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Volcanic evolution of oceanic crust in a Late Ordovician back-arc basin: The Solund-Stavfjord Ophiolite Complex, West Norway

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[1] The stratigraphy of the well-preserved Solund-Stavfjord Ophiolite Complex in the West Norwegian Caledonides documents the volcanic evolution of a spreading center in a Late Ordovician back-arc basin. Basaltic sheet flows, pillow lavas and volcanic breccias are the main components of the ~470–800 m thick extrusive sequence, and are organized stratigraphically in a cyclic manner. Cyclic units vary in thickness from ~5 m to 225 m and are typically composed of basal sheet flows or lava flows with large pillows that are succeeded by flows with progressively smaller pillows and volcanic breccias. Thick, independent breccia units also occur in the stratigraphy. In sheet-flow dominated parts of the sequence the cyclic units are thicker (average 85 m) than in pillow-dominated parts (average 20 m). Detailed logging of closely spaced profiles (~1 km or less apart) shows that the proportions of sheet flows, pillow lavas and volcanic breccias varies laterally. Along an axial segment of less than 10 km, the volcanic products change from predominantly sheet flows, reflecting robust volcanic centers, to pillow lavas to volcanic breccias. Sheet-flow dominated volcanic centers seem to be spaced at intervals of ~25–30 km, and we tentatively interpret their regularity as an expression of volcanic segmentation at an intermediate- to fast spreading center. Observations of modern ocean crust suggest that sheet flows dominate at fast spreading ridges, while pillow lavas dominate at slow-spreading ridges. Volcanic breccias are apparently rare in both of these environments. These features contrast with the stratigraphy of the Solund-Stavfjord Ophiolite Complex, where the proportion of different volcanic products varies laterally and volcanic breccias are common. We emphasize the importance of detailed studies of the volcanic stratigraphy of ophiolites, as complements to those of in-situ oceanic crust, in order to provide a more complete picture of volcanic evolution of oceanic crust in different spreading regimes.

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1. Introduction

[2] Coring by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP), studies by submersibles within the axial grabens of spreading systems [e.g., *Karson and Rona*, 1990; *Smith and Cann*, 1993; *Dilek et al.*, 1998; *Karson*, 2002] and seismic investigations [e.g., *Harding et al.*, 1989; *Detrick et al.*, 1994; *Christeson et al.*, 1994] have resulted in significant advances in understanding the construction of in-situ oceanic crust. These studies have shown that the architecture of oceanic crust and the proportions of its volcanic components (sheet flows, pillow lavas, and volcanic breccias) vary considerably, principally depending on the spreading rate (see summary by *Kennish and Lutz* [1998]). The general picture that has emerged from surface studies of modern oceanic crust is the dominance of sheet flows at fast spreading ridges [*Rosendahl et al.*, 1980; *Francheteau and Ballard*, 1983; *Renard et al.*, 1985; *White et al.*, 2002], and widespread occurrence of pillow lavas at slow-spreading ridges [*Ballard and van Andel*, 1977; *van Andel and Ballard*, 1979; *Crane and Ballard*, 1981; *Smith and Cann*, 1990, 1993; *Smith et al.*, 1995]. However, acquiring a complete and detailed picture of the volcanic architecture of modern oceanic crust is hampered by poor core recovery (generally considerably less than 50%), limited number of drill sites, and nearly one-dimensional nature of drill core. Core recovery has been particularly poor in young, poorly consolidated glassy and/or brecciated volcanic material resulting in a misleading, apparent lack of this material in in-situ upper oceanic crust. Holes 504B and 896A drilled into 5.9 m.y. old, intermediate-spread oceanic crust formed at the Costa Rica Rift are 1 km apart, representing the closest deep drilling sites on the seafloor [*Alt et al.*, 1993]. Two other important drill holes for the lithological development of ocean crust, representative of a slow-spreading ridge, are Holes 417D and 418A in the western Atlantic, situated ~10 km apart [*Robinson et al.*, 1979]. Apart form these examples, information on the volcanic stratigraphy of in-situ oceanic crust is available only from one-dimensional drill cores scattered tens or hundreds of kilometers apart in ocean basins.

[3] Ophiolites have long been regarded as fragments of fossil oceanic crust [e.g., *Moores and Vine*, 1971], and careful studies of their components and their mutual relationships have made significant contributions to a better understanding of the structure and petrology of oceanic crust [e.g., *Moores and Vine*, 1971; *Gass and Smewing*, 1973; *Pallister and Hopson*, 1981; *Varga and Moores*, 1985; *Nicolas et al.*, 1993, 1994; *Boudier and Nicolas*, 1995; *Nicolas and Boudier*, 1995; *Dilek et al.*, 1998; *Furnes et al.*, 2001, 2003]. However, ophiolites generally exhibit geochemical evidence of subduction [e.g., *Pearce et al.*, 1984; *Shervais*, 2001] and are considered to be related to the formation of back-arc as well as fore-arc basins [*Bedard et al.*, 1998] rather than major spreading axes such as the Mid-Atlantic Ridge or East Pacific Rise. Back-arc basins such as the Japan Sea, Coral Sea Basin, South China Basin and Woodlark Basin have magnetic lineations that have been correlated with the geomagnetic timescale, and it is likely that the oceanic crust forms in these basins in a manner comparable to that of major ocean basins. Observations from in-situ young oceanic crust developed in back-arc basins are limited, and the study of ophiolites may hence add considerably to our knowledge of the architecture of oceanic crust generated in these particular tectonic environments.

[4] In this paper we present the results of our systematic study of the volcanic stratigraphy of the Late Ordovician Solund-Stavfjord Ophiolite Complex in western Norway (Figure 1). Using closely spaced profiles, most importantly along two continuous and well-exposed segments ~6 and 16 km long, we document the stratigraphic development and lateral variation of the volcanic

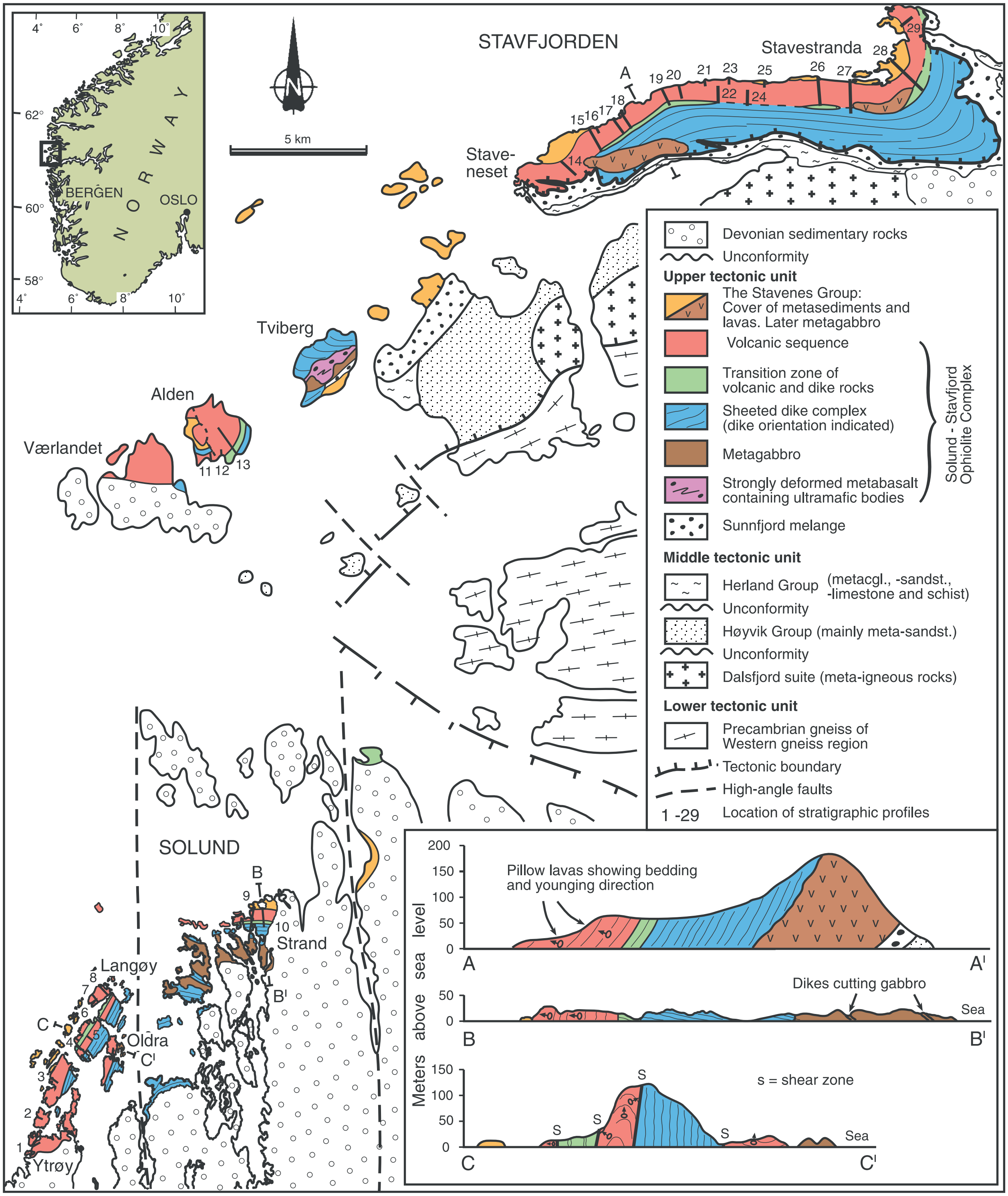

Figure 1. Geological map of the Solund-Stavfjord Ophiolite Complex and adjacent rocks, compiled from *Furnes et al.* [1990, 1992, 2001], *Skjerlie and Furnes* [1990, 1996], *Osmundsen and Andersen* [1994], as well as the present work. The numbers 1 through 29 show the position of stratigraphic profiles through the volcanic sequence of the ophiolite, shown in Figure 7. Three cross sections A-A′, B-B′, and C-C′ illustrate the structure of the ophiolite.

rocks of this ophiolite. We suggest that the 2-dimensional distribution of volcanic rock types in the Solund-Stavfjord Ophiolite Complex can be used to infer effusion rates along its paleo-spreading center, the nature of the volcanic activity and the location of major volcanic edifices. These interpretations have significant implications for magma chamber processes and the existence of magmatic segmentation along-axis of the oceanic spreading center in the back-arc basin in which this ophiolite complex formed. We contend that detailed lithostratigraphic and chemostratigraphic studies of well-preserved extrusive sequences in ophiolites may prove effective in deciphering the evolution of the volcanic oceanic crust.

2. Geology of the Solund-Stavfjord Ophiolite Complex

[5] Magmatic complexes related to the evolution of the Iapetus Ocean occur along the entire length of the Scandinavian Caledonides. Ophiolites and associated island arc complexes can be subdivided into a group of Early Ordovician age (~500 to 470 Ma), and a younger group of Late Ordovician to Early Silurian age (~440 Ma) [*Dunning and Pedersen*, 1988; *Pedersen et al.*, 1991; *Pedersen and Dunning*, 1997; *Hartz et al.*, 2002]. The Solund-Stavfjord Ophiolite Complex, dated to 443 ± 3 Ma [*Dunning and Pedersen*, 1988], associated with basic to acid calc-alkaline volcanic rocks dated to 439 ± 1 Ma [*Hartz et al.*, 2002], belongs to the latter group.

[6] The Solund-Stavfjord Ophiolite Complex, the conformably overlying metasedimentary and metavolcanic rocks (the Stavenes Group), and the tectonostratigraphically underlying Sunnfjord melange occur in the Solund and Stavfjorden areas on the west coast of Norway and constitute the uppermost allochthon in a nappe package overlying Precambrian gneisses (Figure 1). The Stavenes Group had a heterogeneous sedimentary and magmatic development. The magmatic rocks (mainly gabbroic intrusions and some lavas) in the stratigraphically lowest part have typical MORB compositions. At higher stratigraphic levels there are calc-alkaline and alkaline lavas and intrusions [*Furnes et al.*, 1990]. The ophiolite rests with tectonic contact on the Sunnfjord melange [*Alsaker and Furnes*, 1994], an assemblage of fragmented sedimentary and magmatic rocks. The melange tectonostratigraphically overlies metasedimentary rocks of the Herland and Høyvik Groups, that rest on mangeritic gneisses of the Dalsfjord Suite (together constituting the Middle tectonic unit) (Figure 1). The presence of continentally derived sedimentary rocks, both intercalated with the volcanic rocks of the ophiolite and forming the conformable cover of the Stavenes Group, indicate that the basin in which the oceanic crust evolved was situated between a continental margin and an island arc. This inferred tectonic setting is analogous to the modern Andaman Sea [*Furnes et al.*, 1990, 2000].

[7] Recent structural [*Skjerlie and Furnes*, 1990; *Dilek et al.*, 1997] and geochemical investigations [*Skjerlie et al.*, 1989; *Furnes et al.*, 1998; *Ryttvad et al.*, 2000] of the magmatic rocks in the area between Tviberg and Ytrøy (Figure 1) indicate that the ophiolite developed during two different episodes of ocean-floor spreading. The older spreading event is represented by sheeted dikes and plutonic rocks with a general NW structural grain on the island of Tviberg (Figure 1). The part of the ophiolite that formed during the youngest spreading event has a well-preserved sheeted dike complex. There is no evidence for significant block faulting with rotation and tilting of the dikes along faults and the sheeted dike-gabbro boundary is mutually intrusive representing the root zone of the dike complex [*Skjerlie and Furnes*, 1996]. The part of the ophiolite that is represented by the youngest spreading event has thus an internal architecture similar to that of modern oceanic crust that formed at intermediate- to fast spreading centers [*Dilek et al.*, 1997, 1998; *Furnes et al.*, 1998]. This supposition is further substantiated by $\delta^{18}O$ data from the volcanic sequence and the sheeted dike complex in the Strand and Oldra areas (see cross-sections B-B′ and C-C′ of Figure 1) that show a pattern that is comparable with that of the 5.9 Ma in-situ oceanic crust formed at the intermediate-spreading Costa Rica Rift [*Muehlenbachs et al.*, 2003].

