Geochemistry of Dolerite and Metadolerite Dykes from Varanger Peninsula, Finnmark, North Norway

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Dolerite dykes provide the only manifestation of igneous activity in the thick, Riphean to Lower Cambrian, weakly metamorphosed sedimentary sequence of Varanger Peninsula. Major and trace element abundances and ratios from two distinctive generations of mafic dyke, one metamorphosed and cleaved and the other post-metamorphic and fresh, reveal disparate grouping and trends in several variation diagrams. Older metadolerites show an overall major-element compositional similarity with abyssal tholeiites, a relationship which is confirmed by most trace element concentrations and ratios. Certain element abundances, together with the tectonic environment, suggests however that these dykes are representative more of magmas transitional to those producing abyssal and continental tholeiites. The younger dolerites are also subalkaline though less typically tholeiitic than the metadolerites. Comparison of their element contents and ratios reveals calc-alkaline affinities, as well as similarities with data for continental tholeiites. The trend of relative enrichment in Si, Ba, Zr, Rb and alkalies in the dolerites may possibly signify a greater depth of magma generation than that which produced the metadolerites. The petrogenesis of the dyke sets is discussed in the light of the regional geology and recently published K–Ar whole-rock ages which place the dolerites in the uppermost Devonian and date the metadolerites, provisionally, as Riphean.

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Introduction

The geology of Varanger Peninsula in East Finnmark (Fig. 1) has been studied in some detail over the past decade, with emphasis placed on stratigraphical and sedimentological investigations (Siedlecka & Siedlecki 1967, 1971, 1972; Røe 1970; Banks et al. 1971, 1974; Laird 1972; Siedlecka 1972, 1975; Banks & Røe 1974). Tectonic structural observations are principally those of Roberts (1972) and Teisseyre (1972).

As a result of this activity, the essential features of the geology are now fairly clear. In brief, the peninsula is divided more or less in half by a complex, NW–SE-trending, NE-dipping dislocation, the Trollfjord–Komagelv fault-zone (Siedlecka & Siedlecki 1967), along which there has occurred considerable dextral, strike-slip movement (Roberts 1972). South-west of the fault zone is an autochthonous 4000–5000 m-thick succession of shallow water sediments of late Precambrian to Lower Cambrian age, including two Eocambrian (Vendian) tillite formations. This sequence rests unconformably upon Precambrian crystalline basement just to the south-west of Varanger Peninsula.

On the north-east side of the Trollfjord–Komagelv fault-zone is the 9000 m-

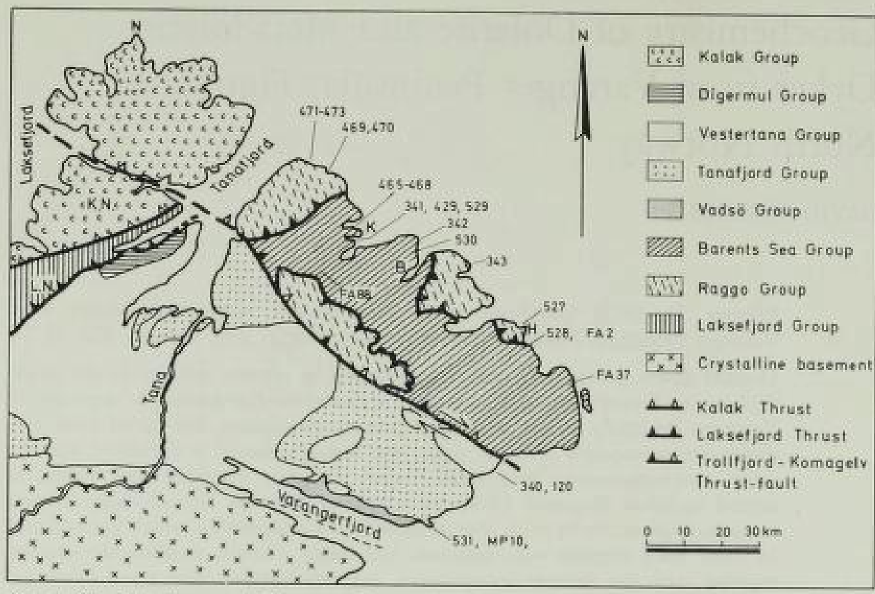

Fig. 1. Geological map of Varanger Peninsula and adjacent areas showing the locations of analysed dolerites and metadolerites. The numbers refer to the samples (Tables 1 and 2). K.N. – Kalak nappe; L.N. – Laksefjord nappe; B – Båtsfjord; K – Kongsfjord; N – Nordkyn; H – Hamningberg. The areas of Raggo Group rocks may include sequences from different allochthonous or parautochthonous units.

thick Barents Sea Group, a sedimentary pile of considered Riphean age; this is overthrust by the equally thick Raggo Group (Siedlecka & Siedlecki 1967, 1972). A lithostratigraphical correlation involving these two groups has been proposed (Siedlecka & Siedlecki 1972), but the validity of this interpretation has been challenged (Laird 1972, Gayer & Roberts 1973). In the alternative scheme of correlation the Raggo sediments are considered as being of Vendian age, and equivalent to the rocks of the Laksefjord Group. Relationships between the different successions (Fig. 1) juxtaposed along the Trollfjord–Komagelv fault zone are the subject of current debate and research.

A significant element in the geological history of Varanger Peninsula is that of dolerite dyke intrusion. Dykes are particularly prominent in the Barents Sea region, north of the fault zone, where they were first recorded by Holtedahl (1918); locally they attain swarm proportions. Towards the south-east they are far less common.

During a tectonic structural investigation of the Barents Sea region by the present author (Roberts 1972), it was found that two main phases of dyke intrusion could be distinguished, one coeval with the major fold-producing deformation and low-grade metamorphic episode (and representing the majority of the dykes), and the other post-dating this regional metamorphism. Dolerites of the older intrusive phase are metamorphosed and cleaved, whereas the younger set are comparatively fresh and unaltered.

Preliminary potassium–argon age determinations have recently been reported on some of the basic dykes (Beckinsale et al. 1975). These appear to indicate that some 650 m.y. separates the two generations of dyke intrusion noted above, the post-tectonic dolerites showing an uppermost Devonian age. In addition, a third set of dykes has apparently been recognised. These are from an area as yet not visited by the present writer. The significance of these radiometric dates is discussed later.

