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HIGH-Mg ARC-ANKARAMITIC DIKES, GREENHILLS COMPLEX, SOUTHLAND, NEW ZEALAND

DAVID J. MOSSMAN[§]

Department of Physics, Engineering and Geoscience, Mount Allison University, Sackville, New Brunswick E4L 1E6, Canada

DOUGLAS S. COOMBS, YOSUKE KAWACHI* AND ANTHONY REAY

Department of Geology, University of Otago, Dunedin, New Zealand

ABSTRACT

Minor dikes 8–70 cm thick of ankaramitic composition were emplaced late in the crystallization of the Greenhills Complex, a layered dunite – wehrlite – hornblende gabbronorite intrusion of Permian age in the volcanic arc-derived Brook Street Terrane of southern New Zealand. Mg contents range from 10 to 28 wt% MgO. The interior of a hornblende ankaramite dike at Steep Head contains phenocrysts of olivine Fo_{93-82}, in some cases skeletal, and scattered phenocrysts of diopside, set in a groundmass of magnesiohornblende. The chilled margins of this dike consist almost wholly of amphibole (91%) and anorthite, An_{99-94} (9%). In other dikes, crystallization of amphibole followed that of olivine, diopside, enstatite, and overlapped with plagioclase. Olivine in these dikes varies in composition from Fo_{90} to Fo_{72}. Diopside contains oriented blebs of magnesiohornblende and edenite. We believe that the components of these amphibole inclusions were in part introduced and in part derived from the host pyroxene by a process of reactive exsolution. Spinel varies from chromite containing 53 wt% Cr_2O_3 through compositions at first increasingly Al-rich, and then through chromian magnetite to virtually Cr-free magnetite. Amphiboles range from magnesiohornblende to edenite, pargasite, and tschermakite, with minor late-stage high-Si magnesiohornblende. The aphyric margin of the Steep Head dike contains 17.4 wt% MgO on a volatile-free basis. Some of the melts may have exceeded this MgO content. Dike centers are more Mg-rich than margins, reaching 28.3% in one case, in part an effect of concentration of phenocrysts by flow differentiation, and in part a result of changing composition of the melt. The presence of abundant magmatic amphibole, especially in the most magnesian rocks, indicates a relatively hydrous magma. Various geothermometers suggest extensive low-temperature re-equilibration. Even where the dikes consist of almost monomineralic amphibole, chemically they are arc-ankaramites with $CaO/Al_2O_3 > 1$, *REE* contents less than twice primitive mantle, low abundances of high-field-strength elements and of incompatible elements, highly calcic plagioclase, and Cr-rich spinels with Ti, Mg, and Cr contents typical of low-K, high-Mg ankaramitic arc-tholeiitic suites. They have some chemical similarities to komatiites, but have lower Ni/MgO, Cr/MgO, and Ti/V values. The most highly magnesian dike-rocks have olivine in excess of diopside, whereas in dikes with lower Mg contents, the proportion of diopside phenocrysts exceeds that of olivine. Progressive fractionation of these two minerals lowered the bulk CaO/Al_2O_3 ratio. Below about 10% MgO, CaO/Al_2O_3 was no longer greater than one, the ankaramitic nature was lost, and evolution continued along an arc-tholeiitic trend. The dike compositions support the hypothesis that the Greenhills Complex is the remnant of an upper-crust magma chamber from which arc-ankaramites, tholeiitic basalts, and more evolved effusive volcanic products in the Brook Street Terrane were erupted. The highly magnesian ankaramitic dikes and their effusive analogues provide another example of an association increasingly recognized in Phanerozoic island-arc systems.

Keywords: Greenhills Complex, Brook Street Terrane, ankaramite, flow differentiation, olivine, clinopyroxene, chromite, amphibole, arc volcanism, reactive exsolution, New Zealand.

SOMMAIRE

De petits filons, de 8 à 70 cm d'épaisseur et de composition ankaramitique, ont été mis en place tardivement au cours de la cristallisation du complexe de Greenhills, massif stratiforme intrusif de dunite – wehrlite – gabbronorite à hornblende d'âge permien lié au cortège volcanique appelé Brook Street Terrane, dans le sud de la Nouvelle-Zélande. Les teneurs en magnésium vont de 10 à 28% MgO (en poids). L'intérieur d'un filon d'ankaramite à hornblende à Steep Head contient des phénocristaux d'olivine Fo_{93-82}, dans certains cas squelettiques, et des phénocristaux épars de diopside, dans une pâte de magnésiohornblende. Les bordures figées de ce filon contiennent presqu'entièrement de l'amphibole (91%) et de l'anorthite, An_{99-94} (9%). Dans d'autres filons, l'amphibole a suivi l'olivine, le diopside et l'enstatite, et a co-cristallisé avec le plagioclase. L'olivine de ces filons

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[§] *E-mail address*: dmossman@mta.ca

[*] *Present address*: Research Centre for Mineral Resources Exploration, A-11 Datun Road, Beijing 100101, People's Republic of China.

varie en composition de Fo_{90} à Fo_{72}. Le diopside contient des microdomaines de magnésiohornblende et d'édenite. A notre avis, les composants de ces inclusions d'amphibole ont été introduits en partie, et d'autre part dérivés du pyroxène hôte par un processus d'exsolution réactionnelle. Le spinelle varie de chromite contenant 53% de Cr_2O_3 (en poids) vers des compositions montrant d'abord une augmentation en aluminium, et ensuite une tendance vers la magnétite chromifère, pour aboutir à la magnétite presque sans Cr. La composition des amphiboles varie de magnésiohornblende à édenite, pargasite, et tschermakite, avec une tendance tardive vers des compositions plus siliceuses de magnésiohornblende. La bordure aphyrique du filon de Steep Head contient 17.4% de MgO sur une base anhydre. Certaines des venues magmatiques ont même peut-être dépassé cette teneur en Mg. Le centre des filons contient davantage de Mg, jusqu'à 28.3% dans un cas, en partie à cause de l'effet de concentration de traînées de phénocristaux en flux, et d'autre part de l'évolution de la composition du magma. La présence d'une abondance d'amphibole magmatique, en particulier dans les roches les plus magnésiennes, indiquerait un magma relativement hydraté. Une batterie de géothermomètres indiquent l'importance de ré-équilibrage à faible température. Même dans le cas de filons contenant presqu'uniquement de l'amphibole, la composition chimique est celle d'ankaramites d'un milieu d'arc, avec $CaO/Al_2O_3 > 1$, la concentration des terres rares moins que deux fois les teneurs chondritiques, de faibles teneurs en éléments à potentiel ionique élevé et en éléments incompatibles, un plagioclase à teneur en calcium très élevé, et un spinelle chromifère typique des suites tholéiitiques d'arc et ankaramitiques, avec teneurs faibles en K et élevées en Mg. Ces roches partagent certaines des caractéristiques des suites komatiitiques, mais elles possèdent des valeurs des rapports Ni/MgO, Cr/MgO, et Ti/V plus faibles. Le filon qui contient la roche la plus magnésienne a plus d'olivine que de diopside, tandis que dans les filons moins magnésiens, la proportion de phénocristaux de diopside dépasse celle des phénocristaux d'olivine. Un fractionnement de ces deux minéraux a abaissé la valeur globale du rapport CaO/Al_2O_3. Au dessous d'environ 10% MgO, le rapport CaO/Al_2O_3 est passé à une valeur inférieure à l'unité, la filiation ankaramitique était perdue, et l'évolution a continué selon la lignée d'un système tholéiitique en milieu d'arc. La composition des filons étaye l'hypothèse voulant que le complexe de Greenhills est un lambeau d'une chambre magmatique sise à faible profondeur, dans laquelle des venues d'ankaramites d'arc, de basaltes tholéiitiques, et de produits effusifs plus évolués du cortège de Brook Street Terrane ont été mis en place. Les filons d'ankaramite magnésienne et leurs analogues effusifs fournissent un nouvel exemple d'une association qui semble devenir de plus en plus répandue dans les systèmes d'arcs insulaires phanérozoïques.

(Traduit par la Rédaction)

Mots-clés: complexe de Greenhills, cortège de Brook Street Terrane, ankaramite, différenciation par écoulement, olivine, clinopyroxène, chromite, amphibole, volcanisme d'arc, exsolution réactionnelle, Nouvelle-Zélande.

INTRODUCTION

The mafic to ultramafic Greenhills Complex (Fig. 1) of Bluff Peninsula, in Southland, New Zealand (Mossman 1973) occurs in the volcanic-arc-derived Brook Street Terrane (Frost & Coombs 1989). It is interpreted as the crustal root of an intra-oceanic island-arc volcano that intruded thick, arc-flank sedimentary rocks dated as probably Artinskian to Kungurian, late Early Permian (Mossman & Force 1969). Zircon from hornblende gabbronorite within the complex has yielded a uranium–lead age of 265 Ma (Kimbrough *et al.* 1992); this is not measurably different from the inferred age of the intruded sedimentary rocks. Adjacent to the Complex and to associated bodies of hornblende gabbronorite (*e.g.*, Service 1937), the sedimentary rocks are metamorphosed to pyroxene hornfels and hornblende hornfels. In the outer parts of the aureole, fine sedimentary and biogenic detail is preserved (Mossman & Force 1969), and the metamorphic grade is inferred to have been no higher than greenschist facies. Corresponding sedimentary rocks in the upper part of the Takitimu Group, 85 km to the northwest, have experienced only very low grade alteration in the zeolite facies (Houghton 1982). Such evidence indicates that the Complex was emplaced at a high level in the crust.

Mossman (1973) described a layered series of dunite, wehrlite, and gabbro with highly calcic plagioclase, $An_{88–91}$. Late-stage trondhjemite dikes also occur. As now exposed, the body appears to have been disrupted into two crudely bowl-shaped parts. In contrast to early dikes, which include very coarse-grained gabbro (Mossman 1970, 1973), volumetrically minor late-stage high-Mg dikes are chilled. The margins of some of these are composed almost entirely of fine-grained hornblende and minor anorthite, which are possible products of quenching. Olivine and clinopyroxene phenocrysts in the high-Mg dikes vary greatly in relative proportion and, in some cases, show evidence of flowage differentiation. Matrices range from monomineralic pale greenish hornblende to medium-grained plagioclase – orthopyroxene – clinopyroxene plus subordinate magmatic brownish and later-stage greenish hornblende and minor tremolite or actinolite.

The high-Mg dikes are interpreted as having formed from evolving, relatively hydrous liquids that initially contained up to at least 17% MgO. Whether or not the interior of the magma chamber was still fluid when they were emplaced is unclear, although the fact that such dikes have not been found in the central parts of the intrusion suggests that this was the case (*cf.* Greenwood & Donaldson 1989) and that they contributed to the magma pool or were derived from it.

Contents of up to 28.3% MgO in olivine-rich dike interiors invite comparison with komatiites, whereas the clinopyroxene-rich nature of some of the dikes suggests

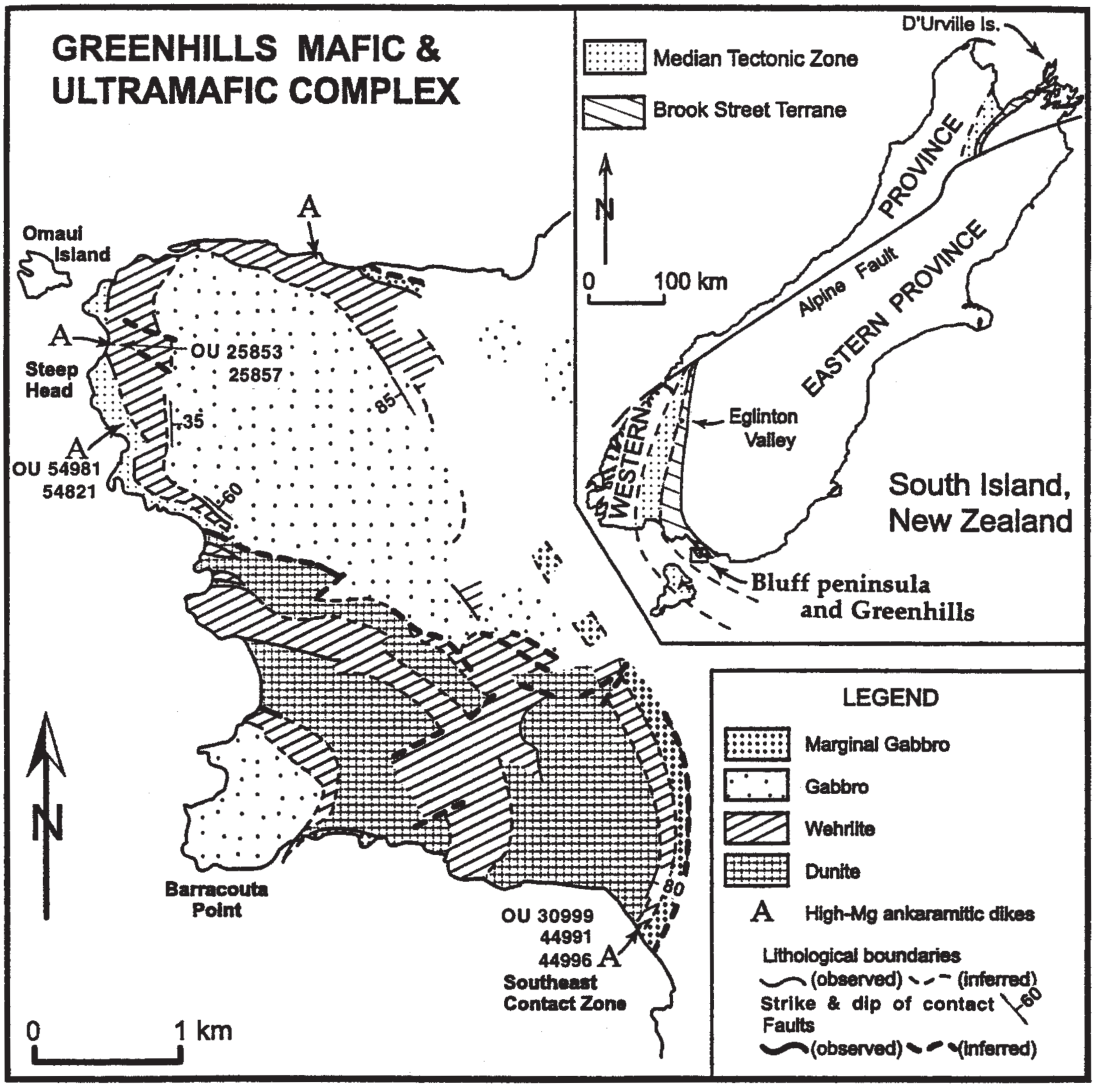

FIG. 1. Greenhills Complex, Bluff Peninsula, Southland, New Zealand (Mossman 1973) showing localities for ankaramitic dikes. Inset: locality map, South Island of New Zealand showing situation of Bluff Peninsula and other localities within the Brook Street Terrane, and the relationship of this terrane to the Median Tectonic Zone (Kimbrough *et al.* 1993), Eastern and Western Provinces, and the Alpine Fault.

a relationship to the ankaramites of island-arc settings. The dikes described here were identified by Mossman (1973) as picrites, but the ratio of CaO to Al_2O_3 is consistently greater than one, a feature used by Della-Pasqua & Varne (1997) to distinguish primitive arc-ankaramite from picrite. Although very minor in volume, the dikes provide evidence for an association of ankaramitic magma with cumulate wehrlite in an intrusive complex in an arc setting. Ankaramites are usually considered to contain abundant phenocrysts of clinopyroxene and olivine, but on grounds of chemical composition and association, the Greenhills dikes under discussion are here referred to as high-Mg arc-ankaramites, even where quenched, almost phenocryst-free, and consisting of almost monomineralic hornblende.

Arc-ankaramites of early Permian age, both effusive and intrusive, occur extensively in the Brook Street Terrane (Landis & Waterhouse 1966, Williams & Smith 1979, Sivell & Rankin 1983, Ballard 1987). A possible link between these and intrusions such as the Greenhills

Complex (Kimbrough *et al.* 1992) is discussed in this paper, but our focus is on the mineralogy and geochemistry of the Greenhills arc-ankaramite dikes.

