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The petrology of high pressure xenoliths and associated Cenozoic basalts from Northeastern Tasmania

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ABSTRACT

Abundant mantle xenoliths are found in widespread undersaturated Cenozoic basaltic rocks in Northeastern Tasmania and comprise lavas, dykes, plugs and diatremes. The basanites and nephelinites, include primitive magmas (11–14 wt.% MgO) with OIB-like geochemical features. Trace element and Pb– and Sr–Nd isotope data suggest that they were generated by mixing of melts derived from low degree (<5%) melting of both garnet- (~90%) and spinel lherzolite (~10%) facies mantle sources with HIMU and EMII characteristics. The associated xenolith suite consists mainly of spinel lherzolite and rare spinel pyroxenite with predominantly granoblastic textures. Calculated oxygen fugacities indicate equilibration of the xenoliths at 0.81 to 2.65 log units below the fayalite–magnetite–quartz (FMQ) buffer. Mantle xenolith equilibration temperatures range from 890–1050 ± 50 °C at weakly constrained pressures between 0.8 and 11.5 GPa. A hot xenolith's geotherm is indicated and attributed to tectonothermal events associated with the break-up of Gondwanaland and/or the opening of the Tasman Sea.

1. Introduction

Cenozoic volcanism is an important feature in the geological evolution of Tasmania (Sutherland, 1969). Xenoliths, cognate inclusions, xenocrysts and megacrysts of upper mantle or lower crustal origin are recorded at more than 190 localities throughout Tasmania (Wass and Irving, 1976; Varne, 1977; Everard, 2001). Most host rocks are lavas, rather than pyroclastics, in contrast to some well-studied localities in the later basaltic fields of Victoria (~7–0 Ma) (Duncan and McDougall, 1989; Price et al., 2003) and in North Queensland (<9 Ma) (Zhang et al., 2001). Because pyroclastics are relatively easily eroded, they are less commonly preserved in the older Tasmanian volcanics. Since collection and extraction is more difficult from tough lavas, Tasmanian xenoliths have been less extensively studied.

Host rocks are strongly biased towards undersaturated compositions (e.g. olivine nephelinite and basanite), with a sole occurrence in olivine tholeiite (Sutherland, 1974). Mantle xenoliths are also widespread in the more fractionated alkaline lineages of the hawaiite–mugearite and equivalent feldspathoidal lineages (e.g. Sutherland, 1974; Everard, 2001).

By far the most common inclusions are spinel lherzolites of the Cr-diopside suite. Garnet lherzolite xenoliths are known at one Tasmanian locality, Bow Hill near Oatlands (Sutherland et al., 1984). Pyroxene-rich members of the Cr-diopside suite are relatively rare in eastern Australia (O'Reilly et al., 1989) and have been located at Bow Hill and Table Cape (Sutherland et al., 2005) and Round Lagoon (Sutherland et al., 2008). However, at about 30 sites, spinel lherzolite is accompanied by Al-augite suite inclusions (mostly websterite and wehrlite). Other xenoliths, of probable lower to mid-crustal origin, include granulite, gabbro, dolerite and anorthosite. Megacryst species reported include clinopyroxene, orthopyroxene, olivine, spinels, kaersutitic amphibole, titanbiotite and titanphlogopite, apatite, alkali feldspar (anorthoclase, sanidine), plagioclase (albite to labradorite) and titanomagnetite. Zircon, corundum (sapphire), and possibly diamond occur as heavy minerals in alluvial deposits derived from Cenozoic basalts, but are very seldom found *in situ* (Everard, 2001). The petrology of mantle-derived and other high pressure inclusions from Australia, including Tasmania, has been reviewed by numerous authors (Frey and Green, 1974; Sutherland, 1974; Wass and Irving, 1976; Griffin et al., 1984; Wass and Shaw, 1984; Dal Negro et al., 1984; Griffin et al., 1987, 1988; O'Reilly et al., 1989; Wilkinson and Stolz, 1997; Roach, 2004). More detailed information on particular Tasmanian localities is provided by Sutherland (1974), Varne (1977), McClenaghan et al. (1982), Everard (1989) and Sutherland et al. (1984, 1996, 2005).

