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Mafic Dykes in the Shackleton Range, Antarctica

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Summary: In addition to some mafic dykes which are already known and which were resampled, a number of mafic dykes were discovered in the Shackleton Range during the 1987/88 GEISHA expedition and sampled for the first time. Field data for 29 dykes, as well as analytical results of petrographic, geochemical, and isotope-geochemistry studies on the basalts of 26 of these dykes, are presented and discussed.

The mafic dykes can be subdivided into five groups on the basis of their petrography and degree of alteration. According to the geochemical analyses, the dyke rocks are continental tholeiites. Geochemical characterization on the basis of trace-elements, especially rare earths, permits subdivision according to magma type. This subdivision shows reasonable agreement with the subdivision according to petrographic criteria.

On the basis of radiometric dating and field relationships, the following ages can be assigned to the five groups of dykes:
Group I, Early Jurassic;
Groups II and III, early Palaeozoic (Middle Devonian to Late Ordovician?);
Group IV, probably Late Proterozoic and
Group V, probably Middle Proterozoic.

These groups of mafic dykes, which can be regarded as indicating extension phases, are discussed with respect to the geotectonic history of the Shackleton Range, and comparisons with neighbouring regions are made.

Zusammenfassung: Während der Expedition GEISHA 1987/88 wurden zusätzlich zu einigen schon bekannten und nochmals beprobten mafischen Gängen mehre weitere solche Gänge in der Shackleton Range neu aufgefunden und erstmals beprobt. Von insgesamt 29 Gängen werden die Feldbefunde dargestellt und von 26 beprobten Gängen die Analysen und Ergebnisse petrographischer, geochemischer und isotopengeochemischer Untersuchungen an den Gangbasalten angeführt und diskutiert.

Nach petrographischen Gesichtspunkten, vor allem unter Einbeziehung des Alterationsgrades, ergibt sich eine Einteilung der mafischen Gänge in fünf unterschiedliche Ganggruppen (I bis V). Nach den geochemischen Analysen handelt es sich bei den Ganggesteinen im wesentlichen um kontinentale Tholeiite. Die geochemische Charakterisierung mit Spurenelementen, speziell auch mit Seltenen Erden erlaubt eine Unterteilung nach der Herkunft von mehreren verschiedenen Magmen. Diese Unterteilung deckt sich ausreichend gut mit derjenigen nach petrographischen Kriterien.

Radiometrische Datierungen und die Verbandsverhältnisse führen zu der folgenden Alterszuordnung.
Ganggruppe I: Unterer Jura,
Gangruppen II u. III: Altpaläozoikum (mittleres Devon- oberes Ordovizium?),
Ganggruppe IV: Vermutlich Jungproterozoikum,
Ganggruppe V:Vermutlich Mittelproterozoikum.

Abschließend werden die auf Extensionsphasen hinweisenden Gruppen der mafischen Gänge in die geotektonische Entwicklung der Shackleton Range eingeordnet und Vergleiche mit benachbarten Regionen angestellt.

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1. INTRODUCTION, PREVIOUS STUDIES, AND GEOLOGICAL SETTING

Mafic dykes are not particularly rare in the mountains at the paleo-Pacific margin of eastern Antarctica and in eastern Antarctica itself. In the Shackleton Range, however, they are much less frequent. These dykes are of interest because they provide valuable information on the geotectonic history of this region, especially on crustal extension phases, and because their field relationships allow at least a relative determination of the age of the rock complexes they penetrate.

In the present paper, the expression „mafic dykes“ is only used for hypabyssal, discordant dyke-like basalt intrusions. In the literature published in English, they are called „dolerite dykes“. Basalt sills are not present in this region, nor have petrographically different mafic dykes (e.g. lamprophyre and lamproite dykes) been found in the Shackleton Range.

The Shackleton Range is located at the southeastern edge of the Filchner ice shelf between 20 °W and 31 °W and between 80 °S and 81 °S. This E-W-trending range (Fig. 1) is divided into seven sections by glaciers and the Fuchs Dome: Haskard Highlands, Lagrange Nunataks, Herbert Mountains, and Pioneers Escarpment in the north and Otter Highlands, Stephenson Bastion, and Read Mountains in the south. In the north, the Shackleton Range is bounded by the huge Slessor Glacier, in the south by the less conspicuous Recovery Glacier. The highest elevations (about 1800 m) are in the Read Mountains, the lowest ones (about 800 m) are near the nunataks at the edge of Slessor Glacier. Morphologically conspicuous is the magnificent southern escarpment of the Read Mountains, which is broken up into a series of cirques.

The geological exploration of the Shackleton Range started with a 1957/58 British expedition (STEPHENSON 1966); other British surveys followed from 1968 to 1971 and 1977/78. Soviet expeditions to the Shackleton Range, in which East German and American geoscientists participated, took place in 1976/77 and 1977/78. The results of these expeditions are documented for the most part by CLARKSON (1972, 1981, 1982, 1983), HOFMANN (1982), HOFMANN & PAECH (1980, 1983), and HOFMANN et al. (1980, 1981). They were of basic importance for the work of the 1987/88 German Geological Expedition in the Shackleton Range GEISHA. The detailed report on this expedition was published in FÜTTERER (1988).

The Shackleton Range is located in the area where the East Antarctic Shield adjoins the younger orogenic zones at the At-

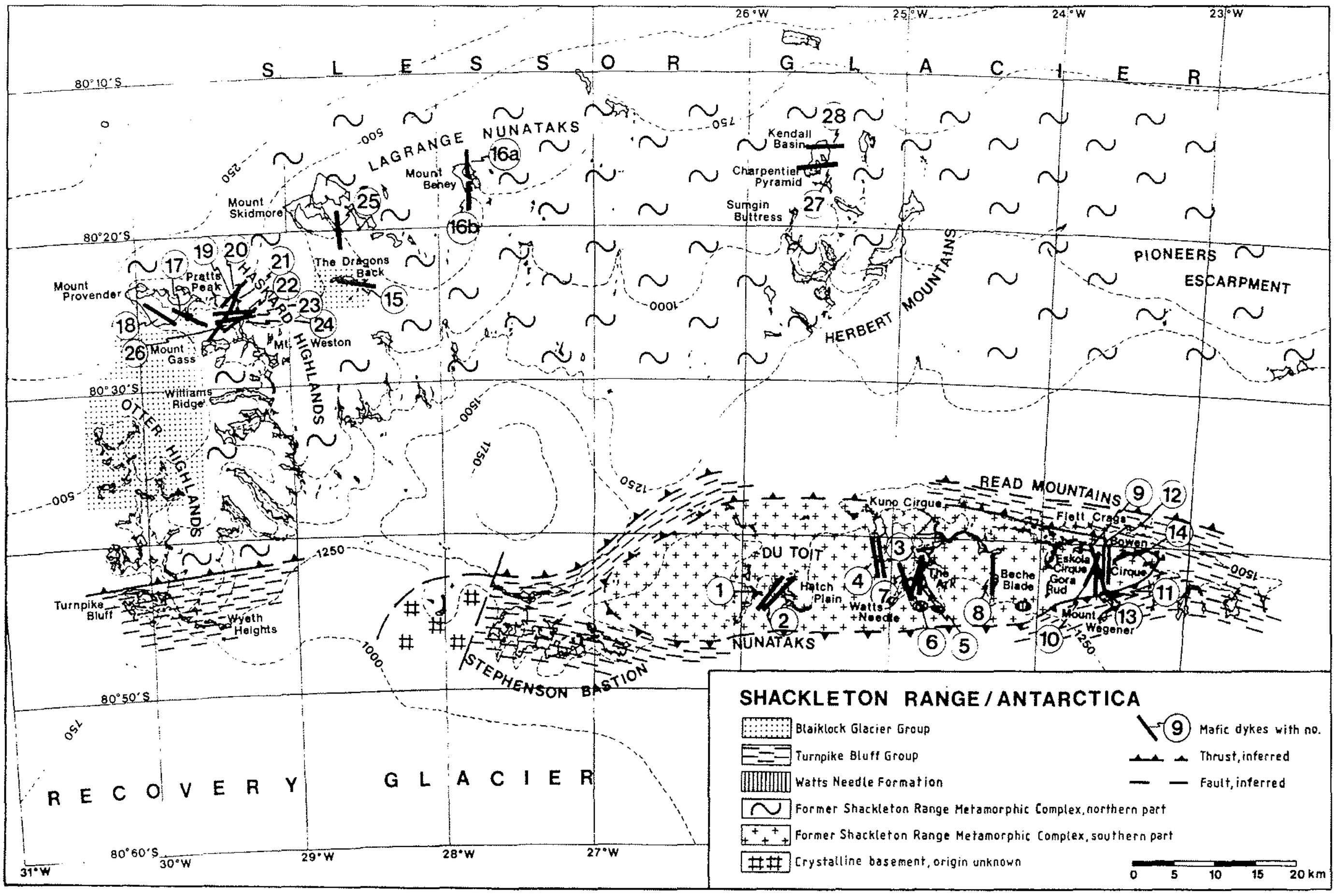


Fig. 1: Geological map of the Shackleton Range showing the positions of the mafic dykes; topography based on the British Antarctic Survey's 1 : 250,000 topographic map of the Shackleton Range (1980); geology modified after BUGGISCH et al. (1990).

Abb. 1: Geologische Kartenskizze der Shackleton Range mit Lage der mafischen Gänge. Topographie nach Topographischer Karte 1 : 250.000, British Antarctic Survey, 1980. Geologie in Anlehnung an BUGGISCH et al. (1990).

lantic end of the Transantarctic Mountains. The E-W trend of the Shackleton Range differs from the prevailing trends in this boundary region and is thus of particular interest to the geologist.

On the basis of discussions during the Workshop on the Geology of the Shackleton Range (April 1990, BGR, Hannover), the geological structure of the Shackleton Range can be summarized as follows (Fig. 1): The mountain range consists predominantly of Precambrian crystalline basement. The main types of rocks are orthogneisses and granitoids, paragneisses and mica schists. Migmatites, quartzites, and marbles are much less frequent.

The history and the structure of the basement, formerly called the Shackleton Range Metamorphic Complex (SRMC), differ in the northern and southern parts of the Shackleton Range. In addition to infracrustal rocks, the northern part of the former SRMC (e.g. the Haskard Highlands and Herbert Mountains) consists of supracrustal metamorphites, which can be divided into several formations. These Precambrian rocks underwent their last, locally thorough dynamothermal metamorphism at the Precambrian to Early Paleozoic boundary during the Ross Orogeny in the Transantarctic Mountains. The southern part of the SRMC (Read Mountains), however, which consists mainly of infracrustal rocks, has evidently preserved its older Precambrian age (for details see chapter 5), and at the time of the Ross Orogeny underwent only very weak to weak dynamothermal metamorphism, mainly within narrow shear zones.

The two parts of the SRMC have similar structures. The predominant strike direction of the rocks and foliation is E-W. Only in the northwestern Shackleton Range (in the Haskard Highlands) are other strike directions (N-S) found.

In the Read Mountains, the SRMC is overlain by younger sedimentary sequences: non-metamorphic clastic sediments and carbonate rocks of the Watts Needle Formation and the very-low-grade to low-grade metamorphic slates and quartzites of the former Turnpike Bluff Group. MARSH (1983) and BUGGISCH et al. (1990) assign the Watts Needle Formation to the Upper Precambrian and the Turnpike Bluff Group to the Lower Cambrian. The rocks of the Watts Needle Formation show a transgressive, discordant contact with the crystalline basement. The rocks of the Turnpike Bluff Group, which are very frequent in the southern Shackleton Range, show a tectonic contact with the underlying rock. The predominant strike direction of the highly deformed Turnpike Bluff Group, as well as that of the fold axes, is E-W, like that of the SRMC.

Only in the northwestern and western part of the range, in the Haskard Highlands and Otter Highlands, is the SRMC unconformably overlain by Lower Paleozoic non-metamorphic sedimentary rocks: BUGGISCH et al. (1990) assign the shales and siltstones of the Haskard Highlands Formation to the Middle Cambrian, the mainly coarse-clastic rocks of the Blaiklock Glacier Group to the Ordovician. These rocks were also found in an isolated occurrence at The Dragons Back in the Lagrange Nunataks. The cover rocks of the northwestern and western Shackleton Range are mainly subhorizontal.

In addition to a few Proterozoic granodiorite dykes (Read Mountains) and numerous Proterozoic pegmatite dykes, mafic dykes of evidently various ages (chapter 5) cut the rocks of the SRMC. Only in two cases were they found in the rocks of the Blaiklock Glacier Group, namely in the northern Haskard Highlands and at The Dragons Back nunatak.

Previous to this expedition, mafic dykes had been described only from the northern part of the Shackleton Range. CLARKSON (1981) published his findings on the petrography, geochemistry, and in some cases the age of eleven dykes in this region; HOFMANN et al. (1980) provided K/Ar dates for three dykes. They are included in the discussion in chapters 5 and 6. During the GEISHA expedition, some of these 14 dykes were visited again and samples were taken, in particular for paleomagnetic studies. Moreover, another 15 mafic dykes were found in the course of this expedition and samples taken, mainly in the southern Shackleton Range in the Read Mountains (PETERS & SPAETH 1988).

