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Evidence for 3.3-billion-year-old oceanic crust in the Barberton greenstone belt, South Africa

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ABSTRACT

Recognition of oceanic crust in Archean greenstone belts has remained a controversial and unresolved issue, with implications for understanding early Earth geodynamics. In the search for early Archean oceanic crust, we present a multi-pronged approach to test for the presence of an ophiolite-type sequence preserved in the Paleoarchean Barberton greenstone belt (BGB) of South Africa. New field observations are combined with detrital U-Pb zircon geochronology and geochemistry on fresh drill-core material from the Kromberg type-section sequence of mafic-ultramafic rocks in the 3.56–3.33 Ga Onverwacht Group of the BGB. Trace element geochemistry indicates that the Kromberg metabasalts were derived from the primitive mantle. The ε_{Nd} values and Nd model ages of the metabasalts record a depleted Archean mantle source similar to CHUR (chondritic uniform reservoir) with no continental (tonalite-trondhjemite-granodiorite [TTG]) crustal contamination. U-Pb geochronology by laser ablation–inductively coupled plasma–mass spectrometry on detrital zircons from an uppermost chert unit indicate a homogeneous age distribution and a gabbroic source in the greenstone belt, in direct contrast to zircons from felsic conglomerates structurally underlying the Kromberg sequence. Collectively, the new data and field observations indicate that the 3.33 Ga Kromberg mafic-ultramafic sequence formed in a juvenile oceanic setting and represents a remnant of tectonically accreted oceanic crust. The identification of oceanic crust preserved as dismembered allochthons in the BGB suggests that horizontal plate tectonic processes were operating on the Archean Earth as early as Mesoarchean times.

INTRODUCTION

Recognition of oceanic crust in Archean greenstone belts is important as it has bearing on the nature of early Earth mantle temperatures and geodynamic processes (e.g., Bickle et al., 1994). Despite decades of research on the topic, confident identification of oceanic crust from the Archean remains controversial. This is particularly the case in the early Archean Barberton greenstone belt (BGB) of South Africa, where models for the origin of the mafic-ultramafic greenstone sequence are highly polarized. Debates concerning the geological origin of the greenstone belt center on whether the mafic-ultramafic sequence formed in a supra-continental (e.g., Van Kranendonk et al., 2009; Van Kranendonk, 2011; Kröner et al., 2013), an oceanic plateau (e.g., Chavagnac, 2004), or a supra-subduction zone (e.g., Furnes et al., 2012; Parman et al., 2001) geodynamic setting. Further complicating matters is the geological architecture and structural complexity of greenstone belts, with some workers proposing a tectonostratigraphy model for the BGB based on reported thrust duplication (de Wit et al., 2011), whereas others have proposed a continuous layered-cake stratigraphy with no major structural breaks (Lowe and Byerly, 1999).

In this paper, we focus on the Kromberg type-section sequence of mafic to ultramafic rocks in the oldest 3.53–3.33 Ga Onverwacht Group of the BGB and test for a continental versus juvenile oceanic setting. We develop a multi-pronged approach combining field observations, scientific drill core, U-Pb detrital zircon ages, and geochemistry of metabasalts to evaluate whether the sequence erupted on top of continental tonalite-trondhjemite-granodiorite (TTG) crust, or whether it represents a preserved remnant of accreted juvenile oceanic crust. The extent to which the Kromberg type section potentially represents an Archean ophiolite is assessed, with important implications for the nature of geodynamic processes on the early Archean Earth.

