A post-Caledonian dolerite dyke from Magerøy, North Norway: age and geochemistry

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A post-Caledonian, NW–SE trending, dolerite dyke on Magerøy has a geochemical signature comparable to that of continental tholeiites. Clinopyroxenes from three samples of the dolerite gave K-Ar ages of ca. 312, ca. 302 and ca. 266 Ma, suggesting a Permo-Carboniferous age. In view of low K_2O contents of the pyroxenes and the possible presence of excess argon, it is argued that the most reliable estimate of the emplacement age of the dyke is provided by the unweighted mean value, namely 293 ± 22 Ma. This Late Carboniferous age coincides with the later stages of a major phase of rifting and crustal extension in adjacent offshore areas. The dyke is emplaced along a NW–SE trending fault. Parallel or subparallel faults on Magerøy and in other parts of northern Finnmark may thus carry a component of Carboniferous crustal extension in their polyphase movement histories.

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In the Caledonides of northernmost Norway, mafic dykes are common in many parts of the metamorphic allochthon and are invariably deformed and metamorphosed, locally in amphibolite facies. In contrast, dykes that are largely unaltered, and which clearly cut Caledonian structures and metamorphic fabrics, are rare. Dolerite dykes of this category are known from the Varanger Peninsula in northeast Finnmark (Beckinsale et al. 1975; Roberts 1975), and have yielded a K-Ar whole-rock age of ca. 362 Ma (Beckinsale et al. 1975; recalculated according to Dalrymple 1979). Elsewhere in Finnmark, a dolerite dyke considered to be of Late- or post-Caledonian age has been reported from the Magerøy Nappe on the island of Magerøy (Andersen 1979, 1981; Roberts & Andersen 1985). The present contribution reports the results of a study of the geochemistry and an investigation of the K-Ar mineral age of this particular dyke.

Geological setting

Magerøy has captured the attention of travellers and geoscientists alike since the early part of the 19th century when Everest (1829) gave the first description of the island's geology. In more modern times, degree theses (Curry 1975; Andersen 1979; Kjærsrud 1985) have provided accounts of regional stratigraphy, structure and metamorphism, while Robins et al. (1987) have described the magmatic rocks of the Honningsvåg Intrusive Suite.

Three principal tectonostratigraphic units are recognised on Magerøy: (1) the Kalak Nappe Complex; (2) the Magerøy Nappe; and (3) the Skarsvåg Nappe (Fig. 1). The Magerøy Nappe comprises five formations of metasediments; mostly sandstone, greywacke and shale, with local limestone and conglomerate (Andersen 1979, 1984; Kjærsrud 1985). Corals, brachiopods and graptolites indicate an Early Silurian (Llandovery) age (Henningsmoen 1961; Føyn 1967; Bassett 1985) for part of the succession. Mylonitic rocks at the base of the nappe exhibit amphibolite-facies parageneses.

Apart from the largely mafic-ultramafic Honningsvåg Intrusive Suite, plutonic rocks in the Magerøy Nappe occur in two main areas (Fig. 1). One of these bodies, the syntectonic (inter-D1/D2) Finnvik granite, yielded a Rb–Sr isochron age of 411 ± 7 Ma (Andersen et al. 1982). Stored samples of gabbros from the Honningsvåg Intrusive Suite have given Rb–Sr and Sm–Nd internal isochron ages ranging from ca. 558 to ca. 468 Ma (Krill et al. 1988). These dates are at variance with the general notion that the magmatic rocks of the Honningsvåg Intrusive Suite intruded and metamorphosed the fossil-bearing metasediments (Curry 1975; Andersen 1981, 1989; Robins et al. 1987). From the faunal and isotopic dating evidence, the polyphase folding and metamorphism in the Magerøy Nappe are inferred to relate to the Late Silurian to Early Devonian, Scandian orogenesis (Andersen 1981; Roberts & Andersen 1985).

Apart from the prominent dolerite dyke that forms the basis of this contribution, other small, isolated, comparatively fresh, dolerite dykes have been reported by Curry (1975) nearer to Honningsvåg, and confirmed by S. Lippard (pers. comm. 1990). Preservation of the Magerøy Nappe on Magerøy and its absence on the adjacent mainland (Fig. 1) is explained by the existence of the Magerøysund Fault. This involves a significant downthrow to the northeast along this NW–SE trending structure, post-dating Scandian orogenesis (Andersen 1981). The Finnvik granite itself extends down to a depth of at least 4 km (Lønne & Sellevoll 1975), but is not exposed on the mainland directly southwest of the Magerøysund Fault.