HOTTEN (1993) has meanwhile presented a paper dealing with all rock samples taken from mafic dykes during the GEISHA expedition. His emphasis, however, was on paleomagnetic studies, which will not be described in more detail here; some of his results will be referred to in the discussion. In our paper, we will deal with the results of petrographic studies of the dykes, including alteration phenomena, and the isotope analyses carried out by HOTTEN (1993) for the age determinations. Geochemical studies, especially analyses of trace-elements and rare earths (REE), were carried out by one of the authors (K.T.) at the Geochemical Institute of Göttingen University on a rather large number of selected samples. Chapter 4 (Geochemistry) deals primarily with the results of the trace-element and REE analyses owing to their great importance for the interpretation of the geotectonic significance of the dykes.

The overall purpose of the present paper is to present all known data on the mafic dykes of the Shackleton Range and discuss them in terms of geochemical affinity and age. Moreover, conclusions are drawn with respect to parent magmas and the geotectonic significance of the dykes.

2. FIELD OBSERVATIONS

All of the 29 dykes observed in the Shackleton Range are shown on the sketch map (Fig. 1) and listed with the field data in Table 1. They are numbered in the order in which they were found in the field. The table not only shows the areas in which they occur and where they crop out, but also gives thickness and orientation. In addition, information is provided on the degree of alteration and country rock.

The mafic dykes are, in general, easily distinguishable from the surrounding rock. Figs. 2 to 5 show several typical, quite different outcrops. The dykes are conspicuous owing to their discordant nature and their darkgrey color, although some show a dark brown color (Fig. 4), caused by weathering, or a dark grey-green color (Fig. 5), caused by alteration. Often, they can be easily detected because of their columnar jointing (Fig. 4); they thus tend to be more easily eroded than the country rock and often form grooves and furrows in the ridges and flanks of the nunataks (Figs. 2 and 3).

Except for three dykes (dykes 4, 10, and 14), which, although easily perceivable and measurable with sufficient accuracy, were not accessible because of their location, all other dykes exposures were accessible for sampling. Samples were taken from 26 dykes, mostly for paleomagnetic studies. Three to seven samples (5-15 kg each) per dyke were collected at regular intervals

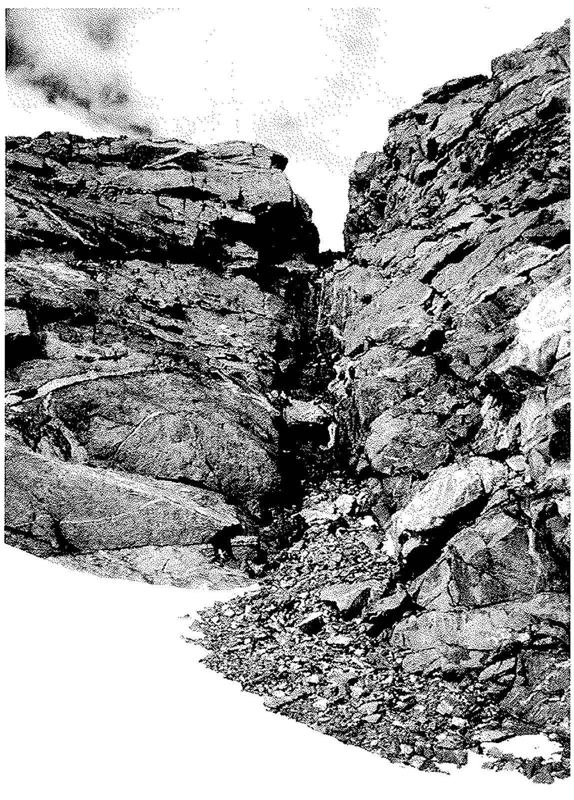


Fig. 2: Basalt dyke 8, northern part of Beche Blade, Read Mountains. Erosion has produced a notch in the surface of the land; width of dyke: 2 m.

Abb. 2: Basalt-Gang 8 im Nordteil von Bleche Blade, Read Mountains. Die Abtragung des Ganges hat zu einer morphologischen Kerbe im Relief geführt. Breite des Ganges ca. 2 m.

Dyke No.	Location	Coordinates	Thickness dip	Field appearance; country rock (CR); previous analyses; other information	Sample no. for chemical analysis
Southern Shackleton Range, western Read Mountains					
1	western margin of Hatch Plain	25° 49' W 80° 44' S	12 m 126° / 85°	slightly altered, with chilled margins; CR: augen gneiss	I.3
2	western margin of Hatch Plain	25° 48' 50" W 80° 44' S	4 m 140° / 85°	slightly altered CR: augen gneiss	II.2
3	southern nunataks on W side of Kuno Cirque	25° 05' W 80° 41' 30" S	9 m 78° / 70°	strongly altered, ophitic texture still recognizable; CR: metasediments	no analyses
4	southern nunataks on W side of Kuno Cirque	25° 05' 10" W 80° 41' 33" S	10 m 80° / 72°	strongly altered; not sampled CR: metasediments	
5	4.5 km northeast of Watts Needle	24° 50' W 80° 42' 30" S	12 m 92° I 78°	relatively fresh, granular basalt with columnar jointing, chilled margins; CR: dark metamorphic rocks with pegmatite dykes	V.2
6	4.4 km northeast of Watts Needle	24° 50' 05" W 80° 42' 30" S	10 m 106° / 70°	relatively fresh, fine-grained basalt; CR: dark metamrophic rocks with pegmatite dykes	VI.2
7	2 km NNE of Watts Needle	24° 54' W 80° 42' 50" S	12 m 70° / 70°	relatively fresh, very fine-grained basalt; CR: slightly foliated granitic gneiss	VII.1 VII.5
Southern Shackleton Range, eastern Read Mountains					
8	NW Beche Blade	24° 20' W 80° 42' 10" S	2m 85° / 80°	slightly altered, with columnar jointing, CR: predominantly pale orthogneiss, also metasediments	VIII.2
9	N side of cirque on NE edge of Eskola Cirque	23° 38' W 80° 40' 50" S	18 m 250° / 75°	distinctly altered, joints show epidote-covered slickensides; CR: thick-banded metasediments	IX.2
10	E edge of Eskola Cirque W side of Gora Rudatschenka	23° 38' W 80° 41' S	3 m 288° / 60°	not sampled CR: metasediments	
11	small nunatak on W side of Bowen Cirque	23° 37' W 80° 42' S	16 m 70° / 86°	columnar jointing, joints lined with epidote; CR: banded metasediments	X.4
12	rock projecting through ice NW side of Bowen Cirque	23° 36' W 80° 41' 30" S	20 m 270° / 70°	CR: metasediments	no analyses
13	W edge of Bowen Cirque E side of Gora Rudatschenka	23° 37' W 80° 42' S	25 m 275° / 70°	columnar jointing; CR: thick-banded metasediments, minor orthogneiss	XII.1 XII.3
14	rock projecting through ice N side of Bowen Cirque	23° 33' W 80° 41' S	5 m 265° / 70°	not sampled	
Northern Shackleton Range, Haskard Highlands and Lagrange Nunataks					
15	outcrops S of Dragons Back Nunataks	28° 33' W 80° 23' 20" S	10 m 190° / 90°	fresh dyke rock; CR: sandstones and siltstones of Blaiklock Glacier Group; corresponds to sample Z736.4-5 (CLARKSON 1981)	XIII.1
16a	north side of Mount Beney	27° 48' W 80° 16' S	4 m 267° / 78°	fresh dyke rock, columnar jointing; CR: gneiss, partly migmatitic, amphibolites	XIV.1
16b	south side of Mount Beney	27° 47' W 80° 17' 30" S	3-4 m 261° / 80°	fresh dyke rock; CR: banded metamorphites; sample corresponds to Z.726 (CLARKSON 1981); possibly a continuation of dyke 16a	XIX.3
17	nunatak 7 km ESE of Mount Provender	29° 40' W 80° 25' S	1.5 m 210° /80°	distinctly altered dyke rock, fine-grained, partly porphyric CR: coarse-grained sediment of Blaiklock Glacier Group; ? corresponds to Z.1039.14 and 15 (CLARKSON 1981)	2.2HD.1
18	nunatak 2 km south of Mount Provender	29° 47' W 80° 24' 40" S	4 m 214° / 80°	strongly altered, fine-grained dyke rock, chilled margins, jointed parallel contact; CR: garnet-bearing gneiss; corresponds to samples Z.1036.11-13 (CLARKSON 1981)	3.2HD.1
19	N side of Pratts Peak	29° 21' W 80° 23' 45" S	0.6 m 142° / 83°	very fine-grained dyke rock; CR: ultramafites	XV.2
20	N side of Pratts Peak	29° 21' W 80° 23' 45" S	0.3 m 320° / 65°	very fine-grained dyke rock; CR: ultramafites	no analyses
21	near top of Pratts Peak	29° 21' W 80° 23' 50" S	1 m 296° / 70°	very fine-grained dyke rock; CR: ultramafites; may correspond to samples Z.1044.11-12 (CLARKSON 1981)	XVI.3
22	NW part of nunatak group S of Pratts Peak	29° 22' W 80° 25' S	1m 353° / 67°	poorly exposed dyke, very friable; CR: garnet-bearing gneiss	no analyses
23	middle of nunatak group S of Pratts Peak	29° 22' W 80° 25' 10" S	3 m 179° / 90°	branching dyke; CR: garnet-bearing gneiss	XVII.2
24	SE part of nunatak group S of Pratts Peak	29° 22' W 80° 25' 30" S	1.5 m 325° / 75°	branching dyke; CR: garnet-bearing gneiss	XVIII.1
25	outcrop SE of Mount Skidmore	28° 40' W 80° 20' S	3 m 84° / 80°	fresh dyke rock; CR: banded gneiss and amphibolites; may correspond to sample 8 (HOFMANN et al. 1980)	XX.2
26	small nunatak NNE of Mount Gass	29° 23' W 80° 26' S	12 m 310° / 70°	distinctly altered dyke rock, dyke intruded along a fault; CR: garnet-bearing hornblende gneiss; may correspond to samples Z.1043 and 16,20 (CLARKSON 1981)	6.2HD.1 6.2HD.2
Northern Shackleton Range, Herbert Mountains					
27	N side of Charpentier Pyramid	25° 37' W 80° 16' 20" S	10 m 340° / 85°	dyke with indistinct columnar jointing; CR: metasediments and amphibolites; corresponds to samples Z.912.4-5 of CLARKSON (1981), poss. also corresponds to sample 2 in HOFMANN et al. (1980)	XXI.4
28	N part of Kendall Basin massif	25° 32' W 80° 14' 45" S	8 m 175° / 90°	strongly jointed and weathered dyke rock, dyke probably intruded along a fault; CR: gneiss, metaquartzite, amphibolites; corresponds to samples Z.916.2-3 in CLARKSON (1981)	11.2.1

Tab. 1: Field observations on mafic dykes in the Shackleton Range.

Tab. 1: Geländebefunde zu mafischen Gängen in der Shackleton Range. Raumlage = Richtung des Einfallens und Größe des Einfallens.

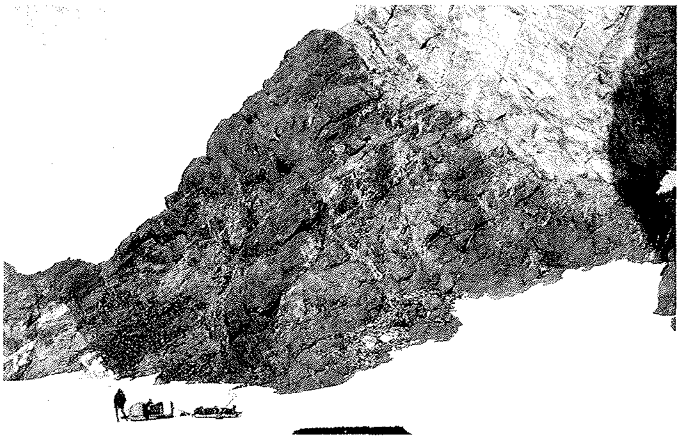


Fig. 3: Basalt dyke 13, eastern flank of Gora Rudatschenka, Read Mountains; width of dyke: 25 m.

Abb. 3: Basalt-Gang 13 in der Ostflanke der Gora Rudatschenka, Read Mountains. Mächtigkeit des Ganges ca. 25 m.