Field relationships

The metamorphosed dolerite dykes, hereafter referred to as the metadolerites, are particularly common in the multilayered distal-turbiditic parts of the Barents Sea Group, especially around Kongsfjord, but also occur in the allochthonous Raggo Group. Dyke thickness is usually 1 to 3 m, rarely up to 10 m. Characteristically the metadolerites lie parallel or subparallel to the axial surfaces of common, close to tight, mesoscopic folds (D_1), although they are themselves sheared and cleaved by the penetrative slaty cleavage or schistosity axial planar to these folds (Roberts 1972). Dyke strike is consistently ENE–WNW with dips vertical or steep to the SSE in the Barents Sea Group and moderate or steep to the NW in the Raggo Group.

The dykes are green- to brown-weathering, the colour depending on grain-size and thickness; the thinner, finer grained dykes show a distinct green coloration. They have narrow, chilled marginal zones, often display pinch- and swell features or true boudinage, and are locally cut by irregular quartz–chlorite–calcite veinlets and segregations. A pale, green-grey, baked aureole zone is frequently present, especially where the dykes intrude pelites. Field relationships, noted in more detail elsewhere (Roberts 1972), indicate that the dyke intrusion accompanied the main, D_1, folding episode but pre-dated the actual cleavage development and a late-D_1 differential flattening phase. The possibility that the dykes are pre-D_1 and have been rotated into the plane of D_1 flattening has been considered, but rejected on several grounds. Nevertheless, is cannot be entirely ruled out that some may be pre-D_1.

The unmetamorphosed dolerite dykes of the present study are quantitatively insignificant, occurring in comparative isolation, and are largely restricted to the south-eastern districts of Varanger Peninsula on both sides of the Trollfjord–Komagelv fault-zone. They clearly post-date the main D_1 folding and regional metamorphic fabric, and trend between NE–SW and N–S. These dykes are generally from 8 to 12 m in thickness, are dark green to almost black and have distinctive chilled marginal facies.

Petrography

The mineralogy and petrography of the fine- to medium-grained *metadolerite* dykes is partially obliterated by a pervasive alteration of the plagioclase and variable chloritization of the constituent mafic minerals, but it is nevertheless possible to recognise the original dominance of primary plagioclase and clinopyroxene and in most cases, the relict ophitic to sub-ophitic texture in the dyke interiors. Towards the margins of several of the dykes, shearing and

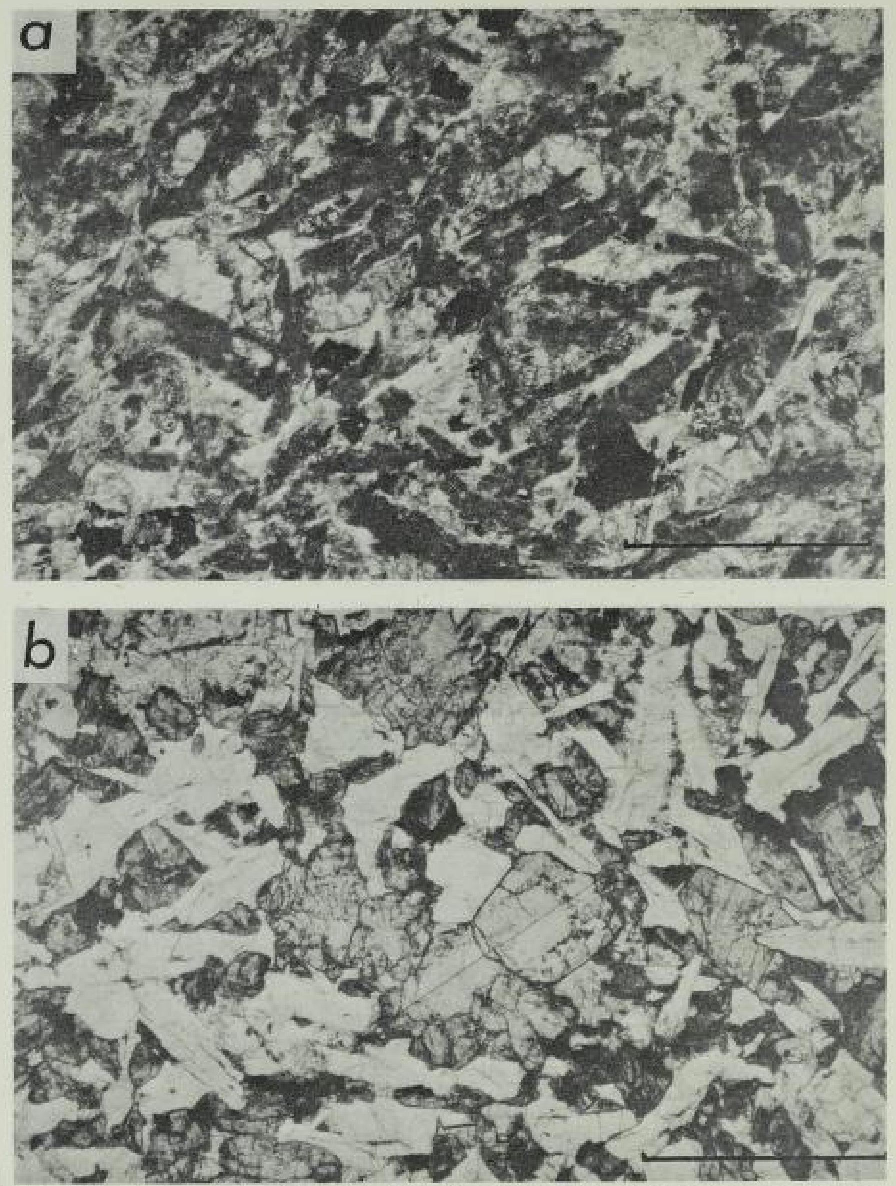

Fig. 2. Photomicrographs of the dykes. (a) Metadolerite. The higher relief clinopyroxene and the strongly altered plagioclase (dark laths) are distinguishable; chlorite and ilmeno-magnetite are the only other minerals. Sample no. 467. Scale, 1 mm. Plane polarised light. (b) Dolerite. Sub-ophitic texture of clinopyroxene and plagioclase with some ore mineral grains. Sample no. 340. Plane polarised light. Scale, 1 mm.

alteration have been such that only chlorite, opaques and some amphibole and epidote are definable, with some ghost-like relics of plagioclase laths. Rarely, where chilled zones have escaped alteration, original microporphyritic texture may be observed with randomly oriented microphenocrysts of clinopyroxene, labradorite and opaques set in a brown cryptocrystalline groundmass.

