Variations in basaltic geochemistry along a propagating rift of the late Ordovician marginal basin of the West Norwegian Caledonides

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ABSTRACT
The late Ordovician Solund-Stavfjord ophiolite complex in the western Norwegian Caledonides records a multi stage seafloor spreading history of an Iapetus marginal basin and contains three structural domains with distinctive tectonomagmatic evolutionary paths. The NNE-trending Domain 1 consisting of high-level gabbro, sheeted dykes and extrusive rocks is interpreted to represent fossil oceanic crust developed along a spreading centre that propagated northwards into pre-existing oceanic crust in the marginal basin. Dyke swarms at the head of this inferred propagating rift range from primitive, high-MgO basalts to highly fractionated quartz-diorites. Southwards along-strike of Domain 1, the abundance of primitive basalts decreases and the proportion of FeTi-basalts increases to become predominant furthest behind the tip of the propagating rift. This geochemical evolution is comparable to that of the basalts of modern propagating rifts at the East Pacific Rise and the Galapagos spreading ridge. We suggest that the chemical variations of the metabasalts reflect changes in magma supply rates and in the increasing size of magma chamber(s) along-strike of the spreading centres.

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Introduction
Propagating rifts are common features along intermediate- to fast-spreading modern mid-ocean ridges and back-arc spreading centres, such as the East Pacific Rise, the Galapagos spreading centre and the Lau Basin (e.g. Sinton et al., 1983; Parson and Hawkins, 1994). Several studies have documented local geochemical variations in terms of the extent of partial melting and degree of fractionation along the axis of modern spreading ridges, as a function of proximity to tectonic features such as ridge offsets and propagating rifts (e.g. Schilling and Sigurdsson, 1979; Natland and Nelson, 1980; Christie and Sinton, 1981; Sinton et al., 1983; Bender et al., 1984; Langmuir and Bender, 1984; Macdonald et al., 1988). Adjacent to transform faults, Bender et al. (1984) found that the extent of partial melting might be lower than elsewhere along a spreading ridge, described as an ‘edge effect’ by Fox and Gallo (1984). Similarly, many of these chemical characteristics, termed ‘magmatic edge effects’, have been observed in connection with small overlapping spreading centres along the East Pacific Rise (Langmuir et al., 1986; Sinton et al., 1991).

Structural evidence for rift propagation has also been cited from the SE-mail: ophiolite (Oman), where cross-cutting dyke relations and mantle flow trajectories are interpreted to indicate the southward propagation of a NW-trending ridge system in the Cretaceous Neo-Tethys (Boudier et al., 1997). However, the occurrence of systematic changes in basalt chemistry associated with rift propagation is not well-established in the ophiolite literature. In this paper, we report the geochemical variations in basalt chemistry along the NNE-trending southern part of the Solund-Stavfjord Ophiolite Complex in the western Norwegian Caledonides which we interpret to have resulted from rift propagation in an Iapetus marginal basin. The mode and nature of these geochemical variations are comparable to those documented from modern propagating rifts and can be explained in an internally coherent petrogenetic model.

Tectonic features of the Solund-Stavfjord Ophiolite Complex
The late Ordovician (443 ± 3 Ma) Solund-Stavfjord Ophiolite Complex (SSOC) in western Norway represents a remnant of oceanic lithosphere developed in a Caledonian marginal basin (Dunning and Pedersen, 1988; Andersen et al., 1989; Skjerlie et al., 1989; Furnes et al., 1990). The ophiolite displays three structural domains (Fig. 1a) that have different types of crustal architecture reflecting the mode and nature of magmatic and tectonic processes that operated during multi stage seafloor spreading evolution of this marginal basin (Dilek et al., 1997). Domain 1 has a NNE-trending structural grain defined by the consistent orientation of dyke swarms in the sheeted dyke complex (Fig. 1b, c). At the northermmost terminus on the island of Tverberg, Domain 1 consists mainly of discrete dykes, whereas in the south, on the islands of Alden, Verlandet, and Olldra, it contains an extensive volcanic sequence composed of pillow lava, pillow breccias, massive sheet flows, and fossil lava lakes stratigraphically overlying a well-developed sheeted dyke complex and high-level, isotropic to vari-textural gabbros (Furnes, 1972; Skjerlie et al., 1989; Furnes et al., 1992) (Fig. 1a, c). Domain 2, which represents the oldest preserved crust in the ophiolite, contains a NW-trending sheeted dyke complex and underlying isotropic gabbros. In the central part of the island of Tverberg, where Domain 1 and 2 approach each other, the sheeted dykes of Domain 2 curve from a consistent NW orientation into an ENE direction, indicating a significant shift in the stress regime in the palaeo-seafloor spreading system. This change in
Fig. 1 (a) Simplified geological map of the Solund-Stavfjord ophiolite complex and adjacent rocks (modified after Furnes et al., 1990; Dilek et al., 1997). (b) Reconstructed palaeo geography of the Caledonian, late Ordovician marginal basin, represented by the Solund-Stavfjord Ophiolite Complex (modified after Dilek et al., 1997). (c) The detailed geology of the islands defining Domain I (Tviberg, Alden and Oldra) from where the analytical data have been collected. Tviberg: modified after Skjerlie et al. (1989); Alden: modified after Furnes et al. (1992); Oldra: modified after Dilek et al. (1997).

