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Water content of the Tanzanian lithosphere from magnetotelluric data: Implications for cratonic growth and stability

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ABSTRACT

Hydrogen strongly influences mantle rheology and is therefore an important factor in the growth and stability of cratons. Hydrogen also strongly affects electrical conductivity so it is possible to infer the hydrogen content of the lithospheric mantle in-situ and test models of craton formation using magnetotelluric data. Tanzania is an ideal natural laboratory to test hypotheses on lithospheric hydrogen content since it contains regions with very different tectonic regimes including the stable Tanzanian Craton and the East Africa Rift that is reworking lithosphere previously deformed in the East African Orogeny. Additionally, the lithosphere is well sampled by voluminous xenoliths that constrain lithospheric composition and the geotherm, which also affect electrical conductivity. Hydrogen contents were calculated for two locations in Tanzania: the first in the stable central Tanzanian Craton and the second on the eastern margin of the craton where incipient rifting is occurring. The central Tanzanian Craton was found to have a high lithospheric mantle water content of $\sim 10^{-2}$ wt% which is comparable to that of the oceanic asthenosphere and is hard to reconcile with the long-term survival of the craton. It is possible that the water was introduced into the lithosphere recently by kimberlite volcanism or that, if the lithosphere has had a high water content throughout its history, the central craton has been shielded from deformation by weaker orogens that surround it. The eastern margin of the craton has a water content of 10^{-3} to 10^{-4} wt% throughout much of the lithospheric mantle that decreases to 10^{-4} to 10^{-5} wt% at the base of the lithosphere and at depths corresponding to the uppermost plume head. Xenolith data show evidence for partial melting of the plume head and the base of the lithosphere in this dehydrated region. The partial melting and dehydration of a plume head beneath a craton is a present-day observation of the processes that may have formed cratonic roots.

1. Introduction

In order for the sub-continental lithospheric mantle (SCLM) to survive entrainment by the convecting asthenosphere it is generally believed it must be chemically depleted, making it buoyant, and dehydrated, making it viscous (Jordan, 1988; Karato and Jung, 2003; Lee et al., 2011; Lenardic and Moresi, 1999; Li et al., 2008; Mei and Kohlstedt, 2000; O'Neill et al., 2008; Pollack, 1986; Sleep et al., 2002). During partial melting of the SCLM incompatible elements such as Fe, Al, Ca and H preferentially partition into melt which ascends to form the crust, leaving the SCLM chemically depleted and dehydrated (Carlson et al., 2005; Griffin et al., 2003, 2009; Lee et al., 2011). In general the level of SCLM depletion will increase with age as the lithosphere experiences more partial melting events (Griffin et al., 2003). Therefore, it is reasonable to expect that the SCLM would be less hydrous than the asthenosphere, which has an estimated water (hydrogen) content of ∼0.01 wt% (Dai and Karato, 2009; Hirschmann, 2010; Karato, 2006). However, recent evidence from xenoliths (Li et al., 2008; Peslier, 2010; Peslier et al., 2010) and magnetotellurics (MT) (Fullea et al., 2011) has suggested that some cratonic SCLM may contain hydrogen at levels similar to the asthenosphere. This is hard to reconcile with both the chemically depleted nature of the lithosphere and the fact that cratons are stable for billions of years.

The main focus of this study is to obtain insight into SCLM hydrogen distribution because it has a large influence on rheology and hence on the stability and evolution of cratons. We use a forward modeling approach in which we test models against MT observations in Tanzania. MT measures electrical conductivity, which is strongly dependent on hydrogen content in the mantle (Karato, 1990, 2006; Karato and Wang, 2013; Yoshino et al., 2009). Tanzania is an ideal natural laboratory to test hypotheses on lithospheric hydrogen content since the rheology of the Tanzanian Craton, which has remained relatively stable since c. 2.6 Ga, contrasts strongly with the surrounding lithosphere which has been multiply reworked by several major tectonothermal events (Ebinger and Sleep, 1998; Maboko, 2000; Stern, 1994;

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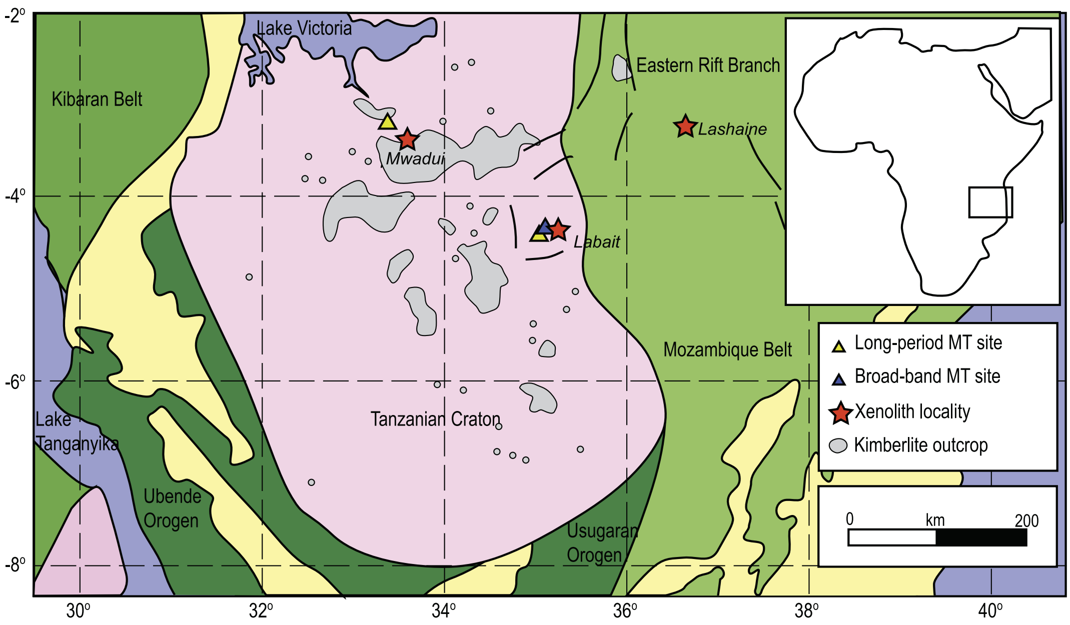

