In-situ dating of the Earth’s oldest trace fossil at 3.34 Ga

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A B S T R A C T
Microbial activity in volcanic glass within the oceanic crust can produce micron sized pits and tunnels. Such biogenic textures have been described from the recent oceanic crust and mineralized equivalents in pillow lavas as old as 3.47–3.45 Ga from the Barberton Greenstone Belt (BGB) of South Africa. In meta-volcanic glasses these microbial traces are preserved by titanite mineralization (CaTiSiO5) and on the basis of morphological, textural and geochemical evidence have been argued to represent Earth’s oldest trace fossils. Here we report the results of in-situ U–Pb dating of titanite that infills trace fossils from the Hooggenoeg Complex of the BGB using laser ablation MC-ICP-MS (multi-collector inductively coupled, plasma mass spectrometry). This yields a titanite age of 3.342±0.068 Ga demonstrating the antiquity of the BGB trace fossils. This radiometric age confirms that a sub-seafloor biosphere was already established in the PaleoArchean and that it likely represented an important habitat for the emergence and evolution of early microbial life on the Earth.

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1. Introduction

Sea floor pillow basalts contain tubular and granular alteration textures in their glassy chilled margins (e.g. Fisk et al., 1998; Furnes et al., 2008; McLoughlin et al., 2008; Staudigel et al., 2008; Thorseth et al., 1995). The biogenicity of such alteration textures has been argued for on the basis of several lines of evidence including: the morphology of the alteration textures (e.g. McLoughlin et al., 2009; Staudigel et al., 2008 and refs therein); the δ13C values of disseminate carbonates found in pillow rims and cores (e.g. Furnes et al., 2001a); microbiological staining and sequencing studies (e.g. Santelli et al., 2008 and refs therein); and chemical imaging of trace amounts of organic material lining the textures (e.g. Furnes and Muehlenbachs, 2003). The body of evidence used to advance a biogenic origin for these glass alteration textures is extensively reviewed elsewhere (e.g. Furnes et al., 2001b; Staudigel et al., 2008). It is hypothesized that microorganisms living in the sub-seafloor colonize fractures and vesicles in the glass in order to obtain electron donors, nutrients, shelter and perhaps to escape predation (Cockell and Herrera, 2008; Furnes et al., 2008). In Phanerozoic volcanic glass the granular bioalteration textures are by far the most abundant and the tubular textures are less common (Fig. 34 in Furnes et al., 2008) but exhibit striking morphological variations including annulated, twisted, spiral shape and branched forms (McLoughlin et al., 2009). A conceptual model of how such microbial communities are thought to etch the volcanic glass has been developed in a series of papers (e.g. Furnes et al., 2008; Staudigel et al., 2008; Thorseth et al., 1992; Thorseth et al., 1995). These bioalteration textures can also be regarded as trace fossils because they record the activities and behaviours of microorganisms and recently an ichnotaxonomy has been proposed to elucidate the morphological diversity of these traces and enable global and stratigraphic comparisons (McLoughlin et al., 2009).

The fossil record of life in volcanic glass extends far beyond the oldest in-situ oceanic crust. The preservation of bioalteration textures in glass now transformed to metamorphic mineral assemblages is made possible by mineralization of the micro-textures on the sub-seafloor prior to deformation and metamorphism. Titanite is a common mineralizing phase and micro-textures with comparable morphologies to those found in the in-situ oceanic crust have now been reported from Phanerozoic ophiolites and Archean greenstone belts (reviewed by Furnes et al., 2007). The sequence of events is: microbial alteration, authigenic mineralization and subsequent metamorphism; this is summarized in Fig. 7 of McLoughlin et al. (2010b). The mineralization process appears to obscure some of the fine morphological detail seen in recent bioalteration textures, such as spirals and annulations, and on average results in filaments with larger diameters than that of the original hollow tubes (Fig. 2 and Furnes et al., 2007). But in all other
respects the mineralized tubes are comparable in morphology and distribution to those found in fresh volcanic glass. In contrast, granular bioalteration textures, the most abundant bioalteration texture in glassy pillow lava rims of the in-situ oceanic crust, that are typically <0.5 μm in diameter are lacking from meta-volcanic glass, probably because these are obliterated by recrystallisation of the host glass during metamorphism.

