HSE systematics of the 3.3 Ga Weltevreden komatiites from the Barberton Greenstone Belt, South Africa and implications for the Archean mantle

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I. Introduction

Komatiites are high-MgO lavas that have the ability to accurately record the compositions of their melting source regions [1]. Models of komatiite origin imply either hot melting in mantle plumes [2] or relatively low-temperature hydrous melting in island arc settings [3]. Distinguishing between the two mechanisms of origin has important bearing on the thermal regime of the early Earth.

The majority of late Archean (2.9-2.7 Ga) komatiite systems were derived from mantle sources that evolved with long-term chondritic Re/Os and contained highly siderophile element (HSE: Os, Ir, Ru, Pt, Pd, Re) abundances at the level similar to that in the modern mantle [4]. In contrast, the source of the 3.6 Ga Schapenburg komatiites contained only 25% of total HSE present in the modern mantle and evolved with strongly suprachondritic Re/Os. [5]. It is unclear when this dramatic change occurred, whether it was the result of differences in the mechanisms of komatiite magma generation, was caused by temporal variations in the absolute HSE abundances in the mantle, or were due to the combination of factors, including, but not limited to, those mentioned.

In order to address these issues, we obtained high-precision HSE abundance and Re-Os isotopic data, as well as major, minor, and trace lithophile element abundance data for a suite of remarkably fresh komatiite samples from the Weltevreden Formation (Welt. Fm.) of the Barberton Greenstone Belt (BGB), South Africa. We use our data to determine the timing and mode of origin of the Weltevreden komatiite system, reconstruct the composition of the early Archean mantle, and discuss implications for the thermal evolution of the mantle and early Earth's accretion history.

II. Hypotheses

I. Weltevreden Formation komatiites formed approximately 3.3 billion years ago.

II. By 3.3 Ga, the terrestrial mantle had absolute and relative HSE abundances similar to those in the modern mantle.

III. Weltevreden komatiites formed via anhydrous and high degree, high temperature partial melting, likely in a mantle plume.

III. Samples

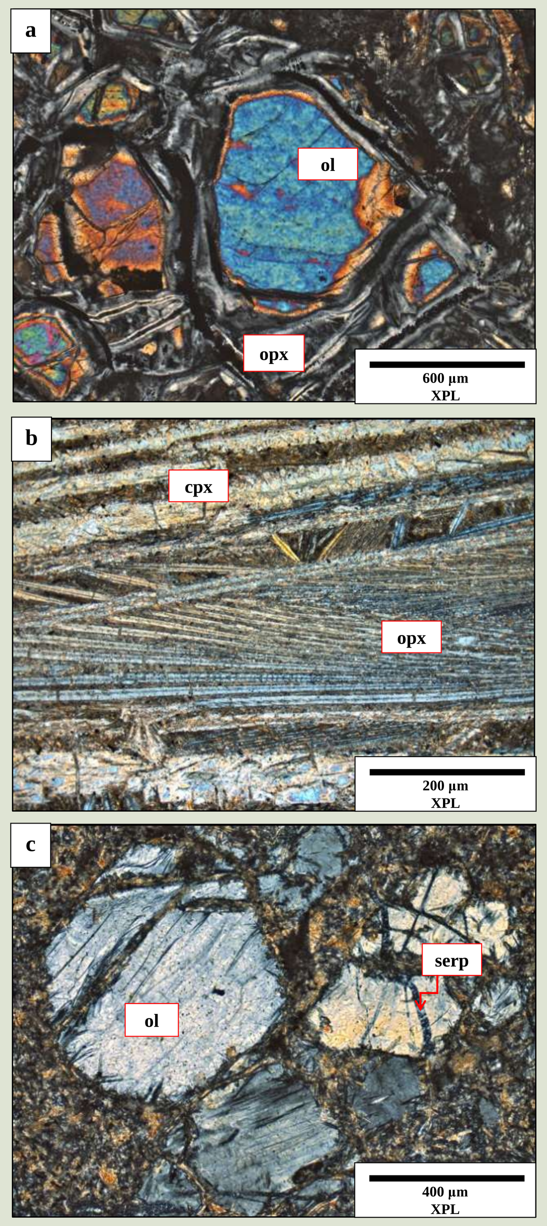


Figure 1. Optical photomicrographs of selected thin sections from the Welt. Fm. komatiite samples:

(a) cumulate [SA501-1]

(b) random spinifex [KBA12-2]

(c) chilled margin [SA564-6]

In total, twelve komatiite samples and an olivine separate from three differentiated lava flows were analyzed. Compared to komatiites of similar age, Welt. Fm. komatiites have retained much of their primary igneous textures and mineralogy.

