

Seawater alteration of the Karmøy Ophiolite Complex, SW Norway: Nd and Sr isotopic evidence

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Sm–Nd and Rb–Sr isotopic data are presented for two magmatic components of the Karmøy Ophiolite Complex, SW Norway. The 493 Ma old Visnes High Level Complex has initial $\epsilon_{Nd} = +6.6$, suggesting a primitive island arc setting. The slightly older East Karmøy Layered Series has initial $\epsilon_{Nd} = +4.3$, indicating a more mature island arc setting. Initial $^{87}Sr/^{86}Sr$ ratios indicate seawater alteration of the Visnes High Level Complex, particularly the upper crustal members, but no detectable interaction of seawater with the East Karmøy Layered Series. Published data reveal that ophiolitic igneous rocks have typically exchanged more of their Sr with seawater than have young MOR-generated oceanic crust. The difference is ascribed to greater circulation of hydrothermal fluids in the subduction-related environments in which many ophiolites formed.

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Several studies have demonstrated the usefulness of Nd and Sr isotopic analysis in the determination of age, mantle source type and seawater alteration of oceanic crust obducted to form ophiolites (Jacobsen & Wasserburg 1979; McCulloch et al. 1980; McCulloch & Cameron 1983; Claesson et al. 1984; Edwards & Wasserburg 1985; Rautenschlein et al. 1985; Jahn 1986). Magmas presently being generated at oceanic ridges, back-arc spreading centres, island arcs and within-plate oceanic islands display different, though overlapping, ranges of Nd isotope ratios. Initial Nd isotope ratios of Phanerozoic ophiolites may be compared with ratios expected for each of these different tectonic settings and used to help constrain the nature of Phanerozoic oceanic crust (for example the Palaeozoic Iapetus ocean). Whole-rock Sm–Nd systems in ophiolites are usually little affected by hydrothermal alteration, seafloor metamorphism and subsequent metamorphic events, all of which may disturb Rb–Sr systems. Hydrothermal alteration by seawater has been identified as a cause of major Sr isotopic variation in ophiolitic rocks, especially the upper crustal, basaltic components (McCulloch et al. 1980). It is only in combination with analysis of the much less mobile Sm and Nd that such secondary effects can confidently be distinguished from primary, magmatic variations.

Numerous fragments of ophiolitic rocks have been identified in the Scandinavian Caledonides of Norway (Furnes et al. 1980a; Sturt et al. 1984). Like those of North America, such as the Bay of Islands ophiolite, Newfoundland, these fragments are generally believed to be remnants of the Lower Palaeozoic Iapetus oceanic crust. Due to their post-obduction deformation and metamorphism in the Caledonian orogeny, the Norwegian ophiolites are relatively poorly preserved. The Karmøy Ophiolite Complex of southwest Norway is one of the best preserved and most complete examples (Sturt et al. 1980) and was for this reason selected for the present study.

An assessment of whether an ophiolite complex represents MORB-type or supra-subduction zone (SSZ)-type magmatism (Pearce et al. 1984) is important for understanding the full significance of ophiolites. The oldest ophiolite complexes in the Scandinavian Caledonides so far dated by the U–Pb zircon method (i.e. Karmøy, Gulfjellet, Leka) yield Lower Ordovician ages (Dunning & Pedersen 1988) and all show geological and geochemical SSZ-type affinities (Furnes et al. 1988; Pedersen et al. 1988). The Karmøy Ophiolite Complex, briefly described below, is geochemically characterized by a transitional N–MORB to IAT trace element pattern for the oldest meta-

basalts. In the younger metabasalts the trace element patterns gradually change to those of typical IAT and boninites and finally become similar to that of E-MORB.

Isotope studies of modern MORB and island arc basalts have shown that the ϵ_{Nd} values of the former may be significantly higher than those of the latter, about +7 to +13 and +8 to -9 respectively (Faure 1986). The purposes of this study are: (1) to test whether Nd isotope data support the geological and geochemical conclusion that the oldest component of the Karmøy Ophiolite Complex represents magmatic activity related to the early stage in an arc-related environment, rather than representing typical MORB, and (2) on the basis of Sr isotopes make an estimate of the extent of seawater alteration of samples from various pseudostratigraphic levels of the ophiolite.

Geology and geochronology

The Karmøy Ophiolite Complex lies in tectonic contact with basement gneisses (Fig. 1) and consist of a number of magmatically different components. Mapping, combined with geochemical and geochronological (U-Pb zircon) investigations, suggest that the evolution of the Karmøy Ophiolite Complex occurred within an Ordovician oceanic, island arc environment with a lifespan of between 11 and 35 Ma (Pedersen 1982; Dunning & Pedersen 1988; Pedersen et al. 1988), and may be summarized as follows:

(a) The oldest axial sequence comprises layered gabbros and ultramafites, isotropic gabbros and plagiogranites, sheeted dykes and pillow lavas. Metabasalts from this sequence have N-MORB geochemistry, but with high Th/Ta ratios indicative of a subduction-related origin. The plutonic suite of the axis sequence has been subdivided on the basis of intrusive relationships into the East Karmøy Layered Series and the apparently younger Veavaagen Layered Series and Visnes High Level Complex. Plagiogranites from the Visnes High Level Complex, whose field occurrence and geochemical composition indicate a comagmatic relationship with the mafic rocks (Pedersen & Malpas 1985), have been dated to 493^{+7}_{-3} Ma (Dunning & Pedersen 1988).

