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THE FIELD CHARACTERISTICS AND PETROLOGY OF ARCHEAN AND PROTEROZOIC KOMATIITES

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Abstract

A review of the geological literature, augmented by recent field and laboratory studies, reveals that komatiites constitute an igneous suite made up of volcanic and hypabyssal rocks ranging in composition from dunite and peridotite to basalt or magnesian andesite. Ultramafic komatiites (MgO > 20 wt. % anhydrous) are rich in olivine and occur as spinifex-textured, massive or pillowed lava flows, as bedded volcaniclastic rocks, and as small dykes and sills. Mafic komatiites (MgO < 20 wt. %) have, as their predominant minerals, olivine, pyroxene (augite or pigeonite) and plagioclase. They occur as massive flows with brecciated or pyroxene spinifex-textured tops, or as pillow lavas. Also common are layered ultramafic-mafic flows and sills. Ultramafic and mafic komatiites characteristically occur in Archean greenstone belts, where in several areas dunitic flows and large dunitic intrusions are the hosts for nickel sulfide deposits. Ultramafic komatiites are unknown in Proterozoic and Phanerozoic terranes, but mafic komatiite lavas, and layered ultramafic-mafic flows and sills, are common in the Proterozoic Cape Smith fold belt of Quebec, and pillow lavas with compositions similar to mafic komatiites occur in Paleozoic ocean-floor sequences in Newfoundland.

Sommaire

D'après la littérature géologique et des travaux récents sur le terrain et au laboratoire, les komatiites constituent une série de roches volcaniques et hypabyssales allant de dunite et péridotite à basalte et andésite magnésienne. Les komatiites ultramafiques (> 20% en poids de MgO, base anhydre), enrichies en olivine, forment (1) des coulées de lave à texture spinifex, massives ou en coussinets, (2) des roches volcaniclastiques litées et (3) des dykes et des filons-couches de faibles dimensions. Les komatiites mafiques (< 20% MgO) se composent surtout d'olivine, pyroxène (augite ou pigeonite) et plagioclase. On les trouve soit en coulées massives bréchifiées à la surface supérieure ou montrant des pyroxènes à texture spinifex, soit en laves en coussinets. On rencontre aussi des coulées et filons-couches ultramafiques–mafiques stratiformes. Les komatiites ultramafiques et mafiques caractérisent les ceintures de roches vertes archéennes; certaines coulées et intrusions dunitiques renferment des gisements de sulfure de nickel. On ne connait pas de komatiites ultramafiques protérozoïques ou phanérozoïques, mais les laves komatiitiques mafiques ainsi que les coulées et filons-couches ultramafiques–mafiques sont courants dans la ceinture protérozoïque du cap Smith, Québec; de plus, des laves en coussinets, ressemblant à des komatiites mafiques en composition, se trouvent dans les fonds océaniques palézoïques de Terre-Neuve.

(Traduit par la Rédaction)

Introduction

Although there are several early descriptions of ultramafic rocks that are now known to be extrusive (*e.g.*, Naldrett & Mason 1968), credit for the recognition and first definitive descriptions of ultramafic lavas must go to Viljoen & Viljoen (1969a, b, c), who realized that many ultramafic units in the Barberton Mountain Land greenstone belt in South Africa had a volcanic origin. They proposed the name *komatiite* for a suite of rocks that included these ultramafic lavas as well as related mafic volcanic rocks and ultramafic dykes and sills. As evidence of extrusion they described chilled flow tops, pillows and the *spinifex* texture, formed by rapid crystallization of ultrabasic and basic silicate liquids.

In following years other descriptions of komatiitic lavas in Canada and Australia were published (Wilson *et al.* 1969, McCall & Leishman 1971, Nesbitt 1971, Williams 1972), but in most cases exposures were not sufficient for the ultramafic rocks to be positively identifield as volcanic. These reports included descriptions of spinifex textures, now found to be characteristic of komatiites, but because of the limitations in exposure, the relationship between spinifex-textured and massive lava remained unclear. Clarification had to await the investigation by Pyke *et al.* (1973) of a large, exceptionally well-exposed outcrop in Munro Township, Ontario. In their paper, Pyke *et al.* (1973) described spectacular ultramafic komatiite flows with spinifex-textured upper portions representing rapidly cooled ultrabasic liquids and massive lower portions formed by gravitative accumulation of olivine. Since that report, descriptions of komatiites elsewhere in Canada and in other parts of the world (Australia, India, Rhodesia, Finland, *etc.*) have shown that the spinifex-textured flows are merely the most unusual in a range of ultramafic extrusive rocks that also includes massive flows, pillowed flows and even bedded volcaniclastic rocks.

Much of this paper is a review of various papers dealing with the field characteristics and petrology of Archean komatiites. Additional information comes from recent work by the authors, including an investigation of Proterozoic komatiites from less well-known occurrences in the Cape Smith–Wakeham Bay belt in northern Québec. The geochemical characteristics of komatiites are reviewed in a separate paper (Nesbitt *et al.* 1979).

Definition and Nomenclature

The ultramafic and related mafic lavas in the Barberton Mountain Land are characterized by unusually high CaO/Al_2O_3 ratios (1.5 to 2), a feature that was emphasized by Viljoen & Viljoen (1969a) in the original definition of komatiite. Similar rocks in other areas typically have lower, more normal CaO/Al_2O_3 ratios ($\sim$1). This difference has led to considerable confusion about the definition and use of the term *komatiite,* and about the names that should be applied to individual members of the rock suite. An attempt is currently being made to establish acceptable definitions and rock names for komatiites: questionnaires were sent out to interested people by R.A. Binns in 1976. Replies have been compiled, and a second questionnaire was circulated in June 1978. A summary paper and a conference on komatiite definition and nomenclature are planned once replies to the second questionnaire have been received.

As this project is not complete, there will be no further discussion of the problem at this stage. The definition and distinguishing criteria of komatiites presented by Arndt *et al.* (1977) will be used, *i.e.* the komatiites will be considered to constitute a suite that includes noncumulate rocks ranging from peridotite ($\sim$40% MgO, 44% SiO_2) to basalt (12% MgO, 52% SiO_2) or andesite (8% MgO, 56% SiO_2), and cumulate rocks from dunite or peridotite ($\sim$40% MgO) to gabbro ($\sim$12% MgO). Individual members are characterized by low $FeO^*/(FeO^* + MgO)$, low TiO_2 and high MgO, Ni and Cr. Some, but not all, have high CaO/Al_2O_3 ratios. Also diagnostic are volcanic structures and textures such as spinifex and polyhedral jointing, as discussed below.

Also because the questions of nomenclature are under discussion, purely descriptive terms will be used to refer to the main groups of komatiites. These terms are *ultramafic komatiite* for olivine-rich rocks with MgO $>$ 20 wt. % (analyses recalculated anhydrous) and *mafic komatiite* for olivine-rich, pyroxene-rich and plagioclase-rich rocks with MgO $<$ 20 wt. %. It is intended that these terms be used in conjunction with the earlier terms, not that they supplant them. Thus ultramafic komatiite would refer to 'peridotitic komatiite' (Viljoen & Viljoen 1969b, Arndt *et al.* 1977) or 'Archean greenstone peridotite' (Nesbitt 1971); mafic komatiite would refer to 'basaltic komatiite' (Viljoen & Viljoen 1969a), 'high-Mg basalt' (Williams 1972), or 'pyroxenitic komatiite and basaltic komatiite' (Arndt *et al.* 1977).

Distribution

Ultramafic and mafic komatiites have been recognized in almost all well-studied Archean shield areas (Table 1), most commonly in greenstone belts, *e.g.*, the Abitibi belt in Canada or parts of the Yilgarn Block in Western Australia, where low metamorphic grade has allowed preservation of diagnostic textures and compositions. In such areas komatiites seem restricted to the basal stratigraphic levels of broad volcanic–sedimentary cycles where they are associated with ultramafic–mafic layered sills and Fe- and Ti-rich tholeiitic basalts. Overlying volcanic rocks include tholeiitic basalts, andesites and dacites with more normal iron contents, succeeded by calc-alkaline lavas and volcaniclastic units, and finally by sedimentary rocks (Naldrett & Goodwin 1977, Jolly 1975, Jensen 1976, Gemuts & Theron 1975, Bickle *et al.* 1975).