Trace fossils found in meta-volcanic glass of the Barberton Greenstone Belt (BGB) in South Africa are the focus of this study (Fig. 1). Their geological setting and key textural characteristics are summarized below. Briefly, they are filamentous micro-textures that are <15 μm in diameter and extend up to 200 μm from a "root zone" that represents the initial crack from which the microbial alteration commenced (Banerjee et al., 2006; Furnes et al., 2004). Based on textural and geochemical evidence, these tubular titanite structures (Fig. 2) have been interpreted to represent the oldest physical traces of life on Earth (Banerjee et al., 2006; Furnes et al., 2004). Based on textural and geochemical evidence, these tubular titanite structures (Fig. 2) have been interpreted to represent the oldest physical traces of life on Earth (Banerjee et al., 2006; Furnes et al., 2004). Based on textural and geochemical evidence, these tubular titanite structures (Fig. 2) have been interpreted to represent the oldest physical traces of life on Earth (Banerjee et al., 2006; Furnes et al., 2004).

### 2. Geological setting and sample locality

The PaleoArchean BGB of South Africa contains some of the world’s oldest and best-preserved pillow lavas (de Wit et al., 1987). The tectonostratigraphy of the Onverwacht Suite comprises the Theespruit, Komati, Hooggenoeg, Noisy, Kromberg and Mendon Complexes that total 15 km in thickness (Fig. 1 and de Wit et al. in press). These complexes are separated by major shear zones or unconformities described in detail in de Wit et al. (in press). The extrusive components include pillow lavas, minor hyaloclastite breccias and sheet flows with several interlayered chert horizons that are between ca. 0.5 to 20 m thick and together this sequence is overlain by the sedimentary rocks of the Fig Tree and Moodies Groups (Fig. 1). Pillow lavas from the Hooggenoeg Complex show no or little deformation (Fig. 2). The Onverwacht Suite has been interpreted to represent fragments of Archean oceanic crust, termed the Jamestown Ophiolite Complex (de Wit et al., 1987), that developed in association with subduction and island arc activity approximately 3.55 to 3.22 Ga (de Ronde and de Wit, 1994). The magmatic sequence of the Onverwacht Suite is exceptionally well-preserved, relatively undeformed away from its margins with the surrounding granitoids and has experienced greenschist facies or lower degrees of metamorphism (e.g., Grosch et al., 2009a; Tice et al., 2004). This relatively well preserved window onto the early Archean Earth has thus provided the focus of many efforts to seek traces of life in both the sediments (e.g. Javaux et al., 2010; Tice and Lowe, 2004) and volcanics (e.g. Furnes et al., 2004; Grosch et al., 2009b).

The ~2700 m thick lava pile of the Hooggenoeg Complex comprises several eruptive pulses described in Furnes et al. (in press). The age of the Hooggenoeg Complex is bracketed by two U–Pb zircon ages of ~3.47 and ~3.45 Ga the locations of which are shown on Fig. 1 (modified from Furnes et al., in press). A maximum age for eruption of the Hooggenoeg Complex is provided by detrital zircons from the basal Middle Marker chert that is exposed along the southeastern limb of the Onverwacht Fold where it has been dated at 3.472 ± 0.005 Ga (Armstrong et al., 1990). Above the Hooggenoeg Complex and within the Noisy Complex appears a large dacitic intrusion in the eastern part of the northern limb of the Onverwacht Fold which has yielded a concordant U/Pb SHRIMP date of 3.445 ± 0.004 Ga (de Wit et al., 1987). The overlying Noisy Complex as recently defined by Furnes et al. (in press) has also yielded several minimum age constraints upon eruption of the Hooggenoeg lavas.

![Fig. 1](image-url) (A) Map of South-Africa showing the location of the Barberton Greenstone Belt (BGB). (B) Sketch map of the BGB. (C) Geological map of BGB indicating the sample location on the Komati river in upper Hooggenoeg Complex (star). The eruptive age of the sample locality is bracketed between two U–Pb zircon ages (locations indicated by solid dots) of 3.472 and 3.455 Ga (see text for explanation).
including, igneous zircons from a flow banded porphyritic lava near the top of the volcaniclastic sequence that gave a concordant SHRIMP date of 3.451 ± 0.005 Ga (de Vries et al., 2006). In addition, along the Komati River downstream from our sample site, zircons from a dacitic crystal-tuff near the top of the Noisy Complex (location shown on Fig. 1) yielded a magmatic U–Pb zircon age of 3455.2 ± 7.5 Ma (Biggin et al., submitted).

