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Increased mantle heat flow with on-going rifting of the West Antarctic rift system inferred from characterisation of plagioclase peridotite in the shallow Antarctic mantle

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ABSTRACT

The lithospheric, and shallow asthenospheric, mantle in Southern Victoria Land are known to record anomalously high heat flow but the cause remains imperfectly understood. To address this issue plagioclase peridotite xenoliths have been collected from Cenozoic alkalic igneous rocks at three localities along a 150 km transect across the western shoulder of the West Antarctic rift system in Southern Victoria Land, Antarctica. There is a geochemical, thermal and chronological progression across this section of the rift shoulder from relatively hot, young and thick lithosphere in the west to cooler, older and thinner lithosphere in the east. Overprinting this progression are relatively more recent mantle refertilising events. Melt depletion and refertilisation was relatively limited in the lithospheric mantle to the west but has been more extensive in the east. Thermometry obtained from orthopyroxene in these plagioclase peridotites indicates that those samples most recently affected by refertilising melts have attained the highest temperatures, above those predicted from idealised dynamic rift or Northern Victoria Land geotherms and higher than those prevailing in the equivalent East Antarctic mantle. Anomalously high heat flow can thus be attributed to entrapment of syn-rift melts in the lithosphere, probably since regional magmatism commenced at least 24 Myr ago. The chemistry and mineralogy of shallow plagioclase peridotite mantle can be explained by up to 8% melt extraction and a series of refertilisation events. These include: (a) up to 8% refertilisation by a N-MORB melt; (b) metasomatism involving up to 1% addition of a subduction-related component; and (c) addition of ~1.5% average calcio-carbonatite. A high MgO group of clinopyroxenes can be modelled by the addition of up to 1% alkalic melt. Melt extraction and refertilisation mainly occurred in the spinel stability field prior to decompression and uplift. In this region mantle plagioclase originates by a combination of subsolidus recrystallisation during decompression within the plagioclase stability field and refertilisation by basaltic melt.

1. Introduction

Plagioclase-bearing spinel peridotite (hereafter plagioclase peridotite) xenoliths are rare compared to the common spinel peridotite varieties. Working mainly in the CMAS ($CaO–MgO–Al_2O_3–SiO_2$) system, experimental studies have synthesised plagioclase peridotite in the laboratory through a subsolidus (metamorphic) reaction involving decompression of spinel peridotite into the plagioclase peridotite stability field (Gasparik, 1984; Herzberg, 1978; Kushiro and Yoder, 1966; O'Hara, 1967; Obata, 1976). A long series of experimental studies in increasingly more complex systems, utilising in addition to CMAS, Na_2O, FeO, Cr_2O_3 and TiO_2, have worked towards refining the understanding of plagioclase peridotite formation under various mantle conditions (Baker and Stolper, 1994; Borghini et al., 2010; Falloon and Green, 1987; Falloon et al., 1999; Gudfinnsson and Presnall, 2000; Jaques and Green, 1980; Walter and Presnall, 1994). Natural examples of plagioclase peridotite formed by metamorphic recrystallisation are mainly restricted to xenoliths from continental settings with some examples also from ocean islands (Canil et al., 2003; Chazot et al., 2005; Obata, 1980; Ozawa and Takahashi, 1995; Rampone et al., 1993). It is much more common, however, for natural occurrences of plagioclase peridotite to be interpreted as the product of refertilisation by metasomatic fluids (Menzies, 1973; Menzies and Allen, 1974; Nicolas and Dupuy, 1984; Piccardo et al., 2007; Rampone and Borghini, 2008; Rampone et al., 1997, 2008), a process that has also been modelled experimentally (e.g., Lundstrom, 2003; Van Den Bleeken et al., 2010). Thus despite its scarcity among mantle xenoliths, occurrences of plagioclase peridotite are important for understanding both the petrogenesis of depleted shallow upper mantle and the character of refertilising fluids (e.g., Müntener et al., 2004, 2010; Piccardo et al., 2007; Rampone and Borghini, 2008; Rampone et al., 2010). Here, we describe plagioclase peridotite samples collected from three localities in Antarctica that form a 150 km long

