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Uniquely fresh 2.7 Ga komatiites from the Belingwe greenstone belt, Zimbabwe

E. G. Nisbet Department of Geological Sciences, University of Saskatchewan, Saskatoon S7N 0W0, Canada
 N. T. Arndt Max Planck Institut für Chemie, Postfach 3060, Mainz D-6500, West Germany
 M. J. Bickle Department of Earth Sciences, Cambridge University, Cambridge CB2 3EQ, England
 W. E. Cameron Department of Geology, Australian National University, Canberra ACT 2600, Australia
 C. Chauvel Max Planck Institut für Chemie, Postfach 3060, Mainz D-6500, West Germany
 M. Cheadle Department of Earth Sciences, Cambridge University, Cambridge CB2 3EQ, England
 E. Hegner, T. K. Kyser Department of Geological Sciences, University of Saskatchewan, Saskatoon S7N 0W0, Canada
 A. Martin 6 Autumn Close, Greendale, Harare, Zimbabwe
 R. Renner Department of Earth Sciences, Cambridge University, Cambridge CB2 3EQ, England
 E. Roedder Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138

ABSTRACT

Extremely fresh Archean komatiite has been discovered near Zvishavane, Zimbabwe. The geochemistry of these rocks opens a window to the Archean mantle and will have profound implications on geophysical and geochemical models of early Earth. In the rocks, olivine is largely pristine and contains inclusions of fresh glass. Surface sampling and a 200-m drill hole have produced complete sections through a series of komatiite flows in which chill zones are preserved and which have MgO content of 17–20 wt%. Some alteration has taken place, but these are nevertheless among the freshest Archean rocks yet found.

provides a much firmer foundation for building models of early Earth.

The fresh komatiite occurs near Zvishavane in southern Zimbabwe and was discovered by A. Martin. The locality is poorly exposed, but several komatiite flows can be identified in a stream section. In order to recover a complete suite through several flows in the freshest part of the succession, a 200-m hole was drilled (SASKMAR hole). The lower 170 m of core was nearly completely recovered and passed through at least six flows.

INTRODUCTION

A remarkably fresh suite of Archean komatiite lava flows has been found in the Belingwe greenstone belt, Zimbabwe. Komatiites are very magnesian lavas, mostly of Archean age. They are derived from the mantle and are samples and also thermometers of Earth's interior. From the study of their geochemistry comes much of the information that serves as the basis for geophysical, geochemical, and tectonic models of early Earth (Bickle, 1978; Richter, 1985). Evidence from komatiites can help us discover the

temperature of the Archean mantle, its composition and how it convected, how the continents segregated, and whether plate tectonics operated during the Archean. Unfortunately, virtually all Archean komatiites have been altered, metamorphosed, deformed, and weathered; thus, much of the basic information for these models of early Earth is from reconstructions of the original chemical composition of what are now mainly assemblages of serpentine, talc, and chlorite. The discovery of nearly fresh Archean komatiites is therefore very significant in that it

STRATIGRAPHIC SETTING

The Belingwe greenstone belt was deposited on an older tonalitic crust (Bickle et al., 1975). The Reliance Formation, which is dominantly komatiitic (Nisbet et al., 1977; Martin, 1978), forms the lower 1 km of a 6-km-thick mafic subaqueous volcanic sequence (Fig. 1). A Pb-Pb isochron using eight komatiitic basalts from the lower part of the Reliance Formation gave an

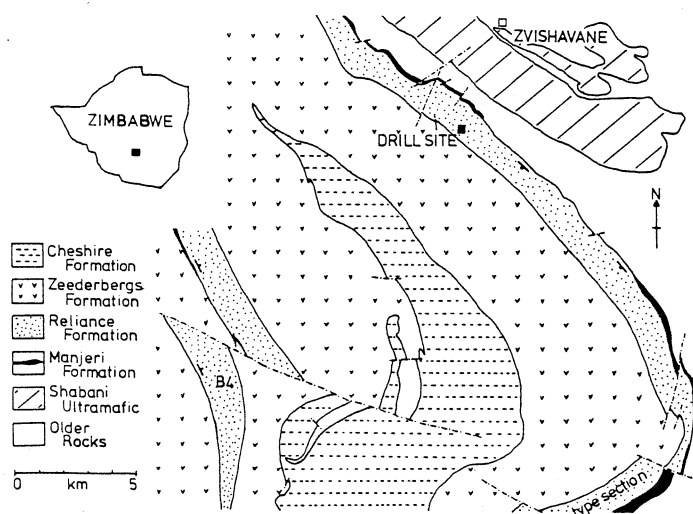


Figure 1. Location map of SASKMAR 1 drill site, south-central Zimbabwe. Other moderately fresh material is exposed at B4 locality. Type section of Reliance Formation (southeast corner of map) was discussed in detail by Nisbet et al. (1977).