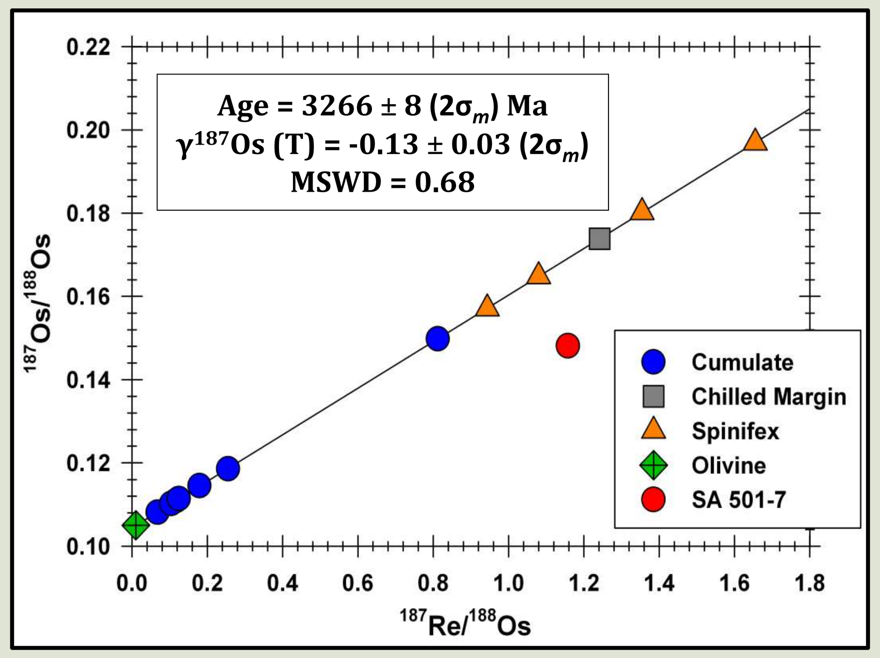
Sample SA501-7 (not shown) shows evidence of increased post-magmatic alteration when compared with the cumulate samples within the same flow. Therefore, this sample was not used in calculating age and initial Os ratios.

ol = olivine
opx = orthopyroxene
cpx = clinopyroxene
serp = serpentinized olivine

IV. Analytical Methods

Analysis	Instrument	Location
Whole-rock: Major/Minor	*Phillips 2404* X-Ray fluorescence mass spectrometer (MS)	Franklin & Marshall College
Olivine grains: Major/Minor	*JEOL JXA-8900R* electron probe microanalyzer	University of Maryland
Olivine grains: Transition Metals	*New Wave* Nd-YAG laser w/ *Thermo Finnigan Element 2* inductively coupled plasma MS	University of Maryland
Os measurements	*Thermo Electron Triton* MS negative thermal ionization	University of Maryland
Re, Ru, Ir, Pd, Pt measurements	*Nu Plasma* inductively coupled plasma MS	University of Maryland

V. Age of the Weltevreden Komatiites



Precise isochron age: 3266 ± 8 Ma.

The near-chondritic γ^{187}Os = -0.13±0.03 indicates that the komatiite source evolved with time-integrated Re/Os that was similar to that in an average chondrite.

SA501-7 plots below the regression line, likely caused by Re mobility long after lava emplacement.