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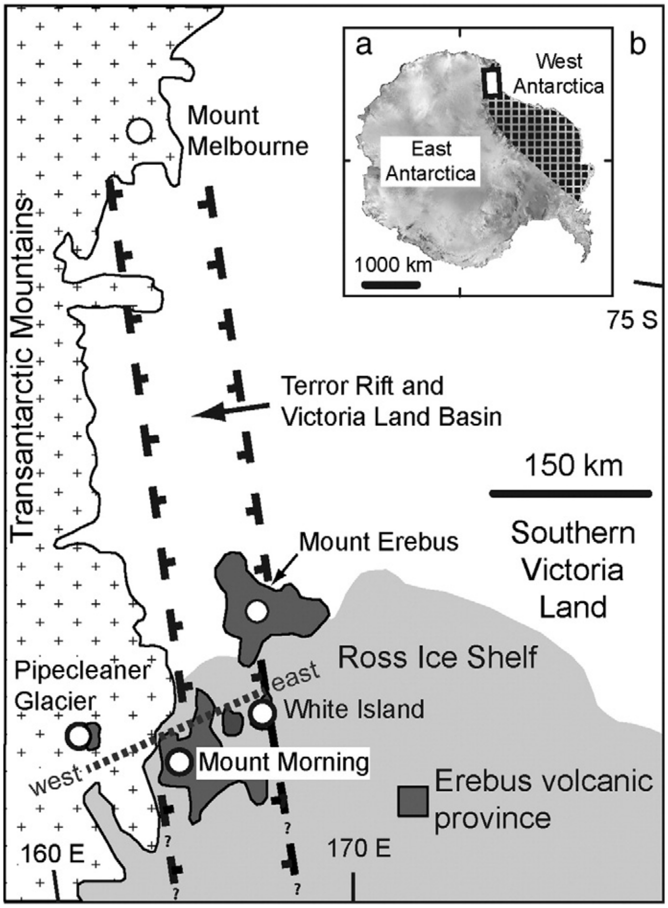

Fig. 1. Map showing location of plagioclase peridotite localities relevant to this study. Inset a) Map of Antarctica. Patterned field marks the extent of the West Antarctic rift system, after LeMasurier (2008). b) Map of Victoria Land. The position of the Terror Rift and the Victoria Land Basin follows Johnston et al. (2008) and Zipfel and Wörner (1992). The dashed grey line shows the approximate west to east trend of Fig. 12 transect.

transect across the western shoulder of the active West Antarctic rift system (WARS; Fig. 1a). Tomography across this section of the WARS shows abnormally high heat flow (Watson et al., 2006) and onshore (Jones, 1996; Martin and Cooper, 2010) and offshore (Behrendt, 1991) faulting and preliminary high-precision GPS measurements (Negusini et al., 2005), suggest the WARS is currently active. Although spinel peridotite xenoliths have long been known to occur in this area of Antarctica (Ferrar, 1907; Prior, 1902, 1907; Smith, 1954; Thomson, 1916), this study is focused on the more unusual plagioclase peridotite sub-set of xenoliths and is aimed at understanding the nature and evolution of the depleted shallow mantle and particularly the degree to which this has involved refertilisation. The localities are, from west to east, Pipecleaner Glacier, in the foothills of the Transantarctic Mountains and Mount Morning and White Island, which are volcanic islands in the adjacent Ross Sea (Fig. 1b). At all three localities xenoliths are hosted in Cenozoic alkalic igneous rocks, which are part of the Erebus volcanic province (EVP) of the McMurdo Volcanic Group in Southern Victoria Land, Antarctica. New petrography, mineral and whole rock major and trace element data and geothermometry are used to characterise the mantle across the active rift shoulder with the objective being to determine the petrogenesis of mantle plagioclase and to understand the cause of abnormally high mantle heat flow in the WARS.

