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Geochemistry of Ferrar Dolerite sills and dykes at Terra Cotta Mountain, south Victoria Land, Antarctica

A.D. MORRISON[1] and A. REAY[2]

Geology Department, University of Otago, P.O. Box 56, Dunedin, New Zealand
[1]Present address: North Flinders Exploration, 24 Greenhill Rd., Wayville SA 5034, Australia
[2] To whom offprint requests should be addressed

Abstract: At Terra Cotta Mountain, in the Taylor Glacier region of south Victoria Land, a 237 m thick Ferrar Dolerite sill is intruded along the unconformity between basement granitoids and overlying Beacon Supergroup sedimentary rocks. Numerous Ferrar Dolerite dykes intrude the Beacon Supergroup and represent later phases of intrusion. Major and trace element data indicate variation both within and between the separate intrusions. Crystal fractionation accounts for much of the geochemical variation between the intrusive events. However, poor correlations between many trace elements require the additional involvement of open system processes. Chromium is decoupled from highly incompatible elements consistent with behaviour predicted for a periodically replenished, tapped and fractionating magma chamber. Large ion lithophile element-enrichment and depletion in Nb, Sr, P and Ti suggests the addition of a crustal component or an enriched mantle source. The trace element characteristics of the Dolerites from Terra Cotta Mountain are similar to those of other Ferrar Group rocks from the central Transantarctic Mountains and north Victoria Land, as well as with the Tasmanian Dolerites. This supports current ideas that the trace element signature of the Ferrar Group is inherited from a uniformly enriched mantle source region.

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Key words: Dolerite, Ferrar magmatic province, flood basalt, south Victoria Land

Introduction

At Terra Cotta Mountain in south Victoria Land (Fig. 1) lower Palaeozoic basement granitoids and overlying Devonian–Triassic Beacon Supergroup sedimentary rocks are intruded by Ferrar Dolerite. Published trace element data for the Dolerite in south Victoria Land are sparse. This study provides further information for regional comparisons between Ferrar Group rocks in the central Transantarctic Mountains (Hergt *et al.* 1989a) and in north Victoria Land (Siders & Elliot 1985, Brotzu *et al.* 1988), as well as with the Tasmanian Dolerites (Hergt *et al.* 1989b) and Jurassic basalts from south-eastern Australia (Hergt *et al.* 1991).

Regional geology, age and tectonic setting

In Antarctica, Mesozoic tholeiites occur from north Victoria Land along the length of the Transantarctic Mountains, and extend through Coats Land into Dronning Maud Land (Fig. 1). Two distinct magmatic provinces are recognized within the Antarctic Mesozoic tholeiites on the basis of geochemical differences (Faure *et al.* 1979, Ford & Kistler 1980, Brewer 1989, Harris *et al.* 1990, Brewer *et al.* 1992). Ferrar Group tholeiites of the Transantarctic Mountains are characterized by high initial $^{87}Sr/^{86}Sr$ ratios (>0.709), and together with the geochemically similar Tasmanian Dolerites (Hergt *et al.* 1989b) and Jurassic basalts from south-eastern Australia collectively comprise the Ferrar magmatic province (Hergt *et al.* 1991). In contrast, Dronning Maud Land tholeiites are characterized by low initial $^{87}Sr/^{86}Sr$ ratios (0.7018–0.7076) and are geochemically similar to parts of the Karoo volcanic province (Harris *et al.* 1990).

The Ferrar Group includes the intrusive Ferrar Dolerite, as well as the coeval Kirkpatrick Basalts and associated volcanogenic sedimentary rocks (Barrett *et al.* 1986). Ferrar Group distribution spans the Transantarctic Mountains over 3000 km from north Victoria Land to the Ohio Range (Fig. 1) with an estimated combined lava and sill volume of 0.5×10^6 km^3, covering an area of 1.0×10^5 km^2 (Kyle *et al.* 1981). Individual sills can be over 400 m in thickness (Gunn 1966), whereas the aggregate thickness of sills may exceed 1000 m (Elliot *et al.* 1985).

Radiometric age determinations for the Ferrar Group range from 236–112 Ma. Recent work by Heimann *et al.* (1994) suggests that eruption of the Kirkpatrick Basalts occurred over a short interval of less than 1 m.y. at 176.6 ± 1.8 Ma. It is considered that the Ferrar Dolerite sills were emplaced over the same short interval.

The Ferrar Group was emplaced in an extensional tectonic setting, possibly the product of a failed rift between East and West Antarctica which marked the initiation of the break-up of Gondwana (Ford & Kistler 1980, Elliot *et al.* 1985, Storey *et al.* 1988a). A number of authors have proposed a connection between rifting and subduction beneath West Antarctica (Elliot 1975, Cox 1978), with emplacement of the Ferrar Group in a

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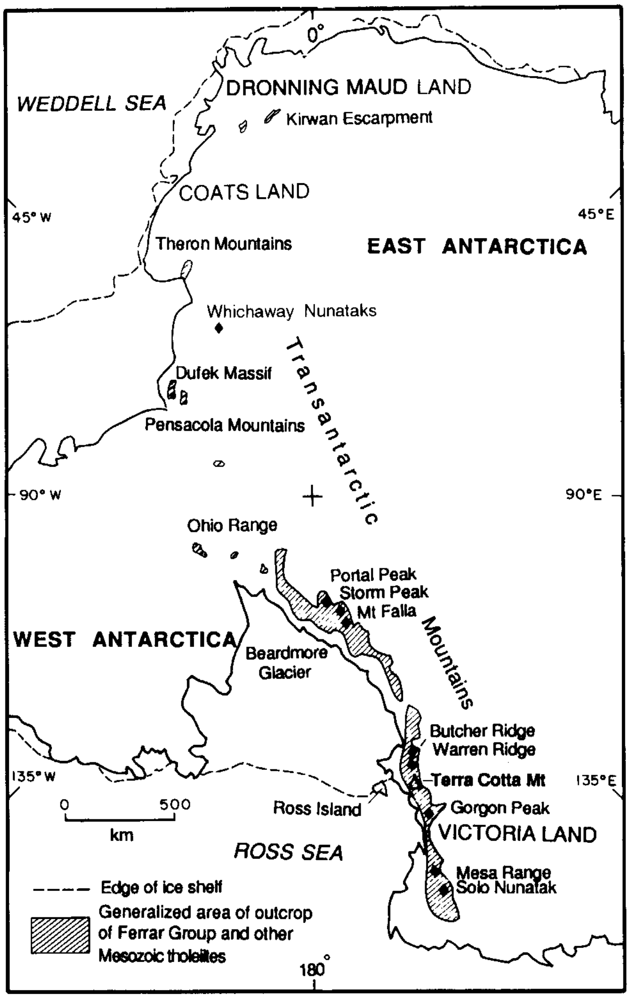

Fig. 1. Distribution of Mesozoic tholeiites, including the Ferrar Group, in Antarctica (modified after Elliot *et al.* 1985) with the location of Terra Cotta Mountain and other studies indicated.

back-arc setting (Dalziel & Elliot 1982, Elliot *et al.* 1985). Subduction beneath the proto-Pacific margin may have continued during the early stages of the Gondwana break-up (Elliot *et al.* 1989b). The role of mantle plumes has been suggested to be important in the formation of some continental flood basalt provinces (e.g. White & McKenzie 1989, Richards *et al.* 1989). However, the lack of a recognizable asthenospheric component in the Ferrar magmatic province suggests that any mantle plume involvement was limited to providing heat (Hergt *et al.* 1991). Brewer *et al.* (1992) favour a model whereby Ferrar magmatism resulted from dehydration melting in the lithospheric mantle in response to limited extension (cf. Gallagher & Hawkesworth 1992). Such a model is consistent with a back-arc tectonic setting and does not require the involvement of a mantle plume.