[8] In spite of polyphase deformation and greenschist facies metamorphism, the Solund-Stavfjord Ophiolite Complex exhibits a well-preserved volcanic sequence, sheeted dike complex, and, locally, high-level gabbros (Figure 1). During the initial emplacement onto the continental margin and subsequent Silurian collisional events, the ophiolitic rocks were deformed into tight to isoclinal, large-scale folds with NE-SW fold axes. This deformation locally has resulted in parallelism between lithological contacts in the volcanic sequence and the dikes, as well as a penetrative foliation. Subsequent extensional deformation resulted in NW-vergent asymmetrical folds and normal faulting [e.g., *Osmundsen and Andersen*, 1994]. Cross-sections (in Figure 1) illustrate the internal structure of the ophiolite. The cross-section in the Stavenes area shows a pronounced parallelism of the bedding in the volcanic sequence and the dikes, resulting from tectonic rotation. In the Strand area (cross-section B-B′) the first generation of major folds resulted in a 90 degree rotation of the volcanic sequence to a subvertical orientation, but the primary angular relationship with the sheeted complex is preserved and the dikes are subhorizontal. Despite the strong deformation of the rocks of the Strand area, it has been possible to document a complete section of ~500 m of volcanic rocks overlain by black schist and metasandstone, a ~150 m thick transition zone of volcanic rocks and dikes, and a ~900 m thick sheeted dike complex rooted into and/or cut by gabbro (all thicknesses quoted are uncorrected for deformation due to variable degree of deformation through the measured sequences). The cross-section C-C′ through the southwestern part of the ophiolite shows that the volcanic rocks and the transition zone between lavas and dikes occur in a major anticline, in tectonic contact with the sheeted dike complex.

[9] For more comprehensive descriptions of the various components of the Solund-Stavfjord Ophiolite Complex and adjacent rocks, its tectonic and geochemical characteristics, the reader is referred to the following papers: *Furnes* [1972]; *Skjerlie et al.* [1989]; *Andersen et al.* [1990]; *Furnes et al.* [1990, 1992]; *Alsaker and Furnes* [1994]; *Skjerlie and Furnes* [1996]; *Dilek et al.* [1997]; *Furnes et al.* [1998, 2000]; *Ryttvad et al.* [2000]; *Furnes et al.* [2001, 2003].

3. Volcanic Components of the Ophiolite

3.1. Sheet Flows

[10] Basaltic sheet flows appear in most parts of the volcanic sequence, but occur in highly variable proportions relative to the other volcanic products. The sheet flows are tabular, massive units. They range in thickness from ~0.5 to ~20 m, but most commonly are between 1 to 3 m (Figure 2A). The thinnest units, comparable with the very thin flows formed at the slow-spreading mid-Atlantic Ridge [*Stakes et al.*, 1984] are generally fine grained throughout, whereas the thickest may be medium grained in their centers. The tops of some flow units, and to a lesser extent their bases, show a gradual transition into poorly- to well-defined pillows. This variety, referred to as sheet flows with pillowed boundaries, is the least abundant type although locally predominant (e.g., profiles 27 and 28 of Figure 7). Similar flows have been reported from the East Pacific Rise and referred to as lobate lava [e.g., *Kennish and Lutz*, 1998; *White et al.*, 2002]. Other sheet flows have surfaces that have developed into rubbly layers (Figure 2B). This type has been termed sheet flow with brecciated boundaries, and is generally most common (e.g., profile 13 of Figure 7). Within the latter flows the boundary between the upper slaggy part of one unit and the basal slaggy part of the succeeding unit cannot normally be distinguished. In some cases, when a sheet flow is thin, the slaggy top and bottom of the same flow unit may coalesce, resulting in flow units with a brecciated character throughout (Figure 2C). In other cases successive flow units have sharp contacts against each other, without any pillows or breccia. In such cases it is difficult to distinguish between flows and some thick, tabular massive basalts may consist of several flow units.

[11] In a few localities there are massive metabasalt flows that have been interpreted as fossil lava lakes. The best examples occur on the northwestern

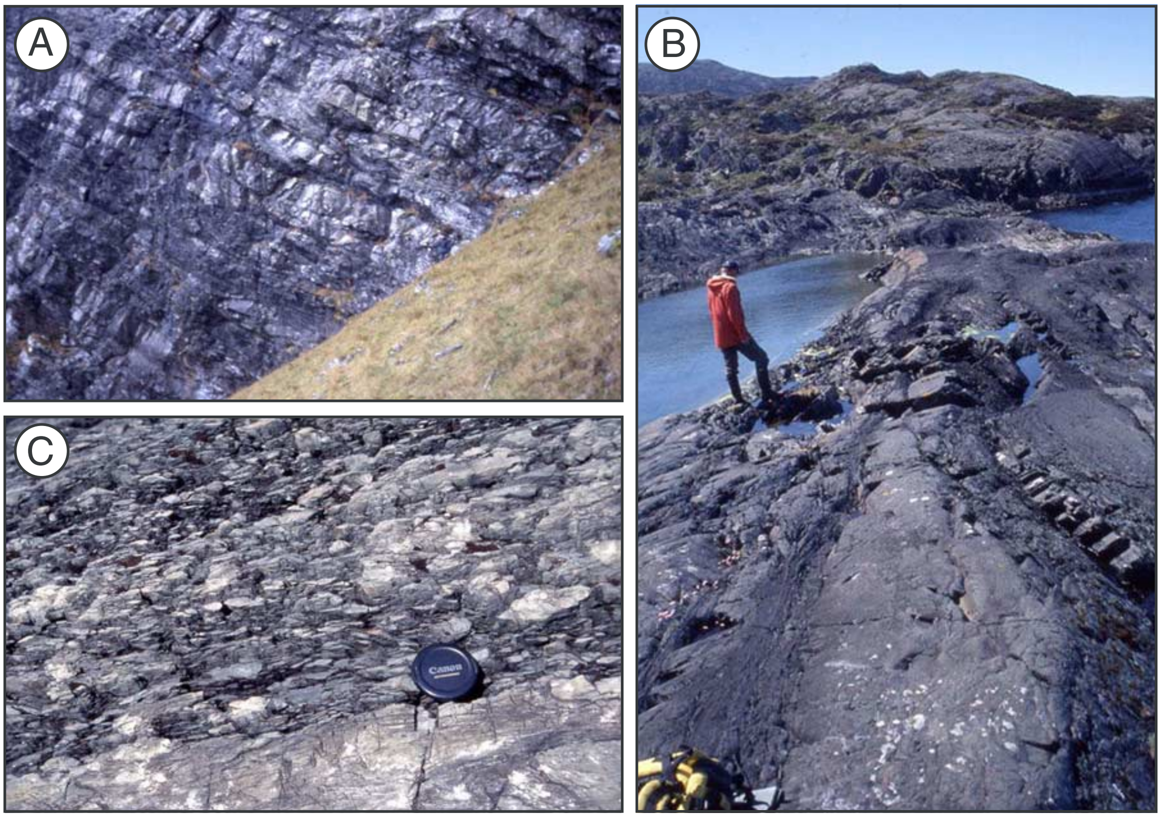

Figure 2. Sheet flows and associated slaggy breccias from the Solund-Stavfjord Ophiolite Complex. (a) A thick pile of tabular sheet flows, consisting of 1–3 m thick massive cores and thin zones of slaggy breccias. Location: the island of Alden (Profile 13). (b) Example of the massive core of a sheet flow pinching out between slaggy breccia. Location of Figures 2b and 2c: From a location between profiles 17 and 18. See Figure 1 for locations. (c) Slaggy breccia between flow units.

part of the island of Alden (Figure 1) within a ~65-m-thick sequence of thick massive metabasalt units interlayered with pillow lava and volcanic breccias. The breccias on top of some of the 5–15 m thick massive lava units consist of jig-saw-like slabs. This kind of brecciation is reminiscent of lava withdrawal and concomitant collapse of the crust of a lava lake [e.g., *Ballard et al.*, 1979; *Francheteau et al.*, 1979]. Within the lower part of one of the flows, breccia zones (up to 10-cm-wide and 5-m-long) are orientated perpendicular to the bedding. The surrounding metabasalt is chilled against these breccias, which are thought to represent gas escape chimneys, as described from lava flows and lava lakes [e.g., *Francheteau et al.*, 1979]. The interpretation of these massive metabasalt units is that they represent successive lava lakes, and that the breccias formed during lava withdrawal and subsequent collapse of solidified crust [*Furnes et al.*, 1992]. Another example of a possible fossil lava lake occurs on the southeastern part of Langøy (Figure 1) where a >26-m-thick massive lava occurring in the lower part of profile 7 (Figure 7) is cut by several thin irregular to planar dikes [*Furnes et al.*, 2001].

3.2. Pillow Lavas

[12] Pillow lavas are the most common type of flow, although, as will be shown below, it may locally be subordinate to sheet flows. The shape of individual pillows (as they appear in cross-section) differs, particularly their lower parts, reflecting the topography of the surface on which they formed. In most cases, in areas with relatively low strain, the upper surfaces of pillows are upwardly convex, whereas the bottoms are moulded on underlying pillows (Figure 3).

Figure 3. Typical pillow lava from the from the Solund-Stavfjord Ophiolite Complex. Location: Profile 2 in Figure 1.

[13] Contrary to the early interpretations of pillows as separate sack-like bodies, more careful studies of three-dimensional outcrops have demonstrated that they rather represent interconnected tubular flow units [*Moore*, 1975]. Measurements of the horizontal and vertical axes in sections normal to the tubes [*Furnes and Fridleifsson*, 1978; *Fridleifsson et al.*, 1982; *Walker*, 1992] have shown a wide range in dimensions. In general, smaller pillows have more circular cross sections and larger pillows have more elliptical sections. This is shown in the compilation of the average dimensions of pillows from 12 different localities of undeformed pillows worldwide (Figure 4a). The average size of the horizontal and vertical axes of these 1306 pillows [*Walker*, 1992] are 0.90 and 0.49 m, respectively, with an axial ratio (horizontal:vertical) of 1.8 (Figure 4a).

[14] The axial dimensions of 543 pillows from several localities from the Solund-Stavfjord Ophiolite Complex have been measured, and the results are shown in Figure 4B–4G. Differences between the H:V ratios of the pillows of the Solund-Stavfjord Ophiolite Complex and the compilation of undeformed pillows (Figure 4a) give a crude measure of the amount of tectonic strain. The size of the pillows shows considerable variations, both within and between localities, from the smallest examples around 10 cm in diameter to the largest with horizontal axes approaching 4 m. Pillows from the SW-part of the Solund-Stavfjord Ophiolite Complex (profiles 1 through 8 (Figure 1) have H:V ratios of 1.7–2.5 and appear to be little deformed (Figure 4A–4E). Their size, however, shows considerable variations, a phenomenon that largely reflect their stratigraphic location. In a recent study of the volcanic development of the SW-part of the Solund-Stavfjord Ophiolite Complex, *Furnes et al.* [2001] showed that the volcanic sequence consists of 6–7 major cyclic units, through which the size of pillows decreases. The pillows of profile 10 in the Strand area (Figure 1) are highly flattened and display an average H:V ratio of 10 (Figure 4f). The volcanic sequence on the Staveneset Peninsula is also strongly deformed, as demonstrated by pillows with an average H:V ratio of 5 (Figure 4g) at a locality between profiles 18 and 19 (Figure 1).

[15] Since only two axes (horizontal and vertical) of pillows could be measured, the axial ratios only reflect flattening of the pillows. However, in localities where exposures allow a limited three-dimensional view it can be seen that the strongly deformed pillows (Figures 4f and 4g) have been stretched, displayed by tectonic lineations subparallel to the long axis. Had the tubes only been stretched, the axial ratio (H:V) would remain constant. Thus the H:V axial ratios of the pillows only give a minimum estimate of the degree of deformation.

3.3. Volcanic Breccias

[16] In this section we describe the fragmental volcanic rocks other than the thin rubbly layers associated with sheet flows. Below they are listed in order of abundance. The most common type is broken pillow/hyaloclastite breccia, irregularly distributed throughout the volcanic sequence. This type of volcanic breccia is composed of a mixture of small, near-spherical pillows, amoeboidal lava blobs, and fragments of pillows (most common), set in a fine-grained hyaloclastite matrix (Figure 5a).

