and its structural pattern has been investigated in detail. Subtle but characteristic, strike-slip related structures; *en echelon* faults steepening downwards, flower-like structures, frequent polarity shifts along strike, reverse drag, concave-upward fault geometries and local folding are identified.

Plaster models of transtensional deformation above basement lineaments demonstrate the development of strike-slip structures, such as positive and negative flower structures and *en echelon* faults. The structures occur at several scales, with distinct R-, R′- and P-shears. A series of experiments with different rates of dip-slip/strike-slip was performed, and the differences of the resulting extensional and transtensional graben structures will be discussed and compared to the structure of the Swaen Graben.

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Activation and reactivation of normal and strike-slip faults: aspects of the structural evolution of Magerøya–Norkinnhalvøya–Varangerhalvøya, Finnmark, N. Norway

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Investigation of the contact of the Barents Sea (Båtsfjord Fm.) and Vadsø (Ekkerøy Fm.) Groups in the Manjunnas area of western Varangerhalvøya (the Manjannus Lens area) clearly shows that it is a simple unconformable relationship, locally angular. This establishes a correlation of the rocks across the Trollfjord–Komagelv Fault, with Barents Sea Group rocks lying on both sides of the fault. Variations in the thickness of the Vadsø Group and the outcrop distribution of the Digermul Group demonstrate that sedimentation of the Barents Sea Group south of the Trollfjord–Komagelv Fault was controlled by ~NE–SW and NW–SE trending extensional faults, forming the 'Langfjord Depression' within the 'Gaissa Basin' in the Tanafjord–Langfjord area (probably forming part of the deeper Timanian Aulacogen). Similarly, differences in thickness of the sediments across the Trollfjord–Komagelv Fault imply a substantial normal displacement for the WNW–ESE trending Trollfjord–Komagelv Fault itself (cf. Siedlecka 1985).

During Caledonian deformation, the Trollfjord–Komagelv fault was reactivated as a dextral strike-slip structure (cf. Siedlecka 1985; Rice et al. 1989). To the south of the fault the NE–SW trending extension faults at the SE margin of the Langfjord Depression caused initial buttressing during SE-directed thrust faulting in the Gaissa Thrust Belt, along a sole which is presumed to underlie the westward continuation of the Barents Sea Group exposed in the Manjunnas Lens, forming NW- to NNW-facing structures on Digermulhalvøya and in the Leirpollen–Trollfjord area; the extensional faults may have structurally inverted as sedimentary inversion occurred, with the uplift of the Barents Sea Group to its present position in the Manjunnas area, but there is no direct evidence for this.

Following the model of Rice et al. (1989), the Kalak Nappe Complex was essentially carried passively above the Trollfjord–Komagelv Fault; however, structural data show that minor strike-slip deformation did occur, accounting for the abundant faults in the Eidsfjord–Hopsfjord area (Roberts 1985) and there is a pronounced, but gradual, strain gradient within the Kalak Nappe Complex across the buried position of the Trollfjord–Komagelv Fault, with fold axial planes becoming recumbent towards the south as well as fold axes rotating and biotite porphyroblasts being tectonically disrupted. Some dip-slip movement also occurred in the faults above the buried position of the Trollfjord–Komagelv Fault; it is unclear as yet if this was due

to either synchronous strike-slip and dip-slip movements (perhaps attributable to lifting on the south side as the Gaissa Thrust Belt was imbricated) or late- to post-Caledonian extension, related to the development of the sedimentary basins in the present Barents Sea. Similarly, the abundant NW–SE trending faults in the Langfjord Depression show evidence of strike-slip displacements and formation during Caledonian shortening.

Note that the model of Rice et al. (1989) implies that the Trollfjord–Komagelv Fault lies below the base of the Kalak Nappe Complex, which deepens to the WNW and underlies the Magerøy Nappe, at a depth of perhaps 8 km. Extensional reactivation of the fault at such a depth requires considerable displacement before a surface expression will be recorded; this is coincident with the gradual WNW decrease in the number of surface fractures for which a Trollfjord–Komagelv Fault reactivation origin can be hypothesized.

In summary, early NW–SE to WNW–ESE extension faults were initially reactivated as strike-slip structures and subsequently as normal faults. NE–SW trending extensional faults acted as a buttress during thrusting and may have inverted.

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Sinistral ductile shear in the NE–SW trending coastal areas of the Western Gneiss Region

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In the Oppdal area of central Norway, Caledonian rock fabrics are dominated by lineations and folds perpendicular to the orogen and presumably formed during southeastward emplacement of thrust nappes as well as during generally southeast-directed recumbent folding of the previously assembled nappe pile.

