Mafic dykes in the Leksdal Nappe at Sørli, Central Norwegian Caledonides: geochemistry and palaeotectonic implications

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Beckholmen, M. & Roberts, D. 1999: Mafic dykes in the Leksdal Nappe at Sørli, Central Norwegian Caledonides: geochemistry and palaeotectonic implications. *Norges geologiske undersøkelse Bulletin 435,* 59-67.

Mafic dykes intruding feldspathic metasandstones of the Leksdal (Särv) Nappe in the Sørli district of Nord-Trøndelag, Central Norway, vary from weakly foliated, porphyritic types to more common, strongly schistose, sparsely phyric to aphyric biotite-amphibole or biotite schists. Analytical data, however, show that the dykes are chemically fairly homogeneous. The geochemical signature of the dykes is transitional, i.e. between tholeiitic and alkalic, and points indisputedly to a within-plate setting. Rare-earth element data show clear LREE-enriched, mildly alkaline tendencies. The geochemistry of the Sørli dykes, based on trace and rare-earth element abundances, is, in fact, quite similar to that of the 'mildly alkaline' group of metadolerites distinguished by earlier workers from diverse parts of the Särv Nappe, and equivalent nappes, over wide areas of the Scandinavian Caledonides.
Although the emplacement age of the Sørli dykes is not known it is inferred to be Vendian, based on data available from comparable dolerite dykes in other parts of the Särv and immediately overlying Seve Nappes. Dolerite dykes of T- and N-MORB affinities in some of the highest thrust-sheets of the Baltoscandian margin successions farther north have yielded Mid to Late Vendian ages, and are inferred to have intruded immediately prior to the actual inception of Iapetus sea-floor spreading. The LREE-enriched, mildly alkaline dykes from Sørli, cutting a fluvial metasedimentary succession at the Middle Allochthon tectonostratigraphic level, are thus assumed to have intruded in a more inboard, continental setting, and most likely at a just slightly earlier stage of latest Neoproterozoic crustal extension and rifting, perhaps in Early Vendian time.

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Introduction

In the Caledonides of Scandinavia, the 'sandstone nappes' of the Middle Allochthon constitute a distinctive though somewhat discontinuous element in the tectonostratigraphy of the mountain chain. Forming part of the original Neoproterozoic to Early Palaeozoic miogeocline of the Baltoscandian margin of the palaeocontinent Baltica, these thick, arkosic sandstone successions were, in places, hosts to widely occurring dolerite dykes. In the higher thrust sheets (Särv Nappes) of the Middle Allochthon, and also in different parts of the immediately overlying Seve Nappe Complex (Seve Nappes) of the basal part of the Upper Allochthon, such mafic dykes are particularly abundant. In the context of tectonomagmatic evolution of the Caledonide orogen, the profuse dyke activity is considered to relate to a phase of Vendian to Early Cambrian crustal extension and rift magmatism, prior to incipient sea-floor spreading and the birth of the Iapetus Ocean (Gee 1975, Roberts & Gale 1978, Kumpulainen & Nystuen 1985, Stephens et al. 1985, Andréasson 1994).

In several areas, and in diverse thrust sheets, many of these mafic dykes, or dyke swarms, have been the subject of geochemical investigations (e.g., Roberts 1975, 1990, Andréasson et al. 1979, Solyom et al 1979, 1985, Stølen 1994a, b, Svenningsen 1994), the results of which are discussed briefly later (p. 65). There have also been a few attempts at isotopic dating that, based on the more reliable U-Pb, Sm-Nd and ^{40}Ar-^{39}Ar methods, are pointing to latest Riphean to Vendian ages of dyke emplacement (ranging from c. 665 to c. 573 Ma) (Claesson & Roddick 1983, Zwaan & van Roermund 1990, Svenningsen 1994, 1996). In one area in Southwest Norway, in the Sveconorwegian crystalline basement of Baltica southeast of the Caledonian front, a dolerite from the Egersund dyke swarm has also yielded a Vendian emplacement age (U-Pb, baddeleyite, 616 ± 3 Ma; Bingen et al. 1998).

In the Caledonides of Central Norway, mafic dykes occurring in the arkose-dominated *Leksdal Nappe* on the southwestern flank of the Tømmerås Antiform, east of Steinkjer, have been studied by Andréasson et al. (1979). Analyses of dykes occurring to the northeast of Tømmerås and also in the Orkanger district, southwest of Trondheim, were incorporated in a later statistical investigation (Solyom et al. 1985), but there was no discussion of these particular dykes or their geochemistry. In this short contribution we describe, and present geochemical data from, mafic dykes occurring in the Leksdal Nappe in the Sørli district of the Grong region, in the county of Nord-Trøndelag.

Regional setting

Sørli lies in the eastern part of the area covered by the 1:250,000 bedrock map-sheet 'Grong' (Roberts 1997), an area which contains most of the elements of Caledonide tectonostratigraphy from the parautochthonous Olden Nappe in

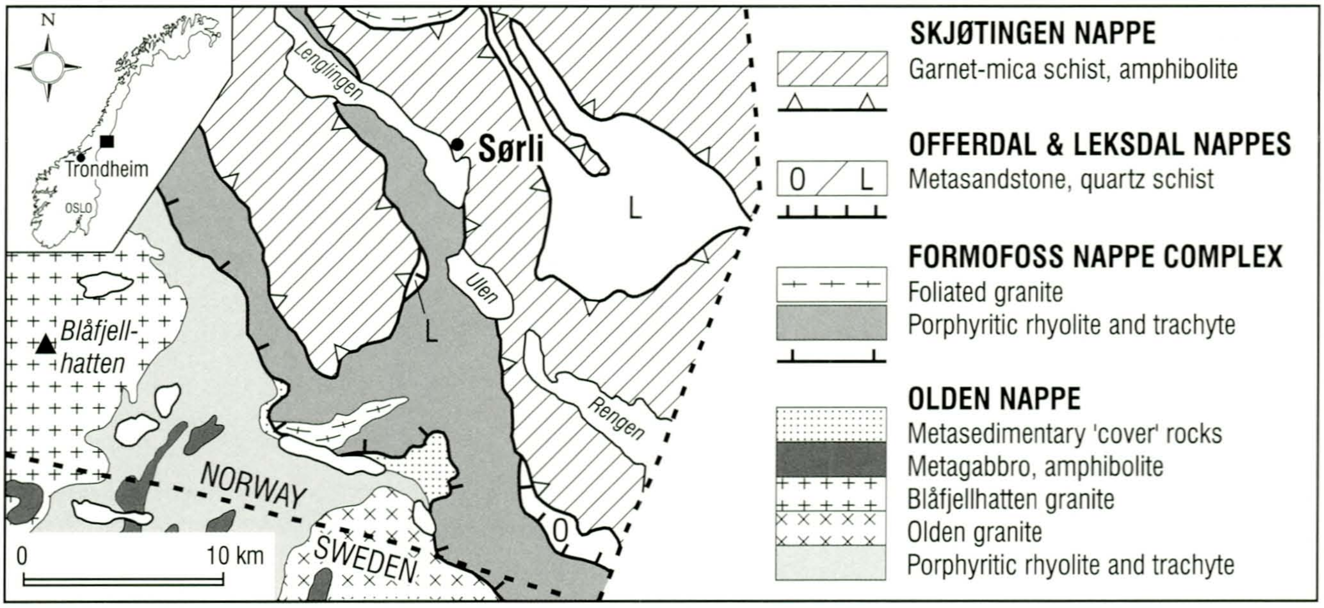

Fig. 1. Simplified geological/tectonostratigraphic map of the Sørli district. In the Offerdal & Leksdal box, O - Offerdal (=Dearka) Nappe and L - Leksdal Nappe.