The Hooggenoeg samples investigated here were collected from a non-vesicular and variolitic pillow lava outcrop on the banks of the Komati River in the south eastern limb of the Onverwacht anticline (Fig. 1). This trace fossil bearing horizon was also the target of a scientific drill hole KD2b described in Grosch et al., (2009b). The pillow lavas are very little deformed and display well-developed chilled margins ~10 mm thick of formerly glassy material that grade inwards into a variolitic zone, consisting of a mixture of altered glass and microcrystalline material (Fig. 2a and d of Banerjee et al., 2006). The pillow rims now comprise a greenschist facies assemblage of chlorite, quartz, epidote, titanite and calcite. Pockets of interpillow hyaloclastites are well developed at this locality and this outcrop also provided the material illustrated in Figs. 1 and 3 of Furnes et al. (2004) and is referred to as locality 6 in Banerjee et al. (2006).

3. Description of the BGB trace fossils

The BGB trace fossils occur in pillow rims and interpillow hyaloclastites. They are mineralized by micro-crystalline titanite and appear dark brown in thin-section. They occur as dense clusters and bands containing a central “root zone” from which they radiate (Fig. 2). Sometimes a paler-coloured band, a few microns wide can be seen at the center of the “root zone”, recording the former location of a fracture in the volcanic glass where the bioalteration initiated. The mineralized tubular structures are curvi-linear and may taper slightly towards their ends, occurring in clusters of up to tens of filaments. They have an average width of 4 μm and are up to 200 μm in length with an average length of 50 μm (Fig. 7 in Furnes et al., 2007). They are commonly segmented by cross-cutting chlorite grains (Fig. 2 D and E).

4. Archean trace fossil — a summary of the evidence for biogenicity and antiquity

There are three reported occurrences of mineralized microbial traces from Archean pillow lavas. The first and also the oldest examples yet described come from the BGB of South Africa (Furnes
et al., 2004; Banerjee et al., 2006; Furnes et al., 2007). Morphologically comparable textures, have also been described from the 3.35–3.31 Ga pillow lavas of the Euro Basalt in Western Australia (Banerjee et al., 2007) and 2.52 Ga pillow lavas of the Wutai Group of North West China (McLoughlin et al., 2010b). The evidence for the biogenicity of these trace fossils has been extensively explained elsewhere (see Banerjee et al., 2006; Furnes et al., 2004; Furnes et al., 2008) and rather here, we summarise the major features that support the biogenicity and especially antiquity of the Barberton trace fossils.

A biogenic origin for the titanite mineralized textures from the Barberton has been advanced on the basis of 3 lines of evidence summarized below:

A. The BGB titanite mineralized tubular structures have comparable morphologies, size and distribution to trace fossils found in recent volcanic glass

The micro-textures are restricted to pillow rim and interpillow breccia samples and extend away from healed fractures along which seawater once flowed (Fig. 2). These tubular structures are similar in size, shape, and distribution to features documented in glassy pillow rims from ophiolites such as the Troodos ophiolite and in-situ oceanic crust (Furnes et al., 2008). Thus the BGB structures are interpreted as being the mineralized remains of microbial trace fossils.

B. The δ13C values of carbonate in the BGB pillows rims records microbial fractionation

Disseminated carbonate from bulk rock samples of pillow rims from the Onverwacht Suite have δ13C values of +3.9 to −16.4 per mil (‰), which are different from those of the crystalline interiors of +0.7 to −6.9‰. Amygdules containing later, secondary carbonate have δ13C values that cluster around zero. The δ13C values from crystalline interior samples are bracketed between those of primary mantle CO2 (−5 to −7‰) and of Archean marine carbonate (0‰), whereas the glassy samples extend to lower δ13C values. Such isotopic contrasts are also seen in pillow lava rims from ophiolites and oceanic crust, where the generally low δ13C values of disseminated carbonate are attributed to metabolic byproducts formed during microbial oxidation of dissolved organic matter in the pore waters (Fig. 2 in Furnes et al., 2008). The isotopically low δ13C values of carbonate in the formerly glassy rims of the BGB pillows are thus interpreted to have also formed by microbial fractionation (Banerjee et al., 2006; Furnes et al., 2004).