To the north and west of the Oppdal area these earlier structures have been refolded in the intense pattern of NE–SW trending subhorizontal folds and stretching lineations that are characteristic of the coastal areas of the Western Gneiss Region from Trondheimsfjord to Moldefjord. The Surnadal Syncline is a well-known example of one of these later folds: it involves the entire tectonostratigraphy, from the basement gneisses of the parautochthon to the Støren nappe of the Upper Allochthon. The syncline is open and upright to the east, and becomes isoclinal and recumbent to the southwest, where it is refolded by still younger NE–SW trending subhorizontal folds of the same pattern.

Further west in the Moldefjord area, in the same tectonostratigraphic units, there is strong evidence for sinistral shear parallel to the axes of these subhorizontal folds. Such evidence includes S-C fabrics, asymmetric tails on porphyroblasts and boudins, asymmetric minor folds in every state of development and rotated boudins of many rock types and sizes.

Petrographic observations, with limited quantitative petrologic studies and the presence of distinctive calcite mylonites, indicate that the sinistral shear was in progress when the rocks were under upper amphibolite facies conditions and continued as they cooled at least down to about 400°C. Structural observations, for example the consistent occurrence of sinistral indicators on both north and south limbs of the folds, suggest that the sinistral shearing took place during and after the development of the folds.

Limited studies up to 20 km north and 10 km south of the Moldefjord area suggest that the subhorizontal lineation, the fold axes and, in many locations, the sinistral shear dominate the structures of the region.

The island of Vigra, just northwest of the Moldefjord trend, is also dominated by subhorizontal lineations and folds, but here the foliation is flat and countless shear indicators, including tails on eclogite boudins, indicate a consistent top-to-west shear. This pattern of sinistral shear on steep foliations and westward shear on shallow foliations is the same as that recognized by others (particularly Seranne) beneath the Devonian basins both to the south (Hornelen) and north (Bjugn). It is most likely that these widespread ductile structures in the Moldefjord area are Early to Middle Devonian in age, and represent the link between the areas of classic Devonian deformation.

Although the focus of the current study is detailed tectonostratigraphic and structural analysis with mapping of key areas at large scales, the preliminary regional implications are obvious. The conspicuous structural pattern of the coastal Western Gneiss Region – intense ductile deformation with subhorizontal NE–SW folding and stretching – is not related to the compressional build-up of the Caledonian orogenic pile, but to its subsequent extensional collapse.

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The Møre–Trøndelag Fault Zone and related Devonian basins: evolution of a transcurrent zone during late Caledonian extension

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Late orogenic extension is now widely described in the Scandinavian Caledonides. The most prominent expressions are the westward vergent extensional fabrics developed in relation to the formation of the Devonian basins in SW Norway, and the exhumation of high-grade metamorphic rocks of the Western Gneiss Region. Late Caledonian extension also occurred in northern Norway (e.g. the Rombak window) and in the Scottish and East Greenland Caledonides, which suggests a phenomenon at the scale of the orogenic belt. The large amounts of extension, measured in zones of different orientation and located several 100 km apart, put strong kinematic constraints on the reconstruction of the extensional system; in particular, it requires the existence of transfer zones accommodating large transcurrent motions. The Palaeozoic precursor of the Møre–Trøndelag Fault Zone is one of the transfer zones of the extensional system.

Field observations in the area adjacent to the Møre–Trøndelag Fault Zone provide evidence of NE-vergent ductile fabrics both in the parautochthonous basement and the Caledonian nappes, which is related to Caledonian mountain building. Close to the Old Red Sandstone basins, this fabric is overprinted by a top-to-SW ductile shearing developed within a several kilometres thick, SW-trending, generally NW-dipping shear zone. This shear zone overprints late Caledonian pegmatites, it evolves up-section into a brittle/ductile detachment bounding the Old Red Sandstone basins, it is folded together with Devonian sediments around SW–NE axes and it is crosscut by NE-trending brittle strike-slip faults that reactivate the steepened limbs of the folds.

The internal geometry of the different outcrops of Old Red Sandstone on Smøla and Hitra is consistent with deposition of syntectonic sediments in releasing bends of a left lateral, NE-trending, NW-dipping detachment. Further NE along the strike, the bedding pattern and early diagenetic deformation of the Old Red Sandstone outcrops in outer Fosen indicate that the detachment was folded in an open syncline and that the top-to-SW motion of the hanging wall controlled the deposition of the Devonian sediments.