Analytical Methods

Analyses of minerals were carried out at different stages of this study, initially with a JEOL JXA–5A electron microprobe using both wavelength-dispersion (WDS) and energy-dispersion (EDS) modes, and later using a JXA 8600 instrument (WDS). Operating conditions included beam diameter 2–3 μm, 15 kV, and 20 nA, and Bence & Albee (1968) correction on drift, dead time, and background, or ZAF correction for more recent analyses. The EDS mode gave substantially higher detection-limits than WDS, *e.g.*, about 0.2% for TiO_2, 0.2% for MnO, 0.4% for MgO, 0.3% for NiO, 0.13% for CaO, 0.4% for Na_2O, 0.1% for K_2O, and 0.2% for Cr_2O_3 in typical analyses of olivine, pyroxene, and amphibole. Details of the computer-controlled procedure for the JEOL JXA–5A are given in Kawachi & Okumura (1978).

For whole rocks, the concentrations of the major elements were determined on fused discs by X-ray fluorescence (XRF) with a Philips PW 2400 spectrometer fitted with a rhodium tube. The flux used was a lithium carbonate – lithium oxide mix (type 1222). Concentrations of trace elements also were determined on the PW2400 using pressed powder discs. Corrections for line overlap and various mass-absorption effects were based on Philips SuperQ software modified with some in-house procedures to improve accuracy and precision. For rare-earth (*REE*) and certain other elements, inductively coupled plasma – mass spectrometry (ICP–MS) analyses were performed at Memorial University of Newfoundland by Simon E. Jackson. Some analyses for the *REE* were carried out by instrumental neutron-activation analyses (INAA) by Roy Johnstone at the Department of Geology, University of Otago. The INAA analyses, following the techniques described by Gibson & Jagam (1980), gave results within analytical error of the ICP values.

Field Relations

Over a dozen late ankaramitic dikes are known at Greenhills. The best exposed are at the margins of the complex at Steep Head in the northwest, and in the southeast contact-zone about 3 km east of Barracouta Point (Fig. 1). They are postdated by only a few minor aplite dikes (Mossman 1973). Unlike many earlier dikes, they have undergone no noticeable solid-state deformation. They range in thickness from only about 4 cm to 1 m. All were emplaced in country rock, mostly wehrlite, that had cooled sufficiently to undergo brittle fracture. The Steep Head hornblende ankaramite dike (Fig. 2) strikes 150°, dips 70° NE, cross-cuts coarse-grained feldspathic wehrlite and earlier dikes and veinlets of medium-grained gabbronorite, and is exposed along 30 m of strike. This dike has phenocryst-free chilled margins consisting mostly of fine-grained amphibole, which grade over a centimeter or less into a phenocryst-rich core. Most of the other dikes studied contain plagioclase, clinopyroxene, orthopyroxene, and hornblende, together with olivine and spinel-group minerals. Fine- and medium-grained dikes of less extreme basaltic to andesitic composition, rich in groundmass hornblende, are locally abundant, especially in the marginal zones of the intrusion. Cross-cutting relations between these and the relatively few high-Mg dikes have not been observed.

Petrography

Country-rock wehrlite (*OU 25853W, 30999W*)

The immediate country-rock wehrlite for dike specimen OU 30999 (OU numbers refer to specimens stored in the Department of Geology, University of Otago, New Zealand) in the southeastern contact-zone consists of an aggregate of diopside averaging $Ca_{48.4}Mg_{47.2}Fe_{4.4}$ and less abundant olivine, $Fo_{86.8–84.7}$. Feldspathic wehrlite OU 25853W at Steep Head is more evolved; diopside, crystals of which locally reach 2 cm in diameter, has an average core composition $Ca_{46.1}Mg_{46.7}Fe_{7.2}$, and $Ca_{46.2}Mg_{45.4}Fe_{8.4}$ at the rims. Olivine, $Fo_{75.2–73.6}$, is less abundant and is commonly included within diopside crystals, and minor anorthite occurs interstitially. In both types of wehrlite, the diopside is heavily charged with blebs of amphibole of late magmatic origin.

Steep Head hornblende ankaramite dike (*OU 25853, 25857, 54983*)

Parts of the margin of a hornblende ankaramite dike, 30 cm thick, at grid reference E47 434991 on the north side of Steep Head (Table 1, Fig. 2), consist of a monomineralic veneer, 0.5–1.0 mm thick, of hornblende crystals, pale green in thin section, typically 0.05–0.1 mm long, crudely oriented parallel to the dike margin (Fig. 3A). Elsewhere, a few percent of interstitial plagioclase, or products of its alteration, extend to the contact. Modal analysis of the marginal zone shows 91.3% hornblende, 8.5% plagioclase, 0.2% opaque grains and a trace of clinochlore. At 3 mm from the contact, hornblende crystals have increased to 0.15 mm in length, and interstitial plagioclase is present; at 6 mm from the contact, the grain size is 0.2–0.3 mm; at 15 mm from the contact, hornblende occurs as plates up to 0.5 mm in diameter. From here to the center, there is no plagioclase, and the groundmass is virtually monomineralic hornblende in random orientation.

Phenocrysts of olivine and subordinate diopside first appear about 4 cm from the contact, and increase progressively in abundance to about 36% olivine and 10% diopside in the central portion of the dike. The whole-

TABLE 1. HIGH-Mg ANKARAMITIC DIKES AND THEIR MINERALOGY, GREENHILLS COMPLEX

	OU 25853/7	OU 44991	OU 30999	OU 44996	OU 54982	OU 54981
Locality	Steep Head	SE C.Z.	SE C.Z.	SE C.Z.	Steep Head	Steep Head
Dike thickness	30 cm	?30 cm	15 cm	70 cm	15 cm	8 cm
MgO wt.%, dike margin	17.4%					10.6%
wt.% in dike interior	28.3%	26.0%	24.2%	17.0%	16.4%	14%
% olivine phenocrysts	[1]0—36	32	[1]20—25	6	16	[1]1—6
% cpx phenocrysts	[1]0—10	2	[1]8—12	25	24	[1]4—3
Olivine	[11]	[19]	[43]	[15]	[10]	[10]
Mg # range	92.7—81.7	85.9—80.5	90.0—76.1	79.9—74.2	74.1—72.4	74.9—72.8
Clinopyroxene						
phenocrysts avg.	[7]	[8]	[11]	[14]	[10]	-
Ca	50.1	48.2	46.7	46.8	45.5	-
Mg	40.3	46.4	46.1	45.1	45.1	-
Fe	9.6	5.4	7.3	8.0	9.3	-
groundmass avg.	absent	[9]	[6]	[10]	[12]	[17]
Ca	-	47.7	46.4	46.1	44.0	45.3
Mg	-	47.9	45.9	44.3	44.8	44.9
Fe	-	4.4	7.7	9.6	11.3	9.8
Orthopyroxene						
groundmass avg.	absent	[9]	[12]	[10]	[15]	[13]
Ca	-	1.2	1.4	2.1	2.2	2.5
Mg	-	84.6	80.3	72.1	73.0	73.9
Fe	-	14.3	18.3	25.8	24.8	23.6
Mg # range	-	87.9—84.5	82.9—79.6	76.4—69.9	78.5—73.2	77.6—73.5
Chromite, magnetite						
in olivine	[6]	[6]	[40]	[5]	[2, in cpx]	-
range Cr_2O_3	53.4—48.4	41.5—33.5	53.1—12.1	25.6—8.7	24.5, 20.3	-
in groundmass	-	[9]	[9]	[8]	[10]	[11]
range Cr_2O_3	-	38.6—30.1	9.44—0.26	12.7—0.79	8.00—3.75	5.81—2.91
Plagioclase	[9]	[14]	[10]	[17]	[12]	[20]
An range	$\text{An}_{99.3—94.0}$	$\text{An}_{95.3—80.8}$	$\text{An}_{88.6—75.3}$	$\text{An}_{94.7—72.0}$	$\text{An}_{90.0—82.7}$	$\text{An}_{90.0—78.8}$
Amphibole						
avg. magmatic brown and 25853 "quench"	[5]	[16]	[6]	[11]	[12]	[10]
Ca	28.7	31.2	29.2	29.6	29.0	29.6
Mg	55.0	59.0	55.8	52.3	51.4	50.9
Fe	16.3	9.8	15.0	18.0	19.6	19.5
Al_2O_3, wt %	6.3	11.5	10.8	10.5	11.3	11.6
green, avg.	[10]		[2]	[7]	trace	present
Ca	28.2	-	29.5	28.2	-	-
Mg	56.8	-	62.0	55.3	-	-
Fe	14.9	-	8.6	16.5	-	-
Al_2O_3, wt %	9.01	-	11.1	8.8	-	-
blebs in cpx, avg.	[5]	[9]	[7]	[9]	[8]	[7]
Ca	29.4	29.6	30.4	29.9	29.7	28.5
Mg	59.4	55.0	57.5	53.3	54.2	52.9
Fe	11.3	15.4	12.1	16.7	16.1	18.7
Al_2O_3, wt %	8.1	10.3	8.5	9.5	8.5	9.1
late stage, avg.			[1]	[5]		present
Ca	-	-	27.1	26.7	-	-
Mg	-	-	57.0	64.0	-	-
Fe	-	-	15.9	9.4	-	-
Al_2O_3, wt %	-	-	5.7	3.3	-	-

SE C.Z. Southeast Contact Zone. MgO wt.% on anhydrous basis.

[1] Range from rim of dike (about 1 cm thick) to interior.

[*n*] Number of electron microprobe analyses made. Mg # = 100Mg/(Mg + Fe).

Ca, Mg, Fe in atomic proportions.

FIG. 2. Hornblende-rich high-Mg ankaramitic dike (OU 25853, 25857, 54983) of the Greenhills Complex intruded into wehrlite at Steep Head. Pitted surface is due to weathering of olivine phenocrysts. Note chilled, phenocryst-poor margins. The rule is 30 cm in length.

rock Mg content increases correspondingly from 17.4 wt% MgO on an anhydrous basis near the margin to 28.3% in the interior. The olivine crystals tend to be euhedral, but a few are conspicuously skeletal (Fig. 4). Variation in grain size and amount of phenocrysts (Fig. 5) are similar to those in Hebridean picrite dikes illustrated by Drever & Johnston (1958). As in all the dikes here described, diopside crystals are liberally studded with oriented inclusions of pale brownish green to greenish brown hornblende. Hornblende more extensively replaces the margins and interiors of some diopside crystals, a few of which are replaced by single hornblende crystals with inclusions of clinochlore. Spinel octahedra, typically about 50 μm in diameter, are abundant. They occur as inclusions in olivine, as granules within embayments in olivine, and as euhedral phenocrysts in the central portion of this and some of the other dikes.

In an experimental study of olivine morphology, Donaldson (1976) showed that a systematic change in shape of olivine crystals from polyhedral or granular through amoeboid (hopper) to platy or feathery correlated with increasing cooling rate and degree of supercooling. He also observed that the larger the normative olivine content of a melt, the slower the cooling rate at which a given olivine morphology will develop. Thus the amoeboid shapes of some of the olivine crystals, together with the high normative olivine content of the dikes, are compatible with slower cooling and a lower degree of supercooling than would lead to similar textures in a less magnesian liquid.

As with other dikes here described, this dike contains some clearly secondary minerals. Minor alteration of plagioclase has given rise to products including montmorillonite, fine-grained white mica, zeolites, and prehnite. Tiny pools of polysynthetically twinned Mg-rich chlorite, possibly formed from glass, are common at the head of embayments in olivine. Olivine crystals in the interior of the dike, as in some of the other high-Mg dikes, are outlined in black by curving or dog-tooth lines of opaque inclusions (Fig. 3B). There is some veining of olivine by serpentine, and marginal replacement by serpentine and secondary fibrous amphibole. Fine-grained patches with inwardly radiating aggregates of amphibole are interpreted as late-stage pseudomorphs after pyroxene.

The near-monomineralic hornblende matrix of this rock might be interpreted (1) as a product of direct quenching of a hydrous melt (Yoder & Tilley 1962), (2) as a replacement of glass, or (3) as a late-stage replace-

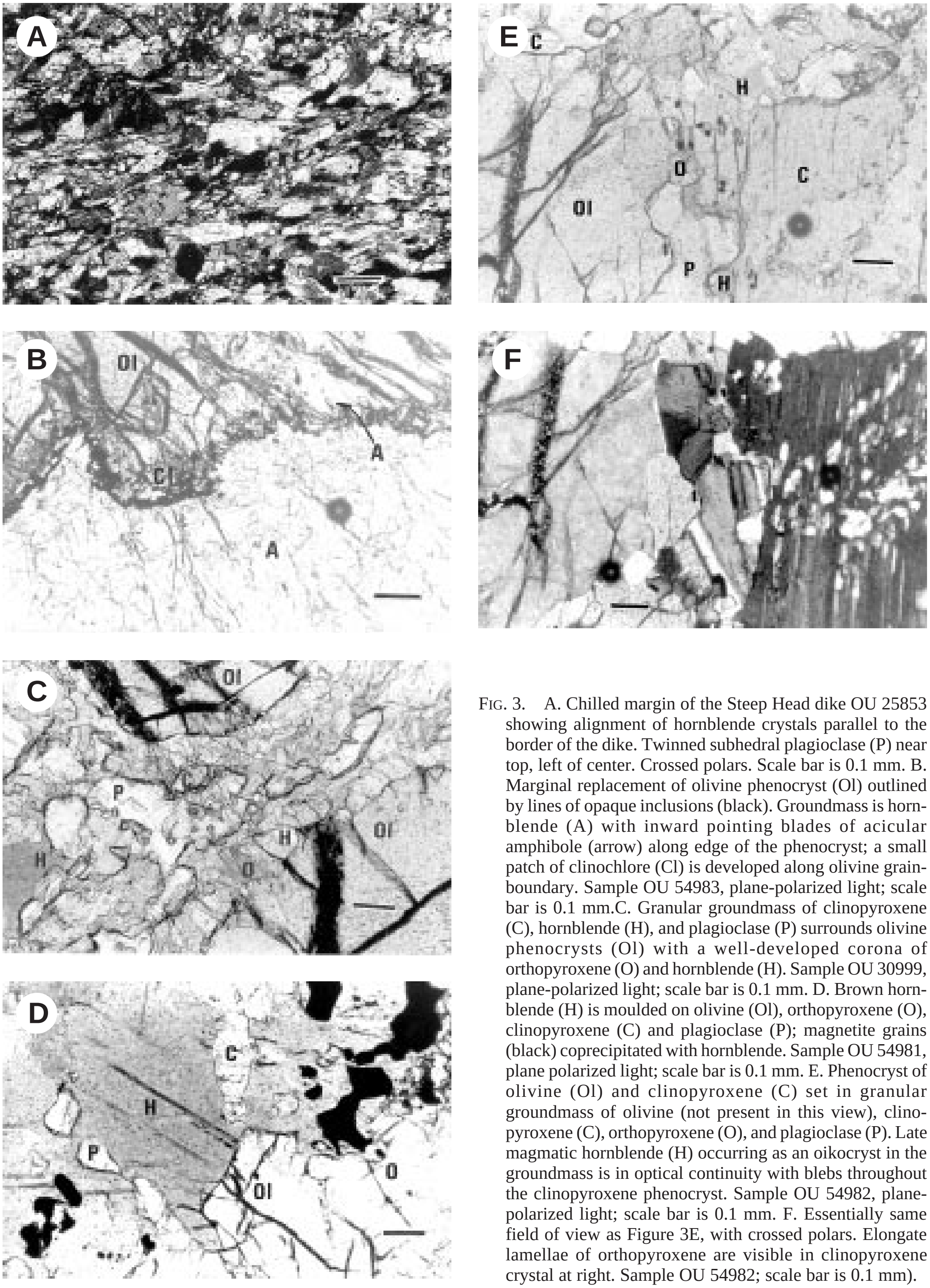

FIG. 3. A. Chilled margin of the Steep Head dike OU 25853 showing alignment of hornblende crystals parallel to the border of the dike. Twinned subhedral plagioclase (P) near top, left of center. Crossed polars. Scale bar is 0.1 mm. B. Marginal replacement of olivine phenocryst (Ol) outlined by lines of opaque inclusions (black). Groundmass is hornblende (A) with inward pointing blades of acicular amphibole (arrow) along edge of the phenocryst; a small patch of clinochlore (Cl) is developed along olivine grain-boundary. Sample OU 54983, plane-polarized light; scale bar is 0.1 mm.C. Granular groundmass of clinopyroxene (C), hornblende (H), and plagioclase (P) surrounds olivine phenocrysts (Ol) with a well-developed corona of orthopyroxene (O) and hornblende (H). Sample OU 30999, plane-polarized light; scale bar is 0.1 mm. D. Brown hornblende (H) is moulded on olivine (Ol), orthopyroxene (O), clinopyroxene (C) and plagioclase (P); magnetite grains (black) coprecipitated with hornblende. Sample OU 54981, plane polarized light; scale bar is 0.1 mm. E. Phenocryst of olivine (Ol) and clinopyroxene (C) set in granular groundmass of olivine (not present in this view), clinopyroxene (C), orthopyroxene (O), and plagioclase (P). Late magmatic hornblende (H) occurring as an oikocryst in the groundmass is in optical continuity with blebs throughout the clinopyroxene phenocryst. Sample OU 54982, plane-polarized light; scale bar is 0.1 mm. F. Essentially same field of view as Figure 3E, with crossed polars. Elongate lamellae of orthopyroxene are visible in clinopyroxene crystal at right. Sample OU 54982; scale bar is 0.1 mm).