Field relationships and petrography

The investigated dolerite dyke occurs in the undulating terrain of central Magerøy (Fig. 1). It was emplaced along a major NW–SE (ca. 310°) trending fault-zone that can be traced from Sardnespollen in the southeast to the coast near Gjesvær in the northwest. The faults and joints in this system offset the dominantly NNE–SSW trending bedding and foliation in the amphibolite-facies metasediments. The NW–SE trend of the fault is parallel to a prominent set of post-Caledonian major and minor faults and master joints that are characteristically developed on Magerøy. Locally, gouges and carbonate-cemented breccias occur along these faults which, in some cases, are expressed topographically in the form of narrow valleys (Andersen 1979). The near-vertical dyke can be traced almost continuously for 3.8 km along the fault. In the poorly exposed boggy and frost-weathered areas on central Magerøy, blocks of the dolerite are easily distinguished from the grey, country-rock metasediments by a characteristic, thin, yellowish-brown weathering crust. The contacts with the country rocks are rarely well exposed. Locally, however, the dyke rock forms a network of intrusions in the fractured rocks along the fault-zone. The thickness of the dyke is at least 8 m. Thin-sections show that the dolerite is fine- to medium-grained and non-porphyritic, with an ophitic to subophitic texture. It consists principally of clinopyroxene, plagioclase, leucoxene and opaques. The plagioclase (An_{45}) generally carries only traces of saussuritisation along cleavages. The clinopyroxene is zoned, in either an irregularly concentric or an hourglass pattern. Microsonde analysis of three grains confirmed an X-ray pattern that the pyroxene is augite. Opaques are mostly ilmenite and haematite, with minor magnetite and pyrite; replacement of primary phases by haematite is locally advanced, especially in the southeastern area, indicating some degree of oxidisation. This can also be seen in the Fe_2O_3/FeO ratio (Table 1). Other minor constituent minerals are apatite, biotite and zircon.

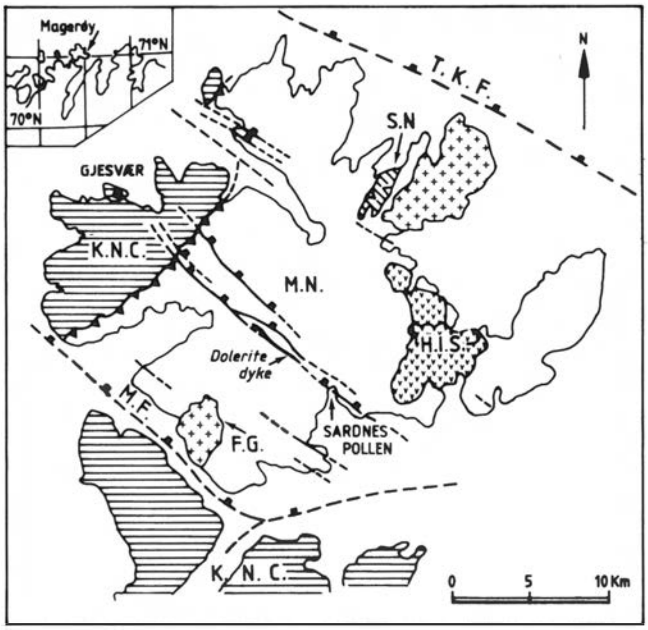

Fig. 1. Simplified map of Magerøy showing the main nappe units, plutonic bodies and major faults, and the location of the dolerite dyke discussed in the text. F.G. – Finnvik granite; H.I.S. – Honningsvåg Intrusive Suite; K.N.C. – Kalak Nappe Complex; M.F. – Magerøysund Fault; M.N. – Magerøy Nappe; S.N. – Skarsvåg Nappe.

Geochemistry

Major and trace elements were analysed on rock powders using an automatic Philips 1450/20 XRF, at NGU, Trondheim. Calibration curves were based on international standards. For the determination of major elements the rock samples were melted with lithium tetraborate 1:7. Ferrous iron, H_2O^+ and H_2O^- were determined by the method outlined in Langmyhr & Graff (1965). Trace elements were determined on pressed rock powders. Rare-earth elements, together with Hf, Ta, Th and U, were analysed by INAA (by Jan Hertogen) at the Department of Physico-Chemical Geology, University of Leuven, Belgium.