Dyke orientation from Domain 1 to Domain 2 occurs along and within a NE-trending shear zone, which is composed mainly of anomalous oceanic crust with serpentinite breccias and fault-bounded serpentinite slivers in deformed isotropic to fissal gabbros. This 1-km-wide shear zone is interpreted as part of a fossil oceanic fracture zone (Skjerlie et al., 1989; Skjerlie and Furnes, 1990), which represents Domain 3 in the SSOC (Dilek et al., 1997). Based on the cross-cutting relations of these three structural domains, the overall construction of their volcanic succession and internal architecture, and the geochemistry of the volcanics and sheeted dykes, Dilek et al. (1997) proposed that the NNE-trending Domain 1 represents the remnant of an intermediate-spreading rift system that propagated northwards into pre-existing oceanic crust that was developed along the NW-trending doomed rift (Domain 2) in the marginal basin (Fig. 1b).

Geochemistry of the propagated rift segment of the SSOC

In Fig. 2(a) the MgO – FeO/MgO relationships for the Domain 1 dykes and lavas from Tviberg, Alden and Oldra (Fig. 1) are shown. The largest variations are shown by the dykes from Tviberg, exhibiting a pronounced range in the MgO content of 4.5–9 wt.% and in the FeO/MgO ratio of 1–3. The metabasaltic dykes and lavas from Oldra in the southern part of the ophiolite (Fig. 1), define a narrower ranges in the MgO...
content (5.6–8 wt.%), and in the FeO/ MgO ratios (1.40–2.65). At the same MgO content, the metabasalts from Olrdra show higher FeO/MgO ratio than those from Tiviberg. The metabasalts from Alden define intermediate compositions between those of Olrdra and Tiviberg. However, since experimental studies on the alteration of basalts have shown that Fe may suffer leaching, while Mg may get enriched under suitable water/rock ratios and temperatures (Mottl and Holland, 1978; Seyfried and Bischoff, 1979), the FeO/MgO ratios may be variably reduced. Ti, on the other hand, is in all alteration studies of basalts reported to be a rather stable element. Hence, to strengthen the validity of the MgO–FeO/MgO relationship, a FeO–TiO2 plot is shown in Fig. 2(b). Clearly the FeO and TiO2 contents in the Tiviberg samples are generally lowest, intermediate in the Alden samples and highest in the Olrdra samples.

A basalt is classified as a FeTi-basalt, when FeO > 12 wt.%, TiO2 > 2 wt.%, and FeO/MgO > 1.75 (Melson et al., 1976; Sinton et al., 1983). Thus, the metabasalts of Tiviberg can be classified as primitive, high-MgO basalts to highly fractionated FeTi-basalts (TiO2 content varies between 1.12 and 2.77 wt.%) and quartz diorites (Skjerle, 1988), whereas those from Olrdra predominantly as FeTi-basalts (TiO2: 2.56 ± 0.20 wt.%; average of 174 analyses) (Ryttvad, 1997). The differences in the FeO/MgO ratios between the metabasalts from Tiviberg, Alden and Olrdra are also shown in Fig. 2(b). The FeO/MgO ratios of the Olrdra metabasalts define a rather smooth Gaussian distribution pattern with a distinct maximum (FeO/MgO: 1.90–1.99). The Alden metabasalts show the similar maximum of the FeO/MgO ratios as those from Olrdra, but they also show a minor second peak (FeO/MgO: 1.60–1.69), defining a slight bimodal distribution.

Comparison with modern propagating rifts

Studies by Sinton et al. (1983) have demonstrated pronounced geochemical changes in basalt compositions along propagating rifts, ranging from a large variety of primitive to highly evolved basalts, rare andesites, and rhyodacites at the propagating tip, to predominantly FeTi-basalts near the propagating tip, or at a short distance behind, to a progressive change into N-MORB farther away from the tip. Thus, in order to compare the geochemical evolution of Domain 1 with that of modern propagating rifts, we evaluated the geochemical characteristics of the metabasalts (FeO/MgO ratio) in relation to distance from the propagating head of four examples from the East Pacific Rise and the Galapagos spreading ridge (Fig. 3a). This compilation shows that the less fractionated lavas are erupted immediately behind the propagating rift tip. At the propagating tip, or a short distance behind it, the compositional ranges reach a maximum. Farther behind the tip (≈ 60–200 km), the basalts gradually approach N-MORB compositions. Although the abundance of FeTi-basalts differs among the four examples shown in Fig. 3(a) a common feature is the maximum compositional variability at, or close behind (≈ 20–40 km), the propagating rift tip.