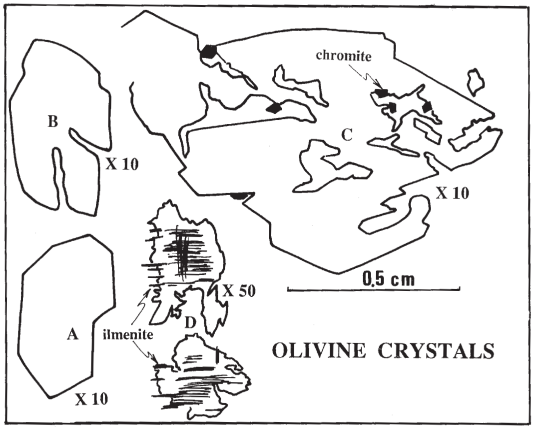

FIG. 4. Outlines of olivine crystals from high-Mg ankaramitic dikes, Greenhills Complex: A, B, and C from Steep Head dike (OU 25857) reveal a gradation from euhedral crystals to hopper-like skeletal forms (Drever & Johnston 1957). Olivine D from the chilled margin of a dike (OU 25868) contains rods of ilmenite as a result of postmagmatic replacement.

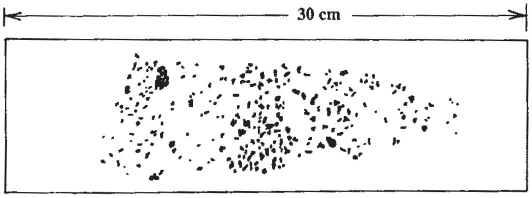

FIG. 5. Sketch showing variation in size and amount of phenocrysts (mainly olivine) across the Steep Head hornblende-rich ankaramite dike. Compare Drever & Johnston (1958, p. 479).

ment either of glass or of a fine-grained pyroxene-bearing mineral aggregate such as occurs in the quench zones of the other dikes. Recognizable grain-shapes of other minerals are not preserved, however, nor are feathery quench-textures. The interpretation remains equivocal.

Hornblende ankaramite dike 0.8 km south of Steep Head (*OU 25826*)

This dike contains phenocrysts of clinopyroxene (18%) exceeding in abundance those of olivine (7%). It also contains sparse phenocrysts of plagioclase and chromian spinel. Clinopyroxene phenocrysts are replaced along their margins and thinly overgrown by pale green hornblende, and olivine by a corona of orthopyroxene. The matrix consists of subequal amounts of brownish green hornblende (some probably primary, some as a replacement of clinopyroxene) and laths of plagioclase, 0.1–0.2 mm long. Grain size does not increase perceptibly inward from the contact.

Dikes in the southeast contact-zone, about 3 km east of Barracouta Point (*OU 30999, 44991, 44992, 44996*)

Hornblende ankaramite dike OU 44991 (26.0% MgO on a volatile-free basis), about 30 cm thick, contains 32% euhedral phenocrysts of olivine ($Fo_{85.9–80.5}$) and about 2% phenocrysts of diopside, both up to 6 mm in diameter, set in a granular groundmass of clinopyroxene, orthopyroxene, abundant pale brownish hornblende, and subordinate plagioclase. Near the edge of the dike, groundmass pyroxene and plagioclase range in diameter from 0.05 to 0.2 mm. Hornblende oikocrysts reach 0.2 mm. In the dike center, the average grain-size is 0.3 mm, except for hornblende crystals, many of which exceed 1 mm. As in most of the dikes, chromian spinel is enclosed in olivine phenocrysts and in the groundmass.

Dike OU 30999, 15 cm thick, contains 24.2% MgO on an anhydrous basis. Modal analyses indicate a barely significant increase in phenocrysts of olivine and clinopyroxene up to 6 mm in diameter, from about 20% and 8%, respectively, within two centimeters of the contact to about 25% and 12% in the dike interior. The olivine has a corona of orthopyroxene (Fig. 3C), and ranges in composition from $Fo_{90.0}$ to $Fo_{76.1}$. The groundmass is granular to micropoikilitic, with variable grain-size, 0.1–1 mm. Hornblende is the most abundant constituent, moulded on or enclosing euhedral grains of plagioclase, clinopyroxene, orthopyroxene, and minor opaque minerals.

Dike OU 44992 (not analyzed) approaches the hornblende ankaramite end-member, with copious phenocrysts of olivine and very little feldspar, but apart from oikocrysts of hornblende and some granules of clinopyroxene and relict plagioclase, the groundmass is thoroughly reconstituted to finely felted secondary amphibole, chlorite and other products of alteration.

A dike 70 cm thick with 17.0% MgO, OU 44996, contains 25% phenocrysts of clinopyroxene, about 5 mm in diameter. These are studded with blebs and larger inclusions of hornblende, which are pale brown in the interior of the host crystals and greenish nearer the edges. Here, they are in optical continuity with similarly oriented crystals of hornblende in the groundmass, which in turn are zoned from brownish centers to greenish margins. Olivine phenocrysts ($Fo_{79.9–74.2}$) are less abundant (~6%) and are mantled with orthopyroxene. The groundmass consists of orthopyroxene, clinopyroxene, and plagioclase about 0.2–1 mm across, together with opaque spinel, abundant 1–2-mm plates of hornblende, secondary actinolitic amphibole, and other minor products of alteration.

Ankaramitic hornblende microgabbronorite dikes at Steep Head (*OU 54981, 54982*)

Two dikes about 200 m south of the Steep Head hornblende ankaramite dike, at grid reference E47 434989, are less Mg-rich, less rich in hornblende, and less finely chilled than the other dikes here described. Ankaramitic hornblende microgabbronorite dike OU 54982, 15 cm thick, contains abundant phenocrysts of clinopyroxene and olivine up to 8 mm in diameter. Phenocrysts are more abundant in the interior of the dike (clinopyroxene 24%, olivine 16%), in which the groundmass is coarser grained (0.1–0.6 mm) than at the contact (0.05–0.3 mm). Olivine ($Fo_{74.1-72.4}$) is deeply corroded. The groundmass contains much orthopyroxene as well as clinopyroxene, plagioclase, brown hornblende (which occurs as small oikocrysts and locally replaces the margins of clinopyroxene phenocrysts) and granules of titaniferous magnetite, 10–50 µm in diameter (Fig. 3D). Some grains of hornblende contain dactylic titaniferous magnetite. Blebs of pale Mg-rich amphibole are well developed in the clinopyroxene phenocrysts (Figs. 3E, F).

The marginal zone of a nearby dike (OU 54981), 8 cm thick, is an aggregate of orthopyroxene, clinopyroxene, and plagioclase grains about 0.1–0.3 mm in diameter, together with finer-grained granules of magnetite and a late-stage rim of hornblende. It contains small flow-aligned phenocrysts of clinopyroxene (4%) and rarer olivine and plagioclase. The matrix in the center of the dike has a grain size of about 0.3 mm. It contains deeply corroded phenocrysts of olivine (6%, $Fo_{74.9-72.8}$) rimmed with orthopyroxene, and less abundant phenocrysts of clinopyroxene (3%), plates of plagioclase to 1 mm, and scattered oikocrysts of late-magmatic brown hornblende moulded on the other minerals. As in other rocks here described, oriented blebs of hornblende in clinopyroxene are in the same optical orientation as hornblende overgrowths on the same crystals.

In OU 54981, the concentration of Mg increases on a volatile-free basis from 10.6% MgO at the margin to 14.0% MgO in the more olivine-rich interior; OU 54982 contains 16.4% MgO in the central part. Both rocks are little altered, and show little replacement of primary magmatic minerals by amphibole.

MINERALOGY

Forsterite

Observed compositions (Tables 1, 2) of olivine in the Steep Head hornblende ankaramite dike OU 25853, 25857 range from $Fo_{92.7}$ to $Fo_{81.7}$, with zoning of up to 9% from core to rim in individual crystals. These compositions are much more magnesian than those of forsterite in the feldspathic wehrlite country-rock, $Fo_{75.2-73.6}$. Compositions of olivine in the southeastern contact zone dike OU 30999, $Fo_{90.0-76.1}$, average Fo_{82}, also contrast with those, $Fo_{86.8-84.7}$, in its country-rock, a feldspar-free wehrlite. Relative abundances of olivine and clinopyroxene in both cases are reversed in the dikes as compared with the country rocks. These facts indicate that the majority of phenocrysts are not xenocrysts

TABLE 2. REPRESENTATIVE EMPA DATA FOR OLIVINE–CHROMITE AND OLIVINE–CHROMIAN MAGNETITE PAIRS IN HIGH-Mg ANKARAMITIC DIKES, GREENHILLS COMPLEX

OU no.	25857		30999A		30999A		30999B		44996		30999		44996	
	*ol	*cr	ol	cr	ol	cr	ol	cr	*ol	*cr mt	*ol	*cr mt	*ol	*cr mt
SiO_2	41.52	0.03	40.85	1.15	40.25	1.33	39.98	1.18	40.27	-	-	-	39.57	-
TiO_2	0.01	0.26	b.d.	b.d.	b.d.	1.02	b.d.	0.60	b.d.	0.42	-	1.16	b.d.	0.11
Al_2O_3	0.07	10.80	b.d.	10.77	b.d.	11.91	b.d.	13.40	b.d.	3.52	-	4.27	b.d.	2.56
Cr_2O_3	0.15	51.54	b.d.	45.17	b.d.	31.19	b.d.	30.60	b.d.	25.62	0.02	14.1	b.d.	8.73
V_2O_3	-	-	-	-	-	-	-	-	-	0.13	-	-	-	0.19
Fe_2O_3	-	6.42	-	9.11	-	19.37	-	19.48	-	37.19	-	45.56	-	56.24
FeO	7.68	23.05	13.82	29.22	17.34	32.13	18.17	30.77	20.03	29.66	21.8	30.20	22.07	30.08
MnO	0.09	0.27	b.d.	0.50	b.d.	0.79	b.d.	0.50	0.34	0.42	-	0.33	0.19	0.17
MgO	50.54	6.73	43.73	3.31	41.47	2.21	41.30	2.97	39.57	1.06	39.5	0.97	37.02	0.61
CaO	0.26	0.06	b.d.	0.13	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	-	—	b.d.	b.d.
NiO	0.26	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.34	0.19	-	—	0.13	0.20
Total	100.58	99.24	98.40	99.36	99.06	99.95	99.45	99.50	100.55	98.21	-	96.59	98.98	98.89
Atomic proportions on basis of 4 O atoms for olivine and 32 O atoms for chromite														
Si	1.002	0.01	1.031	0.32	1.027	0.37	1.020	0.33	1.027	-	-	-	1.034	-
Ti	0.000	0.05	-	-	-	0.21	-	0.12	-	0.10	-	0.27	-	0.03
Al	0.002	3.47	-	3.53	-	3.91	-	4.36	-	1.25	-	1.54	-	0.92
Cr	0.003	11.10	-	9.92	-	6.87	-	6.68	-	6.10	-	3.41	-	2.10
V	-	-	-	-	-	-	-	-	-	0.03	-	-	-	0.05
Fe^{3+}	-	1.31	-	1.91	-	4.06	-	4.05	-	8.43	-	10.51	-	12.88
Fe^{2+}	0.155	5.25	0.292	6.79	0.370	7.48	0.388	7.11	0.427	7.47	-	7.74	0.482	7.66
Mn	0.002	0.06	-	0.12	-	0.19	-	0.12	0.007	0.11	-	0.09	0.004	0.04
Mg	1.819	2.73	1.645	1.37	1.577	0.92	1.571	1.22	1.505	0.48	-	0.44	1.442	0.28
Ca	0.007	0.02	-	0.04	-	-	-	-	-	-	-	-	-	-
Ni	0.005	0.01	-	-	--	-	-	-	0.007	0.05	-	-	0.003	0.05
Total	2.995	24.00	2.968	24.00	2.974	24.00	2.979	24.00	2.973	24.00	-	24.00	2.965	24.00
Mg #	92.1	34.2	84.9	16.8	81.0	10.7	80.4	14.6	77.9	6.0	76.4	4.8	74.9	3.5

30999A, dike edge; 30999B and 30999, dike interior. *Analysis by WDS mode, others by EDS.
FeO, Fe_2O_3, Fe^{2+}, and Fe^{3+} are calculated to conform with chromite (cr) and chromian magnetite stoichiometry.
b.d.: below detection limits. - : not analysed for, and, for atomic proportions table, below detection limits.

detached from the immediate country-rocks. Furthermore, the olivine crystals in the various dikes characteristically contain numerous small inclusions of chromite. Such inclusions are noticeably more sparse in the Greenhills dunites and wehrlites, although the dunites contain larger grains of chromite, averaging about 0.5 mm in diameter (Mossman 1973). It appears that under conditions of slow cooling in the main magma chamber, growing crystals of chromite tended not to be trapped in olivine. We conclude that the phenocrysts in the high-Mg dikes are in general not xenocrystic from the layered series. Their overall range of composition is from Fo_{92} in some crystals in the Steep Head hornblende ankaramite dike to Fo_{72} in the ankaramitic hornblende microgabbronorite dikes near Steep Head. The range in composition in the more Mg-rich dikes suggests a lack of equilibration between crystals and what must have been rapidly evolving melts during emplacement of the dikes.

Calcium contents of 0.22–0.46 wt% CaO, average 0.34%, were determined in WDS analyses of olivine cores, $Fo_{91.0–92.7}$, in the Steep Head hornblende ankaramite OU 25857. These levels imply a significantly higher temperature of crystallization than that of the rims, $Fo_{81.7}$, average 0.10% CaO, of three olivine phenocrysts in the same rock (Jurewicz & Watson 1988). In OU 30999, CaO contents of 0.02 to 0.05% in olivine $Fo_{82–85}$ are near WDS detection limits, but also imply lower temperatures. Determinations of Ca concentration in olivine $Fo_{79.9–72.4}$ in the less Mg-rich dikes are below the EDS detection limit of 0.12%.

Clinopyroxene and hornblende inclusions

Clinopyroxene in feldspathic wehrlite country-rock at Steep Head is diopside which is distinctly richer in Fe and poorer in Ca than that in feldspar-free wehrlite at the southeastern contact-zone (Table 3, Fig. 6). As in all wehrlite of the Greenhills Complex, the diopside crystals are heavily charged with oriented blebs of hornblende typically 10–100 μm long, ranging into larger replacements 0.5 mm long. Similar blebs are locally concentrated along cracks that presumably provided access for late magmatic or other fluids, but the majority are not visibly associated with such imperfections.