Previous work

The Ferrar Dolerite in south Victoria Land has been studied regionally by Gunn (1962, 1963, 1965, 1966) and Hamilton (1965). Gunn (1966) published two geochemical analyses from Terra Cotta Mountain. Little subsequent work has been done in south Victoria Land, although Ferrar Dolerite studies have been published from north Victoria Land (Brotzu *et al.* 1988) and the central Transantarctic Mountains (Hergt *et al.* 1989a). The Kirkpatrick Basalts have been studied in the central Transantarctic Mountains (Elliot 1972, Faure *et al.* 1972, 1974, 1982, Hoefs *et al.* 1980) and north Victoria Land (Kyle *et al.* 1983, Mensing *et al.* 1984, Siders & Elliot 1985). These studies have resulted in much debate over the relative contributions of crustal contamination and an enriched sub-continental lithospheric source region to produce the high initial $^{87}Sr/^{86}Sr$ ratios (e.g. Kyle 1980). Recent interpretations have largely dismissed the role of significant crustal contamination *en route* to the surface. Present models favour an initially depleted mantle source region later enriched by a small amount of subducted sediment (Hergt *et al.* 1989a, 1989b, 1991, Brewer *et al.* 1992). Variable Sr and O isotopic ratios, previously regarded as evidence for crustal contamination have been re-interpreted as reflecting post-magmatic alteration (Fleming *et al.* 1992).

Field relations and petrography

Introduction

A number of separate intrusions of Ferrar Dolerite are recognized at Terra Cotta Mountain (TCM). Scree cover, erosion and a lack of cross-cutting relationships between some intrusions, allow the establishment of only a partial intrusive sequence. The informal names given to the separate Dolerite intrusions are shown in Fig. 2, with an accompanying history of events summarized in Table I.

The sill

A thick Dolerite sill (237 m in measured section) is intruded along the unconformity between the basement and the Beacon Supergroup and is the eastward continuation of a sill exposed to the west of Windy Gully which has been variably referred to as the New Mountain sill (Gunn 1966) and the peneplain sill (Hamilton 1965 fig. 9). The sill is displaced *c.* 450 m vertically by a NE striking normal fault. The main exposure of the sill terminates against the "Terra Cotta dyke", intruded along the fault plane. The sill contains augite, pigeonite and plagioclase set in a mesostasis of granophyrically intergrown quartz and K-feldspar, apatite and Fe-Ti oxides. The sill is sub-divided into a relatively thick floor sequence characterized by a dominantly sub-ophitic to intergranular texture, grading upwards into a granophyric zone located *c.* 200 m above the lower margin. The relatively thin roof sequence, above the granophyric zone, has a distinctive ophitic texture.

North face dyke swarm

A major swarm of dykes is exposed on the north face of TCM.

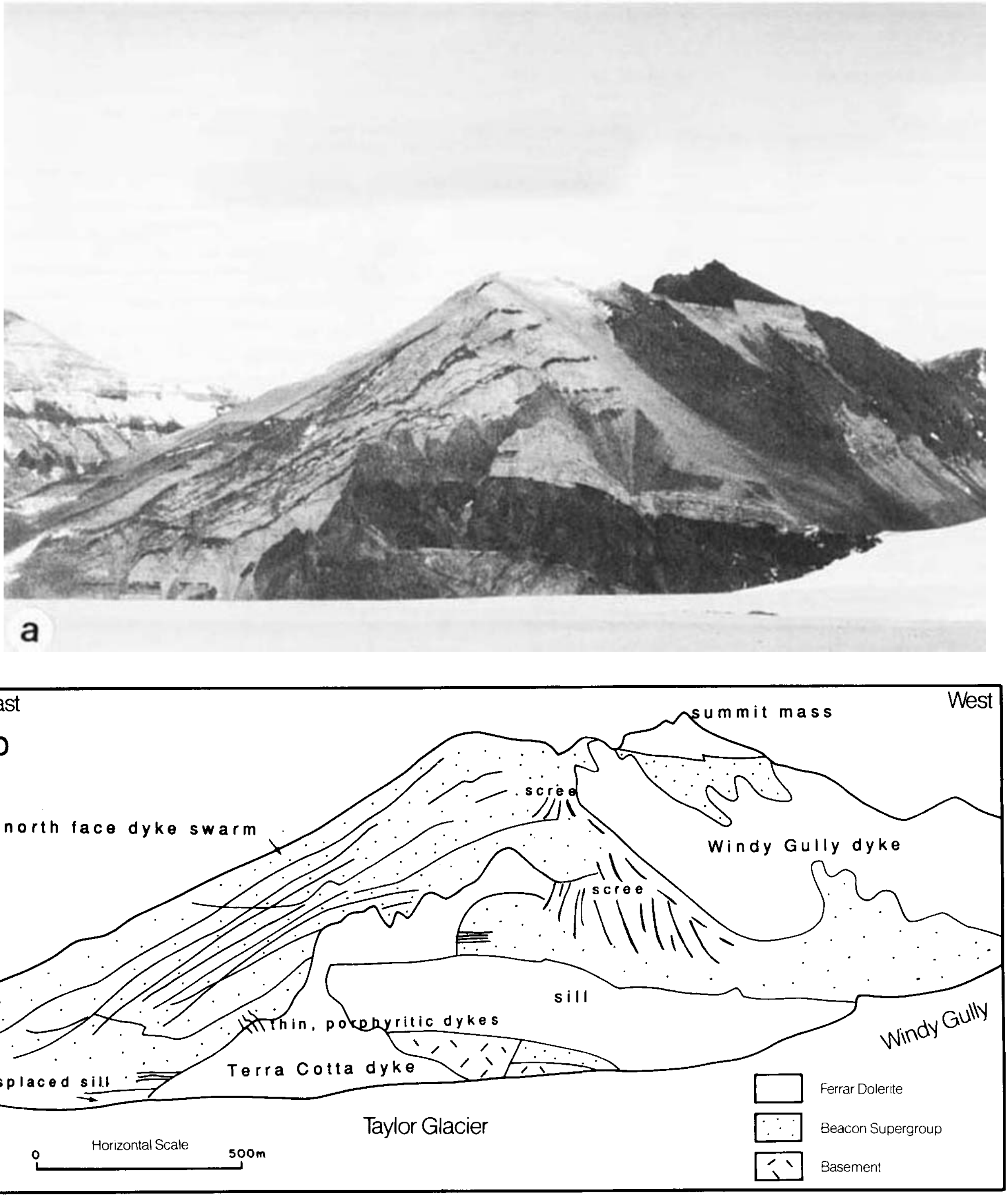

Fig. 2a. Terra Cotta Mountain as viewed from the north (I.M. Turnbull photograph). The height from glacier to summit is approximately 1100 m and the distance across the base of the photograph is approximately 2.5 km. **b.** Line drawing from the photograph identifying the different phases of Ferrar Dolerite intrusion discussed in this paper.

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Table I. Schematic representation of intrusive sequence.

<table>
<tr><td colspan="2">intrusion of the thin porphyritic dykes</td><td rowspan="2">intrusion of Windy Gully dyke</td></tr>
<tr><td rowspan="2">major fault displacing the sill</td><td>intrusion of Terra Cotta dyke</td></tr>
<tr><td>intrusion of north face dykes</td><td rowspan="2">intrusion of summit mass</td></tr>
<tr><td colspan="2">intrusion of the sill</td></tr>
<tr><td colspan="3">minor faulting evident in the basement below the sill</td></tr>
<tr><td colspan="3">deposition of the Beacon Supergroup</td></tr>
<tr><td colspan="3">peneplaination</td></tr>
<tr><td colspan="3">intrusion of granitoids into basement</td></tr>
</table>

Individual dykes are up to 22.5 m thick. Intrusion of the dykes was controlled both by bedding and some pre-existing structural weakness (possibly related to the fault described above). Cross-cutting relationships of dykes within the swarm reveal a complex history of intrusion with a minimum of four phases. Typically the dykes have thin porphyritic chilled margins but their bulk is coarse-grained. Petrographically the dykes resemble the floor sequence of the sill.