Discussion and conclusions

Figure 3(b) shows the progressive changes in the proportion of FeTi-basalts to N-MORB of Domain 1 metabasalts with respect to increasing distance from Domain 3, in which the tip of the rift propagator, represented by NNE-trending dyke swarms in the anomalous oceanic crust of the fossil fracture zone, is situated. There is an apparent shift southwards along Domain 1 from less representation of FeTi-basalts relative to N-MORB on Tiviberg (43%), to a majority of FeTi-basalts on Alden (67%), and finally to a strong predominance of FeTi-basalts (80%) on Olrdra.

The geochemical features in terms of FeO/MgO ratios of the metabasalts of Olrdra, Alden and Tiviberg do show features which are comparable with those of modern propagating rifts when progressively approaching the propagating tip. Thus, from Tiviberg, via Alden to Olrdra, the proportion of metabasalts with FeO/MgO ratios less than 1.75 progressively decreases (Fig. 3b). This is a feature demonstrated by all the four modern propagating rifts when getting farther away (≈ 50–100 km) from the rift head (Fig. 3a). The predominance of FeTi-basalts on Olrdra in the Solund area (Fig. 2), at a present distance ≈ 30 km south of the inferred propagating tip (Fig. 3b), is also largely compatible with the pattern observed at modern propagating rifts (Fig. 3a). The shift from a predominance of FeTi-basalts to N-MORB appears to occur at distances of ≈ 60–200 km behind the propagating rift tip along modern propagating rifts (Fig. 3a). The maximum 30 km length (somewhat more if unfolding the open, gently westward-plunging Devonian folds, see Fig. 1a) of Domain 1 as exposed from beneath the sedimentary cover of the Devonian basinal strata is an unreasonably short distance for N-MORB to appear, and hence it hampers the opportunity of further testing our model against distance from Domain 3. It should also be noted that the increase in the FeO/MgO ratios from Alden to Olrdra (presently 25 km apart), is less than that observed at the modern propagating ridges (Fig. 3). However, the metabasalts on Alden are generally more pervasively deformed than those at Tiviberg and Olrdra, and hence may not be in their original position relative to the two above-mentioned islands. However, even though the along-strike length of Domain 1 in which the data are collected is limited, and detailed age control is lacking, the geochemical patterns shown in Fig. 3(b) strongly indicate that the propagating rift model suggested by Skjerle et al. (1989) and Dilek et al. (1997) can be substantiated in a coherent petrogenetic model.

On the basis of field relationships (particularly those which can be demonstrated on the island of Tiviberg, Fig. 1c), and the differentiation histories of the Olrdra, Alden and Tiviberg metabasalts (as illustrated by the FeO/MgO ratio sections on Fig. 2), a petrogenetic model is proposed for the development of the metabasalts in Domain 1 (Fig. 4). In the Olrdra segment of Domain 1 which represents the area farthest away from the fossil oceanic fracture zone (Domain 3), the FeO/MgO ratios of the metabasalts are characterized by a broad band (≈ 0.4 FeO/MgO unit) with varying MgO content (Fig. 2a). This profound variation in the FeO/MgO ratio may be explained by the generation of individual magma batches at different depths in the mantle and/or subsequent fractional crystallization at different pressures (e.g. Grove et al., 1992; Langmuir et al., 1992). By assuming accumulated fractional melting as the most likely melting process,
Fig. 2 (Left) (a) MgO–FeO/MgO and (b) FeO–TiO₂ relationships for metabasalts from Tivberg (21 analyses, taken from Skjerlie, 1988), Alden (109 analyses, taken from Johansen, 1989) and Oldra (171 analyses, taken from Ryttvad, 1997, and Fonnel 1997). The definition of FeTi-basalts (FeO/MgO > 1.75) has been taken from Sinton et al. (1983). (c) Histogram showing the variation (in percentage) in the FeO/MgO ratio (between 0.90 and 3.09) of the metabasalts from Tivberg, Alden and Oldra. FeO = FeO + Fe₂O₃.