In the Steep Head hornblende ankaramite dike OU 25857, clinopyroxene occurs almost exclusively as diopside phenocrysts, approximately the same size as the olivine phenocrysts, although much less abundant. In the other analyzed dikes, clinopyroxene abounds in the groundmass and occurs also in varying abundance as phenocrysts. Most grains plot in the compositional field of diopside, with more than 45% of the Ca (Wo) component (Fig. 7). With increasing substitution of Fe for Ca and Mg in the more evolved rocks, they extend marginally into the field of augite. Compositions of clinopyroxene in the groundmass overlap with those of the phenocrysts. The Al, Na, and Ti contents in the clinopyroxene resemble those of arc suites such as in New Georgia (Ramsay *et al.* 1984), but are below those of typical lherzolite nodules and MORB. Chromium contents are variable, but typically are about 0.3% Cr_2O_3, as shown by WDS analyses (Table 3).

TABLE 3. REPRESENTATIVE EMPA DATA FOR CLINOPYROXENE IN WEHRLITE COUNTRY ROCK AND IN HIGH-Mg ANKARAMITIC DIKES, GREENHILLS COMPLEX

OU no.	wehrlite Steep Head 25853W		wehrlite SE contact zone 30999W		hbd ankaramite Steep Head 25857		hbd ankaramite SE contact zone 44991		hbd ankaramite SE contact zone 30999A		hbd ankaramite SE contact zone 44996		hbd gabbronorite Steep Head 54982		hbd gabbronorite Steep Head 54981	
	core	rim	core	rim	*core	*core	*core	*rim	*core	*rim	*core[2]	*core[3]	core	rim	gndms	gndms
SiO_2	53.72	53.41	54.73	54.36	52.3	51.5	55.01	53.40	52.7	52.8	54.55	53.95	53.56	53.23	54.06	52.25
Al_2O_3	1.39	1.63	0.83	0.95	2.60	2.58	0.95	2.05	2.36	1.10	2.22	2.03	1.49	1.54	1.29	1.78
TiO_2	b.d.	b.d.	b.d.	b.d.	0.33	0.23	0.05	0.15	0.13	0.12	0.23	0.25	b.d.	0.30	b.d.	0.22
FeO	3.88	5.97	2.47	2.57	4.67	6.12	3.69	4.02	4.86	6.47	6.23	5.93	5.19	7.39	5.58	6.90
MnO	b.d.	b.d.	b.d.	b.d.	0.37	0.36	0.13	0.13	0.09	0.19	0.06	0.20	b.d.	0.32	b.d.	b.d.
MgO	17.45	16.10	17.27	16.93	14.5	13.7	16.88	16.56	16.7	15.7	16.46	15.02	15.82	15.32	16.13	15.26
CaO	23.20	22.98	24.88	24.67	23.7	24.4	23.30	23.57	23.1	23.2	20.55	21.97	23.30	22.28	22.96	22.18
Na_2O	0.35	0.34	0.42	0.50	0.24	0.22	0.24	0.16	0.11	0.25	0.15	0.20	b.d.	b.d.	b.d.	b.d.
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	0.43	0.55	0.21	0.95	0.31	0.04	0.24	0.33	b.d.	0.36	b.d.	b.d.
Total	99.99	100.43	100.60	99.98	99.14	99.66	[1]100.46	100.99	100.36	99.87	100.69	99.88	99.36	100.74	100.02	98.59
Atomic proportions on basis of 6 oxygen atoms																
Si	1.961	1.958	1.980	1.980	1.941	1.922	1.993	1.938	1.928	1.957	1.976	1.980	1.976	1.957	1.981	1.956
Al	0.060	0.070	0.035	0.041	0.114	0.113	0.041	0.088	0.102	0.048	0.095	0.088	0.065	0.067	0.056	0.079
Cr	-	-	-	-	0.013	0.006	0.006	0.027	0.009	0.001	0.007	0.009	-	0.011	-	-
Ti	-	-	-	-	0.009	0.016	0.001	0.004	0.004	0.003	0.006	0.007	-	0.008	-	0.006
Fe	0.118	0.183	0.075	0.078	0.145	0.191	0.112	0.122	0.149	0.201	0.189	0.182	0.160	0.227	0.171	0.216
Mn	-	-	-	-	0.012	0.011	0.004	0.004	0.003	0.006	0.002	0.006	-	0.010	-	-
Mg	0.950	0.880	0.932	0.919	0.802	0.762	0.911	0.896	0.911	0.868	0.889	0.822	0.870	0.840	0.881	0.852
Ca	0.908	0.903	0.965	0.963	0.942	0.976	0.904	0.916	0.905	0.922	0.798	0.864	0.921	0.877	0.902	0.890
Na	0.025	0.024	0.030	0.035	0.017	0.016	0.017	0.011	0.008	0.018	0.011	0.014	-	-	-	-
Total	4.022	4.018	4.017	4.016	3.995	4.013	3.991	4.006	4.019	4.024	3.973	3.972	3.992	3.997	3.991	3.999
Atomic proportions Ca : Mg : Fe																
Ca	45.9	45.9	48.9	49.1	49.9	50.6	46.9	47.4	46.1	46.3	42.5	46.3	47.2	45.1	45.1	43.5
Mg	48.1	44.8	47.3	46.9	42.4	39.5	47.3	47.4	46.3	43.6	47.4	44.0	44.6	43.2	8.8	11.0
Fe	6.0	9.3	3.8	4.0	7.7	9.9	5.8	6.3	7.6	10.1	10.1	9.7	8.2	11.7	46.1	45.4
Mg #	88.9	82.8	92.6	92.2	84.5	80.0	89.1	88.0	86.0	81.2	82.5	81.9	84.5	78.7	83.7	79.8

*Analysis by WDS mode, others by EDS. Mg # = 100Mg/(Mg = Fe). b.d.: below detection. - : not analysed for.

[1] Includes 0.08 % NiO. [2] Area free of inclusions and visible exsolution lamellae. [3] Area with many blebs of hornblende.

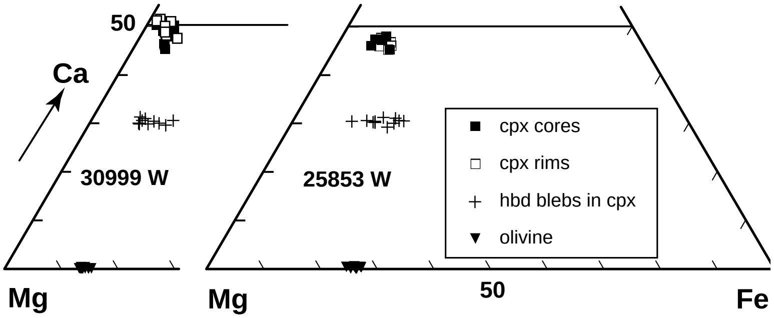

FIG. 6. Concentrations of Ca, Mg and total Fe (atomic proportions) for pyroxene, amphibole, and olivine in wehrlite country-rock next to high-Mg ankaramitic dikes, OU 30999W in the SE contact zone, and OU 25853W at Steep Head, Greenhills Complex.

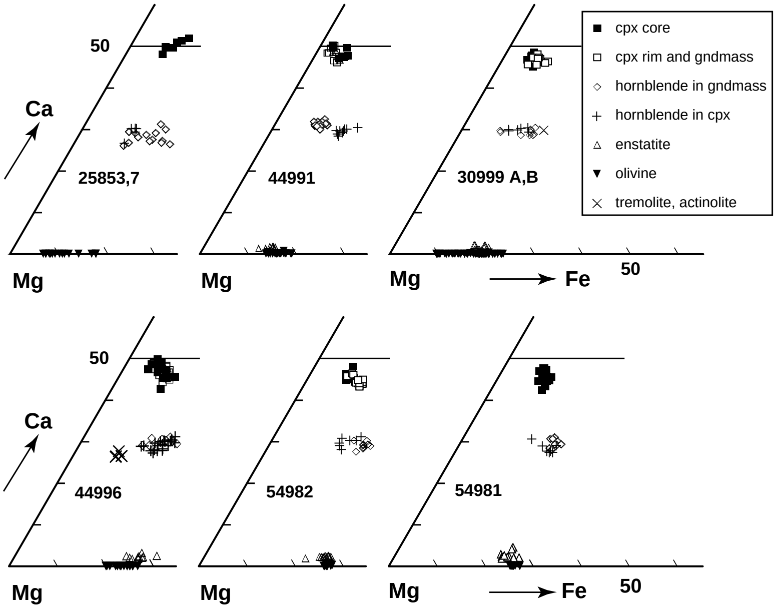

FIG. 7. Concentrations of Ca, Mg and total Fe (atomic proportions) for pyroxene, amphibole, and olivine in high-Mg ankaramitic dikes, Greenhills Complex.

In a few crystals, *e.g.*, OU 44996 and 54982, fine lamellae of orthopyroxene considered to be of exsolution origin, 1–2 μm thick, are oriented parallel to diopside {100}. Phenocrysts and less conspicuously groundmass clinopyroxenes in all analyzed dike-rocks are studded with fine lamellae and broader blebs of pale greenish brown hornblende, typically 10–100 μm long, ranging into larger replacements up to 0.5 mm long (Figs. 3E, F). Shapes are irregular, but the blebs are in optical continuity with each other and, like the finer lamellae, tend to be aligned along {100}, a plane they share with their pyroxene host. Sections perpendicular to *c* show a tendency for blebs to be bounded by the amphibole faces {110} or {010} or both. In contrast to interfaces between host diopside and orthopyroxene lamellae, which are coherent, those with amphibole blebs are in some cases ornamented with minute vacuoles. Their presence suggests the effects of a fluid phase during the replacement process.

TABLE 4. REPRESENTATIVE EMPA DATA FOR AMPHIBOLE INCLUSIONS IN CLINOPYROXENE IN COUNTRY ROCK WEHRLITE AND HIGH-Mg ANKARAMITIC DIKES, GREENHILLS COMPLEX

	25853W		30999W		25857		44991		*30999		44996		*44996	54982		*54981	
	wehrlite		wehrlite		hbd ankaramite		hbd ankaramite		hbd ankaramite		hbd ankaramite		hbd ank	hbd gabbronorite		hbd gabbronorite	
SiO_2	50.48	47.55	46.75	50.20	50.6	51.2	46.66	44.58	49.40	48.20	47.89	48.34	51.17	50.18	48.48	47.72	45.79
Al_2O_3	8.85	10.57	10.09	8.64	8.73	7.31	10.46	12.30	7.88	9.24	9.40	10.10	7.19	8.60	9.54	8.18	9.79
TiO_2	0.66	2.10	0.80	0.43	0.25	0.19	0.85	1.33	0.52	0.64	1.31	0.26	0.64	0.49	0.96	1.19	1.30
Fe_2O_3	3.09	5.89	2.92	2.21	1.85	1.12	5.51	4.37	3.93	3.68	3.94	5.99	2.38	5.83	5.36	7.18	4.79
FeO	4.07	4.14	4.01	3.71	4.63	4.84	2.99	5.58	2.08	3.45	6.23	1.70	5.56	2.31	3.72	4.31	6.43
MnO	b.d.	b.d.	b.d.	b.d.	0.09	0.07	0.08	0.12	0.06	0.09	b.d.	b.d.	0.11	b.d.	b.d.	0.13	0.13
MgO	16.85	15.34	17.54	18.37	18.0	18.3	17.23	15.23	18.40	17.40	15.68	17.54	16.86	16.61	15.89	16.08	15.09
CaO	12.72	12.32	12.73	12.77	13.0	13.0	12.27	12.53	12.70	12.80	12.39	12.23	12.02	12.19	12.48	11.86	12.05
Na_2O	b.d.	b.d.	1.66	1.45	1.06	0.89	1.94	1.97	0.92	1.19	0.83	0.98	0.97	b.d.	b.d.	1.49	1.93
K_2O	0.35	0.54	0.69	b.d.	0.34	0.23	0.49	0.13	0.13	0.02	0.64	0.57	0.16	0.19	0.30	b.d.	0.10
Cr_2O_3	1.14	0.40	0.63	0.52	0.37	0.48	0.43	0.11	1.43	0.98	b.d.	b.d.	0.48	1.92	0.92	0.14	0.19
Total	98.21	98.85	97.82	98.30	98.92	97.63	98.91	98.25	97.45	97.69	98.31	97.71	97.54	98.32	97.65	98.28	97.59
Atomic proportions																	
Si	7.044	6.671	6.647	6.997	7.033	7.191	6.567	6.374	6.952	6.810	6.804	6.793	7.218	6.993	6.851	6.784	6.611
Al	1.456	1.748	1.691	1.420	1.430	1.210	1.735	2.073	1.307	1.539	1.574	1.673	1.195	1.413	1.589	1.371	1.666
Ti	0.069	0.222	0.086	0.045	0.026	0.020	0.090	0.143	0.055	0.068	0.140	0.027	0.068	0.051	0.102	0.127	0.141
Cr	0.126	0.044	0.071	0.057	0.041	0.053	0.048	0.012	0.159	0.109	-	-	0.054	0.212	0.103	0.016	0.022
Fe^{3+}	0.325	0.622	0.312	0.232	0.193	0.119	0.584	0.471	0.417	0.392	0.421	0.634	0.253	0.612	0.570	0.768	0.520
Fe^{2+}	0.476	0.486	0.477	0.433	0.538	0.568	0.352	0.667	0.245	0.408	0.741	0.199	0.656	0.269	0.440	0.512	0.777
Mn	-	-	-	-	0.011	0.008	0.010	0.015	0.007	0.011	-	-	0.013	-	-	0.016	0.016
Mg	3.504	3.207	3.717	3.816	3.728	3.830	3.614	3.245	3.859	3.664	3.320	3.673	3.544	3.450	3.346	3.407	3.247
Ca	1.902	1.852	1.939	1.907	1.936	1.956	1.850	1.920	1.915	1.938	1.886	1.842	1.817	1.820	1.890	1.807	1.864
Na	-	-	0.458	0.392	0.286	0.242	0.529	0.546	0.251	0.326	0.229	0.267	0.265	-	-	0.411	0.540
K	0.062	0.097	0.125	-	0.060	0.041	0.088	0.024	0.023	0.004	0.116	0.102	0.029	0.034	0.054	-	0.018
Total	14.964	14.949	15.523	15.299	15.282	15.238	15.467	15.490	15.190	15.269	15.231	15.210	15.112	14.854	14.945	15.219	15.422
Atomic proportions Ca : Mg : Fe																	
Ca	30.6	30.0	30.1	29.9	30.3	30.2	28.9	30.5	29.8	30.3	29.6	29.0	29.0	29.6	30.3	27.8	29.1
Mg:	56.5	52.0	57.7	59.7	58.3	59.2	56.5	51.5	60.0	57.2	52.1	57.9	56.5	56.1	53.6	52.5	50.7
Fe:	12.9	18.0	12.3	10.4	11.4	10.6	14.6	18.0	10.3	12.5	18.2	13.1	14.5	14.3	16.2	19.7	20.2
Name	maghbd	maghbd	edenite	maghbd	maghbd	maghbd	edenite	pargasite	maghbd	maghbd	maghbd	maghbd	maghbd	maghbd	maghbd	maghbd	edenite

*Analysis by WDS mode, others by EDS. Names according to Leake (1997). maghbd = magnesiohornblende. b.d.: below detection. - : not analysed for.

Fe^{2+}, Fe^{3+}, atomic proportions, and FeO, Fe_2O_3 calculated on the basis of 23 O atoms and 13 tetrahedral plus octahedral cations.