In view of the homogeneous, almost equigranular nature of the dolerite, it was considered sufficient to collect only a limited number of fresh and apparently unaltered samples, spread out along the length of the dyke, in order to obtain reliable information on the chemical composition. Five samples were chosen (nos. 1 to 5 from southeast to northwest), and these do in fact reveal a marked homogeneity in major and trace element contents, with very low standard deviations (Table 1).

Comparing the element abundances with reported average values for continental tholeiites and ocean-floor basalts (Table 1), it is clear that the dyke is more akin to continental tholeiitic rocks than to basalts generated in an ocean-floor setting. This is not unexpected, considering that the dyke penetrated nappe rocks locally exceeding 7 km in thickness (Olesen et al. 1990) and a crystalline basement of unknown but appreciable thickness following the Scandian continent–continent collision.

Features of the *major element* analyses include the comparatively high TiO_2, P_2O_5, total Fe and total alkalies and low Al_2O_3 and MgO concentrations. In view of the high Fe_2O_3/FeO ratios, the CIPW norms were recalculated after adjustment of these ratios to reasonable values, following procedures outlined in Irvine & Baragar (1971). The tholeiitic nature of the dolerite is clearly indicated in FeO/MgO vs. FeO and TiO_2 plots, not shown here.

The more incompatible *trace elements*, in conjunction with the high field strength elements P and Ti, are known to be better discriminants of tectonic environment than the major oxides. As to be expected, plots such as those of Ti–Zr–Y and TiO_2–Zr show the dolerite samples to

Table 1. Major and trace element composition and CIPW norms of samples (nos. 1–5) from the dolerite dyke (major oxide and norms in wt.%, trace elements in ppm), together with mean values and standard deviations (S.D.), and means for continental tholeiites (CON) and ocean-floor tholeiites (OFB).

	1	2	3	4	5	Mean	S.D.	CON	OFB
SiO_2	48.33	49.55	48.01	48.12	48.74	48.55	0.62	48.81	49.91
Al_2O_3	12.71	13.03	12.60	12.79	12.95	12.82	0.17	14.41	16.20
TiO_2	3.16	2.92	3.11	3.23	3.04	7.61	1.02	13.20[1]	
Fe_2O_3	8.46	7.48	7.73	8.42	5.96	5.92	0.69		10.24[2]
FeO	5.38	5.41	6.00	5.72	7.07	3.09	0.12	2.47	1.43
MgO	4.26	3.89	4.18	4.35	4.19	4.17	0.17	5.96	7.74
CaO	7.65	7.40	7.58	7.46	7.86	7.59	0.18	10.05	11.42
Na_2O	3.40	3.10	3.50	3.20	3.10	3.26	0.18	2.90	2.82
K_2O	1.55	1.72	1.52	1.55	1.51	1.57	0.09	0.95	0.24
MnO	0.22	0.21	0.22	0.24	0.22	0.22	0.01		
P_2O_5	0.54	0.56	0.57	0.55	0.59	0.56	0.02		
H_2O^+	1.70	1.57	2.07	1.87	1.42	1.73	0.25		
H_2O^-	1.62	1.46	1.19	1.27	1.65	1.44	0.21		
CO_2	0.07	0.12	0.15	0.09	0.22	0.13	0.06		
Total	99.05	98.42	98.43	98.86	98.52				
Nb	19	23	23	26	21	22.4	2.61	25	5
Zr	248	280	251	251	266	259.2	13.59	149	92
Y	42	48	47	44	43	44.8	2.59	25	30
Sr	318	306	299	311	305	305.8	4.44	401	131
Rb	43	43	40	43	36	41.0	3.08	15	3
Zn	107	95	93	109	94	99.6	7.73		
Cu	22	19	17	22	15	19.0	3.08	99	73
Ni	14	11	12	13	10	12.0	1.58	68	106
Cr	<5	<5	<5	6	<5	5.2	0.45	139	310
V	356	308	363	353	300	336.0	29.57		229
Ba	752	795	707	727	751	746.4	32.95	338	8
CIPW norms									
q	2.3	5.4	2.0	3.0	4.6				
or	9.2	10.2	9.0	9.2	8.9				
ab	28.8	26.2	29.6	27.1	26.2				
an	14.8	16.6	14.2	16.0	17.0				
di	15.7	12.9	15.4	13.8	13.7				
hy	10.4	10.3	10.5	11.9	10.7				
mt	6.8	6.4	6.7	6.9	6.6				
il	6.0	5.5	5.9	6.1	5.8				
ap	1.3	1.3	1.4	1.3	1.4				
cc	0.2	0.3	0.3	0.2	0.5				

[1] Total Fe given as Fe_2O_3.