TABLE 1. GENERAL ENVIRONMENT OF SELECTED OCCURRENCES OF KOMATIITIC VOLCANIC ROCKS AND INTRUSIONS

Location	Age	Tectonic Environment	Associated Rocks	Metamorphic Grade	References
CANADA					
Munro Township, northeast Ontario	2.765 ±0.042	Abitibi greenstone belt, Superior Province, Canadian Shield	Fe-rich tholeiitic basalts, andesites, dacites; tholeiitic layered sills; diabase dykes; siliceous tuffs and cherts	Prehnite-pumpellyite to greenschist facies	MacRae (1969), Arndt (1975, 1977), Arndt *et al.* (1977), Fleet & MacRae (1975)
La Motte-Vassan belt, northwest Quebec	≈2.7	Abitibi Greenstone belt	Tholeiitic basalts and andesites; diabase and gabbro dykes; greywacke	Upper Greenschist facies	Kretschmar & Kretschmar (1975), Gélinas *et al.* (1977), Lajoie & Gélinas (1978), Imreh (1974, 1978)
La Grande area, northern Quebec	≈2.7	Northeast Abitibi greenstone belt		Amphibolite Facies	Stamatelopoulou-Seymour & Francis (1979)
Prince Albert Group, Northwest Territories	≈2.7	Typical Archean greenstone belt environment in east; stable shelf environment overlying sialic basement in west; Churchill Province	Mafic to felsic volcanics, iron formation, rare quartzite in east; quartzites, pelitic and rarely calcareous sediments in west	Amphibolite Facies	Schau (1977)
Cape Smith Fold Belt, northern Quebec	Aphebian <2.30, >1.45; ~1.65(?)	Orogenic belt, part of the Circum-Ungava geosyncline; deformed in the Hudsonian orogeny	Tholeiitic basaltic volcanics and layered mafic-ultramafic sills; minor clastic sediments, dolomites and cherts; rare calc-alkaline volcanics reported	Predominantly greenschist facies; higher grades in north of belt	Wilson *et al.* (1969), Moore (1977), Schwarz & Fujiwara (1977), Francis & Hynes (1978)
Rambler Mine area, Newfoundland	Early Paleozoic	Ocean-floor rocks, uplifted and folded to form part of the Appalacian orogenic belt	Tholeiitic ocean-floor type basaltic lavas and pyroclastics; cherts; felsic porphyries	Greenschist facies	Gale (1973)
SOUTHERN AFRICA					
Barberton Mountain Land, eastern Transvaal and Swaziland.	3.50 ±0.20	Barberton greenstone belt, Kaapvaal Craton	Tholeiitic basalts and intermediate to felsic lavas and volcaniclastics. layered ultramafic-mafic intrusions; cherts	Upper greenschist facies	Viljoen & Viljoen (1969a-1970), McIver (1975), Williams & Furnell (1979)
Belingwe greenstone belt, Rhodesia	~2.8	Belingwe greenstone belt, Rhodesian Craton	Tholeiitic basalt and basaltic andesite; quartzite, siltstones, banded ironstones, stromatolitic limestones	Greenschist facies	Bickle *et al.* (1975), Nisbet *et al.* (1977)
WESTERN AUSTRALIA					
Mt. Monger	≈2.7	Norseman-Wiluna greenstone belt, Eastern Godfields	Tholeiitic basalts and layered mafic-ultramafic sills; clastic and tuffaceous sediments; felsic intrusions	Greenschist to lower amphibolite facies	McCall (1971), Williams (1972), Williams & Hallberg (1972)
Kambalda	≈2.7	Norseman-Wiluna greenstone belt	Low Fe, Ti (komatiitic?) basalts; cherts, carbonaceous shales	Greenschist facies	Woodall & Travis (1969), Ewers & Hudson (1972), Ross & Hopkins (1975)
Scotia	≈2.7	Norseman-Wiluna greenstone belt	Tholeiitic basalts, layered ultramafic flows and sills, black shales andesitic pyroclastics	Greenschist to lower amphibolite facies	Nesbitt (1971), Christie (1975), Nesbitt & Sun (1976)
Mt. Clifford	≈2.7	Norseman-Wiluna greenstone belt	Tholeiitic basalts; cherts	Lower greenschist facies	McCall & Leishman (1971), Barnes *et al.* (1974), Travis (1975)
Yakabindie	≈2.7	Norseman-Wiluna greenstone belt	Fe-rich tholeiitic basalts; layered sills; clastic and volcanigenic sediments	Greenschist facies	Martin & Allchurch (1975), Naldrett & Turner (1977)

Komatiites normally occur as sequences of lava flows, tens to hundreds of metres thick, that alternate with sequences of tholeiites of similar or greater thickness. At the interfaces between sequences, the two magma types are commonly interlayered. Whereas the tholeiitic lavas commonly have fairly uniform compositions, the komatiites characteristically show a wide variability in composition in an irregular or cyclic manner. Cycles open with relatively thin, highly magnesian ultramafic komatiites and proceed upward to thicker, less magnesian mafic komatiites. Many deposits of nickel–iron sulfides have as their hosts thick, massive dunitic flows at the bases of such cycles (Ross & Hopkins 1975, Barrett *et al.* 1977).

The Cape Smith–Wakeham Bay fold belt in northern Québec is the only location in which the presence of Proterozoic komatiitic lavas has been verified. The belt is a highly folded volcanic-sedimentary sequence that unconformably overlies Archean gneissic rocks of the Superior province of the Canadian shield (Dimroth *et al.* 1970, Moore 1977). A variety of sills, some differentiated from peridotite to gabbro, others largely gabbroic or largely ultramafic, have intruded volcanic rocks including highly magnesian lavas, tholeiitic and calc-alkaline volcanic units and clastic sedimentary rocks. The magnesian lavas have many of the characteristic volcanic structures, textures and chemical features of Archean komatiites (Wilson *et al.* 1969, Schwarz & Fujiwara 1977). Spinifex texture has not, however, been observed.

It is unclear whether komatiites exist in Phanerozoic terranes. No clearly noncumulate ultramafic lavas have been reported, but aphanitic volcanic rocks with compositions similar to those of Archean mafic komatiites but for conspicuously lower TiO_2 contents have been recorded within Paleozoic ocean-floor basalts in Newfoundland (Gale 1973, Upadhyay