c. X-ray element mapping of carbon on the walls of the BGB tubular structures

Furnes et al. (2004) and Banerjee et al. (2006) report X-ray elemental maps of thin, <1 μm thick carbon linings on the walls of some of the BGB micro-textures. This carbon does not correlate with the elemental maps of calcium, iron, and magnesium indicating that the carbon is not bound in carbonate (e.g. Fig 7 in Banerjee et al., 2006, analytical methods explained in Banerjee and Muehlenbachs 2003). In recent volcanic glass, biofilms and organic remains containing nucleic acids are commonly observed along the interior surface of microbially generated pits and tunnels (e.g. Furnes et al., 1999). Thus the BGB carbon has been interpreted to represent decayed organic material left on the interior surfaces of microbially generated trace fossils that was subsequently preserved during later titanite mineralization (Furnes et al. 2004).

No plausible abiotic mechanism has yet been advanced to explain the BGB micro-textures. Abiotic processes that have been tested and rejected include: purely chemical dissolution, and the migration of ambient inclusions. These abiotic mechanisms are discussed in detail in Banerjee et al. (2006); Staudigel et al. (2008); and most recently in McLoughlin et al. (2010a) and cannot explain the morphology, distribution and geochemical characteristics of the BGB trace fossils.

The antiquity of the Barberton trace fossils has been argued for from textural observations. The micro-tunnels are segmented by metamorphic chlorite (e.g. Fig. 2), implying that the microbial traces were mineralized by titanite before growth of the cross-cutting metamorphic chlorite. A low-grade, sea-floor metamorphic event is argued to have occurred shortly after extrusion of the Hooggenoeg pillow lava succession (Brandl and de Wit, 1997), and was followed by very low grade dynamothermal metamorphism between 3.23 and 3.29 Ga (Schoene et al., 2008). The last regional deformation in the vicinity of the BGB occurred between 3.1 and 3.2 Ga, and the rocks have not been thermally disturbed since. Maximum temperature for this regional metamorphism have been estimated to be between 200–400 °C on the basis of a geothermometer involving graphite crystallinity measured by laser-Raman spectroscopy on carbonateous cherts (Tice et al., 2004).

Direct dating of Archean trace fossils in volcanic glass was first undertaken on samples from the Pilbara Craton of Western Australia (Banerjee et al., 2007). This study reported a U–Pb age of 2.9 ± 0.1 Ga for titanite mineralized trace fossils that is ~400 Ma younger than the accepted eruptive age for the host pillow lavas of 3.5 Ga given by an interbedded tuff (Nelson, 2005). The titanite date corresponds to the age of a regional metamorphic event related to the last phase of deformation and widespread granite intrusion in the Northern Pilbara at 2.93 Ga (van Kranendonk et al., 2002). This U–Pb titanite age therefore represents a minimum estimate for the timing of titanite formation, especially given that metamorphic chlorite cross-cuts the titanite tubules and so must post-date the titanite mineralization. This implies a <400 Ma post eruptive period during which the bioalteration textures from the Pilbara were mineralized; but does not exclude the possibility that the titanite formed soon after eruption, remained hollow and were mineralized somewhat later. Our goal with the Barberton samples is thus to investigate the duration of this Archean bioalteration window and to see if we could more tightly constrain the antiquity of another example of Archean trace fossils.

5. Analytical techniques

A multi-collector ICP-MS (Thermo Finnigan Neptune) coupled to a 213 nm Nd:YAG laser (New Wave Research UP-213) was used to measure Pb/U and Pb isotopic ratios in titanite at Bergen University. The sample introduction system was modified to enable simultaneous nebulisation of a tracer solution (detector cross calibration and mass bias correction) and laser ablation of the solid sample. Natural Tl (205Tl/203Tl=2.3871; Dunstan et al., 1980), 209Bi and enriched 237Np (>99%) were used in the tracer solution which was aspirated to the plasma using a 50 μl/min PFA nebuliser, dual cyclonic–double pass quartz glass spray chamber and a T-piece tube attached to the back end of the plasma torch. Helium was used as ablation/carrier gas. The aerosol was mixed prior to the torch via a T-piece.