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GEOLOGY AND SAMPLING

The geographical location of the BGB on the border between Swaziland and South Africa is shown in Figure 1. The location of the mafic-ultramafic Kromberg sequence in the ca. 3.5–3.3 Ga Onverwacht Group is marked by an A–A′ profile on the simplified geological map in Figure 1C. The lithological profile of the Kromberg type section (Fig. 1D) consists of tholeiitic massive and pillowed lava flows (Fig. 1E), minor gabbroic intrusions, silicified lapilli tuff, numerous silicified seafloor sedimentary horizons (chert), minor komatiitic basalts, and coarse-grained ultramafic cumulate intrusive rocks. The uppermost part of the Kromberg is marked by a prominent sedimentary chert unit known as the Footbridge Chert, whereas the lowermost part consists of a serpentinized metadunite. Major shear zones consisting of fuchsite-chlorite-carbonate-quartz (listvenite) occur beneath the Footbridge Chert and the metadunite (Grosch et al., 2012; Furnes et al., 2012). Strong deformation fabrics in the form of folded bands are recorded in these listvenitic zones (Fig. 1F). The entire mafic-ultramafic sequence structurally overlies turbidites (Fig. 1G) and coarse-grained polymictitic conglomerates of the ca. 3.432 Ga Noisy Formation (Grosch et al., 2011).

The Kromberg shear zone was the target of an international scientific drilling project (Barberton Scientific Drilling Programme; Grosch et al., 2009a, 2009b); the KD1 drill core is marked in blue in Figure 1D. In this study, 10 surface and 10 drill-core metabasaltic pillow lava samples were selected for trace element geochemical analysis. Details of the stratigraphic location of the surface samples and the depth of drill core samples are provided in Figure DR1 in the GSA Data Repository[1]. In addition, 10 drill-core metabasalts were selected for Sm-Nd isotope analysis also shown in Figure DR1 (labeled with "T" numbers). A U-Pb detrital zircon provenance study was conducted on zircons extracted from the Footbridge Chert in the uppermost Kromberg type section (see Fig. DR1). The presence of ripple marks and flaser-bedded horizons in this unit indicate that these zircons are current- reworked and detrital in origin, and does not represent a primary ash-fall tuff.

ANALYTICAL METHODS

Full details of the analytical methods used are provided in the Data Repository. A Thermo-Finnigan Element 2 single-collector sector field

[1]GSA Data Repository item 2017225, Figure DR1, analytical methods, and Tables DR1–DR3, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

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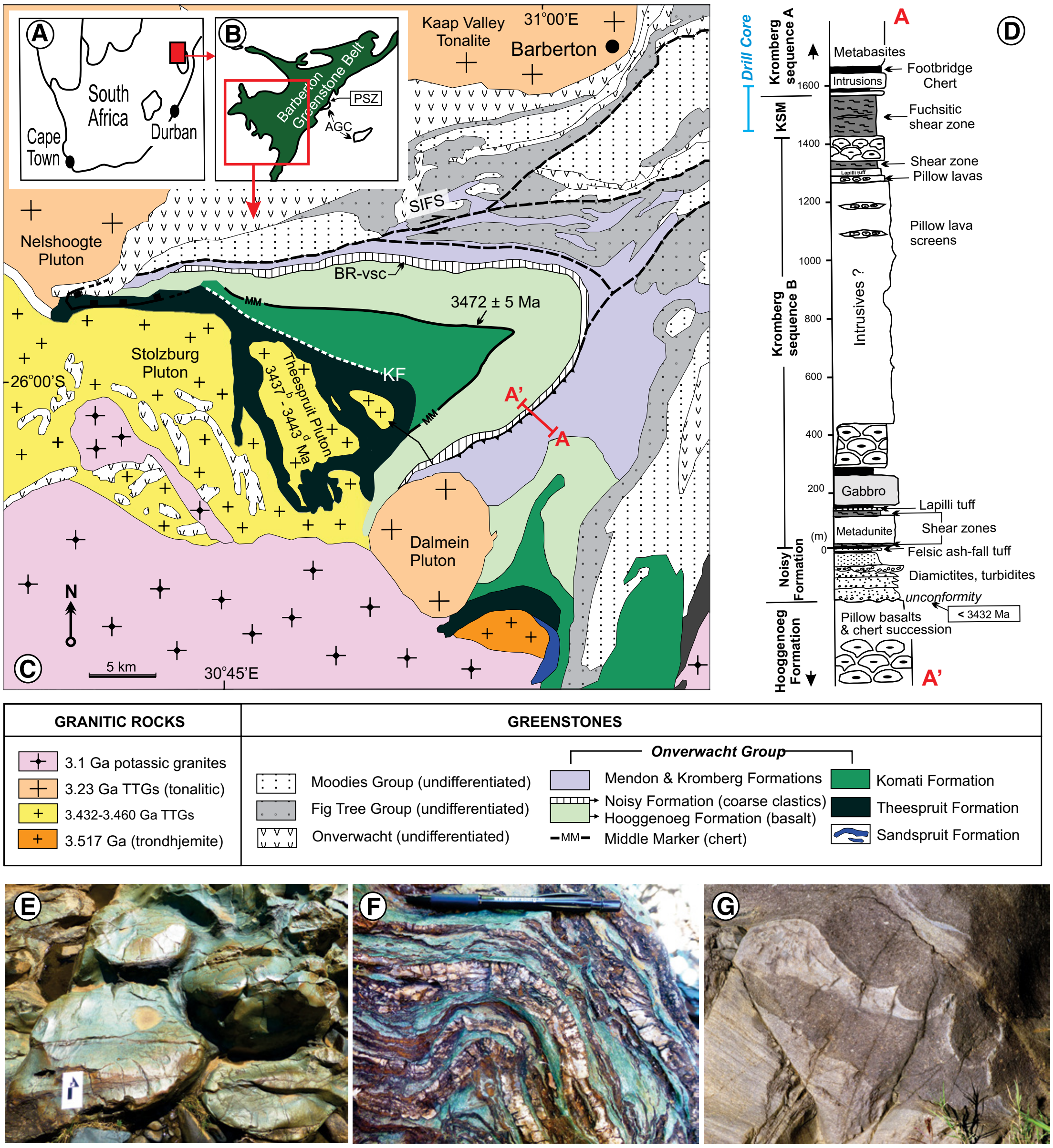