Terra Cotta dyke

A large dyke is exposed on the north face of TCM. The dyke narrows from *c.* 800 m in width at its base to less than 200 m at the top of its exposure. The dyke is intruded along the NE-striking fault plane, truncating and therefore postdating the sill (Fig. 2). Observation of field relations between the dyke and the north face dyke swarm is hindered by the inaccessibility of some exposure. However, the large dyke postdates at least the earliest phase of the dyke swarm. The margins have a fine-grained, sub-ophitic texture with plagioclase, orthopyroxene, augite, and locally pigeonite. Very coarse-grained zones occur inwards from both margins, in places displaying comb textures with curved, branching crystals of orthopyroxene up to 7 cm in length. The interior of the dyke is intergranular in texture and distinguished from the margins and very coarse-grained zones by the absence of orthopyroxene.

Thin, porphyritic dykes

Up to a dozen thin (< 1 m), porphyritic dykes intrude the east margin of the Terra Cotta dyke and the Beacon Supergroup (Fig. 2). No contact relations of the porphyritic dykes with the north face dyke swarm are preserved. Phenocryst phases are orthopyroxene, augite (in places rimming the former) and rare plagioclase.

Windy Gully dyke

A large, W-dipping dyke, at least 50 m thick, forms much of the north-west face of TCM above Windy Gully (Fig. 2). The only exposed margin of the dyke is chilled against Beacon Supergroup sedimentary rocks. The dyke does not appear to be intruded by, and therefore may be younger than, dykes from the north face swarm which outcrop discontinuously in nearby scree. The relationship of the dyke to the Terra Cotta dyke and the thin porphyritic dykes is uncertain. The chilled margin of the dyke is fine-grained with rare, partially resorbed, plagioclase microphenocrysts. Orthopyroxene sub-ophitically encloses smaller grains of plagioclase and augite with little interstitial mesostasis. Inward from the margin, the texture is sub-ophitic to intergranular with orthopyroxene, augite (in places rimming the former) and inverted pigeonite coexisting. Further inward orthopyroxene disappears.

Other dolerite intrusions

Numerous other small Dolerite intrusions are present. However, their relationship to the main intrusive phases exposed on the north face is uncertain. The summit peak consists of a Dolerite mass, the lower chilled margin of which may be a preserved remnant of the base of a sill. The mass is intruded by numerous sub-horizontal dykes. The alteration of the Dolerite in the summit region is more extensive than observed elsewhere. Other Ferrar Dolerite dykes occur in the basement between the Terra Cotta dyke and the sill.

Geochemistry

Introduction

Seventy one samples were analysed by XRF (10 major and 20 trace elements) using a Phillips PW1410/20 AHP machine housed in the Geology Department, University of Otago. The techniques used follow those of Norrish & Hutton (1969) and Norrish & Chappell (1967). Precision was monitored through routine analyses of duplicate samples and the international AGV1 standard. In addition, the laboratory periodically cross-checks XRF-derived trace element data by INAA. Ferrous iron was determined by redox titration following the procedure of Wilson (1955). Mg numbers ($Mg^{\#}$ = (100.Mg/(Mg+Fe^{2+})) atomic) were calculated using an Fe_2O_3 : FeO ratio of 0.15 (after Brooks 1976). Representative analyses of the different intrusions

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are presented in Table II.

The Sill

The sill becomes progressively more basic in composition from the chilled margins ($Mg^{\#}$=45.8) towards the centre ($Mg^{\#}$=58.3) with a silicic granophyric zone located approximately 40 m below the top margin (60696, Table II). The bulk composition of the sill (24 analyses) is more basic than that of the chilled margins (similar to other Ferrar Dolerite sills (Gunn 1966, Hergt *et al.* 1989a)).

North face dyke swarm

Dykes within the swarm have similar compositions, with chilled margin Mg numbers slightly higher than those of the sill (Table II). They are not entirely uniform in composition across their widths with a number of dykes being slightly more basic in their interior relative to their chilled margins. The lack of apparent compositional variation between the identified intrusive phases within the dyke swarm suggests that they are closely related in time and origin.

Terra Cotta dyke

The margins of the Terra Cotta dyke have slightly higher Mg

Table II. Representative major and trace element analyses of the Ferrar Dolerite from TCM.

Sample	60666 SM	60681 SC	60696 SG	60714 NFD#1M	60715 NFD#1C	60738 TCDM	60864 TCDCC	60859 TCDC	60876 TPD	60883 WGDM	60884 WGDC	60886 ED
Wt%												
SiO_2	57.34	54.06	62.37	56.20	54.90	54.94	52.01	53.66	54.18	51.38	51.51	68.26
TiO_2	0.98	0.64	1.40	0.84	0.71	0.63	0.42	0.55	0.65	0.32	0.36	0.85
Al_2O_3	14.08	15.10	11.77	14.80	15.41	14.89	16.27	15.84	15.59	15.68	17.05	11.28
Fe_2O_3*	11.56	10.06	12.76	10.96	10.26	9.81	9.15	9.83	10.32	9.29	7.97	8.61
FeO	8.42	7.31	7.88	8.13	7.29	7.47	n.d	7.52	5.43	7.33	5.69	4.29
Fe_2O_3	2.20	1.94	4.00	1.93	2.16	1.51	n.d	1.47	4.29	1.14	1.65	3.84
MnO	0.18	0.17	0.16	0.17	0.16	0.17	0.17	0.17	0.20	0.18	0.15	0.09
MgO	4.35	6.25	0.86	4.40	5.04	6.63	8.21	6.22	6.44	8.93	8.02	0.46
CaO	8.53	10.25	4.66	9.52	10.29	10.73	11.34	11.36	9.52	12.93	13.19	3.00
Na_2O	1.71	1.27	1.77	1.53	1.41	1.34	1.30	1.42	1.24	0.95	0.92	2.14
K_2O	0.65	0.88	3.12	1.03	0.94	0.80	0.52	0.71	0.46	0.18	0.26	3.97
P_2O_5	0.15	0.09	0.32	0.12	0.10	0.09	0.02	0.08	0.09	0.03	0.04	0.20
L.O.I.	1.75	1.54	1.66	1.40	1.31	1.03	0.34	0.96	2.20	1.08	1.05	1.26
Total	100.34	99.5	99.97	100.07	99.72	100.23	99.75	99.96	100.29	100.13	99.89	99.64
ppm												
Ni	53	73	5	43	49	75	93	67	87	96	101	4
Cu	116	78	52	104	93	85	78	85	81	82	45	23
Zn	101	70	112	92	71	74	58	69	84	60	53	99
Nb	9	4	13	7	6	5	3	5	5	3	4	18
V	266	209	69	248	227	234	167	205	263	207	197	15
Cr	59	127	4	34	57	114	228	20	135	173	139	2
Ba	260	242	702	270	235	253	162	225	303	106	128	921
La	22	20	46	21	16	19	9	16	15	4	<1	47
Ce	45	26	89	36	27	28	15	30	23	5	3	99
Pr	9	6	11	8	5	6	2	9	6	5	6	19
Nd	25	5	36	11	12	8	7	11	11	<1	2	52
Ga	18	16	22	18	17	18	16	18	20	15	17	19
Rb	26	35	114	38	35	32	24	28	19	5	8	111
Sr	139	139	181	134	139	131	132	129	154	123	119	142
Y	37	25	57	31	27	24	15	21	25	14	15	68
Zr	176	117	264	144	121	112	62	88	111	44	59	378
Pb	12	9	20	9	11	11	5	8	12	7	5	18
Th	5	3	11	4	5	4	<1	5	4	2	3	16
U	3	2	6	4	2	3	<1	2	2	<1	<1	5
Sc	36	30	19	33	31	32	26	31	36	35	28	11
Mg num	45.8	58.3	13.2	47.4	52.5	60.3	66.9	58.7	58.4	68.4	69.35	10.7

SM: sill, lower chilled margin; SC: sill, centre; SG: sill, granophyric zone; NFD#1M: north face dyke #1, chilled margin; NFD#1C: north face dyke #1, centre; TCDM: Terra Cotta dyke, eastern margin; TCDCC: Terra Cotta dyke, coarse comb-textured zone; TCDC: Terra Cotta dyke, centre; TPD: thin porphyritic dyke; WGDM: Windy Gully dyke, chilled margin; WGDC: Windy Gully dyke interior; ED: evolved dyke. Fe_2O_3* = total Fe expressed as Fe^{3+}. Mg num = (100.Mg(Mg + Fe^{2+}) atomic) using a standardized iron ratio: Fe_2O_3/FeO = 0.15. n.d. = not determined.

numbers again than those of the sill and the north face dyke swarm (Table II). The very coarse-grained comb textured rocks are significantly more basic than the chilled margins. The interior of the dyke is strongly depleted in Cr relative to the marginal zones.