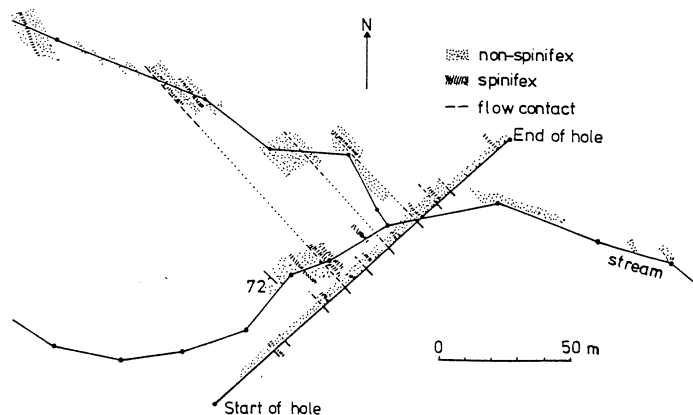


Figure 2. Correlation between surface mapping and SASKMAR 1 drill core. Schematic projection from drill-hole log to surface is along bedding plane. Nonspinifex includes all rocks that do not display spinifex olivine in hand specimen; some of these rocks have microspinifex texture.

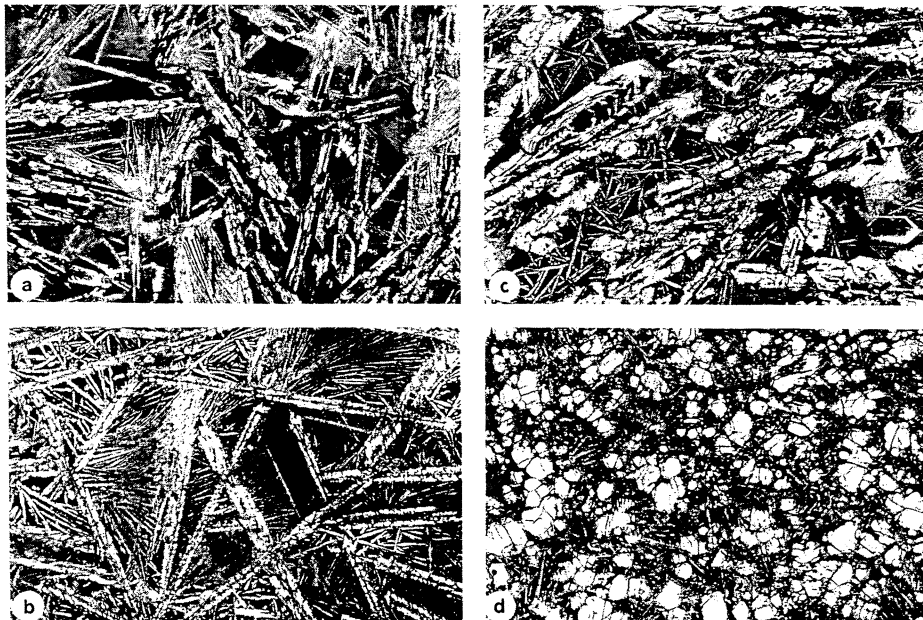
TABLE 1. SUMMARY OF LAYERED FLOWS IN DRILL CORE

	FLOW					
	Tony's	Joe's	Jefferson's	Anderson's	Onias's	Cemuson's
Thickness (m)	10.2	11.3	11.2	12.6	9.7	6.2
A-zone						
Thickness (m)	3.5	4.6	4.1	3.5	3.9	2.7
B-1 zone						
Thickness (m)	0.5	0.65	0.6	?	0.4	Absent
Special features		oriented spinifex	Distinct B-1 zone	Cpx spinifex		Spinifex veins in B zone
Bottom chill	yes	yes	yes	no	yes	?