Plagioclase and clinopyroxene are, or were, the most abundant minerals in the metadolerites. The plagioclase is heavily altered (Fig. 2a), frequently to a cloudy brownish product; microgranular epidote can be recognised in some cases, and some saussuritization has been observed. Where alteration is not so advanced, ragged lath-like shapes from 0.5 to 1 mm in length can be distinguished and compositional determinations are possible, the plagioclase falling in the range An_{42} to An_{54}. Towards the north-westernmost part of Varanger Peninsula where the grade of greenschist facies metamorphism is slightly higher, metadolerite dykes in Raggo Group rocks show partial recrystallization features with some plagioclases recrystallized to aggregates of equigranular epidote, quartz and some calcite.

The colourless clinopyroxene has suffered extensive chloritization as well as fragmentation resulting from the late-D_1 deformation. Many of the ragged crystals show wavy extinction. Much of the pyroxene would appear to be augitic, but in some cases low 2V angles indicate pigeonite; microphenocrysts from a chilled marginal zone of one dyke are definitely of pigeonite, with 2V in the 5°–15° range.

Chlorite is the principal alteration product of the clinopyroxene. In the finer grained facies of the dykes it may completely pseudomorph the pyroxene, although where deformation has been advanced the original pyroxene shape is impossible to recognise. The chlorite also occurs as veinlets and irregular segregations in the dykes; optical examination and X-ray determinations show it to be ripidolite. Uralitization is less common than might be expected in these metadolerites, tending to be restricted to the areas in the north-west with higher greenschist facies metamorphism, or to the more strongly deformed dykes. Even here the colourless amphibole is not an important mineral, and shows extensive chloritization.

Other, quantitatively insignificant minerals in the metadolerites are ilmenite–magnetite, pyrite, quartz, epidote, calcite and some sphene. In some of the dykes from near Kongsfjord, 5–6 mm-sized pyrite cubes are prominent. Generally, however, the opaque mineral is an ilmenite–magnetite mixture, sometimes present as skeletal grains with alteration of ilmenite lamellae to leucoxene. Minor phlogopitic biotite, partially going over to chlorite, has been found in only one dyke, rimming pyroxene. A minor amount of olivine has been determined in the norms of 3 of the metadolerites, but none has been seen in thin-section.

In contrast to the metadolerites, the younger *dolerite* dykes are either completely fresh or show only minor alteration features (Fig. 2b). Their uniform mineralogy is dominated by plagioclase and clinopyroxene in the general size range 0.5–3 mm and 0.3 to 0.6 mm, respectively, and textures are mostly ophitic or subophitic and rarely glomeroporphyritic. The plagioclase shows albite, Carlsbad and pericline twinning and, locally, oscillatory zoning. Sericitization is encountered in some instances, although the feldspar is usually quite fresh. In one dyke from near Hamningberg, a glomeroporphyritic texture is observed with plagioclase laths occurring in scattered clusters from 3 to

5 mm across. Plagioclase composition in the dolerite dykes in general ranges from An_{44} to An_{60}.

Clinopyroxene is colourless and occurs as lath-shaped, equant or subhedral crystals dispersed or moulded between the dominant plagioclase. Twinning is common, both simple and polysynthetic, and 'hourglass' wavy extinctions are sometimes observed; occasionally a faint concentric zoning may be distinguished by small differences in extinction angles. Axial angle determinations show that the bulk of the pyroxene is undoubtedly a pigeonite, although an augite phase may also be present either as peripheral zones to pigeonite crystals or as separate individuals.

The clinopyroxene of the dolerites is altered marginally only to a minor degree, and then to a phlogopitic biotite or chlorite rather than to uralite. Accessory pale green amphibole has been observed in some thin-sections, however. Other accessory minerals in the dolerites are titano–magnetite and minor apatite and calcite.

Chemical composition of the dykes

Major element analyses have been obtained for twenty-four samples, 16 metadolerites and 8 dolerites (Tables 1 and 2). In most cases, specimens were taken from the approximate central part of dykes; additional samples from the margins were collected from three metadolerite dykes for comparison purposes. Trace element concentrations for nineteen of the samples are also presented in the Tables. The major elements Si, Al, Ca, Mg and total Fe were analysed by classical wet chemical methods, while Ti, Mn, Na, K and ferrous iron were determined by the method of Langmyhr & Graff (1965). The trace elements, with the exception of Nb and some Rb determinations were analysed on fused rock powders using a manual Philips 1540 XRF. Niobium and metadolerite rubidium values were determined by XRF using pressed-powder pellets.

The major element data have been plotted on several variation diagrams, all of which have revealed compositional groupings of the two dyke sets. From the alkalies–silica diagram (Fig. 3), both metadolerites and dolerites tend to plot in the subalkaline field (Irvine & Baragar 1971). This was also confirmed by a ternary plot of normative Cpx–Ol–Opx, using the discriminant functions of Chayes (1966).

With alkaline compositions eliminated, the AFM diagram (Fig. 4) serves to show that while the metadolerites are distinctly tholeiitic, though showing no actual tholeiitic trend, the younger dykes plot close to the tholeiitic/calc–alkaline dividing line of Irvine & Baragar (1971). This distinction is confirmed in a SiO_2 vs. *Feo/MgO variation plot, not presented here.

Figs. 5 and 6 show *FeO vs. *FeO/MgO and TiO_2 vs. *FeO/MgO variation and depict definite and disparate trends for both dyke sets. The gentler slopes

* Total iron as FeO.

ble 1. Chemical compositions of the metadolerite dykes

%	465	466	467	468	469	470	471	472	473	529	429	341	342	343
O_2	45.95	48.08	46.75	46.08	47.76	48.61	45.39	44.71	47.84	47.13	46.21	45.56	45.56	46.75
O_3	14.96	15.04	14.87	14.79	15.09	16.26	13.11	13.37	15.36	14.85	15.06	16.14	14.66	15.30
O_3	1.49	0.81	1.60	0.65	1.62	2.25	1.89	2.20	1.54	1.09	1.90	4.24	2.82	1.69
O	10.86	11.37	11.49	12.00	10.79	9.07	13.27	13.85	10.47	8.47	8.54	9.50	10.49	10.68
O_2	1.73	1.98	1.93	1.73	1.81	1.48	3.39	3.50	1.72	1.38	1.40	2.26	1.95	1.51
gO	7.35	7.34	7.21	7.04	5.96	6.46	6.43	6.29	7.18	6.75	6.85	6.96	7.50	7.62
O	12.01	7.43	10.07	6.80	10.75	8.62	10.30	9.81	8.52	14.37	14.36	6.27	10.69	10.41
$_2O$	2.00	2.36	1.80	1.85	2.60	2.49	.17	.13	3.14	.41	.42	2.34	1.54	1.68
O	.05	.05	.05	.05	.08	1.12	.13	.07	.10	.05	.01	2.20	1.15	.86
nO	.23	.21	.23	.29	.02	.20	.23	.21	.24	.25	.16	.20	.21	.20
O_5	.06	.06	.07	.08	.08	.07	.16	.18	.09	.08	.08	.11	.11	.09
O.I	3.25	5.17	3.44	8.00	3.18	3.72	5.98	6.35	4.29	4.42	5.28	4.78	3.34	3.23
tal	99.89	99.85	99.46	100.19	99.74	100.35	100.45	100.67	100.49	99.25	100.26	100.56	100.02	100.02
p.m.														
	89	65	78	105	121	83	190	208	80	54	56	–	–	–
	36	34	35	39	38	30	56	61	28	28	28	–	–	–
	486	1685	1167	320	371	368	739	656	1135	795	759	–	–	–
	2	2	2	2	3	39	7	5	3	2	2	–	–	–
	107	111	116	110	116	113	151	181	111	100	96	–	–	–
	57	58	60	35	26	40	3	58	49	12	74	–	–	–
	76	62	68	66	55	77	59	56	85	56	73	–	–	–
	191	164	166	161	88	144	122	120	182	220	195	–	–	–
	96	98	68	68	71	292	91	25	61	113	67	–	–	–
	2[1]	*	1[1]	6	4[1]	4	4	4	*	*	*	–	–	–