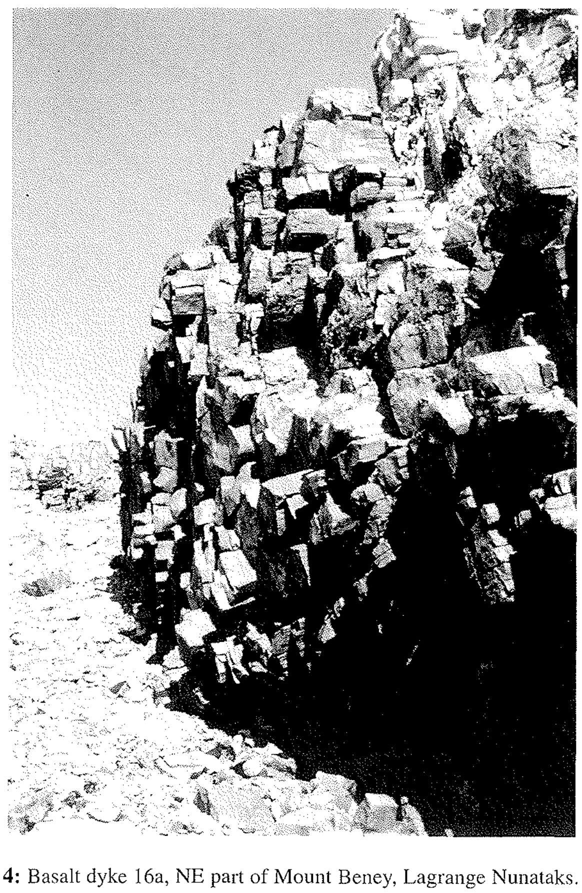


Fig. 4: Basalt dyke 16a, NE part of Mount Beney, Lagrange Nunataks. Width of the dyke: 4 m; dyke shows conspicuous columnar jointing and reddish brown rock surfaces.

Abb. 4: Basalt-Gang 16a im NE-Teil von Mount Beney, Lagrange Nunataks. Breite des Ganges ca. 4 m; der Gang zeigt eine auffällige Säulenklüftung und rot-braune Gesteinsoberflächen.

across the full width of the dyke to provide sufficient rock material for the paleomagnetic studies and the petrographic and geochemical analyses. About 110 samples with a total weight of little more than 1000 kg were collected.

Fig. 5: Basalt dyke 18, Nunatak south of Mount Provender, northern Haskard Highlands; width of dyke: 4 m; dyke is intensely jointed and altered; dyke shows dark green-grey rock colour.

Abb. 5: Basalt-Gang 18 im Nunatak südlich von Mount Provender, nördliche Haskard Highlands. Breite des Ganges ca. 4 m; der Gang ist intensiv geklüftet, alteriert und zeigt dunkel grün-graue Gesteinsfarbe.

2.1 *Distribution and nature of the dykes*

Mafic dykes are distributed over the entire Shackleton Range (Fig. 1). In the southern part of the range, however, they were found only in the Read Mountains, mainly around Gora Rudatschenka in the eastern part. In the Gora Rudatschenka area, it is conspicuous that they were found only in the crystalline basement and not in the overlying Watts Needle Formation or in the Turnpike Bluff Group. No mafic dykes were observed in the Blaiklock Glacier Group in the Otter Highlands, the Turnpike Bluff Group in the southwestern Shackleton Range (Turnpike Bluff and Wyeth Heights) or Stephenson Bastion. This indicates that the dykes are presumably older than these sedimentary sequences.

In the northern part of the Shackleton Range, most of the dykes were found in the northern Haskard Highlands. In the Herbert Mountains in the eastern part of the range, they were observed less frequently; only two dykes were studied. CLARKSON (1981) and HOFMANN et al. (1980), however, mention two other dykes in the Herbert Mountains and Pioneers Escarpment, which we were not able to find. Most of the dykes of the northern Shackleton Range are in the basement rocks of the SRMC. As already mentioned, in two cases (dykes 15 and 17) they also intrude sediments of the Blaiklock Glacier Group, which indicates that at least these two dykes are younger than this youngest sedimentary sequence in the Shackleton Range.

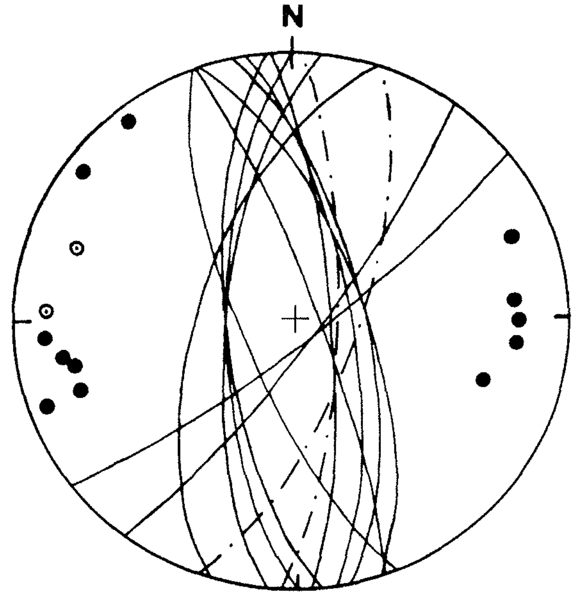
The mafic dykes in the Shackleton Range are 0.3-25 m thick. The thickest dyke (dyke 13; 25 m) is shown in Figure 3. The dykes in the Read Mountains in the south are generally much thicker (10-20 m) than those in the northern Shackleton Range (1-10 m).

Macroscopically, the mafic dyke rocks are fine grained to very fine grained, generally aphyric, less often porphyritic; in some cases where chilled margins were found along the selvages, they are also aphanitic. Almost all dyke rocks in the Read Mountains show a more or less distinctive alteration, indicated by their greenish color; no other variations were observed in the basalts of this area, which contain no phenocrysts. The alteration is assumed to be hydrothermal and presumably low-grade metamorphism (chapter 3). In the northern Shackleton Range, two different types of dykes can be distinguished: the one type, consisting mostly of distinctly greenish, hydrothermally altered basalts (Fig. 5), often contains isolated feldspar phenocrysts 0.3-0.5 cm long and macroscopic clusters of sulfidic ore minerals; the other type seems to be quite fresh, i.e. not greenish, contains small olivine phenocrysts and is characterized by a conspicuous red-brown iron oxide/hydroxide crust. Thus, altogether three different types of mafic dykes were distinguished in the field on the basis of their macroscopic appearance.

2.2 *Field relationships*

All of the dykes were sufficiently exposed to determine their strike and dip. However, due to snow and debris accumulations, it was possible in only a few cases to trace the mostly straight-line exposures of the dykes for more than a few tens of meters to 100 m. Dyke 27 (at Charpentier Pyramid) was traceable over many hundreds of meters. Dyke exposures 16a and 16b (on Mount Beney), which are separated from each other by a large snow field, are probably parts of the same dyke. This is postulated because they have the same orientation, they are linearly aligned, and they are made up of the same kind of rock. This dyke would then be at least 4 km long. Moreover, it is worth mentioning that dykes 23 and 24 both split up into two thinner branches.

All of the dykes are steep to almost vertical, as one might expect of undeformed dykes. The direction and angle of dip are given in Figures 6a and b. It can be seen that the dykes of the Read Mountains (Fig. 6a) show mainly N-S strike directions with little scatter; only two dykes show a distinctly different strike direction (NE-SW). This suggests that the dykes of the Read Mountains belong to a single dyke generation. There is considerably more scatter, however, in the strike directions of the dykes in the northern Shackleton Range (Fig. 6b). In addition to three N-S-trending dykes, there are others with a E-W and NE-SW strike and two dykes trend in NW-SE. This and differences in macroscopic appearance indicate that there are several generations of dykes. Moreover, it should also be noted that some dykes in this region (dykes 18, 22, 26, and 28) are associated with recognizable faults. This leads to the assumption that these dykes are either of the same age as the faulting or younger than at least one phase of the faulting. In the Read Mountains, however, there are indications that the dykes are older than E-W-trending shear zones caused by reverse faulting, since these faults seem to cut the dykes. These dykes are displaced by and/or end abruptly near the faults and the dyke



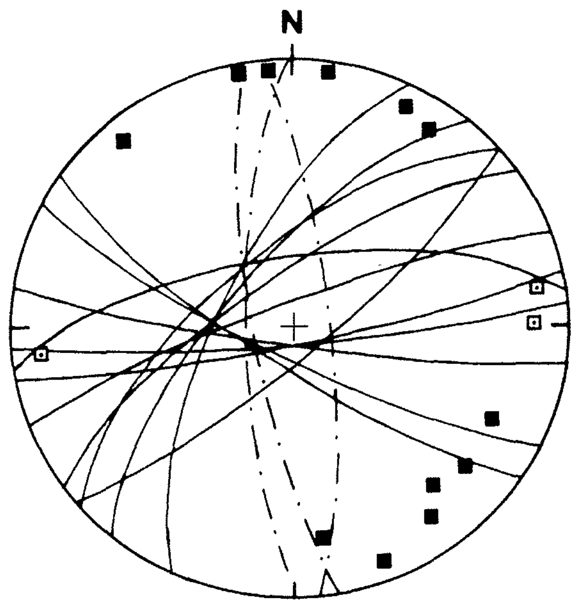


Fig. 6: Stereograms for the mafic dykes; these are represented by poles and great circles (Schmidt net, lower hemisphere). a) Dykes in the Read Mountains; filled circles and solid lines = Group IV; open circles and broken lines = Group V; b) Dykes in the northern Shackleton Range; open squares and broken lines = Group I; filled squares and solid lines = Group II and Group III.

Abb. 6: Lagenkugeldiagramme der Raumlagen der mafischen Gänge, dargestellt durch Polpunkte und Großkreise (Schmidtsches Netz, untere Halbkugel); a) Gänge in den Read Mountains, volle Punkte = Ganggruppe IV, Kreise = Ganggruppe V; b) Gänge in der nördlichen Shackleton Range, offene Quadrate = Ganggruppe I, volle Quadrate = Ganggruppen II und III.

rock near the shear zones seems to be more greenish and fractured. Regrettably, snow cover prevented direct observation of any intersections of a dyke with a fault.

As has been mentioned before, several basalt dykes show columnar jointing. This is especially true for the dykes of the northern Shackleton Range, which appear to be fresh. Only seldom was a distinct, closely spaced jointing parallel to the selvage found (dykes 18 and 28). The stress that affected these dyke rocks apparently had no impact on the other dykes. However, the joints in dyke 9, which is located near a shear zone, and dyke 11 display slickensides that are locally covered with epidote, indicating that the dyke rock was subject to tectonic stress after consolidation.

3. PETROGRAPHY

For petrographic studies, 36 thin sections were prepared from 11 dykes in the Read Mountains and 27 thin sections from 15 dykes in the northern Shackleton Range. Data on petrography, texture, alteration, and modal analyses are given in HOTTEN (1993). Only a summary of this information will be presented here (Tab. 2).

The basalts studied here are mainly fine-grained rocks, sometimes with a high percentage of a very fine-grained matrix. Only very few of them are medium-grained or contain plagioclase, augite or olivine phenocrysts. A glassy matrix was found only once (dyke 16a). When they are not too altered, the unoriented mineral aggregates show the subophitic texture characteristic of hypabyssal mafic rocks.

The basalts of all dykes show a rather monotonous texture, the amounts of the mineral constituents, however, show some variation. The main primary constituents are plagioclase, augite and ore minerals. Minor constituents and accessories are orthopyroxene, olivine, biotite, amphibole, K-feldspar and apatite. Except for apatite, all minerals are more or less altered.

The plagioclase is often zoned and shows albite twinning, often combined with pericline and Carlsbad twinning. Andesine is most frequent, labradorite occurs more rarely, and oligoclase even more seldom. The plagioclase is sometimes so altered that it was impossible to determine the An content. In some of the dykes, plagioclase phenocrysts up to 4 mm long occur. The augite is sometimes zoned and twinned. Occasionally, titanaugite also occurs.

Alteration of the primary igneous constituents has produced a large number of secondary minerals (Tab. 2). Special attention was given to this by HOTTEN (1993), since it was used as a criterion for selecting samples to be studied with various methods and since it is of great importance for the interpretation of the geochemical, isotope-geochemistry, and rock-magnetic laboratory and paleomagnetic data.

The secondary minerals sericite, kaolinite, prehnite, and calcite derive from the partly very thorough alteration of plagioclase; chlorite, epidote, uralite, seladonite, „iddingsite", and chrysotile are alteration products of mafitic minerals. The percentage of chlorite is sometimes >30 vol%; chlorite is thus the most frequent secondary mineral. The percentage of chrysotile may also be rather high, i.e. up to 20 vol.%; in Group V (Tab. 2) olivine, which can only be recognized in the form of the pseudomorphs, is completely replaced by chrysotile. In the modal analysis, which was basically difficult because of the secondary mineralization, the secondary minerals that occur in veins and vesicles were not counted and are therefore not listed in Table 2. In amygdales, for example, quartz occurs together with calcite, chlorite, and serpentine; in two thin sections (dyke 9), pumpellyite was found in cracks.