Thin, porphyritic dykes

The composition of the thin, porphyritic dykes is similar to that of the margins of the Terra Cotta dyke.

Windy Gully dyke

The chilled margin of the Windy Gully dyke is the most primitive chilled margin composition observed, with an Mg number of 68.4 (Table II). The essentially aphyric texture of the sample suggests that the analysis represents a close approximation to the original liquid composition. The Windy Gully dyke is therefore one of the most primitive Ferrar Dolerite magma compositions reported. An analysis of the lower chilled margin of the Painted Cliff sill in the central Transantarctic Mountains (Gunn 1966) has an Mg number of 70.7. Kyle *et al.* (1983) reported Mg numbers of 69 from the same sill.

Table III. Comparison of equivalent fresh and altered samples.

Sample	sill 60666 lower margin	sill 60709 upper margin	sill 60708 altered margin	n. f. dykes 60732 unaltered margin	n. f. dykes 60716 altered margin
Wt%					
SiO_2	57.34	57.30	56.76	54.83	54.51
TiO_2	0.98	0.99	1.06	0.73	0.81
Al_2O_3	14.08	14.11	14.49	15.67	15.70
Fe_2O_3*	11.56	11.53	12.11	10.77	11.28
FeO	8.42	8.40	2.59	8.24	5.42
Fe_2O_3	2.20	2.20	9.23	1.61	5.26
MnO	0.18	0.17	0.18	0.17	0.20
MgO	4.35	4.22	4.66	5.22	5.49
CaO	8.53	8.59	3.28	10.31	4.95
Na_2O	1.71	1.60	2.90	1.46	2.85
K_2O	0.65	1.27	0.54	0.87	1.04
P_2O_5	0.15	0.15	0.15	0.10	0.11
L.O.I.	1.75	0.96	3.98	0.99	3.44
Total	100.34	99.96	99.82	100.2	99.78
ppm					
Ni	53	51	57	56	64
Cu	116	113	120	99	101
Zn	101	98	95	86	95
Nb	9	8	9	6	8
V	266	256	290	248	293
Cr	59	61	73	69	73
Ba	260	329	404	235	340
La	22	24	21	19	21
Ce	45	44	47	21	30
Pr	9	7	9	10	13
Nd	25	23	22	14	16
Ga	18	16	16	21	19
Rb	26	47	22	37	36
Sr	139	137	218	124	284
Y	37	36	39	28	30
Zr	176	176	183	125	131
Pb	12	12	14	13	13
Th	5	7	7	7	4
U	3	2	2	2	2
Sc	36	32	43	32	43

Other dolerite intrusions

A thin (30 cm), mesocratic, aphanitic dyke (60886, Table II) which intrudes the sill near its basal margin, has the most evolved composition ($Mg^{\#} = 10.7$) of all the Dolerite samples analysed. It is concluded that the dyke must represent a late-stage differentiate.

Analyses of dykes from the summit peak area and from within the basement have compositions similar to those of the north face dyke swarm.

Petrogenesis

Introduction

Although the Dolerite intrusions at TCM are part of a voluminous flood basalt province, there is chemical variation between the different suites of intrusions and, as discussed above, typically within individual dykes and sills. Processes which may contribute to geochemical variation within and between the different intrusions are evaluated below and include: hydrothermal sub-solidus alteration, crustal contamination, varying degrees of partial melting, closed system fractionation, magma mixing, and magma generation from a heterogeneous mantle source.

Hydrothermal alteration

Most samples show at least some degree of alteration petrographically. Pyroxenes display widespread alteration to a brown fine-grained mass of chlorite and biotite, and in places to green and brown amphibole. Alteration is most strongly developed where exsolution has occurred in the pyroxenes, particularly in the inverted cores of pigeonite. Augite is typically less altered than pigeonite, but where exsolution in augite is better developed it is accompanied by greater alteration. Orthopyroxene phenocrysts, from samples of the thin porphyritic dykes where they intrude the Beacon Supergroup, are completely altered to chlorite. Plagioclase is less altered than pyroxene, displaying weak clouding. However, replacement of plagioclase by calcite has occurred in strongly altered samples from the upper chilled margin of the sill, a chilled margin of a dyke from the north face swarm, and the thin porphyritic dykes where they are intruded into Beacon Supergroup. Alteration of the Dolerite is increased where the chilled margins are in contact with the Beacon Supergroup. In contrast, where Dolerite intrudes earlier dykes (e.g. cross-cutting relationships within the north face swarm) it remains relatively fresh.

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Extensive alteration of basement granitoids and adjacent sedimentary rocks at TCM has been interpreted as evidence of a fossil hydrothermal system related to the intrusion of the Dolerite (Craw & Findlay 1984, Morrison 1989, Craw *et al.* 1992). In the basement granitoids, feldspar is replaced by sericite and andalusite, and ferromagnesian minerals are replaced by hematite and chlorite. Andalusite, sericite, chlorite and hematite also occur within the Beacon Supergroup immediately above the basement unconformity. Hydrothermal calcite veins cross-cut both the Dolerite and Beacon Supergroup and are associated with secondary overgrowths of quartz in the sandstones. It is considered that the alteration of the Dolerite is a result of the same hydrothermal system that affected the basement and overlying Beacon Supergroup, and is similar to that described from the Skaergaard Intrusion (Taylor & Forester 1979).

The presence of the calcite veining, quartz overgrowths, hematite and andalusite in the Beacon Supergroup suggests element mobility associated with the system. This is further evidenced by comparison between relatively unaltered and altered samples from the chilled margins of the sill, and similarly between samples from chilled margins of the north face dyke swarm (Table III). Most obvious is the relative depletion of the altered samples in CaO, enrichment in Na_2O, Sr and Ba, and increased oxidation state of the Fe. Rb and K may also have been mobile. It is concluded therefore that variation of these elements should be interpreted with caution as it may reflect sub-solidus hydrothermal alteration rather than primary igneous processes. Samples which are obviously altered have been avoided for geochemical analysis, or ignored in the interpretation of igneous processes.