Figure 2. Re-Os isochron diagram . λ ^{187}Re = 1.666^{-11} y^{-1} [6], an early Solar System initial ^{187}Os/^{188}Os = 0.09531 [7] Error bars are smaller than the symbol size

VI. Emplaced Lava MgO Content

We use two approaches to calculate the average MgO contents of the emplaced komatiite lava:

Average MgO content in Chilled Margin (CM) sample

= 30.9 ± 0.4 (2σ) wt.% MgO

Relationship between FeO in the CM sample and composition of olivine, assuming an olivine-liquid Fe-Mg partition coefficient (K_D) of 0.30 [8].

$$\frac{K_D \cdot FeO_{CM}}{FeO_{ol}/MgO_{ol}}$$ **= 31.8 ± 0.7 (2σ) wt.% MgO**

These independent methods yield an average 31.4 ± 0.9 (2σ) wt.% MgO in the emplaced komatiite lava

VII. Mantle Source Characteristics

To determine the mantle source HSE abundances, we use ISOPLOT regressions (projection technique of [9]) of the whole rock and olivine HSE data against MgO contents. We use the accepted MgO content in the Primitive Mantle (PM) of 38 wt.% [10] to calculate the incompatible (Re, Pt, Pd) HSE contents. The compatible (Os, Ir, Ru) HSE contents were calculated from the Os isotopic data and the Os/Ir and Ru/Ir relationships in the lava.

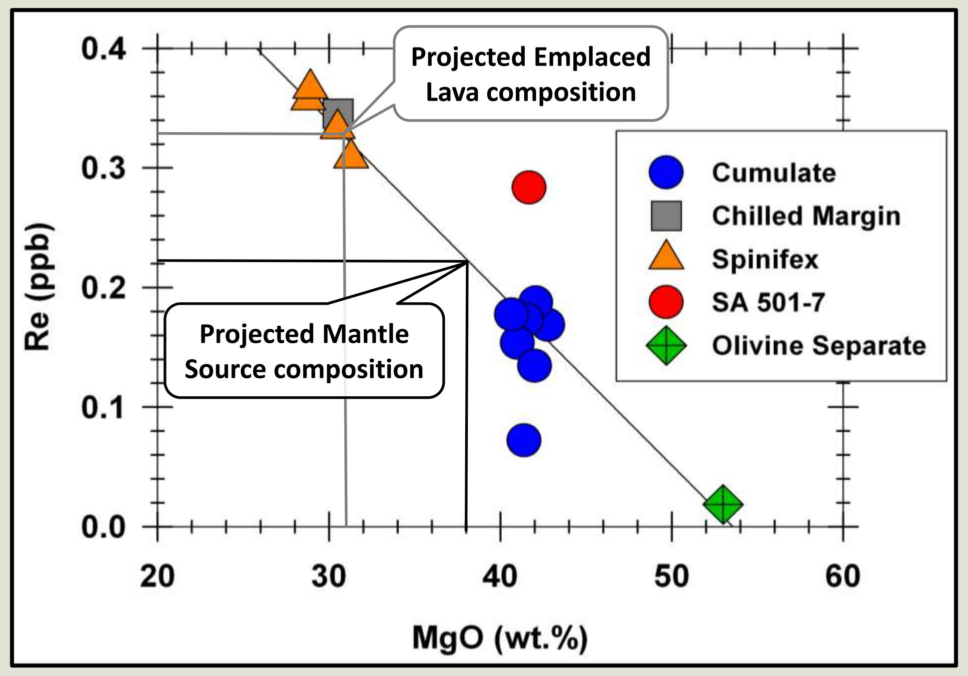
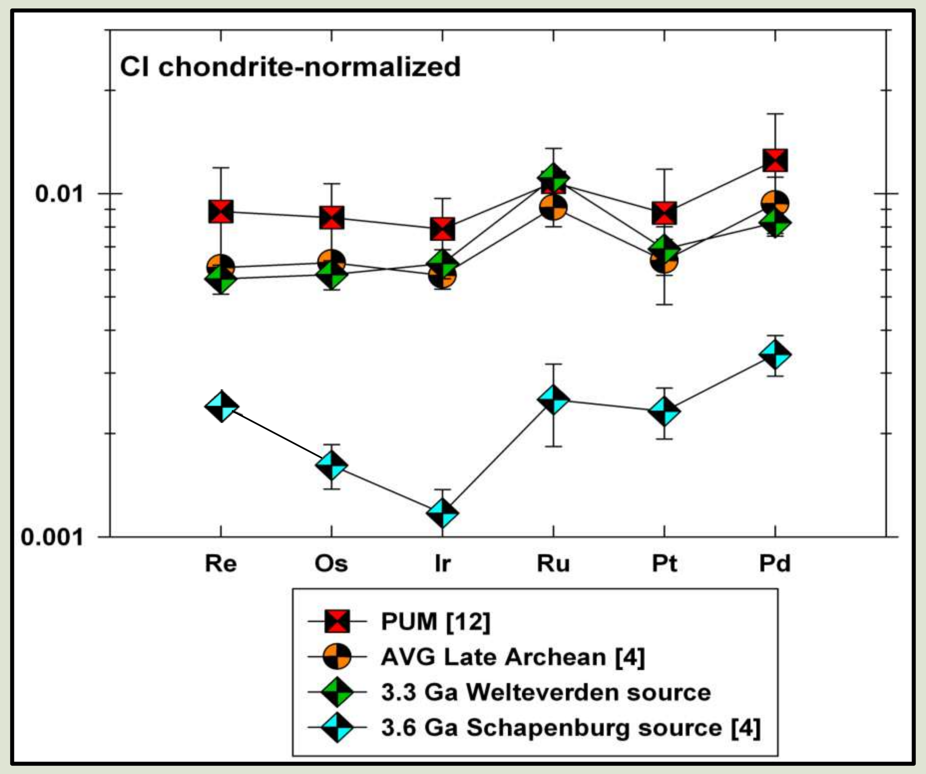


