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Eight good reasons why the uppermost mantle could be magnetic

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ABSTRACT

Wasilewski et al. (1979) concluded that no magnetic remanence existed in the uppermost mantle and that even if present, such sources would be at temperatures too high to contribute to long wavelength magnetic anomalies (LWMA). However, new collections of unaltered mantle xenoliths indicate that the uppermost mantle could contain ferromagnetic minerals. 1. The analysis of some LWMA over cratons and forearcs suggest magnetic sources in the uppermost mantle. 2. The most common ferromagnetic phase in the uppermost mantle is stoichiometric magnetite. Assuming a 30 km-thick crust, and crustal and mantle geotherms of 15 °C/km and 5 °C/km, respectively, the 600 °C Curie temperature implies a 30 km-thick layer of mantle. 3. The uppermost mantle is cooler than 600 °C in Archean and Proterozoic shields (>350 °C), subduction zones (>300 °C) and old oceanic basins (>250 °C). 4. Recently investigated sets of unaltered mantle xenoliths contain pure magnetite inclusions in olivine and pyroxene formed in equilibrium with the host silicate. 5. The ascent of mantle xenoliths occurs in less than a day. Diffusion rates in olivine suggest that the growth of magnetite possible within this time frame cannot account for the size and distribution of magnetite particles in our samples. 6. Demagnetization of natural remanent magnetization (NRM) of unaltered mantle xenoliths unambiguously indicates only a single component acquired upon cooling at the Earth's surface. This is most easily explained as a thermoremanent magnetization acquired by pre-existing ferromagnetic minerals as xenoliths cool rapidly at the Earth's surface from magmatic temperatures, acquired during ascent. 7. Modern experimental data suggest that the wüstite–magnetite oxygen buffer and the fayalite–magnetite–quartz oxygen buffer extend several tens of km within the uppermost mantle. 8. The magnetic properties of mantle xenoliths vary consistently across tectonic settings. In conclusion, the model of a uniformly non-magnetic mantle should be revisited.

1. Introduction

A common assumption underlying the inversion of long wavelength magnetic anomalies (LWMA) is that the mantle does not contribute (Warner and Wasilewski, 1995; Wasilewski, 1987; Wasilewski and Mayhew, 1992; Wasilewski et al., 1979). Here, we challenge this view for eight major reasons and explain why this paradigm may not apply globally. Of the 400 xenoliths measured by Wasilewski and co-workers, magnetic remanence is available for 131 specimens only. This Wasilewski collection includes garnet peridotites and eclogites, i.e., mantle rocks that would not be cold enough to carry a magnetic remanence at mantle depths. Thirty percent of the Wasilewski collection consists of volumetrically minor components of the lithospheric mantle such as wehrlites. Among the remaining samples, thirty percent display macroscopically visible alteration (e.g., #110597; Wasilewski et al., 1979) and approximately twenty percent show contamination by host basalt (e.g., #ANT50; Warner and Wasilewski, 1995). Of the 26 remaining unaltered and uncontaminated samples, surprisingly little rock magnetic data is reported. Saturation magnetization (M_s) was reported for 22 samples, while magnetic susceptibility (K) was reported for only 11 samples. This small dataset shows a large variability (M_s ranges over 3 orders of magnitude, and K by a factor of ~40. The existing dataset is also overrepresented by xenoliths from Western USA (~40%). Some of the specimens show microstructural evidence of incipient partial melting at olivine–chromite grain boundaries (Warner and Wasilewski, 1995). Finally, the depth and temperature of equilibration associated with each xenolith remain unknown. Wasilewski et al. concluded that 1) magnetite constitutes the main magnetic remanence carrier, although a few xenoliths host pyrrhotite and/or native iron and 2) the lithospheric mantle is too weakly magnetic and too hot to contribute to magnetic anomalies.

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2. Reason 1. Mantle contribution to LWMA deduced from satellite data

The origin of LWMA has long been debated (e.g., Dunlop et al., 2010; McEnroe and Brown, 2000; Shive, 1989). For some (e.g., Shive, 1989; Williams et al., 1985), and the magnetizations measured in lower crust rocks are too weak to account for the observed magnetic anomalies. This "missing magnetization" stimulated a quest for strongly magnetized lower crust rocks. For others, there is no missing magnetization when magnetizations measured from rocks are properly reconciled with magnetization computed from magnetic anomalies (e.g., Ravat, 2012).

We propose an alternative hypothesis that additional magnetization could, in some regions, reside in the lithospheric mantle. If this is true, then deep crustal rocks do not need to be as strongly magnetized as previously thought and the Moho should not be considered an absolute magnetic boundary. Up to now this idea has been rejected based on the conclusions of Wasilewski et al. (1979) and Wasilewski and Mayhew (1992) that mantle rocks are too weakly magnetic and too hot to contribute to LWMA. This view, however, is increasingly at odds with a growing number of studies suggesting that the source of some LWMA lies in the lithospheric mantle (Fig. 1): for example, in oceanic basins such as the Ligurian Sea (Chiozzi et al., 2005), the Caribbean Sea (Arnaiz-Rodriguez and Orihuela, 2013; Counil et al., 1989; Guevara et al., 2013), in the forearc mantle such as the Cascadia arc (Blakely et al., 2005; Bostock et al., 2002) and other oceanic regions (Arkani-Hamed, 1993; Arkani-Hamed and Strangway, 1986, 1987; Bronner et al., 2011; Dyment et al., 1997; Harrison and Carle, 1981; Popov et al., 2011; Ravat et al., 2011). In several cold geotherm areas, such as the Amsaga belt in the West Africa Craton or the Bangui region in the Central Africa Craton, magnetization may extend into the lithospheric mantle (Hemant and Maus, 2005a, 2005b; Kochemasov and Chuprov, 1990). Overall, mantle contributions to magnetic anomalies, at least in some regions, are acknowledged to be likely (e.g., Purucker and Clark, 2011; Thébault et al., 2010). In addition, the European Space Agency plans to launch in November 2013 the *Swarm* constellation of three satellites with the objective of resolving the lithospheric magnetic field with an unprecedented accuracy (Maus et al., 2006). This mission will bridge the spectral gap between satellite and airborne/marine magnetic surveys, making this proposal highly relevant to understanding the magnetic contribution of the lithospheric mantle to the overall magnetic signature observed from orbit.

