Geological and geochemical development of the submarine volcanic sequence on Storøya, Leka Ophiolite Complex, North Trøndelag

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The volcanic sequence on Storøya, in tectonic contact with ultramafic and gabbroic rocks of the Leka Ophiolite Complex, consists of a sequence of dominantly submarine, basaltic volcanics with a minimum thickness of 600 m. The dominant rock type is pillow lava, but throughout the sequence massive lavas of variable thickness occur. Layers of fine-grained, laminated sediments and limestone are intercalated with the volcanic sequence. The volcanics are overlain by black shales and green volcaniclastic sediments. Systematic sampling through the volcanic sequence has revealed profound geochemical variations. Plotted in discrimination diagrams, the metabasalts vary from MORB to within-plate basalts, and appear to have formed from a source enriched in trace elements. The geochemical variations can best be explained by applying an open magma chamber model in which assimilation, crystallization and replenishment, together with dynamic melting, occur.

Storøya consists of a sequence of dominantly submarine volcanics with a minimum thickness of 600 m, overlain by black shales and green volcaniclastic sediments that are in tectonic contact with either serpentinized ultramafics or metagabbro of the Leka Ophiolite Complex (Fig. 1a). This volcanic sequence probably represents the highest stratigraphical unit of the Leka Ophiolite Complex (Furnes et al. 1988). Well preserved primary features in the pillow lavas, together with bedding in the intravolcanic sediments, show that the sequence defines a tight, steeply plunging fold. In the core of this fold, a strongly deformed sedimentary sequence stratigraphically overlies the volcanites (Fig. 1b).

Previous workers have dealt mostly with the chemical composition of these volcanic rocks (Prestvik 1974, 1985; Prestvik & Roaldset 1978; Furnes et al. 1988, 1992). In these works it was recognized that two basalt types were present, i.e. metabasalts of alkaline composition as the main type and apparently normal MORB type also occurring. Prestvik (1974) and Prestvik & Roaldset (1978) concluded that the Storøya volcanics were of hawaiitic composition formed in an ocean island setting, a view that in general has been shared by Furnes et al. (1988, 1992). Later Prestvik (1985) proposed, as an alternative explanation, that the Storøya metabasalts represent oceanic crust formed at an anomalous ridge.

The main purpose of this paper is (1) to describe and present a detailed stratigraphic log through the volcanic sequence, and (2) present models that may explain the geochemical development of the metabasalts.

Geological relationships

General

The Leka Ophiolite Complex (Fig. 1a) consists of the following units: A strongly deformed, harzburgitic complex representing a depleted upper mantle (Albrektsen et al. 1991), is overlain by ultramafic cumulates and layered metagabbro. Upwards layered metagabbro grades into laminated and variably textured metagabbros, being host to smaller acidic intrusions (U-Pb zircon dated to 497 ± 2 Ma by Dunning & Pedersen (1988)) and metabasaltic dykes, which grade upwards to a 100% sheeted dyke complex. In the upper part of the sheeted dyke complex on Madsøya the first presence of pillow lavas can be seen. The metabasaltic dykes and pillow lavas of the Leka Ophiolite Complex (excluding Storeya) are tholeiites of island-arc and MORB affinity (Furnes et al. 1988, 1992).

The volcanics

The volcanic sequence at Storøya is dominated by pillow lavas, pillow breccias and massive lavas. Interbedded with the volcanics are several thin beds of sediments. Despite deformation, it has been possible to establish an almost continuous stratigraphic profile of ca. 525 m (Fig. 2). A description of the main rock types in the profile is given below.

The degree of alteration differs within the sequence (Fig. 2). The most severely altered rocks, generally
Legend
- Skei Group (cgl., s.st., mica-schist & limestone)
- Unconformity
- Leka Ophiolite Complex
  - Pillow lava & volcaniclastic rocks
    (Madsøya, Langdraget & Storoya)
  - Metabasalt dykes
  - Q-keratophyre / Plagiogranite
  - Varitextured metagabbro, metabasalt
dykes, plagiogr. veins & metadiorite
  - Layered metagabbro/clinopyroxenite
  - Layered dunite / wehlite
  - Harzburgite / dunite (tectonite)
  - ? thrust
- Solsemøyene Group (limest. mica-schist, s.stone)

Map of Leka and Storøya

Legend:
- Younging direction
- Primary layering/lamination
- Dyke orientation
- Foliation (in harzburgite)
- Regional foliation
- Shear zones observed/inferred