TABLE 2. MINERAL AND GLASS INCLUSION COMPOSITIONS

	Phenocrysts		Olivine		Pigeonite Groundmass	Augite	Glass Inclusion
	Polyhedral ZV10	Hopper ZV12	Quench Lantern ZV87	Spinifex ZV14			
Oxides (wt%)							
SiO ₂	41.40	41.14	40.96	40.80	53.47	50.95	57.85
TiO ₂	-	-	-	-	0.15	0.30	0.73
Al ₂ O ₃	0.07	0.07	0.07	0.06	3.36	4.98	16.39
Cr ₂ O ₃	0.17	0.21	0.22	0.20	0.73	0.70	0.07
FeO	6.50	7.83	9.22	11.08	9.28	7.58	3.24
MnO	0.11	0.12	0.14	0.17	0.23	0.20	0.07
NiO	0.44	0.42	0.39	0.33	0.07	0.04	-
MgO	51.10	49.74	48.82	47.64	27.78	18.24	2.73
CaO	0.22	0.24	0.23	0.25	5.06	17.32	14.53
Na ₂ O	-	-	-	-	0.06	0.15	1.59
K ₂ O	-	-	-	-	-	-	0.08
Total	100.01	99.76	100.05	100.54	100.20	100.46	97.28
Mg	93.3	91.9	90.4	88.5	84.2	81.1	60.0
Mg + Fe							

Note: Total Fe as FeO. Electron probe analyses at the Research School of Earth Sciences, Australian National University. Mineral analyses at 25 kV, 80 nA; glass analysis at 15 kV, 30 nA.



age of 2690 ± 13 Ma (Chauvel et al., unpub. data).

The SASKMAR hole was located near the center of the Reliance Formation, about 2 km southwest of Zvishavane railway station, at lat $20^{\circ}21'S$, long $30^{\circ}02'E$ at grid reference SN 908446.

Layered flows are exposed in the center of the Reliance Formation. One flow is completely exposed in a streambed, but only the spinifex-textured part of the underlying flow is exposed. Both the outcrop quality and the freshness of the ultramafic rocks are locally variable. Measurement of exposed flow contacts implies that the strata dip consistently at 72° to the southwest.

The SASKMAR hole dips at 61° to 051° (northeast) and was sited to intersect the freshest layered flows at about 80–100 m depth. Recovery was partial or poor for approximately the first 30 m but was almost complete for the remaining 170 m. The drill encountered six layered flows, each about 10 m thick (Table 1), between 75 and 150 m drill depth, and numerous thin flows (Fig. 2). Intervening thin flows appear to lie between some of the layered flows. Correlation with surface exposure is good. In general, thick flows contain distinctive spinifex (A) and olivine phenocryst (B) zones and are separated by chills and brecciation. Pervasive, irregular bleaching and alteration is a diagnostic feature of the flow tops. Thin flows occur in the base of the hole. These rocks texturally resemble the chill zones of the layered flows.



Figure 3. Textures in Tony's flow. Width of field 6.5 mm, plane-polarized light in all photomicrographs. a: Sample ZV87. Olivine with plate, hopper, branching, and chain morphologies. Augite is finer grained and more acicular. Dark, optically unresolvable patches are devitrified glass. b: Olivine spinifex, sample ZV14. Olivine has skeletal plate morphology and is 80% serpentinized. Sprays of skeletal pigeonite-augite in devitrified glass fill interstices. c: B-1 zone, sample ZV85. Olivine hoppers and olivine with linked parallel growth blades have grown subparallel to flow top, immediately below spinifex zone. d: Olivine-rich (B-2) zone, sample ZV10. Polyhedral, unaltered olivine phenocrysts and microphenocrysts. e: Lower chill, sample ZV4, showing partially embayed olivine phenocrysts, rare microphenocrysts, and largely altered skeletal plate and hopper olivine in groundmass. Dark area is devitrified glass. Pyroxene can be seen in grayer patches.

