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Metadolerite geochronology and dolerite geochemistry from East Finnmark, northern Scandinavian Caledonides

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Abstract – Dolerite dykes in the East Finnmark Scandinavian Caledonides form three geochemical suites: Digermulhalvøya–Magerøya – WNW–ESE-trending, *c*. 337–332 Ma, possibly also *c*. 293 Ma, continental within-plate; East Varangerhalvøya – NE–SW and N–S, *c*. 376 Ma, continental plate-margin; Styret – NE–SW, also *c*. 376 Ma, chemically intermediate to the other two groups. New K–Ar data from metadolerites on Varangerhalvøya give a 7-point 'lower envelope' isochron of 577 ± 14 Ma (MSWD 1.04). This is concordant with a published upper intercept U–Pb zircon age (567^{+30}_{-23} Ma) from an East Varangerhalvøya dolerite, here re-interpreted to reflect Neoproterozoic basement fracturing contemporaneous with the emplacement of the metadolerites. Intrusion of the younger dolerites at *c*. 376 Ma reactivated this trend, and may be responsible for the published zircon lower intercept age of 392^{+25}_{-36} Ma. Clarification of the intrusion and structural chronology, integrated with extensive new geochemical data, enables a better understanding of the evolution of this part of the Scandinavian Caledonides.

Keywords: Caledonides, Scandinavia, geochronology, dolerite, geochemistry, Timan–Pechora region.

1. Introduction

Northeastern Norway (Fig. 1) contains the westernmost fragments of the WNW–ESE-trending Neoproterozoic–early Palaeozoic Timanian Basin. This has uncertain relationships to the NNE–SSW-oriented Iapetus Baltoscandian continental margin (cf. Nystuen & Siedlecka, 1988). The area may also lie across the boundary of the SW-directed deformation of the Neoproterozoic Timanian orogenic event and the SE-directed deformation of the early Palaeozoic Scandinavian Caledonides (Roberts & Siedlecka, 2002). Within this area, both dolerite and metadolerite dykes occur, although their composition and ages are not well constrained. In this paper, the geochemistry of rare dolerite dykes in the region is investigated and new K–Ar data from the more abundant metadolerites are discussed.

The IUGS timescale (IUGS, 2000) and the regional stratigraphy of Rice & Townsend (1996) are used. All K–Ar age data have been recalculated (Dalrymple, 1979).

2. Regional background

The Scandinavian Caledonides comprise nappes emplaced in two main events (cf. Harris & Fettes, 1988; Fig. 2). The Finnmarkian event (∼ 520–490 Ma) caused ∼SE-directed deformation at the edge of the Iapetus Baltoscandian continental margin, forming the Seve nappes and Middle Allochthon. The subsequent Scandian event (∼ 425–380 Ma) emplaced intra-Iapetus fragments (Köli nappes) over the Finnmarkian orogen. Scandian reactivation through the Finnmarkian belt was followed by imbrication of a basement high (Window Basement) and an external imbricate zone (Lower Allochthon). In Finnmark, northern Norway, the relevant units are the Magerøya Nappe (Köli nappes), the Kalak Nappe Complex (Seve nappes and Middle Allochthon), the Laksefjord Nappe (Middle Allochthon), the Komagfjord Antiformal Stack and Kunes Nappe (Window Basement) and the Gaissa Thrust Belt (Lower Allochthon; Andersen *et al*. 1982; Gayer *et al*. 1987; Rice, 2002; Fig. 1).

This picture is complicated by the development of the WNW–ESE-trending Neoproterozoic Timanian Basin along northern Baltica, broadly contemporary with earliest Iapetus rifting (∼ 800 Ma). Sedimentary rocks from this region lie in two zones (Fig. 1): a shelf zone, forming the Gaissa Thrust Belt and underlying Varanger Parautochthon/East Finnmark Autochthon, and a basinal zone, forming the North Varanger Region. Only the rocks in the former zone can be correlated with the Iapetus Baltoscandian margin sequence (cf. Nystuen & Siedlecka, 1988; Rice, 1994). The two zones are separated by the Trollfjorden–Komagelva Fault, a syn-Caledonian strike-slip fault (Rice *et al*. 1989*a*) with a displacement of less than 200–300 km (Torsvik, Roberts & Siedlecka, 1995).

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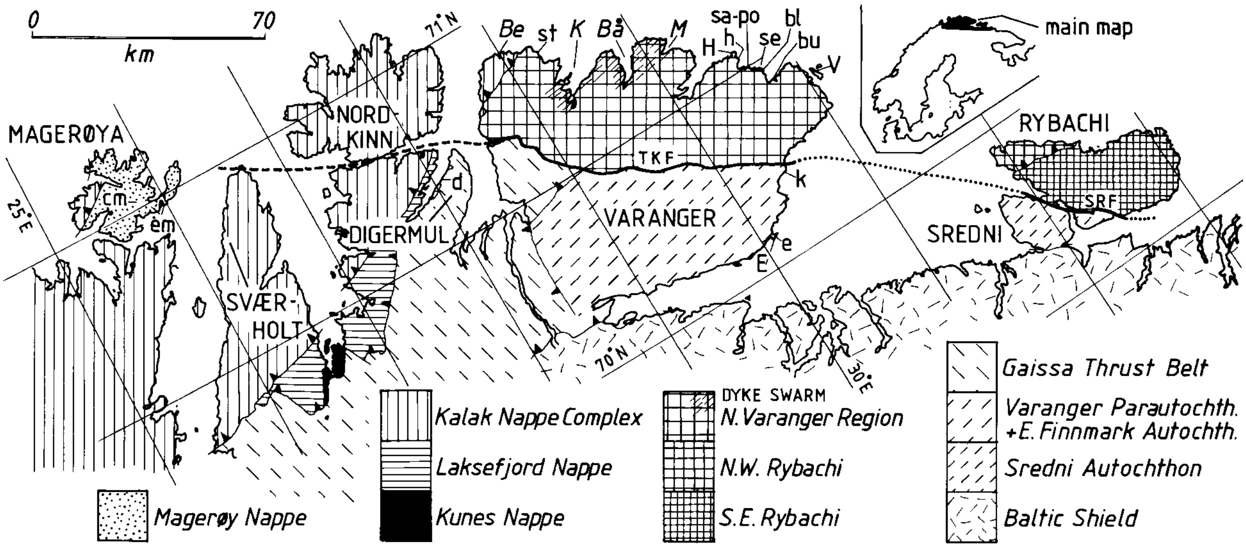

Figure 1. Geological map of the Magerøya–Varangerhalvøya–Rybachi/Sredni area. Areas of metadolerites: Ba – Båtsfjord; Be – Berlevåg; M – Makkaursandfjord; Inhabited places: E – Ekkerøya; H – Hamningberg; V – Vardø. Dolerite dyke localities: bl – Blåsenberg; bu – Bukkemoltagen; cm – central Magerøya; d – Digermulhalvøya; e – Ekkerøya; em – east Magerøya; h – Hamningberg; k – Komagnes; sa-po – Sandfjord–Per Olsadalen; se – Seglkollen; st – Styret. TKF – Trollfjorden–Komagelva Fault, SRF – Sredni–Rybachi Fault.

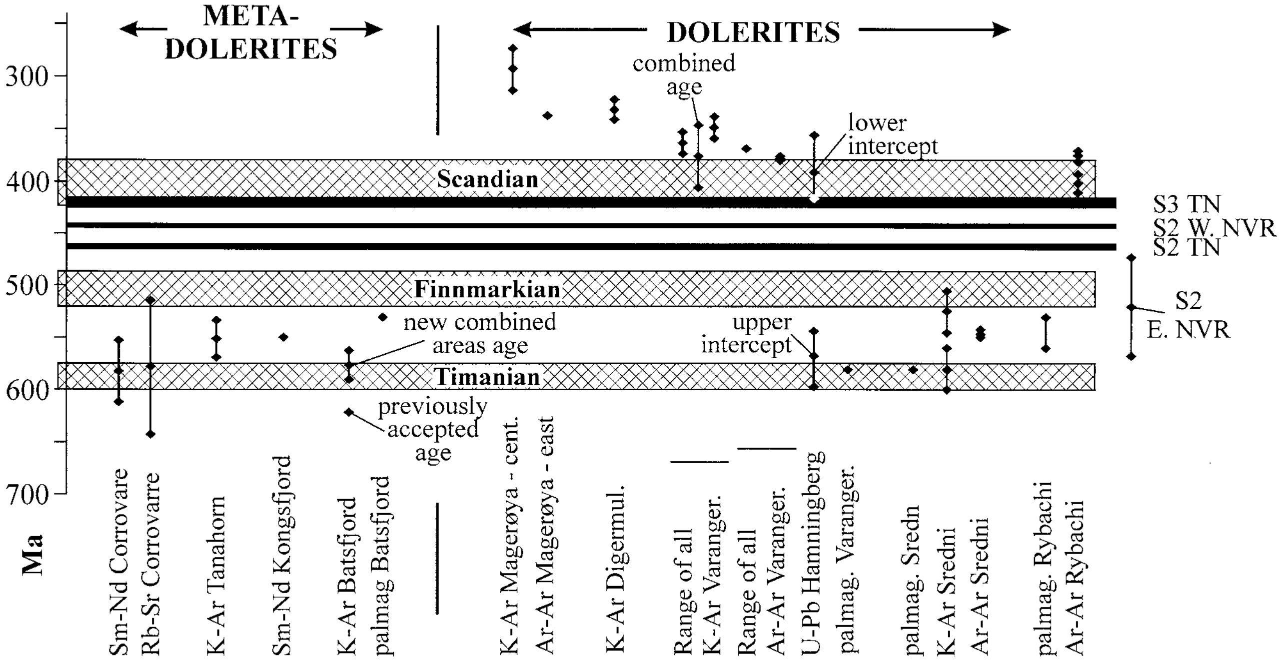

Figure 2. Isotopic and palaeomagnetic constraints on the age of the metadolerites and dolerites (see text for sources).

Within the western part of the North Varanger Region, axes of large-scale upright folds trend ~NE–SW, with a steep slaty cleavage in pelitic rocks (Roberts, 1972; Rice & Reiz, 1994). In the eastern part of the area, orthogonal fold phases formed a regional dome-and-basin outcrop pattern (Siedlecki, 1980), with early axes trending NNW–SSE, and the later essentially NE–SW (Roberts, 1972). Rice *et al.* (1989*a*) argued that the NNW–SSE-oriented structures formed by back-thrusting during strike-slip deformation. Roberts (1996), however, suggested that they formed during pre-Caledonian inversion related to the Timanian orogenic event (*c.* 600–575 Ma).

Dallmeyer *et al.* (1989) and Gorokhov *et al.* (2001) both obtained broadly Scandian deformation ages (440–390 Ma) from the shelf zone sedimentary rocks. In contrast, Rice & Frank (2003) proposed that deformation started in the Finnmarkian event. Mitchell

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(*in* Roberts & Sundvoll, 1990) obtained a K–Ar whole-rock age of 391 ± 9 Ma from ultracataclasites along the Gaissa Thrust, constraining the youngest age of Caledonian movement.

In the eastern part of the North Varanger Region, a Rb–Sr whole-rock cleavage age of 520 ± 47 Ma (MSWD 1.35) was obtained from rocks with a NNE–SSW-trending cleavage (Taylor & Pickering, 1981; Fig. 2). A $^{40}Ar/^{39}Ar$ fine-fraction age of ~ 440 Ma was obtained for the S3 cleavage in the western part of the North Varanger Region, with a suggestion of a Finnmarkian age for the S2 cleavage (Rice & Frank, 2003).

U–Pb discordia data from zircons from a dolerite dyke near Hamningberg (Fig. 1) gave an upper intercept of 567^{+30}_{-23} Ma, interpreted to be the intrusion age and thus constraining the age of early deformation in that area (Roberts & Walker, 1997; Fig. 2). This was used to link the deformation to the Neoproterozoic III Timanian event (600–575 Ma), reported to the east of the Kola Peninsula (cf. Roberts, 1996). The lower intercept age (392^{+25}_{-36}) was ascribed by Roberts & Walker (1997) to an isotopic disturbance related to post-Caledonian extension.

