Patterns of basement structure and reactivation along the NE Atlantic margin

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Abstract: A lineament pattern on the NE Atlantic margin is discussed, illustrated by gravity and magnetic images in the Norwegian Sea, and reviewed in the context of onshore field evidence. While most possible fault trends exist, three major sets predominate. A NE–SW left-stepping lineament set defines the gross geometry of the margin, while interposing northerly trends impose a rhomboidal geometry at a variety of scales. The margin is segmented by NW–SE transfer zones, sometimes involving significant offsets. The principal trends are primarily a function of Mesozoic–Cenozoic plate-wide extensional stress fields. Certain Proterozoic and Caledonian lineaments were, however, opportunistically reactivated according to the extension direction. Caledonian NE–SW orogen-oblique shears, typified by the Møre–Trøndelag Fault Zone, were reactivated via (Jurassic) strike-slip or oblique-slip, and were further exploited during Cretaceous–early Cenozoic extensional episodes leading to continental break-up. Jurassic E–W extension may also have reactivated N–S faults existing in the basement or generated in duplex systems between the NE–SW shears. Precambrian and Caledonian basement lineaments striking at a low angle to the extension direction probably predisposed the formation of major transfer zones.

Keywords: North Atlantic, Caledonian Orogeny, basement, reactivation.

We have recently compiled structural, stratigraphic and potential field data over the NE Atlantic margin as part of a regional exploration synthesis. This work included an overview of the large-scale lineaments associated with the basins on the margin (Fig. 1). A more detailed evaluation of the Norwegian Sea, including the large and underexplored Voring and More Basins, was completed for a recent Norwegian concession round. Gravity (Fig. 2) and magnetic data (Fig. 3) were compiled for most of the Norwegian Sea and processed to highlight contrasts in basement relief. The elongate highs shown on the gravity image (Fig. 2) generally reflect the basement-sediment density contrast (i.e., the edges of basins or intra-basinal highs) and are mainly a function of basement-involved extensional faulting (Blystad et al. 1995). Although most possible fault trends are present, a general pattern is clear. The area is characterized by a dominant NE–SW lineament set and a subordinate but distinct N–S grain. A more diffuse cross-cutting NW–SE set is mainly observable through lineament terminations and offsets (Figs 2 and 3). Landsat lineament mapping (Gabrielsen & Ramberg 1979) shows that these fracture patterns are also strongly represented on the Norwegian mainland. Furthermore, this configuration is not unique to Norway and its shelf, but repeats at a variety of scales along the entire NE Atlantic margin (Fig. 1).

Description of the lineament pattern

NE–SW trends

The Mid-Norwegian Shelf is bracketed by two major lineaments with this orientation. The southeastern margin is formed by a series of elongate fault blocks representing the offshore expression of a major onshore lineament, the Møre–Trøndelag Fault Zone, which is discussed in more detail below. A parallel lineament cluster, which we term the ‘Lofoten Line’, extends from the basins and highs in the Lofoten area (Utrøst Ridge–Ribban Basin–Lofoten High) into elements of the northern Voring Basin (Utgard and Nyk Highs). These features, all of which were active during Mesozoic–Cenozoic extension (Blystad et al. 1995), are well demarcated on the regional gravity image (Fig. 2). The ‘Lofoten Line’ may link into the Vestfjorden–Vanna Fault Complex, a high-angle set of semi-ductile to cataclastic faults traversing the mainland NE of Lofoten and downthrowing the Caledonian nappe pile to the SE against Precambrian gneisses. Palaeomagnetic work on fault brecias within this zone on the island of Kvaloya indicates activity in Permian and Tertiary–Recent times (Olesen et al. in press). Between the bounding lineaments of the Møre–Trøndelag Fault Zone and ‘Lofoten Line’, the NE–SW trend is expressed by the northern portion of the Fles Fault Zone, the Nordland Ridge, the faulted southern margin of the Halten Terrace, and numerous smaller scale faults. Other major representatives of this suite include: (1) a major north-easterly lineament set traversing the southwestern Barents Sea (‘Nordkapp Basin Line’ on Fig. 1) observable on gravity maps (Johansen et al. 1994) that bounds basins dating back to at least the Carboniferous (Gudlaugsson 1994); (2) the apparent extension of the Møre–Trøndelag Fault Zone into the basin margins west of the Shetlands (see discussion below), and (3) the southeastern margin of the Rockall Trough. Together, these lineaments form a left-stepping en echelon suite that dominates the gross geometry of the NE Atlantic margin (Fig. 1).