MINERALOGY OF LAYERED FLOWS

The flows have typical komatiite mineralogy: olivine, augite, magnesiochromite, and, rarely, pigeonite and plagioclase. The upper parts of the

A zones (spinifex-bearing) consist of randomly oriented skeletal plates of olivine 1 mm long near the chilled top, changing gradually into longer, thinner plates ($20 \times 20 \times 0.2$ mm) having morphologies characteristic of more rapid

growth toward the base of the zone (Fig. 3, a and b). Oriented spinifex is developed only in Joe's flow. Flow tops have <20% of euhedral olivine microphenocrysts (0.2–0.6 mm across). The most magnesian skeletal olivine in Figure 3a is Fo_{90.4}, whereas the "chain olivine" of Figure 3b is Fo_{89.4} (Table 2). Delicate skeletal terminations and overgrowths on microphenocrysts are zoned typically to Fo₈₇ and occasionally to Fo₈₄. The matrix of the rocks from the A zone coarsens from a brown, optically unresolvable mass in the uppermost part to skeletal acicular pigeonite-augite grains 2×0.1 mm in brown, devitrified glass. Magnesiochromite ($Cr/[Cr+Al]$ 0.78–0.75, $Mg/[Mg+Fe]$ 0.73–0.45) is generally in close contact with, but not included in, olivine.

In most flows, the transition from the upper A zone to the lower olivine-enriched zone is marked by a layer of originally horizontal olivine crystals equivalent to the B-1 zone in Munro Township examples (Arndt et al., 1977). In Donaldson's (1976) morphological terms, the olivine has a branching form consisting of linked parallel growth blades up to 8 mm across with hopper cross sections (Fig. 3c) and Fo content up to 91.4 wt%.

The lower, or B zone of the layered flows consists of olivine phenocrysts (0.6–2 mm) and microphenocrysts (0.2–0.6 mm), together forming 40%–50% (modal) of the rock, in clusters from a few to about 10 grains, set in a fine-grained matrix of rare skeletal olivine, clinopyroxene, and altered glass. The olivine phenocrysts and microphenocrysts have a polyhedral (Donaldson, 1976) morphology (Fig. 3d), but a few larger crystals have enlarged skeletal forms. Microphenocrysts (Fo_{91–92}) are much more abundant than phenocrysts (Fo_{92–93.5}). Near the base of flows the proportion of polyhedral grains decreases markedly, and the abundance of groundmass skeletal olivine increases. This feature is interpreted as a bottom chill. In the sample of Figure 3e, phenocrysts are Fo_{92–93}, microphenocrysts are Fo_{91.5–92}, and skeletal plate and hopper olivines are Fo_{87–91} in composition.

Some olivine crystals contain small silicate melt inclusions (Fig. 4). These contain clear glass, which appears to be fresh, in contrast to the brown devitrified groundmass. Table 2 lists a preliminary electron probe analysis of a glass inclusion, scanned in a region clear of olivine and the shrinkage bubble. The liquid is evolved (by olivine and possibly minor pyroxene and spinel control).

Some alteration has taken place. The most delicate skeletal olivine crystals show up to 50% replacement by talc (Fig. 3a), and plate olivine is also variably replaced by serpentine and talc (Fig. 3b). Phenocrysts and microphenocrysts of olivine are variably altered to serpentine and magnetite. The groundmass, where originally glassy, is turbid and devitrified.