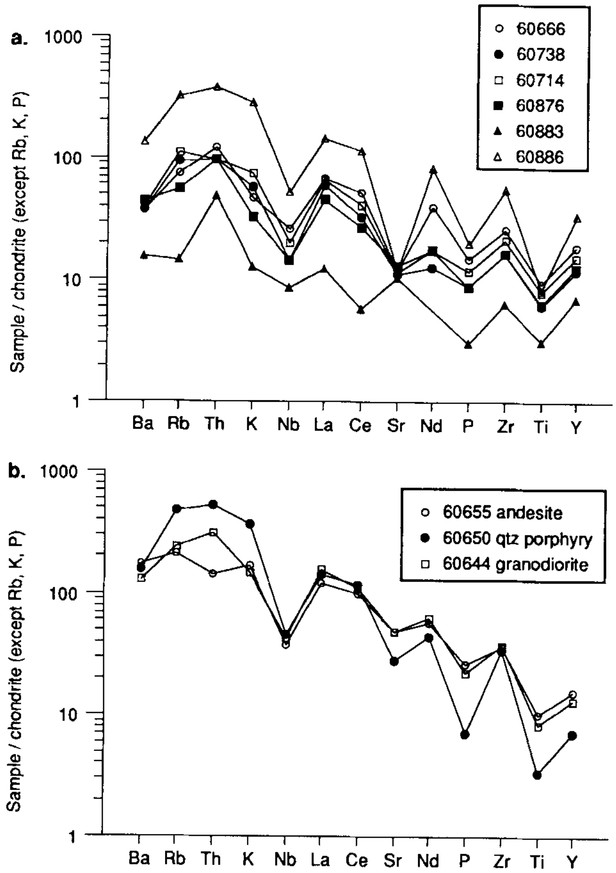

Fig. 3. Spidergrams normalized to chondritic and primitive mantle (Rb, K, P) values after Thompson (1982). **a.** Selected Ferrar Dolerite samples, descriptions are given in Table II. **b.** Spidergrams of basement samples from Terra Cotta Mountain.

Crustal contamination

The high SiO_2, K_2O and LREE concentrations, and high initial $^{87}Sr/^{86}Sr$ ratios of continental tholeiites, relative to oceanic tholeiites, have led some workers to conclude that continental tholeiites have a crustal component (e.g. Thompson *et al.* 1983, Campbell 1985). Local crustal anatexis has been reported associated with Ferrar magmatism with mixing occurring between crustal partial melts and the Ferrar magma, (Storey *et al.* 1988b, Elliot *et al.* 1989a). It is important therefore that the possible effects of crustal contamination *en route* to the surface should be evaluated.

Chondrite-normalized spidergrams of representative Dolerite samples from TCM display large ion lithophile element (LILE)-enrichment (Fig. 3a). The samples are enriched in Rb and Th relative to Ba, K and LREE. Nb, P and Ti form negative anomalies. Similar LILE-enriched spidergram patterns are characteristic of continental tholeiites. In contrast, oceanic tholeiites do not show the same degree of LILE-enrichment. The LILE-enrichment and negative Nb anomalies of continental tholeiites are similar to the spidergrams of crustal rock types suggesting the addition of a small amount of crustal material to an ocean island basalt-like parent (Thompson *et al.* 1983).

Chondrite-normalized spider diagrams of basement granitoid samples from TCM (Morrison 1989, unpublished data) display nearly identical trace element signatures to the Dolerite samples (Fig. 3b). The basement granitoids at TCM include members of both Dry Valleys 1 and Dry Valleys 2 suites, interpreted as Cordilleran and Caledonian I-type granitoids respectively (Smillie 1992). The similarity of the Dolerite and basement granitoids spidergram patterns at TCM may suggest that the Dolerite magma has been contaminated by the granitoids, or that both the Dolerite and the granitoids were derived from the same source region, or separate source regions sharing the same trace element signature.

Crustal contamination by wholesale assimilation (e.g. AFC, De Paolo 1981) or selective contamination (mixing of magma with minimum melts generated in the country rock) can decouple elements and produce enrichment of incompatible elements. Tight correlations on inter-element diagrams between high field strength elements (HFSE), combined with poor correlations between HFSE and LILE can result from selective contamination (Dupuy & Dostal 1984). The more mobile LILE are enriched in the magma with selective contamination, thus changing their

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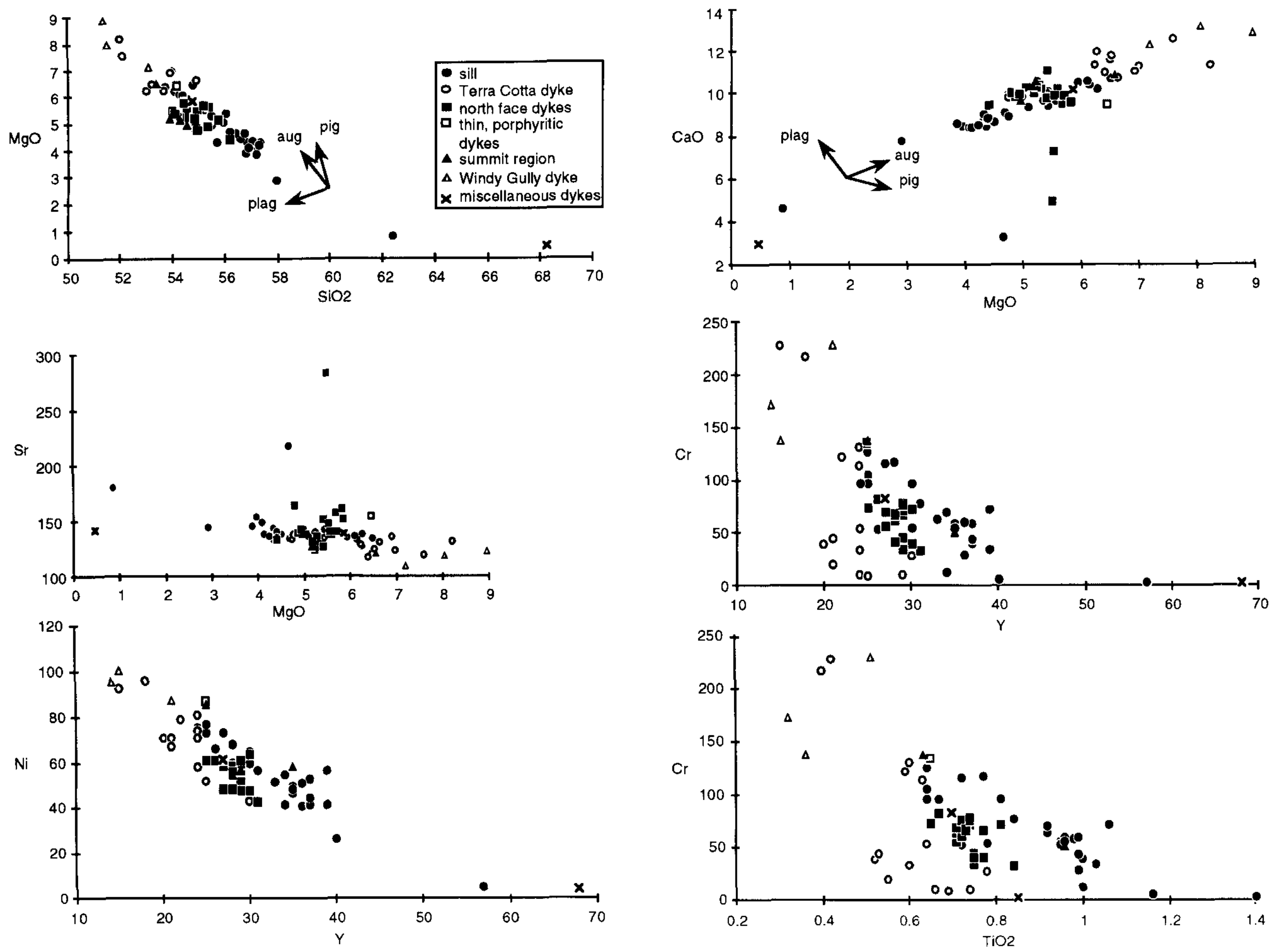

Fig. 4. Selected element variation diagrams. The variation in samples which plot significantly off the main trend is ascribed to sub-solidus alteration. Mineral vectors shown are the trends expected for accumulation of that mineral. Mineral compositions used are from representative microprobe analyses (Morrison 1989).

ratio to the less mobile HFSE and resulting in poor correlations on LILE versus HFSE plots. Correlations between LILE of different mobilities may also be poor. Inter-element diagrams from Terra Cotta Mountain typically display tight correlations between HFSE. In contrast, inter-element diagrams of LILE versus HFSE, and LILE versus LILE display variable correlations (Fig. 4). This could be interpreted as evidence of selective contamination, or may be the result of LILE mobility during sub-solidus alteration, as discussed above. Similar poor correlations between LILE in the Kirkpatrick Basalts from north Victoria Land are coupled with variations in Sr and O isotopic ratios and have been interpreted as resulting from post-magmatic alteration (Fleming *et al.* 1992).