The secondary minerals derive both from autohydrothermal (deuteric) alteration of the primary magmatic minerals and from hydrothermally introduced material. In thin section, they can hardly be distinguished. The dyke rocks of the Read Mountains (Groups IV and V of Tab. 2) were not only subject to hydrothermal alteration, but alteration and/or neoformation was caused by low-grade to very low-grade regional metamorphism. Sometimes, pumpellyite, calcitized hornblende, and strongly uralitized augite occur.

The opaque grains of the basalts were studied in polished sections; a few samples were additionally analyzed using x-ray diffractometer and microprobe. Ore minerals are mostly titanomagnetite, ilmenite, and magnetite; pyrite also occurs and traces of zincblende and chalcopyrite. At least the first two minerals and some of the pyrite are regarded as primary magmatic minerals. Considerably variable sulphur contents (chapter 4, Tab. 3) indicate that the content of sulfide minerals varies, too. More or less maghemitized titanomagnetite, titanohematite, hematite, secondary magnetite, sphene, and leucoxene were found as alteration products of the opaque oxides. The many types of alterations of titanomagnetite, such as high-temperature and low-temperature oxidation, various grades of maghemitization, and other hydrothermal alteration, were thoroughly studied by HOTTEN (1993). This ore mineral, which is the most frequent one in the samples, is the most important carrier of magnetism and knowledge of its properties is of decisive importance for the interpretation of the rock-magnetic and paleomagnetic measurements. Moreover, it is indicative that the degree of alteration of the ore minerals of the basalts is similar to that of the primary magmatic silicate minerals; in the unaltered or only slightly altered basalts, titanomagnetite was also only slightly altered.

The basalts of the mafic dykes of the Shackleton Range were subdivided into dyke groups or dyke generations I to V by HOTTEN (1993) according to their mineral content and according to the type and degree of secondary alteration. Groups I, II and III occur in the northern Shackleton Range, Groups IV and V in the Read Mountains (Tab. 2). These agree remarkably closely with groups originally set up in the field. The dykes are arranged in the five groups in Table 2.

Dyke Group IV		Southern Shackleton Range, Read Mountains, dykes 1, 2, 3,7, 8, 9, 11, 12, 13								
primary igneous minerals		plag.	augite	o-pyr.	biotite	olivine	amphib.	K-fsp.	apatite	opaques
	vol.%	21-50	15-39	<3.3	<1	<1	(<1-13)	<1	<1	1.2-8.5
secondary minerals										
sericite	<1-10	X								
kaolinite	<1-5	X								
prehnite	<1	X								
calcite	<1-4.7	X	X				X			
clinozoisite	<1	X								
epidote	<1	X	X	X			X			
uralite	<1-13		X							
seladonite	<2.4		X							
chlorite	<1-37		X	X	X		X			
iddingsite	<1					X				
chrysotile	<1-7.5		X	X		X				
leucoxene	<1-12									X

Dyke Group V		Southern Shackleton Range, Read Mountains, dykes 5 and 6								
primary igneous minerals		plag.	augite	o-pyr.	biotite	olivine	amphib.	K-fsp.	apatite	opaques
	vol.%	32-46	6-13	<1.9	1-1.8		<1		<1	9-16
secondary minerals										
sericite	<3	X								
kaolinite	<2.4	X								
prehnite	<1	X								
chrysotile	5-20			X		X				
chlorite	5.5-28		X	X	X		X			
seladonite	<1		X							
leucoxene	<1									X

Dyke Group I		Northern Shackleton Range, Lagrange Nunataks, dykes 16a, 16b, 25								
primary igneous minerals		plag.	augite	o-pyr.	biotite	olivine	amphib.	K-fsp.	apatite	opaques
	vol.%	55-60	19-29	2.4-4.5	<1-3.3	<1	<1	<1	<1	4-17
secondary minerals										
sericite	<1	X						X		
kaolinite	<1	X								
prehnite	<1	X								
epidote	<1	X	X							
chlorite	<9.5		X	X	X					
iddingsite	<1					X				
chrysotile	<1					X				

Dyke Group II		Northern Shackleton Range, dykes 15, 19, 20, 21, 23, 24, 26, 27								
primary igneous minerals		plag.	augite	o-pyr.	biotite	olivine	amphib.	K-fsp.	apatite	opaques
	vol.%	45-63	12-18	<2.4	<1.8	<1.5	(<1)	<1	<1	7-19
secondary minerals										
sericite	<3.4	X						X		
kaolinite	<1	X								
prehnite	<1	X								
chlorite	0.2-24		X	X	X		X			
iddingsite	<1					X				
chrysotile	<3.8					X				
uralite	<1		X							
seladonite	<1		X							

Dyke Group III		Northern Shackleton Range, dykes 17, 18, 22, 28								
primary igneous minerals		plag.	augite	o-pyr.	biotite	olivine	amphib.	K-fsp.	apatite	opaques
	vol.%	33-52	8-22	<1-2.6		<1	<1	<1	<1	10-19
secondary minerals										
sericite	<1-11	X						X		
kaolinite	<1-9.6	X								
prehnite	<1	X								
calcite	<1-1.6	X								
chlorite	7.4-25		X	X			X			
chrysotile	<1-10					X				

Tab. 2: Primary igneous mineral composition and secondary minerals in dyke rocks in the Shackleton Range. plag. = plagioclase, o-pyr. = orthopyroxene, amphib. = amphibole, K-fsp. = K-feldspar. Amphibole and secondary uralite are sometimes indistinguishable; the value for amphibole in such cases is in parentheses.

Tab. 2: Primärmagmatischer Mineralbestand und Sekundärmineralisation von Gesteinen verschiedener Ganggruppen der Shackleton Range. Dargestellt in Vol.% sind die primärmagmatischen Minerale (obere Zeile) und deren Umwandlungsprodukte, d.h. Sekundärminerale (X). Plag = Plagioklas, O-Pyr. = Orthopyroxen, K-Fsp. = Kalifeldspat; Amphibol und sekundärer Uralit sind teilweise nicht unterscheidbar; der Wert für Amphibol steht dann in Klammern.

On the basis of the above-mentioned aspects, the basalts of the dyke groups may be briefly characterized as follows:

Group I: Considerable orthopyroxene and biotite content, very little olivine. Only very slight hydrothermal alteration; relatively high percentages of chlorite as the only secondary mineral.

Group II: Orthopyroxene and biotite content lower than in Group I, whereas the olivine content is higher. Distinct hydrothermal alteration.

Group III: Little orthopyroxene, no biotite, very little olivine. Very strong hydrothermal alteration; therefore, commonly a very high chlorite content.

Group IV: Almost no biotite and olivine, comparatively low content of ore minerals, local pumpellyite. In contrast to Groups I to III, intense hydrothermal alteration and low-grade to very low-grade regional metamorphism.

Group V: Comparatively high olivine content (completely serpentinized), distinct biotite content, higher content of opaque minerals than in Group IV, but lower augite content. Like Group IV, strong hydrothermal alteration and low-grade to very low-grade regional metamorphism.

4. GEOCHEMISTRY

Geochemical analysis was carried out on 22 mafic dykes. In addition to the main components, the trace elements Li, Sc, Cr, Co, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Ta, Th, and the lanthanides were determined. One of the main objectives was to obtain information about the geotectonic significance of the dykes.

The analytical results for the different areas of the Shackleton Range are listed in Table 3. Four of the 26 sampled dykes were not analyzed because they were either too strongly altered or because the dykes were rather thin and part of a relatively dense dyke swarm. Two samples were analyzed for each of the thicker dykes 7, 13, and 26; they were collected from the margin and center of the dykes on a line perpendicular to the contact. In general, the samples from the margins were more strongly altered than those from the centers of the dykes. This sampling method was used to determine whether element migration due to alteration, contamination by country rock or in situ differentiation had taken place. Owing to lack of transport capacity, it was not possible to take the usual five samples across the dyke.

4.1 *Methods*

Samples were taken mainly in centers of the dykes to exclude contamination by the country rock. 5-15 kg of each sample were prepared for analysis, which were done in replicate. To determine the accuracy and reproducability, all analyses included replicate analysis of reference samples. The following analytical methods were used:

FeO, ΣH_2O: titration (Herrmann 1975)
Na, K, Rb, Li: AES (Herrmann 1975)
CO_2, S: coulometric titration (Herrmann 1975)
Ba, Sr, Y, Zr, Nb: ICP-AES (Heinrichs & Herrmann 1990)
La, Ce, Sm, Eu, Tb, Yb, Cr, Lu, Sc, Co, Hf, Ta, Th: INAA (Gibson & Jagan 1980)

4.2 *Results*

Previous geochemical studies on altered basalts showed that many elements are considerably affected by post-magmatic changes, such as metamorphism, hydrothermal alteration or weathering (Peters 1989). Especially the alkali element concentrations show marked post-magmatic changes. Therefore, the classic methods for classifying basalts (e.g. a plot of alkali concentration vs. SiO_2 or a triangular plot of FeO_{tot}/alkalis/MgO) cannot be used here. Due to the locally strong alteration, only those elements can be considered that remain relatively immobile during post-magmatic thermal and dynamothermal metamorphism (chapter 3). Comparison of the absolute concentrations in dykes 7, 13, and 26 (two samples each, Tab. 3) indicate that no significant migration of the elements Mg, Cr, Ni, P, Ti, Zr, Nb, Ta, Hf, Y, and REE occurred. Thus, post-magmatic mobility of the light REE, as often postulated for altered basalts (Henderson 1984, for example), can be neglected in the present case. Therefore, the individual dyke groups have been classified and chemically characterized on the basis of their trace-element distribution, particularly the REE.

Mg-values {Mg-value = degree of fractionation of mineral phases rich in MgO and FeO_{tot}: $100\ Mg^{2+}/(Mg^{2+}+Fe^{2+})$} between 43 and 69 as found in the analyzed samples (Tab. 3) indicate a wide range of differentiation, which indicates advanced fractionation of mafic mineral phases. Mg-values around 69 represent a material that is only slightly modified by fractionation of mafic mineral phases, whereas Mg-values greater than 69 indicate cumulates and Mg-values less than 69 differentiates. The dyke basalts of the Read Mountains and Herbert Mountains are characterized by Mg-values of 46 to 64 and 44 to 51, respectively, and thus display a wide range of fractionation. The basalts from the Lagrange Nunataks, however, (except for dyke 15) are characterized by Mg-values from 58 to 69, indicating a generally slight degree of fractionation or only slightly modified material. Comparatively low Mg-values (49-54) of the basalts from the Haskard Highlands (except for a value of 65 in dyke 17) indicate a comparatively high degree of fractionation within a narrow range.

Further indications of fractionation are provided by plots of Mg vs. Ni and Cr vs. Ni (Figs. 7a and b). An undifferentiated basalt is characterized by MgO contents of >8 wt.% and Cr contents >300 ppm (Mengel et al. 1987). In almost all analyzed samples, the concentrations of the elements in question are below these values, thus indicating different degrees of fractionation of mafic mineral phases; the lack of cumulates is conspicuous. The progressive depletion of Mg, Ni, and Cr is assumed to be due to pyroxene and olivine (possibly also Cr-spinel) fractionation. The comparatively uniform trends of fractionation, however, do not allow further conclusions to be drawn about the genetic relationships between the different dyke groups (see