TABLE 3. WHOLE-ROCK GEOCHEMISTRY OF TONY'S FLOW

	ZV87	ZV14	ZV85	ZV12	ZV10	ZV7	ZV4
True depth (m)	8.8	8.2	8.2	7.3	6.8	2.0	0
Oxides (wt%)							
SiO ₂	47.59	48.91	45.26	45.51	45.26	45.80	47.21
TiO ₂	0.42	0.45	0.33	0.29	0.29	0.31	0.38
Al ₂ O ₃	8.53	9.24	6.74	5.97	6.07	6.43	7.81
Fe ₂ O ₃	2.28	2.62	2.13	1.44	1.68	1.80	2.10
FeO	9.03	8.90	8.66	8.89	8.70	8.82	9.01
MnO	0.18	0.18	0.17	0.17	0.17	0.17	0.18
MgO	17.57	15.32	22.98	27.35	26.21	24.87	19.96
CaO	8.70	9.01	6.94	6.15	6.41	6.72	8.08
Na ₂ O	1.07	1.15	0.88	0.80	0.78	0.99	1.07
K ₂ O	0.06	0.08	0.05	0.03	0.04	0.05	0.07
P ₂ O ₅	0.03	0.03	0.02	0.02	0.02	0.02	0.03
S	0.06	0.04	0.05	0.04	0.05	0.05	0.06
H ₂ O+	3.31	3.27	3.41	2.59	2.20	3.08	3.34
H ₂ O-	0.47	0.72	0.57	0.41	0.28	0.29	0.27
CO ₂	0.59	0.46	0.84	0.42	1.04	0.27	0.41
Total	99.89	100.38	99.03	100.08	99.20	99.67	99.98
MgO (anhydrous)	18.4	16.0	24.4	28.3	27.4	25.9	20.8
Elements (ppm)							
Ni	625	470	1110	1470	1460	1400	925
Cr	2400	2080	2770	2370	2330	2480	2610
V	177	187	140	120	118	125	156
Y	8	10	6	6	6	6	7
Zr	20	21	16	14	14	15	18
Rb		3.38	1.24	0.89	1.38	1.59	1.35
Sr	41.5	53.3	32.6	28.5	31.2	31.6	39.0
Ba	11	32	12	4	10	8	22
Nd	1.83	2.62	1.84		2.31		
Sm	0.67	0.96	0.68		0.85		
Ti/Zr	126	128	124	124	124	124	127
Sm/Nd	0.36	0.37	0.37		0.37		
εNd	+2.2	+2.4	+2.4		+2.5		
⁸⁷ Sr/ ⁸⁶ Sr (measured)		0.70560	0.70511	0.70455	0.70501	0.70438	0.7036
δ ¹⁸ O _{wr} (‰)	+6.8	+7.3	+7.0	+6.4	+6.8	+6.6	+6.6
δ ¹⁸ O _{ol} (‰)			+5.7	+5.3	+5.2		

Note: Major elements and Ni, Cr, V, Y, Zr, Ba were determined by XRF; FeO by wet chemistry; and H₂O, CO₂ gravimetrically, all at Australian National University, Canberra. Rb, Sr, Sm, and Nd were determined by isotope dilution at Saskatoon, where isotopic ratios and δ¹⁸O were also measured. The δ¹⁸O value obtained on the NBS-28 quartz standard was +9.6‰. ⁸⁷Sr/⁸⁶Sr on the NBS 987 Sr standard was measured to be 0.710233 ± 0.000010 (2σ mean on 21 measurements); wr - whole rock; ol - olivine. ¹⁴³Nd/¹⁴⁴Nd on the La Jolla Nd Standard was measured to be 0.511839 ± 0.000004 (2σ mean on 15 measurements). Ratios were normalized to ⁸⁸Sr/⁸⁶Sr of 8.3752 and ¹⁴⁶Nd/¹⁴⁴Nd of 0.7219.

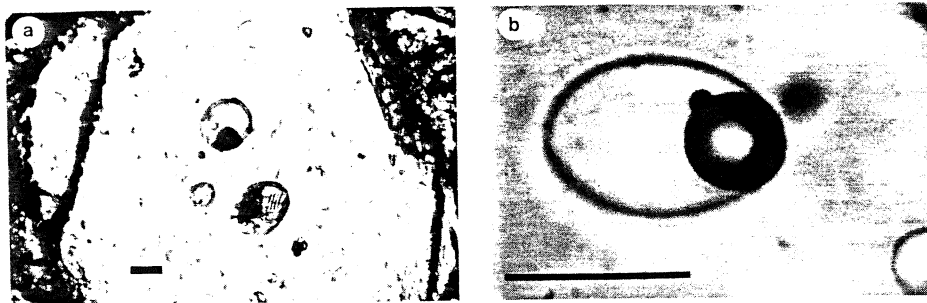


Figure 4. Inclusions in olivine. Scale bars = 10 μm . a: Two large inclusions, both of which display shrinkage bubbles. One is still glass (analysis, Table 2); other has crystallized pyroxene. b: Many inclusions contain tiny ($< 1 \mu\text{m}$) opaque phase at or near shrinkage bubble rim. Qualitative microprobe analyses give high Fe, Ni, and S, and we assume, tentatively, that mineral is pentlandite. Because proportion by volume that mineral occupies in various inclusions is relatively constant, it is probably a daughter phase precipitated from trapped silicate melt on cooling.