Hergt *et al.* (1991) have demonstrated that crustal contamination of the Ferrar magma is not a viable mechanism. They conclude that the very low abundances of some elements (e.g. Ti) would require an unusually depleted parent magma, contaminated by 25–30% assimilation of crustal material with unusually high Rb/Ba, Rb/Sr, SiO_2 and $^{87}Sr/^{86}Sr$. Fleming *et al.* (1992) also considered, on the basis of reinterpretation of isotopic data, that significant crustal contamination of the Ferrar Group is unlikely.

By analogy with these studies, it is concluded that crustal contamination of the Ferrar Dolerite at TCM is not an important process. Poor correlations between LILE are best explained by subsolidus alteration. The LILE-enriched signature of all the samples, including even the most primitive chilled margin sample (60883, Fig. 3a), suggests that the compositional variation between the intrusions cannot be explained by varying degrees of crustal contamination. Furthermore, it suggests that the LILE-enrichment was a characteristic of the primary magma, possibly reflecting the mantle source region.

Closed system fractionation

Mg numbers, Cr and Ni abundances in the Ferrar Dolerite from TCM are too low for magmas in equilibrium with a peridotite source (Basaltic Volcanism Study Project 1981). The primary magma therefore must have undergone significant fractionation prior to intrusion. Any original variation produced by varying

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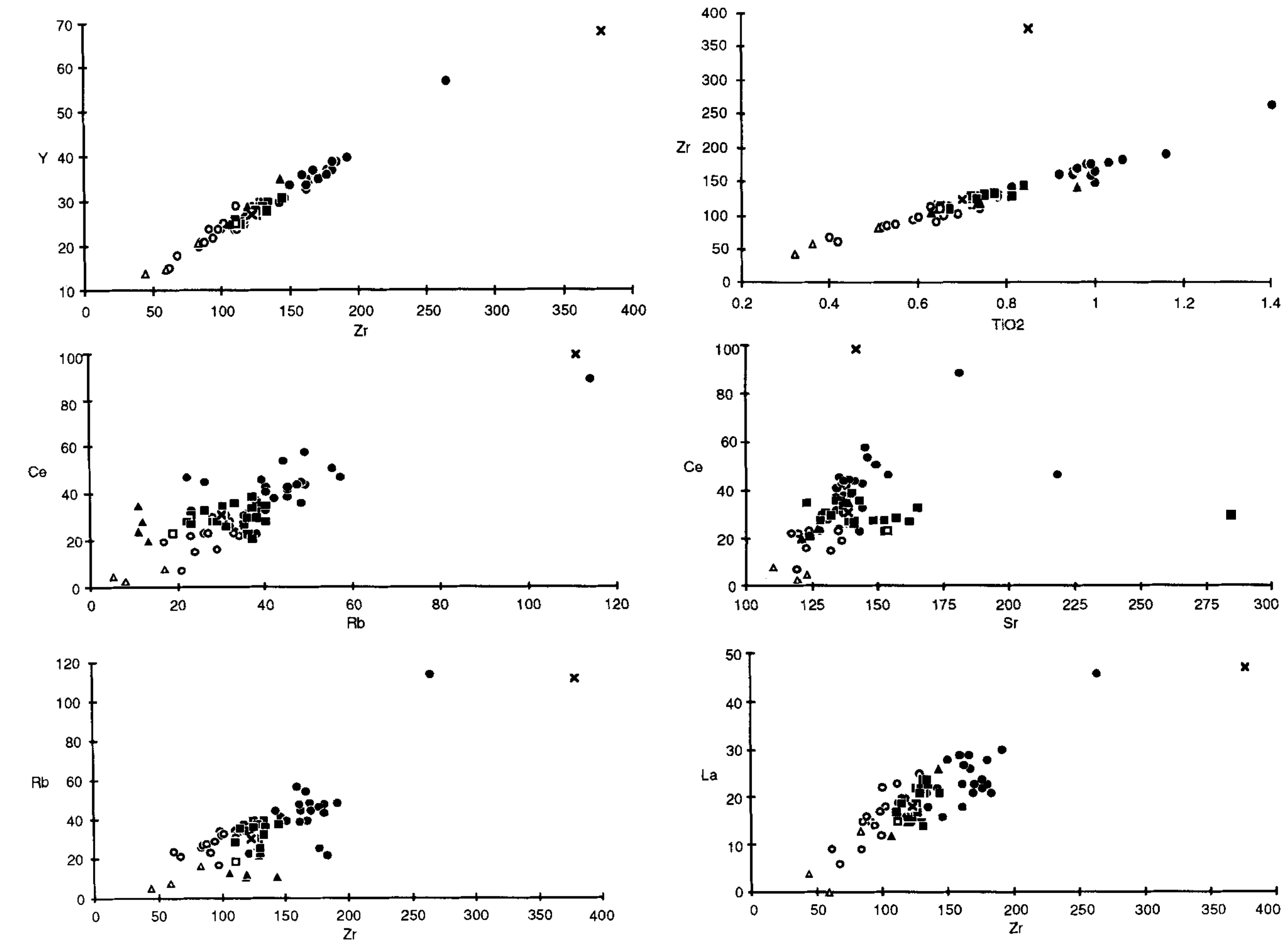

Fig. 4. Continued. Selected element variation diagrams.

degrees of partial melting would have been obscured by the later fractionation process.

On an AFM diagram (Fig. 5) the fractionation trend is one of initial iron-enrichment, starting with the most Mg-rich samples of the Windy Gully dyke, followed by an increase in the alkalis, and finishing with the sample of the evolved dyke intruding the lower margin of the sill. This is typical of tholeiitic trends (e.g. the Skaergaard Intrusion, Wager 1960). The continuous trend on the AFM diagram supports the role of fractionation in producing the geochemical variation within and between the different intrusions.

Good correlations between many elements suggest the different intrusions may be related by a constant fractionation assemblage (Fig. 4). There is considerable overlap on the plots between samples from the north face swarm and the Terra Cotta dyke. However, samples from the sill and Windy Gully dyke plot as separate, more evolved and less evolved groups, respectively. The field constraints on the intrusive sequence suggest a possible trend from more evolved to more basic composition with time. The fractionation assemblage determined from the diagrams must have included plagioclase, augite and a low-Ca pyroxene.

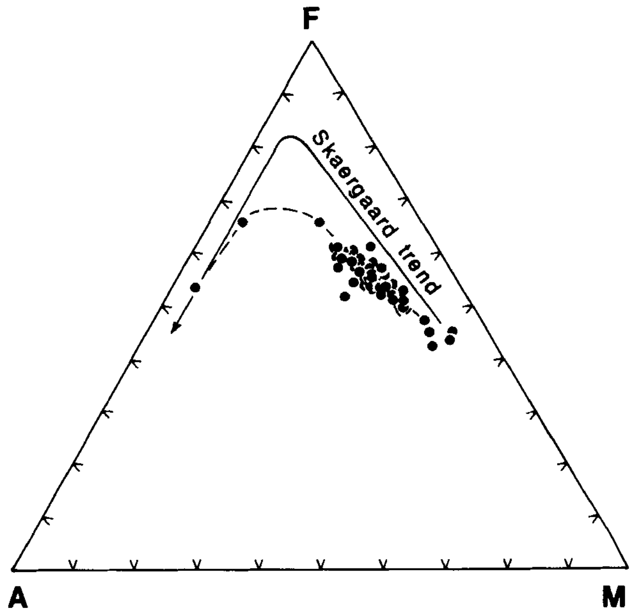

Fig. 5. AFM ternary diagram ($A = Na_2O + K_2O$, $F = FeO^*$, $M = MgO$) for the entire Ferrar Dolerite data set from Terra Cotta Mountain. Skaergaard trend after Wager (1960).