Figure 1. Simplified geological map of southwestern Barberton greenstone belt (BGB) and geology of Kromberg type section. A–C: Geology of Onverwacht Group of BGB and location of Kromberg type section labeled A-A′ (see Grosch et al. [2011, and references therein] for U-Pb zircon ages). D: Volcanic, magmatic, and structural architecture of Kromberg type section of Onverwacht Group. E: Field outcrop of typical tholeiitic pillow lavas in the lower Kromberg. F: Listvenitic alteration, deformation, and folding of ultramafic and quartz-carbonate bands in tectonite zone beneath Footbridge Chert. G: Silicified, turbiditic shallow marine sediments of the ca. 3.432 Ga Noisy Formation, structurally underlying Kromberg mafic-ultramafic sequence. Abbreviations: AGC—Ancient Gneiss Complex; PSZ—Phophonyane shear zone; SIFS—Saddleback-Inyoka fault system; BR-vsc—ca. 3455–3445 Ma Buck Ridge volcano-sedimentary complex; KF—Komatii fault; TTGs—tonalite-trondhjemite-granodiorites; KSM—Kromberg Section Mylonites.

inductively coupled plasma–mass spectrometer (ICP-MS) coupled to a 193 ArF excimer laser (Resonetics RESOlution M50-LR) was used to measure Pb/U and Pb isotopic ratios. Approximately 120 zircons were analyzed from sample FBC2 (see Fig. DR1 for zircon images); however, some analyses showed large analytical uncertainties and deviated from concordia due to polyphase zircon composition and/or Pb loss near cracks in the grains. We therefore screened the data and used only the remaining ^{207}Pb/^{206}Pb ages that were 100% ± 10% concordant. A total of 96 U-Pb zircon analyses are presented in Table DR1 in the Data Repository.

Bulk-rock trace element analysis was performed by ICP-MS analysis using a Thermo-Finnigan Element 2 high-resolution ICP-MS on 100 mg of dry sample. Trace element data on samples and reference literature data are provided in Table DR2. Neodymium isotopic ratios and Sm/Nd ratios were determined using a Finnegan 262 mass spectrometer and isotope dilution techniques. Rare earth elements were separated by specific extraction chromatography using the method described by Pin et al. (1994). The Sm/Nd isotope ratios and calculated Nd model ages are presented in Table DR3.