(b) The oldest axial sequence is cut by medium to coarse grained diorites related to active island

arc magmatism. One of these bodies has been dated 485 ± 2 Ma (Dunning & Pedersen 1988).

(c) The above-mentioned diorites and the oldest axial sequence are cut by a number of dyke swarms, representing a second axial sequence. These metabasalts are characterized by low concentrations of incompatible elements and are geochemically most similar to boninites. Associated acid intrusions can be modelled in terms of fractional crystallization from boninitic parental magmas.

(d) The latest plutonic phase of the Karmøy Ophiolite Complex is represented by cpx-phyrlic gabbros for which the best-fit zircon and sphene discordia gives a U-Pb upper intercept age of 470^{+2}_{-3} Ma (Dunning & Pedersen 1988). Microgabbro from the chilled margin of the largest intrusion shows a low content of incompatible trace elements and a high Th/Ta ratio, characteristic of magmas produced in an island arc environment.

(e) Metabasaltic dykes and extrusives which are geochemically of E-MORB or OIB character represent the latest documented magmatic evolution of the Karmøy Ophiolite Complex.

Samples and analytical methods

Analysed samples include both whole-rock samples and mineral separates from the 493 Ma old Visnes High Level Complex and the probably slightly older East Karmøy Layered Series. The Visnes High Level Complex is represented by a metabasaltic dyke (K53), two metagabbros (J22 and MF) and a plagiogranite (KT1). In addition, the relatively fresh felsic mineral assemblage of KT1 (plagioclase, quartz and trace zircon) was analysed separately for Sm and Nd. The East Karmøy Layered Series is represented by a hornblende-gabbro (MGH), hornblende separated from MGH and from two hornblende-gabbro pegmatites (KP1 and PGH), and also the combined felsic minerals of PGH (apatite, quartz and plagioclase which is partly altered to albite and clinozoisite).

Details of the analytical techniques used at University College Dublin have been published elsewhere (Menuge 1988). For whole-rock samples, $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were determined from unspiked dissolutions, and Sm and Nd concentrations from separate spiked dissolutions. For mineral separates, a spiked and an unspiked ali-

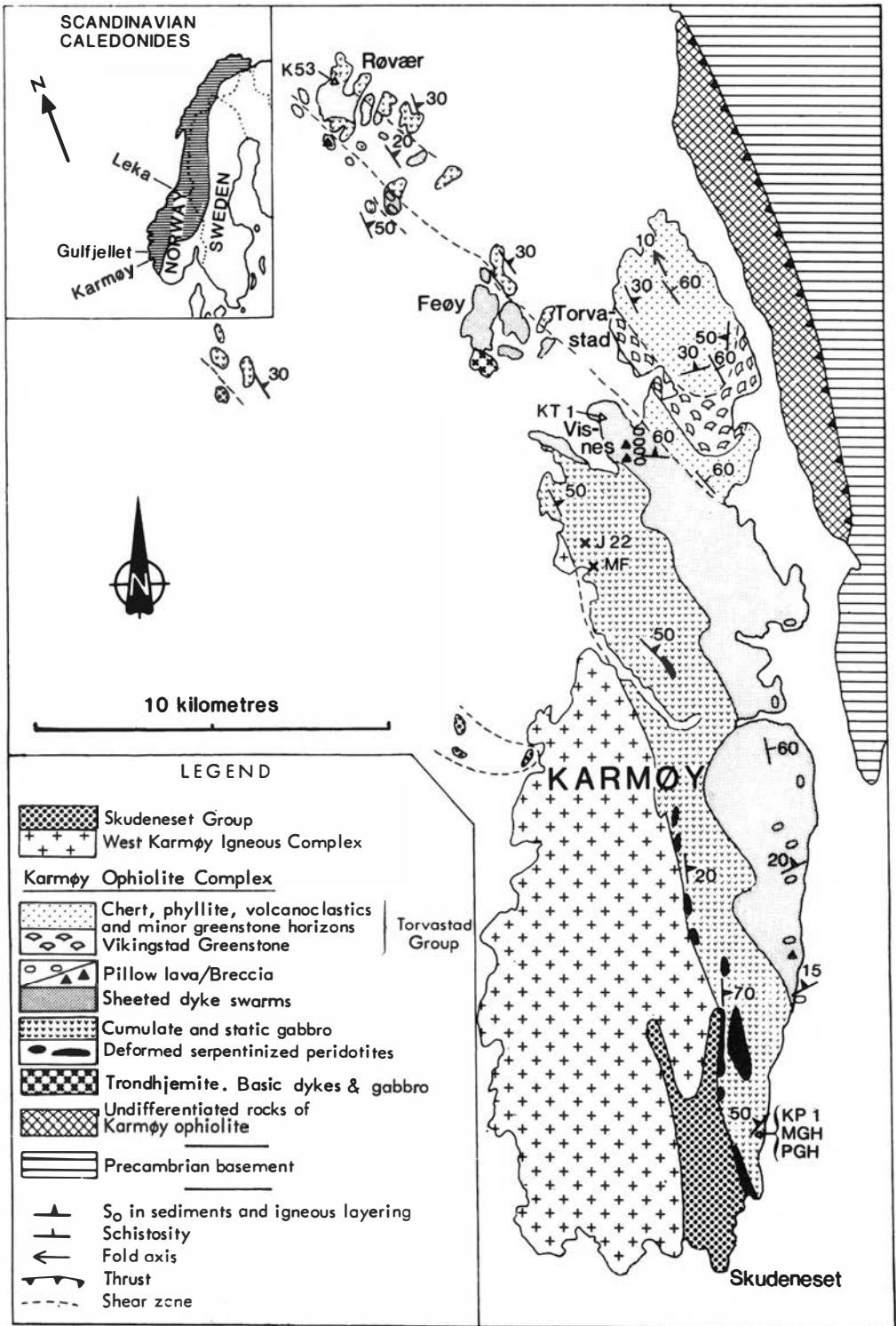


Fig. 1. Geological map of the Karmøy Ophiolite Complex, showing sample localities.