The laser was set up to produce energy density of 3 J/cm² at a repetition rate of 10 Hz. The laser spot size varied between 8 to 60 μm in diameter according to the sample volume available for laser ablation. The laser beam was focused on the sample that was mounted in ca. 3 cm³ ablation cell. The “root zones” from 11 different trace fossil found in a polished thin section, sample numbers 101–BGB-08 were analyzed. During ablation the stage was moved beneath the stationary laser beam at a speed of 10 μm/s. Typical signal intensities measured for the 205Pb, 206Pb, 207Pb and 208Pb were ca. 2000, 30000 and 20000 cps, respectively. The acquisition consisted of a 25 s measurement of all analytes in the gas blank and aspirated tracer solution, followed by measurement of U and Pb isotope signals from titanite, along with the continuous signal from the tracer solution for another 25 seconds. The data were acquired in static mode in a mixed channeltron (IC)–Faraday (FAR) detector array
for isotopes $^{202}$Hg (IC1), $^{203}$Ti (IC2), $^{204}$Hg + Pb (IC3), $^{205}$Ti (IC4), $^{206}$Pb (IC5), $^{207}$Pb (IC6), $^{208}$Pb (IC7), $^{209}$Bi (FAR L4), $^{237}$Np (FAR H4) and $^{238}$U (IC8). Solution signal of $^{203}$Ti was used to cross-calibrate the channeltrons before each analysis.

The data were corrected for channeltron dead time and processed off line in a spreadsheet-based program (LamTool; Kosler et al., 2008) and plotted on concordia diagrams using IsotplotEx (Ludwig, 2003). Data reduction included correction for channeltron yield, gas blank and mass discrimination using the solution signals of Ti, Bi and Np and repeat analyses of the Khan titanite (Heaman, 2009). Correction for common Pb was based on measurement of the non-radiogenic $^{204}$Pb and utilized the Pb isotope composition of Archean galena from the French Bob’s mine in the Barberton Greenstone Belt; it is one of the galena samples used to define the two-stage model of lead isotope evolution (Stacey and Kramers, 1975). Titanite sample from the Lillebukt Alkaline Complex in northern Norway (0.520±0.005 Ga; Pedersen et al., 1989) was periodically measured for data quality control and it gave a pooled concordia age of 0.524±0.024 Ga (6 measurements, 2 sigma).

Energy dispersive x-ray (SEM-EDX) images were acquired with a Zeiss Supra 55VP scanning electron microscope equipped with a Thermo Noran EDS detector at the University of Bergen. The EDX spectra were collected at 15 mm working distance using 15 keV acceleration voltage and 60 μm aperture size. The most abundant fluorescence for each element line was used for imaging.

Focused ion beam milling (FIB) and transmission electron microscopy were done at the GeoForschungsZentrum in Potsdam (GFZ) using a FEI FIB2000 TEM and a FEI TecnalG2 F20 X-TWIN instruments. The field emission gun of the TEM was operated at 200 keV accelerating voltage. Total of four different FIB foils were obtained from different parts of sample number 29-BGB-03 and analyzed by TEM. Datasets from all FIB foils were found to be similar. Further details of the FIB sample preparation and analysis are described in Wirth (2004).

6. Results

Scanning and transmission electron microscope investigations of the BGB sample, together with previous textural and mineralogical observations confirm the similarities between the titanite that infill the tubular structures and the titanite in the “root zones” (Figs. 2 and 3). Elemental distribution maps obtained by SEM-based EDX analysis indicate that there is no appreciable difference in composition between the tubular structures and their respective “root zones” (Fig. 3). In addition, the TEM data shows no variation at the micron or sub-micron scale in porosity, size and shape of the crystals between the polycrystalline titanite in the micro-textures and that in the “root zones” (Fig. 3G and H). Moreover, the TEM images reveal the homogeneity of the phase composition of the trace fossils, suggesting that mineralization of the tubular structures and the “root zones” occurred simultaneously or within a very short time span. This means that a U–Pb age obtained from the central “root zones” will be representative of the whole trace fossil. Unfortunately, our LA MC ICP-MS requires a 40 μm spot size which is too large to date an individual tube. But as explained above, this is not a concern because petrographic arguments suggest that mineralization of the “root zone” and tubes was synchronous.