Most of the amphibole blebs (Tables 1, 4) consist of magnesiohornblende, but they extend into the composition field of edenite and marginally into that of pargasite as defined by Leake *et al.* (1997). As shown in Figure 8, Mg/Fe values in the blebs other than those in OU 44991 tend to be higher than those of groundmass hornblende, and Ca/(Mg + Fe^{2+}) in the hornblende is, as always, much lower than in the host clinopyroxene. The Cr contents of the blebs, although variable, tend to be substantially higher than those of either the diopside hosts or the groundmass hornblende crystals. Thus in OU 30999, seven blebs of hornblende in clinopyroxene average 1.03% Cr_2O_3 ($\sigma = 0.22$), 13 host phenocrysts of diopside average 0.30% Cr_2O_3 ($\sigma = 0.13$), and six hornblende grains in the groundmass average only 0.27% Cr_2O_3 ($\sigma = 0.20$). The blebs thus have not crystallized in equilibrium with the late-stage melts; we suggest that the host crystals of diopside are the source of the high Cr, this being partitioned preferentially into the hornblende blebs. On compositional and textural grounds, the hornblende blebs in diopside are interpreted as being essentially synchronous with the brown or brownish green crystals of hornblende in the groundmass, themselves interpreted as late magmatic. Even if the blebs were postmagmatic, their notably high aluminum contents (^{IV}Al in excess of 1 atom per formula unit, *apfu*) indicate formation at temperatures substantially higher than those at which clearly postmagmatic actinolitic amphibole crystallized in some groundmasses and pseudomorphs. Exsolution of a Ca-poor component from diopside could be expected to proceed at the temperatures of crystallization of such hornblende (*cf.* Nabelek *et al.* 1987). Penetration by magmatic fluid components along defects in the diopside crystals would allow the necessary introduction of (OH), K, Al, and probably some Na and Ti for the hornblende-forming reactions. Partitioning of Ca between diopside and hornblende blebs was accompanied by a net export of Ca. Formation of the hornblende blebs may have contributed to an exsolution process by what might be referred to *as reactive exsolution.* By this, formation of the blebs resulted in an enhanced Ca content relative to Mg and Fe in the remaining clinopyroxene, much as occurs when enstatite or pigeonite exsolves from augite or diopside where P(H_2O) is low. The electron-microprobe data plotted in Figure 8 may accordingly overestimate the Ca content of the pyroxene grains at the time of initial magmatic crystallization.

Late-magmatic hornblende and bleb-like inclusions of hornblende in clinopyroxene are typical of mafic and ultramafic intrusions crystallizing under conditions of high P(H_2O) in inferred arc environments, as in the Duke Island and other bodies in southeastern Alaska (*e.g.*, Irvine 1967), the Smartville Complex of northern California (Beard & Day 1988) and innumerable other examples. Reactive exsolution in such cases may be as important as later metamorphic uralitization, with which process it could easily be confused.

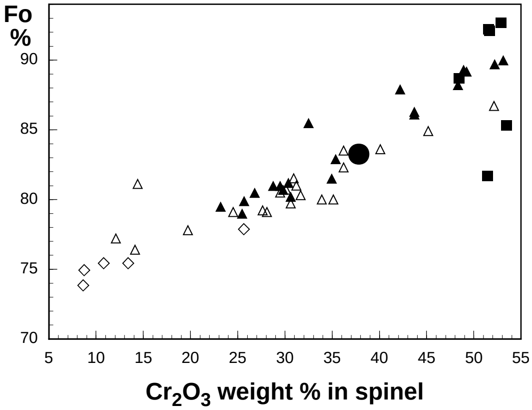

FIG. 8. Relationship between Cr content of spinel inclusions and Fo content adjacent to enclosing olivine, Greenhills high-Mg ankaramitic dikes. Squares: OU 25857; solid triangles: OU 30999 dike center; open triangles: OU 30999 dike margin; diamond: OU 44996; solid circle: average for all analyzed olivine and chromite, OU 44991.

The average composition (Table 1) of groundmass diopside in OU 54981 plots close to the expected position of an 860°C isotherm for equilibration with enstatite (Nabelek *et al.* 1987, Fig. 3), whereas the corresponding averages for OU 44991, 30999, 44996, and 54982 plot close to the expected positions of 750°–800°C isotherms. However, as discussed above, these compositions may have been affected by continuing exsolution with loss of Ca relative to Mg and Fe, and equilibration with the hornblende inclusions.

Enstatite

Enstatite (Tables 1, 5, Fig. 7) occurs as a granular reaction-rim on olivine in all analyzed rocks except OU 25857 and as somewhat larger grains in the groundmasses. In most of the dikes, Fe/Mg values are in the range of those of the coexisting forsterite crystals, extending to still lower Fe/Mg, but in OU 44996 a groundmass fractionation trend continues to higher Fe/Mg values. The Ca contents are low, with average 100Ca/(Mg + Fe) for groundmass enstatite (Table 1) ranging from 1.2 in the most Mg-rich dike analyzed that contains enstatite, OU 44991, to 2.5% in the least Mg-rich, OU 54981. For OU 54981, the average composition plots on the 900°C isotherm of Nabelek *et al.* (1987) for equilibration with diopside, whereas the others would plot close to the expected position of an 800°C isotherm. These figures give only crude estimates of temperature, because of analytical error in small amounts of Ca, and the close spacing of the calculated isotherms.

TABLE 5. REPRESENTATIVE EMPA DATA FOR ORTHOPYROXENE IN ANKARAMITIC HIGH-Mg DIKES, GREENHILLS COMPLEX

OU no.	44991		30999A	30999B		44996		54982		54981	
	gndms	gndms	*on ol	*gndms	*on ol	gndms	gndms	*in plag	gndms	gndms	gndms
SiO_2	57.78	56.96	55.3	55.1	56.2	55.26	55.25	55.04	54.89	55.06	55.73
Al_2O_3	0.76	0.95	1.15	1.02	1.17	1.89	1.14	1.30	1.34	0.87	1.24
TiO_2	b.d.	b.d.	0.05	0.06	0.22	b.d.	b.d.	0.26	b.d.	b.d.	0.20
FeO	8.14	10.41	13.6	12.8	11.7	15.57	17.37	15.32	16.24	16.34	14.52
MnO	b.d.	b.d.	0.33	0.33	0.28	b.d.	b.d.	0.27	0.32	0.36	0.32
MgO	33.01	32.04	29.4	29.5	30.4	27.03	26.03	26.72	26.76	26.88	27.59
CaO	0.66	0.64	0.67	0.87	0.67	0.97	1.06	1.12	1.10	0.96	1.10
Cr_2O_3	b.d.	b.d.	0.05	0.03	0.00	b.d.	b.d.	0.20	b.d.	b.d.	b.d.
Total	100.36	101.00	100.55	99.71	100.64	100.72	100.85	100.24	100.65	100.47	100.70
Atomic proportions on basis of 6 oxygen atoms											
Si	1.997	1.978	1.964	1.968	1.974	1.971	1.985	1.977	1.972	1.983	1.983
Al	0.031	0.039	0.048	0.043	0.048	0.079	0.048	0.055	0.056	0.026	0.052
Cr	-	-	0.001	0.001	0.000	-	-	0.006	-	-	-
Ti	-	-	0.001	0.002	0.006	-	-	0.007	-	-	0.005
Fe	0.235	0.302	0.404	0.382	0.344	0.464	0.522	0.460	0.488	0.181	0.432
Mn	-	-	0.010	0.010	0.008	-	-	0.008	0.010	-	0.010
Mg	1.700	1.659	1.556	1.570	1.591	1.437	1.394	1.430	1.433	0.872	1.463
Ca	0.025	0.023	0.025	0.033	0.025	0.037	0.041	0.043	0.042	0.942	0.042
Total	3.988	4.001	4.009	4.009	3.996	3.988	3.990	3.986	4.001	4.004	3.987
Atomic proportions Ca : Mg : Fe											
Ca	1.2	1.2	1.3	1.7	1.3	1.9	2.1	2.2	2.2	1.9	2.2
Mg	86.8	83.6	78.4	79.1	81.2	74.1	71.1	74.0	73.0	73.2	75.5
Fe	12.0	15.2	20.3	19.3	17.5	24.0	26.7	23.8	24.8	25.0	22.3
Mg #	87.8	84.6	79.4	80.4	82.2	75.6	72.8	75.7	74.6	74.6	77.2

*Analysis by WDS mode, others by EDS. b.d.: below detection. - : not analysed for.

Groundmass and oikocrystic amphibole

Pigeonite has not been found in any of the dikes. Instead, the crystallization of groundmass enstatite and diopside in the dikes other than OU 25853 was followed by that of amphibole. Pale brownish green to greenish brown in color, this amphibole ranges in composition (Tables 1, 6) from predominant magnesiohornblende into the field of tschermakite (Leake *et al.* 1997). Similar hornblende forms the almost monomineralic groundmass of the Steep Head hornblende ankaramite dike OU 25853/25857. Electron-microprobe traverses normal to the *c* axes of hornblende in this body show that the grains become more iron-rich from cores to outer zones without obvious change in color, but in OU 44996 outer greenish zones not only have consistently lower Al contents, they also have higher Mg/Fe, a ratio that is still higher in clearly metamorphic actinolitic amphibole in the same rock (Fig. 8). With this exception, Fe/Mg values in the groundmass amphibole crystals and larger oikocrysts are in general greater than in clinopyroxene of the same rocks (Fig. 8), continuing a trend of magmatic fractionation. Reversal of the trend in the latest magmatic amphiboles is attributed to increasing $f(O_2)$ and crystallization of magnetite.

The average Al content of 60 analyzed possible quench and brownish groundmass hornblende grains in all rocks is 11.22% Al_2O_3, that of 17 greenish outer zones is 7.44% Al_2O_3. Titanium contents are highly variable. In the chilled margin OU 25853 of the Steep Head hornblende ankaramite dike, analyses show 0.14–1.55% TiO_2, and from the interior of the dike, 0.10–1.41%. A similar situation prevails in OU 30999, with an overall range of 0.59–2.12% TiO_2. In both cases the average recorded value in the dike margins is greater than in the dike centers. According to Helz (1973), the Ti content of hornblende tends to increase with increasing temperature of equilibration, and it should decrease with increasing $f(O_2)$ accompanied by a fall in ^{IV}Al, an effect not shown in the present case. Apart from indicating a lack of equilibrium, the observed TiO_2 figures are not adequately explained. In OU 44996, however, a drop from average 1.31% TiO_2 ($\sigma = 0.3$) in 11 compositions of brownish high-Al hornblende (Table 2) to mostly below-EDS detection limits of about 0.2% in greenish outer zones with lower Al contents, is clearly compatible with declining temperature and increasing $f(O_2)$ in the latest magmatic and possibly postmagmatic stages.

Plagioclase

Highly calcic plagioclase occurs across the width of the various dikes except the Steep Head hornblende ankaramite dike, in which it is confined to the selvedges. The modal proportion approaches 9–12% at the outer border of this dike, decreasing to nil inward over the 5-cm thickness of the selvedge. The grain size here is in tenths of a millimeter at most, the composition is anorthite $An_{99–94}$ (Table 1), and twinning is according to Carlsbad and albite laws. In the other dikes, calcic plagioclase with an overall range $An_{95–75}$ accompanies diopside, enstatite, and later hornblende in the groundmass.

TABLE 6. REPRESENTATIVE EMPA DATA FOR GROUNDMASS AMPHIBOLE IN HIGH-Mg ANKARAMITIC DIKES, GREENHILLS COMPLEX

	*25853		*25857		44991		*30999A		*30999B		44996		44996		54982		54981	
	margin of dike		interior of dike				dike margin		interior of dike		interior of dike		interior of dike		oikocrysts		oikocrysts	
	pale green		pale green		pale brown		pale	brownish	brownish	on	platy crystals		later stage		brown	brown	brown	brown
			xtal core	small gn			brown	green	green	olivine	brown	brown	green	green				
SiO_2	50.1	49.8	47.0	51.5	48.82	48.45	44.9	45.8	46.0	46.4	47.62	46.60	51.41	53.56	45.20	44.32	46.80	45.95
Al_2O_3	7.22	5.93	11.9	5.71	11.53	11.58	11.0	10.9	11.5	11.0	10.59	10.57	8.05	6.25	11.20	11.18	11.58	11.89
TiO_2	1.03	0.65	0.10	1.21	0.60	1.35	1.90	1.75	0.55	0.57	1.17	1.38	b.d.	b.d.	1.30	2.14	2.12	1.88
Fe_2O_3	4.93	3.42	6.44	6.48	4.17	4.36	6.24	3.62	3.78	4.83	5.22	6.85	4.76	4.12	6.22	5.19	6.15	9.93
FeO	4.22	5.80	0.00	3.03	2.04	1.27	2.38	4.60	4.75	0.15	4.57	3.74	4.19	3.84	4.67	5.99	4.05	1.72
MnO	0.23	0.19	0.04	0.19	b.d.	b.d.	0.11	0.09	0.10	0.03	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	16.8	17.0	18.7	17.8	17.19	17.77	16.8	16.7	16.2	18.8	16.06	15.48	16.81	18.02	14.98	14.80	15.14	14.88
CaO	11.4	12.6	12.7	11.8	12.97	13.13	11.9	12.6	12.6	12.5	12.76	12.62	12.64	12.61	11.55	11.91	12.63	11.94
Na_2O	1.21	0.69	1.87	0.68	b.d.	b.d.	1.85	1.69	1.83	1.80	0.52	b.d.	b.d.	b.d.	1.80	2.07	b.d.	b.d.
K_2O	0.45	0.31	0.37	0.33	0.40	0.41	0.62	0.54	0.36	0.46	0.63	0.59	0.12	0.12	0.34	0.22	0.29	0.48
Cr_2O_3	-	0.15	-	0.01	b.d.	b.d.	0.05	-	0.51	0.47	b.d.	b.d.	b.d.	b.d.	b.d.	0.42	b.d.	0.37
Total	97.59	96.54	99.12	98.09	97.72	98.32	97.75	98.29	98.18	97.01	99.14	97.82	97.98	98.52	97.26	98.24	98.77	99.04
Atomic proportions																		
Si	7.090	7.161	6.510	7.180	6.801	6.705	6.403	6.507	6.542	6.558	6.680	6.625	7.184	7.400	6.508	6.373	6.568	6.440
Al	1.204	1.005	1.943	0.938	1.893	1.889	1.849	1.825	1.928	1.833	1.751	1.771	1.326	1.018	1.901	1.895	1.916	1.964
Ti	0.110	0.070	0.010	0.127	0.063	0.141	0.204	0.187	0.059	0.061	0.123	0.148	-	-	0.141	0.231	0.224	0.198
Cr	-	0.017	-	0.001	-	-	0.006	-	0.057	0.053	-	-	-	-	-	0.048	-	0.041
Fe^{3+}	0.525	0.383	0.672	0.680	0.437	0.454	0.670	0.387	0.405	0.514	0.551	0.733	0.500	0.428	0.674	0.562	0.650	1.048
Fe^{2+}	0.500	0.697	0.000	0.354	0.238	0.147	0.284	0.547	0.565	0.018	0.536	0.444	0.489	0.444	0.563	0.720	0.476	0.202
Mn	0.028	0.023	0.005	0.022	-	-	0.013	0.011	0.012	0.004	-	-	-	-	-	-	-	-
Mg	3.543	3.643	3.860	3.698	3.569	3.665	3.571	3.536	3.433	3.960	3.358	3.280	3.501	3.710	3.214	3.171	3.167	3.108
Ca	1.729	1.941	1.885	1.763	1.936	1.947	1.818	1.918	1.920	1.893	1.918	1.922	1.893	1.867	1.782	1.835	1.899	1.793
Na	0.332	0.192	0.502	0.184	-	-	0.512	0.466	0.505	0.493	0.141	-	-	-	0.503	0.577	-	-
K	0.081	0.057	0.065	0.059	0.071	0.072	0.113	0.098	0.065	0.083	0.113	0.107	0.021	0.021	0.062	0.040	0.052	0.086
Total	15.142	15.189	15.452	15.006	15.007	15.019	15.443	15.482	15.490	15.469	15.172	15.029	14.914	14.888	15.348	15.452	14.951	14.880
Atomic proportions Ca : Mg : Fe																		
Ca	27.5	29.1	29.4	27.1	31.3	31.3	28.7	30.0	30.4	29.6	30.1	30.1	29.6	28.9	28.6	29.2	30.7	29.2
Mg	56.3	54.7	60.2	56.9	57.8	59.0	56.3	55.4	54.3	62.0	52.8	51.4	54.8	57.5	51.6	50.4	51.1	50.5
Fe	16.3	16.2	10.5	27.1	10.9	9.7	15.0	14.6	15.3	8.3	17.1	18.5	15.5	13.5	19.8	20.4	18.2	20.3
name	maghbd	maghbd	edenite	maghbd	maghbd	maghbd	pargasite	edenite	edenite	edenite	maghbd	maghbd	maghbd	a.maghbd	edenite	pargasite	maghbd	tscherm

*Analysis by WDS mode, others by EDS. **b.d.: below detection. - : not analysed for.**

Fe^{2+}, Fe^{3+}, atomic proportions, and FeO, Fe_2O_3 calculated on the basis of 23 O atoms and 13 tetrahedral plus octahedral cations.