Table 1. Sm–Nd isotopic data.

Sample	$^{143}\text{Nd}/^{144}\text{Nd}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$\mathcal{E}_{\text{Nd}}(T)$
Visnes High Level Complex					
KT1	0.512938 ± 14	14.73	46.50	0.1916	$+6.2 \pm 0.4$
KT1 fel	0.512969 ± 17	1.730	5.413	0.1932	$+6.7 \pm 0.5$
K53	0.513044 ± 15	4.132	11.74	0.2127	$+6.9 \pm 0.4$
J22	0.513331 ± 24	0.851	1.698	0.3030	$+6.8 \pm 0.7$
MF	0.513360 ± 13	1.005	1.889	0.3217	$+6.2 \pm 0.5$
	0.513364 ± 42				
	0.513364 ± 26				
	0.513298 ± 28				
East Karmøy Layered Series					
KP1	0.513218 ± 14	2.681	5.338	0.3037	$+4.6 \pm 0.5$
	0.513211 ± 35	2.717	5.395	0.3045	
MGH	0.513090 ± 16	6.617	14.97	0.2672	$+4.4 \pm 0.5$
MGH hbl	0.513138 ± 26	7.222	15.38	0.2839	$+4.3 \pm 0.7$
PGH hbl	0.513054 ± 15	7.963	18.17	0.2649	$+3.8 \pm 0.5$
PGH fel	0.512640 ± 29	0.289	1.367	0.1278	$+4.4 \pm 0.7$

$^{143}\text{Nd}/^{144}\text{Nd}$ ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The mean value obtained for BCR-1 was 0.512727 (Menuge 1988); this high value is consistent with measurements on other standards of widely differing $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios reported here have been standardized to a value of 0.512640 for BCR-1. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios have been standardized using the mixed normal Sm/Nd solution of Wasserburg et al. (1981). $2\sigma_m$ errors in $^{147}\text{Sm}/^{144}\text{Nd}$ are $\pm 1\%$. Within-run $2\sigma_m$ errors in $^{143}\text{Nd}/^{144}\text{Nd}$ are as shown in the table; for isochron and $\mathcal{E}_{\text{Nd}}(T)$ calculations, reproducibility is taken to be the greater of 0.00002 or the within-run precision. $\mathcal{E}_{\text{Nd}}(T)$ values have been calculated for $T = 493$ Ma using present-day chondritic ratios of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1966$ (renormalized from Jacobsen & Wasserburg 1980).

quot of the same dissolution were used. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, Rb and Sr concentrations were determined from a single dissolution for all samples. Maximum blank levels were approximately 0.25 ng Rb, 1.0 ng Sr and 0.5 ng Nd. Further analytical information is given in Tables 1 and 2.

Results

Sm–Nd isotopic data (Table 1) are plotted on an isochron diagram in Fig. 2, in which the Visnes High Level Complex samples are distinguished from the East Karmøy Layered Series samples.

Table 2. Rb–Sr isotopic data.

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_T$
Visnes High Level Complex					
KT1	0.70622 ± 3	1.353	218.55	0.0179	0.70609 ± 7
K53	0.70667 ± 3	1.165	169.52	0.0199	0.70653 ± 7
	0.70669 ± 5				
J22	0.70444 ± 7	1.800	82.991	0.0627	0.70400 ± 8
MF	0.70542 ± 4	5.284	135.56	0.1128	0.70463 ± 9
East Karmøy Layered Series					
KP1	0.70410 ± 7	1.351	19.235	0.2031	0.70267 ± 10
MGH	0.70459 ± 4	2.393	26.561	0.2606	0.70276 ± 11
	0.70459 ± 9	2.372	26.663	0.2573	0.70278 ± 13
MGH hbl	0.70438 ± 9	1.595	7.2799	0.6336	0.69993 ± 18
PGH hbl	0.70447 ± 9	1.417	17.118	0.2394	0.70279 ± 12
PGH fel	0.70352 ± 6	0.423	127.24	0.0096	0.70345 ± 7

Measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have been normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio obtained for NBS SRM-987 was 0.71038 and the data have been standardized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71019$ for NBS SRM-987. $2\sigma_m$ errors for $^{87}\text{Rb}/^{86}\text{Sr}$ ratios are $\pm 2\%$. Within-run $2\sigma_m$ errors for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are as indicated in table; for calculation of $(^{87}\text{Sr}/^{86}\text{Sr})_T$ ratios, reproducibility of measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is taken to be 0.00007 or the within-run precision, whichever is the greater, and $T = 493$ Ma is used in all cases.