Titanite U–Pb isotopic data obtained by LA MC ICP-MS for trace fossils are given in Table 1 and plotted on a concordia diagram in Fig. 4. The pooled concordia age for 11 trace fossil “root zones” is 3.342±0.068 Ga. The mean isotopic composition of the studied titanites plots slightly above the concordia curve. We interpret this as resulting from a small inaccuracy in the common lead correction that was applied to the raw isotopic data. Accurate common Pb correction is crucial for obtaining correct U–Pb titanite ages but problems in determining the initial lead isotopic composition for Precambrian lavas in general, and for rocks from the BGB in particular, are well known and have been discussed in length by Brevart et al. (1986). Briefly, the Pb isotope composition of sulfides (mostly galena) from the BGB shows a considerable spread in the $^{200}$Pb-$^{204}$Pb and $^{207}$Pb-$^{208}$Pb-$^{206}$Pb isotope ratios (Brevart et al., 1986; Saager and Koppel, 1976). In addition, none of the published galena Pb isotope compositions can produce entirely concordant titanite ages and the galena samples come from a different part of the BGB stratigraphy than the material studied herein. Therefore we propose that for common Pb correction of the studied titanite samples, it is more appropriate to use a general model for common Pb evolution, for example, Stacey and Kramers (1975) or part of it. We therefore chose to use the common lead composition of a galena from the French Bob’s mine in the Barberton Onverwacht Suite that defines the Archean part of the 2–stage lead evolution model of Stacey and Kramers (1975). This is considered by us to be the most appropriate for the common lead correction of the titanite infilling the studied trace fossils. It should also be noted that choice of a different initial Pb composition for correction of titanite data presented in this study affects the concordance of the pooled concordia ages but has no significant effect on the reported age of the trace fossils.

7. Discussion

The 3.342±0.068 Ga titanite age measured here records the age of metamorphic titanite growth and equilibration within these trace fossils. This demonstrates that the trace fossils are Paleoproterozoic in age and provides a minimum age estimate for their formation. In other words, this titanite age underestimates the timing of microbial alteration of the BGB volcanic glasses but nonetheless, confirms their antiquity. The Hooggenoeg lavas have never experienced metamorphic temperature that exceed the closure temperature of the U–Pb isotopic system in titanite ($T_c = 550–650 °C$), thus this age represents the main phase of titanite growth within the textures (c.f. Schoene and Bowring, 2007). Furthermore, petrographic, SEM and FIB-TEM observations confirm that mineralization was synchronous in all parts of the trace fossils i.e. in both the “root zones” and tubular cavities (Figs. 2 and 3).

The difference in age between the infilling titanite (3.342±0.068 Ga) and the eruptive age of the Hooggenoeg Complex (3.47–3.45 Ga) is attributed to either: a long-lived bioalteration window during which microbial alteration persisted; or a time gap after which microbial alteration ceased and before the titanite mineralization commenced. Both of these possibilities are supported by analogy to the modern oceanic crust and ophiolites. An early onset to bioalteration on the Archean seafloor is supported by comparison to modern oceanic spreading centres, where microbes are observed to rapidly colonize juvenile glassy surfaces (Furnes et al., 2007). These bioalteration traces

Fig. 3. Scanning electron microscope images of the trace fossils taken in backscatter mode (A) and elemental distribution maps obtained using energy dispersive X-rays (B–F). Also transmission electron microscope, high-angle annular dark field images (TEM HAADF) of focused ion beam (FIB) foils cut from the trace fossils (G)–(H). Together these show no differences in the elemental composition or mineralogy of the “root zones” and individual tubes. (A) Segmented, filamentosus trace fossils that intersect the surface of the sample and radiate from a central “root zone”. (B) Titanium elemental map. (C) Silica elemental map. (D) Magnesium elemental map. (E) Calcium elemental map. (F) Iron elemental map. (G) FIB foil from a single, tubular trace fossil that intersects the surface of the platinum coated sample. The tubes are filled with polycrystalline, porous titanite and the variation in grey contrast is due to differences in orientation of the individual titanite grains. The semi-circular cross-section of the tube is clearly seen and the interface with the chlorite matrix. (H) FIB-foil from a titanite mineralized “root zone”. No difference in the size, shape or porosity of the titanite crystals can be seen by comparison to the polycrystalline titanite in the individual trace fossil tubes (G) or “root zones” (H). Variation in grey level of (G) and (H) is attributed to the different thickness of both foils, which is also reflected in the HAADF image (note the faint dark circle visible in H is due to the a hole in the amorphous carbon foil used on the TEM grid). Images A–F are from sample 29-BGB-03 and G–H from sample 101-BGB-08.
can remain hollow or become partially filled with authigenic minerals principally clays and iron-oxyhydroxides over time and these may be enriched in titanium, a possible precursor to titanite (e.g. Fig. 12b in Staudigel et al., 2008). Theoretically, as long as there is still fresh glass present and seawater circulation continues, then the microbial bioalteration may go on for millions of years. The major phase of titanite mineralization is argued to occur much later during greenschist facies metamorphism, the timing of which is determined by the regionally geological history. Bioalteration textures can remain hollow for long periods of time, as for example, micro-textures from the little deformed 0.092 Ga Troodos ophiolite (Furnes et al., 2001c) and the 0.122 Ga Ontong Java Plateau (Banerjee and Muehlenbachs, 2003) are largely unmineralized. A summary of this sequence of events is shown in Fig. 7 of McLoughlin et al. (2010b).