Map of Solsemøyene and Tørrflesan

Legend:
- Pillow lava / breccia
- Massive lava
- Metasediments
- Volcaniclastic rocks
- Metagabbro
- Serpentinitized ultramafics
- Layering
- Inverted layering
- Shear zone
- Boundary observed/inferred
confined to the vesicular pillow lavas, have a light green-yellowish colour. The alteration is usually strongest in the outer, vesicular parts of the pillows. Domains of altered rocks may terminate against a sedimentary layer. This indicates that the alteration essentially was a result of oceanic, hydrothermal activity, and also that the pathways of the circulating solutions had changed by the time of deposition of the sedimentary layer. Similar alteration patterns have been described from the Palau-Kyushu Ridge (Mattey et al. 1980) and from the Guaymas Basin (Morrison & Thompson 1983; Shipboard Scientific Party, Leg 65 1983).

**Pillow lava.** – The longest axis of the pillows varies from a few centimetres up to 1 m. Pillows with drain-out structures, generally filled with secondary carbonate or quartz, are often localized along certain layers, thus providing a reliable way-up criterion. Most commonly the structure is represented by one single hole near the top of the pillow (Fig. 2), but pillows with up to six drain-outs are present. Vesicles, rarely exceeding 25%, may occur in a zone a few centimetres thick within the upper part of the pillows (Fig. 2). Pipe vesicles may be present along the lower rim of pillows. By applying the vesicle/depth relations of Moore (1970) and Moore & Schilling (1973), the pillow lavas on Storøya most probably extruded at depths exceeding 600 m.

Some non-vesicular pillows contain spherical, light-grey to yellowish coloured varioles ranging in diameter from 1 to 7 mm. They are most commonly concentrated in a zone 3–4 cm thick along the pillow rim, whereas smaller pillows may have varioles throughout (Fig. 2). Some horizons micro-pillow lava is present. The phyric samples contain phenocrysts of altered plagioclase. All the 89 analysed samples from the volcanic sequence, except five, are aphyric. Most samples are medium- to fine-grained and have a heterograno crystal texture, while the phyric samples contain phenocrysts of altered plagioclase. Petrography

**Massive lavas.** – The massive lava flows (Fig. 2) are commonly 5–10 m thick, and may show a transition to pillow lava towards the top. A thin sedimentary layer is often present at the base of the massive lavas, indicating a halt between successive extrusions. The massive lavas may contain vesicles and drain-outs.

*Slide deposit.* – An unsorted deposit approximately 20 m thick and consisting of subangular fragments of lava (up to 20 cm) in a matrix of reworked hyaloclastite is present in the sequence (Fig. 2). Similar deposits related to vertical uplift of the ocean floor have been described from the rift valley of the Mid-Atlantic Ridge (Ballard & Moore 1977).

**Intravolcanic sedimentary layers.** – Several sedimentary beds are, especially in the lower part of the sequence, intercalated with the volcanics. Some of these beds may attain a thickness of 1 m, and extend laterally for up to 300 m. Others occur as discontinuous pockets between pillows in the lowermost part of pillow lava horizons. The sediments consist of either calcareous mud and/or fine-grained, laminated, clastic siltstones with a green, grey or reddish colour (Fig. 2).

**The metasediments**

The metasedimentary sequence in the core of the fold on Storøya consists of strongly deformed volcanioclastites and shales. The lowest part of this metasedimentary succession is a black shale, containing pockets of calcareous mud, in primary contact with the volcanics. Its thickness varies from 3–4 m to up to nearly 100 m, a variation reflecting faulting activity during deposition. The shale contains considerable amounts of pyrite and in places small chert concretions.

Apart from the black shale, green volcanioclastites (in some layers containing red-brown garnets) and grey shales occur. The banded grey shales, locally interbedded with layers of brecciated chert, are extensively cross-cut by thin quartz veins. Within this metasedimentary succession are thin layers of fine-grained, laminated metasediments and pockets of calcareous mud, similar to those found within the underlying volcanic sequence.