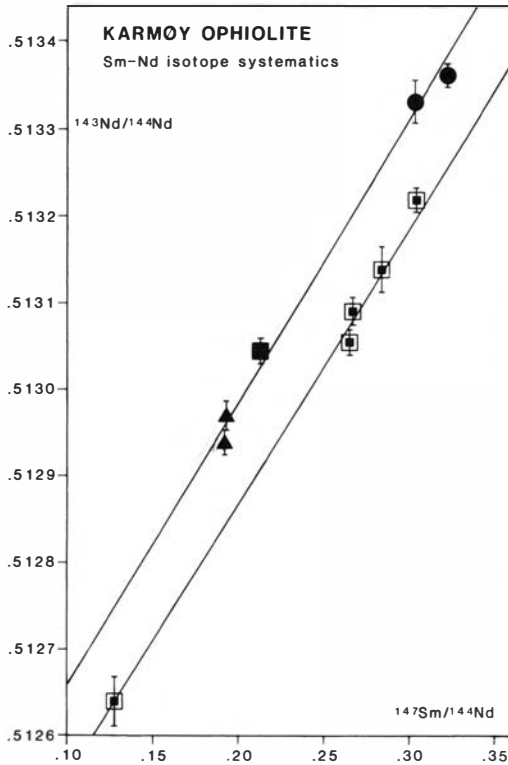


Fig. 2. Sm-Nd isochron diagram. 493 Ma reference lines from the U-Pb zircon dating of Dunning & Pedersen (1988). Solid symbols = Visnes High Level Complex; solid circles = pyroxene gabbro; solid squares = metabasalt sheeted dyke; solid triangles = trondhjemite and trondhjemite mineral separate; open squares = East Karmøy Layered Series samples.

If the East Karmøy Layered Series data are regressed as an isochron (York 1969; Fletcher & Rosman 1982), they yield $T = 497 \pm 49$ Ma, $\mathcal{E}_{Nd}(T) = +4.2 \pm 0.7$ and $MSWD = 2.72$. The Visnes High Level Complex data yield $T = 486 \pm 50$ Ma, $\mathcal{E}_{Nd}(T) = +6.6 \pm 0.7$ and $MSW = 3.88$. Both groups define errorchrons ($MSWD > 2.5$) and the calculated ages and initial ratios should be interpreted with caution. In Fig. 2 the data are therefore shown relative to two reference lines of slope corresponding to the U-Pb zircon age of 493 Ma. The Visnes High Level Complex Sm-Nd data are consistent with the U-Pb zircon age. In the case of the East Karmøy Layered Series, for which no previous isotopic dating is available, the data reinforce the view that the age of these rocks is not substantially greater than that of the Visnes High Level Complex. The different initial ratios of the two groups

require either different time-integrated Sm/Nd ratios or different times of depletion in Nd relative to Sm of their mantle source regions.

Within each group, initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios vary only slightly in excess of analytical errors. It is not clear whether this variation represents initial differences or is due to later open system behaviour. For the Visnes High Level Complex, the mean value of +6.6 is taken as the best estimate of the initial ratio of the Visnes High Level Complex and of its mantle source. The age of the East Karmøy Layered Series is not precisely known and an age of 493 Ma will be assumed for the calculation of initial ratios; even if an age of 550 Ma were assumed the difference in initial ratios would be small (comparable to the analytical uncertainties). All the samples have lower apparent initial ratios than those of the Visnes High Level Complex. The mean value of +4.3 is taken as the best estimate of the initial ratio of the East Karmøy Layered Series.

Rb-Sr isotopic data are given in Table 2. On an isochron plot (not shown) these data scatter and provide no meaningful age information. This scatter contrasts with the small deviations from Sm-Nd isochrons. Fig. 3 shows initial \mathcal{E}_{Nd} plotted against initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for all data compared to the likely isotopic composition field of Lower Ordovician sub-oceanic mantle. The Visnes High Level Complex samples have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7040–0.7065. If $\mathcal{E}_{Nd}(493) = +6.6$ is assumed for the mantle source of these rocks, the expected initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would be in the range 0.7025–0.7037, lower than that of all the samples. One possible explanation is that these rocks lost Rb at some time significantly after their formation 493 Ma ago, perhaps at the time of obduction. However, in this case Rb concentrations before loss of Rb would have to have been several hundred times their present levels in samples KT1 and K53. In view of their presumed submarine formation, it is considered more likely that instead the rocks exchanged Sr with seawater. Lower Ordovician seawater had a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of about 0.7090 (Burke et al. 1982), and could therefore cause the observed shifts to higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in these samples. Interaction with seawater is expected to have no effect on $\mathcal{E}_{Nd}(493)$ values because of the very low Nd concentration of seawater.