Below detection limit.

nalysts: Major elements, P.-R. Graff, Norges geologiske undersøkelse.

[1] — analysed by J. R. Cann, University of East Anglia.

Rb and other Nb — O. Lutro, University of Bergen.

All other trace elements, G. C. Faye and M. Ødegård, Norges geologiske undersøkelse.

mples from the interior and margin of three separate dykes are those of nos. 467–8, 469–70 and 471–2; in each se the higher number is that of the sample from the dyke margin.

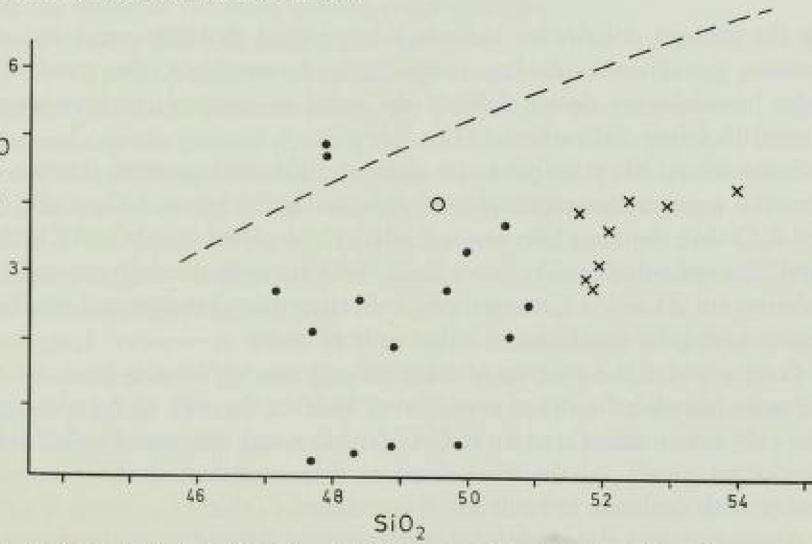

Fig. 3. SiO_2 vs. $Na_2O + K_2O$, wt% volatile-free, variation plot. The dashed line separates alkaline (above) and subalkaline fields (after Irvine & Baragar 1971).

● – metadolerite dykes; x – dolerite dykes; o – dyke sample no. FA88.

Table 2. Chemical composition of the dolerite dykes

wt.%	527	528	531	MP 10	FA 2	FA 37	340	120	FA 88[1]	530
SiO_2	52.82	51.61	50.59	50.84	51.24	51.01	50.98	50.92	47.17	46.
Al_2O_3	15.23	14.79	15.28	14.62	15.17	15.17	14.89	13.09	16.07	15.
Fe_2O_3	1.08	1.94	2.55	1.95	2.84	1.98	2.73	2.20	1.11	3.
FeO	9.20	8.89	7.70	8.37	8.47	8.64	7.82	8.24	11.18	9.
TiO_2	1.15	1.31	.97	.99	1.28	1.08	1.02	1.07	2.94	2.
MgO	5.19	5.91	6.99	7.63	5.82	6.78	7.17	8.00	3.96	7.
CaO	9.07	9.21	10.28	11.20	9.14	9.92	10.65	10.90	8.94	8.
Na_2O	2.76	2.92	2.79	2.20	3.07	2.58	2.34	2.11	2.64	2.
K_2O	1.42	1.01	1.08	.68	1.03	1.00	.68	.64	1.24	2.
MnO	.18	.27	.20	.20	.21	.19	.21	.18	.23	[illegible]
P_2O_5	.11	.12	.09	.06	.11	.08	.09	.13	.11	[illegible]
L.O.I.	.80	1.26	1.69	1.40	2.03	1.46	1.87	1.81	3.96	2.
Total	99.37	99.24	100.21	100.14	100.41	99.89	100.45	99.39	99.62	100.
p.p.m.										
Zr	162	107	73	79	135	194	–	–	120	1
Y	29	24	21	22	21	49	–	–	25	[illegible]
Sr	235	216	334	230	215	238	–	–	267	3
Rb	49	29	29	23	33	35	–	–	27	[illegible]
Zn	94	95	77	84	97	123	–	–	90	[illegible]
Cu	91	103	83	83	104	15	–	–	116	[illegible]
Ni	29	24	44	49	12	17	–	–	59	[illegible]
Cr	65	18	97	110	17	71	–	–	51	1
Ba	468	287	950	411	198	256	–	–	186	3
Nb	13	11	4	–	–	–	–	–	–	[illegible]

[1] — Sample no. FA 88 and possibly sample no. 530 are from another dyke set (see text).
Analysts: Major elements, P.-R. Graff, Norges geologiske undersøkelse.
Nb — O. Lutro, University of Bergen.
All other trace elements, G. C. Faye and M. Ødegärd, Norges geologiske undersøkelse.

for the younger dolerite set indicate a less typical tholeiitic trend and a disposition towards calc–alkaline composition. Interestingly, the trend of the older metadolerites closely follows the trend of compositional variation of abyssal tholeiites (Miyashiro 1975).

Summarizing the principal major element differences between the two dyke sets, the younger unmetamorphosed dolerites are richer in SiO_2, CaO, Na_2O and K_2O than the metadolerites and relatively depleted in Al_2O_3, TiO_2, MgO, total iron and volatiles. The mean Fe_2O_3/FeO ratios in the dolerites and metadolerites are .25 and .17, respectively, indicating that alteration and weathering cannot have been significant in either suite of rocks.