N–S trends

This trend is typified by the eastern and western bounding faults of the Halten Terrace and the southern Fløs Fault Zone.
Fig. 1. An interpretive lineament pattern, with nomenclature, for the NE Atlantic margin and Barents Sea, based on in-house gravity and magnetic maps, structure maps and published data. Colour coding of lineaments indicates confidence with which extensional reactivation of basement faults can be postulated. Basin systems are shaded blue (Jurassic), green (Cretaceous) and yellow (Cenozoic).
Numerous smaller faults parallel these features, particularly on the Halten Terrace. The gravity image clearly picks out the N–S trend as a series of highs representing basement-involved fault blocks stepping westward from the Trøndelag Platform (Fig. 2). The N–S trends appear to interpose between the dominant NE–SW lineaments, creating an overall rhomboidal geometry evident at a variety of scales, and suggesting that the two fault sets may have a common origin. Again, the N–S configuration recurs along the NE Atlantic margin in the Viking Graben, the Geikie Escarpment and the Porcupine Basin (Fig. 1), where a rhomboidal interplay with the NE–SW lineaments is observed. A similar pattern has also been described for the southern Barents Sea (Gudlaugsson, 1994).

Fig. 2. Gravity image of the Mid-Norwegian shelf, based on a regional coverage of shipborne data. The 2 × 2 km grid is provided by Amarok. The three-channel false-colour image is based on (1) adaptive filtering to enhance local anomalies, (2) first derivative horizontal filtering, and (3) principal component analysis. Blue shades indicate negative anomalies, red positive anomalies. Abbreviations: BL, Bivrost Lineament; FF, Fles Fault Zone; HT, Halten Terrace; JML, Jan Mayen Lineament; LH, Lofoten High; MH, Manet High; MTFZ, Møre–Trøndelag Fault Zone; NH, Nyk High; NR, Nordland Ridge; RB, Ribban Basin; SL, Surt Lineament; UH, Utgard High; UR, Utrøst Ridge.
**NW–SE trends**

The Mesozoic–Cenozoic basin system is segmented by a NW–SE ‘transfer’ trend, either sub-parallel to or continuous with the fracture zones of the adjacent Atlantic. These features include the Jan Mayen Lineament, which is coincident with a major southeastwards offset of the basin chain, displaces the ocean-continent boundary and extends into one of the most significant transforms in the North Atlantic (Blystad *et al.* 1995). The Bivrost Lineament (Fig. 2) separates the deep Vøring Basin from a series of simple half-grabens northwest of Lofoten, and also continues oceanward as a transform fault (Olesen *et al.* in press). The Surt Lineament, which traverses the outer Vøring Margin, separates areas with quite different structural configuration and coincides with a major change in magnetic signature. Numerous smaller scale features of this trend are evident. Along the Møre margin, a series of NW–SE transfer zones, separating basement-involved half-grabens of opposing polarity, are highlighted by high-resolution magnetic data (Fig. 3). The transfer trend is also an important influence on basin geometry West of Shetlands and in the Faeroes (Rumph *et al.* 1993). Farther southwestwards, a major NW–SE lineament, well imaged on gravity and magnetic maps (‘Anton Dohrn Transfer’ on Fig. 1), occurs at a major offset in the Rockall Trough geometrically similar to the pattern seen across the Jan Mayen Lineament. On the East Greenland conjugate margin, a significant NW–SE fracture system is reflected in the fjord grain and is also probably linked to adjacent oceanic transforms. These transfer faults played a significant role in the Mesozoic evolution of the East Greenland rift (Surlyk 1977).

**Extensional history**

The structural geometry of the NE Atlantic margin is dominated by the effects of episodic regional extension that began with post-Caledonian orogenic collapse and ended with early Eocene plate separation, an interval of some 300 Ma. Here we concentrate on the later rifting events (Jurassic to early Cenozoic), which overprint and obscure most other episodes on the margin. These extensional phases are described more completely in Lundin & Doré (1997), and only a brief summary is given here.