Analysis of modern oceanic basalts has shown that the overall result of seawater alteration is an increase in their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios but no major

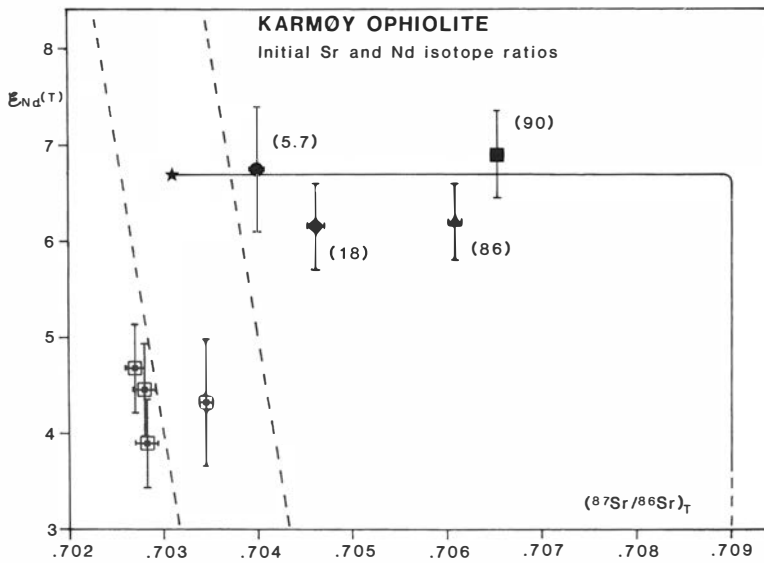


Fig. 3. Initial ϵ_{Nd} and initial $^{87}Sr/^{86}Sr$ ratios of Karmøy Ophiolite Complex samples, $T = 493$ Ma. Symbols as in Fig. 2. Solid line is a mixing curve between depleted mantle-derived magma (star) and Iapetus seawater (see text for details). Numbers in parentheses are minimum volumetric water/rock ratios required to account for the calculated initial $^{87}Sr/^{86}Sr$ ratios of the samples. Dashed lines indicate the likely field of Lower Ordovician mantle-derived magmas.

change in total Sr concentration (e.g. Briquet & Lancelot 1983). However, in detail the process is more complex; experimental data and theoretical constraints led Berndt et al. (1988) to suggest that early seawater alteration at low temperature enriches oceanic crust in Sr and is followed by Sr depletion at higher temperature. Since the reaction path in terms of Sr concentration and $^{87}Sr/^{86}Sr$ ratio cannot be constrained in the present case, water/rock (W/R) ratios can only be determined approximately. W/R ratios required to cause the observed shifts in initial $^{87}Sr/^{86}Sr$ ratio have been calculated by assuming 100% exchange of seawater Sr with no net gain or loss of Sr by the samples. As it is unlikely that 100% exchange occurred this procedure provides a minimum estimate of W/R ratios. 493 Ma old Iapetus seawater is taken to have the following properties: $^{87}Sr/^{86}Sr = 0.7090$ (Burke et al. 1982), $Sr = 7.9$ ppm (Holland 1978), $\epsilon_{Nd} = -5$ (Shaw & Wasserburg 1985) and $Nd = 2.7 \times 10^{-6}$ ppm (Piepgras & Wasserburg 1980). For the mantle source of the Visnes High Level Complex, $\epsilon_{Nd} = +6.6$ and $^{87}Sr/^{86}Sr = 0.7031$ are assumed. The minimum W/R ratios required to generate the observed Sr isotopic ratios have been calculated using the measured Sr concentrations of the samples. The calculated volumetric W/R ratios, assuming a specific gravity of 3 for all samples, are indicated in Fig. 3. The two gabbros have relatively low W/R ratios of 5.7 and 18, whilst the metabasalt and trondhjemite have higher ratios of

90 and 86, respectively. This large variation in W/R ratio is consistent with greater volumes of seawater circulating at shallower depths within the oceanic crust. The Nd isotope ratios and Nd concentrations of the samples were not affected because of the very low concentration of Nd in seawater.

A quite different explanation is required for the East Karmøy Layered Series samples. Firstly, the hornblende separate of gabbro MGH has an improbable $^{87}Sr/^{86}Sr$ ratio of 0.69993 ± 18 , indicating disturbance of its Rb–Sr system. Secondly, the hornblende and felsic mineral fractions of gabbro pegmatite PGH have distinctly different initial $^{87}Sr/^{86}Sr$ ratios of 0.70279 ± 12 and 0.70345 ± 7 respectively, also indicating disturbance. As already noted, the $\epsilon_{Nd}(493)$ values of the five samples show little variation. With the exception of the hornblende separate of MGH, all the samples lie within or slightly to the left of the expected mantle array. There is no evidence for any seawater interaction, despite the fact that four of the samples have <30 ppm Sr and would therefore be sensitive to alteration. However, on the scale of individual crystals (1–10 mm) there has been significant mobility of Rb and/or Sr, the cause and timing of which remains unknown. In spite of this evidence for open system behaviour, three of the five samples have indistinguishable initial $^{87}Sr/^{86}Sr$ ratios with a mean value of 0.70274, which may be the approximate initial ratio of the East Karmøy Layered Series rocks.

Discussion

On the basis of trace element analysis of sheeted dykes and pillow basalts, Furnes et al. (1980b) concluded that the Visnes High Level Complex was derived from a mantle source depleted in incompatible elements. Subsequently this conclusion has been refined and these rocks are now thought to represent early SSZ-type magmatism. The Nd isotopic data presented here are consistent with this hypothesis and substantially strengthen it because Nd isotope ratios are independent of closed-system fractionation processes operating at the time of magmatism. The data may be compared with those published for other ophiolites (Table 3), in particular the Bay of Islands ophiolite of Newfoundland, which is of similar age (Jacobsen & Wasserburg 1979). The range of $\epsilon_{Nd}(493)$ for the Visnes High Level Complex overlaps but is lower than the range for the Bay of Islands ophiolite. Assuming approximately linear evolution of ϵ_{Nd} in the depleted mantle over the past 4 Ga, ϵ_{Nd} values 500 Ma ago would have been 10–15% lower than at the present day. Whilst the Bay of Islands value is within the range expected for 500 Ma old rocks of mid-oceanic ridge or back-arc origin, the somewhat lower value for the Visnes High Level Complex is more consistent with an island arc environment, particularly a primitive arc (Table 3).