2. Geological setting and terminology

Antarctica comprises cratonic East Antarctica and the patchwork of accreted terranes making up West Antarctica, with the Transantarctic Mountain range marking the boundary between the two (Fig. 1). The continental WARS (Fig. 1), to the east of the Transantarctic Mountains, is comparable in scale and similar in morphology to the Basin and Range province of the south western United States. The McMurdo Volcanic Group crops out to the east and in the foothills of the Transantarctic Mountains as discontinuous fields and isolated volcanic centres extending ~2000 km between Cape Adare in the north and Mount Early in the south (Harrington, 1958; Kyle, 1990b). The Terror Rift, in the Southern Victoria Land Basin of the western Ross Sea, near Mount Erebus (Fig. 1b), is the most recently active portion of the WARS (Cooper et al., 1991; Martin and Cooper, 2010). Cenozoic, alkalic eruptive centres crop out at the southern end of the known limits of the Terror Rift, forming the EVP (Fig. 1b). Sample locations relevant to this study are shown in Fig. 1b.

Pipecleaner Glacier is situated to the west of the Terror Rift in the foothills of the Transantarctic Mountains and is underlain by approximately 40 km thick (Bannister et al., 2003), calc-alkalic continental crust. Mount Morning is at the western edge of the Terror Rift on calc-alkalic and alkalic continental crust (Martin, 2009). White Island lies on the eastern margin of the Terror Rift where the continental crust is approximately 20 km thick (Bannister et al., 2003) and chemistry suggests the crust has a tholeiitic cumulate protolith (Berg et al., 1989; Cooper et al., 2007). Monogenetic, basanite cinder cones, lava flows and tuffs make up the Cenozoic volcanic rocks at Pipecleaner Glacier, similar to other EVP localities in the foothills of the Transantarctic Mountains (Kyle, 1990a). Mount Morning is a poly-phase eruptive centre, with a modern basanite–phonolite shield built upon an older basanite–trachyte sequence (Martin et al., 2013). White Island is a basanite to tephriphonolite shield volcano (Cooper et al., 2007). The oldest, fine-grained igneous rocks hosting xenoliths from Mount Morning and White Island are 6.13 ± 0.2 Ma (Martin et al., 2010) and 5.05 ± 0.31 Ma (Cooper et al., 2007) respectively. The age of volcanism at Pipecleaner Glacier is unknown, but comparison with other areas in the EVP indicates that it is likely to be < 5 Ma. At Mount Morning, xenoliths are most abundant in fine-grained, mafic igneous rocks < 1 Ma old (Martin, 2009). Volcanism in the McMurdo Volcanic Group has been associated with strike–slip deformation and decompression melting (Rocchi et al., 2006). All the peridotite xenoliths considered in this study contain both spinel and plagioclase feldspar, but following conventional terminology, these will be referred to as plagioclase peridotite. The next closest locality where plagioclase peridotite occurs is Mount Melbourne ~400 km to the north (Zipfel and Wörner, 1992; Fig. 1b).

3. Description of samples and analytical methods

Ovoid peridotite xenoliths of ≤50 cm in diameter are found in alkalic dykes and lava flows at the three study sites. At the main xenolith locality on Mount Morning (78° 23.901′ S; 163° 49.675′ E), the bulk rock chemistry of the host (OU 78540) is basanite (Table 1). The compositions of the host rocks for xenoliths from White Island (78° 03.952′ S; 167° 25.286′ E) and Pipecleaner Glacier (78° 16′ S; 162° 39′ E) are broadly comparable to the xenolith host at Mount Morning. Mount Morning xenoliths are free from weathering, but there is some alteration of olivine in White Island and Pipecleaner Glacier samples. The boundaries between xenoliths and host are sharp. Eleven specimens have been identified where plagioclase coexists with olivine + clinopyroxene + orthopyroxene + spinel (Table 1). Garnet is never observed in the EVP xenoliths. Amphibole and phlogopite are accessory phases in xenoliths from White Island and Pipecleaner Glacier. Only a single, phlogopite-bearing clinopyroxenite xenolith has been reported from Mount Morning (Martin et al., 2013). The EVP plagioclase peridotites have porphyroclastic to tabular granuloblastic textures (Fig. 2). Mineral mode was determined by counting 300 points in each thin section (Table 1; Fig. 3); with probable error between 2.5 and 6% at the 95.4 confidence level (Chayes, 1956). Whole rock data