Late Jurassic extension, the dominant phase in the northern North Sea, was characterized by a regional E–W least principal stress direction ($\sigma_3$), as reflected in the N–S strike of those basins that can unequivocally be described as Jurassic rifts bordering the NE Atlantic margin (Viking Graben, Halten Terrace, Porcupine Basin and East Greenland Rift on plate reconstructions) (Bartholomew *et al.* 1993). This stress direction may have been inherited from an earlier (Permo-Triassic) extensional episode (Færseth *et al.* 1995). Based primarily on seismic evidence, we identify at least three phases post-dating the Jurassic. The first of these, in the Neocomian, was probably near-continuous with the late Jurassic episode, but was characterized by rotation of the extension vector to NW–SE. In plate tectonic terms, we regard this rotation as a shift in dominance from extensional systems on the northern margin of Tethys to those governed by the northeastwards propagation of Atlantic spreading. Rifting was refocused on to the NE Atlantic margin (e.g. Rattey & Hayward 1993; Earle *et al.* 1989), initiating the chain of broad NE–SW Cretaceous–Cenozoic basins (Voring Basin, Møre Basin, Faeroe–Shetland...
Basin and Rockall Trough) and overprinting the Jurassic (and earlier) rift network (Fig. 1). Further episodes of Middle Cretaceous (probably Cenomanian) and latest Cretaceous to Palaeocene age followed essentially the same extension direction and emphasized the NE–SW grain. Successive rift axes migrated northwesterly towards the present-day continental margin such that, in the Norwegian Sea, pre-opening Palaeocene rifting is confined to the area outboard of the Utgard High and Fles Fault Zone (Skogseid 1994) (Figs 1 and 2).

Arguments for a basement origin

On a broad scale it seems undeniable that rifting and plate separation between Greenland and Norway represents a slightly-modified reopening along the Caledonian suture zone, as envisaged in the ‘Wilson Cycle’ (e.g. Surlyk 1977). On a more local scale, arguments for and against a Caledonian or older origin for individual extensional structures have generated a vast literature, too voluminous to list here. The More–Trøndelag Fault Zone, however, is arguably one of the least equivocal examples of multiple reactivation on the NE Atlantic margin. It consists of a prominent NE–SW cluster of sub-vertical shears and folds that dominates the structure of coastal southern Mid-Norway. Its onshore segment was active during the late Caledonian (Scandian) closure phase (c. 400 Ma), and as a line of sinistral shear during post-orogenic extensional collapse and backsliding of the nappe pile (e.g. Séranne 1992). These tectonic events may in turn have been predisposed by an earlier (?Proterozoic) line of weakness (Gronlie & Roberts 1989; Séranno 1992). The shear zone was rejuvenated (dextrally according to Gronlie & Roberts 1989) in the Mesozoic and preserves along its inland length small fault-controlled (‘pull-apart’) basins containing Middle Jurassic strata (Bøe & Bjerklie 1989). The More–Trøndelag Fault Zone effectively defines the coastline between 62° and 64°N, and thus the margin of the More Basin immediately offshore (Grunnaleite & Gabrielsen in press). To the SW, the lineament seems to continue into the system of en echelon Cretaceous faults linking the More Basin to the West Shetland Basin (Rattey & Hayward 1993).

The More–Trøndelag Fault Zone bears a close affinity to other major Caledonian shears such as the Highland Boundary Fault and Great Glen Fault. The latter, for example, underwent sinistral strike-slip during the Caledonian (Stewart et al. this issue) and in its northeasterly extension, commonly assumed to include the Walls Boundary Fault of Shetland (Fig. 1), was reactivated dextrally in the Mesozoic (Flinn 1992). We suspect that other major NE–SW linear features on the NE Atlantic margin (‘Nordkapp Basin Line’, ‘Lofoten Line’, Rockall margin) are part of the same suite. On plate-tectonically restored maps, the Caledonian shear system may be further extrapolated southwards into the Newfoundland–Grand Banks shelf (e.g. Hubbard et al. 1985).