**Fig. 1.** Simplified geological map of (a) the Leka Ophiolite Complex (modified after Furnes et al. 1988), and (b) Storøya. The position of the stratigraphical profile in Fig. 2 is shown (A–E).
sedimentary layers in the volcanic sequence consist of epidote, biotite, quartz, chlorite, leucoxene and opaques. The metasediments in the core of the Storøya fold consist of biotite, actinolite, quartz, chlorite, calcite, plagioclase, epidote, garnet and graphite, with pyrite as the most common opaque. Actinolite occurs as unoriented, acicular, euhedral crystals. The black shale contains graphite as a common mineral and rock fragments of fine-grained to micro-crystalline quartz.

Geochemistry

Analytical methods

All major oxides and trace elements were analysed by X-ray fluorescence (XRF) at Geologisk Institutt, University of Bergen. The glass-bead technique of Padfield & Grey (1971) was used for the major elements and pressed powder pellets for the trace elements. International standards and Flanagan’s (1973) recommended values were used for calibration.

Alteration effects

It is well known that alteration and metamorphism affect the geochemistry of basic rocks (Melson et al. 1968; Corliss 1971; Tomasson & Kristmannsdottir 1972; Scott & Hajash 1976; Coish 1977; Ludden et al. 1982).

In an attempt to show how alteration and metamorphism have affected the geochemistry on the Storøya volcanics, samples have been collected systematically from two pillows which, visually, have suffered different degrees of alteration. For both pillows the analysed samples were collected systematically along a cross-section. In the visually least-altered pillow, most elements were relatively little affected, except CaO, Sr and Ba, which all showed pronounced variations. The results from the investigation of the extensively altered pillow, which will be published elsewhere (Tveit et al., in prep.), demonstrate that the incompatible elements (Nb, Zr, Y and TiO2) and Cr are antipathetic. Thus, at approximately the highest 130 m of the profile, there is a marked change to a lower TiO2 content, and upwards this gradually decreases. It should also be noted, however, that a metabasalt sample with low TiO2 also occurs at around 100 m above the base of the profile. The most marked change in the incompatible element concentrations is shown by the Zr contents in the top 50 m of the profile. There is, however, at this level only a minor decrease in the Y content. Thus, from the bottom to the top of the profile there is a marked difference in the Zr/Y ratios; with the highest at the bottom and the lowest at the top.

Discussion

Below we will discuss (1) the environment in which the Storøya metabasalts formed, and (2) to what extent the above-described element and ratio variations in the metabasalts on Storøya can be explained in terms of melting and fractionation models from a single source.

Tectonic environment

Different immobile trace elements and their ratios can be used to classify the tectonic setting of basaltic rocks (e.g. Pearce & Cann 1973; Winchester & Floyd 1977). The most useful classification method is the Zr/TiO2–Y/Nb discrimination diagram (Fig. 4), in which the samples from Storøya predominantly plot in the alkaline and subalkaline fields. The Storøya volcanics, plotted in the Zr–Y, TiO2–Zr and Cr–Y discrimination diagrams, show predominantly a within-plate setting (Fig. 5). The associated metasediments have, for comparative purposes, been plotted in the same diagrams. In general they have somewhat higher concentrations in Y and Zr, and hence may represent more differentiated volcaniclastic rocks than the metabasalts. Some of the metabasalt samples plot within, or very close to the MORB field (Fig. 5),

3. Representative analyses of the Storøya volcanics are given in Table 1.

Throughout the profile the rocks are characterized by extensive chemical variations. (Cr, 7–606 ppm; Nb, 9–39 ppm; Zr, 89–353 ppm; Y, 17–72 ppm; and TiO2; 1.12–4.92%). The Zr/Y ratios vary from 3.56 to 15.53.

In the lowest 40 m of the profile the lavas are moderately high in Cr (around 350 ppm). Further up the profile, to about 150 m above the base, the Cr content is very low, becoming variable again up to a level of about 470 m, and the last seven samples of the profile are very high in Cr (around 600 ppm). In general terms the patterns of the incompatible elements (Nb, Zr, Y and TiO2) and Cr are antipathetic. Thus, at approximately the highest 130 m of the profile, there is a marked change to a lower TiO2 content, and upwards this gradually decreases. It should also be noted, however, that a metabasalt sample with low TiO2 also occurs at around 100 m above the base of the profile. The most marked change in the incompatible element concentrations is shown by the Zr contents in the top 50 m of the profile. There is, however, at this level only a minor decrease in the Y content. Thus, from the bottom to the top of the profile there is a marked difference in the Zr/Y ratios; with the highest at the bottom and the lowest at the top.
Våtvik, i.e. lAT to MORB, as well as the sequence Sto røya volcanics range between 3.2 and 4.7 (Furnes et al. 1992). Thus, even though the discrimination diagrams (Figs. 4 and 5) may indicate different tectonic settings, it is more likely that such features have to be explained in terms of petrogenic processes within one source region. It has been pointed out by Prestvik (1982) that during progressive fractionation from evolved tholeiite, through tholeiitic icelandite to icelandite, the samples show a path from the MORB, to the WPB, and finally into the calc-alkaline fields in the Ti–Zr–Y discrimination diagram of Pearce & Cann (1973). Another feature which also makes an explanation in terms of different tectonic settings highly unlikely is the fact that the samples plotting in different parts of the discrimination diagrams alternate through the sequence.