Figure 3. Re vs. MgO plot illustrating projection technique [9] used here.



The Welt. Fm. is calculated to have contained HSE abundances similar to those in average Late Archean komatiite sources and *ca.* 80% of those in modern PUM estimates.

Figure 4. CI chondrite-normalized [11] HSE abundances in the calculated Welt. Fm. komatiite source compared to average Late Archean komatiite sources of [4], a Primitive Upper Mantle (PUM) estimate [12] and the 3.6 Ga Schapenburg komatiite source [4].

VIII. Anhydrous vs. Hydrous Melting

Water is highly incompatible during mantle melting, similar to that of Ce. The H_2O/Ce content in upper mantle is *ca.* 207 [13].

Cerium is calculated to be 0.80 ± 0.05 ppm (2σ) in the Welt. komatiite mantle source. This yields an H_2O content of 166 ppm (0.02%) in the komatiite source.

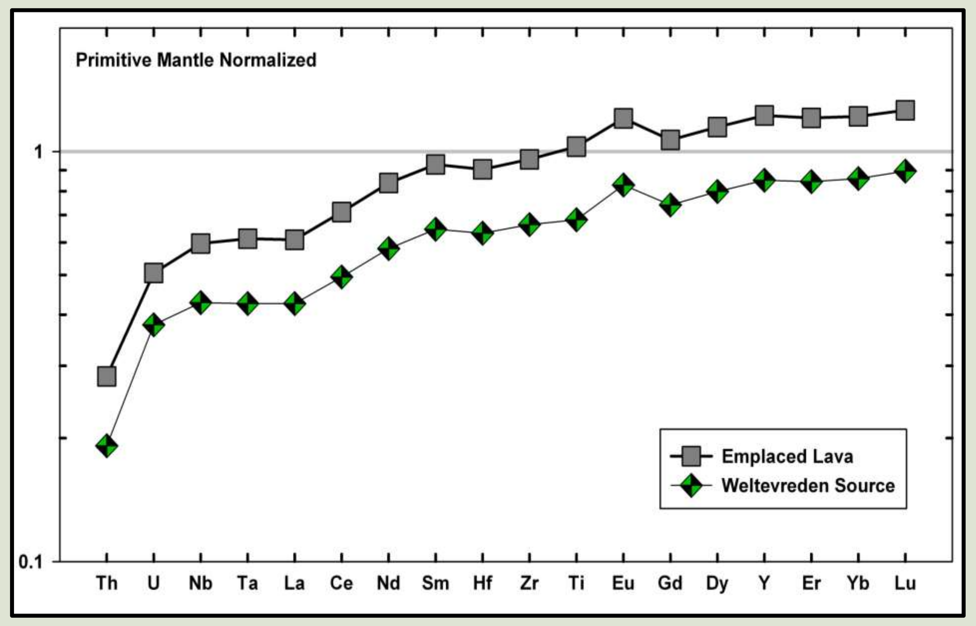


Figure 5. PM-normalized [11] incompatible lithophile element abundances showing strong depletions in the Welt. Fm. source.