RESULTS

U-Pb Detrital Zircon Ages from Silicified Sediments

The ^{207}Pb/^{206}Pb ages are preferred for Archean zircons because they typically show the lowest uncertainty in comparison to the ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages (see Table DR1). In Figure 2A, a concordia diagram is shown for the zircons, indicating an intercept age of 3.33 ± 8.7 Ga (2σ level). In Figure 2B, the ^{207}Pb/^{206}Pb ages for zircon grains from the Footbridge Chert are plotted in a histogram at 2σ-level uncertainty. For comparison, a histogram showing the ^{207}Pb/^{206}Pb zircon ages for underlying conglomerates of the Noisy Formation from Grosch et al. (2011) is shown. Potential detrital sources and major magmatic events of well-known ages in the BGB are highlighted in the background of Figure 2B.

In comparison to the underlying conglomerates, the zircons of the Footbridge Chert are not only much younger, but show a relatively homogeneous age distribution. The FBC2 zircons are not derived from ca. 3.416–3.45 Onverwacht Group felsic intrusions or volcanics, nor are they derived from older felsic rocks of the Theespruit Formation or Steynsdorp pluton gneisses. The FBC2 zircons are more closely associated in age to

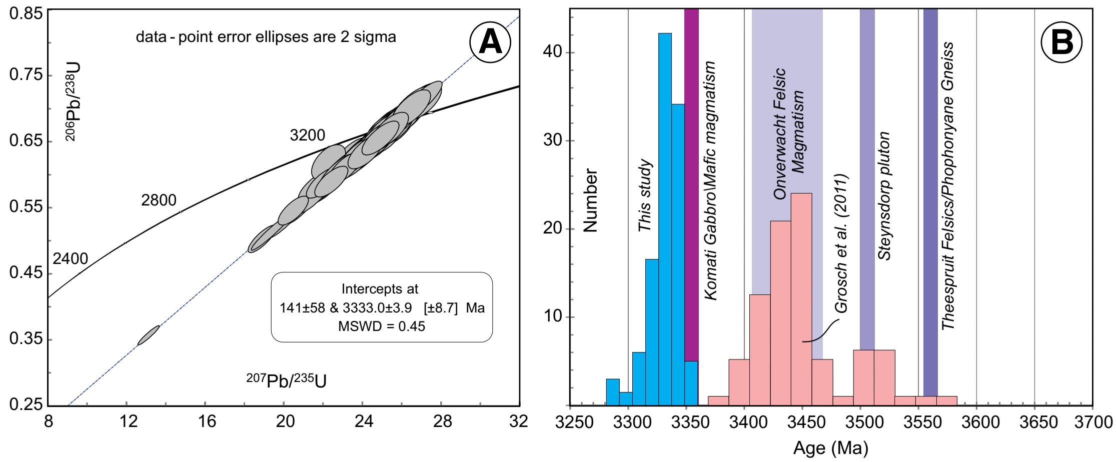

Figure 2. U-Pb dating of detrital zircons from Footbridge Chert (sample FBC2), upper Kromberg section (Barberton greenstone belt), using laser ablation–inductively coupled plasma–mass spectrometry. A: U-Pb concordia diagram of all zircons from Footbridge Chert showing intercept age of 3.33 Ga (MSWD—mean square of weighted deviates). B: Pb-Pb age distribution for concordant grains (this study, total 96 grains), with zircon provenance corresponding to mafic gabbro source.

the ca. 3.353 Ga Komati Formation gabbro and related mafic volcanic rocks (Kamo and Davis, 1994). This indicates that the likely geological setting was an oceanic basin and that sediment for the Footbridge Chert was derived from mafic oceanic igneous activity and not from older felsic TTG basement (Fig. 2B). The absence of older zircon populations means that the Kromberg was not erupted on top of continental crust, and supports a juvenile oceanic origin for the Kromberg sequence of volcanic rocks as indicated by geochemical analysis reported below.