The initial $^{87}Sr/^{86}Sr$ ratios of the Visnes High Level Complex samples (0.7040–0.7065), which were raised by exchange with seawater Sr, follow a similar pattern to that seen in other ophiolites.

McCulloch et al. (1980) noted higher initial $^{87}Sr/^{86}Sr$ ratios in pillow basalts and sheeted dykes than in gabbros in the Cretaceous Samail ophiolite. Similar variations in $^{87}Sr/^{86}Sr$ occur in the Bay of Islands ophiolite (Jacobsen & Wasserburg 1979) and in the 15 Ma old East Taiwan ophiolite (Chou et al. 1978; Jahn 1986). Hydrothermal exchange of Sr appears to be generally far more effective at higher levels in the oceanic crust. This is presumably due to greater permeability and proximity to seawater; at deeper levels, permeability is lower and penetrating seawater will have a lowered $^{87}Sr/^{86}Sr$ ratio due to Sr exchange at higher crustal levels. One notable point is that because the $^{87}Sr/^{86}Sr$ ratio of seawater has varied over geological time, the average $^{87}Sr/^{86}Sr$ ratio of altered oceanic crust would be expected to vary according to the time when hydrothermal alteration occurred, which would normally be at, or very soon after, the time of eruption. The seawater $^{87}Sr/^{86}Sr$ ratio has varied between 0.7068 and 0.7091 over Phanerozoic time (Burke et al. 1982), compared to a relatively slight estimated increase in the mean $^{87}Sr/^{86}Sr$ ratio of the MORB source of about 0.0005 over the same period.

It is difficult to estimate the mean $^{87}Sr/^{86}Sr$ ratios of ophiolites because sampling for isotopic work is normally biased towards the least altered rocks, but the highest ratios reported from the Karmøy, Bay of Islands, Samail, Troodos and East Taiwan ophiolites all indicate that about half the Sr present is seawater-derived. If these results are typical, seawater Sr represents a substantial proportion of the Sr in the upper oceanic crust of

Table 3. Initial ϵ_{Nd} of ophiolites and modern oceanic basalts.

	Age (Ma)	ϵ_{Nd} (T)	Reference
Modern MOR basalts	0	+7.0 – +13.0	White & Hoffman (1982); Faure (1986)
Modern island arc basalts	0	–9.0 – +8.0	Faure (1986)
Modern back-arc basalts	0	+7.5 – +9.0	Hawkesworth et al. (1977); Cohen & O'Nions (1982)
East Taiwan Ophiolite	15	+8.5 – +13.3	Jahn (1986)
Troodos Ophiolite	80	+6.2 – +7.3	Rautenschlein et al. (1985)
Troodos Ophiolite	85	+0.8 – +7.9	McCulloch & Cameron (1983)
Samail Ophiolite	130	+7.5 – +8.6	McCulloch et al. (1980)
Ural Ophiolites	397	+7.3 – +9.0	Edwards & Wasserburg (1985)
Karmøy Ophiolite:	493	+6.2 – +6.9	this paper
Visnes High Level Complex			
Karmøy Ophiolite:	493	+3.8 – +4.6	this paper
East Karmøy Layered Series			
Bay of Islands Ophiolite	505	+6.5 – +8.1	Jacobsen & Wasserburg (1979)

$\epsilon_{Nd}(T)$ values have been calculated using present-day chondritic ratios of $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1966$ (renormalized from Jacobsen & Wasserburg 1980) and arc relative to $\epsilon_{Nd}(0) = 0.0$ for BCR-1.

these ophiolites. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of core samples from present day oceanic crust indicate a much lower degree of alteration however; Kawahata et al. (1987) estimated an average seawater component of only 17% in 6 Ma old pillow basalts and sheeted dykes from DSDP Hole 504B, Costa Rica Rift. Analysis of interstitial waters from young oceanic crust also suggests relatively little increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio due to hydrothermal alteration (Hawkesworth & Elderfield 1978).

The amount of Sr of seawater origin in typical oceanic crust is important because of the constraint which it places on the contribution to subduction-related magmas from the subducted slab. The elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratio without reduced $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of altered oceanic basaltic crust is one criterion by which it might be discriminated from the overlying mantle wedge. A summary of combined Sr and Nd isotope analyses of arc basalts reveals little evidence for a component with these characteristics (Ellam & Hawkesworth 1988). If ophiolites are representative of the degree of seawater Sr present in typical oceanic crust then partial melts or other fluids derived from the subducted slab cannot be more than a minor component of arc volcanics. However, a more likely alternative situation is that ophiolites are not representative, since most have been interpreted as being partly or totally of island arc origin. Sr isotope data from the deep crustal levels of a 400 Ma old intra-oceanic island arc in northern California indicate a proportion of seawater Sr as high as in ophiolites (Brouxel et al. 1987), suggesting that much greater hydrothermal exchange of Sr with seawater occurs in island arcs than in MORBs. The lower proportions measured in young MORBs and inferred from their interstitial waters are probably more representative of subducted ocean crust. If so then the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of subduction-related magmas provide little constraint on the proportion of slab-derived material involved in their formation because of the relatively small difference in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between altered and unaltered MORB.