[2] Total Fe as FeO. Data source for mean CON & OFB element contents – Pearce (1975). The CIPW norms are recalculated after adjusting the Fe_2O_3:FeO ratio in accordance with procedures given in Irvine & Baragar (1971).

cluster in the 'within plate' field. Diagrams devised to distinguish between continental tholeiites and continental alkali basalts, employing Y, Nb and Ti (Figs. 2 and 3), signify that we are dealing with a mafic dyke rock of tholeiitic composition. (For comparative purposes, averages of the Permo-Jurassic alkaline mafic dykes from West Norway and the Devono-Carboniferous dolerites from Varanger Peninsula are included in these diagrams.) The Nb–Zr–Y plot of Meschede (1986) and V–Ti discriminant of Shervais (1982), not shown here, also confirm this tholeiitic composition.

Rare-earth element (REE) analyses of two representative samples of the dolerite show chondrite-normalised patterns which are almost identical, within analytical error (Fig. 4). The spectra show a slight downward convexity, though with just a hint of a positive Eu anomaly. Both the absolute REE values (Table 2) and the ratios of light REE to heavy REE (e.g. the La/Yb

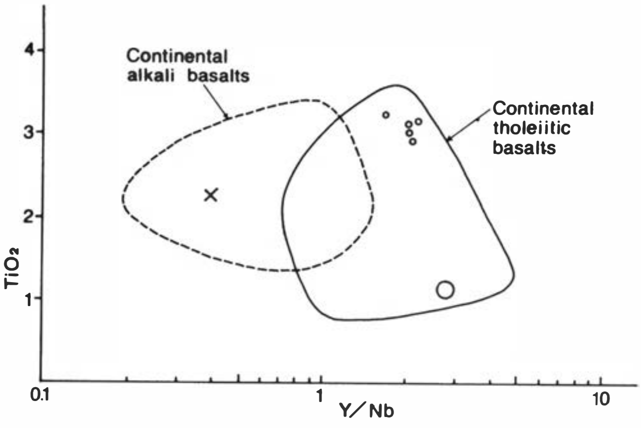

Fig. 2. TiO_2–Nb/Y(log) plot of the dolerite samples. ○ – average value of the Devono-Carboniferous dolerite dykes from Varanger Peninsula (Roberts 1975); × – average value of the Mesozoic alkaline dykes from the Sunnhordland region, West Norway (Færseth et al. 1976). The diagram is from Winchester & Floyd (1976).

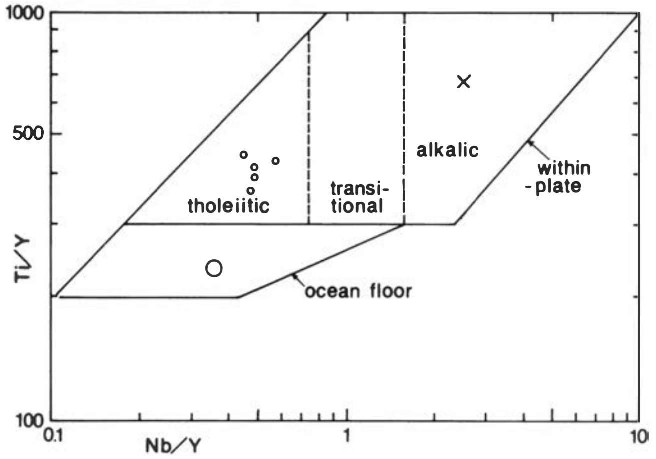

Fig. 3. Ti/Y(log)–Nb/Y(log) plot of the dolerite samples from Magerøy. Symbols as in Fig. 4. Diagram from Pearce (1983).