Most ophiolite complexes seem to have evolved in a marginal basin environment (Pearce et al. 1984; Pedersen et al., 1988). Alkaline basalts from such basins are described from the Lau Basin in the southwestern Pacific (Gill 1976; Volpe et al. 1988) and in the Daito Basin in the western Philippine Basin (Marsh et al. 1980). In both places the alkaline rocks evolved at a late stage in the development of the basin.

The Storøya volcanics are in tectonic contact with serpentinites and metagabbros of the Leka Ophiolite Complex; hence, without a precise age of the sequence, it is impossible to know whether they represent a younger or older magmatic stage compared with the other rocks of the Leka Ophiolite Complex.

However, detailed studies from other, well-dated Norwegian ophiolites, e.g. the Karmøy Ophiolite Complex (Dunning & Pedersen 1988) may give important information applicable to the Leka Ophiolite Complex. The Karmøy Ophiolite Complex shows a geochemical development including (1) formation of an axis sequence represented by IAT and MORB magmatism intruded by (2) boninitic melts. This is intruded by (3) melts of MORB and IAT affinities with subsequent intrusion and extrusion of (4) calc-alkaline melts. Finally, intrusion and extrusion of (5) transitional and alkaline basaltic melts occurred. Pedersen & Hertogen (1990) suggest that the Karmøy Ophiolite Complex formed in a marginal basin similar to the western Philippine basin.

Comparison of the Leka and Karmøy ophiolite complexes shows that both contain the same magmatic units and it is probable that both may have formed in the same marginal basin. By adopting this development for the Leka Ophiolite Complex, the Storøya volcanics most likely represent an oceanic island formed at a late stage.

According to Furnes et al. (1988, 1992) the geochemical scatter in the metabasaltic rocks form Madsøya and Våtvik, i.e. IAT to MORB, as well as the sequence of crystallization in the ultramafic to mafic cumulates (Ol → Cpx → Opx → Pl) and the presence of metaboninites, suggest that the first parts of Leka Ophiolite Complex evolved by spreading over a subduction zone. The pillow lavas with associated volcaniclastic sediments on Langdraget and Storøya (Fig. 1), respectively of marginal basin. Nd isotope data of the IAT/MORB and ocean island types, indicate formation in a marginal basin similar to the western Philippine basin.

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and these may be further subdivided into normal (N), transitional (T), and enriched (E) MORB on the basis of their Zr/Nb, Y/Nb and Zr/Y ratios (Saunders et al. 1980; le Roex et al. 1982). According to Saunders et al. (1980) the Zr/Nb ratios of N-MORB = 40, E-MORB = 3.5–6, and those of the Storøya MORB samples are generally between ca. 5.5–12.6. Regarding the Y/Nb and Zr/Y ratios, those of N-MORB are > 10 and < 3, whereas those of E-MORB are < 3 and > 5, respectively (le Roex et al. 1982). The Storøya MORB samples show Y/Nb and Zr/Y ratios between ca. 0.9–2.4 and 3.6–10.7, respectively. Based on this division, the Storøya volcanics with MORB composition straddle the transition between T-MORB and E-MORB.

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in the formation of the basin, and are therefore the 
youngest magmatic component.

**Petrogenesis**

*Dynamic melting model.* The Storøya volcanics show 
geochemical variations that can hardly be explained 
by simple melting processes from one single source.

In an assessment of how dynamic partial melting 
(Langmuir et al. 1977; McKenzie 1985) of a single source 
may affect REE concentrations, Pedersen & Hertogen 
(1990) developed a model which in this paper will be 
applied to trace elements.

