Geoscience Frontiers 9 (2018) 603–665

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Paleoarchean bedrock lithologies across the Makhonjwa Mountains of South Africa and Swaziland linked to geochemical, magnetic and tectonic data reveal early plate tectonic genes flanking subduction margins

Maarten de Wit[a,*], Harald Furnes[b], Scott MacLennan[a,c], Moctar Doucouré[a,d], Blair Schoene[c], Ute Weckmann[e], Uma Martinez[a,f], Sam Bowring[g]

[a] AEON-ESSRI (Africa Earth Observatory Network-Earth Stewardship Science Research Institute), Nelson Mandela University, Port Elizabeth, South Africa
[b] Department of Earth Science & Centre for Geobiology, University of Bergen, Norway
[c] Department of Geosciences, Princeton University, Guyot Hall, Princeton, NJ, USA
[d] Department of Geosciences, Nelson Mandela University, Port Elizabeth, South Africa
[e] Department Geophysics, GFZ - German Research Centre for Geosciences, Helmholtz Centre, Telegrafenberg, 14473 Potsdam, Germany
[f] GISCAPETOWN, Cape Town, South Africa
[g] Earth, Atmosphere and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 12 June 2017
Received in revised form
2 October 2017
Accepted 5 October 2017
Available online 31 October 2017

Keywords:
Paleoarchean
Barberton Greenstone Belt
Onverwacht Suite
Geologic bedrock and structural maps
Geochemistry and geophysics
Plate tectonics

ABSTRACT

The Makhonjwa Mountains, traditionally referred to as the Barberton Greenstone Belt, retain an iconic Paleoarchean archive against which numerical models of early earth geodynamics can be tested. We present new geologic and structural maps, geochemical plots, geo- and thermo-chronology, and geophysical data from seven silicic, mafic to ultramafic complexes separated by major shear systems across the southern Makhonjwa Mountains. All reveal signs of modern oceanic back-arc crust and subduction-related processes. We compare the rates of processes determined from this data and balance these against plate tectonic and plume related models. Robust rates of both horizontal and vertical tectonic processes derived from the Makhonjwa Mountain complexes are similar, well within an order of magnitude, to those encountered across modern oceanic and orogenic terrains flanking Western Pacific-like subduction zones. We conclude that plate tectonics and linked plate-boundary processes were well established by 3.2–3.6 Ga. Our work provides new constraints for modellers with rates of a 'basket' of processes against which to test Paleoarchean geodynamic models over a time period close to the length of the Phanerozoic.

1. Introduction

There is fierce controversy about how Paleoarchean geology may be interpreted to reveal the nature and pace of global geodynamics that far back in time (3.2–3.6 Ga). Central to the present geologic disputes are whether or not present-day style plate tectonics and linked orogeny with a dominance of horizontal forces operated during the Paleoarchean or even earlier (e.g., De Ronde and Kamo, 2000; Diener et al., 2005, 2006; Dziggel et al., 2006; Moyen et al., 2006, 2007; Stevens and Moyen, 2007; Kusky et al., 2013; Turner et al., 2014; Komiya et al., 2015; Maruyama et al., 2016; Greber et al., 2017; Maruyama and Ebisuzaki, 2017), or if vertical tectonics and linked epeirogeny driven by plume-dynamics and crustal delamination dominated the planet during that time (e.g., Hamilton, 1998, 2011; Zegers and Van Keeken, 2001; Van Kranendonk, 2011a, b; François et al., 2014; Van Kranendonk et al., 2014, 2015; Kröner et al., 2016; Chowdhury et al., 2017). This controversy about the nature of early Archean tectonics has been extensively debated over the last two decades without reaching consensus (de Wit, 1998; Witze, 2006; Hynes, 2014). There is agreement that better modelling of tectonic, igneous and sedimentary processes will provide fundamental keys to unravel