The nature and timing of metamorphism of the Hooggenoeg volcanic glasses is only sparsely characterized. The 3.342±0.068 Ga metamorphic titanite age reported here is comparable to an age obtained by step-heating 40Ar/39Ar analysis of 3.326±0.005 Ga from komatitic basalts of the underlying Komati Complex (Fig. 5 in López-Martínez et al., 1992). Alternatively, the titanite age obtained here may correspond to heating associated with the intrusion of gabbroic magma into the Onverwacht Suite that is recorded by a U/Pb baddeleyite age of 3.351±0.006 Ga obtained from a meta-gabbro in the underlying Komati Complex (Kamo and Davis, 1994).

Subsequent to the metamorphic event discussed here the Hooggenoeg Complex experienced low grade dynamothermal metamorphism during a major deformation event between 3.23 and 3.29 (de Ronde and de Wit, 1994; Schoene et al., 2008). Localised deformation along the margins of the BGB occurred between 3.1 and 3.2 Ga and the rocks have not been thermally disturbed since. Whether the new U–Pb titanite age reported here represents a sub-seafloor burial metamorphism event, a regional low-grade metamorphic overprint, or a contact metamorphic effect arising from gabbroic intrusives, it does not change the fact that the trace fossils are Paleoarchean in age. Moreover, this corroborates and provides an absolute age constraint on previous textural observations of metamorphic chlorite cross-cutting the titanite filled trace fossils (Fig. 4).

This is only the second study to use direct in-situ dating techniques to obtain an absolute age for a candidate biosignature from the Paleoarchean. Other traces of Archean life such as organic
microfossils, stromatolites and geochemical signatures are not possible to date directly. The age obtained here is approximately 0.4 billion years older than the previously published age of 2.9 ± 0.1 Ga from comparable trace fossils in the 3.35 Ga Euro Basin of the Pilbara Craton in Western Australia (Banerjee et al., 2007). Furthermore, the time gap between eruption of the host lavas and the mineralization of the textures, or the co-called "window for bioalteration", is also significantly smaller, being ∼0.13 Ga in the case of the Barberton trace fossils in contrast to ∼0.44 Ga for the Pilbara trace fossils (Banerjee et al., 2007) and ∼0.71 Ga for the Witutai bioalteration textures (McLoughlin et al., 2010b). This time window is controlled by the regional geological history and is much shorter in the case of the Barberton trace fossils, because the greenschist facies metamorphic event responsible for their mineralization and preservation occurred sooner after eruption. A schematic overview of the process is shown on Fig. 5. It is in these types of settings where the titanite growth within the trace fossils was relatively early that this U–Pb dating technique is most powerful in constraining the antiquity of the trace fossils.

8. Conclusion

We report a minimum age of 3.342 ± 0.068 Ga for titanite mineralization of trace fossils from pillow lavas of the Barberton Greenstone belt. These trace fossils therefore represent the oldest directly dated microbial trace of life on Earth and confirm previous textural arguments for the antiquity of these trace fossils (Furnes et al., 2004). It follows that the sub-seafloor biosphere was already established in the Paleoarchean and likely provided an important cradle for the emergence and evolution of microbial life on the Earth. This study further illustrates the importance of U–Pb dating to assessing the antiquity and syngenicity of microbial traces in volcanic glass, as may one day be applied to seeking traces of life in older terrestrial pillow lava sequences.

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References