Because of their small size, there are few whole rock analyses of Tasmanian xenoliths (McClenaghan et al., 1982). Varne (1977) studied nine xenoliths from eight localities in detail, and attributed the textures and chemistry of co-existing minerals to exsolution of spinel from aluminous pyroxenes with falling temperature. He noted that they were broadly similar to spinel lherzolite inclusions elsewhere in the world, and concluded that they were accidental inclusions of upper mantle, genetically unrelated to their host rocks.

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This paper aims to provide new insights into the petrology and geochemistry of the lithosphere underneath Tasmania.

2. Tectonic and geological setting

Tasmania and the surrounding continental shelf comprise the southern protuberance of the Australian continent, which separated from Antarctica at 95 ± 5 Ma, although northward drift was very slow until 45 Ma (Veevers et al., 1991). Bass Strait, although mostly only 30–90 m deep (water), represents a failed rift, and locally more than 10 km of Cretaceous and Cenozoic sediments in the Bass Basin rest on thinned continental crust. Rifting east of Tasmania also commenced in the Late Cretaceous, with the separation of the Lord Howe Rise and opening of the Tasman Sea between 84 Ma and 52 Ma (Veevers et al., 1991; Gaina et al., 2003) The oldest rocks in eastern Tasmania are a thick quartzwacke turbidite sequence of Early Ordovician to Early Devonian age, the Mathinna Supergroup, which was folded in the Middle Devonian (~389 Ma). This event, the Tabberabberan Orogeny, was preceded and followed by widespread granitic magmatism (Black et al., 2005). It probably represents the amalgamation of eastern Tasmania with the distinct western Tasmanian terrane, which records a longer history extending back to at least the Early Neoproterozoic. The relationship between the basement and the Mathinna Supergroup, and similar sequences in the Lachlan Fold Belt of the Australian mainland, is controversial; both old continental crust and tectonically thickened oceanic crust have been advocated (e.g. Gray and Foster, 2004).

Mainly extensional tectonics have prevailed in Tasmania since the Late Paleozoic. From the Late Carboniferous to the Late Triassic, glaciomarine and fluvial shelf sediments were deposited in central and Southern Tasmania (Tasmania Basin), followed by voluminous intrusion of Jurassic dolerite (~177 Ma) prior to continental break-up (Bromfield et al., 2007). In Northeastern Tasmania, these units are thin and following Cenozoic uplift and erosion, are mostly limited to mountain caps.

Cenozoic basaltic volcanics crop out over 4060 km^2, or about 6%, of the Tasmanian landmass. They represent the southern end of the Eastern Australian Volcanic Province, which extends for ~3700 km south from Torres Strait, roughly parallel to the Eastern Highlands and the continental margin (e.g. Vasconcelos et al., 2008). Three main types of activity in Eastern Australia were recognized by Wellman and McDougall (1974): 1) The "central volcanoes" are usually dominated by a single large volcanic complex and typically consist of near-saturated basalts with subordinate felsic rocks. These show a consistent southward age progression and are widely regarded as the track of a mantle plume, now located at 40.8°S and yet to fully impinge on Tasmania (Duncan and McDougall, 1989); 2) the lava fields, which span a wider age range than the central volcanoes in any particular area, but show no simple age progression. They are all mafic rocks and isotopic signatures and trace element patterns identify an OIB-type source as the dominant component (O'Reilly and Zhang, 1995); 3) the volumetrically minor leucitites of central western New South Wales (Cundari, 1973), is not represented in Tasmania.