the core of the Grong-Olden Culmination through the several nappes of the Lower, Middle and Upper Allochthons (Roberts & Gee 1985) into the Helgeland Nappe Complex of the Uppermost Allochthon. The Middle Allochthon is only modestly represented, and mainly as small, lensoid thrust sheets of meta-arenites in the lower Dearka (=Offerdal) and upper Leksdal (=Särv) Nappes.

The greenschist-facies metasandstones, quartz schists and thin quartzites of the lower, dyke-free part of the Middle Allochthon (Dearka/Offerdal Nappe) are inferred to be of Neoproterozoic age. Some 20 km south of Sørli, fluvial sandstones of the Offerdal Nappe are locally highly strained and transformed into thin-banded flagstones of commercial quality. Farther southeast into Jämtland, Sweden, the Offerdal Nappe is thicker and more extensive, and there the metasandstones have formed the basis of an important flagstone industry with long traditions.

The overlying Leksdal Nappe occurs mainly to the east and southeast of Sørli, but also as a small, 2 x 0.5 km lens just west of the lake Ulen (Fig. 1) (Beckholmen & Roberts 1989). Lithologies vary from greenschist-facies, medium- to thick-bedded, feldspathic sandstones to mica-rich sandstones, semi-pelites and thin quartzites and mica schists. Cross bedding is quite common in many sandstone beds, especially in low-strain zones; and the succession as a whole is considered to be of fluvial origin. Flagstones are less well developed, occurring in a few, restricted, ductile high-strain zones and more particularly close to the nappe boundaries. Mafic dykes are fairly common features of the Leksdal Nappe. Depending on the nature of the original host lithology and the degree of strain, the dykes vary from massive and porphyritic to strongly schistose. Comparable variations in dyke character, dependent upon the degree of ductile shear deformation, have been described from the Turtbakktjørna and Svarttjørna lenses, on the southwestern side of the Grong-Olden Culmination (Kautsky 1978, Gilotti 1989).

The mafic dykes

Field relationships and petrography

The mafic dykes occur throughout the folded and schistose psammitic rocks of the Leksdal Nappe but they are never sufficiently numerous to warrant the designation 'dyke swarm', as in other parts of the mountain belt in the Särv and Seve Nappes. On Gunnarfjell, where exposure is comparatively good, one of several subparallel dykes can be followed along strike over several hundred metres.

In field appearance (Fig. 2), the mafic dykes are quite heterogeneous, varying from comparatively massive, weakly foliated, porphyritic types to strongly schistose, finer grained, aphyric or sparsely phyric, biotite-amphibole or biotite schists. In general, this change in character is clearly a reflection of the degree of deformation of the rocks in different parts of the nappe, as well as the dyke thickness. Thicknesses vary from the centimetre scale up to 2-3 m; in these cases, the very thin dykes are generally fine-grained and strongly schistose, and concordant with the tectonised layering, whereas the thickest dykes tend to be variably porphyritic and may lie at a small to moderate angle to the compositional layering.

Mapping has shown that the rocks of the Leksdal Nappe, in this area, have been affected by polyphase Caledonian deformation. In the multilayered, psammite-pelite parts of the succession the earliest, syn-metamorphic folds are tight to isoclinal (Beckholmen 1987), with axial trends and stretching lineations varying from E-W to ESE-WNW. Dykes are particularly thin, and may be excised along the attenuated long limbs of early, asymmetric folds and in localised shear zones. On the contrary, the thicker, more massive dykes occur in zones of markedly lower strain and in fold short limbs and composite hinges, where cross-bedding can also be recognised in favourable localities. There are also examples showing that some of the early folds developed initially adjacent

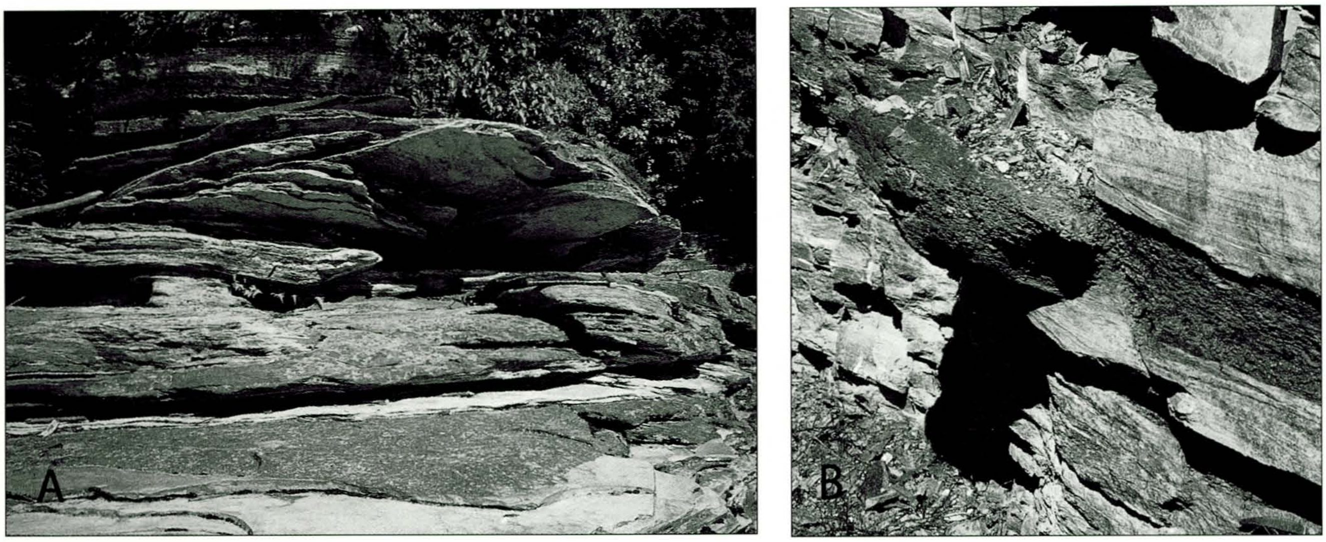

Fig. 2. (A) Mafic dykes in metasandstones, both involved in synmetamorphic, tight folding along WNW-ESE axes; photo, looking northwest. Riverside exposure, c. 150 m NE of the bridge over the Inderdalsåa, c. 3 km WSW of Jule. Grid ref. 4115 1570. (B) Shear-banded mafic dyke in arkosic metasandstones; photo, looking northwest. Tight to near-isoclinal folds in the metasandstones both above and below the dyke. Roadside exposure along the road from Bråsånestangen to Bakken. Grid-ref. 5120 1470.

to the dykes -- the dykes having acted as a buffer to the imposed contractional deformation (Roberts 1989). In these cases the dykes probably lay at fairly high angles to bedding and were progressively rotated into subparallelism with the transposed layering as the simple-shear deformation proceeded (cf. Gayer et al. 1978, Krill 1986).