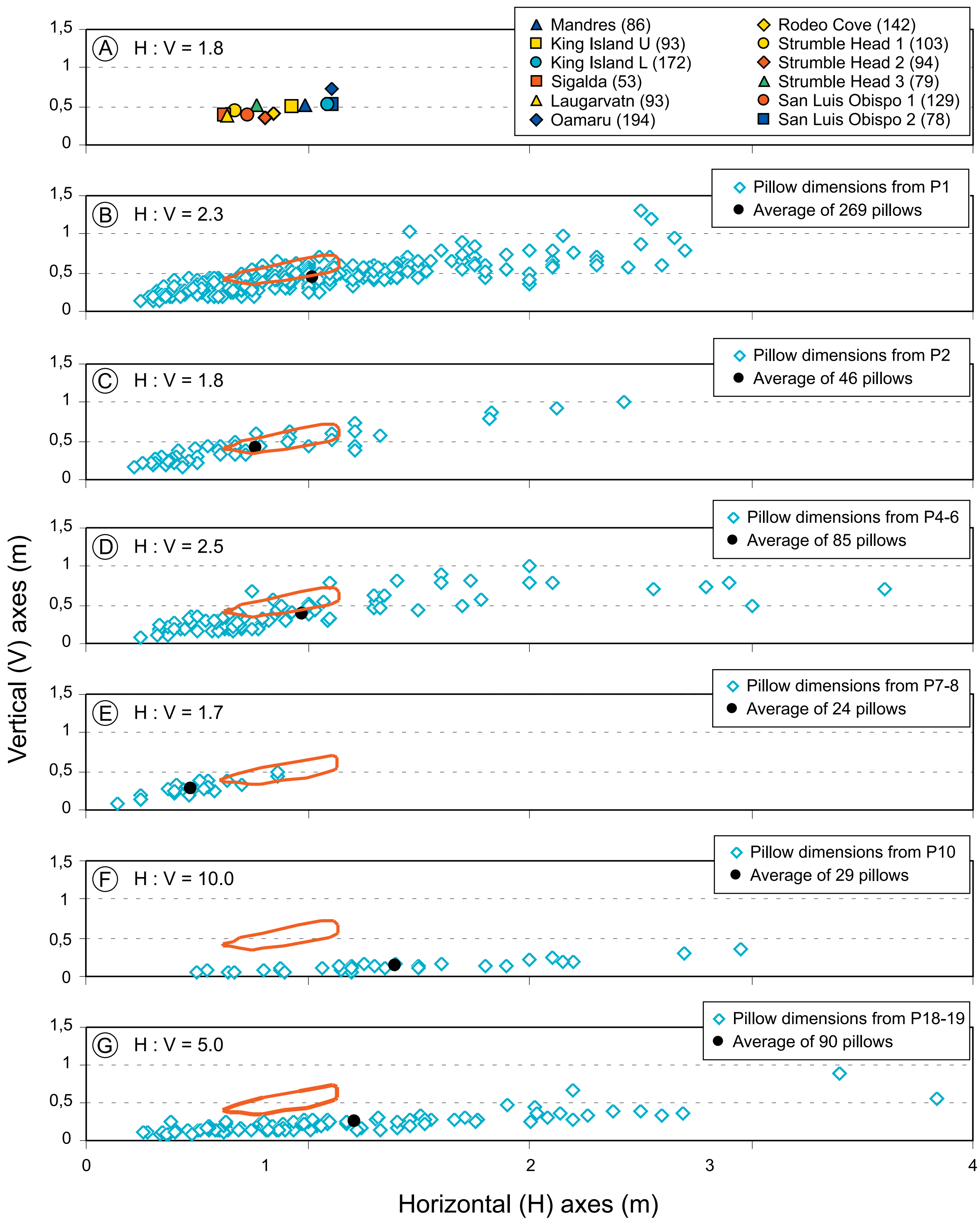

Figure 4. Axial dimensions of pillows. (a) Average axial dimensions of undeformed pillows from 12 locations. Data from *Walker* [1992]. The number of measured pillows from each locality is shown. (b–g) Axial dimensions of pillows from some of the profiles P1, P2, P4–6, P7 and 8, P10, and P18 and 19 (see Figure 1 for location) across the Solund-Stavfjord Ophiolite Complex. The red line in Figures 4b through 4g envelopes the area defined by the data shown in diagram Figures 4a.

The proportion of pillows and larger lava fragments to hyaloclastite matrix varies from fragment-dominated to hyaloclastite-dominated. Lenses and layers of chert (up to a few cm thick), and more rarely siliciclastic sediments occur intercalated within some of the breccias. On the westernmost part of the Staveneset Peninsula (profile 14, see Figure 7), the majority of the volcanic breccias are fine-grained, laminated or bedded volcaniclastic rocks. A prominent feature of these breccias is the common occurrence of subspherical to ellipsoidal epidote nodules. These nodules commonly range in size between a few cm and 50 cm (Figure 5b), but much bigger examples (up to 3 m in the longest dimension) have been observed. Some nodules are reminiscent of hydrothermally infilled hollow pillows. They have remnants of metabasalt along their margins, and some rare examples exhibit drainage structures (Figure 5b). Another type of volcanic breccia, volumetrically much less important, is inter-pillow hyaloclastite (Figure 5c). This type of breccia occurs commonly within pillowed flows. Generally the volcanic breccias are strongly foliated, but locally it is possible to demonstrate that the hyaloclastite matrix consists mainly of μm- to mm-sized angular and blocky shards (Figure 6a). In some cases, mm-sized lava globules (Figure 6b) occur in association with the shards. These textures are similar to modern hyaloclastites.

4. Interpretation of the Volcanic Products

4.1. Pillow Lavas and Sheet Flows

[17] The factors that control the morphology of submarine lavas are (1) rate of cooling, (2) topography of the substrate, (3) viscosity, and (4) effusion rate. Apparently, the most important factors are the viscosity and effusion rate of the lava [*Griffith and Fink*, 1992; *White et al.*, 2002]. Given that all other factors are constant, lower effusion rates favor the formation of pillows, whereas higher effusion rates result in sheet flows [*Gregg and Fink*, 1995].

[18] The pillowed margins of some of the sheet flows may reflect distinct stages of eruptions or local conditions that resulted in lower effusion rates. Such stages are assumed to exist at the beginning and final stages of an eruption, as well as at the termination of a lava flow.

[19] The highly variable proportion of massive to rubbly parts of sheet flows (Figure 2) must imply different flow conditions. The key factors that affect the behavior of flowing lava are viscosity, shear stress and shear strain [e.g., *Shaw et al.*, 1968]. *Peterson and Tilling* [1980] have shown how basalt lavas in Hawaii may change downstream from pahoehoe into aa. If a nonbrecciated lava flow halts and cools, its pre-terminal structure will remain. However, if the lava is impelled to continue to move after having become highly viscous, the critical conditions may be reached for brecciation. It is reasonable to believe that the rubbly character of the boundaries of some of the submarine sheet flows may have developed this way. Whether or not this transition is present in the sheet flows may simply be a function of the distance from the eruption site, combined with variable slopes on which the lava flowed.

4.2. Volcanic Breccia

[20] Volcanic breccias may form by a number of syneruptive and posteruptive mechanisms and at any water depth [e.g., *Carlisle*, 1963; *Honnorez and Kirst*, 1975; *Wohletz*, 1983; *Bergh and Sigvaldason*, 1991; *Fouquet et al.*, 1998; *Furnes et al.*, 2001]. The dominant mechanisms of brecciation in a subaquatic environment may be divided into the following categories: (1) expansion of magmatic volatiles during ascent of the magma and eruption in relatively shallow water (generally less than 500 m water depth for typical MORB), (2) submarine lava fountaining at high eruption rates, (3) thermal shattering due to contact of melt with cold water, (4) spalling of glass rinds during inflation of pillows, (5) syneruptional disintegration and gravitational sliding at the leading edge of pillow lava flows and/or sheet flows on unstable slopes, and (6) posteruptive disintegration connected with steep slopes and fault scarps, resulting in proximal talus and distal bedded finer-grained volcaniclastic rocks.

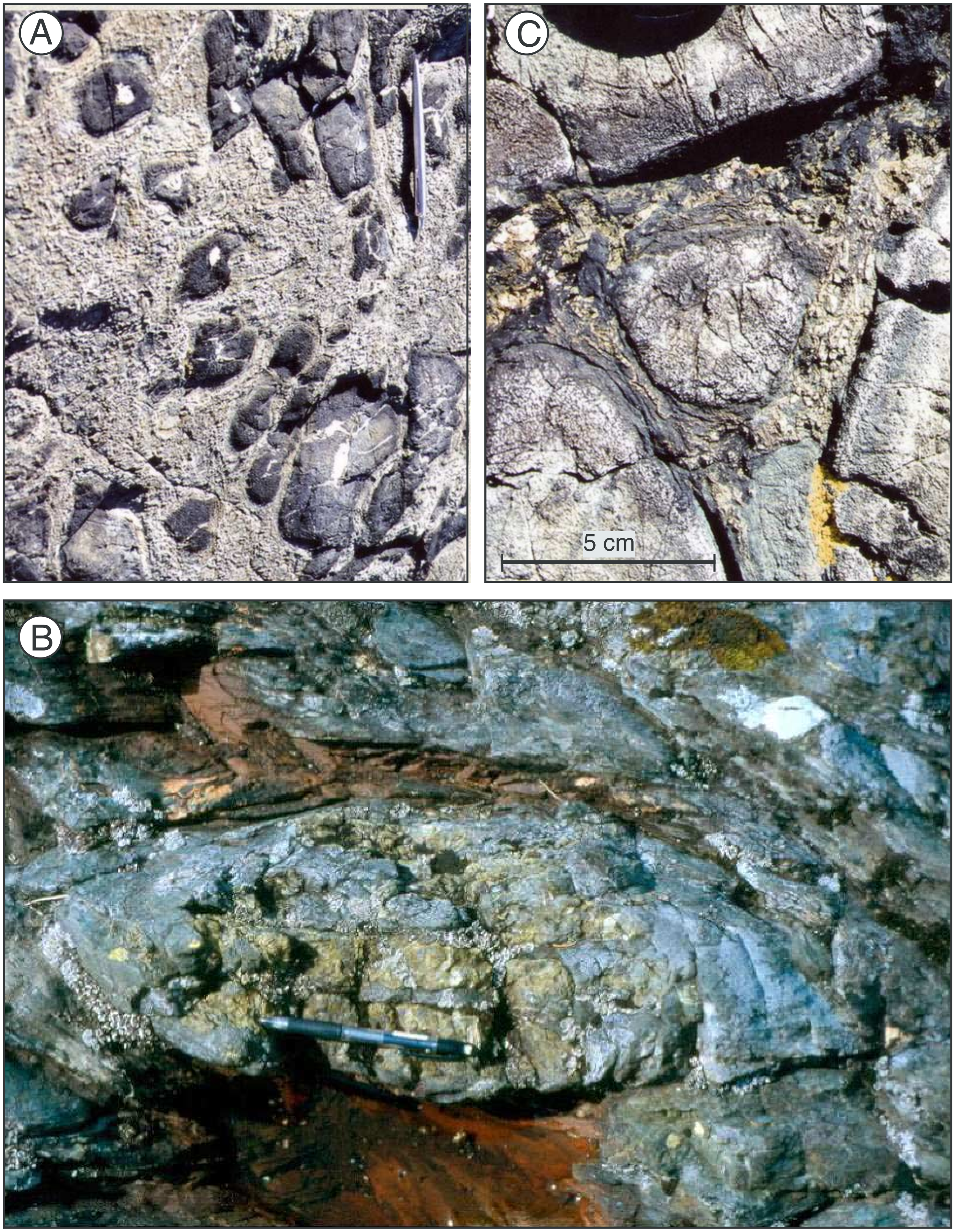

Figure 5. Volcanic breccias from the Solund-Stavfjord Ophiolite Complex. (a) Broken pillow/hyaloclastite breccia with a high proportion of fine-grained hyaloclastite. Pen is 15 cm long. (b) Pillow-like body showing epidote-filled drainage structures, set in a matrix of hyaloclastite. (c) Inter-pillow hyaloclastite. Location: Profile 1 in Figure 1.

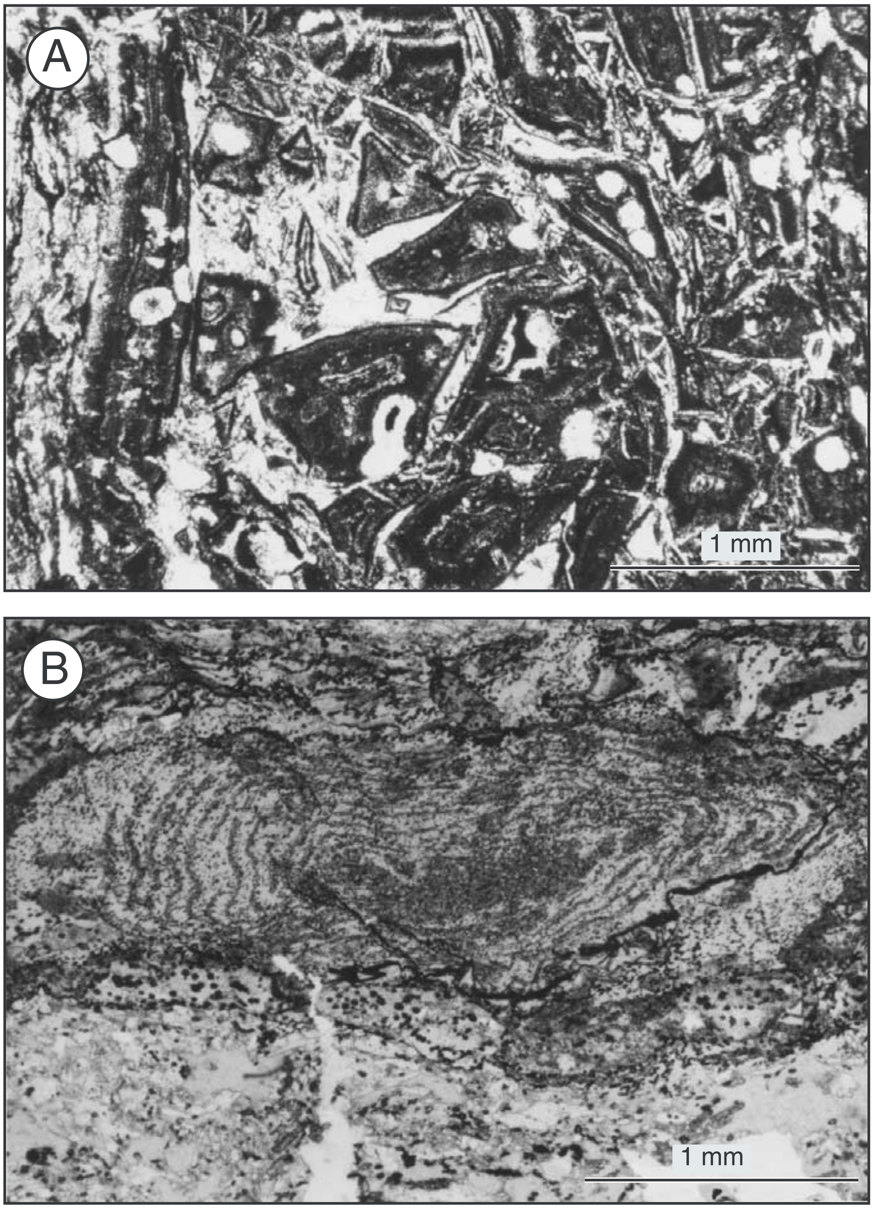

Figure 6. Microphotographs of the matix from broken pillow/hyaloclastite breccia, showing. (a) Angular shards and (b) Zoned globule. The zoning reflects the initial alteration of the sideromelane to palagonite. Location: profile 4 in Figure 1.