Indicating extremely dry conditions in the Welt. komatiite mantle source.

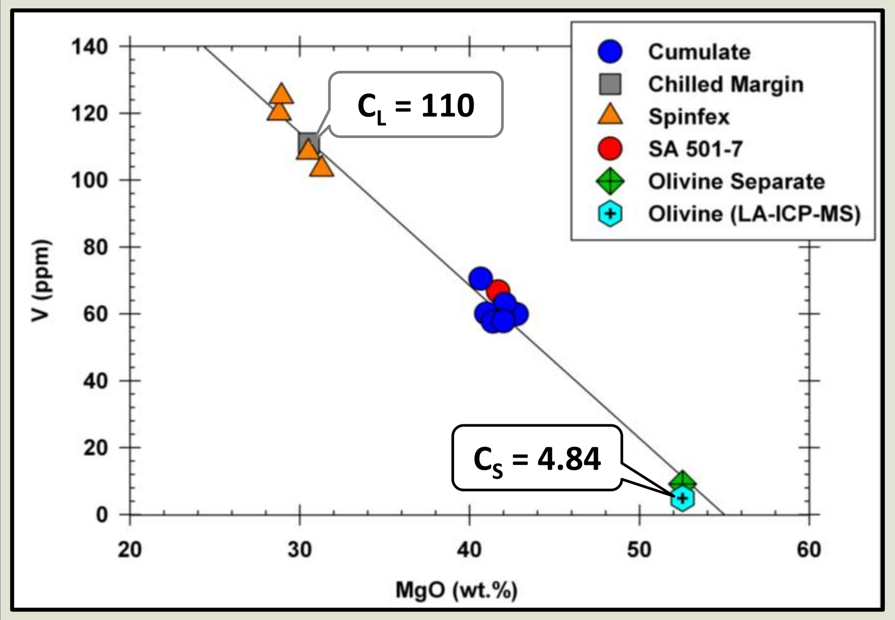
IX. Potential Mantle Temperatures

By following the protocol of [14] and the fact that these lavas likely formed via anhydrous melting, we use the calculated emplaced lava composition to estimate a liquidus temperature of the emplaced lava to be 1600 ± 10°C

This liquidus temperature is translated into the potential mantle temperature of 1830 ± 25°C, with depths of melting initiation of ~530 km following the protocol of [8; 15].

The Welt. komatiite source is calculated to be *ca.* 200°C hotter than contemporary ambient mantle predicted by secular cooling models [16].

X. Origin of the Weltevreden Komatiites



C_L = Avg. V concentration of the chilled margin sample.

C_S = Avg. V concentration of the most MgO-rich olivines.

Vanadium partitioning (D_V) in magmas can be used as a redox indicator [17-18].

$$D_V^{ol/liq} = \frac{C_S}{C_L} = 0.044 \pm 0.003(2\sigma)$$

Experimentally derived ranges [18]:

Arc system: $D_V^{ol/liq}$ < 0.01

Plume system: 0.025 < $D_V^{ol/liq}$ < 0.10

Figure 6. Vanadium vs. MgO abundances in whole-rock komatiite samples, an olivine separate, and average V abundances from (LA-ICP-MS). Error bars are smaller than the size of the symbols.

Taking into account the anhydrous melting of the mantle source, the high calculated potential mantle temperatures, and D_V, we infer a mantle-derived plume origin for the Welt. komatiites.

XI. Concluding Remarks

The Welt. Fm. komatiites are determined to form at 3266 ± 8 (2σ_m) Ma.

These komatiites are calculated to have contained an average of 31% MgO upon emplacement, which are amongst the most magnesian lavas to have erupted onto Earth's surface.

Based on the partitioning behavior of V, the potential mantle temperatures of *ca.* 1800°C, and the highly incompatible element depleted nature of the lava, anhydrous melting in a mantle plume system is inferred for the Welt. Fm.

If the HSE budget of the mantle was established by accretion of large planetesimals after the last major interaction between the core and the mantle, our data indicate that by 3.3 Ga, these materials were largely homogenized within the mantle.

These data significantly enhance our understanding of early mantle thermal regime and can be applied to models focused on early Earth mantle evolution.

XII. References

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