In addition to the fold deformation and thinning, a later tectonic feature of the dykes is that of boudinage. This flattening deformation also affected packages of folded metasedimentary layers, and most likely relates to a fairly late but ductile component of strain of pure shear character. The lensoid nature of the small 'outliers' of the Leksdal Nappe in this region (see above) can probably be ascribed to this episode of deformation.

In thin-section, composite nematoblastic-lepidoblastic to wholly lepidoblastic textures are prevalent among the non-porphyritic dyke rocks, which is a direct reflection of the degree of strain and accompanying metamorphic transformation. In the most extreme cases, the retrogression has yielded biotite schists, in one example with a Fe-rich biotite groundmass surrounding scattered, 1-2 mm-long muscovite metacrysts. In general, however, the schistose dykes are composed of biotite, actinolite and epidote/clinozoisite, with lesser amounts of recrystallised plagioclase, quartz and calcite, and accessory apatite, sphene and titanomagnetite. Relict 2-3 mm plagioclase crysts, where present, are transformed to small recrystallised grains. In some cases, recrystallised plagioclase is associated with profuse small laths and grains of biotite, epidote and calcite. These particular secondary minerals may have been derived from original glomerophyric assemblages of clinopyroxene and plagioclase.

The porphyritic dykes are intensely diaphthoritised. Original plagioclase laths up to 5-6 mm in size have been replaced by a dense mat of sericite surrounded by epidote/clinozoisite. The original pyroxene (?augite), where present, is uralitised and has partly (marginally) or entirely been replaced by actinolite, which shows up as dark green to black laths up to 1 cm in length. In the groundmass, the retrogression has produced a finer grained assemblage of epidote, biotite, quartz, chlorite, sericite and some magnetite.

Geochemistry

A selection of fourteen samples of mafic dykes of varying character, from porphyritic to strongly schistose, were taken from different parts of the nappe. Major and trace elements were analysed on fused glass beads and pressed powder pellets, respectively, using an automatic Philips 1450/20 XRF spectrometer, at the Geological Survey of Norway, Trondheim. Calibration curves were made with international standards. Ferrous iron, H_2O^+, H_2O^- and CO_2 were determined by wet chemical methods. Four of the samples have been analysed by INAA for eight rare earth elements (REE) and the elements Sc, Co, Hf, Ta, Th and U, at the University of Leuven, Belgium, following the method described and evaluated by Pedersen & Hertogen (1990). The 'in house' silicate rock standards used have been repeatedly calibrated against international reference standards. The analytical data are shown in Tables 1 and 2.

The variation in character of the dykes recognised in the field, from markedly porphyritic to non-porphyritic and schistose, does not appear to be reflected in the general major element chemistry (Table 1), except perhaps for the alkalies and for just one or two isolated dykes. K_2O, for example, shows two unusually high and low values of 6.58 and 0.96 wt.%, respectively, in the former case associated with the exceptional occurrence of porphyroblastic muscovite; and in three other dykes, K_2O contents exceed 5 wt.%. Na_2O values, on the other hand, are in some cases quite low. Some of these discrepant values may possibly be ascribed to wall-rock contamination. SiO_2 values range from 45.5 to 49.5%, and TiO_2 from 1.4 to 2.8%. In a classical alkalies-silica diagram (Fig. 3),

Table 1: Mafic dykes from the Leksdal Nappe, Sørli; major and trace element compositions.

Sample	41-87	42-87	57-87	58-87	60-87	71-87	75-87	106-87	112-87	113-87	15-88	17-88	18-88	19-88
SiO_2	45.46	46.38	47.56	47.23	49.45	46.71	45.68	45.64	47.92	48.54	45.45	48.08	45.68	49.20
TiO_2	1.64	2.18	2.45	2.44	2.78	1.36	2.29	1.70	1.58	1.62	2.23	2.30	2.02	2.70
Al_2O_3	14.29	14.07	14.33	14.57	13.90	14.57	14.37	17.06	13.38	16.65	14.29	14.53	14.46	14.87
Fe_2O_3	2.48	2.51	2.51	2.67	4.03	3.25	3.61	3.14	2.23	2.64	4.18	2.85	2.42	3.23
FeO	8.61	9.54	8.71	8.76	8.66	5.99	10.06	6.86	8.43	6.42	7.16	8.95	8.82	9.45
MnO	0.20	0.21	0.17	0.17	0.19	0.15	0.30	0.17	0.18	0.14	0.35	0.19	0.18	0.19
MgO	6.48	5.07	5.10	5.19	4.77	9.85	5.63	6.67	7.38	6.33	4.67	5.49	5.46	4.30
CaO	9.26	8.30	8.95	8.65	8.32	11.75	8.92	12.55	10.49	11.30	7.10	8.73	8.90	7.18
Na_2O	0.23	0.83	0.79	0.87	0.22	1.49	2.23	2.25	2.58	1.77	0.45	0.10	1.25	1.22
K_2O	5.03	5.09	4.64	4.71	4.20	1.71	2.68	0.96	1.80	1.39	6.58	4.73	5.03	4.43
P_2O_5	0.29	0.47	0.84	0.82	0.75	0.38	1.23	0.57	0.32	0.28	0.44	0.40	0.46	0.74
H_2O^+	2.76	2.73	2.43	2.51	2.14	2.33	2.05	1.91	2.06	2.22	3.00	2.32	2.36	1.89
H_2O^-	0.14	0.07	0.06	0.07	0.08	0.08	0.12	0.08	0.13	0.04	0.04	0.03	0.04	0.02
CO_2	3.10	2.70	1.60	1.40	0.00	0.10	0.00	0.00	1.20	4.30	4.30	1.44	3.71	0.15
Sum	99.97	100.15	100.14	100.06	99.49	99.72	99.17	99.56	99.68	100.24	100.24	100.14	100.79	99.57
Zr	119	228	213	196	275	173	217	171	149	158	276	252	209	321
Y	31	34	40	36	43	24	44	25	28	29	34	38	28	35
Sr	313	367	466	457	500	577	404	855	365	411	219	366	358	517
Rb	211	249	223	224	154	73	89	28	51	45	306	232	240	195
Zn	133	125	133	135	115	76	131	78	84	82	118	151	123	121
Cu	≤5	7	≤5	≤5	46	73	24	30	14	45	18	15	11	54
Ni	90	46	49	51	38	183	43	87	85	62	19	24	29	18
Cr	114	64	89	107	81	356	81	154	194	149	12	20	18	15
Ba	715	815	606	640	933	278	794	713	380	381	773	663	635	788
Nb	26	35	37	30	40	26	59	69	23	20	31	27	33	56
V	241	270	204	208	282	188	314	246	255	220	218	233	207	232

the samples straddle the dividing line between the subalkaline and alkaline fields and extend well into the latter field.