[21] On the basis of our field observations and systematic studies of in the Solund-Stavfjord Ophiolite Complex, we suggest the following processes as most likely for the formation of the volcanic breccias. Since all the volcanic rocks are nonvesicular and hence either volatile-poor or, more probably, erupted at great depth [*Moore*, 1965] we regard mechanism (1) as unlikely. The amoeboidal lava blobs associated with broken pillow breccia/hyaloclastite, we attribute to formation during lava fountaining (mechanism 2). The hyaloclastite matrix of broken pillow breccia, in most cases the dominant component of the breccia, shows textural features typical of thermal shattering (mechanism 3), i.e., blocky, equant shards due to simultaneous quenching and brittle fracture and lava drops resulting from surface tension effects (Figure 6). The broken pillows (Figure 5a) associated with the hyaloclastite in variable amounts, are most probably the result of syneruptional and

posteruptional lava disintegration (mechanisms 5 and 6). The common but quantitatively less-important inter-pillow hyaloclastite, we attribute to spalling of pillow rinds during pillow growth (mechanism 4). The presence of chert and siliciclastic sediments within some the thickest broken pillow breccias show that accumulation occurred during several volcanic episodes. The fine-grained laminated, or bedded volcaniclastic rocks (profile 14 of Figure 7) most probably represent resedimented hyaloclastites.

5. Architecture of the Volcanic Sequence of the Solund-Stavfjord Ophiolite Complex

5.1. Volcanic Stratigraphy and Variability

[22] We examined the volcanic stratigraphy of the Solund-Stavfjord Ophiolite Complex in 29 profiles. The most comprehensive coverage is provided by the profiles on the 16 km long Staveneset Peninsula (Figures 1 and 7). The top of the volcanic succession, defined by the conformable cover sediments of the Stavenes Group (Figure 1), is exposed in 11 profiles (3, 9, 10, 14, 15, 16, 25, 26, 27, 28 and 29), and for another 11 of the profiles (1, 2, 7, 8, 13, 17, 18, 19, 20, 21 and 23) the boundary can be located by extrapolation. Eleven of the profiles (9, 10, 13, 15, 17, 19, 22, 24, 26, 27 and 28) extend into the sheeted dike complex, via an up to 200 m thick transition zone of sporadic dikes or dike swarms (Figure 7).

[23] The profiles demonstrate that the thickness of the volcanic sequence varies between ~470 m and ~800 m (uncorrected for tectonic strain). The sheet-lava dominated profiles (13, 26, 27 and 28) that extend through the entire volcanic successions from their tops to the sheeted dike complex, or almost so, show rather thick (~600–800 m) sequences of volcanic rocks (Figure 7). The pillow-dominated sections have more variable thicknesses (Figure 7). It must be stressed, however, that these are the measured present thicknesses. On the basis of the axial ratios of pillows (Figure 4) it can be inferred that the original thickness of the volcanic sequence has been considerably reduced in certain areas as a result of deformation. The nearly 800 m thick pillow-dominated sequence shown in P1 (Figure 7), is little deformed and close to the original thickness of the volcanic sequence. Using the average H:V ratio of the pillow lavas on the Stavenes Peninsula, it is reasonable to assume that the volcanic sequence has been reduced to about half of its original thickness. We hence suggest that the thicknesses of the typical pillow-dominated and sheet-flow-dominated sequences in this area were about 1000 m and 1400 m, respectively.

[24] The 29 profiles (Figure 7) show considerable variability in the volcanic development and the proportions between sheet flows, pillow lavas and volcanic breccias. This is well demonstrated by single or composite profiles (Figure 8), covering almost the whole of the volcanic succession. These show the following variation: sheet flows (2–92%, average 36%), pillow lavas (6–74%, average 41%), and volcanic breccias (2–85%, average 21%).

[25] Figure 7 shows that sheet flows are particularly abundant in the Stavestranda (profiles 26, 27 and 28) and Alden (profile 13) areas, and to lesser extent in the Ytrøy-Langøy (profiles 1–3, 7 and 8) and Strand (profiles 9 and 10) areas (see Figure 1 for location). In these sheet-flow-dominated regions the stratigraphy of the volcanic succession is characterized by pillow lavas and/or volcanic breccias at the lowest stratigraphic levels (hosting dikes), via sporadic occurrences of sheet flows to finally, at the highest stratigraphic levels, a dominance of sheet flows. Particularly in the Stavestranda and Alden areas sheet flows dominate in the upper 2/3 to 3/4 of the sequence. In the volcanic breccia- and/or pillow-dominated areas we do not see any clear changes in the proportions between the volcanic components from bottom to top of the sequence.

5.1.1. Ophiolite Studies Complement Coring of Young Oceanic Crust

[26] Ophiolites are common components of Proterozoic to Tertiary orogenic belts that have a worldwide distribution. *DeWit et al.* [1987] have even suggested that the magmatic rocks of the Barberton greenstone belt represent a 3.5 Ga old ophiolite. Thus the large-scale as well as detailed development

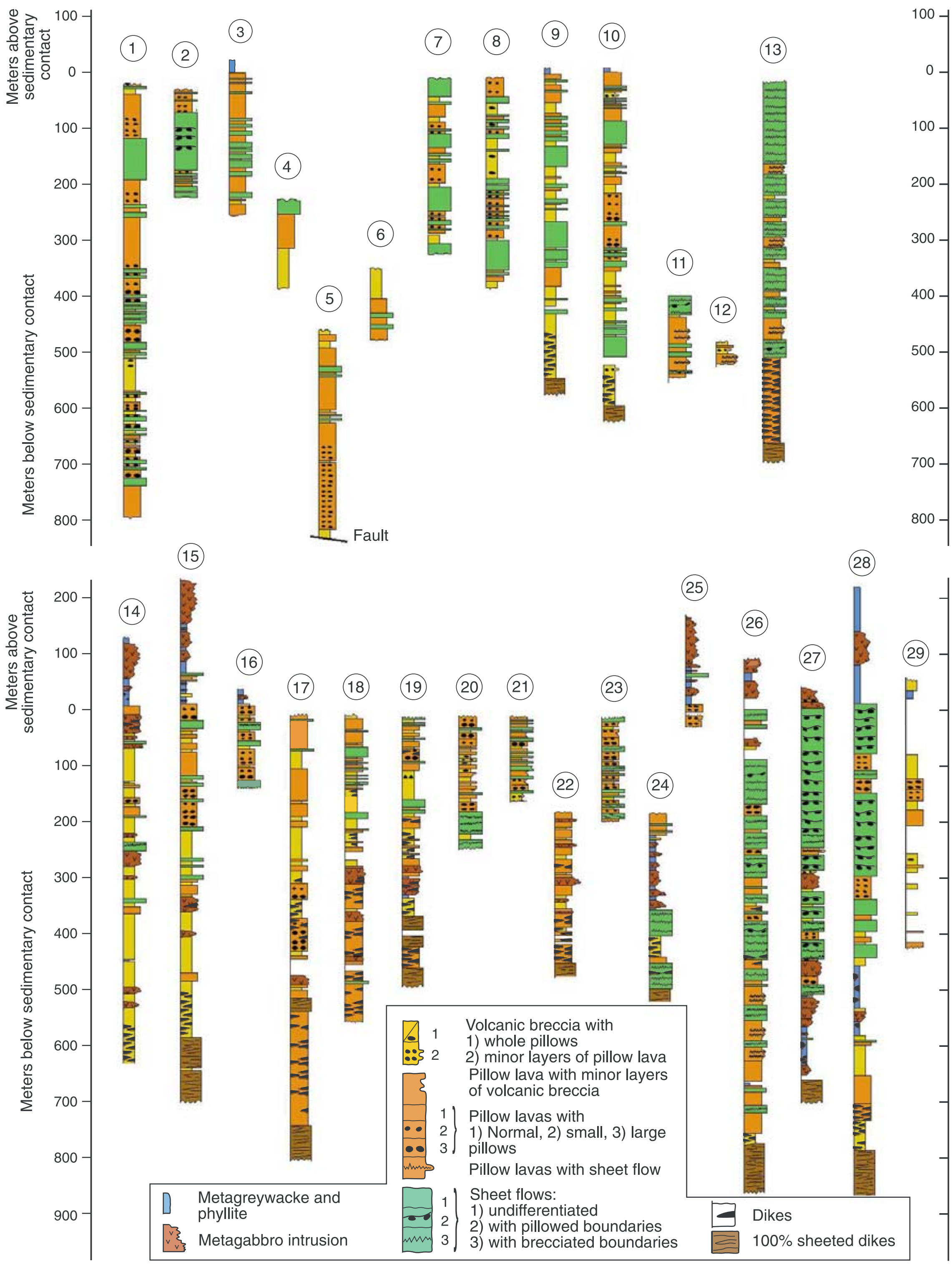

Figure 7. Volcanic stratigraphy of the Solund-Stavfjord Ophiolite Complex. The stratigraphic position of the profiles that do not include the sedimentary cover to the volcanic sequence is estimated from the geological map (Figure 1). The number above each profile corresponds to the geographical location shown in Figure 1.

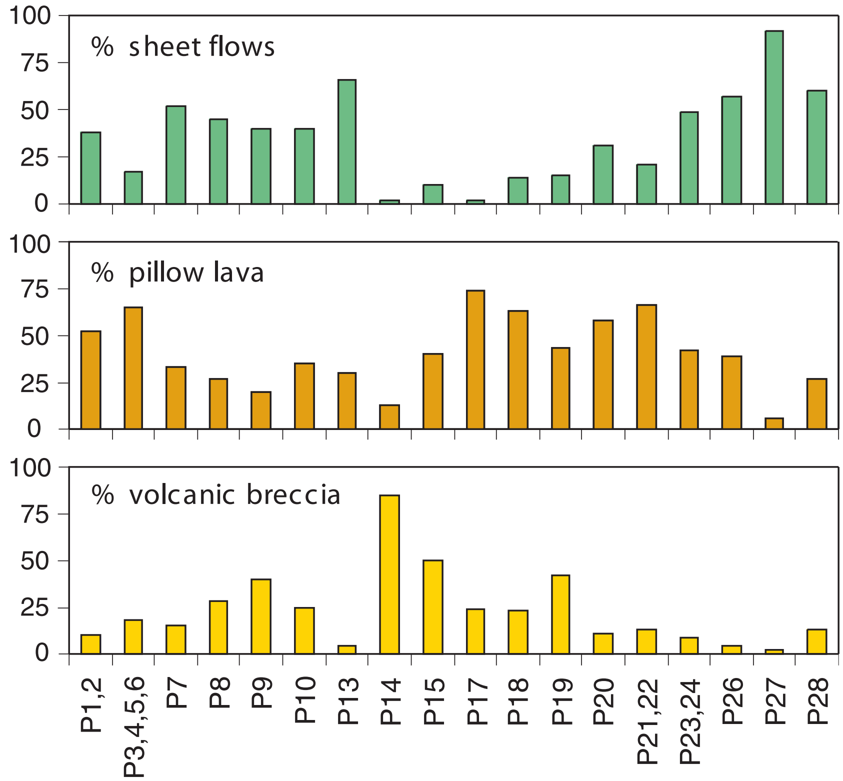

Figure 8. Histograms showing the percentages of sheet flows, pillow lavas and volcanic breccias from the volcanic sequence of the Solund-Stavfjord Ophiolite Complex. Only single profiles or combinations of closely spaced profiles that show the complete or near-complete volcanic stratigraphy have been used for the compilation. See Figure 7 for profile information, and Figure 1 for locations.

of oceanic crust and its variation with time can best be studied in ophiolites. Yet, despite their potential, little work has been carried out on their detailed volcanic stratigraphy and evolution.

[27] A general feature of most cores from in-situ oceanic crust is the scarcity of volcanic breccias, particularly in connection with slow-spreading ridges. The best examples in this respect are represented by the high-recovery (>60%) DSDP Holes 417D and 418A in the western Atlantic, in which the percentages of volcaniclastic rocks, massive flows and pillow lavas have been estimated to 6, 20, and 74, respectively [*Robinson et al.*, 1979]. This feature is in strong contrast to some of the sections through the Solund-Stavfjord Ophiolite Complex, where volcanic breccias are much more abundant (Figure 7). The results of drilling also contrast with surface observations at volcanically active spreading centers. For example, the Serocki Volcano in the seaMARK area is partly buried by volcanic talus [*Bryan et al.*, 1994]. The outstanding questions are hence whether the rarity of volcanic breccias is a real feature of in-situ oceanic crust of the major oceanic basins or whether they simply have not been recovered during drilling (i.e., volcanic breccias may be under-represented in cores). This has been clearly demonstrated by *Haggas et al.* [2002] that the latter possibility is real; wire line log data from ODP Hole 896A at the Costa Rica Rift has indicated ~28% breccia compared to the ~8% recovered in the core. Alternatively, the abundance of volcanic breccias may be higher in a back-arc basin setting than in oceanic crust of major ocean basins, e.g., the Atlantic and Pacific as speculated by *Furnes et al.* [2001]. The geochemical and mineralogical signatures of many ophiolites, including the Solund-Stavfjord Ophiolite Complex [*Furnes et al.*, 1990], suggest that they formed in back-arc basins [e.g., *Pearce et al.*, 1984]. With the exception of detailed volcanological investigations and single

sections through the volcanic succession from Troodos [*Schmincke et al.*, 1983; *Schmincke and Bednarz*, 1990; *Malpas and Williams*, 1991] and Oman [*Einauldi et al.*, 2000, 2003], only limited data are available concerning the detailed volcanic construction of ophiolites. These investigations have only revealed minor occurrences of volcanic breccias. However, the results of the present study show extensive lateral variations in the proportions of the volcanic products. Hence due to the scarcity of detailed stratigraphic descriptions of the volcanic sequences of ophiolites, and incomplete recovery during coring of in-situ oceanic crust, the above questions are basically unresolved.