Region	Read Mountains										
Dyke no.	1	2	5	6	7		8	9	11	13	
Sample	I.3	II.2	V.2	VI.2	VII.1	VII.5	VIII.2	IX.2	X.4	XII.1	XII.3
SiO_2 (wt.%)	49.7	46.9	44.8	45.2	48.0	48.6	49.3	49.5	49.5	49.6	47.8
TiO_2	1.20	2.84	3.23	3.30	1.19	1.22	2.36	1.96	1.92	1.88	2.04
Al_2O_3	14.59	13.52	14.72	14.38	14.77	14.91	12.95	12.88	13.01	13.31	13.18
Fe_2O_3	3.41	4.01	5.22	3.56	3.08	3.09	4.64	3.55	4.06	4.30	4.86
FeO	7.65	10.00	10.21	11.60	7.91	7.48	10.06	10.66	10.00	9.06	8.92
MnO	0.19	0.24	0.22	0.22	0.18	0.19	0.26	0.24	0.24	0.24	0.48
MgO	7.95	6.43	5.83	5.75	8.54	7.96	5.82	5.89	6.00	6.54	6.57
CaO	10.92	9.70	9.04	8.86	11.14	11.31	10.65	10.69	10.30	10.93	10.22
Na_2O	2.22	2.31	2.81	2.74	2.11	1.87	2.13	2.33	2.50	2.33	3.09
K_2O	0.54	0.86	1.30	1.99	0.56	0.73	0.78	0.60	0.91	0.79	0.96
P_2O_5	0.10	0.36	0.57	0.62	0.09	0.10	0.23	0.19	0.18	0.16	0.14
CO_2	0.58	0.95	0.37	0.89	1.11	0.72	0.64	1.36	0.31	0.92	0.26
H_2O	1.49	3.09	2.28	2.19	2.87	2.75	1.58	2.25	2.29	1.36	2.27
S (ppm)	710	2260	690	1500	840	940	1150	1410	190	1260	570
Total	100.61	101.44	100.67	101.47	101.63	101.02	101.52	102.24	101.24	101.51	100.85
Fe as Fe_2O_3	11.91	15.12	16.57	16.45	11.87	11.40	15.83	15.40	15.17	14.37	14.77
Mg value	57	51	47	46	64	63	48	49	50	48	52
Li (ppm)	17	10	25	26	20	23.5	8	10	17	18	20
Sc	41	37	27	28	38	38	46	48	46	44	45
Cr	131	79	127	116	236	236	65	75	84	114	120
Co	45	43	45	51	49	47	49	51	46	48	47
Ni	118	38.5	92	93	151	145	60.5	63	64	80	8.1
Rb	30	33	40	71	37.5	48.5	49	21	49.5	47	56
Sr	167	215	370	370	170	187	183	146	160	170	200
Y	15	24	25	26	14	15	28	32	28	24	20
Zr	81	170	192	216	90	93	155	145	144	124	107
Nb	<8	12	20	16	<8	<8	11	<8	<8	<8	10
Cs	1.2	3.8	2.3	5.1	0.81	1.1	6.0	1.1	1.7	1.1	1.6
Ba	75	233	620	685	73	110	118	125	170	196	228
La	6.3	19.6	29.6	30.2	7.4	6.6	16.3	13.7	12.3	9.8	7.7
Ce	14.3	41.3	61.5	61	16.2	15.5	42.1	28.3	24	22.4	15
Sm	3.0	6.4	8.4	8.5	3.3	2.8	6.2	5.6	5.0	4.3	3.4
Eu	0.96	2.28	2.6	2.6	1.0	1.0	2.0	1.8	1.6	1.4	1.15
Tb	0.52	1.0	1.3	1.5	0.76	0.54	1.4	1.5	1.1	0.9	0.7
Yb	1.9	2.3	2.85	3.1	1.8	1.7	3.4	3.6	3.5	2.4	1.9
Lu	0.31	0.36	0.44	0.5	0.28	0.25	0.48	0.49	0.55	0.36	0.27
Hf	1.57	4.2	5.4	5.4	3.1	1.9	5.0	5.6	3.8	2.1	2.5
Ta	0.36	1.1	1.3	1.2	0.42	0.43	1.1	0.69	0.6	0.65	0.6
Th	1.3	2.0	2.6	3.5	1.6	0.7	3.1	3.9	3.8	n.d.	3.0
La/Nb	>0.78	1.63	1.48	1.89	>0.93	>0.83	1.48	>1.71	>1.54	>1.23	0.77

Tab. 3: Chemical analyses of samples from mafic dykes in the Shackleton Range. Mg value = 100 $Mg^{2+}/Mg^{2+}+Fe^{2+}$

Tab. 3: Geochemische Analysen von Proben mafischer Gänge der Shackleton Range.

Tab. 3 continued

Region	Haskard Highlands								Herbert Mountains	
Dyke no.	17	18	19	21	23	24	26		27	28
Sample	2.2HD.1	3.2HD.1	XV.2	XVI.3	XVII.2	XVIII.1	6.2HD.1	6.2HD.2	XXI.4	11.2.1
SiO_2 (wt.%)	51.4	48.8	46.4	46.5	47.2	47.1	47.0	46.5	50.4	53.7
TiO_2	0.73	2.35	2.55	2.51	2.63	2.53	2.49	2.59	3.20	0.85
Al_2O_3	15.91	14.65	14.68	14.84	14.89	15.10	15.14	15.10	13.09	17.28
Fe_2O_3	1.67	4.88	3.22	2.58	2.38	3.07	3.55	3.01	4.60	0.64
FeO	7.02	7.14	10.76	11.12	11.36	10.39	10.21	10.77	8.17	6.39
MnO	0.15	0.18	0.21	0.21	0.22	0.21	0.20	0.21	0.20	0.12
MgO	8.77	5.34	6.45	6.47	6.35	6.65	6.34	6.26	4.35	5.07
CaO	10.0	7.81	9.30	9.15	9.31	9.31	9.20	9.33	8.20	6.38
Na_2O	1.82	2.21	2.75	2.85	2.86	2.78	2.76	2.85	2.53	3.50
K_2O	0.78	1.57	1.00	1.01	1.00	0.94	1.03	1.03	2.34	2.97
P_2O_5	0.16	0.97	0.50	0.48	0.51	0.49	0.47	0.50	1.36	0.74
CO_2	0.14	0.58	0.92	1.60	0.31	0.43	0.54	0.46	0.12	0.28
H_2O	1.71	2.53	2.04	1.39	1.76	2.19	1.77	1.89	2.40	1.77
S (ppm)	270	1830	1380	1250	1350	1400	1500	1200	840	500
Total	100.29	99.19	100.92	100.84	100.92	101.33	100.85	100.62	101.04	99.74
Fe as Fe_2O_3	9.47	11.46	15.17	14.93	15.00	14.69	14.90	14.98	13.68	7.74
Mg-value	65	54	51	52	51	53	51	49	44	51
Li (ppm)	10	16	8	6	9.5	13	7.3	6.2	15	26
Sc	40	33	35	33	35	34	34	34	33	17
Cr	638	61	93	79	88	83	90	85	26	60
Co	38	30	47	45	46	46	46	45	25	27
Ni	70	23	35	34	37	33.5	35.5	31	10	34
Rb	22	43	28	23	27	25	26	24	56	78
Sr	140	930	310	270	320	290	320	280	320	1210
Y	21	33	41	38	42	39	38	41	79	11
Zr	117	220	206	200	219	206	205	219	363	152
Nb	<8	37	10	<8	11	10	8	9	19	<8
Cs	2.1	2.6	7.2	3.5	2.0	3.6	2.1	2.4	0.27	1.7
Ba	170	2000	520	540	550	540	580	550	1230	1500
La	10.4	81.0	26.0	24.4	25.7	23.7	24.1	24.8	70.7	81.8
Ce	16.4	150.6	46.3	51.3	50.8	47	48.4	50.6	153.1	153.8
Sm	3.3	11.0	7.5	7.8	8.8	7.3	7.7	8.3	19.2	8.9
Eu	1.1	3.1	2.5	2.4	2.5	2.4	2.4	2.6	4.3	2.1
Tb	0.71	1.25	1.30	1.50	1.24	1.35	1.38	1.74	2.84	0.79
Yb	2.4	3.2	3.9	4.0	3.9	4.2	3.9	4.4	6.2	1.5
Lu	0.42	0.47	0.50	0.54	0.54	0.7	n.d.	0.68	0.94	0.24
Hf	2.7	5.3	4.8	6.4	4.9	5.14	5.4	5.2	13.9	5.2
Ta	0.27	2.0	0.65	0.57	0.62	0.62	0.55	0.58	1.44	0.39
Th	1.8	12.0	2.1	2.4	2.0	2.60	2.0	3.0	6.4	12.8
La/Nb	>1.3	2.2	2.6	>3.05	2.34	2.37	3.0	2.76	3.72	>10.2

Tab. 3 continued

Region	Lagrange Nunataks			
Dyke no.	15	16a	16b	25
Sample	XIII.1	XIV.1	XIX.3	XX.2
SiO_2 (wt.%)	49.6	51.5	51.6	51.2
TiO_2	3.21	0.93	0.94	0.74
Al_2O_3	13.14	15.30	15.69	15.91
Fe_2O_3	3.43	2.64	3.14	1.64
FeO	10.10	7.94	7.47	7.24
MnO	0.20	0.17	0.17	0.15
MgO	4.52	6.82	6.50	8.74
CaO	8.25	10.25	10.63	10.10
Na_2O	2.55	2.22	2.21	1.73
K_2O	2.26	0.93	0.83	0.74
P_2O_5	1.43	0.15	0.15	0.16
CO_2	0.08	0.11	0.13	0.12
H_2O	1.53	1.73	1.48	1.67
S (ppm)	1090	390	220	270
Total	100.41	100.73	100.96	100.17
Fe as Fe_2O_3	14.65	11.46	11.44	9.68
Mg value	43	60	58	69
Li (ppm)	19	8	7	10.5
Sc	34	38	37	39
Cr	42	170	173	659
Co	30	43	42	38
Ni	8	92	78	68
Rb	51	31	24	25
Sr	470	180	170	140
Y	81	22	23	20
Zr	399	126	123	121
Nb	17	<8	<8	<8
Cs	1.0	0.7	0.1	2.3
Ba	1120	190	180	150
La	64	10.4	11.6	10.1
Ce	140	17	19.9	19.6
Sm	17.3	3.4	4.3	3.2
Eu	4.2	1.1	1.1	0.98
Tb	2.5	0.74	1.09	0.59
Yb	6.0	2.7	3.0	2.4
Lu	1.0	0.39	0.45	0.41
Hf	10	2.5	6.3	2.6
Ta	1.46	0.32	0.35	0.31
Th	3.99	1.5	2.6	1.68
La/Nb	3.77	>1.3	>1.45	>1.26

chapter 3). Although dykes 17 (Haskard Highlands) and 25 (Langrange Nunataks) show normal Ni concentrations, the comparably high concentrations of Mg and Cr suggest that these two dykes are derived from different types of magma.

Therefore, the differentiation parameter „Mg-value" and the correlation of Mg, Ni, and Cr do not provide sufficient information on the genesis since these relationships refer only to the degree of fractionation and/or fractionation trends of mineral phases rich in MgO and FeO_{tot}. For a more precise characterization, REE distribution patterns and trace element patterns can be used. The distribution of the incompatible REE and trace elements is represented in spider diagrams (Figs. 8 and 9). For clarity, the distribution patterns in the basalts from the Read Mountains (Figs. 8a and b), as well as from the Haskard Highlands, Herbert Mountains, and Lagrange Nunataks (Figs. 9a and b), are considered separately. Chondrite-normalized (Nakamura 1974) or n-MORB-normalized (Hofmann 1988) REE and trace element concentrations were used.

Conspicuous are the generally low trace-element concentrations, especially of the REE. In all basalts, the REE distribution (Figs. 8 and 9) shows a general concentration of the light REE (LREE) relative to the heavy REE (HREE). Conspicuous in all samples are negative Eu anomalies of variable distinctness, as well as positive and negative P and Ti anomalies, which are indicators of initial, advanced or completed fractionation of plagioclase, apatite and Ti-magnetite in the magma.

The REE and trace-element distributions in the basalts from the Read Mountains vary and thus cannot be derived from the same magma. Three types of REE distribution can be recognized (Fig. 8a). The first type, i.e. the flat, parallel, chondrite-standardized REE patterns and low REE ratios of the slightly modified samples VII.1 and VII.5 (dyke 7) and XII.1 (dyke 13) indicate that they had the same, rather „primitive" parent magma. An enrichment of about 1.5 throughout the REE spectrum in dyke 13 with respect to dyke 7 may be due to crystal fractionation. Extensive clinopyroxene fractionation can be excluded, since separation of pyroxene would be visible as a depletion of the HREE relative to the LREE. Conspicuous are the different chrondrite-normalized Tb values in samples VII.1 and VII.5 of dyke 7. This difference indicates an *in situ* enrichment or depletion of orthopyroxene within certain zones of the dyke. The differences in the absolute Mg and Fe concentrations and Mg-values between these samples support this assumption. A slight negative Eu anomaly of sample VII.1 compared to sample VII.5 indicates similar conditions with respect to plagioclase.

The second type is characterized by an enrichment of the HREE relative to the LREE (samples VIII.2, dyke 8; IX.2, dyke 9; and X.4, dyke 11). Differences in the light REE may indicate inhomogeneities in the initial peridotite. The conspicuously uniform HREE distribution pattern is not due to clinopyroxene accumulation, since no unusually high Cr concentrations were found in these samples. Instead, the uniform distribution pattern of the HREE reflects the chemical properties of the initial peridotite.

The third type is characterized by a very uniform REE distribution pattern (samples V.2, dyke 5, and VI.2, dyke 6). The light REE are enriched relative to the HREE. A slight negative Eu anomaly in sample VI.2 indicates initial plagioclase fractionation.