Since the elements K and Na are known to be particularly mobile during metamorphism, the analytical data were plotted in other diagrams featuring more immobile elements such as P, Ti, Zr, Nb and Y (Floyd & Winchester 1975); and in all these cases the data again reveal alkaline tendencies. The average Nb/Y ratio of 1.1, however, (which includes one analysis with an exceptional ratio of 2.76) is only slightly above the suggested divide between alkali basalts (>1.0) and tholeiites (< 1.0) (Pearce & Cann 1973, Solyom et al. 1985). On this basis, the Sørli metadolerites can thus be classified as mildly alkaline.

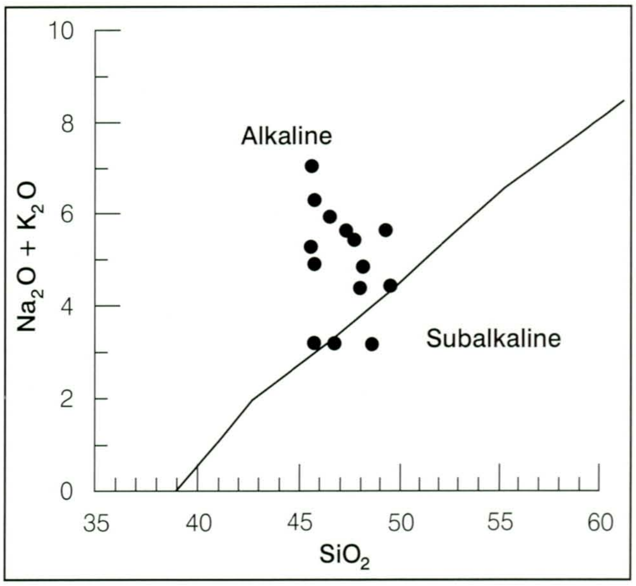

Fig. 3. Alkalies-silica diagram showing the distribution of the Sørli mafic dyke samples (filled circles).

In the V-Ti/1000 diagram of Shervais (1982) the dyke samples fall equally on either side of the dividing line between alkaline basalts and MORB (Fig. 4), denoting some measure of transitional geochemical character, irrespective of their pal-

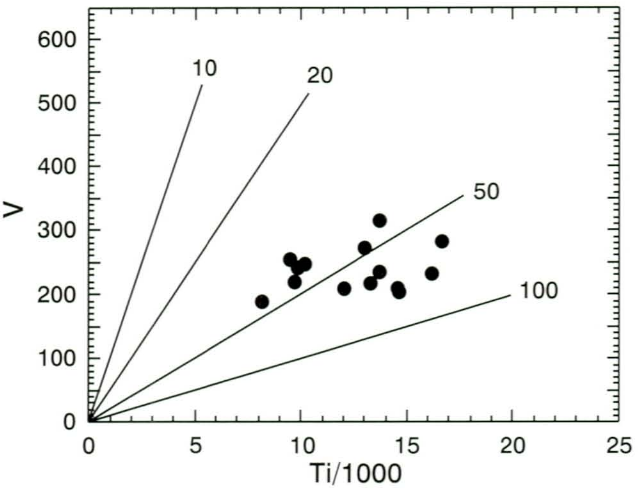

Fig. 4. The Sørli mafic dyke samples plotted on the V-Ti diagram of Shervais (1982). The Ti/V ratio field between 20 and 50 covers MORB, back-arc basin and continental basalts; that between 50 and 100 is for alkali and ocean-island basalts.

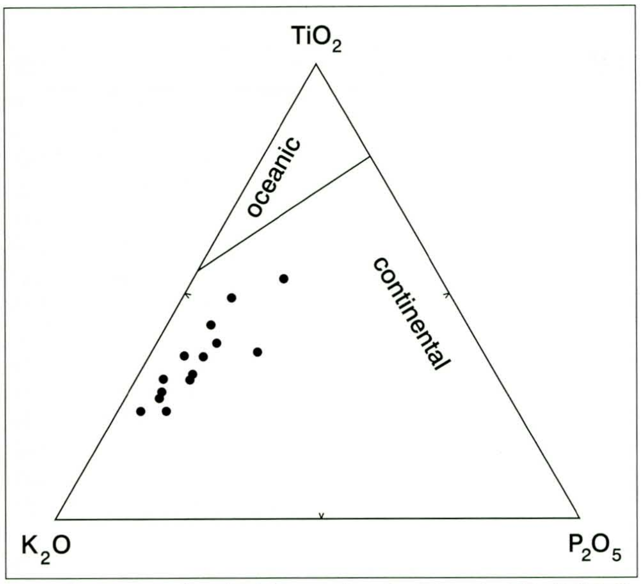

Fig. 5. The same Sørli mafic dyke samples plotted on the TiO_2-K_2O-P_2O_5 diagram of Pearce et al. (1975).

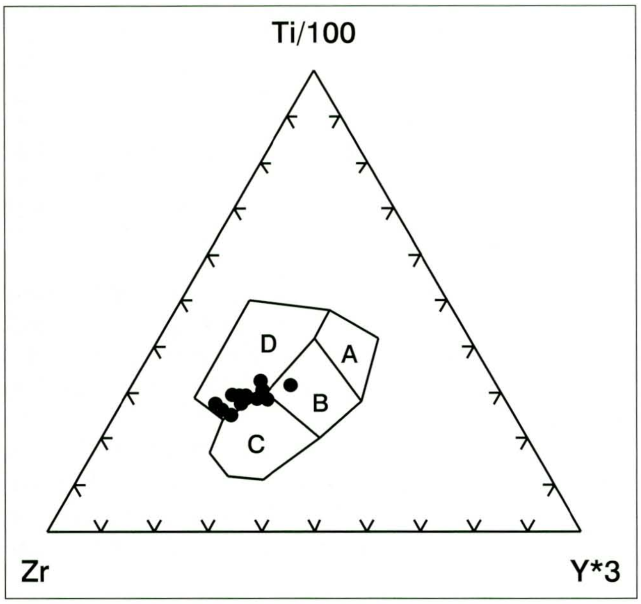

Fig. 6. Ti-Zr-Y discriminant diagram of Pearce & Cann (1973) showing the distribution of the mafic dyke samples from Sørli. Field A – low-K tholeiites; B – ocean-floor tholeiites; C – calc-alkaline basalts; D – within-plate tholeiites.

aeoenvironmental setting. We do know, of course, that the dykes were emplaced into fluvial feldspathic sandstones, and this non-oceanic affiliation is also confirmed in the TiO_2-K_2O-P_2O_5 diagram of Pearce et al. (1975) (Fig. 5).