5.1.2. Volcanic Products and Spreading Rate

[28] Observations of the eruption styles of recent basalts at oceanic spreading centers have shown that the areal ratio of sheet flows versus pillow lavas increases with the spreading rate [*Ballard et al.*, 1979, 1981; *Bonatti and Harrison*, 1988]. At the fast spreading East Pacific Rise (spreading rate >15 cm/yr) 70–100% of the basalts are sheet flows, whereas at the slow-spreading mid-Atlantic Ridge and Red Sea (spreading rate around 1–2 cm/yr), pillow lavas comprise 90–100% of the basalts. Higher ratios in intermediate- to fast spreading ridges represent a manifestation of more voluminous eruptions than at slow-spreading ridges. *Bonatti and Harrison* [1988] proposed a near linear relationship between spreading rate and the proportion of sheet lavas.

[29] The lack of evidence of block faulting and rotation of dikes, the mutually intrusive character of the dikes and gabbro, as well as the locally high abundance of sheet flows suggest that the Solund-Stavfjord Ophiolite Complex represents oceanic crust generated at an intermediate spreading rate [*Dilek et al.*, 1997; *Furnes et al.*, 1998, 2000]. If we use the average values for the volcanic components (excluding the volcanic breccias), the amounts of sheet flows and pillow lavas are 47 and 53%, respectively. These values are consistent with suggestions concerning the spreading rate. However, within short distances, it is possible to find stratigraphic sections that are dominated by sheet flows (profiles 13 and 27) and others that are entirely pillow-dominated (profiles 17 and 22) (Figure 7). Hence applying such criteria randomly would lead to contradictory conclusions concerning spreading rates.

5.2. Cyclic Units

[30] Volcanic and tectonic processes at ocean spreading centers may exhibit a cyclicity. Volcanic cyclicity has been reported from both in situ oceanic crust [*van Andel and Ballard*, 1979; *Hyndman and Salisbury*, 1984; *Karson et al.*, 1987; *Staudigel et al.*, 1996] and from ophiolites [*Schmincke and Bednarz*, 1990; *Einauldi et al.*, 2000, 2003; *Furnes et al.*, 2001, 2003]. These studies have indicated that extrusive sequences have been constructed during a relatively small number (3 to 7) of major cyclic units. A typical cyclic unit in the Solund-Stavfjord Ophiolite Complex, as defined by *Furnes et al.* [2001], is represented by a stratigraphic sequence that is composed of sheet flows and/or flows with large pillows at the base, succeeded by lavas with progressively smaller pillows and volcanic breccias. In some cases the volcanic breccias may be absent. The thicknesses of well-defined major cyclic units vary from ~15 m up to ~225 m (Figure 9, panel A1). Minor cyclic units, with thicknesses of ~2–5 m, are defined by a thin basal sheet flow, merging into pillow lava with decreasing pillow size (Figure 9, panels A2 and B). They only occur in sequences dominated by pillow lava.

[31] Where the volcanic succession of the Solund-Stavfjord Ophiolite Complex is pillow-dominated it generally comprises thinner and more numerous cyclic units than when the sequence is sheet-flow-dominated. This is demonstrated in Figures 10a and 10b, which shows cyclic units in representative pillow-lava dominated and sheet-flow dominated sequences. We have observed that 22 cyclic units in typical pillow-lava-dominated sequences have an average thickness of 20 m (max. 51 m, min. 5 m), whereas 14 cyclic units in the most typical sheet-flow-dominated profiles have an average thickness of 85 m (max. 220 m, min. 43 m).

[32] An important question is whether cyclic units resulted from single eruptions or several consecu-

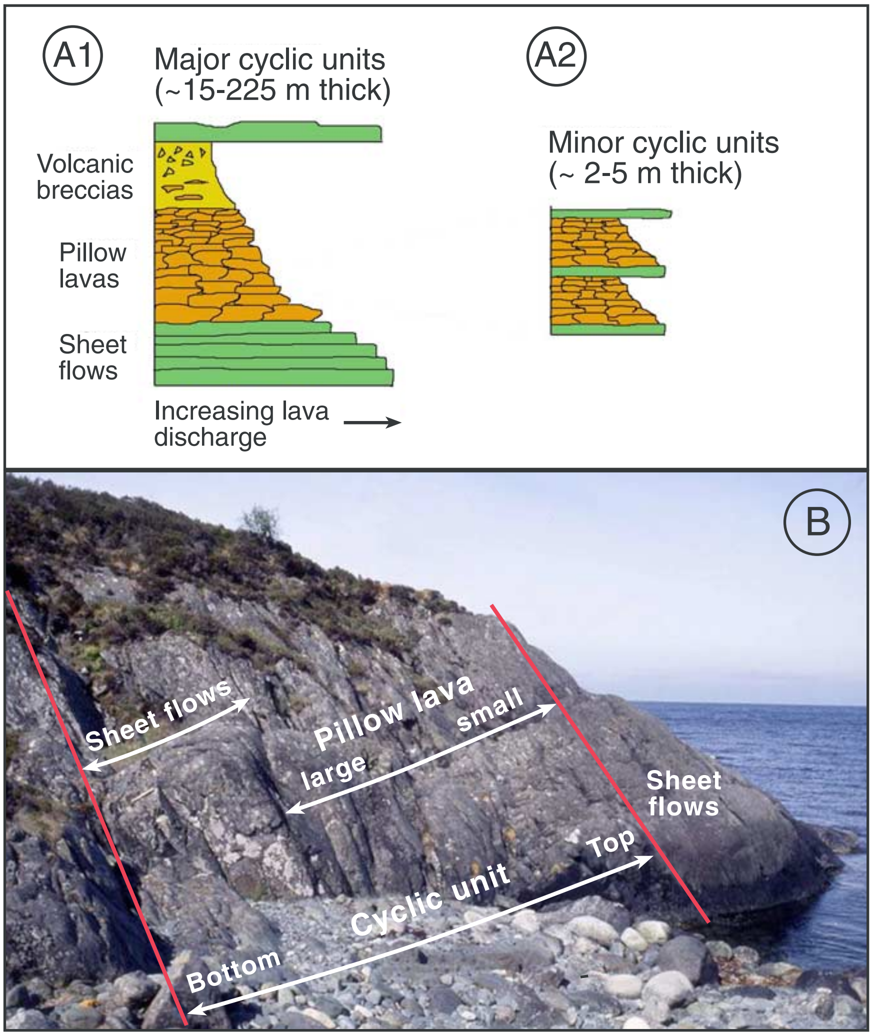

Figure 9. Schematic illustration of typical major (A1) and minor (A2) cyclic units. Photograph of a minor cyclic unit (5 m thick) built up of two massive sheet flows, followed stratigraphically upward by pillows with decreasing size. Location: Profile 21 (see Figure 1).

tive eruptions. We have approached this question in two different ways: geochemical fingerprinting and field observations. A recent geochemical investigation of the lava sequence of the Solund-Stavfjord Ophiolite Complex [*Furnes et al.*, 2003] demonstrated the existence of distinct compositional subdivisions within some thick, well-defined, cyclic units. These subdivisions indicate that some cyclic units were constructed by repeated eruptions. The geochemical variations are interpreted as the result of episodes of replenishment and mixing in the source magma chamber [*Furnes et al.*, 2003]. However, in other cases, there is little geochemical difference within or between successive cyclic units. On the basis of our geochemical data alone it is difficult to determine the number of individual eruptions responsible for either the construction of the cyclic units or the whole of the volcanic sequence, and whether the number of eruptions in sheet-flow-dominated sequences differed from that in pillow-dominated successions.

[33] Beds of chert within cyclic units indicate several periods of volcanic quiescence. Within the 100 m thick succession of massive sheet flows of the major cyclic unit P2 (Figure 7), 21 beds of chert, ranging in thickness from 2 cm up to 25 cm, would indicate that this sequence (consisting of 24 sheet flows) was constructed by at least 21 eruptions [*Furnes et al.*, 2001]. On the basis of the

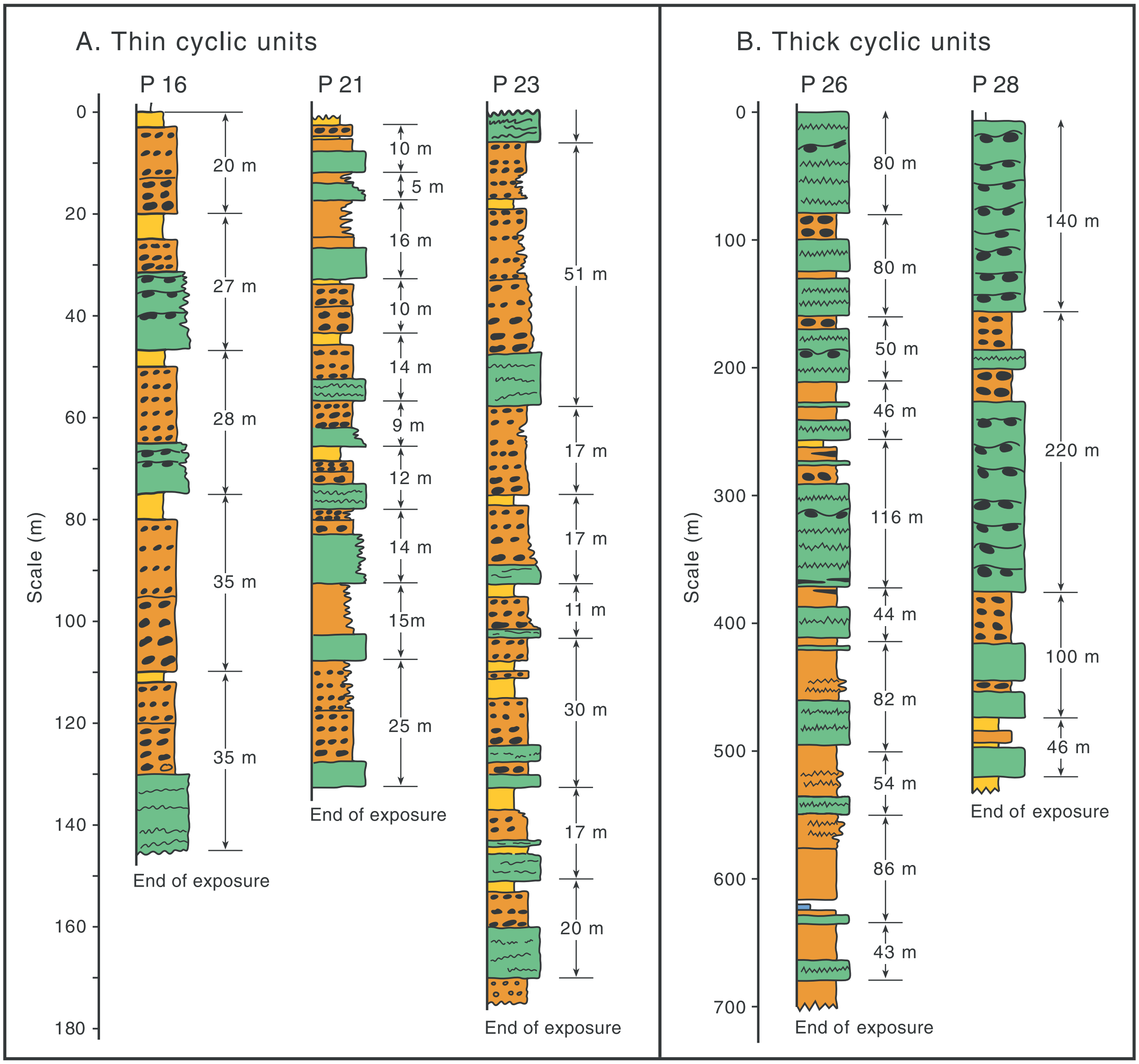

Figure 10. (a) Cyclic units from three pillow-dominated profiles (P16, 21, 23). (b) Cyclic units from two sheet-flow dominated profiles (P26, 28). Explanation of profiles as in Figure 7.

available field and geochemical data we suggest that the major cyclic units (Figures 9, panel A1, and 10) represent multieruptional constructions, during which magma chamber conditions and consequently the magma composition could change considerably.

[34] Chert layers have not been observed within minor cyclic units (Figure 9, panel A2), and geochemical data through a sequence of 15 such units show, apart from a few of the massive sheet flows, little within-cycle variation [*Hellevang*, 2002]. We hence regard minor cyclic units as representing the products of single eruptions, or individual phases of an eruption.

5.3. Volcanic Centers

[35] The productivity and longevity of magmatic activity is highly variable along spreading axes. Major volcanic centers are spaced at intervals as a function of the spreading rate [e.g., *Okino et al.*, 2002; *White et al.*, 2002]. Within the axial grabens of active oceanic ridges volcanic centers are characterized by fissure eruptions forming oval shields with their longest diameters oriented along-axis

[e.g., *White et al.*, 2002]. They are locations of high magma discharge and are marked by volcanic cores that consist predominantly of sheet flows.

[36] In Figure 11 all the profiles have been arranged in their correct geographical as well as stratigraphical position, enabling a fairly detailed 2-dimensional representation of the volcanic development of the Solund-Stavfjord Ophiolite Complex. It appears that two major volcanic centers, defined by thick sequences of sheet flows (the Stavestranda and Alden volcanic centers), and apparently one somewhat smaller center (the Langøy volcanic center), are intersected by the section.