TABLE 2. FIELD CHARACTERISTICS OF SELECTED EXAMPLES OF KOMATIITIC VOLCANIC ROCKS AND INTRUSIONS

Location	Ultramafic Flows	Mafic Flows	Layered Flows	Volcaniclastics	Intrusions
CANADA					
Munro Township	Spinifex-textured and massive flows; rare pillows, some with spinifex texture	"Pyroxenitic komatiite" - olivine or pyroxene-rich mafic komatiite; pyroxene spinifex-textured, brecciated, massive or pillowed "Basaltic komatiite" - Pyroxene or pyroxene-plagioclase mafic komatiite; Rarely spinifex-textured, commonly pillowed or massive	Fred's Flow-description in text	Flow breccias	Small ultramafic dykes and sills; large layered ultramafic-mafic sills
La Motte-Vassan belt	Spinifex-textured, massive and pillowed flows; conspicuous parallel and oblique layering in B-divisions of spinifex-textured flows	Are present in the belt, but have not been described in any detail	Not reported	Thinly-bedded ultramafic tuffs; massive, coarse ultramafic breccias	Small ultramafic dykes and sills
La Grande area	Spinifex-textured and massive flows		Not reported	Thinly-bedded, fine-grained, ultramafic volcanigenic sediments	Not reported
Prince Albert Group	Spinifex-textured flows	Not reported	Not reported	Not reported	Small ultramafic dykes and sills
Cape Smith Fold Belt	None present	Pillowed and massive, polyhedrally and columnar-jointed flows. No spinifex texture. Some basal olivine cumulates	Lens-shaped or laterally extensive; pillowed or brecciated tops; pillowed bases; columnar-jointed basalt and peridotite in interiors; initial magma with 12-16% MgO	Flow top breccias; coarse and fine hyaloclastites	Thick (to 300m) laterally persistent, composite sills with peridotite, minor pyroxenite and gabbro; also wholly gabbro and largely peridotitic sills.
Rambler Mine area	None present	Pillowed basalts	Not reported	Not reported	Not reported
SOUTHERN AFRICA					
Barberton Mountain Land	Spinifex-textured flows; massive flows with progressive downward increase in olivine content; some pillowed flows	Geluk Type - highly magnesian (16 to 22% MgO) pillowed or massive flows. Some pyroxene spinifex. Badplaas type - coarsely crystalline, clinopyroxene-enriched flows. Usually massive. Barberton type - pyroxene and plagioclase-bearing, massive or pillowed, commonly variolitic, some pyroxene spinifex	Certain layered ultramafic-mafic units may be extrusive	Not reported	Thin, coarse-grained, porphyritic or poikilitic-textured peridotite sills and dykes; layered ultramafic-mafic sills
Belingwe Greenstone Belt	Pillowed flows are common; massive flows have brecciated tops and bases, and columnar-jointed interiors; Spinifex-textured flows are uncommon	Pillowed lava, some with amygdules, many with ocelli; massive flows with columnar pyroxene spinifex texture	One flow (13 m thick) with pyroxene spinifex textured top underlain by random clinopyroxene texture, clinopyroxene cumulate and cumulate wehrlite. Another possible flow (70 m thick) with a quartz gabbro upper section	Tuffs, agglomerates and possible pillow breccias of mafic komatiite composition	Peridotitic conformable units (possibly flows); Layered ultramafic-mafic sills
WESTERN AUSTRALIA					
Mt. Monger	Spinifex-textured and massive flows, some with amygdaloidal tops	"High-Mg basalts" - massive flows with pyroxene spinifex-textured or brecciated tops. No pillows. Varioles and amygdules are common.	Not reported	Not reported	Probable ultramafic dykes and sills; layered sills differentiated from harzburgite through orthopyroxenite, norite, gabbro to granophyre.
Kambalda	"Thick flows" - 10-30 m thick, with brecciated tops, thin spinifex-textured layers (6 m) and a pronounced downward increase in olivine content Overlain by "thin flows" (0.3 to 7 m) which commonly are spinifex-textured	Massive, pillowed or brecciated basalts called metatholeiites but with low Fe and Ti similar to mafic komatiites	Not reported	Mafic hyaloclastites and flow breccias	Some massive peridotitic units may be intrusive
Scotia	Spinifex-textured and massive flows	Low Ti metatholeiites	Not reported	Extensive fragmental units of variable thickness	Some massive dunites may be intrusive.
Mt. Clifford	Spinifex-textured flows and massive flows with downward increase in olivine content	"High-Mg basalts" - flow morphology not reported	Not reported	Fragmental ultramafic sedimentary units containing elongated and flattened ultramafic fragments in a bedded albite and pyrite-rich matrix	Peridotitic sills; Large dunitic intrusions
Yakabindie	Spinifex-textured and massive flows	"Pyroxenites", "Magnesian basalts" and "basalts" distinguished on the basis of mineralogy and MgO contents. No information on flow morphology	Not reported	Not reported	Small peridotitic sills; large dunitic intrusions

TABLE 3. DESCRIPTIONS OF OTHER KOMATIITE LAVAS AND INTRUSIONS

North America*

Dundonald Township, Ont.: ultramafic and mafic komatiite lava flows, layered mafic-ultramafic flows and sills (Naldrett & Mason 1968)
Timmins area, Ont.: ultramafic and mafic komatiite lavas (Pyke 1970, 1975)
Kirkland Lake-Lake Abitibi traverse, Ont.: ultramafic and mafic komatiites, commonly pillowed (Jensen 1976)
Michipicoten belt, Wawa, Ont.: a single pillowed mafic komatiite (Brooks & Hart 1972)
Griffin Lake, Northwest Territories: ultramafic komatiite flows, almost completely spinifex-textured (Hall 1978)
Betts Cove, Nfld.: mafic komatiitic pillow lava and sheeted dykes, some rich in hopper olivine, in a Lower Ordovician ophiolite (Upadhyay 1976)

Southern Africa*

Jamestown schist belt, Barberton Mountain Land: highly sheared mafic and ultramafic komatiites correlative with those in the lower Onverwacht Group (Anhaeusser 1972)
Roodekrans ultramafic complex, Krugersdorp district: mafic and ultramafic komatiite lavas (Anhaeusser 1976)
Shangani mine area, Rhodesia: nickel sulfide deposit in a peridotitic intrusion; ultramafic and mafic komatiite lavas (Viljoen *et al.* 1976)

Australia

Scotia mine area, Eastern Goldfields: ultramafic and mafic komatiite lavas and some volcaniclastic rocks overlying massive peridotite containing the nickel sulfide deposit (Nesbitt 1971, Christie 1975)
Trough Wells, Eastern Goldfields: a thick, massive ultramafic lava flow (Lewis & Williams 1973)
Jimberlana dyke, Eastern Goldfields: a Proterozoic layered peridotite-pyroxenite-gabbro intrusion of probable komatiite affinity (Campbell 1977)

India

Kolar gold field: pillowed mafic komatiites (Viswanathan 1974)
Dharwar greenstone belts: highly metamorphosed ultramafic and mafic rocks, possibly of komatiitic origin (Naqvi 1976)

Finland

Various greenstone belts in eastern Finland: ultramafic and mafic komatiites (Mutanen 1976)

Greenland

Godthåb area: ultramafic and mafic enclaves in felsic gneisses are interpreted as highly metamorphosed komatiites and tholeiites (McGregor & Mason 1977)

Central Sahara

Proterozoic spinifex-textured ultramafic komatiites (Chayka 1977)

Kola Peninsula, U.S.S.R.

Ultramafic and mafic komatiites of a range of Lower and Middle Precambrian ages (Suslova 1977)

* Pillow lavas in the Vermilion district, Minnesota (Green & Schulz 1977) and some of the Ventersdorp lavas, South Africa (McIver 1975) have Fe- and Ti-rich compositions resembling those of tholeiites rather than komatiites (Arndt & Brooks 1978).

1976) and from other diverse locations (Brooks & Hart 1974). Other volcanic rocks described as picritic in older literature (*e.g.*, the upper pillow lavas at Troodos, Cyprus: Searle & Vokes 1969) have similar compositions. Little has been published on the field characteristics and petrology of these lavas and it is not known how closely they resemble Archean komatiitic lavas. Whether or not such Phanerozoic magnesian lavas qualify as komatiites hinges on the questions of definition and nomenclature that are currently under review.

Ultramafic Komatiite Volcanic Rocks

In Tables 1 and 2, and in the following sections, the mineralogy, textures and field characteristics, firstly of the ultramafic komatiites, then of the mafic komatiites, are summarized. References to original papers containing detailed descriptions of these rocks may be found in Tables 1 and 3.

Mineralogy

The mineralogy of ultramafic komatiites is simple, with principal primary phases being olivine (Fo_{90-95}), aluminous augite and basaltic glass. Chromite is usually present in minor amounts. Representative analyses are given in Table 4. Invariably the glass is devitrified to a submicroscopic intergrowth of hydrous minerals, and usually the olivine is partly or completely replaced pseudomorphically by serpentine and chlorite. In relatively fresh samples the pyroxene is unaltered, but in more highly metamorphosed examples it is replaced by chlorite or tremolite. Similarly, chromite may be unaltered or partly or completely replaced by magnetite.