A similar palaeogeography has been described from the Rybachi–Sredni Peninsulas (Fig. 1), where a 2 km thick Neoproterozoic shallow-water succession on Sredni and southern Rybachi is separated from a *c.* 4 km thick basinal succession on Rybachi by the Sredni–Rybachi Fault (Siedlecka, Lyubtsov & Negrutsa, 1995). Although the basinal sequence can be correlated with the North Varanger Region stratigraphy, the Sredni shelf sequence cannot be correlated with that on Varangerhalvøya (Siedlecka, Lyubtsov & Negrutsa, 1995).

SW-directed deformation on Rybachi has been ascribed to pre-Caledonian Timanian inversion, with structures indicating younger dextral strike-slip movements lying adjacent to and north of the Sredni–Rybachi Fault, offsetting NE–SW-trending (meta-) dolerite dykes (Roberts, 1996). Palaeomagnetic and isotopic data suggest emplacement of these dykes in late Neoproterozoic III–Early Cambrian times (Roberts & Onstott, 1995; Torsvik, Roberts & Siedlecka, 1995), potentially constraining the folding to a pre-Caledonian age.

3. Mafic dykes

3.a. Metabasic dykes

The locally abundant metadoleritic dykes in the Middle Allochthon have transitional WPB–MORB (within-plate basalt–mid-ocean ridge basalt) compositions, related to Iapetus rifting (Roberts, 1975, 1990; Gayer *et al*. 1985; Rice, 1987).

In the North Varanger Region, strongly deformed metabasite dykes around Kongsfjord (Fig. 1) are up to 10 m thick and lie parallel to fold axial surfaces (Rice & Reiz, 1994). In contrast, metabasite dykes between Båtsfjord and Makkaursand (Fig. 1) are weakly deformed, although also parallel to the cleavage in the country rocks; the difference may be due to differences in country rock competence. Geochemically, the metabasites are of transitional WPB–MORB type (Roberts, 1975).

K–Ar whole-rock dating of these metabasites gave ages from 1945 ± 58 to 571 ± 17 Ma or down to 551 ± 17 Ma if a sample from the adjacent Kalak Nappe Complex is included (Beckinsale, Reading & Rex, 1975; Fig. 2) with an age of *c.* 650 Ma taken generally to be the intrusion age. Whilst analysis of a further 16 samples (Table 1) also gave a spread of ages, the lower envelope to *all* the analyses, including the one from the overlying Kalak Nappe Complex, gives a 7-point isochron representing an age of 577 ± 14 Ma (MSWD = 1.04; all errors for new ages reported in this paper are 95 % confidence limits; Fig. 3). This is interpreted as the intrusion age; all the older ages, plotting above the 7-point lower envelope, are re-interpreted as reflecting excess-Ar data, a phenomenon typical of compressional zones. For the newer analyses, fresh material was obtained from the core of large, fracture-free blocks from thick dykes with little internal deformation. One dyke from Kongsfjord has also been Sm–Nd dated to 550 Ma (Andersen & Sundvoll, 1995), similar to both the K–Ar age above and also the age of Iapetus rifting dykes in the Kalak Nappe Complex in westernmost Varangerhalvøya (551 ± 17 Ma, Beckinsale *et al*. 1975; Fig. 2) and the westernmost part of the Kalak Nappe Complex (582 ± 30 Ma, Sm–Nd & 578 ± 64 Ma, Rb–Sr; Zwaan & van Roermund, 1990).

3.b. Doleritic dykes

3.b.1. Distribution

Fresh, essentially undeformed and unmetamorphosed doleritic dykes occur in several areas of northern Finnmark. In central Magerøya, Scandian deformation is cut by a 3.8 km long continental tholeiitic dolerite of 293 ± 22 Ma age (K–Ar, Asselian: Roberts, Mitchell & Andersen, 1991; Fig. 2). Further east on the island, three within-plate tholeiitic dykes crop out, one of which (samples MA8, 9) may be a continuation of the dyke described by Roberts, Mitchell & Andersen (1991). However, $^{40}Ar/^{39}Ar$ plagioclase data from sample MA6 gave a Viséan age (337.3 ± 0.4 Ma: Lippard & Prestvik, 1997; Fig. 2).

On the coast of Digermulhalvøya, an 11 m thick WNW–ESE-trending dyke with poor hexagonal jointing cuts Caledonian folds in Late Cambrian to Tremadocian rocks of the Gaissa Thrust Belt (Fig. 1; Reading, 1965). K–Ar whole-rock dating gave an age of 332 ± 10 Ma, interpreted as the intrusion age (Beckinsale, Reading & Rex, 1975; Fig. 2).

Table 1. Sample localities and new K–Ar isotopic data for the Kongsfjord–Båtsfjord–Makkaursandfjord metadolerites

Sample no.	Locality	Map sheet	Grid reference*	% K	^{40}Ar rad nL $g^{-1} \times 10^{-1}$	Age (Ma)
419	Makkaursandfjord	2436 II	9395 4175	1.108	3.403	645
420	Makkaursandfjord	2436 II	9395 4175	1.070	3.625	701
421	**Makkaursandfjord**	**2436 II**	**9365 4080**	**1.297**	**3.501**	**555**
422	**Makkaursandfjord**	**2436 II**	**9365 4080**	**1.530**	**3.915**	**552**
423	**Makkaursandfjord**	**2436 II**	**9385 4047**	**1.666**	**4.252**	**551**
404	Båtsfjord	2436 III	0655 4360	1.000	3.251	677
405	Båtsfjord	2436 III	0655 4360	1.320	4.194	664
408	**Båtsfjord**	**2436 III**	**0645 4335**	**1.203**	**3.155**	**564**
414	**Båtsfjord**	**2436 III**	**0570 4190**	**1.752**	**4.674**	**572**
415	Båtsfjord	2436 III	0545 4155	1.209	4.141	707
416	Båtsfjord	2436 III	0545 4155	1.490	5.136	709
441	Kongsfjord	2436 III	9735 4865	1.601	6.008	763
442	Kongsfjord	2436 III	9735 4865	1.338	5.159	780
443	Kongsfjord	2436 III	9560 4725	0.274	1.217	874
444	Kongsfjord	2436 III	9560 4725	1.420	4.202	625
446	Kongsfjord	2436 III	9435 4675	1.130	4.784	841

Bold samples lie on the lower envelope to the data and define an isochron of 577 ± 14 Ma; Samples analysed in 1975–1976 at the laboratory of the Institute of Geological Sciences, Gray's Inn Road, London (now the British Geological Survey). Two more samples used in the isochron were published by Beckinsale, Reading & Rex (1975) and are not tabulated here (samples R17, 571 ± 17 Ma & R53, 551 ± 17 Ma).
* All grid references refer to map edition 3-NOR.

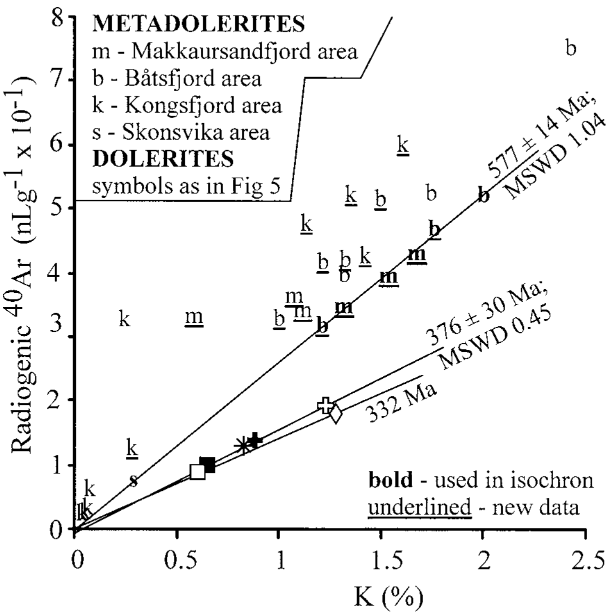

Figure 3. Plot of K–Ar data from metadolerites and dolerite dykes in the Digermulhalvøya and Varangerhalvøya areas. Data from Beckinsale, Reading & Rex (1975, recalculated) and new data from this article (Table 1).

At Styret, in northwest Varangerhalvøya, a 400 m long dyke cuts folded Neoproterozoic III rocks of the Løkvikfjellet Group. The intrusion, which is up to 7 m thick, trends 258°, except for an irregular coastal segment trending 090° (Fig. 4). S2 in the western part of the North Varanger Region formed at *c*. 440 Ma (Rice & Frank, 2003). K–Ar whole-rock dating gave a post-Caledonian age of 362 ± 10 Ma, interpreted as the intrusion age (Beckinsale, Reading & Rex, 1975; Fig. 2).

In eastern Varangerhalvøya, NE–SW-trending, generally left-stepping dolerite dykes have been observed at six localities north of the Trollfjorden–Komagelva Fault whilst to the south of the fault, N–S-trending, right-stepping dolerite dykes occur at two localities (Figs 1, 4; Table 2; Røe, 1970; Beckinsale, Reading & Rex, 1975; Roberts, 1975). The dykes are up to 15 m thick and generally less than 0.5 km long, although the Sandfjord–Per Olsadalen dyke is 3 km long. K–Ar whole-rock analyses gave ages between 349 ± 10 and 363 ± 10 Ma (Beckinsale *et al*. 1975), which, combined with the K–Ar data from the Styret dolerite dyke, give an isochron of 376 ± 30 Ma (MSWD = 0.45; Fig. 3). Ar/Ar analyses of plagioclase separates from three of these dolerite dykes (Ekkerøya, Komagnes and Sandfjord; Fig. 1) gave overlapping, but much better defined, ages between 368.57 ± 0.23 and 377.6 ± 1.8 Ma (Guise & Roberts, 2002; Fig. 3).

3.b.2. Petrography

Most samples have an ophitic to sub-ophitic texture, but in samples 39/95 and 39/97 a typical glomerophyric texture is developed and sample 38/95 has a seriate texture. Generally, they are fine- to medium-grained but some are relatively coarse-grained, with plagioclase laths up to 2 mm long; fine-grained interstitial regions have not been seen. The samples are fresh or only weakly altered; slight sericitization is common in the coarse-grained plagioclase and narrow chlorite and phlogopitic biotite rims have formed around some clinopyroxenes. No olivine has been seen. The opaque phase is mainly titanomagnetite, with a skeletal texture; needles of apatite occur in most samples.