---

* Corresponding author.
E-mail address: maarten.dewit@mandela.ac.za (M. de Wit).
Peer-review under responsibility of China University of Geosciences (Beijing).

https://doi.org/10.1016/j.gsf.2017.10.005

the origin and formation of Earth's earliest continental crust (3.5–4.0 Ga) in addition to understanding their linked paleo-environments and ecosystems. However, such models must be tested against robust empirical field and laboratory data in order to unravel the geodynamic evolution of Earth (e.g., St-Onge et al., 2006; Hawkesworth and Kemp, 2006; Keller and Schoene, 2012; Korenaga, 2013; Ernst et al., 2016; Hawkesworth et al., 2016; Weller and St-Onge, 2017).

Recent field, rock and mineral analyses have provided some evidence for modern-like plate tectonics by 3.0–3.2 Ga (e.g., Smithies et al., 2007; Polat et al., 2008; Mints et al., 2010; Shirey and Richardson, 2011; Van Kranendonk, 2011a, b; Dhuime et al., 2015; Smart et al., 2016; Halla et al., 2017) and possibly as early as 3.8–4.0 Ga (Komiya et al., 1999, 2002, 2004, 2015; Furnes et al., 2007, 2009, 2014, 2015; Maruyama and Komiya, 2011; Adam et al., 2012; Turner et al., 2014; Maruyama et al., 2016; Greber et al., 2017). However, these data are not generally accepted as conclusive before ca. 3.2 Ga, and have been interpreted to reflect mantle plume magmatism or subduction processes (Bédard, 2006; Cawood et al., 2006; Ernst et al., 2016; Johnson et al., 2017).

Numerical modelling based on elevated mantle temperatures and crustal geotherms, as are generally assumed for the Archean, is consistent with mantle plume activity driven by dry mantle convection (Davies, 2007; Arndt et al., 2013; Fischer and Gerya, 2016). Similar modelling and experimental petrology assuming a more hydrous mantle, shows that plate tectonics is also capable of removing excess heat produced in the Archean at rates comparable to, and possibly even lower than its current rate at mid-ocean ridges (de Wit and Hynes, 1996; Korenaga, 2013); and that under wetter mantle conditions, subduction-related processes can also account for high-magnesium basalts and komatiites at significantly lower temperatures than under dry mantle conditions (e.g., Parman et al., 1997, 2001, 2004; Grove and Parman, 2004; Parman and Grove, 2004a, b; Arndt, 2013; Blichert-Toft et al., 2015; Sobolev et al., 2016).

Field observations linked to thermochronology and metamorphic petrology have questioned the existence of ubiquitous higher geothermal gradients everywhere during the Paleoarchean, and argued for subduction-like processes to account for these findings (e.g., Diener et al., 2005, 2006; Dziggel et al., 2006; Moyen et al., 2006, 2007; Stevens and Moyen, 2007; Schoene and Bowring, 2010; Grosch et al., 2012). These interpretations have been disputed on the basis, for example, of rheological processes in subduction zones (e.g., Van Kranendonk et al., 2014, 2015). However, recent metamorphic modelling has pointed to a lack of detailed knowledge about variability of rock rheologies at subduction margins (Hodges, 2017; Yamato and Brun, 2017). Resolving these issues concerning modern systems will no doubt influence diverse interpretations concerning the (albeit rare) relatively high pressure/low temperature metamorphic assemblages at ca. 3.2 Ga discovered by Moyen et al. (2006) and linked to subduction-like processes; in addition to Archean diamonds with subduction-like carbon signatures (Smart et al., 2016), and titanium isotopes of shales linked to subduction processes at 3.5 Ga (Greber et al., 2017).

But none of these findings have provided convincing evidence to distinguish between dominance of different geodynamic regimes (e.g., Adam et al., 2012; Martin et al., 2014). Whilst there is no compelling theoretical argument against efficient subduction processes at that time (Hynes, 2014), most modellers insist that tectonics during the early Archean was radically different and was driven by plume-lid tectonics (e.g., Fischer and Gerya, 2016). Sufficient deterministic field observations linked to geochemistry are crucially lacking to resolve these controversies.