In areas of higher metamorphic grade, especially where CO_2 is introduced during the alteration process, the ultramafic lavas become completely recrystallized and the primary phases are replaced by a variety of secondary minerals

TABLE 4. COMPOSITIONS OF COMMON MINERALS IN KOMATIITIC LAVAS

	1	2	3	4	5	6	7	8
SiO_2	41.8	50.98	–	55.2	57.1	52.1	51.6	54.4
TiO_2	–	–	0.45	0.11	0.04	0.26	0.35	0.03
Al_2O_3	–	5.04	13.9	2.02	0.91	2.48	3.10	27.6
Cr_2O_3	0.21	–	46.8	0.63	0.50	–	–	0.00
Fe_2O_3	9.8†	8.52†	7.03	9.4†	7.9†	7.2†	9.48†	1.06†
FeO			27.9					
MnO	–	–	0.52	0.26	0.21	0.16	0.21	0.00
MgO	48.2	17.33	4.20	28.9	32.0	17.5	17.7	0.06
CaO	0.27	16.37	–	4.02	1.18	19.1	17.2	11.6
Na_2O	–	–	–	0.04	0.01	0.11	0.13	5.12
Total	100.3	98.3	100.8	100.6	99.8	98.9	99.9	99.8
$\frac{MgO}{MgO+FeO}$*	0.90	0.78	–	0.85	0.88	0.81	0.77	–

1. Olivine from spinifex-textured ultramafic komatiite (Arndt *et al.* 1977, Table 2). 2. Aluminous augite from spinifex-textured komatiite (Nesbitt 1971, Table IV). 3. Chromite from spinifex-textured komatiite (Arndt *et al.* 1977, Table 4). 4. Magnesian pigeonite in pyroxene spinifex texture, Fred's flow (Arndt & Fleet 1979). 5. Bronzite from cumulate layer, layered komatiite flow (Arndt & Fleet 1979). 6. Augite from cumulate layer, Fred's flow (Arndt 1977, Table 1). 7. Augite from mafic komatiite lava flow (Arndt *et al.* 1977, Table 3). 8. Plagioclase (An_{56}) from gabbro, layered flow (unpublished analysis).
† Total iron expressed as FeO.

including antigorite (instead of chrysotile or lizardite in less metamorphosed rocks), talc, magnesite, dolomite, anthophyllite, and secondary enstatite and olivine (Binns *et al.* 1976, Eckstrand 1975, Williams 1972, Oliver *et al.* 1972).

Textures

In the relatively slowly cooled central parts of flows, the mineral grains tend to be relatively large and nonskeletal, and have equant or prismatic habits. Olivine is polyhedral or granular, usually 0.2 to 0.7 mm in average dimensions (Donaldson's (1976) terminology is used to describe the olivine habits). Chromite forms euhedral octahedra (0.05 to 0.2 mm) and augite occurs as somewhat skeletal, prismatic grains (0.1 to 0.3 mm). In thick, layered ultramafic–mafic flows and sills (discussed below) all mineral grains are coarser and even the pyroxenes have nonskeletal habits.

By contrast, in the quenched margins of flows or in pillows, all minerals are finer grained and usually are skeletal. Olivine occurs

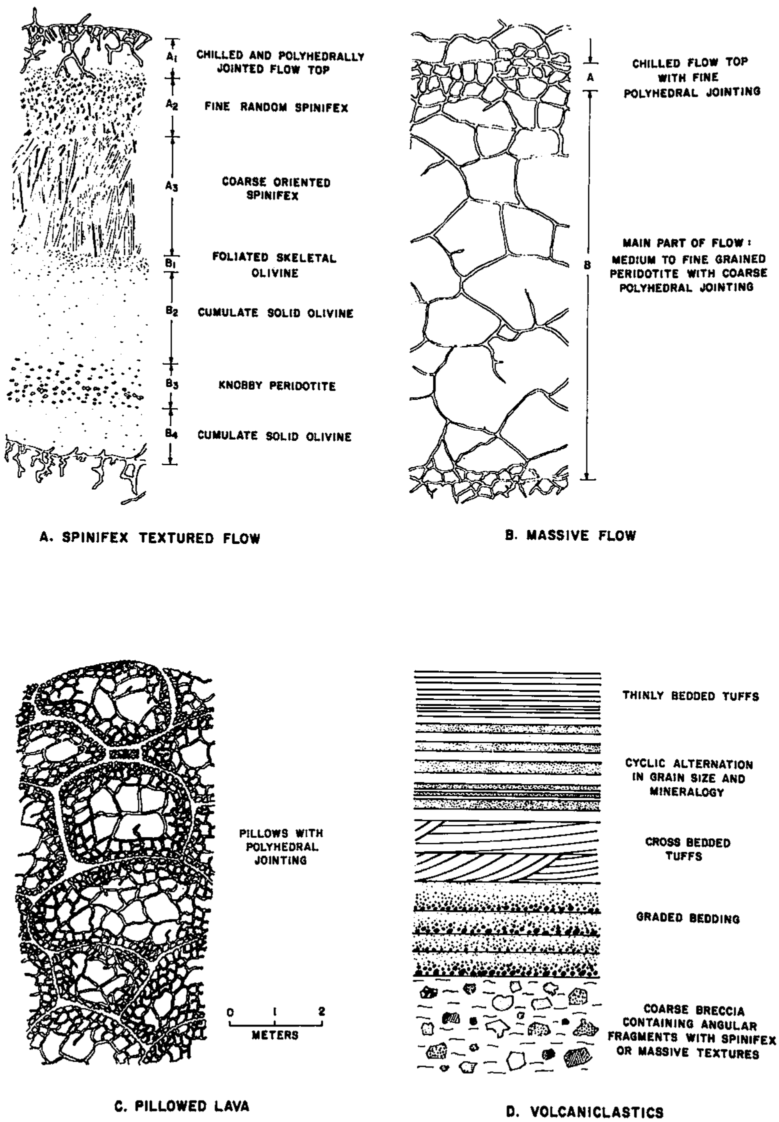

FIG. 1. Diagrammatic representations of common types of ultramafic lavas and volcaniclastic rocks.

as delicate chains, plates or dendrites (0.1 to 0.5 mm); chromite forms intricate highly skeletal, cruciform grains, and the pyroxene forms feathery dendrites (Fleet 1975, Gélinas & Brooks 1974).

In the phenocryst-free upper sections of lava flows, where temperature and perhaps composition gradients are steep, spinifex textures form by rapid growth of mafic minerals from chilled flow-tops down into supercooled ultrabasic liquids (Nesbitt 1971, Donaldson 1976, Arndt *et al.* 1977). In this texture, large, platy, skeletal grains of olivine 3 cm or greater in length are arranged in parallel groups or radiating clusters. They lie in a matrix of fine dendritic augite, skeletal chromite and devitrified glass.

TABLE 5. MODAL ANALYSES OF KOMATIITES[1]

	1	2	3	4	5	6	7	8	9	10
Olivine	41.3	84.1	54.7	15.7	-	-	-	-	-	59.4
Clinopyroxene	48.6	8.5	35.3	61.8	72.1	31.7	40.8	35.2	58.6	13.0
Orthopyroxene	-	-	-	-	-	-	-	-	30.7	5.7
Pigeonite	-	-	-	-	8.3	-	-	-	-	-
Amphibole	-	-	-	-	-	6.3	-	7.2	-	0.2
Chlorite	-	-	-	-	-	-	9.8	6.8	8.6	-
Glass	9.4	6.8	9.6	20.5	19.3	-	-	-	-	21.6
Plagioclase	-	-	-	-	-	59.4	40.0	45.3	-	-
Quartz	-	-	-	-	-	1.1	1.4	4.1	-	-
Chromite	0.8	0.5	tr	2.0	-	-	-	-	-	1.0
Fe-Ti oxides	-	-	-	-	tr	1.5	tr	1.4	2.1	-

1. Olivine spinifex-textured ultramafic komatiite lava (P9-168)[2].
2. Cumulate zone, ultramafic komatiite flow (P9-190).
3. Massive ultramafic lava (P9-194).
4. Mafic komatiite lava with olivine phenocrysts (P9-176).
5. Mafic komatiite lava with randomly oriented pyroxene needles (P9-227).
6. Mafic komatiite lava with pyroxene and plagioclase (P9-110).
7. 'String-beef' pyroxene spinifex-textured lava, Fred's flow (P9-107).
8. Gabbro, Fred's flow (P9-173).
9. Augite-bronzite cumulate, Fred's flow (P9-203).
10. Olivine cumulate, Fred's flow (P9-199).

[1] Where altered, proportions of primary phases are estimated.
[2] All analyses refer to rocks from Munro Township (Arndt 1975).