4. Geochemistry

4.a. Sampling

Samples were collected from nearly all known dolerites on Varangerhalvøya and Digermulhalvøya (Table 2,

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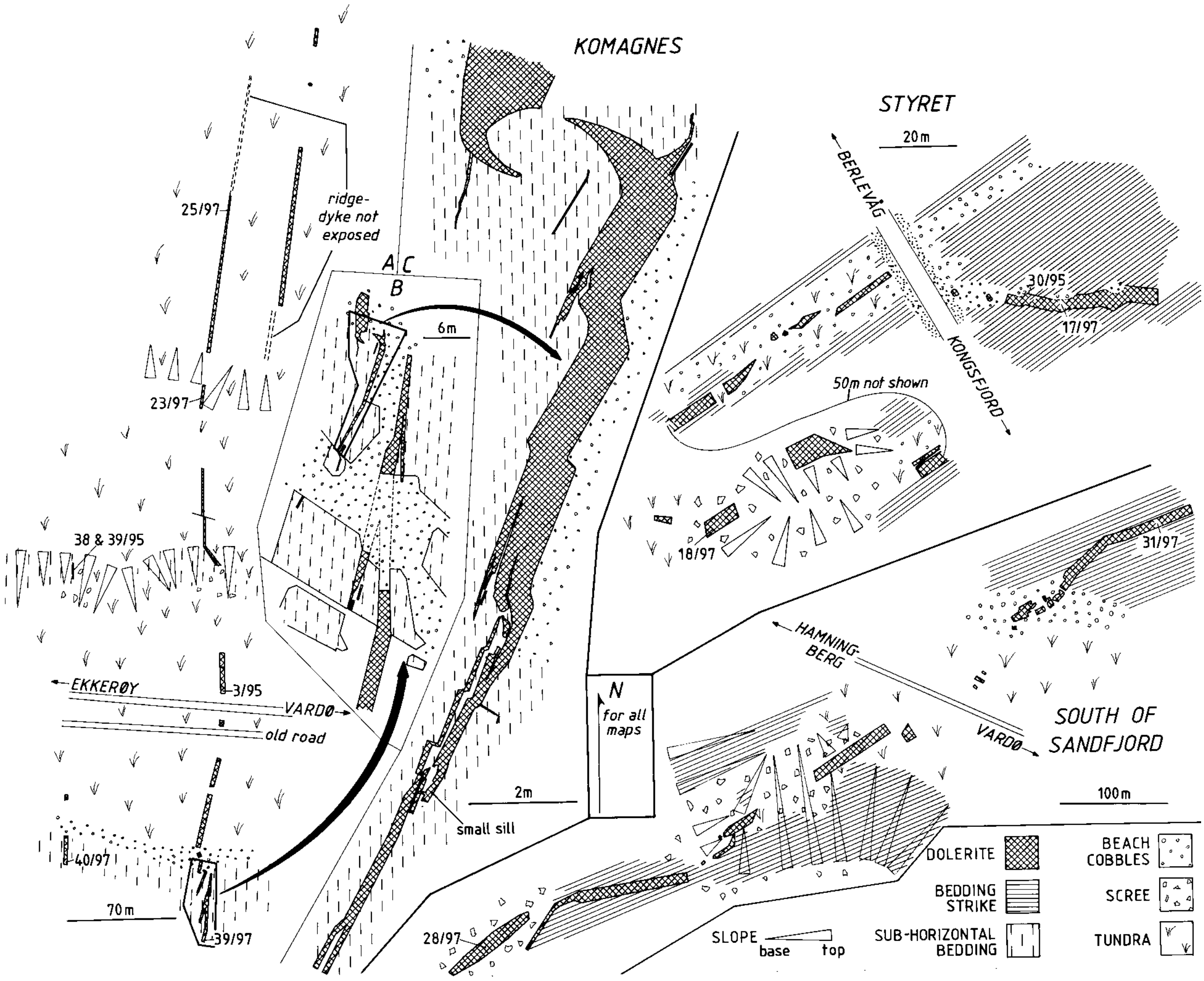

Figure 4. Sketch maps of the dolerite dykes at Komagnes, Styret and Sandfjord; based on compass bearings and length measurements.

Fig. 4). Unfractured samples were taken from the middle of the dykes; an exception was sample 39/95 from the Komagnes dyke chilled margin, but this has the same geochemistry as other Komagnes samples.

4.b. Analytical techniques

Samples were crushed in an iron jaw-crusher and reduced to powder in an agate disc-mill. Major and some trace elements were determined by X-ray fluorescence (Phillips 2400) at Vienna University. Major elements were analysed on fused discs and trace elements on pressed pellets.

REE and some trace elements were analysed by inductively coupled, plasma spectrometry at Cardiff University, using a Perkin-Elmer Sciex Elan 5000-A instrument. A mixed acid hot-plate digestion method was employed, using sequentially concentrated ultra-pure grade HNO_3 and HF, aqua regia, and 5M HCl, to produce solutions of the powdered samples. These solutions were diluted to appropriate concentrations for the elements analysed. The isotopes analysed were selected to avoid interference, but where unavoidable, suitable corrections were applied. Precision and accuracy were checked using an external calibration and analysis of basalt standard reference material BIR9.

4.c. Results

The results are given in Table 3. The Magerøya data (Roberts, Mitchell & Andersen, 1991; Lippard & Prestvik, 1997) are included in the description and figures. The data have been divided into three groups: (1) Digermulhalvøya and Magerøya dykes, (2) Styret dyke and (3) Hamningberg, Sandfjord–Per Olsadalen, Seglkollen, Blåsenberg, Ekkerøya and Komagnes dykes, collectively referred to as the East Varangerhalvøya dykes, although there are slight and systematic differences within the group.

4.c.1. Rock classification

The Total Alkalis–Silica (TAS; Le Maitre *et al*. 1989; Fig. 5a) plot shows that the East Varangerhalvøya and Styret samples lie on a linear trend, crossing from the basalt to basaltic-andesite fields, close to the

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Table 2. Dolerite dyke sample localities

Dyke	Sample	Map sheet	Grid reference*	Description of locality
Digermul	42/96	2236 II	3985 4130 (2)	East part of section in sea
	48/97	2236 II	3984 4131 (2)	West part of section in sea
	50/97	2236 II	3990 4120 (2)	Base of waterfall section
Styret (Fig. 4)	30/95	2236 I	8325 6005 (2)	Shore section
	17/97	2236 I	8325 6005 (2)	Shore section
	18/97	2336 I	8292 6005 (2)	Up on raised beach level
Hamningberg	36/95	2436 II	1140 2697 (3)	Road section
	27/97	2436 II	1105 2682 (3)	Up on raised beach
Sandfjord (Fig. 4)	28/97	2436 II	1080 2384 (3)	Beach section
	31/97	2436 II	1055 2366 (3)	Up on raised beach
Per-Olsadalen	35/97	2435 I	0850 2245 (3)	Small river gully
	36/97	2435 I	0870 2250 (3)	Small river gully
Seglkollen	37/97	2535 IV	1543 1935 (3)	Obvious cliff section east of road
Blåsenberg	29/97	2535 IV	1540 1878 (3)	Shore section
	30/97	2535 IV	1525 1873 (3)	Road section
(Bukkemoltangen	*not analysed*	*2535 IV*	*1640 1567 (3)*	*Supra- to sub-tidal section)*
Ekkerøya	4/95	2435 II	9050 7647 (3)	Shore cliff section
	20/97	2435 II	9047 7685 (3)	Up on top of peninsula
Komagnes (Fig. 4)	3/95	2435 II	0400 9123 (3)	Outcrop just N of road
	38/95	2435 II	0385 9130 (3)	Thin dyke in cliff
	39/95	2435 II	0385 9130 (3)	Thin dyke in cliff
	23/97	2435 II	0410 9145 (3)	Outcrop looking over valley to N
	25/97	2435 II	0412 9152 (3)	Outcrop in Komagdalen
	39/97	2435 II	0402 9105 (3)	South end of dyke at very low tide
	40/97	2435 II	0385 9110 (3)	Shore section at low tide

* Number in brackets refers to the ( )-NOR map edition. The Bukkemoltangen locality (found in 2001) has been included for completeness as it has not been reported before.

alkaline-tholeiitic discriminant zone, defined by a range of alkaline–sub-alkaline discriminant lines (Rollinson, 1993). Of the East Varangerhalvøya samples, those from Hamningberg have the most evolved compositions (SiO_2 53.4 %, alkalis 4.15 %), followed by those from the Sandfjord–Per Olsadalen dyke and then those from Seglkollen, Blåsenberg, Ekkerøya and Komagnes. The Digermulhalvøya samples have lower SiO_2 (49.4 %) and higher alkali (4.82 %) contents, lying in the transitional and alkaline zones, and close to the trachybasalt field. The samples from east Magerøya, together with two samples from central Magerøya, also lie in this transition zone, whilst the remainder from central Magerøya are more alkaline, passing into the trachybasalt field, with SiO_2 values of 49.72 %, at 5.2 % alkalis.

Winchester & Floyd (1977) proposed that values of Y/Nb $<$ 1.49 indicate alkaline compositions, whilst Pearce & Cann (1973) proposed a value of $<$1; together these suggest a transition zone between Y/Nb $=$ 1 to 1.49 (cf. Pearce, 1982; Fig. 5b). On this basis, two Digermulhalvøya samples lie in the transitional field, whilst the third lies just within the sub-alkaline field (mean Y/Nb 1.47), together with the east Magerøya samples and two central Magerøya samples. The remaining central Magerøya samples are more sub-alkaline (mean Y/Nb 2.02). In the Varangerhalvøya samples, there is an eastwards increase in mean Y/Nb values from the Styret dyke (Y/Nb 2.41), to the Hamningberg and Sandfjord–Per Olsadalen dykes (Y/Nb $\sim$ 3.00) to the Seglkollen, Blåsenberg, Ekkerøya and Komagnes dykes (Y/Nb $\sim$ 3.54; Table 4). Thus alkalinity increases eastwards in the Digermulhalvøya–Magerøya dykes and westwards in the Varangerhalvøya dykes. This pattern of trends is, with slight modifications, repeated in many plots in the following text.

4.c.2. *Magmatic evolution and contamination*

Chondrite-normalized REE patterns of the Digermulhalvøya and Magerøya samples are identical, with steep, slightly concave-upward patterns, reflecting LREE enrichment, with no Eu_N anomaly (Fig. 6a). However, both La and Lu concentrations are higher in the central Magerøya dykes and the La_N/Lu_N ratio is significantly higher (9.19 v. 7.49; Table 4). The samples from eastern Varangerhalvøya also have concave-upwards patterns but at lower REE concentrations. La and Lu values and ratios increase to the north-west, showing differences between the Komagnes–Ekkerøya–Blåsenberg–Seglkollen dykes (Lu $\sim$ 0.34), the Sandfjord–Per Olsadalen dyke (Lu $\sim$ 0.41) and the Hamningberg dyke (Lu $\sim$ 0.44). The latter also has a significantly higher La_N/Lu_N value than the Sandfjord–Per Olsadalen dyke (La_N/Lu_N 4.27 v. 3.35; Table 4). The Sandfjord–Per Olsadalen and Hamningberg samples also show very slight negative Eu_N anomalies (0.91–0.89; Table 4). The three samples from Styret are chemically so similar that the points are almost indistinguishable (Fig. 6a), with La and Lu concentrations and ratios similar to that of the East Varangerhalvøya samples (La_N/Lu_N 3.06 v. 2.84–3.15; Table 4), but the pattern is smooth, with no LREE enrichment, and no Eu_N anomaly.

Table 3. Whole-rock geochemical data for the dolerite dykes from Digermulhalvøya and Varangerhalvøya