Comparison of the analyses of marginal and interior samples from the three different metadolerite dykes reveals very little in the way of definite trends. The only consistencies are seen in CaO depletion and increase of volatiles from interior to margin; of the trace elements only strontium shows a consistent change with depletion towards the dyke margins (Table 1).

An attempt was also made to identify possible differences in the chemistries of metadolerites from the Barents Sea Group and overthrust Raggo Group in view of the importance of the age of the Raggo rocks in the regional strati-

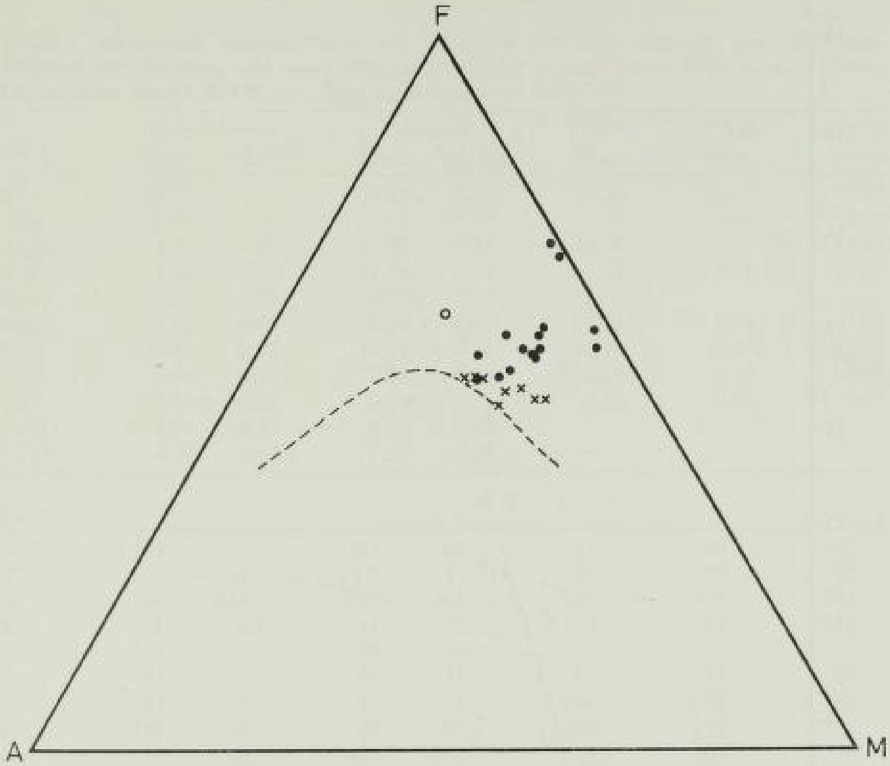

Fig. 4. AFM diagram. The dashed line separates the field of tholeiitic and calc-alkaline compositions (after Irvine & Baragar 1971). Symbols as in Fig. 3.

graphic and structural development, but no distinction could be observed in either the major or the trace element concentrations.

Trace element data and mean values are given in Tables 1, 2 and 3. Considering the elements which are comparatively insensitive to weathering processes and greenschist facies metamorphism, the Y/Nb ratio provides a useful means of determining the general petrological character of magma types (Pearce & Cann 1973). Although Nb determinations are few, the Y/Nb ratios from the metadolerites (mean of <12) are appreciably higher than those from the dolerite dykes (mean of <3). This is further confirmation that while the metadolerites have characteristics of abyssal tholeiites, the younger dolerites show a less typically tholeiitic and an increasing alkali character, i.e. they are 'transitional' (Pearce & Cann 1973). Further indications of differing compositional character of the two generations of dyke are provided by a Ti–Zr–Y variation diagram (Pearce & Cann 1973). In this (Fig. 7) the dolerites plot somewhat transitionally across the ocean floor, calc–alkaline and within-plate fields, while the metadolerites fall in the ocean floor and, partly, LKT fields.

The element ratio Sr/Ba plotted as a function of K concentration (Condie et al. 1969) again illustrates the similarity of the older metadolerites to submarine tholeiites (Fig. 8), in spite of the fact that these elements are some of the most mobile during alteration and low-grade metamorphism and have

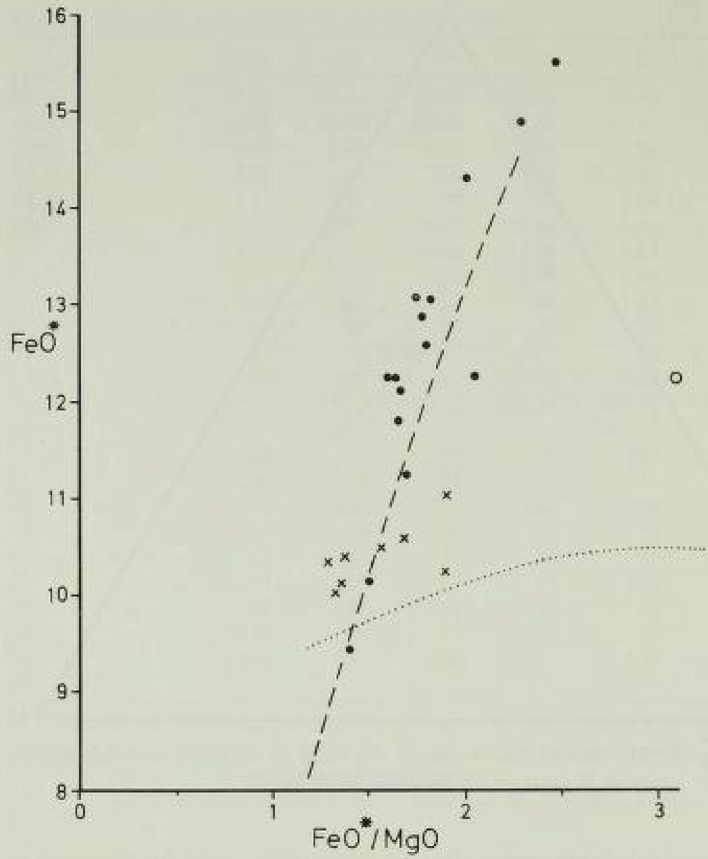

Fig. 5. Variation plot of FeO* vs. FeO*/MgO (FeO* = total iron as FeO), symbols as in Fig. 2. Dashed line — average compositional variation trend of abyssal tholeiites; dotted line — the compositional trend of the Tofua Island (Tonga) tholeiite (both trend lines after Miyashiro 1975).

comparatively high mean values in the present case. Interesting here is the fact that the dolerites occupy the fields of either average continental tholeiites or the Antarctic and Tasmanian tholeiites. Other element ratios plotted on other 'Condie' diagrams show similar distributions for both dyke sets. The K/Rb ratio of ca. 240 for the dolerites compares well with the value of 300 obtained for continental basalts (Gast 1965). The mean Rb content of 3 ppm for the metadolerites is equivalent to the 2 ppm average for abyssal tholeiites (Condie et al. 1969); that for the dolerites, 33 ppm, is close to the average (36 ppm) for continental basalts.