Field characteristics

Ultramafic lava forms a variety of types of lava flow and flow breccia.

(*a*) *Spinifex-textured Lava Flows.* The most spectacular type of ultramafic komatiite flow, the type that has received most attention in the geological literature, is that with a spinifex-textured upper section and a cumulate lower section (Fig. 1a). Flows of this type have been described in detail (Pyke *et al.* 1973, Barnes *et al.* 1974, Arndt *et al.* 1977, Imreh 1978, Lajoie & Gélinas 1978), and will be discussed here only briefly.

Individual flows range in thickness from less than a metre to greater than 20 m. The thickest flows are the dunitic units which form the bases of ultramafic–mafic flow sequences. The flows may extend hundreds of metres along strike with little variation in thickness, or they may end abruptly in bulbous terminations.

Spinifex-textured flows (Fig. 1a) have a chilled flow-top (the A_1 zone of Pyke *et al.* 1973) containing a small proportion of solid olivine phenocrysts and a larger proportion of skeletal hopper olivine grains in an augite–glass matrix. The flow top exhibits unusual polyhedral jointing. Underlying the chilled zone is spinifex-textured lava. Pyke *et al.* (1973) recognized a single spinifex-textured layer (A_2 zone) in which the grain size progressively increases from top to base. Lajoie & Gélinas (1978), Ross & Hopkins (1975) and Barnes *et al.* (1974) recognized two divisions, an upper division (A_2) containing relatively small randomly oriented chain-like crystals, and a lower division (A_3) in which larger platy crystals are arranged in intersecting, upward-pointing cones. The lower cumulate section (*B* zone) of spinifex-textured flows is enriched in polyhedral or rounded or less commonly, elongate skeletal grains of olivine. The uppermost part (B_1) contains hopper grains oriented roughly parallel to the flow top. In some flows, a knobby-weathering zone (B_3) that contains irregular patches of pyroxene–glass matrix material occurs part way through the olivine cumulate zone, dividing it into two similarly textured divisions (B_2 and B_4), each of which contains polyhedral or granular olivine in a sparse augite–glass matrix. The base of each flow is depleted in olivine and is chilled to aphanitic rock containing fine skeletal olivine grains. Model analyses of various parts of ultramafic lava flows are given in Table 5, and chemical analyses of primary phases are listed in Table 4.

Spinifex-textured flows are believed to form by extrusion of ultrabasic lava containing a small number of olivine phenocrysts. These settle towards the base of the flow, growing and being joined by additional olivine grains that crystallize from the melt, to form the basal cumulate zone. Spinifex texture forms by rapid growth of olivine crystals downward from the chilled flow-top into the underlying phenocryst-free, supercooled liquid (Pyke *et al.* 1973, Arndt *et al.* 1977, Donaldson 1976).

A variant of the typical spinifex-textured flow is described by Lajoie & Gélinas (1978). In examples from LaMotte Township, Québec, the contact between the spinifex-textured and cumulate zones is interpreted as erosional. The lowermost spinifex crystals are cut and fragments from them are trapped in concave depressions in the contact. The underlying *B* division shows layering resulting from grain-size variations, either parallel or oblique to the flow contacts. Also reported are normal and reverse grading within the layers. These features are interpreted to be the result of flowage of lava beneath a crust of previously formed spinifex-textured lava.

The proportion of spinifex-textured to cumulate lava varies considerably. Normally between one third and two thirds of the flow is spinifex-textured, but in flows from Griffin Lake, Northwest Territories (Hall 1978), almost all of each flow has this texture, with only a thin rubbly zone (less than 10% of the flow's thickness) at the base. At the other extreme, the thick dunitic flows that host nickel sulfide deposits (Ross & Hopkins 1975) and the thinner flows in which olivine in the cumulate zone is loosely packed (Arndt *et al.* 1977) may have spinifex zones that are only a small fraction of the flow's total thickness.

(*b*) *Massive Flows.* Most ultramafic lava flows are not spinifex-textured but massive throughout (Fig. 1b). The lava in these flows contains rounded or polyhedral olivine grains in an augite-glass matrix, a texture similar to that of the cumulate zones of spinifex-textured flows although the olivine grains are less closely packed (Table 3). Occasionally the majority of grains are skeletal, as in the thick flow described by Lewis & Williams (1973). In some flows the olivine grains are concentrated towards the centre, leaving the margins depleted in olivine, presumably a result of flowage differentiation. In others there is a progressive downward increase in the proportion of olivine.

A characteristic feature of massive ultramafic flows is polyhedral jointing of the type restricted to flow tops of spinifex-textured flows. These joints are relatively fine and angular near the margins of flows and produce distinct polyhedra ranging in average dimensions from about 3 to 10 cm. At the centres of flows they are longer, thicker, more widely spaced and gently curved, and outline crudely elliptical volumes of lava 10 to 50 cm across. These joints presumably form during cooling of the lava, perhaps in a manner similar to columnar joints.

Although not common, amygdules 3–10 mm across filled with chlorite or serpentine have been reported in some areas (Lewis & Williams 1973, Barnes *et al.* 1974; in the Carnilya Hill area, Western Australia: C.D. Arndt, pers. comm.). Generally the amygdules, which represent infilled vesicles formed by the release of volatiles from the lavas, are confined to the tops of massive ultramafic flows.

(*c*) *Pillowed Flows.* Pillows in ultramafic lavas have shapes, dimensions and, presumably, modes of origin similar to pillows in other types of subaqueous volcanic rock. Dimensions range from about 30 cm to several metres (Nisbet *et al.* 1977, Pyke *et al.* 1973, Imreh 1978) Characteristically they are polyhedrally jointed throughout, with the polyhedra finer at the margins than at the centres. Textures seem similar to those of massive lava flows. Arndt *et al.* (1977) described pillows (referred to as lava lobes: p. 333), in which a 'shell' of spinifex-textured lava wraps around an olivine cumulate core at the bottom of each pillow.

(*d*) *Volcaniclastic rocks.* Fragmental ultramafic volcanic rocks have recently been described by Gélinas *et al.* (1977) and Stamatelopoulou-Seymour & Francis (1979). The volcaniclastic rocks are intimately associated with ultramafic komatiite lava flows. Gélinas *et al.* (1977) described two types in LaMotte Township, Québec: type *A* consists of fine-grained, thinly bedded tuffs that have accumulated in channels between ultramafic pillows; type *B*, a massive breccia containing angular fragments from all parts of ultramafic lava flows, occupies an erosional channel in a sequence of flows. Stamatelopoulou-Seymour & Francis (1979) describe a thinly bedded ultramafic sediment characterized by a cyclic variation in fragment size and mineralogy with climbing ripples, graded bedding and soft-sediment-deformation structures.

In neither area are primary minerals preserved. Gélinas *et al.* (1977) interpreted the secondary mineral assemblages to indicate that the clasts are chloritized shards, granules and globules, or larger angular fragments, either once glassy or with textures identical to the lavas in associated flows. Dimensions of the fragments range from less than 0.5 mm for the shards to several tens of centimetres for the angular fragments.

Both volcanic and sedimentary processes contribute to the formation and deposition of these fragmental rocks. A cautious discussion of the relative importance of sedimentary reworking during deposition, and of detrital, pyroclastic or hyaloclastic processes in the origins of the fragments, is given by Gélinas *et al* (1977).

Mafic Komatiites

Mafic komatiites include lavas with a wide range of compositions and an even more diverse range of mineralogies and textures. Concentrations of MgO range from 20% (the lower limit of ultramafic komatiites) to less than 7%, and SiO_2 contents range from about 48% to more than 55%.

Mineralogy

The most magnesian mafic komatiites, those with more than about 15% MgO, usually have olivine (and minor chromite) as liquidus phases. Between about 12 and 15% MgO, the dominant mineral in some flows is olivine and textures and overall mineralogy resemble those of ultramafic komatiites. In other flows with roughly the same compositions, olivine is absent and the abundant minerals are calcic pyroxenes, *i.e.,* pigeonite and augite. In this composition range the mineralogy seems to depend on the conditions under which the lava crystallized. For example, in the central parts of flows and in sills, where liquids crystallize under conditions approaching equilibrium, the minerals olivine, bronzite and augite might appear from a magma with 15% MgO. The same liquid solidifying rapidly at the top of a flow would crystallize magnesian pigeonite and augite, and olivine would not appear. The effects of crystallization conditions on the mineralogy and textures of komatiite lavas are discussed by Arndt & Fleet (1979).