Locality Sample	Diger 42/96	Diger 48/97	Diger 50/97	Styret 30/95	Styret 17/97	Styret 18/97	Hamn 36/95	Hamn 27/97	Sandfj 28/97	Sandfj 31/97	Per Ol 35/97	Per Ol 36/97	Seglk 37/97	Blåsen 29/97	Blåsen 30/97	Ekker 4/95	Ekker 20/97	Komag 3/95	Komag 38/95	Komag 39/95	Komag 23/97	Komag 25/97	Komag 39/97	Komag 40/97
SiO_2	49.79	49.83	49.40	52.31	52.22	52.25	53.20	53.40	52.72	51.95	52.80	52.57	51.96	52.03	51.78	51.35	51.70	51.95	51.38	51.81	51.59	51.65	52.16	52.29
TiO_2	3.29	3.19	3.31	2.04	2.06	2.04	1.46	1.49	1.28	1.24	1.28	1.27	1.15	1.20	1.18	1.03	1.04	1.04	1.03	1.05	1.00	1.06	1.09	1.11
Al_2O_2	13.87	13.73	13.73	13.98	13.90	13.94	15.09	14.85	13.99	14.00	14.12	14.06	14.28	14.40	14.15	14.83	14.76	14.48	14.59	14.56	14.64	14.53	15.60	14.60
Fe_2O_2	15.10	14.87	15.72	13.32	13.36	13.25	12.11	12.27	13.42	13.10	13.37	13.24	12.46	12.72	12.68	11.77	12.09	12.05	12.11	12.08	11.70	12.05	11.85	12.16
MnO	0.25	0.26	0.27	0.23	0.23	0.25	0.18	0.18	0.22	0.21	0.23	0.22	0.20	0.20	0.22	0.20	0.20	0.21	0.22	0.20	0.20	0.21	0.24	0.26
MgO	4.92	4.19	5.13	5.47	5.52	5.42	4.90	4.55	5.60	5.72	5.56	5.69	6.75	6.33	6.55	6.79	6.52	6.77	7.22	6.57	6.76	6.60	6.02	6.41
CaO	7.63	7.55	7.51	8.72	8.78	8.91	8.92	8.84	9.20	9.11	9.30	9.13	10.67	9.40	9.75	10.04	10.61	10.52	10.69	10.54	10.90	10.66	10.37	10.22
Na_2O	3.22	3.20	2.67	2.94	2.85	2.70	2.72	2.64	2.78	2.94	2.73	2.80	2.46	2.81	2.54	2.90	2.47	2.38	2.23	2.43	2.36	2.37	2.44	2.51
K_2O	1.43	1.62	1.36	0.91	0.99	0.89	1.43	1.47	1.04	1.00	1.05	1.03	0.67	0.96	0.88	1.20	0.72	0.70	0.44	0.71	0.67	0.69	0.44	0.84
P_2O_2	0.67	0.65	0.66	0.19	0.19	0.20	0.20	0.20	0.17	0.16	0.17	0.16	0.15	0.17	0.15	0.13	0.13	0.13	0.12	0.13	0.12	0.13	0.13	0.14
Total (dry)	100.17	99.09	99.76	100.11	100.10	99.85	100.21	99.89	100.42	99.43	100.61	100.17	110.75	100.22	99.88	99.97	100.24	100.23	100.03	100.08	100.04	99.95	100.34	100.54
LOI	2.66	2.24	3.45	1.52	1.47	1.79	1.00	0.95	0.55	1.07	1.06	0.91	1.13	1.45	1.55	1.27	0.95	0.96	1.71	4.01	1.56	1.26	1.06	n.d.
Cr	37.8	33.3	35.9	43.4	41.9	44.1	71.5	142.7	27.1	35.4	23.9	27.9	59.1	60.9	57.1	88.2	77.7	89.2	93.1	81.0	83.1	123.8	99.0	103.8
Co	45.6	44.7	49.4	46.0	46.9	46.8	39.7	40.2	48.6	49.9	48.5	48.6	47.3	48.4	48.7	47.2	48.0	46.9	47.7	46.1	46.5	43.8	48.1	46.3
Ni	23.7	23.7	25.8	24.9	25.7	25.6	38.0	39.1	28.3	29.9	28.2	29.6	45.7	46.8	49.7	52.4	48.0	49.7	53.8	47.6	49.3	46.0	55.0	50.4
Cu	25	25	24	40	42	40	107	108	124	122	122	124	109	126	129	114	111	126	122	122	124	123	128	108
Sc	31.4	29.0	30.6	31.1	32.8	30.8	28.8	28.6	34.7	35.3	32.8	34.9	32.8	37.4	34.4	34.9	35.1	36.9	37.1	36.1	35.3	33.4	43.1	35.9
V	423	414	413	391	402	400	324	316	359	361	362	352	340	354	353	337	338	346	329	343	329	338	342	347
Zn	123.5	123.7	131.7	95.6	101.5	98.1	91.0	97.7	88.5	88.3	90.1	88.3	83.4	95.2	87.9	85.9	83.7	77.4	76.8	78.2	74.0	76.0	82.1	83.2
Rb	34.1	40.2	31.4	23.8	28.2	20.9	50.6	51.5	35.7	33.0	37.1	34.2	22.9	28.7	27.9	39.9	24.5	22.1	6.1	15.5	22.0	20.9	5.4	26.9
Cs	1.95	2.27	1.14	0.55	0.51	0.25	1.51	1.52	0.81	0.90	2.31	0.87	0.65	3.90	1.84	0.84	0.92	0.81	0.48	0.55	1.02	0.71	0.37	1.07
Ba	736	816	677	213	245	202	416	454	278	258	276	283	252	823	570	1161	544	271	227	261	238	240	262	328
Sr	323	318	308	254	257	245	259	259	228	224	229	234	238	258	264	383	256	223	239	237	224	236	279	227
Ta	1.68	1.69	1.65	0.98	0.96	0.96	0.87	0.79	0.72	0.66	0.79	0.73	0.59	0.58	0.53	0.56	0.60	0.54	0.52	0.45	0.53	0.51	0.49	0.56
Nb	25.05	25.72	24.91	11.41	11.37	11.70	8.96	8.97	8.29	7.91	8.23	8.05	5.76	6.20	6.00	5.42	5.53	5.47	5.15	5.61	5.09	5.51	5.46	6.10
Hf	6.47	6.65	6.17	4.73	4.74	4.81	4.28	4.50	3.23	3.17	3.21	3.19	2.54	2.80	2.71	2.36	2.53	2.42	2.31	2.42	2.34	2.70	2.43	2.71
Zr	222.1	233.3	216.2	152.8	152.4	154.7	136.6	138.4	103.5	99.8	107.2	103.8	86.4	91.1	88.5	76.2	76.7	76.9	76.2	78.8	73.8	78.3	80.1	87.9
Y	35.0	35.7	40.5	27.4	27.6	28.0	27.0	27.6	24.4	23.8	24.6	24.4	20.1	21.8	21.4	19.1	19.9	19.5	18.7	19.6	18.7	19.4	19.5	20.8
Th	4.13	4.36	3.96	2.28	2.33	2.30	5.06	5.12	3.57	3.47	3.71	3.62	2.46	2.92	2.86	2.37	2.42	2.51	2.30	2.44	2.28	2.53	2.38	2.80
U	0.82	0.84	0.74	0.55	0.56	0.55	1.04	1.08	0.76	0.76	0.79	0.79	0.51	0.57	0.54	0.50	0.50	0.52	0.49	0.49	0.44	0.49	0.48	0.56
La	34.17	34.90	37.36	11.47	11.72	11.79	17.18	18.14	12.66	12.40	12.90	12.70	9.48	10.86	10.40	8.64	9.27	8.90	8.49	8.97	8.60	9.07	9.04	10.23
Ce	75.81	77.28	81.03	27.76	28.34	28.15	37.91	39.67	28.10	27.42	28.54	28.16	21.66	24.58	23.40	19.03	20.30	19.63	18.82	19.85	18.96	20.16	19.90	22.72
Pr	10.19	10.25	10.63	4.03	4.14	4.14	5.04	5.29	3.74	3.67	3.80	3.74	2.97	3.31	3.16	2.61	2.72	2.68	2.58	2.72	2.58	2.76	2.73	3.05
Nd	40.94	41.64	43.25	18.30	18.40	18.86	20.45	21.21	15.54	15.07	15.62	15.78	12.34	13.74	13.08	10.72	11.40	11.12	10.79	11.02	10.58	11.34	11.48	12.64
Sm	8.31	8.24	8.92	5.05	4.99	4.99	4.63	4.89	3.66	3.65	3.83	3.73	2.98	3.41	3.29	2.69	2.65	2.68	2.71	2.85	2.61	2.78	2.84	3.09
Eu	2.99	2.87	3.09	1.66	1.73	1.72	1.42	1.47	1.17	1.13	1.19	1.17	1.01	1.20	1.15	1.07	1.00	0.98	0.96	0.98	0.94	0.97	0.93	1.04
Gd	8.36	8.50	9.24	5.43	5.49	5.56	5.12	5.12	4.08	3.99	4.28	4.04	3.38	3.70	3.80	3.23	3.40	3.17	3.03	3.27	3.13	3.21	3.12	3.52
Tb	1.30	1.30	1.40	0.94	0.95	0.97	0.87	0.88	0.72	0.72	0.73	0.72	0.61	0.67	0.63	0.57	0.58	0.57	0.56	0.57	0.56	0.58	0.58	0.62
Dy	7.37	7.35	7.78	5.72	5.73	5.69	5.24	5.39	4.50	4.43	4.53	4.48	3.77	4.14	4.00	3.43	3.68	3.62	3.47	3.60	3.43	3.66	3.56	3.77
Ho	1.46	1.45	1.55	1.11	1.15	1.15	1.08	1.13	0.96	0.93	0.96	0.96	0.79	0.88	0.86	0.76	0.81	0.76	0.77	0.77	0.75	0.76	0.78	0.82
Er	3.85	3.69	4.12	3.06	3.09	3.07	3.06	3.13	2.75	2.70	2.73	2.80	2.27	2.50	2.53	2.22	2.32	2.26	2.15	2.23	2.19	2.30	2.17	2.33
Tm	0.54	0.55	0.59	0.45	0.43	0.45	0.46	0.46	0.43	0.41	0.42	0.42	0.34	0.37	0.36	0.33	0.34	0.33	0.33	0.34	0.31	0.34	0.34	0.36
Yb	3.35	3.29	3.47	2.67	2.73	2.76	2.88	2.89	2.64	2.61	2.66	2.67	2.19	2.32	2.26	2.11	2.14	2.14	2.02	2.08	2.03	2.15	2.20	2.26
Lu	0.51	0.49	0.53	0.41	0.41	0.41	0.44	0.45	0.41	0.40	0.42	0.40	0.34	0.36	0.35	0.32	0.36	0.33	0.32	0.34	0.33	0.34	0.34	0.36

Diger – Digermul; Hamn – Hamningberg; Sandfj – Sandfjord; Per Ol – Per Olsadalen; Seglk – Seglkollen; Blåsen – Blåsenberg; Ekker – Ekkerøya; Komag – Komagnes.

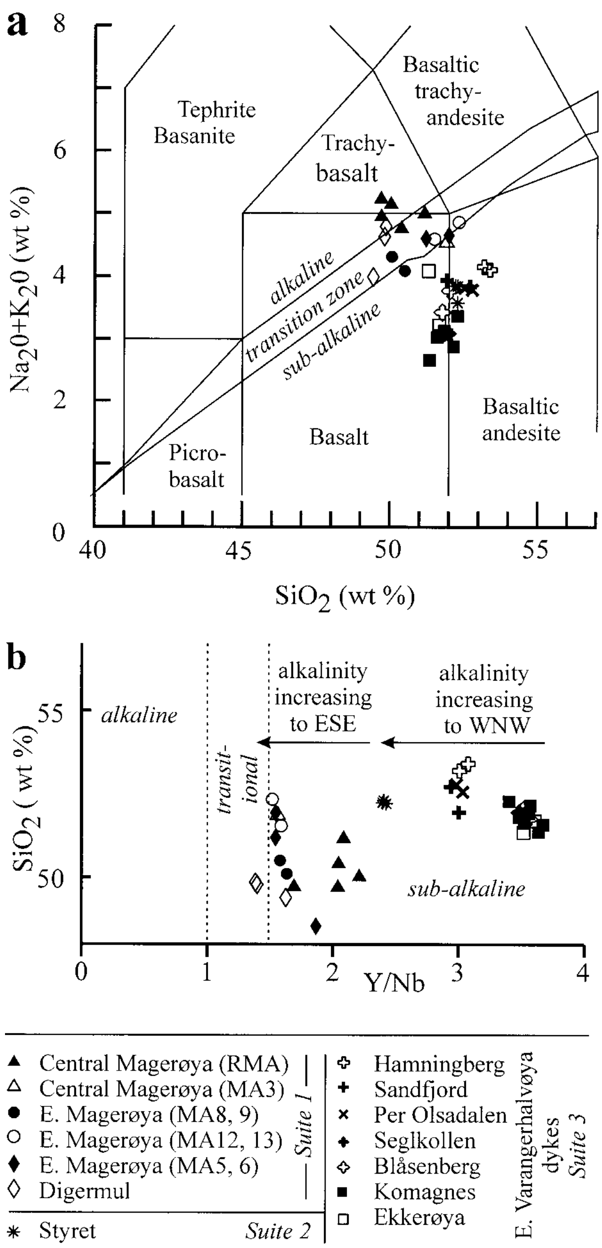

Figure 5. (a) Total Alkalis–Silica plot (TAS) of Le Maitre *et al.* (1989). (b) Plot of Y/Nb v. SiO_2, showing the degree of alkalinity in the dolerite dykes.