CHEMICAL AND ISOTOPIC COMPOSITIONS

Table 3 lists geochemical data from Tony's flow. Preliminary inspection of the core suggests that the other flows are petrographically and thus chemically similar, with the exception of Anderson's flow (Fig. 2, Table 1), which has clinopyroxene spinifex and is probably less magnesian. In Tony's flow the lower chill has about 5% olivine phenocrysts plus microphenocrysts, and if these are subtracted from the analysis, a value of 18–19 wt% MgO (anhydrous) is obtained for the liquid from which samples ZV87 (with no polyhedral olivine) and ZV4 crystallized. Sample ZV12 has the lowest FeO/(FeO + Fe₂O₃) molar ratio of 0.13. Assuming Fe₂O₃/(FeO + Fe₂O₃) = 0.10 on eruption, and a K_D value for Fe-Mg of 0.33 (Roeder and Emslie, 1970), the olivine that crystallizes from a liquid of the composition of sample ZV87 should be Fo_{90.5}. This compares with an observed value of Fo_{90.4} (Table 2). TiO₂, CaO, Sr, Zr, Na, and K show inverse variation with MgO, implying olivine control. Ti/Zr and Sm/Nd ratios are constant through the flow and are slightly higher than chondritic, averaging 125 and 0.37, respectively. These appear to be the original igneous values. Volatile contents are extremely low compared to other Archean komatiites; H₂O values reflect minor alteration of olivine to serpentine and talc, and hydration of glass. CO₂ values (Table 3) may represent thin crosscutting veins of calcite, because carbonate is not visible in thin section except in veins. Original CaO/Al₂O₃ ratios were probably 0.9–1.0.

Sr isotopes (Table 3) show significant variation within the flow, and some initial ratios are unreasonably low when calculated for an age of 2.7 Ga. This is the result of disturbed Rb content; whereas Sr shows an excellent correlation with MgO for the sample suite (Fig. 5), Rb does not and clearly has been mobile. Preliminary

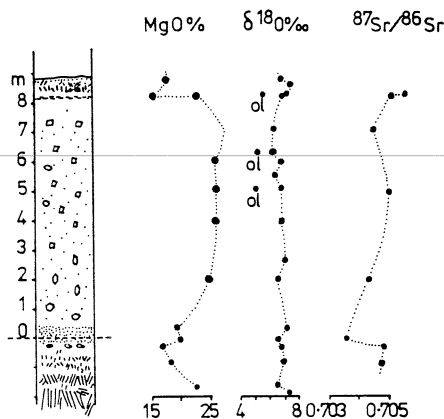


Figure 5. Textural and geochemical characteristics of Tony's flow and upper part of Joe's flow in surface exposure. Texture patterns in column: dots = chill; lines = spinifex olivine and B1 olivine; lower dots and hollow oblongs = main B-2 zone. Region below 0 = Joe's flow. Geochemical data are for whole-rock samples, except for three measurements of $\delta^{18}\text{O}$ in olivine; note contrast between these and corresponding whole-rock results.

results show that whole-rock $\delta^{18}\text{O}$ values are about 1‰ higher than those obtained from olivine. We consider the olivine results to be close to the original magmatic values, alteration of the glass causing the higher whole-rock values. Nd isotopes, which are less susceptible to post-eruptive processes, give ϵ_{Nd} values ranging from +2.2 to +2.5.

IMPLICATIONS

The discovery of nearly fresh Archean komatiite, erupted upon continental crust, is of major significance both for igneous petrology and for our general understanding of Archean Earth. Previously, the only well-preserved komatiites were Cretaceous rocks from Gorgona (Gansser et al., 1979; Aitken and Echeverria, 1984). In

the Belingwe flows, chill zones represent lavas with 17%–20% MgO (i.e., temperatures of around 1400 °C just prior to chilling), but the range of olivine compositions implies that parental melts were considerably richer in MgO. There appears to have been only minor interaction with the underlying continental crust on ascent or eruption. More generally, the discovery of these nearly pristine mantle-derived samples provides a more firm base of geochemical data upon which models of the chemistry of the early mantle can be built.

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