Names according to Leake (1997). maghbd = magnesiohornblende; tscherm= tschermakite; a.maghbd = (actinolitic) magnesiohornblende.

Chromian spinel, magnetite, and ilmenite

Chromium-rich spinel (Tables 2, 7) occurs as inclusions in phenocrysts of olivine and, to a lesser extent, in phenocrysts of diopside in all the dikes, as well as in the matrix, in which magnetite may also be present. Grain size is typically 20–200 μm, some grains reaching 1 mm. The Cr content of the spinel inclusions correlates closely with the Fo content of the immediately enclosing olivine (Fig. 8). The extent of zoning is slight; the core to rim composition of a typical inclusion in olivine in OU 30999, for example, varies from 35 to 34 wt% Cr_2O_3 only. These facts indicate that the melts were progressively impoverished in Cr during the crystallization of olivine, and furthermore that grains tended to be trapped shortly after growth, although some were preserved in groundmass of more evolved composition.

Compositions range from chromite with nearly 54 wt% Cr_2O_3, through less Cr-rich chromite and chromian magnetite to essentially Cr-free magnetite, the less Cr-rich examples being characteristic of the less Mg-rich dikes OU 44996, 54982, and 54981 and of the groundmass of the more Mg-rich dikes, such as OU 30999. While olivine, diopside, and chromite were the only phases crystallizing, the Al contents of the melts would have been enhanced, and chromite followed a trend of falling Cr and increasing Al (Fig. 9). Peak Al contents in chromite of about 17 wt% Al_2O_3 were reached with about 37% Cr_2O_3. Subsequently, Cr and Al both decline in a series ranging through chromian magnetite to magnetite with simultaneous crystallization of plagioclase and hornblende and increasing substitution by Fe^{3+}.

In keeping with chromian spinel from other volcanic arcs, the Greenhills suite is low in Ti. In many cases the Ti content is even lower than in field AA (Fig. 10) shown by Arai (1992) for arc-derived chromium-rich spinel on a plot of TiO_2 *versus* Fe#, *i.e.*, 100 $Fe^{3+}/(Cr + Al + Fe^{3+})$. Ti contents are much lower than in field II (Fig. 10) representing intraplate settings, and generally lower than in the small field for MORB rocks shown by Arai (1992) to overlap fields AA and II, with Fe# less than 10 and Ti less than 1% TiO_2. With increasing Fe#, Ti increases in the spinels of the Greenhills dikes (Fig. 10). The substantial scatter is probably in part the result of incipient exsolution of ilmenite, lamellae of which, only 2–4 μm thick, have been observed in groundmass magnetite in the interior of dike OU 30999 (Table 7). Compositions of coexisting ilmenite – magnetite indicate partial re-equilibration under postmagmatic conditions at about 645°C, $\Delta\log f(O_2) = 2.7$ relative to the FMQ buffer (Frost *et al.* 1988).

It can be shown that on a plot of Cr#, $100Cr/(Cr + Al)$ *versus* Mg#, $100/(Mg + Fe^{2+})$, the Greenhills spinel-group minerals fall in a broad field shown by Kepezhinskas *et al.* (1993) for various subduction-related suites, including plutons of the North Kamchatka arc and ankaramites from West Epi, Vanuatu.

WHOLE-ROCK GEOCHEMISTRY AND DISCUSSION

Results of whole-rock major and minor element analyses of the dike rocks are presented in Table 8. Particularly striking are the high Mg contents, ranging from 28.3 wt% MgO on an anhydrous basis in the central zone (OU 25857) of one Steep Head dike to 10.6% MgO in the marginal zone (OU 54981a) of another.

TABLE 7. REPRESENTATIVE EMPA DATA FOR GROUNDMASS CHROMITE, CHROMIAN MAGNETITE, Cr-POOR MAGNETITE, AND 4-μm ILMENITE EXSOLUTION LAMELLAE, HIGH-Mg ANKARAMITIC DIKES, GREENHILLS COMPLEX

OU no.	44991	*30999	*30999	44996	54982	54981	*30999	*30999
							host mt	il in mt
SiO_2	0.95	0.13	0.16		1.34	1.36	0.07	0.16
TiO_2	0.59	2.11	4.31	0.89	2.34	2.82	2.39	48.20
Al_2O_3	17.58	2.62	2.05	1.69	2.42	2.71	1.74	0.03
Cr_2O_3	36.88	7.39	6.67	6.73	4.78	3.48	0.29	b.d.
V_2O_3	-	1.39	0.80	-	-	-	0.92	1.74
Fe_2O_3	10.79	52.57	50.07	58.58	54.16	54.40	61.39	9.14
FeO	29.34	31.99	33.54	31.19	34.68	34.12	32.60	35.80
MnO	b.d.	0.22	0.31	0.08	b.d.	0.39	0.10	1.04
MgO	4.86	0.59	0.72	0.51	0.36	1.03	0.48	3.69
CaO	b.d.	0.25	0.27	b.d.	0.33	b.d.	0.13	0.11
NiO	b.d.	0.19	0.17	0.16	b.d.	b.d.	0.18	b.d.
Total	100.99	99.45	99.07	99.83	100.41	100.31	100.29	99.91
Atomic proportions on basis of 24 cations for spinels and 2 for ilmenite								
Si	0.25	0.04	0.05	-	0.40	0.40	0.02	0.004
Ti	0.12	0.48	0.98	0.20	0.53	0.63	0.54	0.894
Al	5.45	0.93	0.73	0.60	0.85	0.95	0.62	0.001
Cr	7.68	1.76	1.60	1.61	1.13	0.82	0.07	-
V	-	0.34	0.19	-	-	-	0.22	0.034
Fe^{3+}	2.14	11.93	11.42	13.38	12.17	12.17	13.97	0.170
Fe^{2+}	6.46	8.07	8.50	7.91	8.66	8.48	8.24	0.737
Mn	-	0.06	0.08	0.02	-	0.10	0.03	0.022
Mg	1.91	0.27	0.33	0.23	0.16	0.46	0.21	0.136
Ca	-	0.08	0.09	-	0.11	-	0.04	0.003
Ni	-	0.05	0.04	0.04	-	-	0.04	-
							usp 7.3	ilm 89.8
							mt 92.8	hem 10.2

*Analysis by WDS mode, others by EDS.

FeO, Fe_2O_3, and atomic proportions are calculated on the basis of 24 cations and 32 O atoms for spinels, and 2 cations and 3 O atoms for ilmenite.

b.d.: below detection limits. - : not analysed for, or for atomic proportions table, below detection limits.

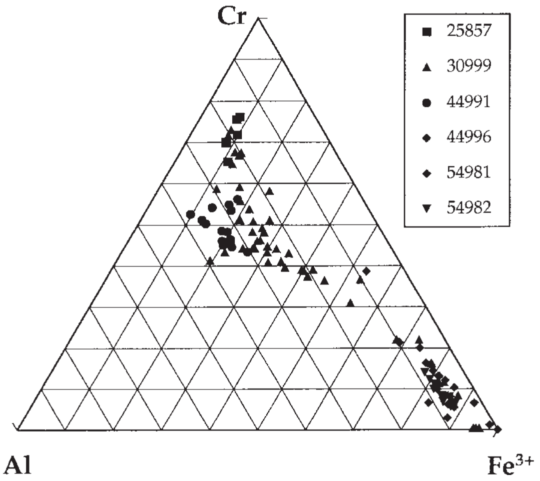

FIG. 9. Proportions of Fe^{3+}, Al and Cr in chromite, chromian magnetite, and magnetite, Greenhills high-Mg ankaramitic dikes.

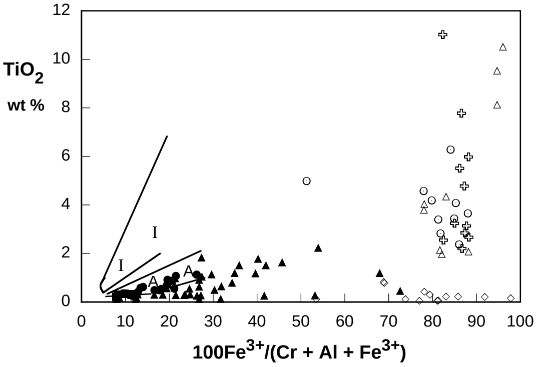

FIG. 10. Relationship between TiO_2 (weight %) and Fe# = $100Fe^{3+}/(Cr + Al + Fe^{3+})$ for chromite and chromian magnetite in Greenhills high-Mg ankaramitic dikes (symbols as for Fig. 9) compared with fields for chromian spinel in intraplate magmas (I–I) and arc magmas (A–A) according to Arai (1992).

Relationship to arc-ankaramites, komatiites, and picrites

The significance of any similarity in mode of occurrence of the high-Mg dikes with lamprophyres as normally understood is negated by extremely low alkali contents, especially K, and their general mineralogy.

The mineralogy of the dikes closely matches that of the enclosing wehrlites, as shown, for example, by comparison of mafic minerals of dike OU 44991 (Fig. 7) with those of wehrlite 30999W (Fig. 6), and dikes OU 54981, 54982 (Fig. 7) with those of wehrlite 25853W (Fig. 6). Both the mafic minerals and the highly calcic plagioclase in the dikes match those found in the layered series of the Greenhills Complex, which ranges from dunite, through wehrlite, eucritic gabbro and allivalite, to hornblende gabbronorite. We conclude that the dikes represent liquids in various stages of evolution that have evolved in, or replenished, the magma chamber represented by the layered series.

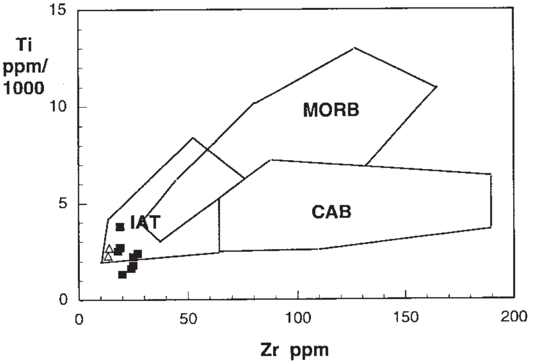

FIG. 11. Ti–Zr plot for Greenhills high-Mg dikes (filled squares) and arc-ankaramites from Epi, Vanuatu (Barsdell & Berry 1990) (open triangles), with fields of island-arc low-potassium tholeiites (IAT), mid-ocean ridge basalt (MORB), and calc-alkaline basalts (CAB) after Pearce & Cann (1973).

As discussed above, geochemical features of the clinopyroxene and chromian spinel in the dikes are typical of other subduction-related suites. This affinity is also indicated in whole-rock Ti–Zr and V–Ti diagrams (Figs. 11, 12), in which the Greenhills rocks plot either within the fields outlined by Pearce & Cann (1973) and Shervais (1982) for island-arc low-potassium tholeiites sampled by them, or narrowly extend those fields to more extreme compositions. It is noteworthy that arc-ankaramites from the island of Epi in Vanuatu (*e.g.*, Table 9, no. 2) described by Barsdell (1988), Barsdell & Berry (1990), and Della-Pasqua & Varne (1997) have compositions very similar to the less extreme Mg-rich Greenhills dikes and occupy similar fields in Figures 11 and 12, and also in Ni–MgO and Cr–MgO plots, discussed below.

The high Mg contents invite comparison with komatiites and certain picrites as well as with ankaramites and clinopyroxene-rich gabbros of island-arc settings such as those of Vanuatu and of Smartville, California (Beard & Day 1988). Low *REE* abundances (Table 10, Fig. 13A) in the high-Mg Greenhills dikes, less than twice that of primitive mantle of Sun &

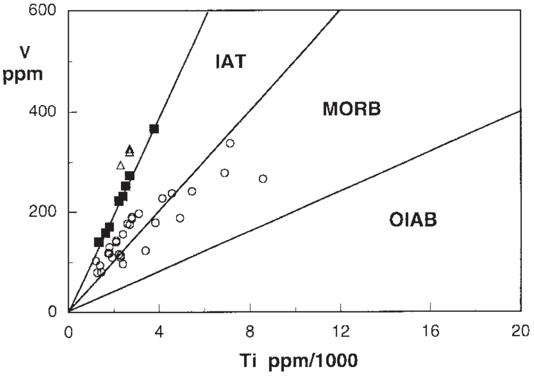

FIG. 12. V–Ti plot for Greenhills high-Mg dikes and arc-ankaramites from Epi, Vanuatu (Barsdell & Berry 1990), with fields of island-arc tholeiites (IAT), mid-ocean ridge basalt (MORB) and ocean-island and alkaline basalts (OIAB), after Shervais (1982). The symbols are as in Figure 11. Also shown as open circles: representative peridotitic and basaltic komatiites from Onverwacht Group, South Africa (Jahn *et al.* 1982) and from Belingwe, Rhodesia, Western Australia, and Ontario, Canada (Nesbitt *et al.* 1979, Nisbet *et al.* 1987).

TABLE 8. ANALYTICAL DATA FOR HIGH-Mg ARC ANKARAMITIC DIKES, GREENHILLS COMPLEX

OU No.	25857/25853		44991	30999	44996	54982	54981/54981a	
	centre	margin	interior	interior	interior	interior	centre	margin
SiO_2	43.84	47.69	45.93	46.20	48.03	47.36	47.93	46.73
TiO_2	0.22	0.37	0.27	0.30	0.40	0.42	0.45	0.63
Al_2O_3	5.21	8.95	5.83	6.70	9.60	10.12	11.48	14.27
$Fe_2O_3^*$	10.04	9.40	10.89	10.71	10.72	11.59	11.55	11.24
MnO	0.18	0.15	0.19	0.19	0.19	0.21	0.21	0.18
MgO	26.79	16.98	25.67	23.89	16.84	16.36	13.97	10.56
CaO	7.58	12.56	9.29	9.77	12.18	12.81	13.33	15.10
Na_2O	0.53	1.05	0.61	0.77	0.95	0.67	0.76	0.88
K_2O	0.14	0.32	0.10	0.15	0.20	0.03	0.04	0.03
P_2O_5	0.03	0.04	0.03	0.03	0.04	0.02	0.02	0.02
L.O.I.	4.64	0.99	0.58	0.75	0.49	0.21	0.35	0.51
Total	99.20	98.50	99.39	99.46	99.64	99.80	100.09	100.15
MgO, anhydrous	28.3	17.4	26.0	24.2	17.0	16.4	14.0	10.6
100Mg/(Mg+0.8Fe)	87	82	85	85	80	78	75	70
CaO/Al_2O_3	1.45	1.40	1.59	1.46	1.27	1.27	1.16	1.06
CIPW Norm components, normalized to 100%, volatile-free, $Fe_2O_3/FeO = 0.2$								
di	22.02	35.76	26.77	27.56	31.65	31.72	31.18	32.80
hy	14.68	10.53	12.46	10.98	15.69	16.80	19.21	9.32
ol	42.55	20.20	38.69	36.11	18.27	17.25	11.22	11.04
Ol (mol)	Fo_{87}	Fo_{83}	Fo_{86}	Fo_{85}	Fo_{81}	Fo_{79}	Fo_{76}	Fo_{72}
ppm								
Sr	44	99	70	81	152	132	155	200
Rb	*1.04	*1.02	1	2	2	b.d.	b.d.	b.d.
Ba	31	43	23	40	39	9	20	11
Th	*0.35	*0.30	b.d.	*0.15	b.d.	b.d.	b.d.	b.d.
U	b.d.	1	1	1	1	b.d.	1	2
Ta	*0.04	*0.05	-	*0.1	-	-	-	-
Nb	*0.41	*0.62	-	-	-	-	-	-
Zr	20	25	24	25	27	18	19	19
Hf	*0.45	*0.57	-	*0.49	-	-	-	-
Y	4	8	6	7	9	8	10	10
Ga	6	9	7	8	10	10	12	14
V	140	222	158	171	231	252	273	366
Ni	516	231	626	566	293	233	184	83
Cr	1725	1505	1526	1531	1012	954	683	189
Cu	7	16	28	54	67	87	72	231
Pb	4	4	2	3	6	2	4	3
Zn	63	54	59	61	62	68	67	59
La	*1.21	*1.30	5	2	4	3	b.d.	3
Ce	*2.76	*3.202	b.d.	*2.33	3	3	4	4
Pr	*0.45	*0.50	-	-	-	-	-	-
Nd	*2.21	*2.73	-	*1.77	5	3	5	3
Sm	*0.82	*1.03	-	*0.7	-	-	-	-
Eu	*0.31	*0.34	-	*0.29	-	-	-	-
Gd	*1.05	*1.28	-	*b.d.	-	-	-	-
Tb	*0.19	*0.23		*0.19				
Dy	*1.28	*1.37	-	-	-	-	-	-
Ho	*0.28	*0.33	-	-	-	-	-	-
Er	*0.89	*1.01	-	-	-	-	-	-
Tm	*0.13	*0.15	-	-	-	-	-	-
Yb	*0.83	*1.04	-	*0.78	-	-	-	-
Lu	*0.13	*0.15	-	*0.14	-	-	-	-

b.d.: below detection. - : not analysed for.