In less mafic komatiites (MgO between 12 and 9%), plagioclase is present, pyroxene is abundant, and olivine occurs only as rare, skeletal phenocrysts. In the least mafic komatiites, quartz is present as well as augite and plagioclase, and olivine is absent.

Accessory phases in mafic komatiites are glass in all rapidly cooled lavas, chromium-rich spinel in Mg-rich types, and hornblende and iron–titanium oxides in less mafic types.

As with the ultramafic komatiites, there always is some alteration of the primary phases. Glass invariably is devitrified, and as yet no fresh olivine has been reported (except in cumulate zone of thick, layered mafic–ultramafic flows). Of the pyroxenes, augite most commonly escapes alteration; pigeonite and bronzite almost always have been replaced by chlorite or serpentine. Plagioclase usually, but not always, is albitized or saussuritized. With higher metamorphic grade the primary mineralogy is replaced by assemblages that include antigorite, various chlorites, tremolite, actinolite or hornblende, epidote, clinozoisite and carbonate minerals (Viljoen & Viljoen 1969b, Williams 1972, Barrett *et al.* 1977, Jolly 1974).

Textures

Where present, olivine adopts habits similar to those previously described. Rounded, polyhedral or various types of skeletal grains may be present, with the specific habit depending on cooling conditions.

Augite and bronzite grains that crystallize in the centres of flows are prismatic and solid. These grains may settle to form cumulate layers or else they crystallize in place, in the company of plagioclase, minor quartz, amphibole and opaque phases in less mafic komatiites, to produce fine- to medium-grained subophitic textures. In chilled margins of flows and in pillow lavas, fine-grained augite adopts a range of skeletal, acicular, dendritic or whiskery spherulitic habits (Fleet 1975). Pyroxene spinifex is a macroscopic texture that has as its dominant textural element skeletal megacrysts composed of clusters of composite needles with pigeonite cores and augite mantles (Arndt & Fleet 1979). At the upper margins of flows these needles are oriented perpendicular to the flow contacts to produce unusual 'string beef' (Arndt 1977) or 'columnar' (Nisbet *et al.* 1977) pyroxene spinifex texture. Pigeonite–augite needles in the central parts of flows are fine grained and commonly randomly oriented. Although the matter is under review, we believe that only macroscopic textures in which the pyroxene grains show preferred orientation should be called spinifex. The matrix of the pyroxene needles consists of finer augite grains and glass in more magnesian lavas, and augite, plagioclase and quartz in less magnesian lavas.

Spherical volumes of relatively felsic lava, called varioles or ocelli, are common in mafic komatiites from many areas (Viljoen & Viljoen 1969a, Williams 1972, Nisbet *et al.* 1977). Ferguson & Currie (1972) suggested that they might be droplets of immiscible silicate liquid.

Field characteristics

(*a*) *Olivine-bearing mafic komatiites.* These lavas have textures and volcanic structures very similar to ultramafic komatiites (Fig. 2a). Olivine spinifex texture overlying olivine cumulate has been reported, but seems not to be common. More commonly the flows are massive throughout or pillowed. Polyhedral jointing is conspicuous and characteristic of this type of flow.

(*b*) *Pyroxene-rich mafic komatiites.* Illustrated in Figure 2b is a complex flow containing a variety of volcanic structures and textures. Some flows contain all these features: a brecciated flow top, a layer of pyroxene spinifex texture, a massive central zone made up of randomly oriented pyroxene needles, and a basal pyroxene-

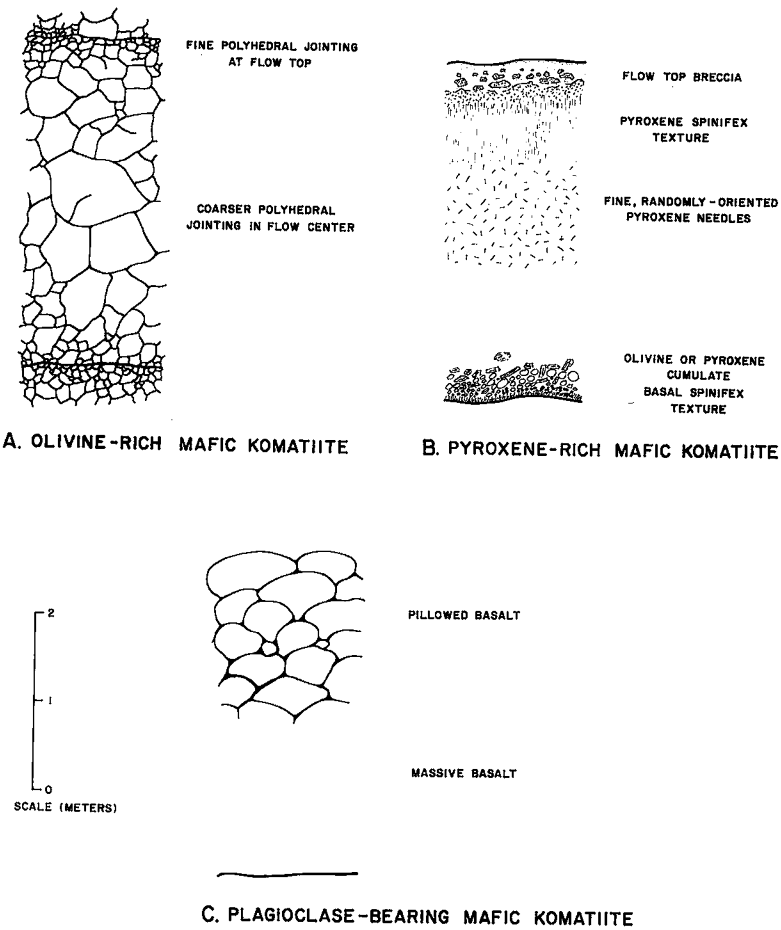

FIG. 2. Diagrammatic representations of common types of mafic komatiite lava flows. Textures are exaggerated for clarity.

or olivine-rich cumulate layer. Most flows, however, contain only some of these features. Pillows, usually massive, but in some cases with thin rims of pyroxene spinifex texture, are not uncommon. Polyhedral jointing once again is characteristic.

(*c*) *Plagioclase komatiites*. The least mafic komatiites, which are rich in plagioclase and contain modal quartz, only rarely have unusual volcanic structures or textures (Fig. 2c). They are usually massive or columnar-jointed with brecciated or ropy flow tops, or they are pillowed. Only in rare examples do they contain thin bands of pyroxene spinifex texture. The chilled margins of flows and pillows contain fine skeletal pyroxene needles and sparse skeletal olivine microphenocrysts in a glassy matrix. Centres are massive with subophitic textures, and are medium grained even in relatively thin flows.

Some composite lava flows 2 to 5 m thick in the Cape Smith fold belt have upper sections with basaltic mineralogy and textures, and lower sections enriched in mafic minerals. The differentiation in these flows resembles but is not so pronounced as in the much thicker, conspicuously layered flows described below.

LAYERED MAFIC-ULTRAMAFIC FLOWS

In some areas, thick lava flows with peridotitic lower portions and gabbroic upper portions are interlayered with normal komatiitic flows. Archean layered flows in Munro Township (Arndt 1977, Arndt *et al.* 1977) and in the Belingwe greenstone belt, Rhodesia (Nisbet *et al.* 1977) have been described in detail and will be discussed here only briefly. They will be compared with recently recognized thick, layered flows from the Proterozoic Cape Smith fold belt.

Layered flows are characterized by pronounced differentiation, which has produced truly ultramafic cumulate layers, and quartz-normative gabbroic upper sections. They also are distinguished by their unusually great thicknesses: Fred's flow in Munro Township is about 120 m thick; one flow in the Belingwe belt is 13 m thick and another possible flow is 70 m thick; the flows in the Cape Smith belt range from 30 to at least 80 m thick. Fred's flow can be traced for several kilometres along strike with little diminution in thickness. Some of the flows in the Cape Smith belt are similarly persistent along strike, but others are roughly lenticular in cross-section and appear to be the result of ponding on the underlying topography, or of differentiation *in situ* of large lava sacks or tubes analogous to, but much larger than, typical pillows.