In the dynamic melting process considered, melt is 
continuously extracted as soon as it is produced. At any 
time during melting there is a certain amount of pore-
melt present in the source which, after melting, becomes 
trapped in the residue. If the amount of pore-melt is 
the same as the total degree of melting, the model will be 
a batch melting model, whereas if the amount of pore-melt 
is zero it will be similar to a pure fractional melting 
model. In Fig. 6 the results of the modelling are superim-
posed on the geochemical data from Storeøya, and the 
data show vertical and lateral scatter. The variations in 
the Nb/Zr ratios cannot be explained by fractional 
crystallization, as shown by the vectors in the left-hand part 
of the diagram, demonstrating the effect of 25% crystalli-
zation of a chosen fractionate with the composition of 
\( O_{40.4} C_{50.3} P_{0.3} \) (Fig. 6). Only the Y concentrations 
will be affected. It is thus more likely to explain the lateral 
scatter as a result of the different degree of melting of a 
source with a varying content of pore-melt.

The data points to the right of the hatched area in Fig. 
6 show a weak vertical trend. This trend can be explained 
by an increased degree of melting with a variable degree 
of mixing of the pore-melts within the melting zone.

Dynamic melting may explain variations of Nb, Zr 
and Y in the samples from Storøya. The variations in the 
Nb/Zr ratio may be the result of different degrees of 
mixing of pore-melts produced by increased degree of 
melting. Subsequent fractional crystallization will give an 
increased Y concentration, while the Nb/Zr ratio will 
remain nearly unchanged.

*Simple fractionation.* The Zr/Y ratios of the samples 
from Storeøya vary considerably, and the only process 
that affects this ratio is fractionation of clinopyroxene 
(Pearce & Norry 1979). To test if such a fractionation 
could produce the observed variations in Zr/Y, an at-
temt was made to calculate back from the most primi-
tive Storøya sample with regard to Cr. This element has 
the highest partition coefficient of the trace elements 
entering clinopyroxene. When calculating back from the 
most primitive sample to the actual Cr values of the 
other samples, a new Zr/Y ratio was calculated. The 
recalculated Zr/Y ratio would, by comparing with the
initial ratio, indicate the effect of fractionation. Partition coefficients for the calculations are given in Table 2. All calculations were performed twice, with different partition coefficients for Cr with regard to clinopyroxene of O1 and O2, respectively. The results from the calculations (Fig. 7a) show that 21-39% clinopyroxene fractionation is needed to reduce the Cr concentration from 606 ppm to 7 ppm (i.e. to the sample with the lowest Cr concentration). Crystallization of 39% clinopyroxene would give a maximum increase in the Zr/Y ratio of 20.63%. Starting with the values of the most evolved sample (Cr = 606 ppm), the Zr/Y ratio will increase from 4.46 to 5.38. Most of the samples from Storøya have a much higher Zr/Y ratio than this (Fig. 5).

Fig. 7b shows the increase in the Zr/Y ratio by increasing the clinopyroxene fractionation. As is evident from this figure, considerable fractionation is needed to increase significantly the Zr/Y ratio.

It may be concluded that the variations seen in the Zr/Y ratios in the samples from Storøya cannot be explained by simple Rayleigh fractionation of clinopyroxene from one source.

Cyclic fractionation with assimilation, replenishment and mixing. – It appears difficult to explain all the geochemical variations of the Storøya volcanics in terms of melting models and/or by closed system Rayleigh fractionation. Open system models, in which assimilation, crystallization, replenishment and mixing occur prior to eruption of a magma batch, have been considered by several authors (e.g. O'Hara 1977; O'Hara & Mathews 1981; Hagen & Neumann 1990). Two models were considered by Hagen & Neumann (1990): i.e. the 'batch replenishment model' (AFCB), and the 'continuous replenishment model' (AFCR).

For the modelling of the Storøya samples, the 'batch replenishment model' (AFCB) of Hagen & Neumann (1990) seems the most realistic, considering the development of the ultramafic cumulates on Leka. According to Furnes et al. (1988), geochemical analyses of these rocks give clear signs of resetting in the bottom of each cyclic unit. Similar resettings are also present in other layered intrusions (Irvine 1970; Henderson & Gijbels 1976). This suggests that the addition of new magma into a magma