Using the incompatible trace elements Y, Nb and Zr, partly in association with Ti, the Ti-Zr-Y diagram of Pearce & Cann (1973), for example (Fig. 6), indicates a largely within-plate character for the Sørli dykes, and this is confirmed on the Zr/Y-Zr plot (Fig. 7) of Pearce & Norry (1979). On the Nb-Zr-Y diagram of Meschede (1986), there is a tendency for the samples to fall in the tholeiitic (rather than alkaline) sub-field of the within-plate association (Fig. 8). However, the transitional, within-plate, geochemical character of the Sørli dykes is also depicted quite clearly in the Ti/Y-Nb/Y log-log plot of Pearce (1982) (Fig. 9).

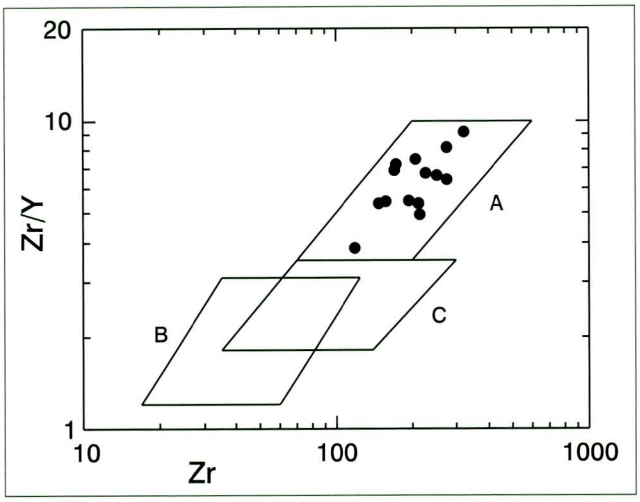

Fig. 7. Zr/Y- Zr plot of the same dyke samples; diagram from Pearce & Norry (1979). Field A - Within-plate basalts; B - Volcanic arc basalts; C - Mid-ocean ridge basalts.

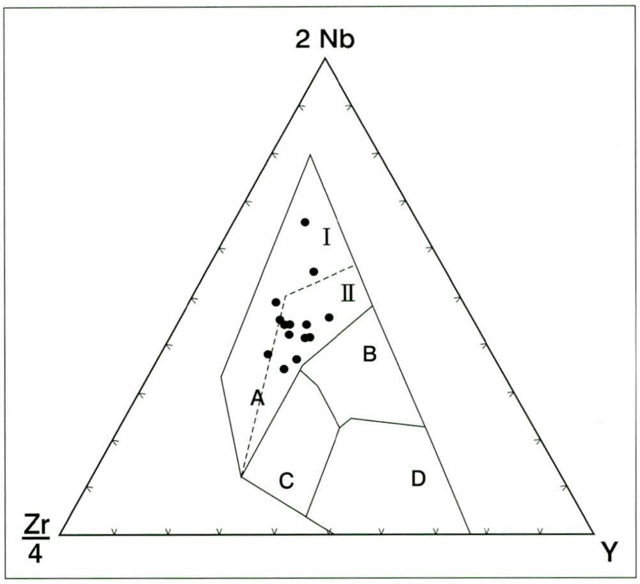

Fig. 8. The same Sørli dyke samples plotted on the Nb-Zr-Y diagram of Meschede (1986). Field A – within-plate basalts (AI – within-plate alkali basalts; AII – within-plate alkali basalts and tholeiites); B – E-type MORB; C – within-plate tholeiites and volcanic arc basalts; D – N-type MORB and volcanic arc basalts.

The rare earth element (REE) contents of three fairly representative samples and another characterised by higher Fe, P and Nb contents were analysed by INAA. The data are given in Table 2. The chondrite-normalised patterns show a clear LREE enrichment, and no trace of any Eu anomaly (Fig. 10). Lanthanum enrichment varies from c. 90 to 145 times chondritic abundances in the main group of three samples (Fig. 10), but reaches close to 300 in the case of sample 75-87. La_N/Lu_N ratios vary from 7.7 to 11.4 for the three comparable samples, but for sample 75-87 this same ratio is 20. Apart from this anomalous, highest-LREE sample, the other analyses and ratios, and chondrite-normalised patterns, are very similar to those of a 'mildly alkaline' group of mafic dykes reported

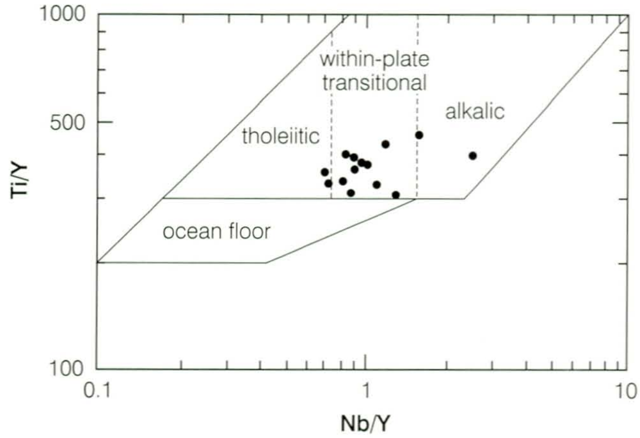

Fig. 9. The Sørli dykes plotted on the Ti/Y- Nb/Y diagram of Pearce (1982), where the 'within-plate' field is subdivided into tholeiitic, transitional and alkaline types.

Table 2: Rare-earth element and Ta, Hf, Th, U and Sc contents (ppm) of the representative samles of mafic dykes from the Leksdal Nappe, Sørli.