The trace element patterns of the basalts from the Read Mountains (Fig. 8b) are very nonuniform and no distinct types as

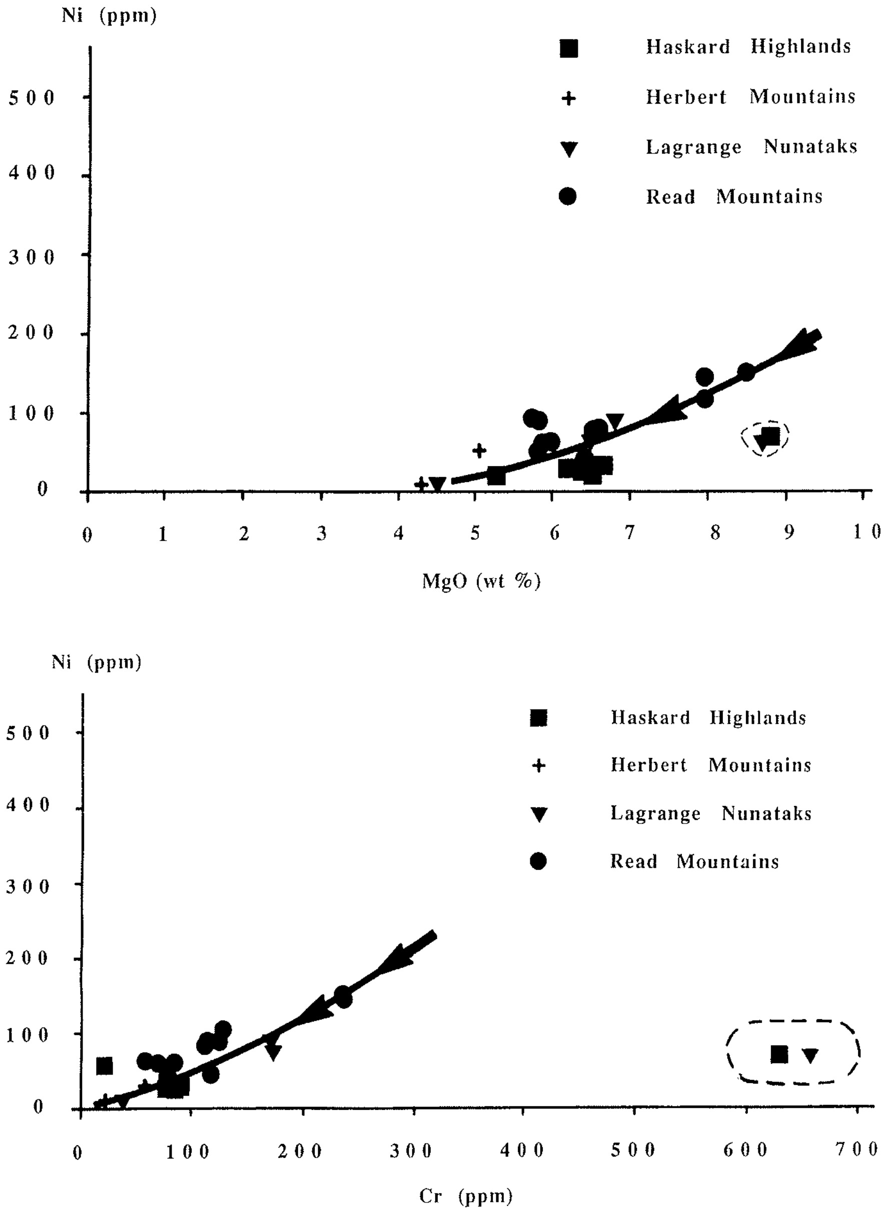


Fig. 7: Mafic dykes: fractionation trend (arrow). a) MgO versus Ni; b) Cr versus Ni.

Abb. 7: Diagramme zur Darstellung der Fraktionierung in den Gesteinen der mafischen Gänge. a) MgO versus Ni, b) Cr versus Ni.

found for the REE can be recognized. The variations in the pattern for the elements Rb to K and Sr are due to post-magmatic mobility during thermal and dynamothermal metamorphism. Conspicuous negative P anomalies and positive Ti anomalies are assumed to be due to mechanical separation of apatite and/or accumulation of Ti-magnetite.

The trace-element patterns (Figs. 9a and b) of most of the basalts from the Haskard Highlands, especially the REE distribution patterns, are very uniform and most probably reflect derivation from the same magma. Slight Eu anomalies indicate initial plagioclase fractionation. Samples 2.2 HD.1 (dyke 17) and 3.2 HD.1 (dyke 18) differ distinctly from most the other samples with respect to both their REE and their trace-element patterns. Whereas sample 3.2 HD.1, compared to the other samples taken in the region, is characterized by generally rather low REE and trace-element values and negative P anomaly (apatite fractionation), and thus was assigned to yet another parent magma, sample 2.2 HD.1 is characterized by considerably higher light REE values. The HREE values, however, are almost identical with those of the majority of the other samples. The considerable scatter in the case of the light REE and the clustering in the case of the HREE are probably due to different melting temperatures of a homogeneous initital peridotite. The same is true for the trace-element patterns.

The basalts from the Lagrange Nunataks show a negative P anomaly suggesting complete apatite fractionation (Figs. 9a and b). Slight positive and negative Ti anomalies in the different samples indicate initial late-stage fractionation of Ti-magnetite and thus an inhomogeneous ore distribution in the magma. The variations of the other trace elements can be explained by inhomogeneities of these elements in the initital peridotite or by different degrees of partial melting. One sample (sample XIII.1, dyke 15) shows significantly higher REE and trace-element concentrations, indicating a different parent magma.

The samples from the Herbert Mountains show distinct diffe-

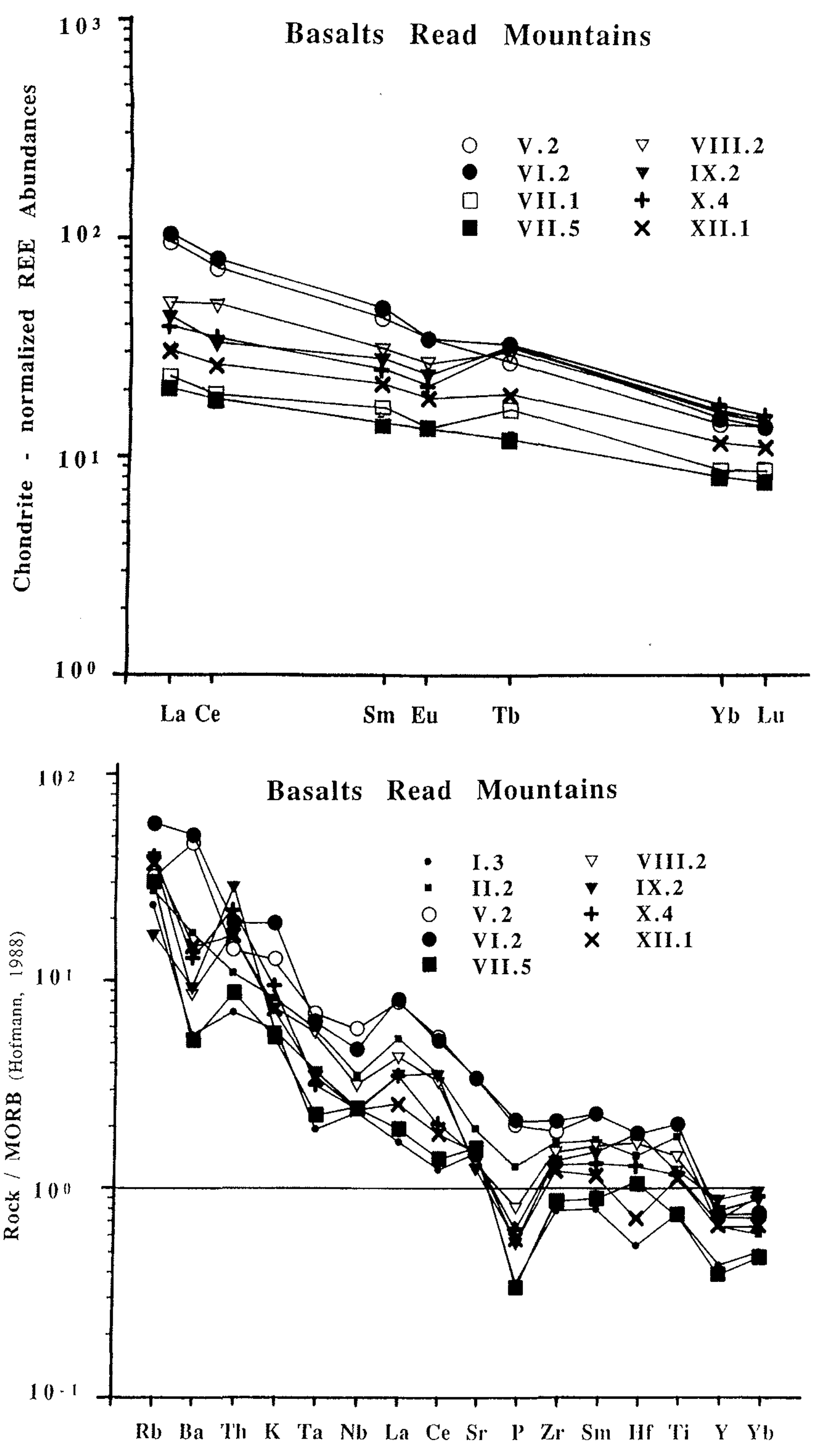


Fig. 8: Spider diagrams for samples of selected dyke basalts in the Read Mountains; a) selected rare earths (REE); b) selected trace-elements.

Abb. 8: Spider-Diagramme für eine Probenauswahl von Gangbasalten der Read Mountains, a) für ausgewählte Seltene Erden (REE), b) für ausgesuchte Spurenelemente.

rences between the LREE and HREE distribution patterns, as well as in the total trace-element spectrum (Figs. 9a and b). These differences may indicate a different degree of partial melting of the mantle material with the formation of significantly different parent magma. Moreover, it is quite possible, that post-magmatic thermal alteration affected the REE and trace-element distribution pattern in this strongly altered material. Conspicuous is sample 11.2.1 (dyke 28) with its distinct negative Nb and Ta anomalies.

Occurrences in various parts of the Shackleton Range were selected to clarify the genetic relationships. Groups of samples with similar Mg-values were compared to minimize any influence of synmagmatic fractionation of mafic mineral phases. The REE and trace-element patterns of selected samples are shown in Figures 10a and b. Especially the REE distribution patterns indicate that the different basalt groups derive from very similar parent magmas. A genetic relationship can be postulated between dykes 5 and 6 (Read Mountains), 15 (Lagrange Nunataks) and 27 (Herbert Mountains), 17 (Haskard Highlands) and 25

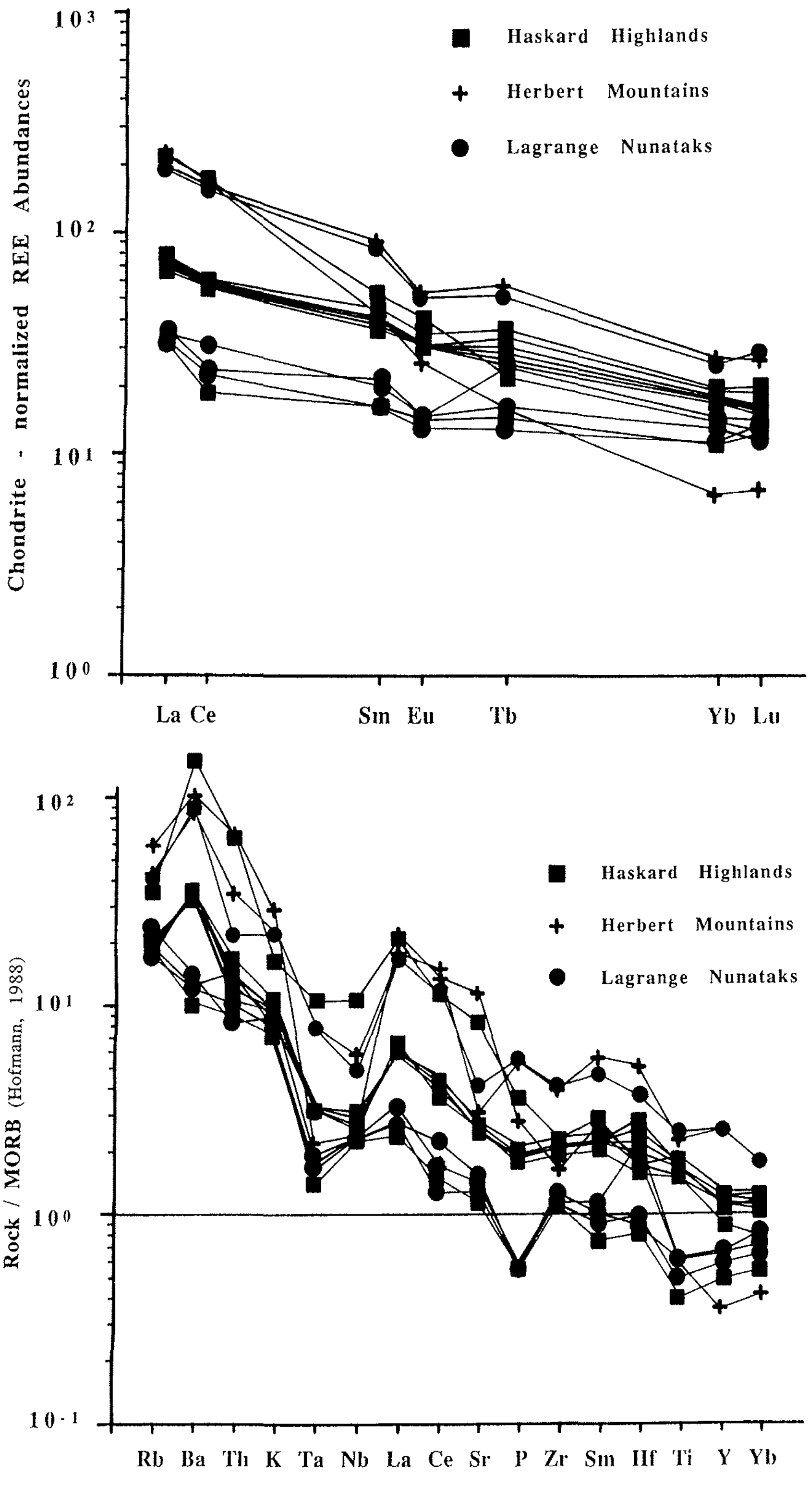


Fig. 9: Spider diagrams for the dyke basalts in the northern Shackleton Range; a) selected rare earths (REE); b) selected trace-elements.