[37] The stratigraphically clearest of these major volcanic centers is the Stavestranda occurrence. We have not been able to observe directions of lava flow, and hence the exact location of the eruptive center(s) relative to the exposed section is not well constrained. During a voluminous eruption thick sheet flows may travel tens of kilometers from a vent [*Keszthelyi and Self*, 1998], and the sheet flows recorded in the section through the volcanic centers may have had vents some distance from the preserved section. However, since the sheet flows in the Stavestranda area are laterally extensive and the volcanic succession is thicker than elsewhere, we regard nearby vents as most likely. If this is correct, the diameter of the volcanic shield constructed by sheet flows was at least 5 km. The thick sequence of sheet flows on Alden extends onto the adjacent island of Værlandet (Figure 1). The volcanic rocks on the latter consist predominantly of thick, massive sheet flows, but the low ground on this island does not present a long section through the relatively flat-lying lavas. However, existing observations suggest that Alden also represents part of a major volcanic center of comparable size to that of the Stavestranda volcanic center (Figure 11). The proportion of sheet flows at the Langøy volcanic center is lower than in the other examples, and may represent a somewhat less prominent center characterized by less-frequent voluminous eruptions.

5.4. Along-Axis Development

[38] The 16 profiles on the Staveneset Peninsula are presumed to be arranged approximately along-axis as defined by the consistent orientation of the sheeted dike complex, as well as the constancy in the thickness of the volcanic sequence and dike complex (Figure 7). They show a progressive change in volcanic products from predominantly sheet flows in the east, to pillow lavas in the central part, and ultimately volcanic breccias in the west (Figure 11). The eastern part of this region is entirely dominated by sheet flows. Through a 2–3 km wide zone of inter-fingering sheet flows and pillow lava, the volcanic pile changes into a 5 km long zone that is dominated by pillow lava (Figure 11). This zone is comparable with modern pillow-lava-dominated spreading axes as the mid-Atlantic Ridge [*Smith and Cann*, 1990, 1993; *Smith et al.*, 1995], where a large number of small volcanic seamounts with diameters between 0.5 and 3 km have been identified on the floor of the inner valley. We regard this part of the volcanic succession as representing numerous small-volume pillow-lava eruptions from minor volcanic centers. Further to the west the proportion of pillow lavas decreases, and is gradually overtaken by volcanic breccias (Figure 11). The relationship between the volcanic breccias and the other volcanic rocks indicates different modes of eruption. For example, in profiles 8, 9 and 10 (Figure 7), the volcanic breccias are associated with sheet flows, and we consider these as possible examples of brecciation accompanying high eruption rates. The volcaniclastic, bedded deposits, as for example encountered in profiles 14 and 15 (Figure 7), are considered to have resulted from repeated episodes of reworking and redeposition of syneruptional and posteruptional volcanic breccias. We speculate that volcanic activity was subordinate to tectonic activity, in accordance with the general volcanological development that indicates that the Staveneset area is situated between two major volcanic centers (the Stavestranda and Alden volcanic centers) (Figures 11 and 12).

5.5. Evidence of Volcanic Segmentation

[39] A number of studies of active spreading ridges have shown an along-axis, repetitive character of seafloor features, both with respect to tectonic and volcanic development; the amplitude of these

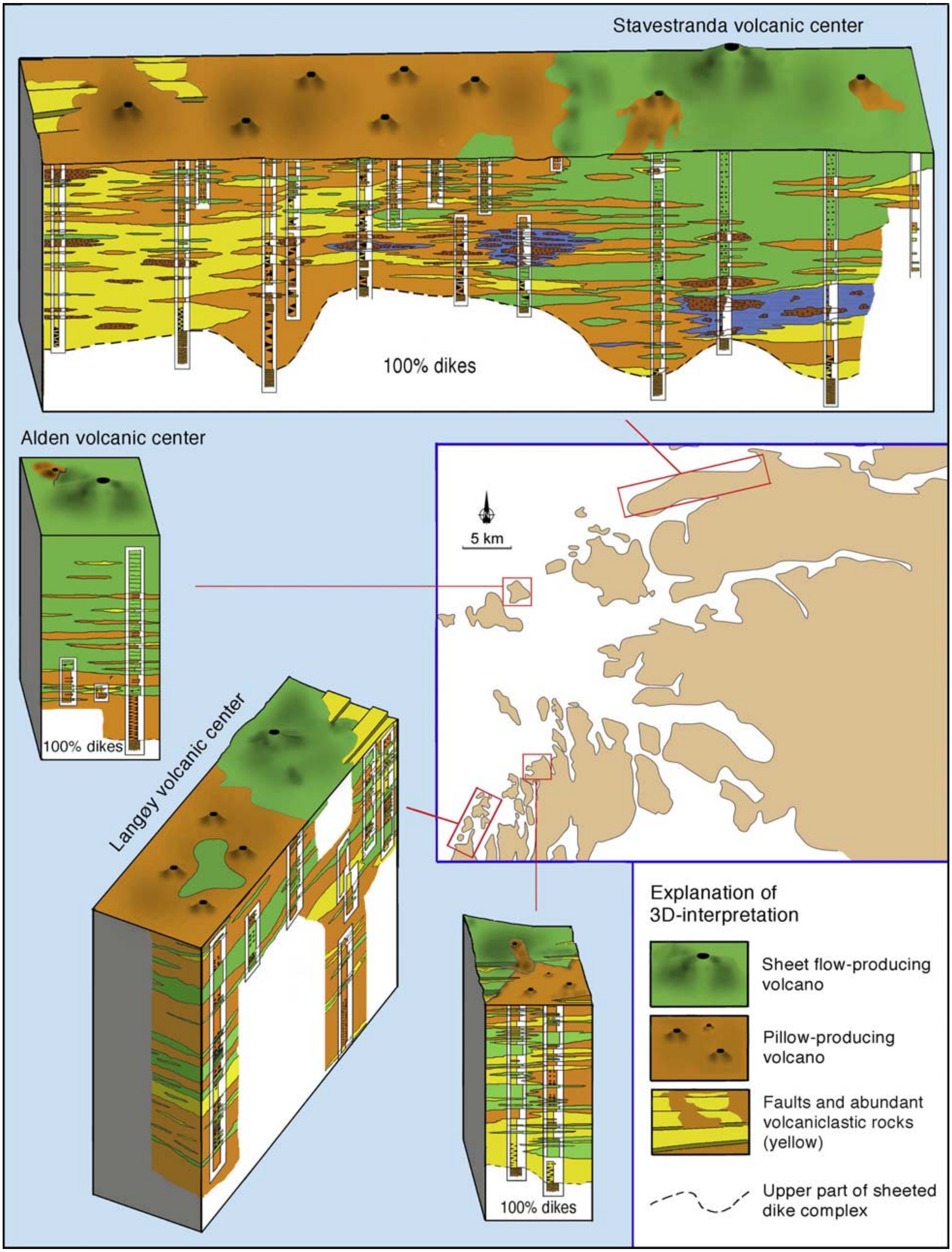

Figure 11. Volcanic stratigraphy of the Solund-Stavfjord Ophiolite Complex and a 3-dimensional, topographic interpretation. All the sections are interpreted to be approximately ridge parallel. For explanation of profiles, see Figure 7.

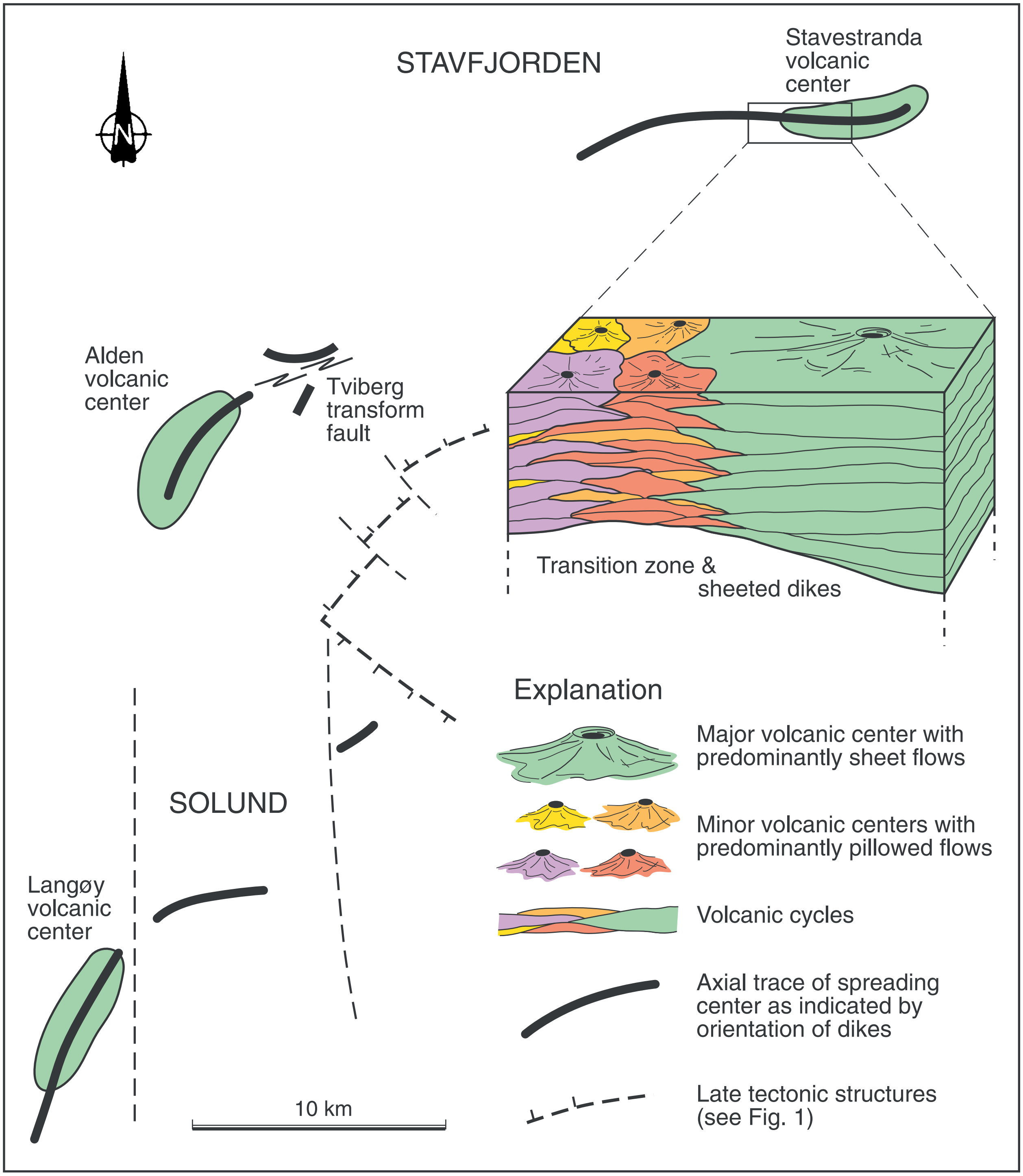

Figure 12. Sketch map showing the distribution of major volcanic centers (the Stavestranda, Alden, and Langøy volcanic centers) and development of cyclic units of the Solund-Stavfjord Ophiolite Complex. See Figures 1 and 7 for the geographical position, and general geological relationships.

features are dependent on the spreading rates [e.g., *Macdonald et al.*, 1992; *Phipps Morgan and Parmentier*, 1995; *White et al.*, 2000, 2002]. Thus with respect to magmatic segmentation, a phenomenon related to mantle upwelling and melting [e.g., *Choblet and Parmentier*, 2001], magmatically robust third-order centers are regularly spaced at distances of ~85–100 km for ultraslow-spreading ridge systems [*Crane et al.*, 2001; *Okino et al.*, 2002], and ~10–30 km for fast spreading ridge systems [*White et al.*, 2002]. Third-order volcanic segments on fast spreading ridges are defined by overlapping spreading centers, each of which constitutes a single volcanic system [*White et al.*, 2000]. The middle part of segments is characterized by voluminous magmatic activity, producing a high proportion of sheet flow lavas, whereas toward their ends pillow lavas constitute the dominant type of flows.

[40] The distribution of the volcanic rocks of the Solund-Stavfjord Ophiolite Complex (Figure 11) suggests the presence of three major magmatic centers, represented by thick sequences of sheet flows at Stavestranda, Alden, and Langøy (Figure 11). Following the trace of the spreading axis, as indicated by the orientation of dikes, the distances between the volcanic centers are ~20–30 km. These distances are, however, minima since the region was affected by W- to NW-vergent folding during late-stage extensional deformation [*Osmundsen and Andersen*, 1994]. An expression of this folding is visible in the eastern part of the Staveneset Peninsula, where the strike of the dikes bends from E-W to NW-SE (Figure 1). In the unexposed area lying between Staveneset and Tviberg (Figure 1), the ophiolite may be similarly folded, and if so, the original distance between the Stavestranda and Alden centers could easily be some 25–40% larger. In this context it is pertinent to mention that the structural relationships and rocks of the island of Tviberg (Figure 1) suggest transform fault activity during generation of the oceanic crust [*Skjerlie and Furnes*, 1990]. The Tviberg area (Figure 1) separates the Stavestranda and Alden volcanic centers, and may thus represent a fossil tectonic boundary between two ridge segments. The distances between the three volcanic centers, as indicated, would seem to correspond to those separating the volcanic centers of third-order segments along fast spreading ridges. Thus the westerward transition from the sheet-flow-dominated Stavestranda volcanic center to pillow lava dominance into ultimately volcanic breccias, that, to a significant extent are volcaniclastic sediments, may indicate the vicinity of an active tectonic zone to the west of Staveneset (Figure 1). This appears rather similar to the pattern observed within the third-order segments of the East Pacific Rise, where smaller, axial magma chambers near the end of the segments, create pillow lavas, in contrast to the sheet lavas at the centers [*White et al.*, 2002]. Admittedly, three volcanic centers may not provide a representative picture of repetitive features that may have characterized the volcanic development of the Solund-Stavfjord Ophiolite Complex. If, on the other hand, they do represent third-order volcanic segmentation, their spacing is consistent with generation at an intermediate or fast spreading rate.