Sample	57-87	75-87	15-88	17-88
La	49.7	101	36.9	31
Ce	108	212	82	70
Nd	52.4	94	42.4	37.1
Sm	9.8	15.6	8.3	7.74
Eu	2.84	4.50	2.38	2.31
Tb	1.25	1.71	1.15	1.13
Yb	2.9	3.6	3.3	2.9
Lu	.44	.52	.49	.39
Ta	2.57	3.52	2.01	1.69
Hf	5.5	5.3	6.7	6.1
Th	5.3	10.1	3.7	2.9
U	1.3	2.4	1.4	.84
Sc	27.1	24.5	30.0	32.4

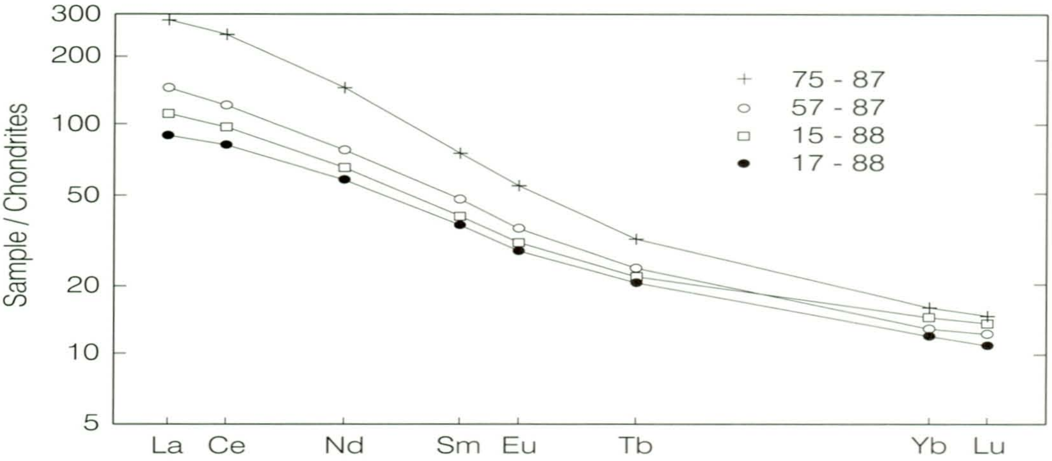

Fig. 10. Chondrite-normalised REE profiles for three representative samples and one other sample of the Sørli mafic dykes. Sources of chondritic values for normalisation: Masuda et al. (1973), Nakamura (1974) and Evensen et al. (1978).

from the Särv Nappe (Solyom et al. 1985). This also comes out quite clearly in a chondrite-normalised La/Sm-La/Yb variation plot (Fig.11).

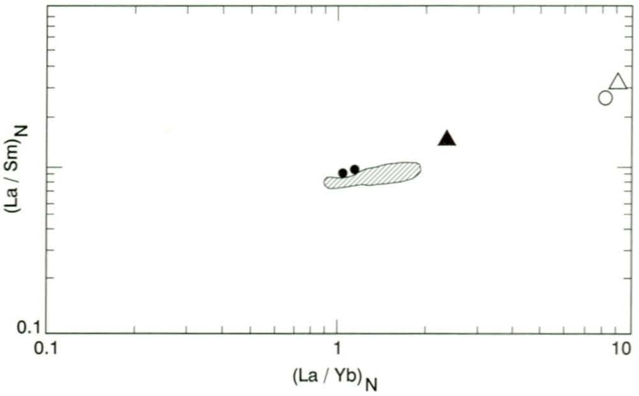

Fig. 11. Chondrite-normalised plot of ratios La/Sm vs. La/Yb. Circle – Sørli average (n=3); open triangle – Särv Nappe mildly alkaline dolerite dykes (mean); filled triangle – Särv Nappe tholeiitic dolerite dykes (mean) (Solyom et al. 1985); two dots – dolerite dykes from the Corrovarre Nappe, Troms (Roberts 1990); elongate lined area – Palaeogene T-MORB tholeiitic lavas and dykes from the Vøring Plateau (Viereck et al. 1988).

In summary, the trace and rare-earth element geochemical signatures of the Sørli dykes are denoting transitional, within-plate features with clear, LREE-enriched, mildly alkaline tendencies. The continental, within-plate signature is consistent with their field occurrence in continental, fluviatile, feldspathic sandstones.

Discussion

The occurrence of mafic dykes and dyke swarms throughout the successions of the Särv and Seve Nappes which originally formed parts of the Baltoscandian passive margin and Baltica-Iapetus, continent-ocean transition zone is now generally accepted to relate to a major episode of Late Neoproterozoic, rift-related magmatism. Reviews of this phase of miogeoclinal basin development, essentially a precursor stage of extension in the break-up of the palaeocontinent Rodinia, can be found in Roberts & Gale (1978) and Kumpulainen & Nystuen (1985).

Constraints on the timing and duration of rifting and emplacement of individual dykes in the various Caledonian nappes and thrust sheets are comparatively few. From the type area of the Ottfjället dolerite dykes in the Särv Nappe, in

Jämtland, Central Sweden (some 150 km SSW of Sørli), Claesson & Roddick (1983) obtained a ^{40}Ar-^{39}Ar intrusion age of 665 ± 10 Ma. Similar dykes from the Sætra (=Särv) Nappe of the Oppdal area, south-central Norway, yielded a Rb-Sr isochron age of 745 ± 37 Ma (Krill 1983). In more recent years, Sm-Nd and U-Pb zircon dating of mafic dykes from the Seve/Kalak and Särv Nappes of Troms, northern Norway, and neighbouring areas in northern Sweden, has yielded Vendian ages - 582 ± 30 Ma (Sm-Nd, Zwaan & van Roermund 1990); 573 ± 74 Ma (Sm-Nd, Svenningsen 1994); and 608 + 1 Ma (U-Pb zircon, Svenningsen 1996). The comparable geological and tectonostratigraphic situations of these dykes make it reasonable to assume that most, though not necessarily all of this rift-related dyke intrusion along the Baltoscandian margin occurred during the Vendian period. The Sørli metadolerite dykes are probably too deformed and metamorphosed to yield any meaningful isotopic intrusion age. Based on the evidence from other areas, however, we consider that these particular dykes are also likely to have intruded during Vendian time.

Clues as to the relative ages of the abundant mafic dykes in the Särv and Seve Nappes may be obtained from their geochemical signatures as well as from the nature of the host-rock lithologies and their positions in Caledonide tectonostratigraphy. A bipartite division of Särv Nappe dolerite dykes into (1) a large and characteristic tholeiitic group and (2) a subordinate but quite significant mildly alkaline group was demonstrated by Solyom et al. (1985) based on a statistical discriminant analysis of samples over a 600 km-long by 200 km-wide belt. The Sørli mafic dykes thus appear to belong to the second, mildly alkaline group.

Farther north, in Troms, tholeiitic dolerite dykes in the Corrovarre Nappe show homogeneous T-MORB affinities (Roberts 1990), comparable to those of Tertiary dykes and lavas from the North Atlantic Vøring Plateau (Viereck et al. 1988). The Corrovarre Nappe occurs in the uppermost part of the Kalak Nappe Complex, which is believed to be a northern equivalent of the Seve Nappes (Roberts 1988, Andréasson et al. 1998). Studies by Andreasson et al. (1992), Stølen (1994a,b, 1997) and Svenningsen (1994, 1995), in Troms and Norrbotten, have also shown that the mafic dykes there, in thrust sheets of the Seve Nappe Complex, are mainly of T-MORB to locally N-MORB character. These particular dykes occur mainly as swarms and in the higher nappes (derived from a setting in the outermost parts of the continent-ocean transition zone) they cut calcareous arenites of marine origin. The youngest isotopic dates so far recorded (see above) are from these T-MORB tholeiitic dolerites, which accords with their interpretation as dykes intruded immediately prior to the inception of Iapetus sea-floor spreading (Roberts 1990, Stølen 1994b).