In primitive mantle-normalized spider diagrams (Sun & McDonough, 1989; Fig. 7), the East Varangerhalvøya samples have slightly concave-upwards patterns, with negative Nb_N, Ta_N and P_N anomalies and a very slight negative Ti_N anomaly. They all have a positive K_N anomaly, but whilst the Hamningberg, and Sandfjord–Per Olsadalen samples have small negative Sr_N and Ba_N anomalies, the others have positive anomalies for these elements. No Rb_N anomaly is seen except in the variable values from the Komagnes dyke. The Styret dyke (Fig. 7a) is similar to the Hamningberg and Sandfjord–Per Olsadalen dykes in having negative P_N and Nb_N anomalies, but there is no Ta_N anomaly and elements between Nd_N and Dy_N

Table 4. Element ratios and Eu_N anomalies for the dolerite and metadolerite dykes in the Magerøya–Digermulhalvøya–Varangerhalvøya–Rybachi/Sredni area

	Y/Nb	Zr/Y	Th/Ta	Nb/Ta	La_N/Lu_N	Rb/Sr	Rb/Ba	Eu/Eu*	Cr/Ni
Magerøya (central)	2.02 ± 0.19	5.79 ± 0.31	3.05 ± 0.09	13.01 ± 0.62	9.19 ± 0.78	0.133 ± 0.009	0.055 ± 0.004	–	96.57 ± 2.98
Magerøya (east)	1.57 ± 0.04	5.70 ± 0.10	–	–	–	0.113 ± 0.011	0.053 ± 0.003	–	93.05 ± 4.08
Digermul	1.47 ± 0.13	6.07 ± 0.64	2.48 ± 0.09	15.08 ± 0.16	7.49 ± 0.24	0.111 ± 0.013	0.047 ± 0.002	1.06 ± 0.03	96.92 ± 3.43
Styret	2.41 ± 0.02	5.54 ± 0.03	2.38 ± 0.03	11.89 ± 0.28	3.06 ± 0.04	0.096 ± 0.012	0.110 ± 0.006	0.99 ± 0.02	123.17 ± 2.62
Hamningberg	3.04 ± 0.05	5.04 ± 0.04	6.15 ± 0.47	10.83 ± 0.75	4.27 ± 0.10	0.197 ± 0.002	0.118 ± 0.006	0.89 ± 0.00	175.51 ± 2.38
Sandfjord-Per Olsadalen	2.99 ± 0.04	4.27 ± 0.07	4.97 ± 0.23	11.24 ± 0.67	3.35 ± 0.05	0.153 ± 0.008	0.128 ± 0.005	0.91 ± 0.01	180.39 ± 2.63
Seglkollen-Blåsenberg	3.52 ± 0.04	4.21 ± 0.09	4.87 ± 0.63	10.59 ± 0.78	3.15 ± 0.13	0.105 ± 0.008	0.058 ± 0.029	1.00 ± 0.03	215.05 ± 8.44
Ekkerøya	3.56 ± 0.06	3.92 ± 0.11	4.13 ± 0.14	9.45 ± 0.33	2.89 ± 0.08	0.073 ± 0.038	0.064 ± 0.030	1.06 ± 0.06	309.24 ± 89.08
Komagnes	3.55 ± 0.09	4.05 ± 0.10	4.80 ± 0.38	10.76 ± 0.96	2.84 ± 0.10	0.100 ± 0.006	0.040 ± 0.008	0.99 ± 0.03	225.64 ± 16.08
Rybachi	2.96 ± 0.77	2.28 ± 0.60	–	–	–	0.131 ± 0.068	0.177 ± 0.046	–	2.01 ± 0.98
Sredni	2.45 –	4.67 –	–	–	–	0.074 –	0.173 –	–	1.65 –
Båtsfjord	9.25 –	2.95 –	–	–	–	0.233 –	0.207 –	–	2.57 –
Kongsfjord	19.83 ± 14.34	2.21 ± 0.32	–	–	–	0.003 ± 0.002	0.025 ± 0.006	–	2.77 ± 0.57
Berlevåg	11.56 ± 3.67	3.12 ± 0.30	–	–	–	0.027 ± 0.044	0.100 ± 0.066	–	1.96 ± 0.23

Data from this article, Roberts (1975), Roberts *et al.* (1991), Roberts & Onstott (1995) and Lippard & Prestvik (1997).

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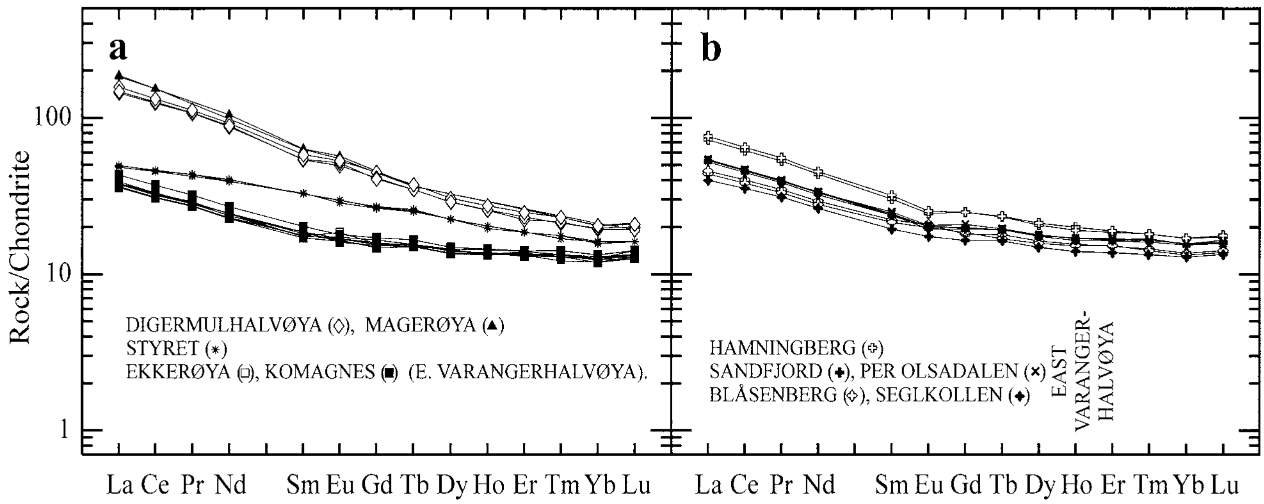

Figure 6. Chondrite-normalized plots of the REE (Sun & McDonough, 1989). Symbols as in Figure 5.

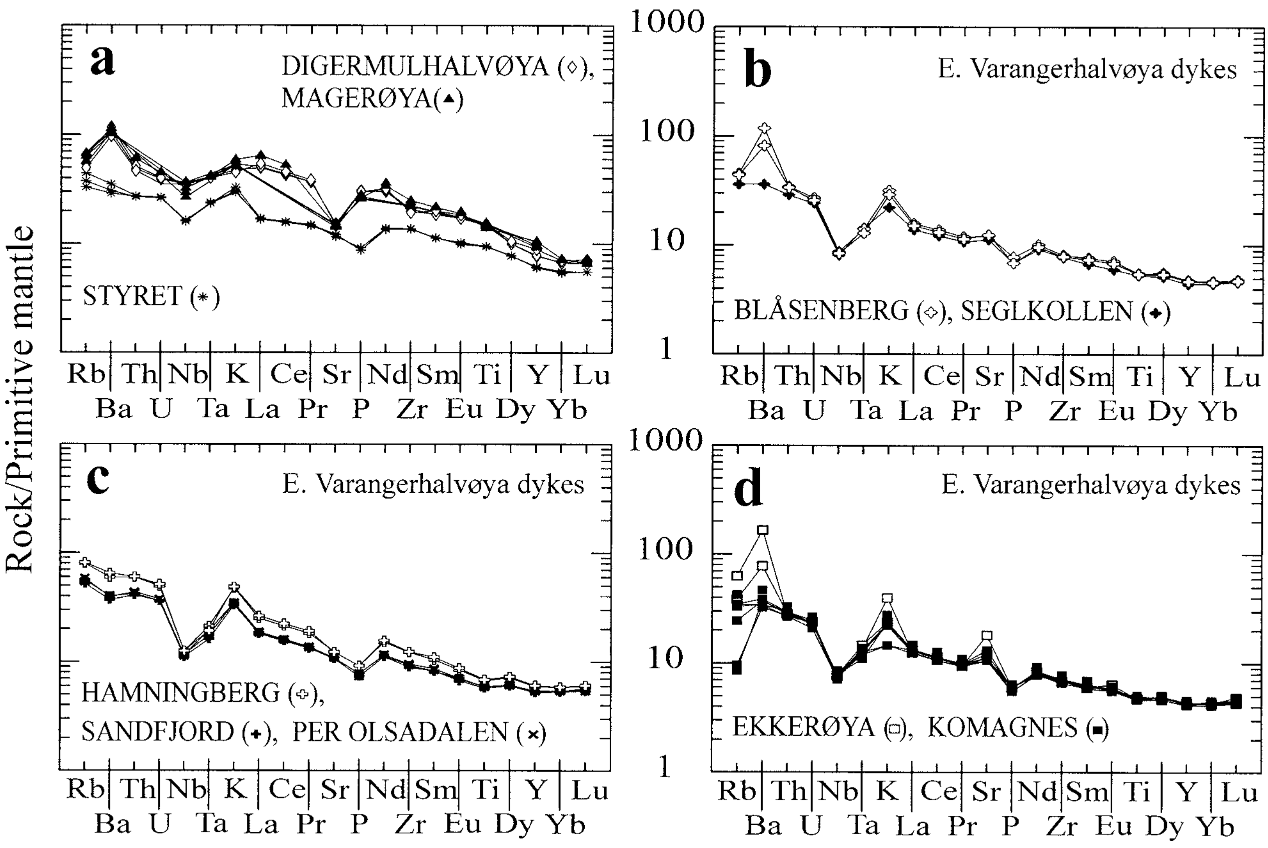

Figure 7. Spider plots, normalized to primitive mantle values (Sun & McDonough, 1989). Symbols as in Figure 5.

are slightly enriched. Sr_N is slightly depleted whilst Ba_N and Rb_N are enriched. The Digermulhalvøya–Magerøya data (Fig. 7a) are very similar on spider plots but the pattern is concave-downwards, with the Ce_N–Th_N line being horizontal. Elements between Nd_N and Yb_N lie above the Yb_N–La_N line, but there is no P_N anomaly. Nb_N, Ta_N and U_N show slight and Sr_N a marked negative anomaly.

The mean composition for each dyke has been divided into four components (Pearce, 1983; but using normalizing values in Pearce & Parkinson, 1993; Table 5) representing (1) an initial depleted mantle partial melt (MORB component), (2) a within-plate enrichment component, from the sub-continental crust lithosphere, (3) a fractional crystallization component and (4) a component which might reflect either early subduction-zone enrichment or late continental crust contamination. Subduction was not active in the area and hence subduction zone enrichment is not referred to in the following description. Application of this

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Table 5. Mean percentage contribution of four magmatic processes

	Sr					K_2O					Rb					Ba					Th					Ta				Nb			
Dyke	ppm	M	W	F	C	wt%	M	W	F	C	ppm	M	W	F	C	ppm	M	W	F	C	ppm	M	W	F	C	ppm	M	W	F	ppm	M	W	F
Magerøya	**306**	33	71	−3	0	**1.67**	9	51	−3	43	**40**	2	15	−1	84	**773**	1	9	−1	91	**5.15**	3	25	−1	74	**1.69**	8	90	1	**22.0**	12	103	−15
Digermul	**316**	31	69	0	0	**1,42**	10	60	0	30	**35**	2	17	0	81	**743**	1	9	0	90	**4.15**	3	31	0	66	**1.67**	9	91	0	**25.2**	10	90	0
Styret	**252**	25	44	31	0	**0.93**	10	26	28	37	**24**	2	6	7	86	**220**	2	7	9	82	**2.30**	4	13	16	68	**0.97**	9	43	47	**11.5**	14	34	52
Hamningberg	**259**	24	43	33	0	**1.45**	6	16	13	64	**51**	1	3	2	94	**435**	1	4	3	93	**5.09**	2	6	5	88	**0.83**	11	51	39	**9.0**	18	43	39
Sandfjord	**226**	28	49	23	0	**1.02**	9	23	12	56	**34**	1	4	2	93	**268**	2	6	3	90	**3.52**	2	8	4	85	**0.69**	13	61	26	**8.1**	20	48	32
Per Olsadalen	**231**	27	48	25	0	**1.04**	9	23	14	55	**36**	1	4	2	93	**279**	2	6	3	89	**3.67**	2	8	5	85	**0.76**	12	55	33	**8.1**	20	47	33
Seglkollen	**261**	24	42	8	26	**0.92**	10	26	4	60	**28**	1	5	1	93	**697**	1	2	0	97	**2.89**	3	10	1	86	**0.56**	15	71	14	**6.1**	27	63	10
Blåsenberg	**238**	26	46	4	23	**0.67**	14	36	5	46	**23**	2	6	1	94	**252**	2	6	1	91	**2.46**	3	12	2	83	**0.59**	16	75	9	**5.8**	28	67	5
Ekkerøya	**318**	20	35	0	46	**0.96**	9	25	2	64	**32**	1	4	0	94	**852**	1	2	0	97	**2.40**	3	12	1	83	**0.58**	16	72	12	**5.5**	30	70	0
Komagnes	**238**	26	46	0	27	**0.64**	14	37	0	49	**17**	2	8	0	90	**261**	2	6	0	92	**2.46**	3	12	0	85	**0.51**	18	82	0	**5.5**	30	70	0