5.6. Magma Chamber Character and Volcanic Development

[41] The construction of major volcanic cyclic units reflects chemical and physical processes, such as replenishment, mixing, fractional crystallization, inflation and amalgamation, in the magma chamber from which the lavas erupted. Since the evolution of chambers may vary considerably [e.g., *Grove et al.*, 1992; *Sinton and Detrick*, 1992; *Gudmundsson*, 1998], it is to be expected that the construction and the thickness of the cyclic units likewise also vary.

[42] The general consensus is that low magma flux results in small, short-lived magma chambers, whereas high magma flux results in larger, persistent magma chambers [e.g., *Smith and Cann*, 1993]. Field studies of submarine lavas [*Griffith and Fink*, 1992], as well as laboratory simulations of various lava flow morphologies [*Gregg and Fink*, 1995] have shown that high and low effusion rates result in products that were comparable to sheet flows and pillow lavas, respectively. The implication of these observations may be that large magma chambers have the potential of erupting large volumes of magma and a high proportion of sheet flows, whereas smaller magma chambers would erupt smaller volumes and produce predominantly pillow lavas. The relationships outlined in Figure 11 may thus define areas in which the volcanic evolution of the Solund-Stavfjord Ophiolite Complex was associated with the development of larger magma chamber(s), resulting in the construction of extensive shields of sheet flows in the

upper part of the volcanic succession. Contemporaneously with the extrusion of sheet flows, volcanic activity between the major centers gave rise to smaller, pillow-lava-dominated volcanoes, probably fed from smaller magma chambers.

[43] The number of major cyclic units appears to be lower in the major volcanic centers than in the adjacent pillow-lava-dominated areas. In this connection we have to consider whether a cyclic unit was the result of eruptions from a single volcanic center or several vents and to what extent there was inter-fingering of lavas from different eruptional sites? It seems reasonable to assume that the possibility of interfingering was different for major and minor volcanic centers. In the case of major volcanic centers, i.e., the Stavestranda and Alden volcanic centers, there was little, if any possibility that lava flows from adjacent, small pillow-lava volcanoes could interfinger with the sheet flows, except for in the peripheral parts of the volcanic edifices. On the other hand, it seems likely that pillow lava flows from several closely spaced, minor volcanoes could interfinger. In this connection information about the distribution and size of volcanoes (represented by seamounts) at active spreading centers is pertinent. From the median valley of the central Atlantic slow-spreading ridge, *Smith and Cann* [1990] reported a dense population of seamounts (average of 80 per 10^3 km^2). From a segment of the fast spreading East Pacific Rise (7°–22°S) the observations of *Abers et al.* [1988] indicated a considerably lower frequency (average of 27 per 10^3 km^2). The heights of the seamounts range from ~50 m up to 650 m (the majority in the 50–150 m range), and the most common radius is ~500 m (range ~200 m to ~1500 m) [*Smith and Cann*, 1992]. Many of the seamounts overlap with each other and are difficult to recognize, and the above mentioned numbers are hence regarded as minimum [*Smith and Cann*, 1992]. Using this as representative during the construction of pillow-dominated terrane, we may infer that any section would probably contain lava flows from several low, adjacent volcanoes (Figure 12). In addition, during eruptions at the major volcanic centers, voluminous sheet flows may eventually pass into pillow lavas toward their terminations and interfinger with pillow lavas from minor volcanic centers.

[44] We envisage that the major volcanic centers, characterized by thick accumulations of sheet flows, were constructed during a few extended periods of volcanic activity (Figure 12) that each involved a number of individual eruptions. Parts of the volcanic sequence that are pillow-dominated, appear to have been built up, on the other hand, during a larger number of shorter-lived volcanic episodes.

6. Summary

[45] The Late Ordovician Solund-Stavfjord Ophiolite Complex in the western Norwegian Caledonides represents a fragment of oceanic crust that formed in a back-arc basin. It displays a well-preserved volcanic sequence consisting of sheet flows (including some ponded in lava lakes), pillow lavas, and volcanic breccias. We examined the volcanic sequence along 29 profiles, several of which cover the entire volcanic stratigraphy, to define its 2-dimensional architecture. The main results of this study are:

[46] 1. Uncorrected for tectonic strain, the thickness of the volcanic sequence varies between ~470 m and ~800 m. Sheet-flow-dominated sequences are generally the thickest, whereas the pillow-dominated sequences are variable in thickness but generally thinner than those of sheet-flow sequences.

[47] 2. The proportions of sheet flow, pillow lava and volcanic breccia vary between 2–92%, 7–74% and 2–85%, respectively. Thus local sequences may be dominated by any of these.

[48] 3. In sections dominated by sheet flows, volcanic breccias and pillow lavas are nonetheless the oldest eruptive products.

[49] 4. The volcanic sequence can be subdivided into several stratigraphic cyclic units. Sheet-flow-dominated cyclic units are in general considerably thicker (average 85 m) than pillow-lava-dominated units (average 20 m).

[50] 5. In one 16 km long, along-axis segment of the ophiolite, there is a lateral transition from sheet-flow dominance into a pillow lava-dominated

succession, and then into a breccia-dominated sequence.

[51] 6. Thick sequences of sheet-flows represent major volcanic centers that developed where magma-delivery was highest. Viewing the ophiolite as a whole, it appears that such centers were around 25–30 km apart from each other. This pattern is reminiscent of third-order volcanic segmentation in active, fast spreading ridges, where magmatic centers in the middle of segments give way laterally to pillow lava and volcaniclastic rocks.

Acknowledgments

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References

Abers, G. A., B. Parson, and J. K. Weissel, Seamount abundances and distribution in the southeast Pacific, *Earth Planet. Sci. Lett.*, *87*, 137–151, 1988.

Alsaker, E., and H. Furnes, The geochemistry of the Sunnfjord Melange: Sediment mixing from different sources during obduction of the Solund-Stavfjord Ophiolite Complex, Norwegian Caledonides, *Geol. Mag.*, *131*, 105–121, 1994.

Alt, J. C., et al., *Proceedings of the Ocean Drilling Program*, *Initial Reports*, vol. 148, College Station, Tex., 1993.

Andersen, T. B., K. P. Skjerlie, and H. Furnes, The Sunnfjord Melange, evidence of Silurian ophiolite accretion in the west Norwegian Caledonides, *J. Geol. Soc. London*, *147*, 59–68, 1990.

Ballard, R. D., and T. H. van Andel, Morphology and tectonics of the inner rift valley at lat 36°50′N on the Mid-Atlantic Rigde, *Geol. Soc. Am. Bull.*, *88*, 507–530, 1977.

Ballard, R. D., R. T. Holcomb, and T. H. van Andel, The Galapagos Rift at 86°W: 3. Sheet flows, collaps pits, and lava lakes of the rift valley, *J. Geophys. Res.*, *84*, 406–422, 1979.

Ballard, R. D., S. Francheteau, T. Juteau, and W. Normark, The East Pacific Rise at 21°N: The volcanic, tectonic, and hydrothermal processes of the central axis, *Earth Planet. Sci. Lett.*, *55*, 1–10, 1981.

Bedard, J. H., K. Lanziere, A. Tremblay, and A. Sangster, Evidence of forearc-spreading from the Betts Cove ophiolite, Newfoundland: Oceanic crust of boninitic affinity, *Tectonophysics*, *284*, 233–245, 1998.

Bergh, S. G., and G. E. Sigvaldason, Pleistocene mass-flow deposits of basaltic hyaloclastite on a shallow submarine shelf, South Iceland, *Bull. Volcanol.*, *53*, 597–611, 1991.

Bonatti, E., and C. G. A. Harrison, Eruption styles of basalt in oceanic spreading ridges and seamounts: Effects of magma temperature and viscosity, *J. Geophys. Res.*, *93*, 2967–2980, 1988.

Boudier, F., and A. Nicolas, Nature of the Moho transition zone in the Oman ophiolite, *J. Petrol.*, *36*, 777–790, 1995.

Bryan, W. B., S. E. Humphris, G. Thompson, and J. F. Casey, Comparative volcanology of small axial eruptive centers in the MARK area, *J. Geophys. Res.*, *99*, 2973–2984, 1994.

Carlisle, D., Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia, *J. Geol.*, *71*, 48–71, 1963.

Choblet, G., and E. M. Parmentier, Mantle upwelling and melting beneath slow spreading centers: Effects of variable rheology and melt productivity, *Earth Planet. Sci. Lett.*, *184*, 589–604, 2001.

Christeson, G. L., G. M. Purdy, and G. J. Fryer, Seismic constraints on shallow crustal emplacement processes at fast spreading East Pacific Rise, *J. Geophys. Res.*, *99*, 17,957–17,974, 1994.

Crane, K., and R. D. Ballard, Volcanics and structures of the FAMOUS-Narrowgate Rift: Evidence for cyclic evolution, *J. Geophys. Res.*, *86*, 5112–5124, 1981.

Crane, K., H. Doss, P. Vogt, E. Sundvor, G. Cherkashov, I. Poroshina, and D. Joseph, The role of the Spitsbergen shear zone in determining morphology, segmentation and evolution of the Knipovich Ridge, *Mar. Geophys. Res.*, *22*, 153–205, 2001.

Detrick, R. S., J. Collins, R. Stephen, and S. Swift, In situ evidence for the nature of the seismic layer 2/3 boundary in the crust, *Nature*, *370*, 288–290, 1994.

DeWit, M. J., R. A. Hart, and R. J. Hart, The Jamestown Ophiolite Complex, Barberton mountain belt: A section through 3.5 Ga oceanic crust, *J. Afr. Earth Sci.*, *6*, 681–730, 1987.

Dilek, Y., H. Furnes, and K. P. Skjerlie, Propagating rift tectonics of a Caledonian marginal basin: Multi-stage seafloor spreading history of the Solund-Stavfjord ophiolite in western Norway, *Tectonophysics*, *280*, 213–238, 1997.

Dilek, Y., E. M. Moores, and H. Furnes, Structure of modern oceanic crust and ophiolites and implications for faulting and magmatism of oceanic spreading centers, in *Faulting and Magmatism at Mid-Ocean Ridges*, *Geophys. Monogr. Ser.*, vol. 106, edited by R. Buck et al., pp. 219–265, AGU, Washington, D.C., 1998.

Dunning, G. R., and R. B. Pedersen, U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: Implications for the development of Iapetus, *Contrib. Mineral. Petrol.*, *98*, 13–23, 1988.

Einauldi, F., P. A. Pezard, J.-J. Cocheme, C. Coulon, C. Laverne, and M. Godard, Petrography, geochemistry and physical properties of a continuous extrusive section from the Hilti massif, Semail ophiolite, *Mar. Geophys. Res.*, *21*, 387–407, 2000.

Einaudi, F., M. Godard, P. Pezard, J.-J. Cochemé, C. Coulon, T. Brewer, and P. Harvey, Magmatic cycles and formation of the upper oceanic crust at spreading centers: Geochemical study of a continuous extrusive section in the Oman ophiolite, *Geochem. Geophys. Geosyst.*, *4*(6), 8068, doi:10.1029/2002GC000362, 2003.

Fouquet, Y., J.-P. Eissen, H. Ondreas, F. Barriga, R. Batiza, and L. Danyushevsky, Results of deep-water basaltic explosive volcanic activity?, *Terra Nova*, *10*, 280–286, 1998.

Francheteau, J., and R. D. Ballard, The East Pacific Rise near 21°N, 13°N and 20°S: Inferences for a long strike variabilty of axial processes of the mid-ocean ridge, *Earth Planet. Sci. Lett.*, *64*, 93–116, 1983.

Francheteau, J., T. Juteau, and C. Rangan, Basaltic pillars in collapsed lava-pools on the deep ocean-floor, *Nature*, *281*, 209–211, 1979.

Fridleifsson, I. B., H. Furnes, and F. B. Atkins, Subglacial volcanics-on the control of magma chemistry on pillow dimensions, *J. Volcanol. Geotherm. Res.*, *13*, 103–117, 1982.

Furnes, H., Meta-hyaloclastite breccias associated with Ordovician pillow lavas in the Solund area, west Norway, *Norwegian J. Geol.*, *52*, 385–407, 1972.

Furnes, H., and I. B. Fridleifsson, Relationships between the chemistry and axial dimensions of some shallow water pillow lavas of alkaline olivine basalt- and olivine tholeiitic composition, *Bull. Volcanol.*, *41–2*, 1–11, 1978.

Furnes, H., K. P. Skjerlie, R. B. Pedersen, T. B. Anderson, C. J. Stillman, R. Suthren, M. Tysseland, and L. B. Garmann, The Solund-Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: Geology, geochemistry and tectonic environment, *Geol. Mag.*, *127*, 209–289, 1990.

Furnes, H., R. J. Johansen, and K. P. Skjerlie, FeTi-poor and FeTi-rich basalts in the Solund-Stavfjord ophiolite complex, west Norwegian Caledonides: Relationships and genesis, *Neues Jahrb. für Mineral. Monatsh.*, *4*, 153–168, 1992.

Furnes, H., Y. Dilek, K. P. Skjerlie, H. L. Ryttvad, and H. C. Fonneland, Variations in basaltic geochemistry along a propagating rift of the Late Ordovician marginal basin of the West Norwegian Caledonides, *Terra Nova*, *10*, 21–26, 1998.

Furnes, H., K. P. Skjerlie, and Y. Dilek, Petrology, tectonics, and hydrothermal alteration of a fossil backarc oceanic crust: Solund-Stavfjord ophiolite complex of the western Norwegian Caledonides-a review, in *Ophiolites and Oceanic Crust: New Insights From Field Studies and the Ocean Drilling Program*, edited by Y. Dilek et al., *Spec. Pap. Geol. Soc. Am.*, *349*, 443–460, 2000.

Furnes, H., B. Hellevang, and Y. Dilek, Cyclic volcanic stratigraphy in a Late Ordovician marginal basin, west Norwegian Caledonides, *Bull. Volcanol.*, *63*, 164–178, 2001.