A fundamental distinction between plate tectonics and plume- or delamination-driven Archean tectonics, for example, could be made with evidence for, or absence of, relatively large horizontal lithosphere motions, respectively, based on paleomagnetism. Todate, quantifying large-scale horizontal motions and rates using paleomagnetism have been convincing only in Mesoarchean terranes (2.7–3.0 Ga; Strik et al., 2007; de Kock et al., 2009). Yet results from two Paleoarchean regions have produced similar paleolatitude estimates: (1) A short episode of large scale motion (12–673 cm/yr) has been obtained between 3.46 and 3.48 Ga from the Pilbara craton in Australia (Suganuma et al., 2006); and (2) About 1100 km motion, averaged over 9 million years at 3445 Ma, yield an equivalent to a latitudinal velocity of ca. 12 cm/yr from the Makhonjwa Mountain (MMt) sequences (Biggin et al., 2011). Whilst this is fast by today's standards, the lower numbers are well within the range of plate velocities observed in the Phanerozoic. The reliability of the data emerging from these studies is far from certain, but there are no grounds for their outright dismissal.

By contrast, geological field observations have revealed significant local Paleoarchean horizontal crustal motions of up to 10 km. For example, large-scale tectonic extension during formation of volcano-sedimentary listric basins as early as 3.45 Ga (e.g., Nijman and de Vries, 2004), as well as significant horizontal shortening episodes linked to foreland basin evolution during regional thrusting at ca. 3.4 Ga and 3.2 Ga (de Wit, 1982; Lamb, 1984a, b; Paris, 1987; De Ronde and de Wit, 1994; Lowe, 1994; De Ronde and Kamo, 2000; Grosch et al., 2011) suggest horizontal tectonic processes that possibly, but not definitively, link to plate tectonic motions (e.g., see Van Kranendonk et al., 2009, 2014 for counter arguments). Thus a first order tectonic model for the early Archean Earth remains elusive and malleable. The interpretations and models remain controversial in part because of a lack of field geology systematically linked to modern chemical and magnetostratigraphy, and a lack of high resolution geophysics of tectonic structures linked to precise geochronology. In this context both the timing and mechanism of onset of unambiguous subduction processes remain important to establish.

Here, we summarize recent advances in linked field and laboratory studies across the world's best well-preserved Paleoarchean crustal blocks that flank the escarpment along the eastern margin of southern African Highlands (Fig. 1). This region, known geologically as the Barberton Greenstone Belt and geographically as the Barberton Mountain Land, was recently renamed the Makhonjwa Mountains (de Wit, 2010; following Hall's original terminology, 1918). We use the name Makhonjwa Mountains (MMts) because the term 'greenstone belt', and the definition it generally carries, is restrictive, anachronistic and no longer conducive to developing a deeper understanding of Earth history (de Wit and Ashwal, 1995). We therefore appropriately apply terminology used for modern orogenic belts to what have, until recently, been collectively and uncritically categorized as 'greenstone belts'.

Collectively, our results provide new rates of a 'basket' of processes against which to test Paleoarchean geodynamic models over a time period close to the length of the Phanerozoic. We show that paleo-oceanic components (basalts and komatiites and their linked intrusive complexes) of this region formed predominantly in oceanic environments at water depths of ca. 2–4 km; and that for more than 300 million-years these environments were generated in a variety of back-arc type environments. We find that absolutely none of the geochemical analyses presently available from this region plot in plume domains, no matter what sort of discriminant diagrams are used. We consolidate structural field evidence that reveals the region contains three separate terranes comprising at least seven litho-tectonic complexes, all with chemical signatures indistinguishable from modern rocks found in and around subduction systems. Based on high-resolution aeromagnetic and electrical conductivity surveys across the major shear systems