Considering the above petrological affinities, the strontium content in the metadolerite dykes is anomalously high, being over 5 times the mean for abyssal basalts (Pearce & Cann 1973). Although this high average is caused by three particularly Sr-rich samples (Table 1), the generally high values are noted even in the Sr-depleted dyke-margin samples, and it is therefore suggested that this is likely to reflect high primary values in the original

Table 3. Means and standard deviations for major and trace elements from the metadolerites and dolerites, and mean element values for average ocean floor basalts (OFB), calc-alkaline basalts (CAB) and continental tholeiites (CON)

	Metadolerites		Dolerites		OFB[3]	CAB[3]	CON[3]
wt.%	Mean	Std. dev.	Mean	Std. dev.	Mean	Mean	Mean
SiO_2	46.60	1.16	51.25	0.70	49.56	52.12	48.81
TiO_2	1.98	0.67	1.11	0.13	1.42	1.07	2.47
Al_2O_3	14.92	0.85	14.78	0.72	16.09	18.07	14.41
Fe_2O_3[1]	13.69	1.82	11.41	0.38	11.19	9.78	13.20
MnO	0.21	0.06	0.20	0.03			
MgO	6.92	0.49	6.69	0.97	7.69	5.00	5.96
CaO	10.03	2.45	10.05	0.84	11.34	9.67	10.05
Na_2O	1.64	0.98	2.60	0.35	2.80	2.95	2.90
K_2O	0.43	0.66	0.94	0.27	0.24	0.94	0.95
P_2O_5	0.09	0.04	0.10	0.02			
L.O.I.	4.60	1.44	1.54	0.40			
p.p.m.							
Zr	103	52	125	48	83	106	149
Y	38	11	28	11	28	23	25
Sr	771	418	245	45	121	435	401
Rb	3[2]	0.6	33	9	2.6	23	15
Zn	119	25	95	16			
Cu	43	22	80	33	73	35	99
Ni	67	10	29	15	106	50	68
Cr	159	38	63	39	280	135	139
Ba	95	69	428	274	8.4	260	338
Nb	3.5	2	10	2.5	2.5	3.3	25

[1] Total Fe as Fe_2O_3.
[2] Excluding sample 470.
[3] Taken from Pearce (1973).

magma. The average Sr content of 245 ppm in the dolerites is somewhat lower than the average for continental tholeiites in general (Condie et al. 1969), yet higher than for certain basalts of this type, e.g., some of the Karroo dolerites.

Ba averages of 95 ppm and 428 ppm for the metadolerites and dolerites, respectively, are higher than those for mean abyssal tholeiites and continental basalts, a feature which could bear some relationship to the high strontium values and which is probably also a primary feature of the magmas.

Of the remaining elements, Ni, Cr and Zn are consistently higher in the metamorphosed dykes, whereas Cu shows greater concentrations in the dolerites. Ni values are lower than the averages for both submarine and continental basalts, possibly a reflection of a negligible content of olivine; the higher Ni content, 67 ppm, in the metadolerites may be associated with the higher Ti values and the more abundant ilmeno-magnetite in these dykes. The low Ni values in the dolerites may be related to the abundance of pigeonite, rather than augite, in the rock (McDougall & Lovering 1963).

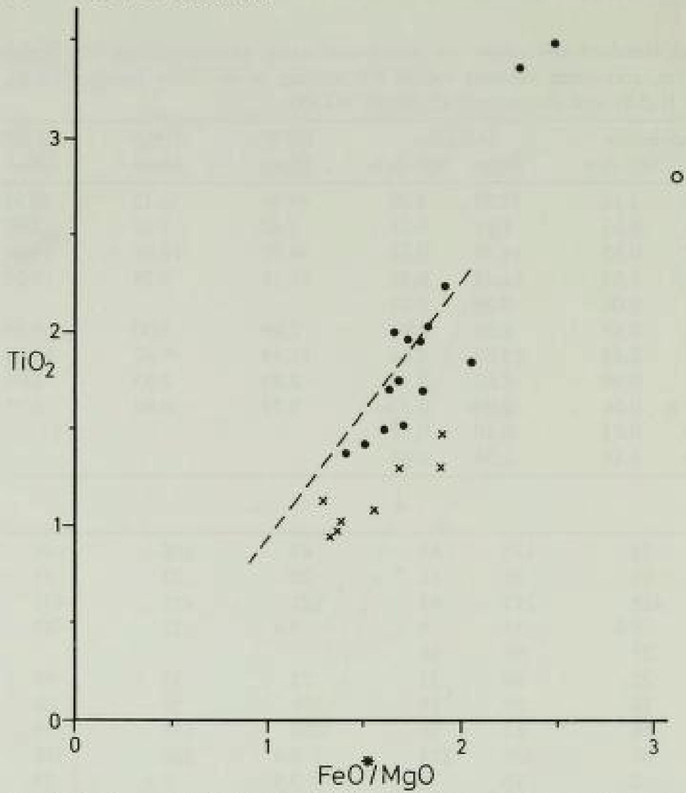

Fig. 6. TiO_2 vs. FeO^*/MgO diagram, symbols as before. The dashed line shows the average trend of compositional variation of abyssal tholeiites (after Miyashiro, 1975).

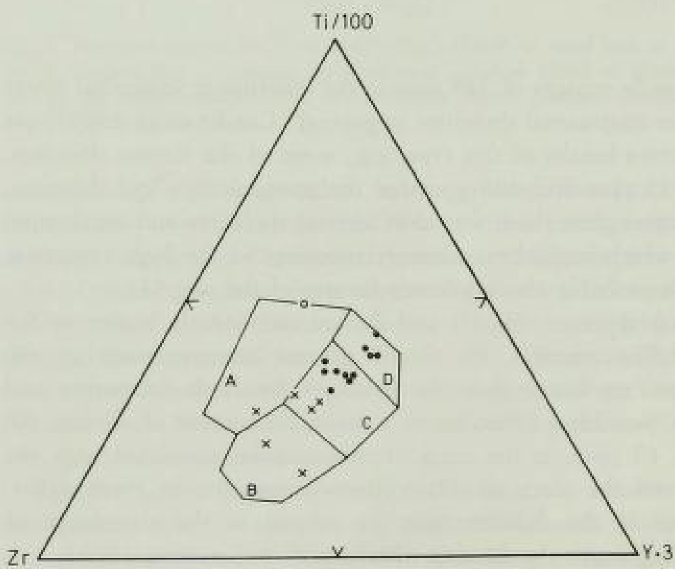

Fig. 7. Ti–Zr–Y plot of the dolerite and metadolerite samples; symbols as in previous figures. The various fields, representative of magma types (after Pearce & Cann, 1973), are as follows: within-plate basalts plot in field A, ocean floor basalts in field C, calc-alkali basalts in fields B and C, low-potassium tholeiites in fields D and C.