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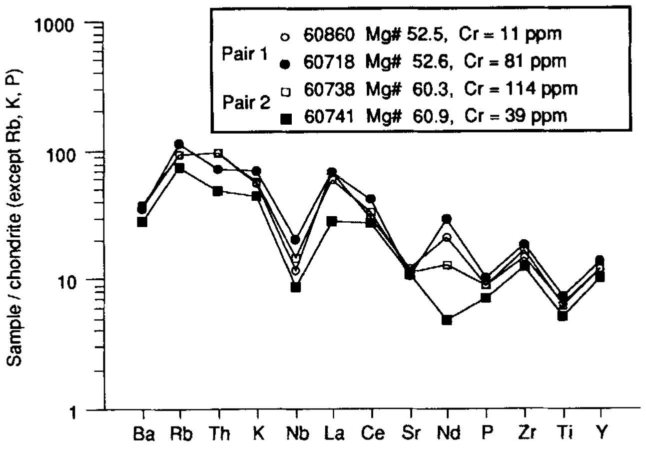

Fig. 6. Spidergrams of dolerite sample pairs with equivalent Mg numbers, but different Cr concentrations. Sample locations: 60860 Terra Cotta dyke centre, 60718 north face dyke margin, 60738 Terra Cotta dyke margin, 60741 Terra Cotta dyke margin.

A plot of Sr against MgO (Fig. 4), shows that the abundance of Sr increases only slightly with differentiation (i.e. $D_{bulk}^{Sr} \approx 1$), further indicating that plagioclase must be part of the fractionating assemblage. But since $D_{plag}^{Sr} = 1.83$ (Henderson 1982) it must have been accompanied by at least one other phase in which Sr is incompatible.

It is concluded that much of the major and trace element geochemical variation within and between intrusions may be explained by fractionation of an assemblage composed of *c.* 50% plagioclase and sub-equal amounts of Ca-rich and Ca-poor pyroxene. This is consistent with conclusions of Kyle *et al.* (1981) on the Ferrar fractionation assemblage.

The presence of plagioclase in the fractionation assemblage suggests fractionation occurred under relatively low pressure, crustal conditions. This is typical of continental flood basalt provinces and has led to the formulation of a model for flood basalt volcanism involving the fractionation of the primary magma in lower crustal magma chambers, followed by later fractionation as the magma rose to higher levels (Cox 1980, Morrison *et al.* 1985). In such a model it is possible that magma resident in crustal magma chambers may have mixed with fresh influxes of magma from lower levels. It is important therefore to investigate the effects of mixing magmas.

Open system fractionation: periodically replenished, tapped and fractionating (RTF) magma chambers

Periodically replenished, tapped and fractionating (RTF) magma chambers have been described by O'Hara & Mathews (1981). Cox (1988) postulated the possible role of RTF magma chambers to explain the enormous volumes, but limited compositional range of continental flood basalts suggesting that they are erupted in a "quasi steady-state". Geochemically, RTF chambers have the ability to decouple elements by exploiting differences in their distribution coefficients, (O'Hara & Mathews 1981). Cox (1988) has demonstrated that the products of RTF chambers should demonstrate poor correlations between highly compatible and highly incompatible elements.

Inter-element plots of highly compatible elements (Ni and Cr) versus examples of incompatible elements (Y and TiO_2) are presented in Fig. 4. Ni displays a reasonable correlation with the selected incompatible elements with a moderate amount of scatter. In contrast, the more highly compatible element Cr displays a very poor correlation with the incompatible elements. For a given value of Y or TiO_2, Cr displays a wide range of values.

The observed behaviour of Cr is consistent with the operation of RTF processes. The higher degree of decoupling of Cr versus an incompatible element by comparison with the results for Ni, perhaps reflects the higher D_{bulk} of Cr. Processes other than RTF can produce decoupling and should be considered. These processes are discussed by Cox (1988) and include variable partial melting for different magma batches followed by fractionation, anomalous accumulations of phenocrysts in non-cotectic proportions, variable crustal contamination, or a heterogeneous source region. In Fig. 6 chondrite-normalized spidergrams are presented for sample pairs with equivalent Mg numbers, but markedly different Cr concentrations. If the Cr depletion is a result of the assimilation of a low-Cr contaminant or derivation from a heterogeneous source region, one would expect a correlation between LILE-enrichment and Cr-depletion. Fig. 6 suggests that this is not the case. The coincidence of the plots for each pair suggests that LILE-enrichment is not related to Cr-depletion but the two are the result of separate processes.

It is concluded that the poor correlation of Cr with incompatible elements is not the result of crustal contamination or a heterogeneous source and is best explained by the operation of RTF processes.

Regional Ferrar magmatic province comparison: implications for the involvement of a LILE-enriched, sub-continental lithospheric mantle source

Regional studies of some continental flood basalt provinces have recognized separate high- and low-Ti magma types (e.g. Erlank *et al.* 1988). All the Dolerite samples analysed from TCM have relatively low TiO_2 (< 1.5 wt %), Ti/Y (<180) and Ti/Zr (< 6) and are therefore classified as low-Ti tholeiites. The TCM compositions are equivalent to the "Mount Fazio chemical type" recognized from the Kirkpatrick Basalt in north Victoria Land (Siders & Elliot 1985, Fleming *et al.* 1992). Hergt *et al.* (1991) consider that the Ferrar magmatic province represents an extreme example of the low-Ti magma type.

A regional comparison of the calculated average composition from different studies within the Ferrar magmatic province is presented in Fig. 7. The spidergram pattern of the Dolerite at TCM is remarkably similar to those from north Victoria Land (Siders & Elliot 1985, Brotzu *et al.* 1988), the central Transantarctic Mountains (Hergt *et al.* 1989a) and the Tasmanian

Dolerites (Hergt *et al.* 1989b). The data from TCM therefore provide evidence from south Victoria Land to support the conclusions of Hergt *et al.* (1989a, 1989b, 1991) that the trace element characteristics of the Ferrar magmatic province are remarkably uniform over a very large area from the central Transantarctic Mountains to northern Victoria Land and Tasmania, despite different degrees of evolution. Equivalent trace element signatures have also been reported in some Dolerites from Coats Land (Brewer 1989, Brewer *et al.* 1992).

The LILE-enriched trace element characteristics, high initial $^{87}Sr/^{86}Sr$ ratios and low εNd values of the Ferrar magmatic province are suggestive of a strong crustal component in the magma. However, the similarities of these features over such a large area is difficult to explain by a process of crustal contamination *en route* to the surface and has implications for an enriched lithospheric mantle source region (Hergt *et al.* 1989a, 1989b, 1991, Brewer *et al.* 1992). Kyle (1980) first proposed that the LILE-enriched nature and high $^{87}Sr/^{86}Sr$ ratios characteristic of the Ferrar magmatic province are not the result of crustal contamination, but are inherited from the mantle source. Kyle suggested several possible models for the development of heterogeneities in the mantle, including the derivation of ^{87}Sr and LILE from an underlying subduction zone by dehydration of the down-going slab. This argument for a link between a previous subduction episode and an enriched lithospheric mantle source is further suggested by the similarity of the low-Ti flood basalts to arc tholeiites. Pearce (1983) attributed the LILE-enriched character of island arc tholeiites to a subduction component derived from the recycling of crustal material from the down-going slab into the overlying mantle wedge by hydrous fluids. In addition to the LILE-enrichment, many island arc tholeiites also display negative Nb and Ti anomalies, (Briqueu *et al.* 1984), and thus have similar spidergram patterns to the Ferrar magmatic province. This similarity between low-Ti flood basalts and arc thoeliites, and the absence of low-Ti magma types from intra-plate ocean island basalt settings, has led to suggestions that previous subduction episodes may be important in the development of low-Ti source regions (Hawkesworth *et al.* 1988).