The principal features of the Archean layered flows are illustrated in Figure 3a. Underlying a flow-top breccia is a spinifex-textured layer. In Fred's flow, olivine spinifex overlies 'string beef' pyroxene spinifex. The Belingwe flows contain only pyroxene spinifex texture. Gabbroic sections are medium grained, with textures like those of intrusive sills. Pyroxene cumulate layers, which contain augite or bronzite or both, are relatively thin. They are underlain by a much thicker interval of olivine cumulate. A layer of pyroxene-rich equigranular medium-grained rock forms the basal several metres of each flow.

The Proterozoic layered flows share with their Archean counterparts their gabbroic upper sections, the thin cumulate pyroxene layer, the thicker layer of olivine cumulate and the equigranular or pyroxene-rich quench-textured basal layer. However, the upper and lower flow contacts are different. The upper third to two thirds of the gabbroic layer is fine-grained and columnar-jointed (as are parts of the olivine cumulate layer). In some cases a thin breccia forms the top of the flow; in others the upper several metres are pillowed. A layer of pillows, 1–2 m thick, occurs at the base of many flows.

Thick, layered flows are believed to have formed by differentiation following eruption of magnesian komatiite lavas with 12 to 20% MgO. The olivine cumulate layers form by gravitative settling of olivine phenocrysts and of olivine that crystallized following eruption. Pyroxene crystallization and accumulation follow. In the Archean flows the spinifex-tex-

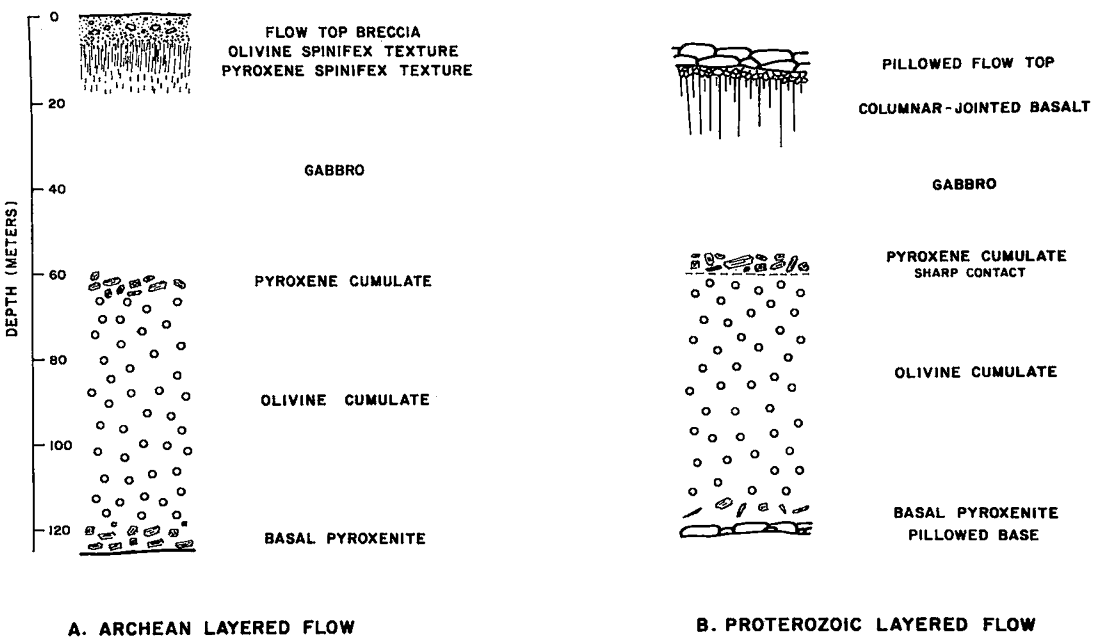

FIG. 3. Diagrammatic representation of layered ultramafic–mafic lava flows. Textures are exaggerated for clarity.

tured layers form by growth of mafic minerals downward from the crust of flow-top breccia. In the Proterozoic flows, the tops become pillowed, or solidify to give a fine-grained rock in which columns later develop. Finally, in both types, the residual, fractionated liquid solidifies to produce gabbro.

Komatiitic Intrusions

Certain types of intrusive rock in areas of komatiitic lavas have mineralogical, chemical and certain textural features similar to those of the lavas, and are believed to be genetically related. There are several types, which have been divided somewhat arbitrarily for the purposes of description into three groups: small ultramafic dykes and sills, large dunitic intrusions, and layered peridotite–gabbro sills. Intrusions composed solely of gabbro of komatiitic affinity probably exist, but have not yet been described.

Small ultramafic dykes and sills

Concordant and discordant ultramafic intrusions invade mafic and ultramafic komatiite lava flows in several locations (Barberton Mountain Land: Viljoen & Viljoen 1970, Williams & Furnell 1979; Munro Township: Arndt *et al.* 1977; Belingwe greenstone belt: Nisbet *et al.* 1977). The examples described range in thickness from less than a metre to 20 or 30 m, and some have been traced along strike for up to 250 m, in many cases to the limits of outcrop.

The ultramafic sills and dykes have mineralogy similar to ultramafic lava flows: olivine grains are set within a matrix of augite and devitrified glass. Usually the olivine grains are concentrated towards the centre, leaving the margins of the intrusion relatively rich in pyroxene. Textures in the intrusions resemble those of ultramafic lavas, except that textures resulting from extremely rapid cooling are absent. Whereas pyroxene in lavas is fine grained and acicular, pyroxene in the intrusions tends to be coarse and to poikilitically enclose olivine grains, which also are coarser (0.5 mm to 1 cm) than in lavas. In several dykes in Munro Township, bands of pyroxene spinifex texture (10–50 cm wide) occur along both margins, 10–20 cm from the contacts with adjacent lavas.

Small intrusions of this type may represent feeders to the ultramafic lava flows, or they may be incidental intrusions into the lava pile.

Large dunitic intrusions

Much larger intrusions with dunitic cores and peridotitic margins have been reported in Archean areas in Canada and Australia. What is interpreted as a single intrusion, now broken by folding and faulting into a number of separate lenses, extends from Wiluna to Mt. Clifford in Western Australia, a distance of several hundred kilometres (Naldrett & Turner 1977, Barrett *et al.* 1977). Individual lenses have thicknesses ranging from 300 to 1500 m. Other Australian intrusions (in the Forrestania area) and Canadian intrusions (the Dumont complex, in Québec) are somewhat smaller, but of the same magnitude. The intrusions are concordant on a regional scale, but locally discordant.

Individual lenses have dunitic cores composed entirely of coarse (3 mm), interlocking grains of olivine (Fo_{91-95}) (usually serpentinized or replaced by talc and magnesite), minor chromite and, in some locations, interstitial nickel–iron sulfides. Margins of the lenses are peridotitic and contain anhedral grains of augite and orthopyroxene (altered to tremolite, serpentine and talc) in addition to olivine. Naldrett & Turner (1977) interpreted a crude cyclic variation in MgO, CaO, Al_2O_3, Ni and Cu in the marginal peridotites to be a result of sequential influxes of magma into the intrusion.

The dunitic intrusions are economically important because they contain very large deposits of low-grade disseminated nickel sulfides (*e.g.*, Mt. Keith, Western Australia; Dumont, Québec), or rich deposits of massive sulfides (Perseverance and the deposits of the Forrestania area, Western Australia).