### Table 2. Partition coefficients used in the described modelling.

<table>
<thead>
<tr>
<th>OL</th>
<th>Opx</th>
<th>Cpx</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>1.5(a)</td>
<td>5(c)</td>
<td>10(d)/20(c)</td>
</tr>
<tr>
<td>Y</td>
<td>0.01(b)</td>
<td>0.2(b)</td>
<td>5(b)</td>
</tr>
<tr>
<td>Zr</td>
<td>0.01(b)</td>
<td>0.03(b)</td>
<td>0.12(e)</td>
</tr>
<tr>
<td>Nb</td>
<td>0.01(b)</td>
<td>0.15(b)</td>
<td>0.1(b)</td>
</tr>
</tbody>
</table>

**Notes:** The partition coefficients are from; (a) Irving (1978); (b) Pearce & Norry (1979); (c) Lindstrøm (1976); Cox et al. (1979); and (e) McCallum & Charette (1978).
chamber happens in pulses rather than by continuous replenishment. For mathematical details and a computer program, the reader is referred to Hagen & Neumann (1990). In this model, the initial magma, i.e. the end product from the previous cycle, is exposed to simultaneous crystallization and assimilation over a period of time. The magma chamber is subsequently filled with new magma from a deeper source, which mixes immediately with the existing magma to yield a homogeneous melt. The supply of new magma is assumed to take place instantaneously compared to the time needed for assimilation and crystallization. A fraction of the magma will be extruded if the new volume in the magma chamber exceeds a critical value.

The various parameters used in the modelling, such as the element concentrations of (1) the contaminant, (2) the replenishing magma, (3) the bulk distributions coefficients, and (4) the rate parameters (R_a, R_c, R_r), have been estimated as follows. The contaminant has the following elemental concentrations: Cr = 70 ppm, Y = 28 ppm and Zr = 240 ppm. These values represent an average of all the Storøya samples. The composition of the replenishing magma is unknown and can only be inferred. The concentrations of Cr, Y and Zr are chosen as 600, 12 and 80 ppm, respectively (Thompson et al. 1984). For the estimation of bulk partition coefficients used in the model, crystallization of a mineral assemblage consisting of 50% plagioclase, 20% olivine and
Fig. 6. Diagram showing variations in the Nb/Zr ratio and Y concentrations of the Storøya volcanics. The Nb, Zr and Y values of the samples have been adjusted for fractional crystallization of olivine, clinopyroxene and plagioclase assuming parental magmas with 750 ppm Cr. Superimposed on the data points are curves showing modelled variations in the trace-element contents of average melts (hatched area) and increment melts that are formed by dynamic partial melting. Trace-element compositions are calculated as a function of variations in the degree of melt extraction (given by the larger numbers) and amount of pore-melt (given by the smaller numbers) in the source region. Equations are given in Pedersen & Hertogen (1990). The element concentrations of Nb, Zr and Y of the source are assumed to be 4.3 times chondrite, 2.3 times chondrite and 3.1 times chondrite, respectively (Sun & Hanson 1975). The modelling has been carried out assuming a source consisting of 55% olivine, 40% orthopyroxene and 5% clinopyroxene. Partition coefficients are given in Table 2.

30% clinopyroxene (Pearce & Norry 1979) is assumed. This assemblage gives the following bulk partition coefficients (D) when using the partition coefficients given in Table 2: $D_{Cr} = 3.3$, $D_{V} = 0.167$ and $D_{Zr} = 0.043$ (i.e. $D_{Cr}^{Cpx/melt} = 10$).

The relationship between the mass added by assimilation and mass removed by crystallization ($R_a$ and $R_c$, respectively) is a function of temperature. According to Taylor (1980) the $R_a/R_c$ ratio has been estimated to have an upper limit of 0.3 for a magma at 1150°C and a wall rock at 150°C, whereas at a temperature of 1000°C for the latter, the ratio may reach unity (DePaolo 1981). Choosing an $R_a/R_c$ ratio of 0.67 best fits the data. This implies that the country rocks would have a temperature higher than 150°C, but less than 1000°C. For the modelling, the other variables have been set to: $F = 0.92$, $R_a = 0.2$, $R_c = 0.3$ and $R_r = 0.001 – 0.16$. As will be demonstrated below, some of the variations as demonstrated in Fig. 5, may, by application of the 'batch replenishment model' of Hagen & Neumann (1990), be modelled by the choice of the above parameters.