	Ce					P_2O_5					Zr				Hf				Sm					TiO_2				Y				Yb		
Dyke	ppm	M	W	F	C	wt %	M	W	F	C	ppm	M	W	F	ppm	M	W	F	ppm	M	W	F	C	wt %	M	W	F	ppm	M	W	F	ppm	M	F
Magerøya	**94**	9	57	−6	40	**0.59**	13	55	0	32	**273**	30	52	18	**6.20**	37	67	−4	**9.65**	30	48	−3	26	**3.08**	46	60	−6	**45.5**	68	13	0	**3.55**	95	5
Digermul	**78**	11	68	0	21	**0.66**	12	49	0	39	**224**	37	63	0	**6.43**	35	65	0	**8.49**	34	54	0	12	**3.26**	43	57	0	**37.1**	84	16	0	**3.37**	100	0
Styret	**28**	19	33	55	−6	**0.19**	26	30	58	−15	**153**	34	18	49	**4.76**	30	22	48	**5.01**	37	17	50	−3	**2.05**	43	8	49	**27.7**	71	0	30	**2.72**	78	22
Hamningberg	**39**	14	24	24	38	**0.20**	25	29	37	9	**138**	38	20	43	**4.39**	33	24	44	**4.76**	39	18	35	9	**1.48**	60	11	29	**27.3**	72	0	29	**2.89**	74	26
Sandfjord	**28**	19	33	23	25	**0.17**	30	34	25	12	**102**	51	27	22	**3.20**	45	33	23	**3.66**	50	23	19	8	**1.26**	70	13	17	**24.1**	81	0	19	**2.63**	81	19
Per Olsadalen	**28**	18	32	23	26	**0.17**	30	34	26	10	**106**	49	26	25	**3.20**	45	33	23	**3.78**	49	22	19	11	**1.28**	69	13	18	**24.5**	80	0	21	**2.67**	80	20
Seglkollen	**24**	22	38	7	33	**0.16**	31	36	8	24	**90**	57	30	12	**2.76**	52	38	10	**3.35**	55	25	10	10	**1.19**	75	14	12	**21.6**	91	0	10	**2.29**	93	7
Blåsenberg	**22**	24	42	4	29	**0.15**	34	38	5	23	**86**	60	31	9	**2.54**	56	41	2	**2.98**	62	28	5	5	**1.15**	77	14	9	**20.6**	95	−1	6	**2.19**	97	3
Ekkerøya	**20**	27	47	0	27	**0.13**	39	44	−1	18	**76**	68	36	−3	**2.45**	58	43	−1	**2.67**	69	32	−1	1	**1.04**	85	16	−1	**19.5**	100	−1	0	**2.13**	100	0
Komagnes	**20**	26	46	0	28	**0.13**	39	44	0	17	**79**	66	34	0	**2.48**	58	42	0	**2.79**	66	30	0	4	**1.05**	84	16	0	**19.5**	101	−1	0	**2.13**	100	0

ppm, wt % = mean whole-rock compositions. Mean percentage contribution values: M = MORB; W = within-plate enrichment; F = fractional crystallization; C = crustal contamination. C = 0 and F = 0 where columns not shown.

model presupposes that the dolerites were derived from a MORB-composition melt (i.e. a partial melt of the depleted upper mantle) rather than from an ocean island basalt (OIB) composition mantle plume. Two arguments support this supposition. First, the Varangerhalvøya area lies adjacent to the Barents Sea, an area of major post-Caledonian extension, which possibly led to the formation of a small ocean basin some 500 km to the northeast of Varangerhalvøya (Gabrielsen, 1984; Nikishin *et al*., 1996; Gudlaugsson *et al*., 1998). This suggests that contemporary basaltic intrusions might be expected in neighbouring areas. Second, plotting a typical ocean island basalt composition (OIB; Sun & McDonough, 1989) on the Ta/Yb–Th/Yb plot (Fig. 8a; Pearce, 1983) shows that it is not possible for the Finnmark dolerites to have been derived from an OIB source, using the trends typical for the contamination processes.

For the East Varangerhalvøya and Digermul–Magerøya suites, the samples with the lowest Yb value have been taken to define the MORB and within-plate enrichment *values* for that suite. The differences between the average values, using the within-plate enrichment *curves* for each dyke, was used to determine the fractional crystallization component; hence no fractional crystallization is recorded in the samples with the lowest Yb content in each suite. The remaining material has been taken to have come from crustal contamination. In these calculations, the Styret dyke was included with the East Varangerhalvøya dykes. The concentrations were then converted from ppm to percentages (Table 5).

Negative results occur in several places in the Table 5. These indicate where, for several reasons, the analytical value or the value inferred by the model of Pearce (1983) differs from that expected. Generally the negative values are small. However, the −15 % fractional crystallization component value for the Magerøya data is an exception and is reflecting the lower bulk Nb value in these samples compared to the Digermulhalvøya data, contrary to the expected higher value, since Yb is higher in the Magerøya dykes than in the Digermulhalvøya dyke. The high negative percentage crustal contamination values of Ce and P_2O_5 in the Styret dyke are a result of the measured concentrations being lower than the interpolated within-plate enrichment values.

Note that except for the Komagnes, Ekkerøya, Blåsenberg and Seglkollen samples, the Sr concentration in the dolerites lies below the interpolated value suggested by the method of Pearce (1983) for defining the boundary between the within-plate enrichment and the crustal contamination components. Whilst such low values of Sr *might* be acceptable, depending on the crustal contaminant, it is unlikely that Sr would be unaffected by subduction zone enrichment.

The data from the East Varangerhalvøya dykes for elements unaffected by crustal contamination show

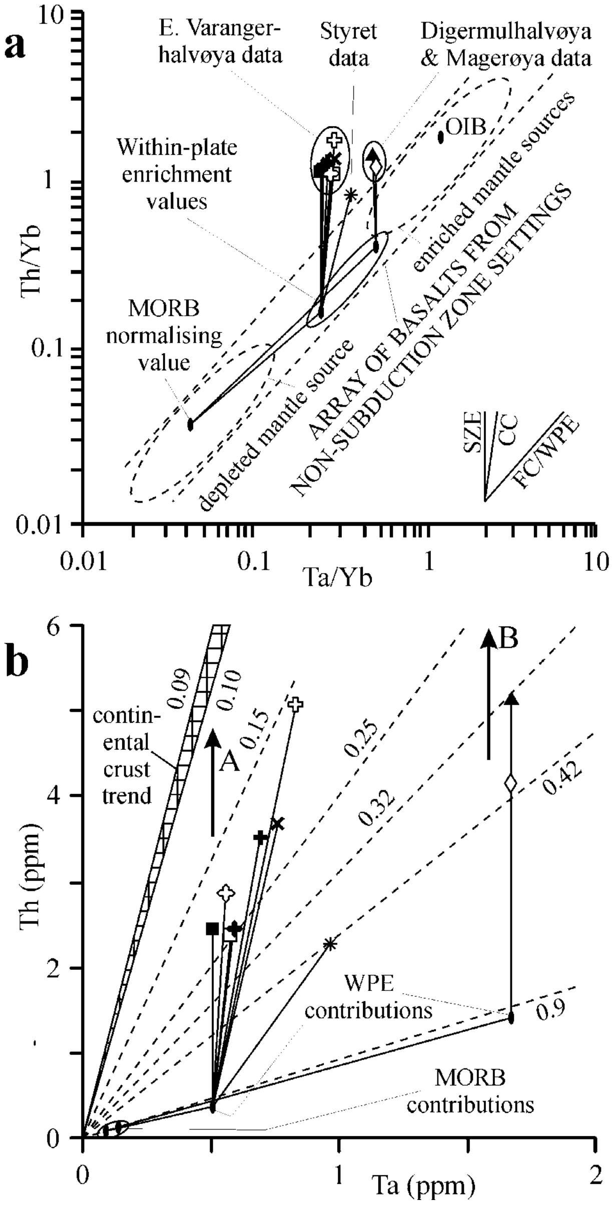

Figure 8. (a) Plot of Ta/Yb v. Th/Yb (Pearce, 1983; Wilson, 1989). OIB analysis from Sun & McDonough (1989). (b) Ta v. Th (Wooden *et al*. 1993). Symbols as in Figure 5. Range of crustal compositions is from Condie (1993).

the MORB and within-plate enrichment percentage components fall to the northwest, as the bulk-rock composition for these elements increases due to fractional crystallization. For the Digermulhalvøya–Magerøya data, the trend is variable, with the lower MORB within-plate enrichment values being in the east for Sr, Nb, Hf and TiO_2 and in the west for Zr, Y and Yb. For these elements, the Styret dyke clearly falls along the same trend as the East Varangerhalvøya dykes; in several cases the Styret and Hamningberg dykes have almost identical whole-rock and percentage values (Sr, Zr, Hf, Y, Yb), whilst in others the latter is closer to but not the same as the Sandfjord–Per-Olsadalen data (Nb, TiO_2).

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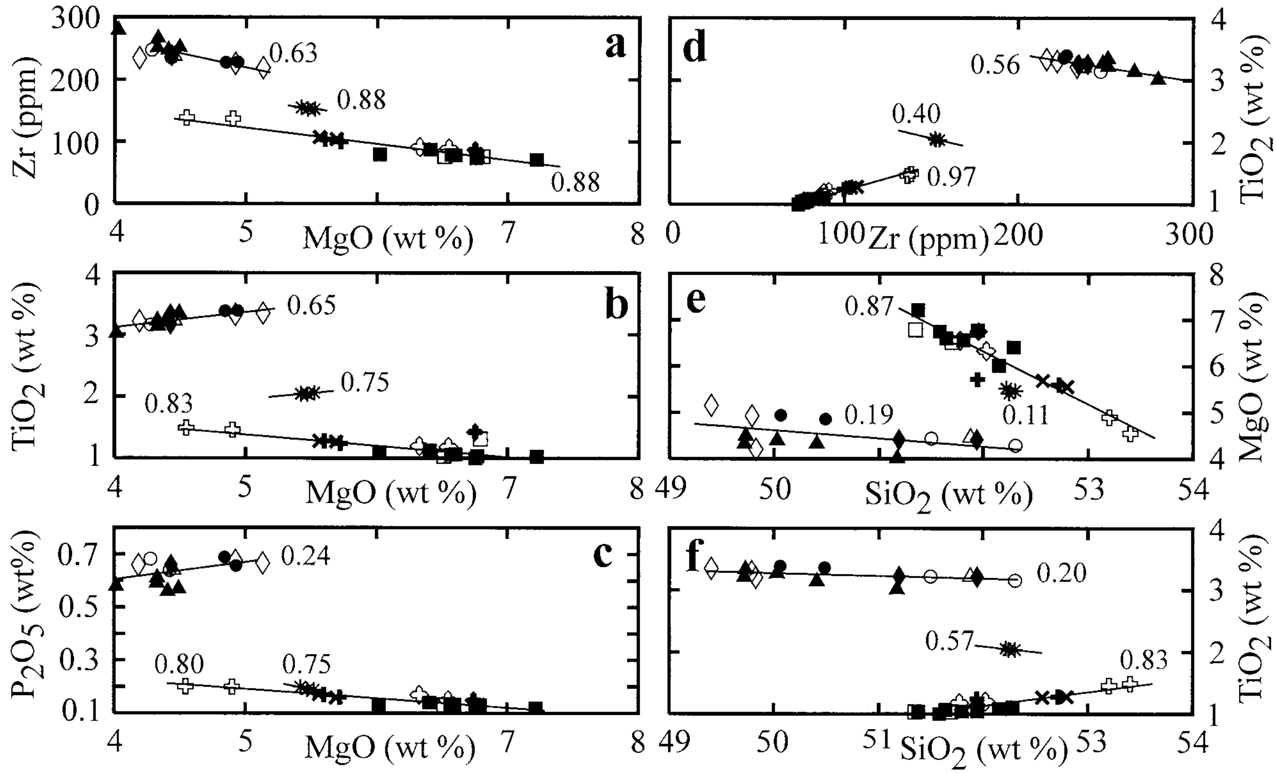

Figure 9. Bivariate plots; some using compatible and others incompatible elements. Symbols as in Figure 5.