The hornblende-bearing samples from the East Karmøy Layered Series have initial \mathcal{E}_{Nd} values around +4.3, about 2‰ units lower than the rocks of the Visnes High Level Complex, and probable initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of ca. 0.7027. These results are consistent with an island arc origin and both MOR and back-arc environments are unlikely. Overall, the initial Nd isotope ratios and trace element geochemistry of the two groups of the

axial sequence are comparable to those of the Cretaceous Troodos ophiolite of Cyprus, for which a primitive subduction-related environment has also been proposed (McCulloch & Cameron 1983; Rautenschlein et al. 1985). The change from lower initial \mathcal{E}_{Nd} in the East Karmøy Layered Series to higher values in the slightly younger Visnes High Level Complex, suggesting a change from mature to primitive island arc setting, was perhaps caused by a change in the site of subduction.

Summary

Sm-Nd isotopic data are consistent with the published zircon U-Pb date of 493 ± 7 Ma for the Visnes High Level Complex. A Sm-Nd errorchron age of 497 ± 49 Ma for the East Karmøy Layered Series supports the view that this unit is only slightly older than the Visnes High Level Complex. Both groups of samples analysed have a depleted mantle Nd isotopic signature, but they are distinctly different from each other. The Visnes High Level Complex has mean $\mathcal{E}_{\text{Nd}}(493) = +6.6$, consistent with a primitive SSZ-type environment, whilst the East Karmøy Layered Series has mean $\mathcal{E}_{\text{Nd}}(493) = +4.3$, indicating a more mature SSZ-type setting. These conclusions are consistent with arguments based on geological and geochemical data. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Visnes High Level Complex samples vary in a fashion consistent with seawater alteration; the upper crustal rocks suffered much greater exchange of Sr with seawater than the lower crustal rocks. The Rb-Sr systems of some East Karmøy Layered Series primary minerals have been disturbed but none of the samples suffered significant alteration of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio by interaction with seawater. A review of published data indicates that the basaltic layers of ophiolites have suffered considerably greater seawater alteration than modern MOR-generated basaltic crust. This difference is probably due to more extensive hydrothermal circulation in SSZ-generated crust, from which most analysed ophiolites were derived.