The relationships between the SW-directed ductile shear with folding and the brittle transcurrent faulting along a general northeasterly trend, which together form the prominent feature of the area, have been a topic of debate. Observation of shear criteria on both limbs of the tight folds indicates a consistent top-to-SW ductile shear; i.e. a right-lateral component of motion on the SE-dipping limbs and left-lateral movement on the NW-dipping limbs. However, it appears that the folds are overprinted by ductile-to-brittle faults that reactivate the steep foliation planes and display a left-lateral sense of motion on both limbs. Similar structural relationships can be documented in the Sunnfjord area where stress tensor determination (orientation and relative values of σ_1, σ_2, σ_3) from measurements of the orientation of slickensides provides constraints on the understanding of the late (brittle) stages. It indicates that the stress regime evolved through time from extensional (σ_1 vertical and σ_3 horizontal) to transcurrent (both σ_1 and σ_3 horizontal). The direction of extension (σ_3) remained constant throughout, whereas rotation of the σ_1 to a horizontal position led to folding of the shear zone, parallel to the direction of extension. Such an evolution is explained by progressive unloading of the Western Gneiss Region and Vestranden due to extension, which involved a permutation of the maximum stress from vertical at the onset of late orogenic extension, to horizontal in the subsequent stages.

Mapping the directions of late orogenic extension throughout SW Norway shows a change in orientation. Westward shearing along west-dipping foliation in the coastal part of the Western Gneiss Region corresponds to extension. Top-to-SE shearing along NW-dipping foliation close to the Møre–Trøndelag Fault Zone is coeval with left-lateral wrenching. A symmetrical change is observed in the northern Scottish Caledonides, which suggests that the late orogenic extension of the Scandinavian and British Caledonides was developed within a large-scale releasing relay between the left-lateral Møre–Trøndelag Fault Zone in Norway and the Highland Boundary Fault in Scotland.

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Svalbard's pre-Devonian terranes: Caledonian and Precambrian tectonics

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Restoration of Svalbard to its pre-Tertiary location adjacent to northeast Greenland results in a structural configuration that is open to a variety of interpretations. The Caledonian orogenic belts on Svalbard are dominated by N–S trending structures; they are disrupted by N-trending faults and separated by Old Red Sandstone graben. In the Mesozoic, when Svalbard was located northeast of Greenland, these structural trends were oriented obliquely to both the North and East Greenland fold belts. Establishing the relationships between the Svalbard terranes and these Greenland orogens is crucial to an understanding of the pre-Mesozoic evolution of the Arctic.

The Svalbard Caledonides are composed of at least three tectonostratigraphic terranes, characterized by independent geological histories; they occur in the eastern, central (northwestern) and southwestern parts of the archipelago. The Southwestern Terrane provides evidence of a Grenvillian basement, a thick Late Proterozoic (including Vendian) succession, a remarkable Early Ordovician subduction complex (with blueschists and eclogites) and an unconformably overlying (?middle) Late Ordovician to Early Silurian carbonate to turbidite sequence. The central Terrane has likewise proved to contain a Grenville component (granites and gabbros) but, in contrast to the other terranes, it experienced high P/T metamorphism (with eclogites) in the Late Proterozoic (ca. 600–650 Ma); no evidence of the Early Ordovician subduction has been detected.

Svalbard's Eastern Terrane, the subject of the Swedarctic research from 1990 to 1993, differs greatly from both these more westerly provinces. No evidence of either the Early Ordovician or the Late Proterozoic orogenic episodes has been detected; indeed, a record of continuous sedimentation (Middle and Upper Hecla Hoek) throughout most of the Late Proterozoic (from ca. 800 Ma) to the Middle Ordovician requires greater separation of this terrane from the others than exists today. Recent work has shown the existence on Nordaustlandet of a substantial Grenvillian province, unconformably overlain by volcaniclastic sequences at the base of the Middle Hecla Hoek. Ny Friesland has yielded no such evidence; instead, a complex thrust intercalation of Early Proterozoic metaigneous (granites and dolerites) and metasedimentary rocks has been identified. The differences in Caledonian and Precambrian history between Nordaustlandet and Ny Friesland can be related to sinistral movements along the Sorgsfjorden Fault Zone. Remarkably, it is this Eastern Terrane that is most similar in its tectonostratigraphic evolution to that of the Caledonian fold belt in East Greenland.

The major N-trending fault zones that separate Svalbard's Caledonian Terranes all show at least local evidence of strike-slip displacements. These structures are usually ductile and found in the crystalline rocks. Adjacent Old Red Sandstones show brittle deformation that can be related to normal or reverse movements, but less obviously strike-slip. Transcurrent sinistral displacements of several hundreds of kilometres provide a logical explanation for the present distribution of the Svalbard terranes and at the same time allow a Caledonian assembly that is compatible with the stratigraphic and tectonic history of North and East Greenland.

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