For elements affected by crustal contamination, higher bulk compositions and lower MORB and within-plate enrichment values occur in the Magerøya dykes compared to those from Digermulhalvøya, except for P_2O_5. For these elements, only Ta, P_2O_5 and Sm have similar (broadly) values in the Styret and Hamningberg samples; in the other elements, the Styret MORB and within-plate enrichment values are higher than the Hamningberg values.

However, in some elements affected by crustal contamination (Rb, Ba, Th), the MORB component is often very small, with no geographical trend from Komagnes to Magerøya, whilst the crustal contamination component is large, although again usually showing no clear geographic trend except that in a few instances the percentage crustal contamination value for the Styret dyke is more comparable to the Digermulhalvøya–Magerøya data (K_2O, Rb, Th) than the East Varangerhalvøya dykes. The within-plate enrichment and fractional crystallization data show the same NW–SE geographic trends as described above, but not so clearly defined and the Styret dyke is not comparable to either of the other suites.

Figure 8b plots Ta and Th values for the four components (Wooden *et al.*, 1993), although the fractional crystallization and crustal contamination data have been combined, since these two processes operated simultaneously. The trends of crustal contamination plus fractional crystallization are parallel in the East Varangerhalvøya and Digermulhalvøya–Magerøya suites, although the lever rule indicates that the contamination source was different. For the East Varangerhalvøya dykes, lower Ta/Th ratio values, reflecting greater contamination plus fractional crystallization, lie to the northwest (Fig. 8b, Table 4). These dykes had a common contamination source, compositionally lying in the direction of arrow A, with Ta/Th < 0.15 (Fig. 8b). The two slopes Ta/Th $= 1.0$ to 0.9 are typical for a range of Precambrian upper crustal rocks (Condie, 1993). In contrast, the Digermulhalvøya–Magerøya dykes were affected by a source with a composition in the direction of arrow B, with Ta/Th perhaps as low as 0.32. Such a source would have been more mafic in composition than that which affected the East Varangerhalvøya dykes. The Styret dyke, although having the same within-plate enrichment value as the East Varangerhalvøya dykes, shows crustal contamination from a source more akin to that of the Digermulhalvøya–Magerøya dykes. The lower crustal contamination values in the Styret and Digermulhalvøya–Magerøya dykes are consistent with their relatively minor Ta_N anomalies (Fig. 7).

Figure 9 shows bivariate plots using compatible and incompatible major and trace elements. The Magerøya data plot consistently with the samples from Digermulhalvøya and these have been combined for determining the best-fit line. R^2 values are greater for the East Varangerhalvøya data (0.80–0.97) compared

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to the Digermulhalvøya–Magerøya data (0.19–0.65; Fig. 9). The small spread of data from Styret makes the R^2 values unreliable although sometimes the Styret data is more akin to the Digermulhalvøya–Magerøya than the East Varangerhalvøya data. In all three data sets, Zr increases with decreasing MgO, but both TiO_2 and P_2O_5 decrease with decreasing MgO in the Digermulhalvøya–Magerøya samples. Compared to SiO_2 and Zr, TiO_2 also shows atypical behaviour, decreasing in concentration in more evolved samples. These atypical trends might reflect minor fractionation of ilmenite, titanomagnetite and apatite (Fig. 7). Within the East Varangerhalvøya data, there is a tendency for more evolved samples to come from the northwest.

4.c.3. Tectonic discrimination

Several tectonic discrimination plots have been tested, but, since they all show essentially the same features, only three are illustrated here. The compositions of the initial MORB and intermediate within-plate enriched stages (Pearce, 1983; Table 5) are shown where appropriate. The Ti/Y–Zr/Y (Pearce & Gale, 1977; Fig. 10a) as well as the Nb/Y–Ti/Y, and the TiO_2–Nb/3–Th plots (Pearce, 1982; Holm, 1985; not illustrated) indicate a plate-margin origin for the East Varangerhalvøya samples and within-plate origins for the Digermulhalvøya–Magerøya and Styret data. Similarly, on the Zr–Ti/100–Y*3 discriminant (Pearce & Cann, 1973; not illustrated), the Digermulhalvøya–Magerøya and Styret data lie within the within-plate field; the other samples lie at the boundary of the calc-alkaline and mixed fields. On the Zr–Ti plot (Pearce, 1982; not illustrated), all the samples lie on the MORB trend/field, but those from Digermulhalvøya and Magerøya lie wholly in the within-plate field, whilst the other samples lie within the MORB field, overlapping into the volcanic arc field.

On the Zr/4–Nb*2–Y plot (Meschede, 1986; Fig. 10c) the initial MORB melt lies within the N-type MORB field, but after within-plate enrichment the Digermulhalvøya–Magerøya data fall at the boundary of the alkaline/tholeiitic within-plate basalts and the tholeiitic within-plate/volcanic-arc basalts, whilst the samples from Varangerhalvøya lie in the latter field with, again, the Styret dyke data lying between the two other groups. In the Ta–Hf/3-Th plot (Wood, 1980; Fig. 10b), a similar initial progression from N-type MORB to tholeiitic within-plate basalts is seen, followed by a trend towards calc-alkaline basalts as a result of crustal contamination and fractional crystallization.

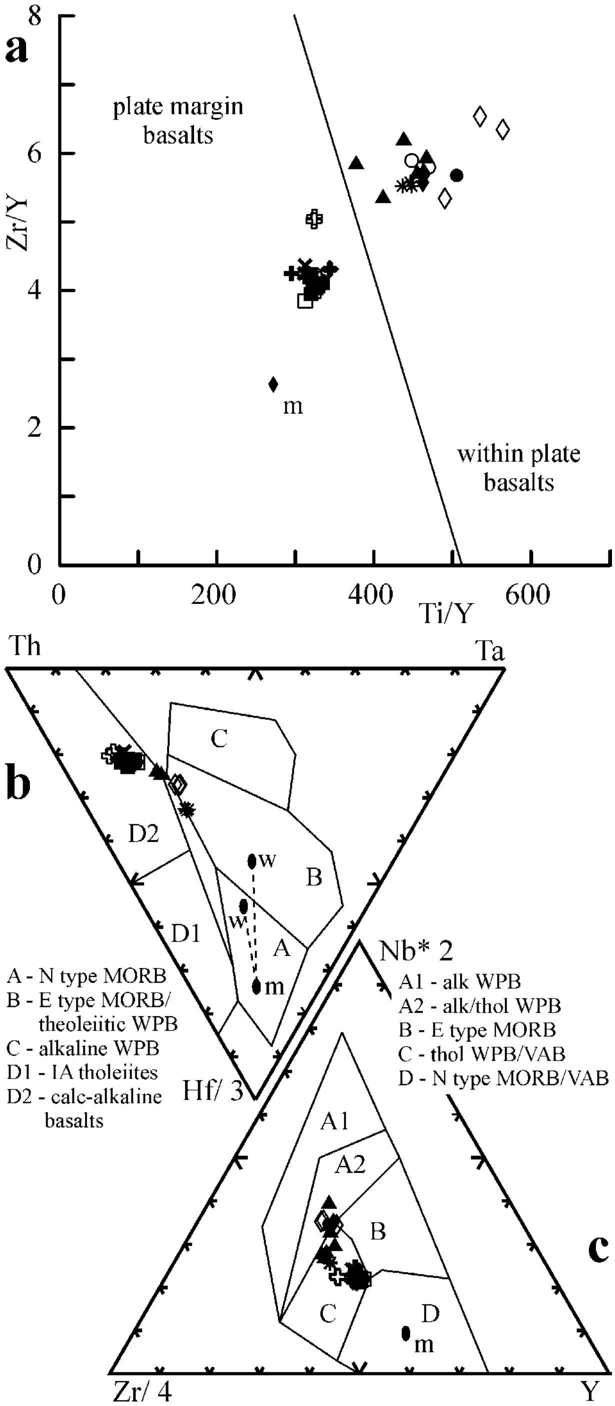

Figure 10. Tectonic discriminant plots of (a) Pearce (1982); (b) Meschede (1986) and (c) Wood (1980). Symbols as in Figure 5. 'm' indicates the calculated MORB composition of the dolerites using the Pearce (1983) method. 'w' indicates the composition after only within-plate enrichment in (b).

5. Discussion

5.a. Dyke groups

The aim of the paper is not to account in detail for the minor variations in geochemistry but rather to use the broad differences and similarities to combine the dolerite dykes into coherent groups and to use these to constrain regional geological models. In this respect, the dykes can be divided into three main groups: (1) Digermulhalvøya–Magerøya, (2) East Varangerhalvøya and (3) Styret.

5.a.1. Digermulhalvøya–Magerøya dykes

The Digermulhalvøya and Magerøya dykes plot in a distinct group or trend, separate from the East Varangerhalvøya dykes. In detail, the Digermulhalvøya dyke has more in common with the east Magerøya dykes than the central Magerøya dyke. In major and trace element plots, they all show similar sub-alkaline to transitional alkaline compositions, with the Digermulhalvøya and east Magerøya dykes being slightly more alkaline. High K_2O values suggest derivation from a low degree of partial melting, seen also in the high REE concentrations. Nb_N and Ta_N values in the spider diagrams indicate little crustal contamination occurred, confirmed by the low percentage crustal contamination in Table 5 (see also Fig. 8). Within-plate enrichment, however, was significant. In tectonic discriminant plots they lie in a cluster, sometimes quite distinct from the other samples, in the within-plate/continental fields, consistent with their transitional alkaline compositions and high trace element and REE concentrations. These samples also have a significant Sr anomaly (Fig. 7), suggestive of plagioclase crystallization. Wilson (1989, p. 307) ascribed similar negative Sr anomalies in continental flood-basalts to plagioclase fractionation. However, the absence of a negative Eu_N anomaly in the Digermulhalvøya–Magerøya data (Fig. 6, Table 4) makes this unlikely. An alternative explanation is that, at high pressures, the clinopyroxene-melt Sr partition coefficient was affected (Blundy & Green, 2000); such an explanation would also seem consistent with a continental within-plate setting compared to a continental plate-margin setting.

These dykes all have a ~NW–SE structural trend. As the Digermulhalvøya and east Magerøya dykes also have, within error, identical emplacement ages (*c.* 337–332 Ma; Fig. 2), they are presumed to be co-genetic. The central Magerøya dyke may have been emplaced later, in the earliest Permian (293 ± 22 Ma). Although Lippard & Prestvik (1997) suggested this date was too young, due to post-intrusion Ar-loss, the slight geochemical differences between the dykes suggest they *might* have different emplacement ages. Emplacement of all these dykes was almost certainly related to post-Caledonian extension in the Barents Sea, accommodated by normal reactivation of the Trollfjorden–Komagelva Fault under the Caledonian nappes (Roberts, Mitchell & Andersen, 1991; Lippard & Prestvik, 1997). Further examples of this Digermulhalvøya–Magerøya suite may be present in the remote areas of Sværholthalvøya and Nordkinnhalvøya (Fig. 1).