Layered mafic-ultramafic intrusions

Many of the layered peridotite–gabbro intrusions that are commonly found in areas of komatiitic volcanism are unrelated to the komatiite lavas but have magmatic affinities with iron-rich tholeiitic volcanic rocks. Examples of this type of sill are described by Naldrett & Mason (1968), MacRae (1969), Williams & Hallberg (1973) and Viljoen & Viljoen (1970). Other layered sills are comagmatic with the komatiites. The two types are best distinguished by chemical criteria (the tholeiitic intrusions are richer in Fe and Ti: Arndt *et al.* 1977) but the komatiitic sills may also be identified by petrological characteristics shared with the komatiitic layered flows described previously. The komatiitic sills have very thin layers of pyroxene cumulate and a preponderance of olivine cumulate. Estimated initial magma composition are highly mafic, with MgO contents between 13 and 25%. The tholeiitic sills have thick layers of pyroxene cumulate, and their high Fe contents are reflected in an abundance of iron oxides, features that they share with tholeiitic layered flows (Arndt *et al.* 1977, Arndt 1977).

Layered intrusions probably of komatiitic affinity have been identified in Proterozoic areas. The Jimberlana dyke in Western Australia, dated at 2.4 Ga, has similar petrological features and compositions to the Archean layered sills (Campbell 1977).

Laterally extensive layered sills with gabbroic upper sections and cumulate lower sections are a conspicuous feature of the mafic igneous succession in the Cape Smith fold belt. Above a fine-grained, chilled contact zone is a 10–20 m thick transitional zone with amphibolitized pyroxenite at the base grading up into pyroxene-rich peridotite and then passing gradually into the overlying main peridotite. The latter, typically columnar jointed, is commonly 30–40 m thick, and consists of euhedral olivine (80%) and oikocrystic pyroxene (20%). A relatively thin (10 m) cumulate pyroxenite layer or a zone of rhythmic layering, with alternating pyroxene-rich and olivine-rich bands, overlies the main peridotite zone. Feldspar appears immediately above this unit and the rock grades rapidly into pyroxene gabbro. In some cases the contact between gabbro and the underlying ultramafic rocks is sharp, and an erosional origin is suggested by truncation of the rhythmic layers by the gabbro.

The overlying gabbroic complex consists of three units. The lowermost is a relatively massive pyroxene gabbro which contains olivine in its lower portion. This is succeeded by a crudely layered gabbro unit characterized by fluctuating color index and schlieren enriched in blue opalescent quartz, leucoxene and biotite. Finally, a number of sills are capped by a dark grey quartz diorite.

The fine-grained basal chilled margins of some of sills indicate a komatiitic initial liquid running 12–16 wt. % MgO. Although the lower gabbros are also komatiitic in composition, the uppermost gabbros and diorites are enriched in iron and titanium, indicating possible tholeiitic affinities (Francis & Hynes 1978).

The uppermost several metres of the sills consist of fine-grained columnar-jointed basaltic rock, slightly less mafic than that of the lower border zone. The contact with overlying rock is chilled and has quench textures.

Both the Archean and Proterozoic layered sills probably form by essentially *in situ* differentiation of highly basic komatiitic magmas. In the case of the Cape Smith sills, however, the presence of isolated wholly gabbroic or largely ultramafic sills and the erosional contacts between gabbro and ultramafic rocks in layered sills suggest continued movement of magmas during and following eruption.

Discussion

Diagnostic features of komatiites

In the original definition (Viljoen & Viljoen 1969a) and in subsequent modifications (*e.g.*, Brooks & Hart 1974, Arndt *et al.* 1977), komatiites have been considered to form a series of rocks with compositions ranging from peridotite to basalt or andesite. The implication has been that these rocks represent magmas with a similar range in compositions. Of these magmas, only those with ultrabasic compositions, and the rocks formed from them, are unique; the less mafic rocks have some unusual characteristics but do not differ sufficiently from other types of picrite or basalt to justify separate names. Definition of komatiites therefore relies heavily on identification of rocks *formed by crystallization of ultrabasic liquids.* The characteristic features of these rocks then form a foundation of any set of diagnostic criteria. Other rocks that are said to constititute part of the series owe their status to features, either morphological, textural, mineralogical or chemical, that they share directly or by extrapolation with the rocks derived from ultrabasic liquids.

To identify the rocks formed from ultrabasic liquids, both textural and compositional criteria must be considered. *Olivine spinifex textures, skeletal habits of mineral grains,* and an *abundance of glass* usually are sufficient to indicate that a rock is derived from a silicate liquid with little accumulation of mafic minerals. *Mineral composition* (high Mg/Fe in mafic minerals, high Cr/Al in chromite, *etc.*), *high modal abundances of mafic minerals,* and *ultrabasic whole-rock compositions* may then be used to show that the liquid from which the rock crystallized was ultrabasic. It is not implied, nor is it necessary to demonstrate, that the rock had an identical composition to the liquid from which it formed. Accumulation of olivine may result from the growth of spinifex texture, especially the coarse spinifex in A_3 divisions, or from the settling of olivine grains, even skeletal crystals. The extent of such accumulation is not likely to be great, however; *e.g.*, if the rock has 28% MgO, the liquid from which it formed probably also was ultrabasic, although somewhat less magnesian.

Other features, although they do not seem to relate directly to the unique character of rocks formed from ultrabasic liquids, are present often enough to serve a useful diagnostic role. Included here would be *polyhedral jointing*, and *chemical criteria* (*e.g.*, high MgO/MgO + FeO*), high CaO/Al_2O_3 and low TiO_2). These criteria and spatial associations can then be used to identify as komatiitic such ultramafic rocks as porphyritic, massive, or pillowed flows, or the olivine-enriched basal sections of flows and sills.

Spatial associations also are useful in identifying mafic komatiites, which commonly form sections of volcanic sequences in which the composition varies from ultramafic to mafic. The identification may be substantiated by features shared with the ultramafic komatiites, of which the most useful are *spinifex textures* (usually the pyroxene type), *polyhedral jointing*, and the *chemical criteria* mentioned above. Once again, other features can serve a secondary diagnostic role. These include *varioles* or *ocelli* (Nisbet *et al.* 1977), and unusual mineral compositions such as highly magnesian pigeonite.

It must be recognized that some basalts that have been derived from komatiitic magmas may have no unusual volcanic structures, textures, mineralogy or chemical features. In the absence of clear spatial associations with obvious komatiites, the least mafic massive or pillowed basalts or individual units in layered flows or sills cannot be positively identified as komatiitic. The chemical criteria have local applications (Arndt *et al.* 1977, Williams & Furnell 1979), but by themselves are generally not definitive.

Finally, spinifex texture, where present, is a positive indicator of komatiitic affinity. Its absence, however, does not necessarily imply that a rock is not komatiitic. Massive ultramafic lava grades along strike into spinifex-textured lava in Archean areas. Proterozoic highly mafic lavas in the Cape Smith fold belt share so many of the features of Archean lavas that they too probably are komatiitic, but they do not show spinifex textures. Explanation of this phenomenon will require investigation of the spinifex texture, particularly of the chemical or environmental factors that control its formation.

Eruptive environment

From the morphology and textures of komatiite lavas a number of deductions can be made about their eruptive environment. Obviously it was subaqueous, and in all probability, submarine. The common presence of minor interlayered cherts and siliceous tuffs, pillows, clastic debris between pillows, and flow top or isolated hyalotuffs and breccias allows no other interpretation. Nowhere is there evidence of subaerial eruption. The graded and cyclic bedding, cross bedding and climbing ripples in ultramafic tuffs suggest deposition by turbidity currents.

The rate of eruption was great. The paucity of interflow sediments indicates that eruptions were frequent and that little time elapsed between eruptions during which sediments could accumulate. The very thick, laterally extensive flows of very fluid lava (*e.g.*, Fred's flow) can only be explained by extremely rapid outpouring of lava. Explosive activity, however, was minimal, as indicated by the rarity of vesicular lavas and the absence of obvious pyroclastic units.

The topography of the surface on which the lavas flowed may be reflected in the flow morphologies. In areas like Munro Township, thin flows are commonly spinifex-textured, laterally extensive and vary little in thickness along strike, suggesting eruption onto a relatively flat surface on which slopes were gentle. Ponding of lava flows in the Cape Smith sequences indicates a more rugged topography. In the Duparquet area, Québec, ultramafic flows rarely are spinifex-textured; they are impersistent along strike, and commonly grade from lenticular massive units into flow breccias. These characteristics are interpreted to indicate eruption onto a rugged, steeply sloping surface.

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