The N–S grain, although regionally an expression of Jurassic rifting, can be related in the North Sea and southern Norway to ancestral tensional fractures dating back to at least the Permian, and possibly to shear zones in the Proterozoic basement (Færseth et al. 1995). For hints of a Caledonian origin, however, the More–Trøndelag Fault Zone again proves the most productive model. Séranno (1992) suggests from field evidence that during sinistral post-orogenic movement Devonian (ORS) basins formed in extensional detachments within releasing bends in the fault complex. Major late or post-Caledonian sinistral motion is also typical of the Great Glen Fault, Highland Boundary Fault and other significant NE–SW lineaments (e.g. Coward 1990). In this regime N–S fractures probably formed in extensional duplexes or pull-aparts between the NE–SW shears, as evidenced by kinematic indicators of E–W extension (Séranne 1992) and numerous conjugate N–S fractures mapped from Landsat data (Gronlie & Roberts 1989) along the More–Trøndelag Fault Zone. We further point to the similarity, at least in a superficial sense, between the overall pattern of gravity lineaments in the Norwegian Sea (Fig. 2) and strike-slip duplexes described by Woodcock and Fischer (1986) (Fig. 4). This model has been proposed for initiation of the northern North Sea Basin by Coward (1990), and could provide a general explanation for the rhomboidal lineament geometry evident along the whole of the NE Atlantic margin.

While transfer zones may be formed during rifting as a means of accommodating displacement between adjacent rift segments (Morley et al. 1990), work on extensional terrains has shown that the position of such zones may be determined by pre-existing cross-cutting lineaments or tectonic grain (Cartwright 1992). We believe that this was the case with elements of the NW–SE transfer trend of the NE Atlantic margin (Fig. 1). Immediately north of the study area, the western margin of the Barents Shelf, defined by the Senja Fracture Zone and the Hornsund Fault, can perhaps be considered the master lineament of this trend. This shear/passive plate margin (‘De Geer Line’) experienced a long history of deformation from Caledonian times to the mid-Cenozoic (e.g. Faleide et al. 1993). The Senja Fracture Zone runs more or less directly into a major Proterozoic NNW-trending zone of steeply-dipping shears, the Bothnian–Senja shear zone, which can be mapped across the Scandinavian mainland as far as the Gulf of Bothnia (Henkel 1991). Individual fault segments of the NE-trending Vestfjorden–Vanna Fault Complex (Fig. 1) show significant offsets and changes in polarity at their intersection with this shear zone (Olesen et al. in press). This onshore example of an interaction between a major Proterozoic shear and a Permian–Recent normal fault merits further field study. To the SW, the Bivrost Lineament is suggested by magnetic signature to occur at the offshore continuation of a major continental-scale structure, the Protogine Zone (Olesen et al. in press). This deformation zone constitutes the western margin of the Transscandinavian Granite-Porphryy Belt, and underwent several episodes of activity in the Proterozoic (Jarson et al. 1990). Much farther SW, the ‘Anton Dohrn Transfer’ (Fig. 1) has been described as representing a major terrane boundary within the Laurentian craton, separating Proterozoic crust (Islay Terrane) to the south from Archaean crust (Lewisian Terrane) to the north. This concept is based on radiometric dates from Scotland and Rockall Bank (Dicken 1992) and on upper crustal contaminants in basaltic lavas within the Rockall Trough (K. Hitchen pers. comm.).

Other, lesser NW–SE transfers are more difficult to assign a basement origin. It is, however, established that NW–SE fracture systems are prominent in the Precambrian basement on both sides of the Caledonian orogen. The Bothnian–Senja shear zone is one of the more significant members of a NW–SE suite of Proterozoic lineaments that traverse the Baltic Shield, and which are reported to have influenced basement faulting and thrust imbrication during the Caledonian orogeny (Romer & Bax 1992). A similar suite of NW–SE fractures is strongly expressed in the Lewisian basement of NW Scotland, and also influenced Caledonian structuring and magma emplacement.
It may provide the deep-seated anisotropy giving rise to the NW–SE transfer system in the Mesozoic–Cenozoic basins west of Scotland (Rumph et al. 1993). Very speculatively, this grain is also consistent with both the average Caledonian nappe transport direction and the post-Scandian backsliding vector as described in Norway (e.g. Fossen 1992). The curiously linear nature of the transfer zones identified on the high-resolution aeromagnetic data on the Møre margin (Fig. 3) may favour a compressional origin, since linear tear faults are common in thrust belts (Mitra 1988) while linear transfer zones are unusual in extensional systems (Morley et al. 1990).