5.a.2. East Varangerhalvøya dykes

The East Varangerhalvøya dykes have very similar geochemistries, forming a cluster or a trend distinct from the Digermulhalvøya–Magerøya data. On the TAS plot (Fig. 5a) they range from basalts to basaltic andesites. Element ratios (Table 4) show a small but gradual variation towards the northwest. The REE data also show increasing values toward the northwest, reflecting increasing fractional crystallization and continental crustal contamination in that direction (Fig. 6).

The Seglkollen, Blåsenberg, Komagnes and Ekkerøya dykes all have positive anomalies of Ba, K and, to a lesser extent, Sr (Fig. 7). This pattern is typical of magmas which have undergone crustal contamination. In contrast, the Hamningberg–Sandfjord–Per Olsadalen dykes show minor negative Sr anomalies (Fig. 7), taken to reflect plagioclase crystallization, consistent with their slight negative Eu_N anomalies.

The East Varangerhalvøya samples have slight negative P anomalies (Fig. 7), but although this suggests apatite crystallization, bivariate plots show that P was still incompatible, increasing as MgO decreased (Fig. 9). The Ta/Th ratio (Fig. 8b) and marked Nb and Ta anomalies (Fig. 7) suggest a relatively high component of the LILE is attributable to crustal contamination (Table 5).

The dykes north of the Trollfjorden–Komagelva Fault cut Neoproterozoic pelitic rocks with an epizone-grade slaty cleavage (Roberts, 1972; Rice *et al.* 1989*b*). The Hamningberg dyke yielded a zircon U–Pb upper intercept discordia age of 567^{+30}_{-23} Ma (Roberts & Walker, 1997), interpreted as the age of intrusion, whilst the Sandfjord–Per Olsadalen dyke cuts a NE–SW-oriented cleavage dated to 520 ± 47 Ma (Taylor & Pickering, 1981). The dykes south of the Trollfjorden–Komagelva Fault cut sub-horizontal and essentially unmetamorphosed late Neoproterozoic III mudstones and sandstones in which no penetrative deformation has occurred, although Gorokhov *et al.* (2001) obtained Scandian Rb–Sr ages from ultra-fine illite fractions in the Varanger Parautochthon. Finally, in this paper it is concluded that the East Varangerhalvøya dolerites, together with the Styret dyke, yield a combined K–Ar whole-rock isochron age of 376 ± 30 Ma (MSWD 0.45). This result complements the Ar/Ar data of Guise & Roberts (2002), and taken together they give strong evidence that this was the emplacement age.

The geochemical similarities clearly demonstrate that the East Varangerhalvøya dykes form a coherent suite, but the constraints on the age of emplacement are conflicting. This is discussed in Section 5.b.

5.a.3. Styret dyke

The Styret dyke shows similarities and differences compared to the other groups and in different plots may lie with one or the other. The data lie with the East Varangerhalvøya samples in the TAS plot (Fig. 5a), but with the Digermulhalvøya–Magerøya samples in tectonic discrimination plots (Fig. 10). In contrast, it

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lies intermediate between the other groups in bivariate plots (Figs 8, 9).

However, the REE pattern does not show LREE enrichment and the spider plot also differs from the other samples (Figs 6, 7). The dyke must be younger than the Caledonian epizone cleavage age of *c.* 440 Ma (Rice & Frank, 2003), consistent with the K–Ar whole-rock age data of 362 ± 10 Ma (Fig. 2; Beckinsale, Reading & Rex, 1975) and the fact that the K–Ar data for this dyke fall on the 376 ± 30 Ma isochron (Fig. 3).

5.b. Re-assessment of isotopic age constraints

The emplacement age of the East Varangerhalvøya dykes is critical to interpretations of the regional geology. Roberts & Walker (1997) proposed that a zircon U–Pb upper-intercept age of 567^{+30}_{-23} Ma constrained the intrusion age of the Hamningberg dyke, with a later overprint at 392^{+25}_{-36} Ma. This interpretation received support from palaeomagnetic data, which show similar poles for the Komagnes and pre-Caledonian Båtsfjord dykes (Torsvik, Roberts & Siedlecka, 1995; Fig. 2). However, an alternative model could be the growth of zircon in basement fractures and intrusion of the metadolerite dykes at ~ 567 Ma, with later fracture reactivation (*c.* 392 Ma) and dolerite dyke emplacement (*c.* 376 Ma). The NE–SW orientation of the Kongsfjord and Båtsfjord dykes shows that NE–SW-oriented fractures formed in pre-Caledonian times (*c.* 550–580 Ma; Fig. 2), overlapping with the U–Pb age, whilst the NE–SW-oriented Styret dyke shows that post-Caledonian reactivation of this trend occurred. Essentially, the NE–SW trend was a long-standing direction of weakness.

Beckinsale, Reading & Rex (1975), in contrast, argued that K–Ar whole-rock ages, now confirmed at 376 ± 30 Ma, were emplacement ages. This interpretation receives support from several directions. First, the 332 ± 10 Ma K–Ar whole-rock age of the Digermulhalvøya dyke is within error the same as the 337.3 ± 0.4 Ma age of the structurally and geochemically similar east Magerøya dykes (Lippard & Prestvik, 1997), demonstrating that, in this case, the method gave reliable age-of-intrusion results. Second, the K–Ar whole-rock age of the Styret dyke (362 ± 10 Ma) is consistent with a post-Caledonian age; S3 cleavage formation in this westerly part of the peninsula occurred at *c.* 440 Ma (Rice & Frank, 2003) and the youngest Caledonian deformation age determined in Finnmark is 391 ± 9 Ma (Mitchell, *in* Roberts & Sundvoll, 1990). Third, the concordance of the results from the K–Ar and Ar/Ar (Guise & Roberts, 2002) methods is taken as a strong indicator that they are giving reliable results and that this is applicable to all the East Varangerhalvøya dykes. Note that the most convincing K–Ar isochron age of 376 ± 30 Ma overlaps with the lower U–Pb intercept age of 392^{+25}_{-36} Ma (Roberts & Walker, 1997).

In conclusion, the interpretation of the U–Pb zircon age data from the Hamningberg dyke given by Roberts & Walker (1997) is rejected. The Hamningberg dolerite, like the other East Varangerhalvøya dykes, was emplaced in post-Caledonian times, at *c.* 376 Ma.

5.c. Comparison with the other dykes in the area

The dykes on Rybachi and Sredni (Fig. 1), essentially still doleritic, might be of the same age as either the pre-Caledonian metadolerites in the Kongsfjord and Båtsfjord regions or the dolerite dykes on Varangerhalvøya; possibly both ages are represented (Fig. 2). The correlation is clearly critical for extrapolating deformation–dyke relationships from one area to another. The Kongsfjord and Båtsfjord suites suffered epizone alteration whilst the Rybachi and Sredni dykes underwent anchizone and diagenetic zone alteration, respectively (Rice & Roberts, 1995). The change in dyke trend across the Sredni–Rybachi Fault is directly comparable to that in the Varangerhalvøya dykes.

On the TAS plot, neither suite is comparable to the Varangerhalvøya dolerites. However, Y/Nb values for the Rybachi–Sredni suites (Roberts & Onstott, 1995) are comparable to the East Varangerhalvøya dykes, and on tectonic discriminant plots there is a closer affinity between these dyke groups than with the Kongsfjord–Båtsfjord metadolerites. Conversely, spider plots constructed from the limited trace element data show that the Rybachi–Sredni and the Kongsfjord–Båtsfjord dykes are similar in having very variable patterns, each dyke appearing to be different. Essentially, the lack of REE and comprehensive trace element data make comparisons inconclusive.

5.d. Regional considerations

In post-Caledonian time, an extended period of fracturing and dolerite dyke emplacement occurred between *c.* 376 and 332 Ma (possibly extended down to 293 Ma). The parallelism of the Digermulhalvøya–Magerøya dykes with the buried Trollfjorden–Komagelva Fault suggests emplacement as a result of post-Caledonian extension in the Barents Sea (Roberts, Mitchell & Andersen, 1991; Lippard & Prestvik, 1997). The east Magerøya and Digermulhalvøya dykes were emplaced at the same time (337–332 Ma) and have essentially identical trace and REE characteristics. The central Magerøya dyke has a slightly different composition, although very similar, and possibly a younger age (293 Ma; Roberts, Mitchell & Andersen, 1991). Lippard & Prestvik (1997) suggested this age was ‘down-dated’, as it differed from the age they obtained, but as the geochemistries differ, *both* ages might be correct.

The interpretation presented here casts strong doubt on the palaeomagnetic age data of Torsvik, Roberts & Siedlecka (1995) which purported to demonstrate

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that both the dolerite and metadolerite dykes were emplaced in pre-Caledonian times. Since the dolerites are clearly of post-Caledonian age, the validity of *all* of the palaeomagnetic age data must be doubted, even when it appears to support other data.

The *c.* 376 Ma old Varangerhalvøya dolerites reflect early post-Caledonian extension, but the extensional direction is not readily constrained. Both the dykes north and south of the Trollfjorden–Komagelva Fault make an angle of $\sim 67°$ with the fault (112° trend) and, thus, neither orientation is suggestive of simple strike-slip reactivation. The NE–SW trend of the dykes north of the Trollfjorden–Komagelva Fault parallels a known pre-existing direction of weakness, used by the Kongsfjord and Båtsfjord dykes. Equally, the N–S trend of the dykes south of the Trollfjorden–Komagelva Fault parallels the N–S dykes of ~ 546 Ma minimum age south of the Sredni–Rybachi Fault (Roberts & Onstott, 1995) and hence could be a reactivation direction on Varangerhalvøya. Last, although both the Komagnes and Ekkerøya dykes have en échelon segments stepping right, suggesting sinistral movement along a Riedel shear (R or R′), this may be more an effect of local surface stresses rotating the regional stress pattern than a true reflector of the stress pattern.

However, ~ 30 km north of Varangerhalvøya, the Austhavet Fault, which coincides with the post-Caledonian shelf–basin boundary, is inferred to have had a sinistral movement (Gabrielsen, 1984). Inferring a late sinistral transtension on the Trollfjorden–Komagelva Fault could allow the σ_1 and σ_3 directions to rotate far enough to allow reactivation of the pre-Caledonian NE–SW and N–S fracture directions as subnormal to σ_3 (NE–SW) and as en échelon fractures along the R′ direction reactivating N–S fractures.

6. Conclusions

The NE–SW orientation of the metadolerites and dolerites in the Varangerhalvøya area reflects a longstanding orientation of crustal weakness. This was first utilized during the emplacement of the metadolerites dyke swarm with a best fit age of 577 ± 14 Ma (MSWD 1.04). This age is compatible with Sm–Nd and Rb–Sr ages of some metadolerites emplaced in the western part of the Kalak Nappe Complex and is taken to reflect crustal extension and thinning, with dyke intrusion, during the Neoproterozoic III.

This event is also seen in the upper intercept U–Pb age of zircons from the NE–SW-trending Hamningberg dolerite dyke (Roberts & Walker, 1997), here interpreted to simply reflect basement fracturing, but without intrusion. This re-interpretation removes the only constraint for the occurrence of Timanian-aged deformation on Varangerhalvøya.

Later reactivation of this NE–SW trend at *c.* 390–370 Ma, with contemporary N–S dyke emplacement south of the Trollfjorden–Komagelva Fault, resulted in the emplacement of dolerite dykes. These have tholeiitic plate-margin compositions reflecting within-plate enrichment of a MORB source, with subsequent fractional crystallization and crustal contamination by the upper crust.

In the Digermulhalvøya–Magerøya area, post-orogenic, WNW–ESE-trending continental within-plate dolerite dykes occur. These were emplaced between 337 and 293 Ma (possibly in two separate events) and have compositions reflecting a lower degree of partial melting and with a crustal contamination from an unknown source of more mafic composition than that which affected the East Varangerhalvøya dykes.

The Styret dyke, in the western part of Varangerhalvøya is part of the same suite as the East Varangerhalvøya dykes, but was affected by the same crustal contaminant as the Digermulhalvøya–Magerøya dykes. This may be indicating a fundamental change in the type of continental crust at some point between the East Varangerhalvøya and Styret dykes.

All three suites of dolerite dykes are consistent with emplacement as a result of crustal extension during latest Devonian to perhaps earliest Permian times, associated with development of the Barents Sea to the north.

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