Trace Element and Neodymium Isotope Geochemistry

The Kromberg metabasaltic drill core and surface sample compositions are plotted in Th/Yb versus Nb/Yb space in Figure 3A. Most Kromberg metabasalts have compositions very similar to that of the primitive mantle. They are also very similar in composition to oceanic plateau basalts of the 2.9 Ga Sumozero (Baltica; see Puchtel et al., 1999) and 2.7 Ga Abitibi (Canada; see Laflèche et al., 1992) greenstone belts. Their Th/Yb versus Nb/Yb ratios contrast with those of supra-subduction zone–related metabasalts of the early Archean 3.7 Ga Isua greenstone belt from southwest Greenland (Fig. 3A). A similar trend in Kromberg metabasalt geochemistry is observed in Ce/Nb versus Th/Nb compositional space, with compositions clustering around primitive mantle values (Fig. 3B). The Kromberg metabasalts are distinguished from subduction arc-related Archean metabasalts of the 3.8–3.7 Ga Isua greenstone belt (Polat et al., 2002) and share strong similarities with the juvenile oceanic plateau–related basalts of the Sumozero and Abitibi greenstone belts as well as modern-day oceanic plateau basalts (e.g., Broken Ridge oceanic plateau [Indian Ocean] and Ontong Java Plateau [Pacific Ocean]). The trace element geochemistry indicates an oceanic primitive-mantle origin for the Kromberg metabasalts, with no significant continental-crust or subduction-zone influence in the mantle source region.

Initial $^{143}Nd/^{144}Nd$ ratios were calculated at 3.33 Ga for the 10 metabasaltic drill-core samples and were used to calculate ε_{Nd} values and Nd model ages (T_{DM} [DM—depleted mantle]; Table DR3) to constrain mantle source characteristics and any potential role of continental crust contamination in the magma source region. A relatively narrow range in ε_{Nd} (t = 3.33 Ga; t is time) values is recorded by the Kromberg metabasalts of between +0.10 and +2.43. The ε_{Nd} (t = 3.33 Ga) values are close to the chondritic uniform reservoir (CHUR) value of ε_{Nd} = (0) and strongly positive. The calculated Nd model ages (T_{DM}) are typically early Archean, indicating an Archean mantle source. The ε_{Nd} values and Nd model ages all support a juvenile oceanic origin and a primitive to depleted Archean mantle source region for the Kromberg metabasalts.

EVIDENCE FOR 3.33 Ga OCEANIC CRUST IN THE BARBERTON GREENSTONE BELT

The geodynamic setting of the Onverwacht Group including the Kromberg sequence has been argued to range from eruption in a continental setting followed by partial convective overturn of the felsic mid-crust (Van Kranendonk, 2011; Kröner et al., 2013) to formation in an Archean arc or back-arc setting (e.g., Furnes et al., 2012; Parman et al., 2001). Our new findings call both of these geodynamic models into question. Moreover, the identification of oceanic crust characterized as ophiolites in Archean greenstone belts like the BGB has proven to be a highly contentious issue (e.g., Bickle et al., 1994; de Wit et al., 2011). According to some