**Discussion**

We argue that some (and perhaps many) of the key lineaments observable in the extensional basins can be ascribed a Caledonian or older origin. More importantly, however, we argue that the current dominance and visibility of the lineament sets is because these, out of a wide variety of basement fracture trends, were conveniently orientated to accommodate the extensional forces leading to NE Atlantic break-up. Most prominent are NE–SW shears such as the Møre–Trøndelag Fault Zone, which trends parallel to the present-day continental margin and almost precisely normal to the Cretaceous–Cenozoic extension direction (Fig. 1). Thus, after an episode of strike-slip or oblique-slip that probably accommodated Jurassic extension, orthogonal extension allowed the lineament to function as a basin margin in early Cretaceous times. Given its maximum possible extrapolation to the SW, this lineament bounds a substantial portion of the Cretaceous–Cenozoic basin chain on the NE Atlantic margin (Fig. 1). The evidence is reasonably good that Precambrian and Caledonian lineaments striking at a low angle to the extension direction were predisposed to form major NW–SE transfer zones. A basement origin for the N-S trends is less clear, but is advocated by some North Sea workers (e.g. Færseth et al. 1995). An inception of these fractures in post-Caledonian strike-slip duplexes is possible and is consistent with the field evidence along the Møre–Trøndelag Fault Zone. We observe that the most likely examples of reactivation on the NE Atlantic margin involve subvertical shears (e.g. Møre–Trøndelag Fault Zone, Great Glen Fault, Bothnian–Senja shear zone), conforming to the view that extensional regimes should preferentially reactivate steeply-dipping structures (e.g. Sibson 1985).

We point out some curious features of the principal NE–SW lineament set. These reactivated shears trend obliquely to the Caledonian orogen as defined by the trend of the thrust front in Scandinavia and the Moine Thrust in Scotland, and appear remarkably consistent either side of the orogen. Their left-stepping nature (implying dextral offsets) also appears at first difficult to reconcile with formation in a collision generally assumed to have had a major oblique sinistral component (e.g. Torsvik et al. 1990). Figure 4 shows one possible solution to this problem, in which lineaments bounding terranes accreted on to the Laurentian and Baltic margins may have been dextrally offset, rotated and amalgamated during oblique sinistral collision. This idea, based on analogy with micro-scale shear-sense indicators (Simpson & Schmid 1983), is similar to the model of rotating lineament-bounded basement blocks (‘mega-augen’) derived for the Grampian Highlands by Jacques & Reavy (1994). It is also consistent with reported initial dextral (top to the northeast) movement on the Møre–Trøndelag Fault Zone, occurring simultaneously with Scandian thrusting and prior to late/post-Caledonian sinistral reactivation (Séranne 1992). A related problem stems from the extrapolation of the Møre–Trøndelag Fault Zone between Mid-Norway and Scotland assumed by many workers.
(Gronlie & Roberts 1989; Blystad et al. 1995; Grunnaite & Gabrielsen in press). A similar connection has been proposed between the HBF and the Hardangerfjord Shear Zone in southern Norway (Fig. 1), based on graben offsets (Dikkers 1977), basement geochemistry (Frost et al. 1981), palaeo-geography (Doré 1991) and satellite gravity images (Bostrom 1989). These correlations conflict with traditional Caledonian models, since they would require the shears to intersect Baltic and Laurentian basement complexes that were originally on opposite sides of the Iapetus Ocean (see arguments in Klemperer & Hurich 1990). This may mean that the offshore workers have simply made wrong correlations based on chance alignments. Both ideas could be reconciled, however, by a model akin to that in Fig. 4, which would allow shears to propagate or amalgamate across the orogen during Baltica–Laurentia suturing. A more extreme view, that these cross-cutting shears existed prior to Iapetus formation, would fit with Mason’s (1988) hypothesis of a northern Iapetus of no great width that simply opened and closed in the same place, but would conflict with most published palaeomagnetic evidence on Laurasian assembly (e.g. Torsvik et al. 1990).

Finally it must be noted that, despite an empirical similarity between offshore basin trends and onshore basement trends, and despite some prominent examples of reactivated lineaments, direct evidence for both the scale and mechanism of reactivation on the NE Atlantic margin is still in short supply. Further field study of major lineaments with apparent onshore and offshore expression (such as the Møre–Trondelag Fault Zone and Bothnian–Senja shear zone) would appear to provide the most fertile ground for future research.

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