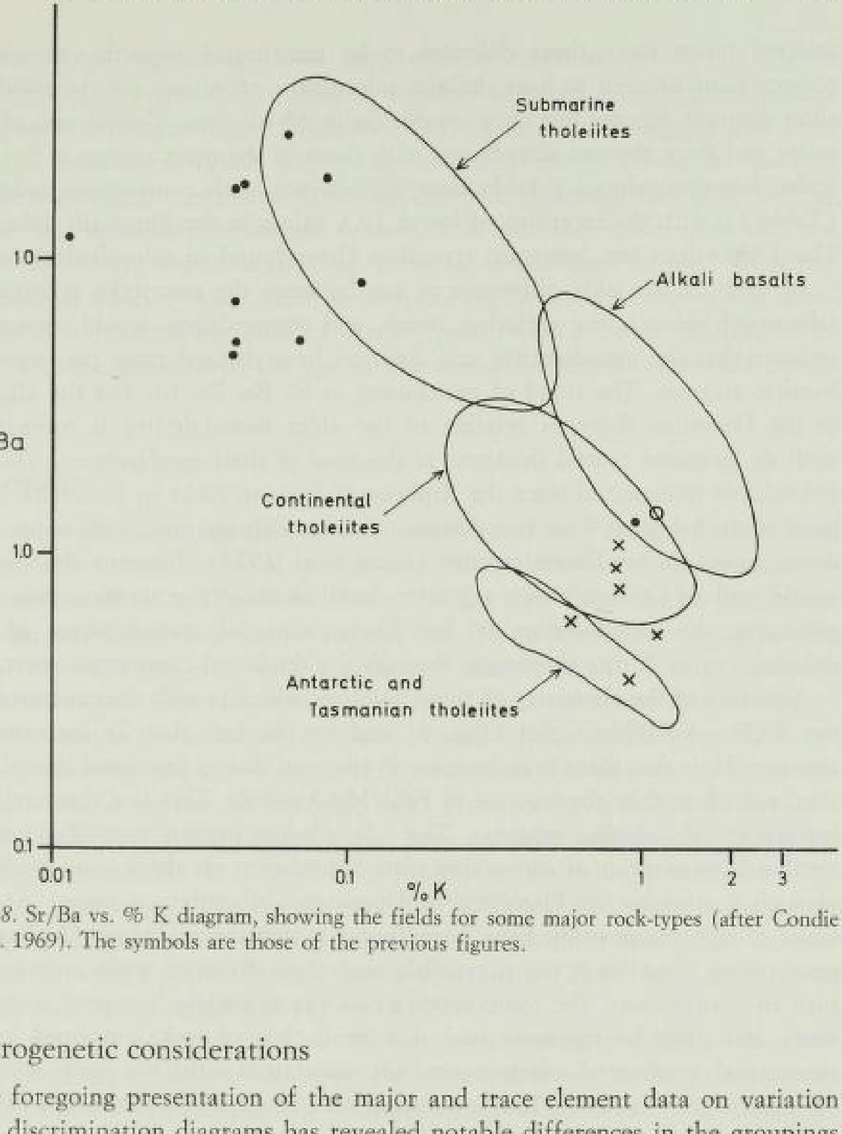

Fig. 8. Sr/Ba vs. % K diagram, showing the fields for some major rock-types (after Condie et al. 1969). The symbols are those of the previous figures.

Petrogenetic considerations

The foregoing presentation of the major and trace element data on variation and discrimination diagrams has revealed notable differences in the groupings and trends between the two dyke generations. The older metadolerites show a reasonably close correspondence to oceanic tholeiites both on element concentrations (Sr and Ba excluded) and on various ratios, in particular the low potassium and niobium values and high K/Rb ratios (Engel et al. 1965). This is in spite of the low-grade greenschist metamorphism, in which both Rb and K as well as Sr and Ba are particularly mobile elements. The possibility that the chemistry of the metadolerites has been modified to some extent by the metamorphism is clearly present. This may account for some of the scatter in certain diagrams, but otherwise there are no consistent trends indicative of element abundance modification by metamorphic processes in these dykes.

The younger dolerite dykes are petrographically more difficult to classify. While tending towards tholeiitic affinities, certain element variation plots and selected ratios show these dolerites to be transitional towards calc–alkalic compositions or even to have definite calc–alkalic affinities; yet the alkalies–silica diagram denotes that they are decidedly sub-alkaline. Comparison of the major and trace element abundances with those of the main groups of basaltic rocks, however, shows a fairly close equivalence with continental tholeiites (Table 3), with the exception of lower TiO_2 values in the Finnmark dolerites. The TiO_2 values are, however, typical of those found in calc–alkaline rocks.

In view of the wide difference in age between the two dyke generations (discussed below), the differing trends and compositions would appear to indicate that the metadolerites and dolerites have derived from two separate basaltic magmas. The trend of enrichment in Si, Ba, Zr, Rb and the alkalies in the Devonian dolerites relative to the older metadolerites is compatible with an increased crustal thickness at the time of their emplacement. This is, indeed, not unexpected since the Riphean to Silurian rocks in Finnmark have been subjected to at least two phases of major deformation, with nappe-pile development, in pre-Devonian time (Sturt et al. 1975). Element abundances would probably reflect either a greater depth of magma generation than that producing the metadolerites or, less likely, a partial contamination of the dolerite magma during its passage through the thickened continental crust.

A feature of the chemistry of these dolerites which is well demonstrated by the TiO_2 – FeO/MgO plot (Fig. 6) and by the fact that Zr increases at constant Ti, is that there is no increase in titanium during fractional crystallisation, as indicated by the increase in FeO/MgO and Zr. This is a characteristic feature of calc–alkaline magmas. The calc–alkaline magma type is generally attributed to eruption at converging plate boundaries, yet there is no evidence of such a situation in Finnmark in Devonian/Carboniferous times. A few rocks of this composition have been found at continental edges (J. Pearce, pers. comm.), and it is not impossible that these dolerites were intruded in such an environment. The composition in no way resembles 'hot spot' volcanic rocks, but could be representative of a small class of rocks emplaced in an extensional continental environment not associated with 'hot spot' activity (J. Pearce, pers. comm.). It is interesting here to note that the trends of the various fold episodes on Varanger Peninsula indicate a progressive dextral rotation of the regional maximum shortening direction with time (Roberts 1972). The latest gentle to open warps have NW–SE to E–W axial trends, exactly normal to the c. NNE–SSW dolerite dykes which were undoubtedly intruded in a tensional regime.