Up to now, there are no reliable dates for the mildly alkaline mafic dykes from the Särv Nappe. However, in view of their transitional, within-plate geochemical traits and emplacement in a more inboard, fluvial, continental setting, they should be expected to represent a relatively slightly earlier phase of dyke intrusion dating from the initial stages of crustal extension and rifting in, perhaps, Early Vendian time. The dolerite dyke in the Egersund swarm that provided the c. 616 Ma baddeleyite age belongs to an alkaline subsuite (Bingen et al. 1998, Bingen & Demaiffe 1999). Although these particular dykes are not situated in the Caledonian allochthon they do represent hypabyssal magmatism from the Late Neoproterozoic passive margin of Baltica, and thus suggest that the time gap between intrusion of the distinctive alkaline/mildly alkaline and N-/T-MORB mafic dyke swarms may have been comparatively short.

Conclusions

Mafic dykes intruding feldspathic metasandstones of the Leksdal Nappe in the Sørli district of Nord-Trøndelag, Central Norway, vary from massive porphyritic types to more common, strongly schistose, aphyric biotite-amphibole or biotite schists. Despite these differences in appearance, and the fact that metamorphic grade reached greenschist facies, geochemical data from vari-textured dykes from different parts of the nappe show a reasonable homogeneity, with just one or two exceptions, and the samples cluster fairly well on most trace-element discriminant diagrams.

The geochemical signature of the dykes is transitional, i.e., between tholeiitic and alkalic, and points indisputedly to a within-plate setting. Rare-earth element data show clear LREE-enriched, mildly alkaline tendencies. The geochemistry of the Sørli dykes, based on the more reliable trace and rare-earth elements, is, in fact, quite similar to that of the 'mildly alkaline' group of (meta)dolerites distinguished by Solyom et al. (1985) from diverse parts of the Särv Nappe, and equivalent nappes, over wide areas of the Scandinavian Caledonides.

Although the emplacement age of the Sørli dykes is not known it is inferred to be Vendian, based on the data available from comparable dolerite dykes in other parts of the Särv and immediately overlying Seve Nappes. Dolerite dykes of T- and N-MORB affinities in some of the highest thrust-sheets of the Baltoscandian margin successions farther north have yielded Mid to Late Vendian ages, and are inferred to have intruded immediately prior to the actual inception of Iapetus sea-floor spreading. The LREE-enriched, mildly alkaline dykes from Sørli, cutting a fluvial metasedimentary succession in the Middle Allochthon tectonostratigraphic level, are thus assumed to have intruded in a more inboard, continental setting, and most likely at a slightly earlier stage of latest Proterozoic crustal extension and rifting, perhaps in Early Vendian time.

Acknowledgements

We are grateful to the reviewers, Harald Furnes, Bernard Bingen and Per-Gunnar Andréasson, for their critical comments and helpful suggestions that led to improvements in the manuscript. Thanks are due to Irene Lundqvist for her digital drafting of the figures.

References

Andréasson, P.G. 1994: The Baltoscandian margin in Neoporoterozoic-early Palaeozoic times. Some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides. *Tectonophysics 231*, 1-32.

Andréasson, P.G., Solyom, Z. & Roberts, D. 1979: Petrochemistry and tectonic significance of basic and alkaline-ultrabasic dykes in the Leksdal Nappe, northern Trondheim Region, Norway. *Norges geologiske undersøkelse 348,* 47-72.

Andréasson, P.G., Svenningsen, O., Johansson, I., Solyom, Z. & Xiaodan, T. 1992: Mafic dyke swarms of the Baltica-Iapetus transition, Seve Nappe Complex of the Seve Mts., Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 114,* 31-45.

Andréasson, P.G., Svenningsen, O.M. & Albrecht, L. 1998: Dawn of Phanerozoic orogeny in the North Atlantic tract: evidence from the Seve-Kalak Superterrane, Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 120,* 159-172.

Beckholmen, M. 1987: Feltdagbok fra berggrunnsgeologisk kartlegging på kartblad 'Sørli' 1923-2. *Norges geologiske undersøkelse Rapport 045/87.010D.*

Beckholmen, M. & Roberts, D. 1989: SØRLI. Berggrunnskart 1923 2 - 1:50 000, foreløpig utgave. *Norges geologiske undersøkelse.*

Bingen, B., Demaiffe, D. & van Breemen, O. 1998: The 616 Ma old Egersund basaltic dyke swarm, SW Norway, and late Neoproterozoic opening of Iapetus Ocean. *Journal of Geology 106,* 565-574.

Bingen, B. & Demaiffe, D. 1999: Geochemical signature of the Egersund basaltic dyke swarm, SW Norway, in the context of late-Neoproterozoic opening of the Iapetus Ocean. *Norsk Geologisk Tidsskrift 79,* 69-86.

Claesson, S. & Roddick, J.C. 1983: ^{40}Ar-^{39}Ar data on the age of metamorphism of the Ottfjället dolerites, Särv Nappe, Swedish Caledonides. *Lithos 16,* 61-73.

Evensen, N.M., Hamilton, P.G. & O'Nions, R.K. 1978: Rare-earth abundances in chondritic meteorites. *Geochimica Cosmochimica Acta 42,* 1199-1212.

Floyd, P.A. & Winchester, J.A. 1975: Magma type and tectonic setting discrimianation using immobile elements. *Earth and Planetary Science Letters 27,* 211-218.

Gayer, R.A., Powell, D.B. & Rhodes, S. 1978: Deformation against metadolerite dykes in the Caledonides of Finnmark, Norway. *Tectonophysics 46,* 99-115.

Gee, D.G. 1975: A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science 275A,* 468-515.

Gilotti, J.A.1989: Boudin, augen, horse? A lesson from the Svarttjørna-Turtbakktjørna Lens, Trøndelag, Norway. (extended abstract) *Geologiska Föreningens i Stockholm Förhandlingar 111,* 385-390.

Kautsky, F. 1978: New occurrences of mega-lenses of the Särv Nappe in northern Trøndelag, Norway. *Norsk Geologisk Tidsskrift 58,* 237-240.

Krill, A.G. 1983: Rb-Sr study of dolerite dikes and psammite from the Western Gneiss Region of Norway. *Lithos 16,* 85-93.

Krill, A.G. 1986: Eidsvoll quarry, Oppdal, South Norway: a one-outcrop model for some aspects of Trollheimen-Dovrefjell tectonics. *Norges geologiske undersøkelse Bulletin 404,* 23-32.

Kumpulainen, R. & Nystuen, J.P. 1985: Late Proterozoic basin evolution and sedimentation in the westernmost part of Baltoscandia. In Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas.* John Wiley & Sons Ltd., Chichester, 213-232.

Masuda, A., Nakamura, N. & Tanaka, T. 1973: Fine structures of mutually normalized rare-earth patterns of chondrites. *Geochimica Cosmochimica Acta 37,* 239-248.