Furnes, H., B. Hellevang, B. Robins, and A. Gudmundsson, Geochemical stratigraphy of the lavas of the Solund-Stavfjord Ophiolite Complex, W. Norway, and magma-chamber dynamics, *Bull. Volcanol.*, *65*, 441–457, 2003.

Gass, I. G., and J. D. Smewing, Intrusion, extrusion and metamorphism at constructive margins: Evidence from the Troodas massif, Cyprus, *Nature*, *242*, 26–29, 1973.

Gregg, T. K. P., and J. H. Fink, Quantification of submarine lava-flow morphology through analog experiments, *Geology*, *23*, 73–76, 1995.

Griffith, R. W., and J. H. Fink, Solidification and morphology of submarine lavas: A dependence on extrusion rate, *J. Geophys. Res.*, *97*, 19,729–19,737, 1992.

Grove, T. L., R. J. Kinzler, and W. B. Bryan, Fractionation of Mid-Ocean Ridge Basalt (MORB), in *Mantle Flow and Melt Generation at Mid-Ocean Ridges*, *Geophys. Monogr. Ser.*, vol. 71, edited by J. P. Morgan, D. K. Blackman, and J. M. Sinton, pp. 281–310, AGU, Washington, D.C., 1992.

Gudmundsson, A., Magma chambers modeled as cavities explain the formation of rift zone central volcanoes and their eruption and intrusion statistics, *J. Geophys. Res.*, *103*, 7401–7412, 1998.

Haggas, S. L., T. S. Brewer, and P. K. Harvey, Architecture of the volcanic layer from the Costa Rica Rift, constraints from core-log integration, *J. Geophys. Res.*, *107*(B2), 2031, doi:10.1029/2001JB000147, 2002.

Harding, A. J., J. A. Orcutt, M. E. Kappus, E. E. Vera, and J. D. Mutter, et al., The structure of young oceanic crust at 13°N on the East Pacific Rise from expanding spread profiles, *J. Geophys. Res.*, *94*, 12,163–12,196, 1989.

Hartz, E. H., M. W. Martin, A. Andresen, and T. B. Andersen, Volcanic rocks in the Devonian Solund Basin, Western Norway: Large landslides of Silurian (439 Ma) rhyolites, *J. Geol. Soc. London*, *159*, 121–128, 2002.

Hellevang, H., Volcanic and petrological evolution of Late Ordovician oceanic crust: The Stavenes segment of the Solund-Stavfjord ophiolite, Candidatus Scientiarium thesis, Univ. of Bergen, Bergen, 2002.

Honnorez, J., and P. Kirst, Submarine basaltic volcanism: Morphometric parameters for discriminating hyaloclastites from hyalotuffs, *Bull. Volcanol.*, *44–2*, 1–25, 1975.

Hyndman, R. D., and M. H. Salisbury, The physical nature of young upper oceanic crust on the Mid-Atlantic Ridge, Deep Sea Drilling Project Hole 395A, *Init. Rep. Deep Sea Drill. Project*, *78B*, 839–848, 1984.

Karson, J. A., Geologic structure of the uppermost oceanic crust created at fast- to intermediate-rate spreading centers, *Ann. Rev. Earth Planet. Sci.*, *30*, 347–384, 2002.

Karson, J. A., and P. A. Rona, Block-tilting, transfer faults, and structural control of magmatic and hydrothermal processes in the TAG area, Mid-Atlantic Ridge 26°N, *Geol. Soc. Am. Bull.*, *102*, 1635–1645, 1990.

Karson, J. A., et al., Along-axis variations in seafloor spreading in the MARK area, *Nature*, *328*, 681–685, 1987.

Kennish, M. J., and R. A. Lutz, Morphology and distribution of lava flows on mid-ocean ridges: A review, *Earth Sci. Rev.*, *43*, 63–90, 1998.

Keszthelyi, L., and S. Self, Some physical requirements for the emplacement of long basaltic lava flows, *J. Geophys. Res.*, *103*, 27,303–27,324, 1998.

Macdonald, K. C., et al., The East Pacific Rise and its flanks 8–18N: History of segmentation, propagation and spreading direction based on SeaMARC II and sea beam studies, *Mar. Geophys. Res.*, *14*, 299–344, 1992.

Malpas, J., and D. Williams, Geology of the area surrounding the CY-1 and CY-1A boreholes, in *Cyprus Crustal Study Project*, Paper 90–20, edited by J. Malpas, P. T. Robinson, and C. Xenophontos, pp. 29–40, Geol. Surv. of Can., Ottawa, Ontario, 1991.

Moore, J. G., Petrology of deep-sea basalt near Hawaii, *Am. J. Sci.*, *263*, 40–52, 1965.

Moore, J. G., Mechanism of formation of pillow lava, *Am. J. Sci.*, *63*, 269–277, 1975.

Moores, E. M., and F. J. Vine, The Troodos Massif, Cyprus and other ophiolites as oceanic crust: Evaluation and implications, *Philos. Trans. R. Soc. London, Ser. A*, *268*, 443–466, 1971.

Muehlenbachs, K., H. Furnes, H. C. Fonneland, and B. Hellevang, Ophiolites as faithful records of the oxygen isotope ratio of ancient seawater: The Solund-Stavfjord Ophiolite Complex as a Late Ordovician example, in *Ophiolites in Earth's History*, edited by Y. Dilek and P. T. Robinson, *Geol. Soc. London, Spec. Publ.*, in press, 2003.

Nicolas, A., and F. Boudier, Mapping oceanic ridge segments in Oman ophiolite, *J. Geophys. Res.*, *100*, 179–197, 1995.

Nicolas, A., C. Freydier, M. Godard, and A. Vauchez, Magma chambers at oceanic ridges: How large?, *Geology*, *21*, 53–56, 1993.

Nicolas, A., F. Boudier, and B. Ildifonse, Dike patterns in diapirs beneath oceanic ridges: The Oman ophiolite, in *Magmatic Systems*, edited by M. P. Ryan, pp. 77–95, Academic, San Diego, Calif., 1994.

Okino, K., D. Curewitz, M. Asada, K. Tamaki, P. Vogt, and K. Crane, Preliminary analysis of the Knipovich Ridge segmentation: Influence of focused magmatism and ridge obliquity on an ultraslow spreading system, *Earth Planet. Sci. Lett.*, *202*, 275–288, 2002.

Osmundsen, P. T., and T. B. Andersen, Caledonian compressional and late-orogenic extensional deformation in the Staveneset area, Sunnfjord, *J. Struct. Geol.*, *16*, 1385–1401, 1994.

Pallister, J. S., and C. A. Hopson, Samail ophiolite plutonic suite: Field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber, *J. Geophys. Res.*, *86*, 2593–2644, 1981.

Pearce, J. A., S. J. Lippard, and S. Roberts, Characteristics and tectonic significance of supra-subduction zone ophiolites, in *Marginal Basin Geology*: *Volcanic and Associated Sedimentary and Tectonic Processes in Modern and Ancient Marginal Basins*, edited by B. P. Kokelaar and M. F. Howells, *Spec. Publ. Geol. Soc. London*, *16*, 77–99, 1984.

Pedersen, R. B., and G. R. Dunning, Evolution of arc crust and relations between contrasting sources: U-Pb (age), Nd and Sr isotope systematics of the ophiolite terrain of SW Norway, *Contrib. Mineral. Petrol.*, *128*, 1–15, 1997.

Pedersen, R. B., H. Furnes, and G. R. Dunning, The U/Pb age of the Sulitjelma Gabbro, north Norway: Further evidence for the development of a Caledonian marginal basin in Ashgillian/Llandoverian time, *Geol. Mag.*, *128*, 141–153, 1991.

Peterson, D. W., and R. I. Tilling, Transition of basaltic lava from pahoehoe to aa, Kilauea volcano, Hawaii: Field observations and key factors, *J. Volcanol. Geotherm. Res.*, *7*, 271–293, 1980.

Phipps Morgan, J., and E. M. Parmentier, Crenulated seafloor: Evidence for spreading-rate dependent structure of mantle upwelling and melting beneath a mid-oceanic spreading center, *Earth Planet. Sci. Lett.*, *129*, 73–84, 1995.

Renard, V., R. Hekinian, J. Francheteau, R. D. Ballard, and H. Backer, Submersible observations at the axis of the ultra-fast spreading East Pacific Rise (17°30′ to 21°30′), *Earth Planet. Sci. Lett.*, *75*, 339–353, 1985.

Robinson, P. T., M. F. Flower, H. Staudigel, and D. A. Swanson, Lithology and eruptive stratigraphy of Cretaceous oceanic crust, western Atlantic, in *Init. Rep. Deep Sea Drill. Project*, edited by T. Donelly and J. Francheteau, *51*/*52*/*53*, p. 1535–1556, 1979.

Rosendahl, R. B., et al., *Initial Reports*: *Deep Sea Drilling Project*, vol. 54, U.S. Govt. Print. Off., Washington, D. C., 1980.

Ryttvad, H. L., H. Furnes, K. P. Skjerlie, and R. Rolfsen, Geochemistry and petrogenesis of extrusive rocks, dikes and high-level plutonic rocks on the island of Oldra, Solund-Stavfjord Ophiolite Complex, western Norway, *Norw. J. Geol.*, *80*, 97–110, 2000.

Schmincke, H.-U., and U. Bednarz, Pillow, sheet flow and breccia flow volcanoes and volcano-tectonic hydrothermal cycles in the Extrusive Series of the northeastern Troodos ophiolite (Cyprus), in *Ophiolites Oceanic Crustal Analogues. Proceseding of the Symposium "Troodos 1987,"* edited by J. Malpas et al., pp. 185–206, Geol. Surv. Dep., Minist. of Agric. and Nat. Resourc., Nicosia, Cyprus, 1990.

Schmincke, H.-U., M. Rautenschlein, P. T. Robinson, and J. M. Mehegan, Troodos extrusive series in Cyprus: A comparison with oceanic crust, *Geology*, *11*, 405–409, 1983.

Shaw, H. R., D. L. Peck, T. L. Wright, and R. Okamura, The viscosity of basaltic magma: An analysis of field measurements in Makaopuhi lava lake, Hawaii, *Am. J. Sci.*, *226*, 225–264, 1968.

Shervais, J. W., Birth, death, and resurrection: The life cycle of suprasubduction zone ophiolites, *Geochem. Geophys. Geosyst.*, *2*, Paper number 2000GC000080, 2001.

Sinton, J. M., and R. S. Detrick, Mid-ocean ridge magma chambers, *J. Geophys. Res.*, *97*, 197–216, 1992.

Skjerlie, K. P., and H. Furnes, Evidence for a fossil transform fault in the Solund/Stavfjord Ophiolite Complex: West Norwegian Caledonides, *Tectonics*, *9*, 1631–1648, 1990.

Skjerlie, K. P., and H. Furnes, The gabbro - dyke transition zone demonstrated on Tviberg, Solund-Stavfjord Ophiolite Complex, *Geol. Mag.*, *133*, 573–582, 1996.

Skjerlie, K. P., H. Furnes, and R. J. Johansen, Magmatic development and tectonomagmatic models for the Solund-Stavfjord Ophiolite Complex, West Norwegian Caledonides, *Lithos*, *23*, 137–151, 1989.

Smith, D., and J. R. Cann, Hundred of small volcanoes on the medial valley floor of the Mid-Atlantic Ridge at 24–30°N, *Nature*, *348*, 152–155, 1990.

Smith, D., and J. R. Cann, The role of seamount volcanism in crustal construction at the Mid-Atlantic ridge (24°–30°N), *J. Geophys. Res.*, *97*, 1645–1658, 1992.

Smith, D., and J. R. Cann, Building the crust at the Mid-Atlantic Ridge, *Nature*, *365*, 707–715, 1993.

Smith, D., J. R. Cann, M. E. Dougherty, J. Lin, S. Spences, C. Macleod, J. Keeton, E. McAllister, B. Brooks, R. Rascoe, and W. Robertson, Mid-Atlantic Ridge volcanism from deep-towed side-scan sonar images, 25–29°N, *J. Volcanol. Geotherm. Res.*, *67*, 233–262, 1995.

Stakes, D. S., J. W. Shervais, and C. A. Hopson, The volcano-tectonic cycle of the FAMOUS and AMAR valleys, Mid-Atlantic Ridge 36°47′N: Evidence from basalt glasses and phenocryst compositions for a steady-state magma chamber beneath the valley mid-sections, *J. Geophys. Res.*, *89*, 6995–7028, 1984.

Staudigel, H., T. Plank, W. M. White, and H.-U. Schmincke, Geochemical fluxes during seafloor alteration of the upper oceanic crust: DSDP Sites 417 and 418, in *Subduction*: *Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 19–38, AGU, Washington, D.C., 1996.

van Andel, T. H., and R. D. Ballard, The Galapagos Rift at 86°W: 2. Volcanism, structure, and evolution of the rift valley, *J. Geophys. Res.*, *84*, 5390–5406, 1979.

Varga, R. J., and E. M. Moores, Spreading structure of the Troodos ophiolite, Cyprus, *Geology*, *13*, 846–850, 1985.

Walker, G. P., Morphometric study of pillow-size spectrum among pillow lavas, *Bull. Volcanol.*, *54*, 459–474, 1992.

White, S. M., K. C. Macdonald, and R. M. Haymon, Basaltic lava domes, lava lakes, and volcanic segmentation on the southern East Pacific Rise, *J. Geophys. Res.*, *105*, 23,519–23,536, 2000.

White, S. M., R. M. Haymon, D. J. Fornari, M. R. Perfit, and K. C. Macdonald, Correlation between volcanic and tectonic segmentation of fast-spreading ridges: Evidence from volcanic structures and lava flow morphology on the East Pacific Rise at 9°–10°N, *J. Geophys. Res.*, *107*(B8), 2173, doi:10.1029/2001JB000571, 2002.

Wohletz, K. H., Mechanisms of hydrovolcanic pyroclast formation: Grain-size, scanning electron microscopy, and experimental studies, *J. Volcanol. Geotherm. Res.*, *17*, 31–63, 1983.