Abb. 9: Spider-Diagramme für die Gangbasalte der nördlichen Shackleton Range, a) für ausgewählte Seltene Erden (REE), b) für ausgesuchte Spurenelemente.

(Lagrange Nunataks), as well as between 19 and 24 (Haskard Highlands). This grouping is also reflected in the trace-element distributions. Moreover, the fact that there are slightly positive Nb (La) anomalies in dykes 17 and 25, in contrast to the slightly negative Nb anomalies in dykes 5, 6, 15, 19, 24, and 27, should also be considered.

4.3 *Discussion of the geochemical analyses*

The classic methods mentioned above for classifying basalts are not applicable to the mafic dykes of the Shackleton Range owing to post-magmatic thermal alteration and dynamothermal metamorphism demonstrated by the authors and the mobility of certain elements, in particular alkalis, associated with it. The analyses of the two samples taken from each of three dykes do not show any distinct differences. This indicates that no substantial

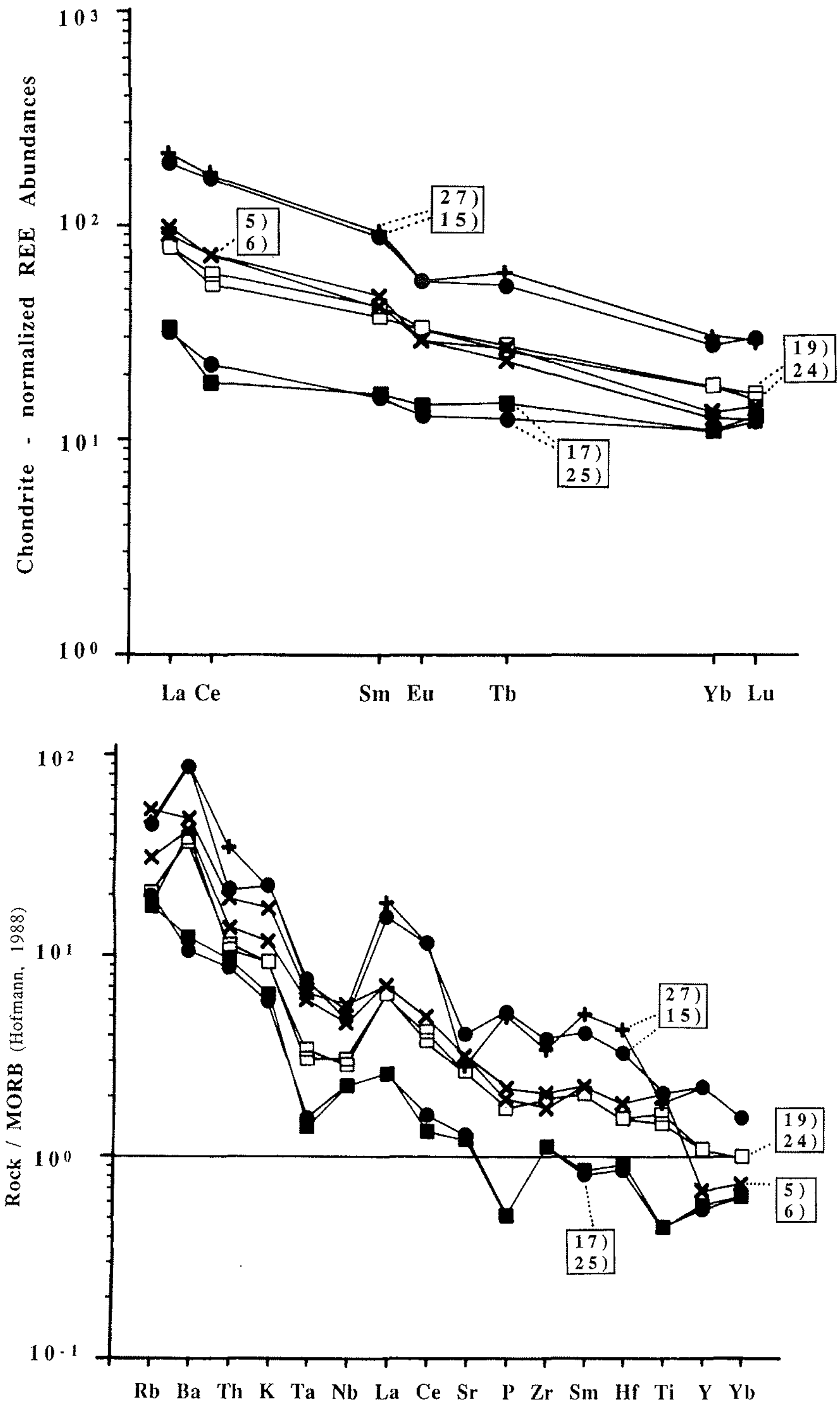


Fig. 10: Spider diagrams for comparison of dyke basalt samples from various areas of the Shackleton Range selected on the basis of their Mg-values {100 Mg/ $(Mg+Fe^{2+})$}; a) selected rare earths (REE); b) selected trace-elements.

Abb. 10: Spider-Diagramme für den Vergleich einer nach den Mg-Werten getroffenen Probenauswahl der Gangbasalte aus verschiedenen Teilgebieten der Shackleton Range, a) für ausgewählte Seltene Erden (REE), b) für ausgesuchte Spurenelemente.

Symbol	Dyke no.	Sample No.	Mg-value	Locality
X	5)	V.2	47	Read Mountains
	6)	VI.2	46	Read Mountains
●	15)	XIII.1	43	Lagrange Nunataks
+	27)	XXI.4	44	Herbert Mountains
■	17)	2.2HDI	65	Haskard Highlands
●	25)	XX.2	69	Lagrange Nunataks
	19)	XV.2	51	Haskard Highlands
	24)	XVII.2	51	Haskard Highlands

differentiation of the material took place during the evolution of these rocks. The complex petrogenetic development of the basalt groups with fractionation of P-, Ti-, (Fe-) and Mg-rich mineral phases and inhomogeneities within the dykes (possible *in situ* enrichment of certain mineral phases within a dyke), however, does not permit the use of discrimination diagrams to determine their geotectonic setting (for example, as used by PEARCE & CANN 1973, CANN & HEATH 1976, FLOYD & WINCHESTER 1978, PEARCE 1983).

The generally low concentrations of REE and trace elements, especially those of La, Ce, Zr, Sm, Hf, Eu, and Ti suggest that, compared to alkali basalts, most or even all of the basalts studied here are tholeiites. Their synmagmatic development is characterized mainly by progressive fractionation of mafic mineral phases (olivine, pyroxene, Ti-magnetite, and possibly Cr-spinel), as well as apatite and plagioclase. These differentiation trends may be interpreted as a further indication that the basalts are tholeiites.

The regional differences in the chemical composition of the basalts studied here, which can sometimes also be detected within a single region, indicate that the basalts cannot have been derived from a common magma. The variations in the trace element patterns indicate that these are due to different degrees of partial melting of mantle material and/or a slightly heterogeneous composition of the original material, which was probably caused by metasomatic mobility of certain elements before melting (mantle metasomatism). According to their geochemical characteristics and on the basis of their regional distribution, the basalts can be divided into several suites in the following areas:

1. The distinct differences in the trace-element patterns and REE distribution of the basalts from the Read Mountains suggest the presence of at least three different parent melts with a very limited REE and trace-element distribution within the suites.

2. The uniform trace-element and REE distributions in most of the dyke rocks of the Haskard Highlands may be due to derivation from the same magma with differences in the degree of melting of the parent peridotite. However, at least one dyke of this region must have derived from a distinctly different magma.

3. In addition to the paucity of P (apatite fractionation), the basalts of the Lagrange Nunataks are characterized by slight variations in the trace-element and REE distribution patterns. This characteristic feature is due to a differing degree of melting of a single parent peridotite or to metasomatic mobility of the respective elements in the mantle before melting.

4. In particular because of their REE distribution patterns, the two analyzed basalts from the Herbert Mountains must have been derived from two different primary magmas.

Consequently, it is possible that six or even more different primary magmas existed in the Shackleton Range.

The different suites of basalts from the Herbert Mountains, Lagrange Nunataks, and Haskard Highlands are characterized by a close chemical and thus genetic relationship. However, these show no chemical and/or genetic relationship with the suites of the Read Mountains.

Because of locally intense alteration and differentiation, quite a number of elements cannot be used for interpretation of the geotectonic significance of the basalt groups. Among all incompatible elements, only the La and Nb concentrations can be used for interpretation. This is based on a comparison of the spider diagrams for typical plate-tectonic provinces with the spider diagrams for the suites studied here. Depletion of Nb relative to La is the only criterion that remains. None of the other element values can be used for distinguishing between dykes because, in addition to alteration, intense fractionation, especially of apatite and Ti-magnetite, also causes significant changes in the concentrations of incompatible elements.

According to Thompson et al. (1983), the distinction between continental flood basalts (CFB) and subduction-related suites represents a special problem. The spider diagrams of these suites are almost identical (Basaltic Volcanism Study Project 1981). Thompson et al. (1983) regard distinct Nb and Ta anomalies and La/Nb ratios as the most suitable method for discrimination between these suites. According to Thompson et al. (1983) and Holm (1985), mainly La/Nb ratios with a maximum between 1 and 2 are characteristic of CFB, whereas island-arc basalts are characterized by a La/Nb ratio of up to 6, but no maximum is observed.

The La/Nb ratios (Tab. 3) for all of the samples are between 0.77 and 3.77 (mean 1.89); sample 11.2.1 collected from the strongly altered and weathered dyke 28, which shows a La/Nb ratio of >10.2, is an exception. Almost none of the trace-element patterns shows a distinct negative Nb anomaly or a Ta anomaly. If the REE distribution patterns are also considered, both mid-oceanic ridge basalts (n-MORB), with their depleted LREE values, and oceanic island basalts (OIB = e-MORB), with their high LREE concentrations, can be excluded. Hence it is concluded that the basalt suites studied here must, from a geochemical point of view, be considered as derived from continental, tholeiitic cycles of volcanism. This is also suggested by the character of the country rock. Additionally, only basalt dykes 16a, 16b, 17 and 25, due to their slightly positive Nb (La) anomaly, can be interpreted as „Initial Rift Tholeiites" (as defined by Holm 1985).

Sample 11.2.1 with its distinct negative Nb anomaly is possibly a tholeiitic island-arc basalt. It must, however, be mentioned again that the rock is strongly altered, a fact that makes it doubtful that it can be assigned to the island-arc type.

5. AGES OF MAFIC DYKES OF THE SHACKLETON RANGE

Age determinations were carried out on a number of samples from mafic dykes using the conventional K/Ar method. Emphasis was put on samples of only slightly altered rocks (dyke Groups I and II) from the northern Shackleton Range.

Sm and Nd isotope analyses were also conducted to determine the age of altered and sometimes metamorphosed rocks from dykes in the Read Mountains (Groups IV and V). This did not yield the results hoped for because the $^{147}Sm/^{144}Nd$ variance in the samples taken from these dykes was too low; it was not possible to plot isochrons. Model ages based on these analyses are discussed below.

The K/Ar age determinations were carried out at the Institute for Geology and Dynamics of the Lithosphere (IGDL) of Göttingen University, the Sm and Nd isotope determinations in the Central Laboratory for Geochronology (ZLG) of Münster University. Sample preparation for the analyses was done at the Geological Institute of the RWTH of Aachen. Hotten (1993) reported in detail on the preparation, performance, and evaluation of these age determinations. Only the results are discussed here together with the few existing age dates.

The raw data and ages obtained from the K/Ar determinations are given in Table 4. Six dykes in the northern Shackleton Range were studied: samples from dykes 16a, 16b, and 25, consisting of only slightly altered rock material (Group I), as well as samples from dykes 15, 24, and 27, consisting of more distinctly altered material (Group II). For K/Ar age determinations on material from the Read Mountains, only two samples from dyke 5 (Group V) were studied.