The similarity of the Dolerite trace element signature with that of the early Palaeozoic basement granitoids at TCM supports suggestions that the Ferrar magma was generated within the lithospheric mantle. In addition, it may imply that the source region was enriched before the early Palaeozoic. This interpretation is supported by Nd- and Pb-isotopic studies of Mesozoic continental flood basalts across Gondwana which yield Proterozoic ages, suggesting an old lithospheric mantle source (Hawkesworth *et al.* 1988, 1990).

The currently favoured model for the petrogenesis of the Ferrar magmatic province involves a sub-continental lithospheric mantle source region initially variably depleted in certain major (Ti, Na and P) and trace (Rb, Ba) elements, and later enriched in highly incompatible elements and Sr and Pb isotopes by the introduction of a small amount of subducted sediment (Hergt *et al.* 1991).

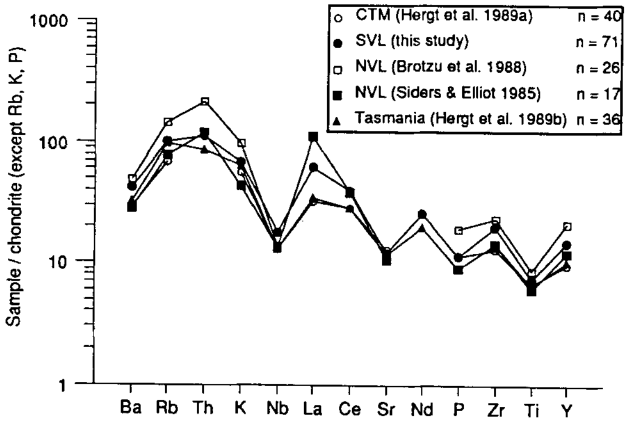

Fig. 7. Regional comparison of spidergrams from the Ferrar Group and Tasmanian Dolerites. Individual spidergrams represent the average composition from each study. Data from Siders & Elliot (1985) excludes the "high-Ti" samples (Scarab Peak chemical type of Fleming *et al.* 1992).

Conclusions

Ferrar Dolerite intrusions at TCM display geochemical variation both within and between intrusions. Good correlations between major elements and many trace elements suggest that crystal fractionation was an important process responsible for much of the geochemical variation. However, the poor correlations between some elements indicates the operation of other processes.

The Dolerite has been affected to varying degrees by sub-solidus alteration as the result of a hydrothermal system established in the country rocks. This alteration has resulted in some element mobility.

Trace element signatures of the Dolerite are LILE-enriched. The presence of this feature in even the most primitive compositions suggests that it is inherited from the source region, rather than resulting from crustal contamination en route to the surface.

The poor correlation of Cr with incompatible elements is difficult to explain by closed-system fractionation and is consistent with the operation of a periodically replenished, tapped and fractionating (RTF) magma chamber. The lack of correlation of Cr-depletion with LILE-enrichment suggests that the Cr-depletion cannot be completely explained by assimilation of a low-Cr contaminant, or by source heterogeneity.

The LILE-enriched trace element signature of the Ferrar Dolerite at TCM is very similar to that of Ferrar Group rocks from the Transantarctic Mountains and north Victoria Land, as well as the Tasmanian Dolerites and south-eastern Australian basalts. The remarkable similarity of this feature over such a large area is difficult to explain by crustal contamination *en route* to the surface. This study therefore provides data from south Victoria Land to support interpretations that the trace element and isotopic characteristics are inherited from a uniformly enriched mantle source region.

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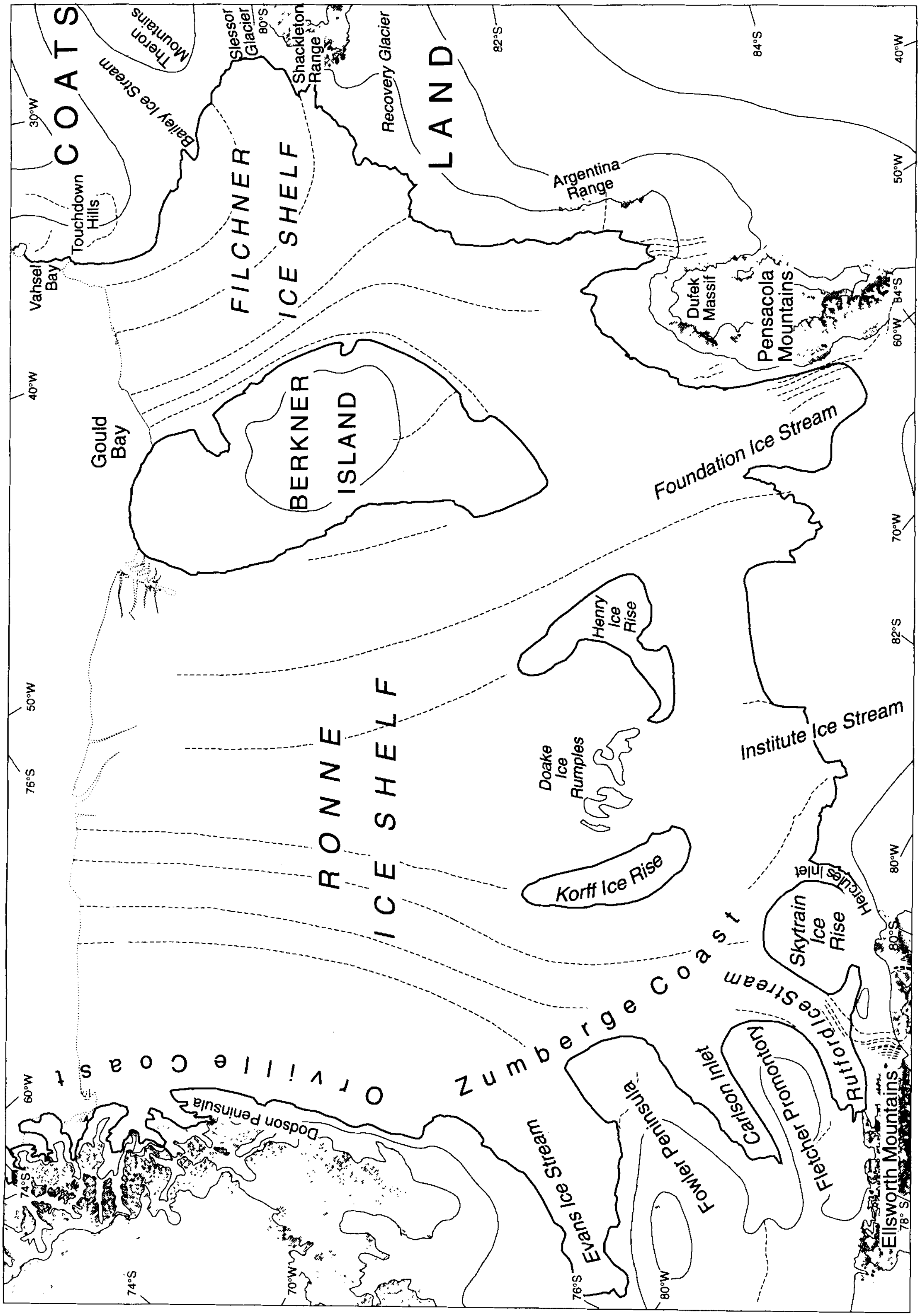
Antarctic Science **Handy Atlas Map No. 9.**

IMW Sheets ST 17–20, ST 21–24, ST 25–28, SU 16–20, SU 21–25, SU 26–30. Ronne and Filchner ice shelves, 1:5 000 000 scale, contour interval 500 m. Pecked lines represent glacier flow lines and dotted lines ice fronts.



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