Fig. 7. a. The diagram shows how much clinopyroxene must be crystallized to go from the most primitive to the most evolved sample on Storøya. It also shows how much the Zr/Y ratio of the most primitive sample will increase by such a crystallization. The two vectors give the results with partition coefficients for Cr with regard to clinopyroxene of 10 and 20, respectively. b. The curve demonstrates how the Zr/Y ratio changes with different degrees of clinopyroxene fractionation.
Attention will be focused on the elemental patterns represented by the samples 39–46 (Fig. 8a). The elemental patterns shown here are common within the profile shown in Fig. 5. The trends for the incompatible elements Zr and Y seem to be a result of simple fractionation, as their concentrations increase stratigraphically upwards. The concentration of the compatible element Cr increases from sample 39 to 42, suggesting resetting. Thereafter the Cr concentration decreases from 149 ppm to 15 ppm between sample 42 and 43, and stays constant from sample 43 to sample 46.

Fig. 8b shows the effect that the AFCB model of Hagen & Neumann (1990) has on the concentrations by starting with the elemental values of sample 39. The modelling gives approximately the same increases for the incompatible elements as the results from the analysis show. Regarding Cr, the modelling gives nearly the same reduction in concentration as if going directly from sample 39 to sample 43 (Fig. 8a).

It must be stressed that this modelling gives no control for the time of each cycle or for the time between each extrusion. This means that the system may have suffered many cycles between each of the samples used in Fig. 8a. It also must be pointed out that the parameters $F$, $R_a$, $R_e$ and $R_r$, apart from the chosen elemental concentrations in the replenishing magma, have been kept constant during the modelling. Variations in the elemental concentrations can be explained by changing one or more of the parameters listed above. A situation like this is shown in Fig. 8c, where $R_r$ has been changed after two cycles. All the other parameters and concentrations have been kept constant and with the same values as for the modelling shown in Fig. 8b. During the first two cycles $R_r$ has a value of 0.16, and results in an increase for all the elements, including Cr. Thereafter $R_r$ was given a value of 0.001, which results in a pronounced decrease in Cr concentration, while Zr and Y increase to a higher extent than prior to the change of $R_r$. The Zr/Y ratio increases steadily throughout the modelling. As shown in Fig. 8b, Cr approaches a constant concentration both prior to and after the change of $R_r$. This development is very similar to what can be seen in Fig. 8a, where Cr is constant between samples 43 and 46.

It should be pointed out that some of the element patterns, as for example represented by samples 1–8, 15–18 and 68–71 of the profile in Fig. 5, cannot be fully explained by any of the above-mentioned models alone. A combination of dynamic melting and cyclic fractionation, however, may explain most of the trends in the volcanic sequence, because the melting zone is able to deliver melts with different elemental ratios and concentrations to a magma chamber on a higher level.

Conclusions

The volcanic and sedimentary rocks on Storøya, representing the assumed highest stratigraphical level of the Leka Ophiolite Complex, probably formed in a marginal basin.

The vesicle content of the volcanics reflects extrusion at a water depth in excess of 600 m. A higher number of extrusions in the lower than the upper part of the sequence is indicated by the distribution of intercalated sedimentary horizons. The field patterns of the altered rocks indicate that the pathways of the circulating solutions have changed during the deposition of the intervolcanic sedimentary layers. This demonstrates that the alteration is the result of early, oceanic hydrothermal activity.

The Storøya volcanics have suffered lower greenschist facies metamorphism, which, combined with the extensive hydrothermal alteration, has changed the original geochemistry considerably. Only TiO$_2$, Cr, Zr, Y, Nb...
Volcanic sequence on Storøya, Leka Ophiolite Complex

and Nd, seem to be stable enough to be used as petroge-
netic indicators. The Storøya volcanics are enriched in incompatible
trace elements but have large elemental variations. Dis-
"crimination diagrams indicate alkaline ocean island
basalts, although some are typically T- to E-MORB. The
metasedimentary sequence on top of the volcanics has the
same geochemical affinities as the volcanics.
The large variations in Y (17–72 ppm), Zr (89–
757 ppm) and Nb (9–72 ppm) may to some extent be
explained by dynamic melting. However, some of the
geochemical variations in the sequence seem to be ex-
plained best as a result of magma chamber processes.
Investigations have shown that the large variations
cannot be the result of simple fractionation alone. On
the other hand, an open system model may explain
many of the large element variations in the se-
quency. Such a model can also explain trends where
both compatible and incompatible trace elements show
enrichment, or trends where different incompatible ele-
ments indicate resetting and fractionation at the same
time.

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