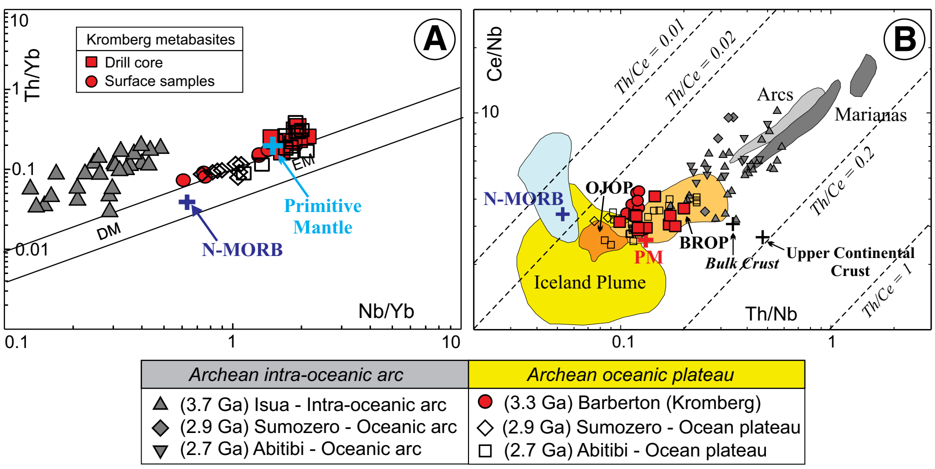

Figure 3. Trace element geochemistry of Kromberg (Barberton greenstone belt) metabasalts from drill core and surface samples. A: Th/Yb versus Nb/Yb ratios for Kromberg metabasalts corresponding mainly to primitive mantle. B: Ce/Nb versus Th/Nb global diagram. Kromberg basalts have trace element ratios that are similar to late Archean oceanic plateau basalts (e.g., Abitibi greenstone belt, Canada) and primitive mantle. Reference data are from Puchtel et al. (1999), Laflèche et al. (1992), and Polat et al. (2002). Abbreviations: DM—depleted mantle; EM—enriched mantle; N-MORB—normal mid-oceanic ridge basalt; OJOP—Ontong Java oceanic plateau ; PM—primitive mantle; BROP—Broken Ridge oceanic plateau.

workers (e.g., Bickle et al., 1994), positive confirmation of an Archean ophiolite requires the presence of at least three out of the following four geological features: (1) a mafic massive and pillowed, sediment-free lava sequence; (2) a sheeted dike unit; (3) gabbros and ultramafic cumulate rocks; and (4) tectonite peridotite. The presence of sheeted dikes in the Kromberg sequence is at best controversial (see Cloete, 1999). However, massive and pillowed lava flows with thin subordinate chert units are abundant as are ultramafic cumulate rocks (Fig. 1). Tectonized peridotite has also been described in the Kromberg sequence (Grosch et al., 2012). Furthermore, listvenitic alteration in tectonized mafic-ultramafic rocks (Fig. 1F), similar to that found in Phanerozoic ophiolites (e.g., Oman), has been described in the Kromberg type section (see Grosch et al., 2012). In addition, metamorphic constraints across the section have revealed the presence of an inverted metamorphic field gradient supporting thrust repetition (Grosch et al., 2012), again similar to metamorphic evidence preserved in Phanerozoic ophiolites (e.g., Newfoundland). In summary, field and metamorphic observations support that the Kromberg sequence of rocks share strong similarities to oceanic crust in Phanerozoic ophiolites.

The detrital zircon data from the Footbridge Chert as well as the trace element geochemistry and Sm/Nd isotope data on the Kromberg metabasalts all support a juvenile oceanic origin for the Kromberg type section, consistent with field observations and metamorphic data. The detrital zircon ages of the Footbridge Chert are homogeneous and indicate a mafic gabbro source, and are distinct from the broad zircon age distribution displayed by the underlying Noisy Formation turbidites and conglomerates and related ca. 3.41–3.56 Ga Onverwacht TTG felsic magmatic and volcanic rocks. Trace element geochemistry indicates that the Kromberg metabasalts were derived from the primitive mantle and are similar to oceanic basalts of other Archean greenstone belts (Fig. 3). Similarly, Sm-Nd isotope compositions indicate that the metabasalts were derived from a juvenile, depleted mantle source (similar to CHUR) that did not involve any continental crust contamination or TTG basement.

CONCLUSIONS

The balance of field, geochronological, and petrological evidence presented herein supports a model in which the mafic-ultramafic rocks of the Kromberg type section represent Mesoarchean oceanic crust that formed in a juvenile ocean basin 3.33 b.y. ago. The Kromberg sequence was subsequently tectonically accreted and stacked over the ca. 3.432 Ga Noisy conglomerates and turbidites during the Mesoarchean. Considering the ophiolite criteria of Dilek and Furnes (2014), the Kromberg sequence may represent a remnant of a Mesoarchean subduction-unrelated ophiolite preserved in the BGB. We argue that greenstone belts more generally may consist, at least in part, of dismembered slices of Archean oceanic crust. On this basis, it is proposed that proto-tectonic processes similar to those of modern-day Earth may have operated on the early Earth during Mesoarchean times.

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