Meschede, M.1986: A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. *Chemical Geology 56,* 207-218.

Nakamura, N. 1974: Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrite. *Geochimica Cosmochimica Acta 38,* 757-775.

Pearce, J.A 1982: Trace element characteristics of lavas from destructive plate boundaries. In Thorpe, R.S. (ed.) *Andesites.* John Wiley & Sons Ltd., Chichester, 525.548.

Pearce, J.A. & Cann, J.R. 1973: Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters 19,* 290-300.

Pearce; J.A. & Norry, M.J. 1979: Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks. *Contributions to Mineralogy and Petrology 69,* 33-47.

Pearce, T.H., Gorman, B.E. & Birkett, T.C. 1975: The TiO_2-K_2O-P_2O_5 diagram: a method of discriminating between oceanic and non-oceanic basalts. *Earth and Planetary Science Letters 24,* 419-426.

Pedersen, R.B. & Hertogen, J. 1990: Magmatic evolution of the Karmøy ophiolite complex, SW Norway: relationships between MORB-IAT-boninite-calkalkaline and alkaline magmatism. *Contributions to Mineralogy and Petrology 104,* 277-293.

Roberts, D. 1975: Geochemistry of dolerite and metadolerite dykes from Varanger Peninsula, Finnmark, North Norway. *Norges geologiske undersøkelse 322,* 55-72.

Roberts, D. 1988: The terrane concept and the Scandinavian Caledonides: a synthesis. *Norges geologiske undersøkelse Bulletin 413,* 93-99.

Roberts, D. 1989: Mid-Norden Project. Excursion in the Caledonides of Nord-Trøndelag and part of Jämtland, September 1989: bedrock and ore geology. *Norges geologiske undersøkelse, unnumbered Guide/Report,* 36 pp.

Roberts, D. 1990: Geochemistry of mafic dykes in the Corrovarre Nappe, Troms, North Norway. *Norges geologiske undersøkelse Bulletin 419,* 45-53.

Roberts, D. 1997: Geologisk kart over Norge. Berggrunnsgeologisk kart GRONG, M 1:250 000, *Norges geologiske undersøkelse.*

Roberts, D. & Gale, G.H. 1978: The Caledonian-Appalachian Iapetus Ocean. In Tarling, D.H. (ed.) *Evolution of the Earth's crust.* Academic Press, London, 255-342.

Roberts, D. & Gee, D.G. 1985: An introduction to the structure of the Scandinavian Caledonides. In Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas.* John Wiley & Sons Ltd., Chichester, 55-68.

Shervais, J.W. 1982: Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth and Planetary Science Letters 39,* 101-118.

Solyom; Z., Gorbatschev, R. & Johansson, I. 1979: The Ottfjäll dolerites. Geochemistry of the dyke swarm in relation to the geodynamics of the Caledonide orogen of Central Scandinavia. *Sveriges geologiska undersökning C756,* 1-38.

Solyom, Z., Andréasson, P.G. & Johansson, I. 1985: Petrochemistry of Late Proterozoic rift volcanism in Scandinavia. II: The Särv dolerites (SD) – volcanism in a constructive arm of Iapetus. *Lund Publications in Geology 35,* 1-42.

Stephens, M.B., Furnes, H., Robins, B. & Sturt, B.A. 1985: Igneous activity within the Scandinavian Caledonides. In Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas.* John Wiley & Sons, Ltd., Chichester, 623-656.

Stølen, L.K.1994a: The rift-related mafic dyke complex of the Rohkunborri Nappe, Indre Troms, northern Norwegian Caledonides. *Norsk Geologisk Tidsskrift 74,* 35-47.

Stølen, L.K.1994b: Derivation of mafic dyke swarms in the Rohkunborri Nappe, Indre Troms, northern Norwegian Caledonides: chemical constraints. *Geologiska Föreningens i Stockholm Förhandlingar 116,* 121-131.

Stølen, L.K.1997: Bedrock geology of the Altevatn-Måskanvarri area, Indre Troms, northern Scandinavian Caledonides. *Norges geologiske undersøkelse Bulletin 432,* 5-23.

Svenningsen, O. 1994: The Baltica-Iapetus passive margin dyke complex in the Sarektjåkkå Nappe, northern Swedish Caledonides. *Geological Journal 29,* 323-354.

Svenningsen, O. 1996: Passive margins – past and (almost) present. (Extended abstract) *Geologiska Föreningens i Stockholm Förhandlingar 118,* A41-42.

Viereck, L.G., Taylor, P.N., Parson, L.M., Morten, A.C., Hertogen, J., Gibson, I.L. & the ODP Leg 104 Scientific Party 1988: Origin of the Palaeogene Vøring Plateau volcanic sequence. *Geological Society of London Special Publication 39,* 69-83.

Zwaan, K.B. & van Roermund, H.L.M. 1990: A rift-related mafic dyke swarm in the Corrovarre Nappe of the Caledonian Middle Allochthon, Troms, North Norway, and its tectonometamorphic evolution. *Norges geologiske undersøkelse 419,* 25-44.

Appendix

Grid references and brief descriptions of the dyke samples analysed. All samples are from 1:50,000 map-sheet 'Sørli', 1923-2 (3-Nor edition, blue coordinates, 33W VM). Dyke thicknesses vary from a few decimetres to 2-3 metres.

Sample no.	*Grid ref.*	*Brief sample description*
41-87	5365 1510	Green-grey, foliate, aphyric to sparsely phyric, bio-hbl amphib/schist.
42-87	5350 1510	Similar to above. Lepidoblastic, sparsely phyric. Chlorite + clinozo. present.
57-87	5085 1475	Green-grey, fine-grn., bio. amphib/schist. Abundant biotite and epidote.
58-87	5085 1475	Similar to above. Bio-amphib. schist, aphyric, lepidoblastic.
60-87	5025 1425	Green-grey, foliate, aphyric, bio-hbl amphibolite.
71-87	5230 1555	Green-grey, foliate amphibolite, with 5 mm chl-amph. crysts.
75-87	4985 1805	Med-grained, foliate amphib., actin-bio-clinozo: actin 2 mm.
106-87	4920 2410	Green-grey, schistose amphib., with small-scale crenulation folds.
112-87	4865 1680	Porph. metadol., uralitised px (<1 cm) + sericit. plag (5 mm), foliate.
113-87	4990 1735	Porph. metadol., sauss.plag crysts (4 mm) + some retrogr. px., foliate.
15-88	4110 1570	Green-grey, aphyric, schistose biotite (+musc) amphibolite.
17-88	5090 1470	Green-grey, fine-grn., aphyric, schistose bio-amphibolite.
18-88	5090 1470	Similar to above, aphyric, foliate metadolerite/amphibolite.
19-88	5040 1430	Green-grey, aphyric, biotite-rich amphibolite.

Manuscript received May 1999; revised manuscript accepted August 1999.