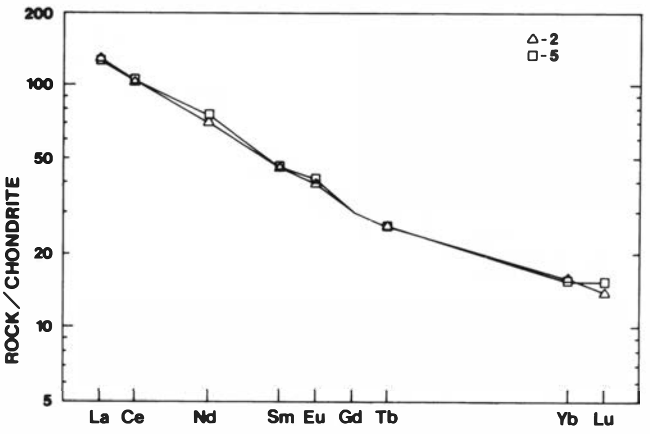

Fig. 4. Chondrite-normalised REE patterns for Magerøy dolerite sample nos. 2 and 5.

ratio of 7.2) are typical of continental tholeiitic dykes, sills and lavas worldwide (cf. Dupuy & Dostal 1984).

K–Ar age determinations

Since the reliability of whole-rock K–Ar ages of dolerites has been disputed, on the grounds of both 'excess argon' (Lanphere & Dalrymple 1971) and argon loss from groundmass phases (Miller & Mussett 1963), pyroxene was separated from three of the chemically analysed rocks, and their conventional K–Ar ages determined. The pyroxenes were separated magnetically, and partly with the aid of heavy liquids. The analytical procedures have been described by Wilkinson et al. (1986), and the results of the triplicate potassium and duplicate radiogenic argon analyses are given in Table 3. Despite the fact that pyroxene has been found to contain 'excess argon' (Hart & Dodd 1962; McDougall & Green 1964), the decision to analyse a separated mineral, rather than a whole rock, was taken in anticipation of facilitating the interpretation of the analytical data obtained.

The younger age of the pyroxene from Sample 1 stands apart from the remaining two, whose ages are concordant at the 1σ confidence level. (All three ages are, however, concordant at the 2σ level.) In order to interpret these pyroxene K–Ar ages, given the possibility of incorporated 'excess argon', it is necessary to seek indicators for the phonomenon. If a uniform concentration of 'excess argon' were incorporated into this suite of pyroxenes, then an increasing age anomaly would inversely correlate with the potassium content; this, in fact, is precisely the effect observed here. Such an argument would lead to the youngest age (i.e. from the pyroxene having the highest potassium content) being preferred.

However, the presence of excess argon in pyroxene is not universal, and perturbation of the potassium–argon isotopic system could arise by argon loss in phases which are non-retentive of argon, and which have been incorporated in trace amounts into the mineral separate analysed. With a mean whole-rock K_2O of 1.57 wt.%, the level of extraneous mineral contamination necessary to change the concentration of the 'pyroxene' separate from 0.03% to 0.05% would only have to be of the order of 1%. To test the possibility of argon loss, as a consequence of alteration, being responsible for the spread of ages we have also calculated (Table 3) the specific ^{36}Ar content of each of the separates. It is evident that Sample 1, having the youngest age, also contains nearly a factor two greater concentration of ^{36}Ar. It has been suggested (Baksi 1985) that the ^{36}Ar content of rocks may be used as a criterion for judging their suitability for K–Ar dating. An increasing level of ^{36}Ar has been demonstrated to correlate with increasing alteration. This evidence would lead us to conclude that the ages of Samples 2 and 5 should be regarded as the best indicators of the true age of the pyroxene. This accords with field and thin-section observation that weathering and alteration are minimal in the northwesternmost exposures of the dyke.

On the basis of the three available sets of data, it is not possible to unambiguously resolve which of these two propositions is valid. However, in consequence of the

Table 2. Rare-earth element and Sc, Hf, Ta, Th and U contents (ppm) of representative samples from the dolerite.

Sample no.	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Sc	Hf	Ta	Th	U
2	44.3	94	46	9.6	3.19	1.36	3.6	0.49	30:7	6.3	1.71	5.1	0.94
5	43.3	94	49	9.7	3.31	1.37	3.5	0.54	32.8	6.1	1.67	5.2	0.95

Table 3. K–Ar age data for the Magerøy dolerite.

Sample no.	Mineral	K_2O (wt.%)	Radiogenic ^{40}Ar ($mm^3\,gm^{-1}$)	^{36}Ar ($10^{-6}\,mm^3\,g^{-1}$)	%Atmos. Contam.	Age Ma ± 1σ
1	Pyroxene	0.051 ± 0.001	$(4.68 \pm 0.12)10^{-4}$	4.61	73.8	264 ± 8
			$(4.75 \pm 0.12)10^{-4}$	3.91	70.2	268 ± 9
2	Pyroxene	0.037 ± 0.001	$(3.86 \pm 0.09)10^{-4}$	2.46	64.6	297 ± 11
			$(3.98 \pm 0.10)10^{-4}$	3.42	71.1	306 ± 11
5	Pyroxene	0.027 ± 0.001	$(2.94 \pm 0.07)10^{-4}$	3.43	70.3	309 ± 14
			$(2.99 \pm 0.07)10^{-4}$	2.72	72.2	314 ± 14

Constants: $\lambda_e = 0.581 \times 10^{-10}\ a^{-1}$ $\frac{^{40}K}{K} = 1.167 \times 10^{-2}$ atom percent.