Whole-rock determinations of cooling age were carried out on all samples. To be able to recognize the effect of secondary alteration on age determinations, measurements were made not only on whole-rock samples from three dykes of the northern Shackleton Range, but also on pure plagioclase and pyroxene (Tab. 4). The mineral dates for samples from dyke Group I (dykes 16a, 16b, and 25) were all about 180 Ma within the limits of error. Moreover, the age of 195 ± 20 Ma published by HOFMANN et al. (1980) for a dyke in the Lagrange Nunataks, which may correspond to our dyke 25, is in relatively good agreement with our value.

As for dyke 15 of Group II, the highest age was obtained from pyroxene, the lowest age from plagioclase and an age between the two was obtained from the whole-rock sample (Tab. 4). As the plagioclase is sericitized, which can be seen under the microscope, as well as by X-ray diffractometry, whereas the pyroxene does not show any alteration, it can be postulated that the plagioclase has a mixed age between that of formation of the plagioclase and the sericitization, thus lowering the whole-rock age. The pyroxene age, however, corresponds best to the true cooling age of the dyke, which accordingly is 370 Ma. The K/Ar whole-rock age of 297 ± 12 Ma published by CLARKSON (1981) for this dyke from The Dragons Back nunatak must therefore be regarded as too low.

Similar conclusions also apply to the two other dated dykes of Group II. The whole-rock ages of 406.0 ± 16.9 Ma and 425.6 ± 9.1 Ma for the distinctly altered material of dykes 24 and 27 are probably too low due to secondary alteration and thus represent only minimum ages. The same early Paleozoic ages are postulated for all other dykes of Group II because they are very similar petrographically and sometimes also geochemically, and their field relationships are not incompatible with these ages. Disregarding the fact that dyke 15 is associated with the Ordovician Blaiklock Glacier Group, all of the Group II dykes cut the metamorphites of the northern part of the SRMC, for which PANKHURST et al. (1983) postulate an age of about 500 Ma for the last tectonic and metamorphic climax. Because they are very strongly altered, it was not possible to determine the age of the rocks of dyke Group III for which the same conditions are true; therefore, similar ages may be postulated for the Group III dykes. Other published ages also support our ages for the mafic dykes in the northern Shackleton Range. CLARKSON (1981) gives a K/Ar whole-rock age of 457 ± 18 Ma for a dyke in Pioneers Escarpment and HOFMANN et al. (1980) give K/Ar whole-rock ages of 391 ± 31 Ma and 417 ± 33 Ma for two dykes in the Herbert Mountains. The last age agrees well with our date for probably the same rock (dyke 27).

With respect to the age of the mafic dykes of the northern Shackleton Range it can be said in summary that the basalts of dyke

Sample No.	Description	Dyke no.	Fraction µm	K2O wt.%	40Ar* nl_{STP}/g	40Ar* %	Age Ma	Error Ma
XIV/1	whole rock	16a LN	-	0.88	5.34	75.42	179.2	4.9
XIV/1	plagioclase	16a LN	125-250	0.62	3.85	94.40	182.9	11.3
XIV/1	pyroxene	16a LN	125-250	1.81	11.12	97.26	181.2	4.4
XIX/3	whole rock	16b LN	-	0.84	5.02	76.62	176.6	4.7
XIX/3	plagioclase	16b LN	250-325	0.20	1.24	91.61	182.1	8.2
XIX/3	pyroxene	16b LN	250-325	1.51	9.11	97.10	178.0	3.7
XX/3	whole rock	25 LN	-	0.74	4.49	50.56	179.1	7.2
XIII/1	whole rock	15 LN	-	2.23	27.97	95.03	352.3	7.5
XIII/1	plagioclase	15 LN	125-250	1.44	14.10	97.74	280.8	6.5
XIII/1	pyroxene	15 LN	125-250	1.60	21.16	97.76	369.7	4.2
XVIII/1	whole rock	24 NHH	-	0.90	13.21	48.04	406.0	16.9
XXI/4	whole rock	27 HM	-	2.45	37.90	96.71	425.6	9.1
V	whole rock	5 RM	-	1.22	39.62	90.05	800.5	15.8
AS 33	biotite	5 RM	100-180	-	579.74	98.91	(1250-1350)	

Tab. 4: K/Ar determination data. 2σ confidence interval; NHH = northern Haskard Highlands; LN = Lagrange Nunataks; HM = Herbert Mountains; RM = Read Mountains.

Tab. 4: Ergebnisse der K-Ar-Altersbestimmungen. Fehlerangabe 2σ; NHH = nördliche Haskard Highlands, LN = Lagrange Nunataks, HM = Herbert Mountains, RM = Read Mountains.

Group I intruded approximately during the Early Jurassic, whereas the emplacement of the basalts of dyke Groups II and III probably required a longer period of time, namely between the Middle Devonian and Early Silurian (Late Ordovician?). The approximate ages determined in paleomagnetic studies by HOTTEN (1993) for eight dykes of these three groups also agree well with these findings.

A sample from dyke 5 (Group V) in the Read Mountains yielded a K/Ar whole-rock age of about 800 Ma (Tab. 4). The isotopic composition of Ar in biotite in another sample from the same dyke was also determined, but there was not enough biotite to determine its K_2O content. Assuming that it ranges between 9.0-10.0 wt.%, dates between about 1250 and 1350 Ma are obtained. This biotite age must be regarded as a minimum age at which the cooling of the dyke took place. The much younger whole-rock age must be viewed as a mixed age between the primary cooling phase of the rock and a younger dynamothermal event which took place at the same time as the Ross Orogeny. Evidence of metamorphism is described in chapter 3.

A K/Ar age of 823 ± 67 Ma (pers. comm. H.J. Paech) has been obtained for dyke 9 (Group IV) in the Read Mountains. It was determined for pyroxene and is not necessarily a mixed age.

The following information on Sm/Nd model ages of seven samples from four dykes in the Read Mountains is given only with reservation. This reservation and the informative quality of the model ages have been discussed in detail by HOTTEN (1993). In principle, Sm/Nd model ages do not provide information on the age of the solidification and cooling phases, but on the time at which the melt separated from the mantle material. Therefore, they cannot be directly compared with the above-mentioned K/Ar ages, which they must exceed by a certain - in general unknown - period of time. This is the case for the following model ages for dyke 5 (Group V) and dyke 9 (Group IV). Two samples from dyke 5 yielded Sm/Nd model ages of 1753 ± 48 Ma and 1661 ± 57 Ma, and two samples from dyke 9 yielded ages of 1758 ± 108 Ma and 1249 ± 158 Ma. Ages of 978 ± 68 Ma and 888 ± 123 Ma were obtained for two samples from dyke 1 and 783 ± 64 Ma for a sample from dyke 13 (both Group IV).

Although it must be emphasized here again that these model ages are not the true ages of the dykes, it must also be said that they do not contradict the assignment of all dykes of the Read Mountains to the Late Precambrian. They also indicate, just like the K/Ar age data, that there were at least two dyke generations. According to the K/Ar age determinations, the age of the basalts of dyke Group IV is probably around 800 Ma, that of dyke Group V around 1300 Ma. These rather general and uncertain radiometric dates cannot be confirmed by the paleomagnetic data, since the paleomagnetic studies of the dykes of the Read Mountains did not provide particularly useful results and, moreover, the apparent pole migration path of East Antarctica during the Precambrian is unknown or not known with sufficient accuracy (HOTTEN 1993).

Again it must be pointed out (cf. chapter 2) that the location and the relationship of the dykes with the surrounding rock in the Read Mountains justifies the postulation that they are of Late Precambrian age. They cut only the crystalline basement, but not the younger cover, and are thus younger than the main metamorphism, which according to PANKHURST et al. (1983) took place about 1700-1550 Ma ago. However, they are probably older than another weaker dynamothermal event, which took place almost at the same time as the Ross Orogeny, i.e. about 500 Ma ago. This is also the age of phyllonites in shear zones which appear to cut the dykes; this could not be unambiguously confirmed, however, since the conditions of exposure are rather poor. The shear zones probably resulted from this more recent event.

6. CONCLUSIONS

The classification of the mafic dykes in the Shackleton Range on the basis of field evidence (chapter 2) was basically confirmed by petrographic studies (chapter 3); five dyke groups were set up. Evidence of alteration found in the field and under the microscope constitues one of the main criteria in this classification.

The geochemical analyses (chapter 4) suggest a subdivision which is almost the same as the petrographic classification into dyke Groups I to V (chapter 3). Therefore, there is no reason to change this classification. Geochemical methods, however, allow further subdivision into at least six parent magmas. The petrographically defined Group I (dykes 16a, 16b, 25) is confirmed by geochemical methods; for geochemical reasons, dyke 17 of Group III may also be assigned to Group I. For Groups II and III, which are classed together because of their ages, the geochemical data indicate at least two further parent magmas, if not more. This is also the case for Group IV of the Read Mountains, for which the geochemical data also indicate at least two parent magmas. Group V of this region also shows special geochemical characteristics.

Radiometric dating - supported by the paleomagnetic studies in the case of Groups I and II - also confirms the classification used here. Accordingly, Group I must definitely be assigned to the Mesozoic (about 180 Ma), and a Middle Proterozoic age at the youngest (about 1300 Ma) is postulated for Group V. Groups II and III, the ages of which show considerable scatter, can be assigned to intrusion events during the Early Paleozoic, and Group IV to similar events during the Late Proterozoic.

It seems to be of importance that with respect to their strike direction the dykes of Group I also represent an exception in the northern Shackleton Range. In general, they strike N-S, whereas the dykes of Groups II and III have a wide scatter around E-W (Fig. 6b). Most of the dykes of Groups IV and V in the Read Mountains strike N-S (Fig. 6a). The dykes of Group V do not differ from those of Group IV with respect to strike direction. As a whole, the division of the dykes into the groups given above is also reflected in their strike directions.

Taking all aspects into consideration, at least four generations of mafic dykes can be distinguished in the Shackleton Range, represented by Groups I, II + III, IV, and V. There are still no sufficient criteria for a clear distinction between Groups II and III or for further division of Group IV.

Geochemical studies provided evidence that the rocks of the mafic dykes are contintental tholeiites, the rocks of dyke Group I are „Initial Rift Tholeiites". The dykes intruded the continental crust and provide evidence of extensional phases affecting greater or smaller areas.

The Jurassic dyke Group I must certainly be regarded as associated with extension at the beginning of the break-up of Gondwana and must be assumed to have a temporal and genetic relationship with the mafic rocks of the Ferrar Group, which is widespread at the Pacific margin of East Antarctica. SPAETH & SCHÜLL (1987) described Mesozoic mafic dykes of the same type in the western part of Neuschwabenland, where they trend mainly NE-SW and are thus parallel to the continental margin. The Group I dykes of the Shackleton Range trend N-S and are thus almost parallel to the margin of this part of East Antarctica, which was formed when Gondwana broke up and is now assumed to be west to northwest of the Shackleton Range. The fact that Group I occurs in the northwestern part of the range and is missing in their other regions is probably due to the proximity of these dykes to the postulated faulted continental margin.

Using paleomagnetic data and comparisons of paleopole positions, HOTTEN (1993) succeeded in proving that the crustal fragment of the Shackleton Range is autochthonous, i.e. probably did not drift as a terrane and did not rotate. The evidence is based mainly on studies of dykes of Group I, but also of Group II.

Evidence of extension provided by the Paleozoic Groups II and III cannot be clearly related to a major geotectonic event. Therefore, HOFMANN et al. (1980) suggest that older dykes of these groups must be assigned to a late stage of the Ross Orogeny, whereas younger dykes document an early phase of the break-up of Gondwana, i.e. a „Paleozoic Gondwana break-up".

Groups IV and V, which are of different Precambrian ages, can be regarded as indications of extensional movements at the beginning of major geotectonic cycles. The Middle Proterozoic Group V (about 1300 Ma) preceded the Nimrod Orogeny. However, age dates for this orogeny (about 1000 Ma) are not known from the Shackleton Range, which may mean that it was not affected by the events of the Nimrod Orogeny. The Late Proterozoic Group IV, for which a date of about 800 Ma was determined, is thus older than the Ross Orogeny; there is much evidence of dynamothermal events in the Shackleton Range at the time of the Ross Orogeny (about 500 Ma).

Precambrian mafic dykes are postulated to be more widespread near the Pacific margin of Antarctica. FIELITZ & SPAETH (1991) described nearly 100 dolerite dykes in the Heimefrontfjella area in the western part of Neuschwabenland, most of which they assign to the Precambrian. Many of them were more strongly affected by metamorphism than those in the Shackleton Range, but it is characteristic that almost all of them trend N-S. This may indicate a close geotectonic relationship between Heimefrontfjella and the Shackleton Range.

Precambrian mafic dykes were found only in the southern part of the Shackleton Range, i.e. in the southern part of the SRMC of the Read Mountains. It can be postulated, however, that basalt dykes were actually present in the older sections of the northern SRMC, but were intensely deformed by the strong dynamothermal events at the time of the Ross Orogeny and are now found as amphibolite bodies. Future field work in the northern Shackleton Range should also include the study of such amphibolites.

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