* Analysis by ICP for OU 25857 and 25853, INNA for OU 30999, all others by XRF.

** Total Fe as Fe_2O_3.

TABLE 9. ANALYTICAL DATA FOR HIGH-Mg ROCKS THAT ARE COMPARED WITH THE ANKARAMITIC DIKES, GREENHILLS COMPLEX

	1	2	3	4	5	6	7
OU No.,	26648	arc an-	peridotitic	pyroxenitic	picrite dike		komatiite
Rock type	ankaramite	karamite	komatiite	komatiite			
Locality	Eglinton Valley, NZ	Epi, Vanuatu	Munro Township, Ontario, Canada		Skye		Gorgona, Colombia
					interior	margin	
SiO_2	49.01	48.2	44.0	48.3	42.52	45.64	45.7
TiO_2	0.42	0.39	0.26	0.62	0.49	0.78	0.44
Al_2O_3	5.84	11.5	6.79	10.8	8.12	13.11	9.8
Cr_2O_3	0.14	0.12	0.30	0.21	0.20	0.14	0.14
Fe_2O_3	1.63	*9.9	*10.5	2.36	2.41	3.69	-
FeO	6.36	-	-	7.4	8.72	7.43	*11.1
MnO	0.17	0.16	0.19	0.18	0.18	0.16	-
MgO	17.06	13.5	26.0	13.9	27.42	14.58	23.9
CaO	16.44	14.4	7.0	10.0	6.27	10.72	8.4
Na_2O	0.56	1.05	0.38	2.24	0.72	1.39	0.60
K_2O	0.31	0.31	0.13	0.0	0.23	0.13	0.01
P_2O_5	0.08	0.07	-	-	0.04	0.08	-
H_2O	2.21	-	-	3.08	2.07	1.71	-
L.O.I.	-	0.1	4.3	-	-	-	-
Total	100.25	99.58	99.9	99.8	99.95	100.15	100.1
MgO, anhydrous	17.4	13.7	27.2	14.5	28.2	14.9	23.9
100Mg/(Mg+0.8Fe)	83	77	85	76	85	75	83
CaO/Al_2O_3	2.82	1.25	1.03	0.93	0.77	0.82	0.86
CIPW Norm components, normalized to 100%, volatile-free, $Fe_2O_3/FeO = 0.2$							
di	55.69	36.78	15.18	25.27	10.29	19.36	13.99
hy	6.58	8.30	20.27	14.37	6.06	10.15	18.14
ol	15.06	14.69	39.55	16.38	53.13	23.18	34.20
Ol (mol)	Fo_{84}	Fo_{78}	Fo_{85}	Fo_{78}	Fo_{86}	Fo_{77}	Fo_{84}

* Total Fe as FeO or Fe_2O_3. - : not analysed for.

1: Brook Street Terrane, Williams & Smith (1979). Total includes CO_2 0.02%; Cr_2O_3 from Cr, reported as 990 ppm.

2: Barsdell & Berry (1990). Zr 13.5 ppm, V 295 ppm; Cr_2O_3 from Cr, reported as 820 ppm.

3, 4: Arth et al. (1977). Total for #3 includes NiO 0.05%, and for #4, NiO 0.01% and CO_2 0.74%.

5, 6: Gibb (1968, p. 428). Totals include CO_2 0.56%, 0.59% respectively.

7: Aitken & Echeverria (1984, Table 5, #156).

McDonough (1989), indicate a primitive nature. The same applies to very highly magnesian "picrite basalt" flows from a Triassic–Jurassic island-arc system at Kamloops Lake, British Columbia (Fig. 13B), which contain 34–37% MgO on a volatile-free basis (Russell & Snyder 1997). Arc-ankaramite eruptive rocks in the Brook Street Terrane, Eglinton Valley, New Zealand and from Epi (Barsdell & Berry 1990) have broadly similar patterns slightly enriched in the light *REE*, and picrites from the Hebridean Province of Scotland, still more so (Kent 1995). Some komatiites (Fig. 13C) give similar flat, low-*REE* patterns, but others are moderately enriched or impoverished in light *REE* (*e.g.*, Arth *et al.* 1977, Jahn *et al.* 1982).

In the Greenhills dikes here described, CaO/Al_2O_3 is consistently greater than one (Table 8), a feature used by Della-Pasqua & Varne (1997) to distinguish primitive arc-ankaramite from picrite. Examples of the latter are provided by a highly magnesian flow-differentiated dike in Skye (Gibb 1968, and Table 9, anal. 5 and 6) in which this ratio is 0.77–0.82, and by other representative picritic "magnesian basalts" from the same province (Kent 1995) in which CaO/Al_2O_3 ranges from 0.59 to 0.72. In komatiites, CaO/Al_2O_3 is commonly close to unity, but in many cases it is less than one, as in Table 9, columns 4 and 7, and in other cases it is higher, for example, 1.56 in a peridotitic komatiite from the Theespruit Formation of the Onverwacht Group, South Africa (Jahn *et al.* 1982).

The authors of the Basaltic Volcanism Study Project (BVSP 1981) showed that Ni/MgO values in typical komatiites fall between lines B and D in Figure 14. The fractionation of olivine causes evolution along gently curving paths reaching line A at about 15% or less MgO in the case of some basaltic members of komatiitic suites such as the Onverwacht Group of South Africa (Jahn *et al.* 1982). The Greenhills high-Mg dikes plot with arc ankaramites from D'Urville Island and those of West Epi in a gentle curve on and below line A (Fig. 14). Olivine fractionation from the extremely Mg-rich "picrites" of Kamloops Lake, British Columbia, interpreted here as arc-ankaramites, could be expected to generate a course close to the Greenhills arc-ankaramite trend. Cr/MgO values are similarly higher in representative komatiites than in arc-ankaramites.

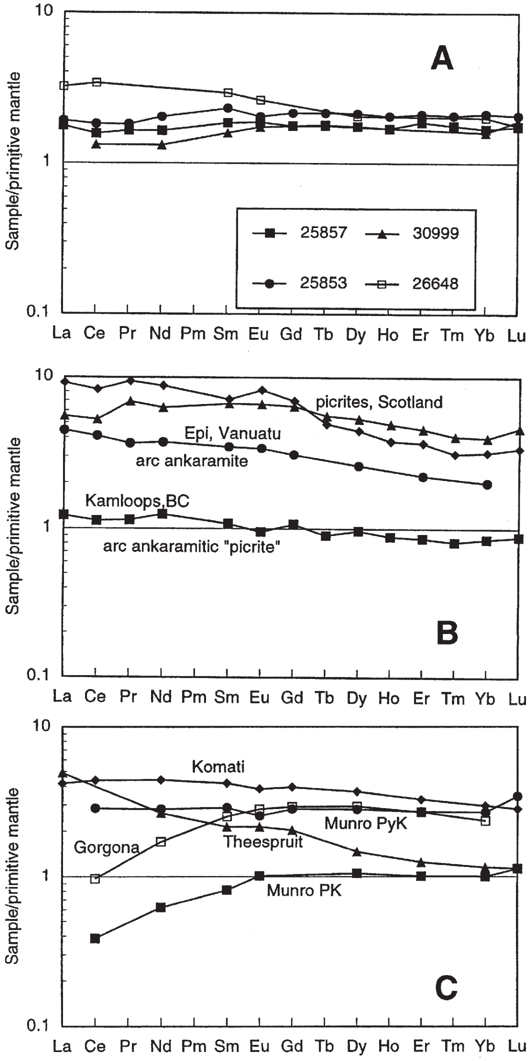

FIG. 13. *REE* in Greenhills dikes and other high-Mg rocks normalized to primitive mantle of Sun & McDonough (1989). A. Brook Street Terrane. Greenhills high-Mg ankaramitic dikes, OU 25853 (rim), OU 25857 (core) and OU 30999 (Table 8); also, Eglinton Valley ankaramite OU 26648 (Table 9, #1). B. Arc-ankaramite, Epi, Vanuatu (Table 9, #2); ankaramitic "picrite", Kamloops Lake, British Columbia (average of 4, 35.5% MgO, CaO/Al_2O_3 = 1.56, Russell & Snyder 1997); picrites, North Mull and South Harris, Scotland (Kent 1995). C. Komati and Theespruit: basaltic komatiite and peridotitic komatiite with 13.12 and 31.34% MgO, and CaO/Al_2O_3 of 1.00 and 1.56, respectively, Onverwacht Group, South Africa (Jahn *et al.* 1982); Munro PK, Munro PyK: peridotitic komatiite and pyroxenitic komatiite (Table 9, #4, 5), Munro Township, Ontario; Gorgona: komatiite, Gorgona Island, Colombia, 23.9% MgO, CaO/Al_2O_3 = 0.86 (Aitken & Echeverría 1984).

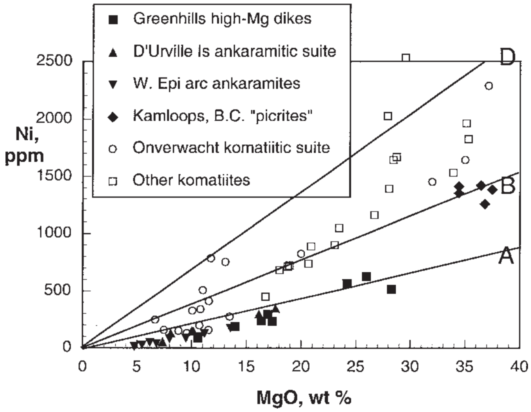

FIG. 14. MgO/Ni relationships for Greenhills high-Mg arc ankaramitic dikes and representatives of: ankaramitic suite volcanic rocks from D'Urville Island, Brook Street Terrane, New Zealand (Sivell & Rankin 1983), arc-ankaramitic suite of Epi, Vanuatu (Barsdell & Berry 1990); arc-ankaramitic "picrites" of Kamloops Lake, British Columbia (Russell & Snyder 1997), komatiitic suite, Onverwacht Group, South Africa (Jahn *et al.* 1982), komatiites from Rhodesia, West Australia, and Munro Township, Ontario (Nesbitt & Sun 1976, Nesbitt *et al.* 1979). See text.

Thus, in spite of some chemical analogies that the more Mg-rich Greenhills dikes show with komatiites, the latter are distinguished by commonly having lower CaO/Al_2O_3 values, and by higher Ni/Mg, Cr/Mg, and Ti/V.

Contents of high-field-strength elements in the Greenhills dikes are low, mostly less than double those of primitive mantle (Sun & McDonough 1989). As expected in arc-related volcanism (Pearce 1983), values for Nb and Ti are low in multi-element distribution diagrams, a feature also shown by P, whereas the large-ion lithophile elements provide a humped peak, which, however, reaches no more then ten times primitive mantle (Fig. 15). As expected, the phenocryst-free dike margin OU 25853 is enriched in most elements relative to its highly magnesian, olivine-charged interior OU 25857. Surprisingly, the analyzed dikes with the lowest Mg and highest Al contents (OU 54981, 54981a, and 54982, Table 8), have the lowest values for K, Ba, and P, with Rb below detection. Primary phases in these dikes are little altered, and so their low contents of mobile elements cannot be due to preferential loss during secondary alteration. This finding implies in turn that these dikes are not simple fractionates of the more Mg-rich melts.

Ankaramites are usually described as containing abundant phenocrysts of clinopyroxene as well as less

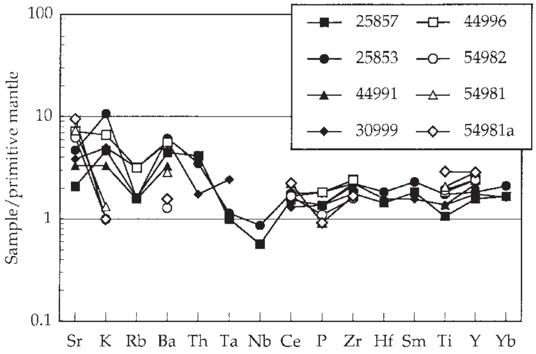

FIG. 15. Multi-element distribution patterns for high-Mg ankaramitic dikes, Greenhills Complex, normalized to primitive mantle of Sun & McDonough (1989). Data as in Table 9.

abundant olivine. Historically, the term referred to rocks of basanitic alkaline affinity (Le Maitre 1989), but its extension to alkali-poor rocks with similar phenocrystic assemblages in arc-tholeiitic suites is well established. Thus Barsdell & Berry (1990) used the term arc-ankaramite for primitive basaltic rocks of volcanic arcs, whether tholeiitic, calc-alkaline, or alkaline, but with high Mg-number, clinopyroxene phenocrysts in excess of olivine, and specifically including low-K types. Some of the Greenhills dike rocks meet these criteria as well as having CaO/Al_2O_3 in excess of one. However, the most magnesian examples contain normative and modal olivine in excess of clinopyroxene, while also having the highest values of CaO/Al_2O_3, 1.45–1.56. In light of the tectonic setting, very low K content and other characteristics, the Greenhills suite can be described as of primitive, arc-tholeiitic nature. Even where quenched, almost phenocryst-free, and consisting of almost monomineralic hornblende, the high-Mg dike rocks here described with 10–28% MgO meet the chemical criteria for ankaramites. Chemically, they are tholeiitic arc-ankaramites.

Hydrous nature of the melt

The geological setting of the Greenhills Complex indicates an origin as a high-level magma chamber in a volcanic arc. Hornblende is abundant in all the high-Mg dike rocks as a possible quenched phase, as a late-magmatic partial replacement of clinopyroxene, and as a late-magmatic groundmass and oikocrystic phase. It occurs in megacrystalline early dike-rocks and is ubiquitous throughout the gabbroic rocks of the Complex and the more evolved rocks in the remainder of the Bluff Peninsula, in some cases forming large oikocrysts. Its abundance testifies to an H_2O-rich melt, a signature of subduction-zone volcanism according to Gaetani *et al.* (1993). Gaetani *et al.* demonstrated that the presence of H_2O contents of 2–4 wt% at pressures of as little as 2 kbar, corresponding to ~6 km depth, delays crystallization of plagioclase, and results in extended crystallization of olivine and clinopyroxene from ocean-island basaltic magmas. Early dunitic and wehrlitic cumulates may result, as in the Greenhills Complex. At the shallow depths envisaged, explosive eruptions from the magma chamber may be anticipated.