$\lambda_\beta = 4.96 \times 10^{-10}\ a^{-1}$ (Steiger & Jäger 1977).

low K_2O contents of the pyroxenes (0.03–0.05 wt.%), the uncertainties in the calculated ages are such as to render the three ages statistically indistinguishable at the 2σ confidence level. In these circumstances, the best estimate we are able to make for the age of the dyke is the unweighted mean of the three values, namely 293 ± 22 Ma.

Discussion

Assessing the suggested emplacement age of 293 ± 22 Ma for the dyke requires a brief consideration of the regional fault systems and offshore geology. Intrusion of the dyke has apparently been controlled by a pre-existing NW–SE trending fault, one of a set of faults on Magerøy which post-dates the Scandian folds and parallels the assumed trend of the Magerøysund Fault. The latter probably transects the 411 ± 7 Ma Finnvik granite and is itself a parallel or subparallel structure to the offshore extension of the Trollfjord–Komagelv Fault Zone (TKFZ) just north of Magerøy (Fig. 1) (Siedlecka & Siedlecki 1967; Lippard & Roberts 1987; Townsend 1987; Gabrielsen & Færseth 1989).

The post-Caledonian geological evolution of the southwestern Barents Sea involved an important phase of latest Devonian to Mid or Late Carboniferous clastic sedimentation in fault-controlled, NE–SW oriented basins (Rønnevik 1981; Faleide et al. 1984; Gabrielsen et al. 1990). Faults of NW–SE to WNW–ESE trend were also probably active in this pre-Permian, extensional, rifting phase, including the TKF directly north of Magerøy and associated structures (Gabrielsen & Færseth 1989). By contrast, the period from Permian to Early Jurassic was one of comparative quiescence. Thereafter followed another major period of rifting (Kimmerian) and basinal sedimentation in Mid-Jurassic to Early Cretaceous time.

The dolerite dyke age of ca. 293 ± 22 Ma reported here is thus geologically reasonable, emplacement coinciding with the later stages of a major phase of rifting and extensional faulting in adjacent offshore areas. At this terminal stage of the period of crustal extension, basaltic magma would presumably have had sufficient time to have penetrated into the uppermost levels of the continental crust along favourable fractures or specific segments of major faults. This is also in keeping with the geochemical signature of the dolerite, with the REE patterns and absolute abundances of high field strength elements suggesting that some contamination by crustal material may have occurred during the ascent of the magma. On most published time-scales (e.g. Harland et al. 1990), 293 Ma falls in the Late Carboniferous (Stephanian). Taking into account the error bar, the range is from Mid-Carboniferous to Mid-Permian, with samples 2 and 5 in the Middle Carboniferous. It is thus reasonable to assume that NW–SE trending faults on Magerøy, and other parallel to subparallel faults elsewhere in northern Finnmark (Lippard & Roberts 1987), including the TKFZ, probably participated to varying extents in this phase of Carboniferous extension.

Conclusions

A NW–SE trending dolerite dyke on Magerøy, at least 8 m thick and exposed over a strike length of ca. 3.8 km, post-dates all Caledonian structures and metamorphic fabrics. The chemical composition of the dyke indicates a close similarity to continental tholeiites.

Pyroxenes separated from three samples of the dolerite gave K–Ar ages of ca. 312, ca. 302 and ca. 266 Ma. Because of low K_2O contents of the pyroxenes, and the possible presence of 'excess argon', it is argued that the unweighted mean value, namely 293 ± 22 Ma, is the best estimate that we can make for the age of emplacement of the dyke.

A Late Carboniferous age coincides with the later stages of a major phase of rifting and extensional faulting that is known to have occurred at this time in the adjacent offshore area of the southwestern Barents Sea. Many of the NW–SE trending faults on Magerøy and in other parts of northern Finnmark, including the TKFZ, may carry a component of Permo-Carboniferous extension in their movement histories.

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