3. Reason 2. Magnetic minerals in upper mantle rocks

The upper mantle consists mainly of lherzolites, harzburgites and dunites, and accessorily of pyroxenites, wehrlites and eclogites (e.g., Jackson, 1998).In continental areas, the lithospheric mantle (consisting of plagioclase- and spinel-peridotites) is below the Curie temperature (T_c)[1] and can contribute to magnetic anomalies, whereas garnet-lherzolites, present at greater depths, are too hot to carry a magnetic remanence. Mantle peridotites are found at the Earth's surface either as ophiolite (e.g., Nicolas, 1986), as Alpine-type peridotites (e.g., Liou et al., 2007), or as xenoliths (e.g., Nixon, 1987). Exposed mantle rocks alter through serpentinization, a process that forms abundant magnetite (e.g., Alt and Shanks, 2003; Borradaile and Lagroix, 2001; Frost et al., 2013; Toft et al., 1990). Even weakly altered massifs are serpentinized (Christensen, 1971; Ferré et al., 2005; Le Roux et al., 2007).

Mantle xenoliths, due to their rapid ascent, provide the most pristine samples of the lithospheric mantle (Carlson, 2007; Haggerty and Sautter, 1990; Nixon, 1987). Inclusions of iron-rich phases, such as magnetite and ilmenite, may form in olivine and pyroxene at mantle conditions (e.g., Sen and Jones, 1988), during xenolith ascent, or by a combination of crack healing and metasomatism (Drury and van Roermund, 1989; Hervig, 1989; Neal et al., 2001). Also, xenoliths may be contaminated by the host magma during ascent by grain boundary

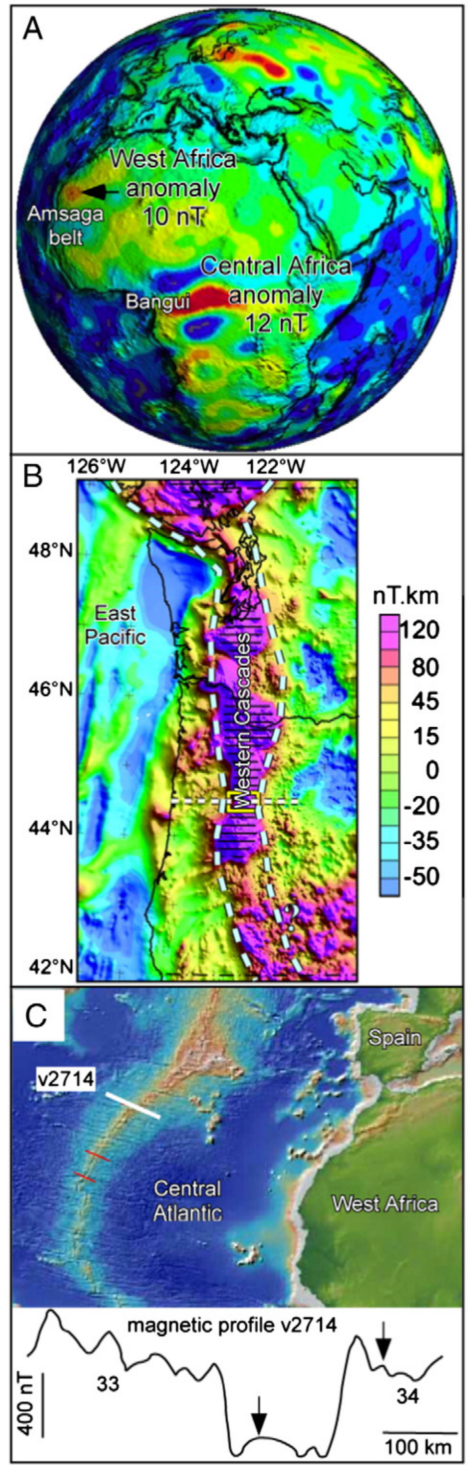

Fig. 1. The analysis of magnetic anomalies suggests the presence of magnetic sources in the upper mantle over both continental and oceanic areas such as: A. The Bangui anomaly in the Central African Craton (Kochemasov and Chuprov, 1990; Ouabego et al., 2013) and the Amsaga anomaly in the West African craton (Hemant and Maus, 2005a, 2005b); B. The Cascadia subduction zone (Blakely et al., 2005); and C. Domains of serpentinized oceanic lithosphere (Dyment et al., 1997).

[1] The temperature above which ferromagnetic minerals lose their magnetic ordering and become paramagnetic.