Fig. 1. Map of the study area showing the Tanzanian Craton, Usagaran Orogen, Mozambique Belt and main fault zones associated with the East African Rift. Stars show the locations of xenolith-bearing kimberlites or volcanoes that were used in this study. Triangles show the locations of MT stations used in this study, in the central Tanzanian Craton and at Labait respectively. Kimberlite localities are taken from the World Kimberlites Database (Faure, 2006).

Tenczer et al., 2007). Additionally, the Tanzanian lithosphere is well sampled by xenoliths (Bellucci et al., 2010; Chesley et al., 1999; Gibson et al., 2013; Griffin et al., 1993; Lee and Rudnick, 1999; Rudnick et al., 1994) which constrain the SCLM composition and geotherm. Constraining these variables allows the MT data to be used to determine hydrogen content (e.g. Hirth et al., 2000). We present MT data from two regions in Tanzania, one in the central Tanzanian Craton that shows no evidence for recent tectonism and one on the eastern margin of the craton that is currently undergoing incipient rifting. Together with geotherm calculations and experimentally-based predictions of electrical conductivity, we use these MT data to determine the hydrogen content of the lithospheric and upper asthenospheric mantle.

2. Geological background

The Tanzanian Craton (Fig. 1) is comprised of several Archean rock packages which cratonized by c. 2.6 Ga (Maboko, 2000; Manya et al., 2006) and have U–Pb zircon ages between ∼ 3.0 and 2.6 Ga (Maboko, 2000; Manya et al., 2006; Möller et al., 1998). Lithospheric thickness of the Tanzanian Craton is estimated at 170–200 km from xenolith data (Griffin et al., 1993) and variably 150 ± 20 km to 200 km (Adams et al., 2012; O'Donnell et al., 2013; Weeraratne et al., 2003) to up to 350 km (Ritsema et al., 1998) from seismic data. The Tanzanian Craton has remained stable since c. 2.6 Ga but the surrounding lithosphere has been affected by several major tectonothermal events (Fig. 1). The c. 1.8 to 2.0 Ga Usagaran Orogeny on the south-eastern side of the craton was a likely subduction-related event (Möller et al., 1995) that appears to have involved collision of a previously rifted ribbon of the Tanzanian Craton (Reddy et al., 2003). The Neoproterozoic East African Orogen (Stern, 1994) stretches several thousand kilometers through north–east Africa and Arabia, East Africa, Madagascar, India and Antarctica and was a principal collision zone in the assembly of Gondwana. In Tanzania it is represented by the c. 640 Ma north–south striking Mozambique Belt on the eastern side of the Tanzanian Craton (Stern, 1994; Tenczer et al., 2007). The orogeny reworked the Tanzanian Craton as well as introducing juvenile material (Möller et al., 1998). Since the Eocene/Late Oligocene the East African Rift System has developed along the eastern margin of Africa. Beginning with volcanism in Ethiopia at c. 40–45 Ma (Ebinger et al., 1993), rifting has progressed southwards with time. The rift bifurcates around the Tanzanian Craton with most magmatism in this region having occurred within the last 12 Myr (Corti et al., 2007; Roberts et al., 2012). Gravity (Ebinger et al., 1989; Moucha and Forte, 2011), petrological (Aulbach et al., 2008; Hilton et al., 2011; Pik et al., 2006) and seismic data (Adams et al., 2012; Fishwick and Bastow, 2011; Prodehl et al., 1997; Ritsema and van Heijst, 2000; Weeraratne et al., 2003) suggest that one or more mantle plumes are responsible for the East African Rift. The Tanzanian Craton sits at an average elevation of 1250 m due to the thermal impact of the plume (Ebinger et al., 1989).

The long history of deformation surrounding the Tanzanian Craton suggests that the craton is significantly stronger than the surrounding lithosphere and makes it an ideal place to test models for lithospheric hydrogen content. Two locations will be analyzed in this work (Fig. 1). The first is in the central Tanzanian Craton, ∼80 km south–east of Mwanza. This region is considered 'pristine' cratonic lithosphere, although it is likely to be underlain by a plume head (Weeraratne et al., 2003). Additionally, xenoliths from the c. 40 to 53 Ma Mwadui kimberlite pipe (Griffin et al., 1993; Stachel et al., 1998), located ∼45 km to the south–east, allow some constraints to be made on lithospheric composition. The second location is ∼5 km south of Mt Hanang on the eastern margin of the Tanzanian Craton. This region was chosen because xenoliths from nearby Labait show that asthenospheric melts from the plume have refertilized the lowermost lithosphere (Chesley et al., 1999; Lee and Rudnick, 1999; Vauchez et al., 2005) while the overlying lithosphere retains a cratonic signature. Comparison between these two locations allows an assessment of whether cratonic lithosphere is dehydrated, whether more hydrous lithosphere is more likely to be deformed and the impact of partial melting on hydrogen content.

3. Methodology

The hydrogen content of mantle xenoliths is the most direct observation of lithospheric hydrogen (e.g. Bell and Rossman, 1992;