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References

- Berndt, M. E., Seyfried, W. E., Jr. & Beck, J. W. 1988: Hydrothermal alteration processes at midocean ridges: experimental and theoretical constraints from Ca and Sr exchange reactions and Sr isotopic ratios. *Journal of Geophysical Research* 93, 4573–4583.
- Briqueu, L. & Lancelot, J. R. 1983: Sr isotopes and K, Rb, Sr balance in sediments and igneous rocks from the subducted plate of the Vanuatu (New Hebrides) active margin. *Geochimica et Cosmochimica Acta* 47, 191–200.
- Brouxel, M., Lapierre, H., Michard, A. & Albarede, F. 1987: The deep layers of a Paleozoic arc: geochemistry of the Copley-Balaklala Series, northern California. *Earth and Planetary Science Letters* 85, 386–400.
- Burke, W. M., Denison, R. E., Hetherington, E. A., Koepnick, R. B., Nelson, M. F. & Omo, J. B. 1982: Variation of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ throughout Phanerozoic time. *Geology* 10, 516–519.
- Chou, C. L., Lo, H. J., Chen, J. H. & Juan, V. C. 1978: Rare earth element and isotopic geochemistry of Kuanshan igneous complex, Taiwan. *Proceedings of the Geological Society of China* 21, 13–24.
- Claesson, S., Pallister, J. S. & Tatsumoto, M. 1984: Samarium-neodymium data on two late Proterozoic ophiolites of Saudi Arabia and implications for crustal and mantle evolution. *Contributions to Mineralogy and Petrology* 85, 244–252.
- Cohen, R. S. & O'Nions, R. K. 1982: Identification of recycled continental material in the mantle from Sr, Nd and Pb isotope investigations. *Earth and Planetary Science Letters* 61, 73–84.
- Dunning, G. R. & Pedersen, R. B. 1988: U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: Implications for the development of Iapetus. *Contributions to Mineralogy and Petrology* 98, 13–23.
- Edwards, R. L. & Wasserburg, G. J. 1985: The age and emplacement of obducted oceanic crust in the Urals from Sm–Nd and Rb–Sr systematics. *Earth and Planetary Science Letters* 72, 389–404.
- Ellam, R. M. & Hawkesworth, C. J. 1988: Elemental and isotopic variations in subduction related basalts: evidence for a three component model. *Contributions to Mineralogy and Petrology* 98, 72–80.
- Faure, G. 1986: *Principles of Isotope Geology (2nd edition)*, 589 pp. John Wiley & Sons, New York.
- Fletcher, I. R. & Rosman, K. J. R. 1982: Precise determination of initial ϵ_{Nd} from Sm–Nd isochron data. *Geochimica et Cosmochimica Acta* 46, 1983–1987.
- Furnes, H., Roberts, D., Sturt, B. A., Thon, A. & Gale, G. H. 1980a: Ophiolite fragments in the Scandinavian Caledonides. *Proceedings of the International Ophiolite Symposium, Cyprus, 1979, Cyprus Geological Survey Department*, 582–600.
- Furnes, H., Sturt, B. A. & Griffin, W. L. 1980b: Trace element geochemistry of metabasalts from the Karmøy ophiolite, southwest Norwegian Caledonides. *Earth and Planetary Science Letters* 50, 75–91.
- Furnes, H., Pedersen, R. B. & Stillman, C. J. 1988: The Leka Ophiolite Complex, central Norwegian Caledonides: field characteristics and geotectonic significance. *Journal of the Geological Society of London* 145, 401–412.
- Hawkesworth, C. J. & Elderfield, H. 1978: The strontium isotopic composition of interstitial waters from sites 245 and 336 of the deep sea drilling project. *Earth and Planetary Science Letters* 40, 423–432.
- Hawkesworth, C. J., O'Nions, R. K., Panhurst, R. J., Hamilton, P. J. & Evensen, N. M. 1977: A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea. *Earth and Planetary Science Letters* 36, 253–263.
- Holland, H. 1978: *The Chemistry of the Atmosphere and Oceans*, 351 pp. John Wiley, New York.
- Jacobsen, S. B. & Wasserburg, G. J. 1979: Nd and Sr isotopic study of the Bay of Islands Ophiolite Complex and the evolution of the source of midocean ridge basalts. *Journal of Geophysical Research* 84, 7429–7445.
- Jacobsen, S. B. & Wasserburg, G. J. 1980: Sm–Nd isotopic evolution of chondrites. *Earth and Planetary Science Letters* 50, 139–155.
- Jahn, B. 1986: Mid-ocean ridge or marginal basin origin of the East Taiwan Ophiolite: chemical and isotopic evidence. *Contributions to Mineralogy and Petrology* 92, 194–206.
- Kawahata, H., Kusakabe, M. & Kikuchi, Y. 1987: Strontium, oxygen, and hydrogen isotope geochemistry of hydrothermally altered and weathered rocks in DSDP Hole 504B, Costa Rica Rift. *Earth and Planetary Science Letters* 85, 343–355.
- McCulloch, M. T. & Cameron, W. E. 1983: Nd–Sr isotopic study of primitive lavas from the Troodos ophiolite, Cyprus: Evidence for a subduction-related setting. *Geology* 11, 727–731.
- McCulloch, M. T., Gregory, R. T., Wasserburg, G. J. & Taylor, H. P., Jr. 1980: A neodymium, strontium, and oxygen isotopic study of the Cretaceous Samail Ophiolite and implications for petrogenesis and seawater-hydrothermal alteration of oceanic crust. *Earth and Planetary Science Letters* 46, 201–211.
- Menuge, J. F. 1988: The petrogenesis of massif anorthosites: a Nd and Sr isotopic investigation of the Proterozoic of Rogaland/Vest-Agder, SW Norway. *Contributions to Mineralogy and Petrology* 98, 363–373.
- Pearce, J., Lippard, S. J. & Roberts, S. 1984: Characteristics and tectonic significance of supra-subduction zone ophiolites. In Kokelaar, B. P. & Howells, M. F. (eds.): *Marginal Basin Geology*, 77–94. Blackwell, Oxford.
- Pedersen, R. B. 1982: The Karmøy ophiolite plutonic suite. Cand. Real. thesis, University of Bergen.
- Pedersen, R. B. & Malpas, J. 1985: The origin of oceanic plagiogranites from the Karmøy ophiolite, Western Norway. *Contributions to Mineralogy and Petrology* 88, 36–52.
- Pedersen, R. B., Furnes, H. & Dunning, G. R. 1988: Some Norwegian ophiolite complexes reconsidered. *Norges geologiske undersøkelse, spec. publ.* 3, 80–85.
- Pieppgras, D. J. & Wasserburg, G. J. 1980: Neodymium isotopic variations in seawater. *Earth and Planetary Science Letters* 50, 128–138.
- Rautenschlein, M., Jenner, G. A., Hertogen, J., Hofmann, A. W., Kerrich, R., Schmincke, H.-U. & White, W. M. 1985: Isotopic and trace element compositions of volcanic glasses from the Akaki Canyon, Cyprus: implications for the origin of the Troodos ophiolite. *Earth and Planetary Science Letters* 75, 369–383.
- Shaw, H. F. & Wasserburg, G. J. 1985: Sm–Nd in marine carbonates and phosphates: Implications for Nd isotopes in seawater and crustal ages. *Geochimica et Cosmochimica Acta* 49, 503–518.
- Sturt, B. A., Thon, A. & Furnes, H. 1980: The geology and preliminary geochemistry of the Karmøy ophiolite, S.W. Norway. *Proceedings of the International Ophiolite Symposium, Cyprus, 1979, Cyprus Geological Survey Department*, 538–554.

- Sturt, B. A., Roberts, D. & Furnes, H. 1984: A conspectus of Scandinavian Caledonian ophiolites. In Gass, I. G., Lippard, S. J. & Shelton, A. W. (eds.): *Ophiolites and Oceanic Lithosphere*, 381–391. Blackwell, Oxford.
- Wasserburg, G. J., Jacobsen, S. B., DePaolo, D. J., McCulloch, M. T. & Wen, T. 1981: Precise determination of Sm/Nd ratios, Sm and Nd isotopic abundances in standard solutions. *Geochimica et Cosmochimica Acta* 45, 2311–2324.
- White, W. M. & Hofmann, A. W. 1982: Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution. *Nature* 296, 821–825.
- York, D. 1969: Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters* 5, 320–324.