Fig. 3 (Right) (a) Variations in basalt geochemistry of propagating rifts (East Pacific Rise and Galapagos spreading centre) as demonstrated by FeO/MgO ratios in relation to distance from transform fault. Modified from Sinton et al. (1983). (b) Histograms of the FeO/MgO ratios for the metabasalts from Tivberg, Alden and Oldra (Domain 1) in relation to distance from the tip of the propagated rift impinging on the oceanic fossil fracture zone (Domain 3) on the southern part of Tivberg.

experiments show that the FeO content of a primary magma will increase significantly with increasing depth of partial melting, and the higher the pressure during subsequent fractional crystallization, the more FeO-rich will be the liquid become (Langmuir et al., 1992). Our data on the Oldra metabasalts would favor a model in which melting occurred at depths of around 12–20 kbar from a previously, strongly depleted mantle (as shown by the high εNd values of 7.8–8.4) (Ryttvad, 1997). Relationships between compatible and incompatible elements (e.g. Cr–Zr) indicate that subsequent mixing of melt batches at supposedly various levels within and above the mantle column of melting took place. Fractional crystallization of olivine, plagioclase and clinopyroxene at various pressures less than 8 kbar, further modified the liquids (Ryttvad, 1997). The model for Oldra, depicted in Fig. 4, assumes crustal to subcrustal magma chambers which would have to be of such a size that new, incoming batches of less fractionated magma would only rarely bring the composition of the mixed liquids out of the FeTi-basaltic field.

A large part of the metabasalts from Alden are compositionally similar to those from Oldra, both in terms of FeO/MgO ratios (Fig. 2) and Nd-isotopes showing εNd values of 7.8–8.7 (Furnes et al., 1992), and hence a similar model is suggested for the Alden segment of Domain 1 (Fig. 4). Parts of the Alden volcanics are strongly dominated by massive sheet flows (Furnes et al., 1992) indicative of high eruption rate of voluminous magma batches.
Fig. 4 Petrogenetic cartoon depicting a generalized model for the magmatic development of Domain I from the tip of the propagating rift in the north, where basaltic dykes intrude the sheared gabbroic rocks of Domain 3 (on Tivberg), to Oldra situated 30 km south of Domain 3.

which again may indicate the presence of sizeable magma chamber(s). However, in the FeO/MgO–MgO diagram some of the Alden metabasalts show less FeO enrichment than those from Oldra, defining an intermediate position between those of Oldra and Tivberg (Fig. 2). This may indicate that melting in general took place at somewhat lower pressure and/or that the liquids did not reach the same evolved level during fractional crystallisation as did liquids from the Oldra segment.

Of the investigated metabasalts from Domain I, those from Tivberg show the largest MgO variation, and the lowest FeO/MgO ratio at a given MgO content (Fig. 2). These features may be explained as a result of partial melting and fractional crystallisation at shallower depth than those from Alden and Oldra (Langmuir et al., 1992). The NNE-striking dyke swarms on Tivberg might have originated from small, isolated, ephemeral magma pools, causing high-MgO liquids to solidify when magma supply was low. Intermittent high magma supply rates, combined with long residence times of magmas during which more extensive crystal fractionation could take place, would yield, however, a spectrum of liquids from rather primitive basalts, via FeTi-basalts to silicic differentiates (Christie and Sinton, 1981). The dykes and gabbro from Tivberg are more enriched in the most incompatible trace elements (e.g. Tb and LREE) than those from Solund (Furnes et al., 1982). This may reflect generation of melts from a less depleted mantle source, as indicated in Fig. 4.

Proximal to the thick, cold wall of transform fault boundaries and/or fracture zones, lateral conductive heat flow reduces the ambient temperature and disrupts the upward migration of the hot upwelling asthenosphere, diminishing the volume of basaltic melt generated and impeding the ability of the melt that is segregated to reach the surface. At the initial stage of magmatism along a new spreading ridge, as in this case at the propagating tip of Domain I, the cooling on the transform fault rocks (Domain III) at the island of Tivberg, small uncoalesced blobs of primary magma will freeze and produce high-MgO, low-FeTi basalts (Christie and Sinton, 1981). As a result, the total magmatic budget supplied to shallow-level magma chambers decreases as the transform is approached and the crust thins correspondingly (Fox and Gallo, 1984). The thin and relatively cold crust proximal to transform faults will allow deep sea water penetration, which results in hydration of ultramafic rocks and subsequent mobilisation of serpen- 

tinite diapirs along shear zones. The proposed magmatic and tectonic model (Fig. 4) for the origin of Domain 3 as an oceanic fossil fracture zone separating Domains 1 and 2 is hence consistent with the thermal conditions for a ridge–transform intersection.

The documented geochemical variations in the metabasalt compositions along-strike of the Solund-Stavfjord ophiolite are consistent with the data available from modern propagating rifts, and combined with the structural evidence they attest to rift propagation along an intermediate-spread ridge system in the late Ordovician Caledonian marginal basin in western Norway.

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