Thermal history

Application and interpretation of various geothermometers to these rocks are compromised by the extensive re-equilibration believed to have occurred during cooling in a water-rich environment. For an anhydrous liquid otherwise having the composition of the average monomineralic hornblende matrix in the interior of the Steep Head hornblende ankaramite dike, OU 25857, olivine should first appear at about 1420°C (BVSP 1981). The estimated temperature would be increased if the initial liquid corresponded more closely to the bulk-rock hornblende-plus-olivine composition, but would be reduced with increasing H_2O content. The most magnesian composition observed in the phenocrysts is $Fo_{92.7}$, in reasonable agreement with predicted ~Fo_{95}. For the chilled margin of the same dike, OU 25853, the anhydrous saturation-surface should be reached at about 1400°C, crystallizing olivine ~Fo_{94}. Phenocrysts of less magnesian compositions, some zoned to $Fo_{81.7}$, appear to be out of equilibrium with the inferred liquids. Similarly, observed compositions of $Fo_{74.9–72.8}$ for olivine in the least magnesian of the high-Mg dikes studied, OU 54981, are discordant with a predicted Fo_{90} at about 1350 and 1290°C for anhydrous liquids corresponding, respectively, to the bulk-rock interior and marginal zones of this dike.

Use of the QUILF program (Frost & Lindsley 1992) suggests a temperature of 989°C (D.H. Lindsley, pers. commun.) for an assemblage of forsterite – diopside – enstatite – magnetite and fictive ilmenite in OU 30999 (23.89% MgO), with $f(O_2)$ about 2.2 log units above FMQ. This may represent a temperature during reaction with hornblende. The assemblage in dike OU 44996 (16.84% MgO) gave a temperature of 1102°C, suggestive of its solidus, with $f(O_2)$ about 2 log units above FMQ, but with evidence of Fe–Mg exchange which probably continued to lower temperatures.

Olivine–spinel thermometry for the olivine–chromite pair OU 25857 (Table 2) and for three other pairs from the same rock suggests temperatures of 619°C, 635°C, 726°C, and 780°C (A.A. Poustovetov, pers. commun.), using an equation that Poustovetov (1999) developed based on the approach of Sack & Ghiorso (1991). This finding suggests major re-equilibration during cooling, and is compatible with the development of hornblende blebs and reactive exsolution in the associated diopside phenocrysts, and with incipient exsolution of ilmenite from magnetite at about 645°C in a less Mg-rich dike, as described above.

At the time the dikes were emplaced, the country-rock wehrlites had cooled sufficiently to allow brittle fracture and emplacement of dikes only 8–70 cm thick with sharply defined parallel walls. The interior of the magma chamber, 5 km in diameter, may still have been fluid, however. Although only 8 cm thick and size-graded inward, dike rock OU 54981 cooled sufficiently slowly to yield a holocrystalline hornblende microgabbronorite, and although the very high-Mg dike, OU 25857, was rapidly quenched below its solidus, its subsequent cooling, and that of the other dikes, would have been slow.

We postulate initial emplacement of the dikes at about 1400° to 1250°C depending upon their composition. Chilling to solidi of about 1100°C embraced crystallization of magmatic hornblende following that of enstatite. Subsequent cooling was slow as a result of the heat reservoir provided by the Greenhills Complex. Pyroxenes re-equilibrated to temperatures of 900–800°C or less, accompanied by the formation of hornblende blebs in diopside. Crystallization of postmagmatic hornblende with declining Al content, olivine–chromite re-equilibration, and incipient exsolution of ilmenite continued to about 600°C. Minor high-Si hornblende, chlorite, chrysotile, and other secondary minerals formed at still lower temperatures.

Flow differentiation

Two possible explanations, not mutually exclusive, must be considered for the contrasting composition of the selvedges and interiors of some of the dikes and the distribution of phenocrysts within them (Fig. 5). In the case of the picritic dikes of Skye, Harker (1904), reiterated by Bowen (1928, p. 158), considered "that a peridotitic liquid followed after the basaltic liquid, sweeping out the central portion of the partly consolidated doleritic dike". Bowen recognized that the basaltic liquid might itself have been interstitial to early crystals in the peridotitic magma and was squeezed off, penetrating into narrow fissures before being followed by the peridotitic portion of the magma as the fissures opened.

The composition of the aphanitic chilled margin of Steep Head dike OU 25853/7 indicates the existence of a melt with 17.4% MgO on an anhydrous basis. The interior of this dike has 28.3% MgO volatile-free, and consists essentially of phenocrysts of olivine and minor diopside in a monomineralic groundmass of hornblende that contains on average (anhydrous) 19% MgO and that appears at least in part to be of quench origin. As some of the olivine phenocrysts are skeletal, at least some of the olivine must have crystallized from the melt that surrounded it. To flow along the center of the dike, the final melt contained more than 19% MgO and was more Mg-rich than the olivine-free melt that was quenched along the margin. However, the observed contents of 28.3, 26.0, and 24.2% MgO in the interiors of dikes OU 25857, 44991, and 30999 almost certainly do not represent liquid compositions, and the abundant olivine and subordinate diopside phenocrysts in these rocks are considered to be in part accumulative and transported.

In the central portion of this and other dikes, the concentration of phenocrysts far exceeds the 5–8% required, according to Komar (1972a, b), to create a physical differentiation within a flowing magma. This being the case, flowage differentiation, which by definition involves the mechanical redistribution of phenocrysts within a single liquid, must have occurred. The differentiation includes both number and size of grains, with a rapid fall-off toward the margins. Whereas individual exceptions may occur, derivation of the olivine phenocrysts from the immediate country-rock wehrlites is rejected, as discussed above. Their variable composition in the interiors of the more magnesian dikes is compatible with mixing of crystals derived from different sites in a magma chamber, as described by Marsh (1996). Furthermore, the presence of skeletal crystals of olivine suggests that some differentiation by crystal fractionation occurred within the dikes. Combined with the evidence for an overall more mafic melt phase in dike interiors compared with selvedges, a more complex process is indicated than was described by Gibb (1968, 1971) for the classic examples of flow differentiation in ultrabasic dikes of southwestern Skye.

Reactive exsolution

Oriented blebs of hornblende in clinopyroxene are interpreted as having formed under late-stage magmatic conditions, overlapping the temperature interval for exsolution of orthopyroxene lamellae, estimated as about 850°–750°C. This scenario suggests a process of reactive exsolution involving introduction of K, (OH), and probably Al and Na, while Mg, Fe, and Cr are preferentially partitioned from the clinopyroxene host into the hornblende blebs. Partitioning of Ca would leave the host relatively enriched in Ca, as happens when orthopyroxene exsolves from diopside or augite. Reactive exsolution would be favored by the expanded field of clinopyroxene promoted by crystallization of H_2O-enriched basaltic melts.

Dike emplacement in relation to magmatic evolution

Mossman (1973) demonstrated that the Greenhills Complex consists of a layered series with basal dunite overlain by wehrlite, a transition zone of feldspathic wehrlite, and more than 600 m of gabbro (gabbronorite), with very calcic plagioclase ($An_{91–88}$). There is a layer of allivalite (gabbro consisting essentially of anorthite and olivine) in the gabbro zone, and minor late-stage trondhjemite. More evolved gabbronorite occurs within the immediate proximity, making up most of the remainder of Bluff Peninsula. Intrusion breccias attest to disturbances in the magma chamber, and reversals in cryptic layering suggest that fresh pulses of magma may have entered from time to time. Observed ranges of composition of olivine crystals in the layered series and in the ankaramitic dikes are shown in Figure 16. Olivine crystals in the feldspathic wehrlite cut by the Steep Head dike OU 25853/7 have compositions $Fo_{75–73}$, whereas phenocrysts in the dike are in the range $Fo_{93–82}$. This is close to the range recorded by Mossman (1973) for the dunites ($Fo_{90–80}$) and suggests that this late dike results from the entry of a fresh pulse of magma with Mg/Fe approximating that from which the main layer of dunite had formed earlier as a cumulate. Dikes OU 44991 and 30999 have compositions of olivine phenocrysts compatible with crystallization from magma approximating that from which the dunites and wehrlites formed as cumulates, and the less magnesian dikes OU 44996, 54981, 54982 are interpreted as representing melts at similar stages of evolution to those from which the feldspathic wehrlites and the more mafic members of the layered gabbros had earlier formed.

Effect of magmatic evolution on ankaramitic characteristics

As shown in Figure 17, the ratio CaO/Al_2O_3 drops in linear fashion as a function of the ratio Mg/(Mg + Fe) in the high-Mg ankaramitic dikes. This coherent compositional trend is evidence that the dikes may be closely related genetically. Reconnaissance study of other late dikes (open circles in Fig. 17) shows that this trend is continued in low-alkali dikes of basaltic composition, with 9.13 to 3.37% MgO. The most Mg-rich example of these contains plentiful pseudomorphs of amphibole after phenocrystic clinopyroxene. Another member of the suite is a micronorite, whereas the least magnesian of those plotted consists almost entirely of plagioclase and fine-grained hornblende, together with 3% biotite.

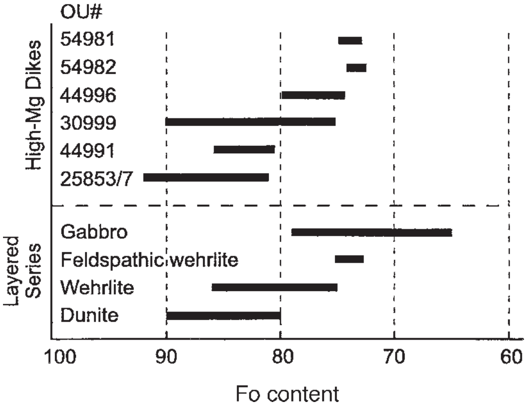

FIG. 16. Forsterite contents of olivine phenocrysts in the Greenhills high-Mg ankaramitic dikes and in the layered series of the Complex. Data for dunite, wehrlite, and gabbro from Mossman (1973).

The initial liquids in the most Mg-rich dikes may have been undersaturated in diopside, and olivine crystallized in abundance as it also did in the main magma chamber in the upper crust to provide the dunite cumulates of the layered series. Once diopside appeared on the liquidus, its continuing crystallization together with olivine depleted the melts in Ca as well as in Mg, reducing the CaO/Al_2O_3 ratio in the melt. When plagioclase commenced to crystallize, it was extremely calcic ($An_{99–89}$) and in small amount, thus having negligible effect on CaO/Al_2O_3. Eventually, orthopyroxene and hornblende appeared on the liquidus, the orthopyroxene initially as a reaction rim on olivine, and later as independent crystals, as in the less extreme Mg-rich dikes. We conclude that primitive low-alkali arc-ankaramites can evolve into more normal arc-tholeiite compositions.

Ankaramites in the Brook Street Terrane

Ankaramites of early Permian age, including dikes, flows, and tuffs or breccias, are widespread in the Brook Street Terrane (Landis & Waterhouse 1966, Williams & Smith 1979, Sivell & Rankin 1983, Ballard 1987). Common to all of these are abundant conspicuous green phenocrysts of chromian diopside. A relationship

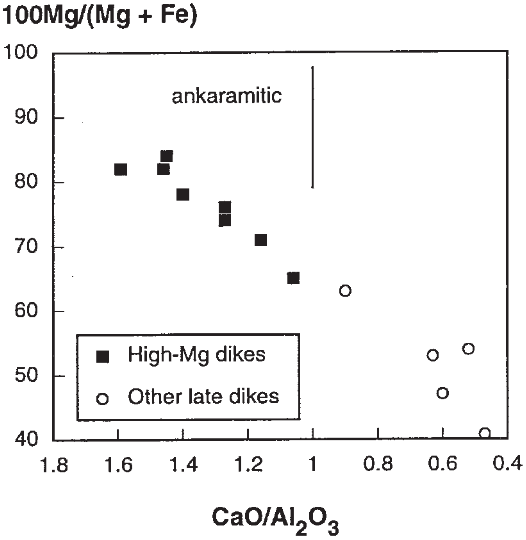

FIG. 17. Relationship between CaO/Al_2O_3 and 100Mg/(Mg + Fe) for high-Mg and other late dikes, Greenhills Complex. According to Della-Pasqua & Varne (1997), CaO/Al_2O_3 (weight percent) greater than 1.00 is an indicator of ankaramitic affinities.

between these ankaramites and the Greenhills Complex was suggested by Kimbrough *et al.* (1992). The present study confirms that primitive ankaramitic liquids existed within the Greenhills Complex, and they may be expected to have existed similarly in other dunite–wehrlite complexes intrusive into the Brook Street (Sivell & Rankin 1983). Metabasaltic members of the Brook Street Terrane on D'Urville Island (Fig. 1) have primitive *REE* patterns only slightly enriched in light *REE* compared with the Greenhills ankaramitic dikes, as do ankaramites from the Eglinton Valley (Williams & Smith 1979, and Fig. 13A). Multi-element distribution patterns of these metabasalts also appear to be closely analogous to those of the Greenhills dikes, if slightly more evolved.

We regard the Greenhills Complex as the upper-crust magma-chamber remnant of a volcano from which both ankaramites and more evolved low-K basaltic and perhaps andesitic products were erupted. Sivell & Waterhouse (1988) have demonstrated similar geochemical characteristics in the Early Permian Gympie Group Volcanic Suite of southeastern Queensland, Australia. These volcanic rocks include coarse clinopyroxene-phyric ankaramites. Following other workers, Sivell & Waterhouse (1988) interpreted the Gympie Group as a remnant of a major intra-oceanic volcanic arc, of which the Brook Street Volcanic Suite in New Zealand formed a part, and which was disrupted by the later opening of the Tasman Sea.

CONCLUSIONS

The high-Mg hornblende-bearing and other ankaramitic dikes were emplaced late in the sequence of events that generated the Greenhills Complex. This complex is the remnant of the upper-crust magma chamber of an island-arc volcano. Features of major- and minor-element composition, including low abundances of small, highly charged cations (Nb, Ta, P, Ti) and little-fractionated *REE* patterns, are typical of H_2O-rich low-K tholeiitic suites developed early in the history of island arcs. The dikes provide a model for magma evolution in the complex as a whole. Crystallization in the dikes, first of olivine, then joined by diopside, followed by anorthite and later enstatite, giving way to hornblende, parallels the development of dunite followed by wehrlite and feldspathic wehrlite cumulates in the layered series of the complex, followed by hornblende gabbronorites with highly calcic plagioclase. Reversals of cryptic layering in the layered series suggest the entry of fresh pulses of magma into the magma chamber, as do the late high-Mg dikes that cut rocks that had cooled sufficiently to undergo brittle fracture, and which, in some cases, have compositions more evolved than the dikes that cut them. The most highly magnesian dike-rocks, with up to 28% MgO, have olivine phenocrysts in excess of diopside, or are quenched to almost monomineralic hornblende. Nevertheless, they are ankaramitic rather than picritic in the sense of having CaO/Al_2O_3 greater than one. Where the composition is somewhat more evolved, diopside phenocrysts exceed olivine, and progressive fractionation of these two minerals resulted in a falling CaO/Al_2O_3 value. Once whole-rock MgO contents dropped to about 10%, CaO/Al_2O_3 was no longer greater than one, the ankaramitic nature was lost, and evolution continued on an arc-tholeiitic to andesitic trend. Processes such as flow differentiation and reactive exsolution, which gave rise to oriented blebs of hornblende in diopside, contributed to the evolution of the dikes. Effusive ankaramitic and more evolved basaltic to andesitic breccias of comparable age in the same terrane provide evidence of explosive eruptions of H_2O-charged magma from this or similar magma chambers.

The dikes illustrate the chemical resemblance emphasized by Ernst (1987), of highly magnesian tholeiitic island-arc "picrites" and ankaramites to komatiites, but reveal significant differences. With their effusive analogues in the Brook Street Terrane, they provide another example of an increasingly recognized ankaramitic association in Phanerozoic island-arc systems.

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