By contrast, the chemistry of the metadolerites would, at first glance, appear to signify that the crust underlying the sediments into which these dykes were intruded was thinner in this northernmost Scandinavian region and possibly largely of oceanic character at the time of dyke emplacement, assuming that the magma chemistry is a direct reflection of the physico-chemical conditions and compositions in the lower crust and upper mantle. On the other hand it is clear that these dykes, intruded as they are into a thick pile of Riphean sediments concomitant with deformation, do not represent material from oceanic ridge (spreading) axes despite their chemical affinity to abyssal tholeiites. This tectonic environment, together with our knowledge of palaeogeographic reconstructions (Siedlecka 1975), would rather suggest that some form of transitional regime, perhaps of continental margin character, was host to the metadolerite intrusion. Reflecting on the high abundances of Sr and Ba, which was considered a primary feature, it is therefore conceivable that the older dykes are representative of rocks of transitional abyssal tholeiite/continental tholeiite type; such hybrid rocks can be intruded during the initial stages of continental break-up (J. Pearce, pers. comm.). Some implications of this, and the question of the age of the metadolerites, are discussed briefly below.

Discussion

The only radiometric age data on the basic dykes from Varanger Peninsula, as noted earlier, are those of preliminary K–Ar whole-rock determinations (Beckinsale et al. 1975). Metadolerites of the type described in the present account and sampled from the Barents Sea Group have given dates ranging from 935 to 1946 m.y. with a preferred mean of c. 1075 m.y., although Beckinsale et al. recognise the unreliability of these particular ages in view of the consistently low potassium contents. A metadolerite sample from the Raggo Group showing the same intrusive/tectonic relationships as those in the Barents Sea Group has, on the other hand, given an age of 542 ± 17 m.y.

The dolerites of the present study have provided rather more consistent dates of around 355 ± 10 m.y., from 6 samples, which is considered a fairly reliable intrusive age (Beckinsale et al. 1975). In addition, these authors have sampled apparently uncleaved dykes from the Båtsfjord area which cut the thrust beneath supposed Raggo Group equivalents. These have given K–Ar whole-rock ages averaging about 640 ± 19 m.y.

As yet, this 640 m.y. dyke set has not been studied in detail in the field. The chemistry of these dykes is poorly known although in the present study samples nos. FA88 and possibly 530 may be representatives of this Båtsfjord-type dyke set. These show higher values for titanium and alkalies than the metadolerites. A more detailed study of the chemistry of these particular dykes is planned.

A comparison of the chemical and radiometric data obtained from the Varanger Peninsula dykes, on a wider regional basis, has revealed that the uppermost Devonian dykes are apparently unique in the northern Russo–Fennoscandian region. Siedlecka (1975), in a comprehensive survey of the Russian literature on the Timan–Kanin–Ribachiy region, found no reports of basic dyke ages younger than 500 m.y.; these particular 500 m.y. dykes, dolerites and camptonites, are from the northern Timans (Malkov 1972, Table 1). In the same region, gabbroic rocks were intruded in the period 620–640 m.y., and a metamorphic event is dated at 525–520 m.y. Nearer to Finnmark, there is an isolated K–Ar age of 600 ± 20 m.y. for a dolerite (.32% K) from the Sredniy Peninsula (Bekker et al. 1970).

Turning to central and west Finnmark, metadolerites similar in petrography and intrusive/tectonic relationships to those in the Raggo and Barents Sea Groups are fairly common in the Gaissa, Laksefjord and Kalak nappes (Føyn 1960, Gayer & Roberts 1971, Sturt et al. 1975). Rb–Sr* whole-rock isochrons of 530 ± 50 m.y. (now revised to 515 ± 7 m.y.) and 535 ± 60 m.y. have been obtained for the cleavage in the autochthon (Pringle 1972) and in the Laksefjord nappe (Sturt et al. 1975), respectively; these dates may also roughly correspond to the dyke intrusion ages, alhough some of the dykes could be of earlier, pre-deformation, Vendian emplacement.

The problem of the two suggested Laksefjord/Raggo/Barents Sea Group correlation schemes has already been outlined (p. 56). The single 542 ± 17 m.y. date of Beckinsale et al. (1975) for the Raggo metadolerite could possibly be interpreted in favour of similar dyke and deformation ages for the Laksefjord and Raggo Groups. This does not, of course, imply that the sediments of these two groups are necessarily correlatives, although they *may* in fact be of roughly equivalent age. Alternatively, the westernmost part of the Raggo Group, on the basis of biotite porphyroblasts common throughout the nearby Nordkyn Peninsula (Roberts, unpublished results) and also present in the Raggo (Teisseyre 1972), could possibly represent a segment of the Kalak Nappe.

Returning to the matter of the virtually identical structural/dyke-intrusive features displayed by the Raggo and Barents Sea Groups (Roberts 1972), these must now be considered in the light of the Beckinsale et al. 935–1946 m.y. preliminary dates. Clearly, there are seemingly incompatible data here, but *if* the c. 1075 m.y. age is confirmed then this would denote a folding and metamorphic event of about the same age for the Barents Sea Group, an orogenic pulse which would invite comparison with the Carolinidian deformation of N.E. Greenland (Haller 1970) and signify an even older age for the Barents Sea Group than has hitherto been suggested (e.g., Siedlecka & Siedlecki 1971, Siedlecki 1975). At the same time, an implication of the chemistry and tectonic setting of these metadolerites would be that we are possibly dealing with an incipient stage of continental break-up in the period 1100–950 m.y. B.P. There is no evidence from the younger dolerites, on the other hand, either from the chemistry or from the regional geology, of a comparable megatectonic movement in uppermost Devonian time. It must be stressed once again, however, that the above assumptions are based on the results of the preliminary K–Ar studies, the oldest dates of which are the most suspect; moreover, they are not strictly compatible with what we know of the geology of Ribachiy (Siedlecka 1975) or of the character and age of deformation throughout Finnmark. Further radiometric work on the dykes and on the metasediments should certainly help to resolve several of these fundamental problems.

* Based on ^{87}Rb : $\lambda = 1.39 \times 10^{-11} yr^{-1}$.

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