The Tasmanian volcanics are variable in form, comprising large crater fills, prominent necks, small plugs and diatremes, dykes, thick piles of lava, long subaerial valley flows, small flow remnants, subaqueous pillow lavas and aquagene volcaniclastic deposits. Activity had commenced by 70 Ma (Everard et al., 2004) and continued to 8.5 Ma (Baillie, 1986), with a peak in the Late Miocene and Early Oligocene (c. 21–31 Ma) (e.g. Sutherland and Wellman, 1986; Sutherland et al., 2002). Although entirely mafic, they vary widely in composition (e.g. SiO_2 37.0–53.6 wt% anhydrous) from rare olivine melilitite, through olivine nephelinite ($ab<5$), basanite ($ne>5$, $ab>5$) and alkali basalt ($0<ne<5$) to transitional olivine basalt ($0<hy<10$), olivine tholeiite ($hy>10$) and quartz tholeiite (Q) (normative classification of Johnson and Duggan, 1989). In the IUGS total alkali–silica classification (Le Maitre, 2002), the equivalent terms are mostly foidite, basanite, basalt and basaltic andesite. Evolved alkaline types, such as hawaiites and mugearites and their foid-rich counterparts are also locally present. Many of the lavas have high Mg# (molar 100 Mg/Mg + Fe^{II}) > 67, consistent with equilibration with mantle xenoliths which contain olivine of Fo_{87-90}. High contents of the compatible elements Ni (>200 ppm) and Cr (>300 ppm) are also consistent with primary melts (e.g. Frey et al., 1978; Sutherland, 1989).

The origin of this volcanism is controversial. Some workers (e.g. Lister and Etheridge, 1989; O'Reilly and Zhang, 1995) have advocated a "plume swathe" model of passive mantle upwelling, possibly a delayed effect from continental rifting, with local controls from stress fields and lithospheric fractures. An alternative view is that the lava field volcanism is also migratory and related to multiple plumes (e.g. Sutherland, 1981, 1991, 2003).

3. Sample localities

In Northeast Tasmania, Cenozoic basalts are widespread and display a wide range of age and composition, comparable to the rest of Tasmania, although olivine melilitites and strongly evolved alkaline types are absent. The samples of this study have been collected from localities listed in the electronic supplementary file (Appendix A) and shown in Fig. 1. The occurrences are all associated with magnetic anomalies, evident in the Northeastern Tasmanian Survey conducted by Mineral Resources Tasmania in 2007, which assisted in the determining the form of their host basalts.

At the Sideling, 29 km NE of Launceston, olivine nephelinite rests on Mathinna Supergroup basement, capping a prominent hill at c. 680–781 m above sea level. There is an associated intense positive magnetic anomaly, and our preliminary geophysical modelling suggests an underlying feeder and associated flow remnant. Mantle xenoliths are abundant throughout the nephelinite, but our samples (NJ310A and B) were collected from a small quarry near the base of the flow on the southern side, where they are particularly large up to (~150 mm) and abundant. A sample of the host rock, from the summit of the hill, yielded a $^{40}Ar/^{39}Ar$ plateau age of 29.4 ± 0.5 Ma (Everard et al., 2004).

At Warrentinna, 7 km N of Branxholm, up to 40 m of basalt, also resting on Mathinna Supergroup, caps a small ridge. The physiography of the area suggests that upstanding flow remnants, possibly valley-filling lavas, were left after preferential erosion of the surrounding less resistant Mathinna Supergroup At least two flows are present. The lower flow is a very coarse-grained basanite (~45% SiO_2) and lacks obvious xenoliths, but they are abundant in a fine-grained nephelinite on the ridge crest. The lavas resemble, and are probably outliers of the long valley-filling flows of alkali basalt, basanite and nephelinite widespread in the Ringarooma valley (Brown and McClenaghan, 1982). These have been dated by K/Ar at 16.0–16.4 Ma at three sites near Winnaleah, 6–11 km NNE and E of Warrentinna (McClenaghan et al., 1982) and also have normal magnetic polarity.

At the Sandy Creek locality, 11 km N of Winnaleah, olivine nephelinite with abundant but mostly small mantle xenoliths is well exposed in a small quarry. The associated magnetic anomaly is weak and negative, suggesting a small flow remnant of reversed polarity, probably no more than 10 m thick, resting on Devonian granite. A possible feeder of similar, reversely magnetized nephelinite is present 3.5 km to the NNW. There is no direct evidence for the age, but the occurrence is petrographically similar to the 16 Ma Ringarooma Valley flows.

The samples MNET 39A–K have been collected from a quarry on Logans Road, about 15 km NW of St Helens, where a small area of basaltic rock, surrounded by Devonian granite, is associated with an intense positive magnetic anomaly. Preliminary geophysical modelling suggests an underlying feeder and associated flow remnant (Zaw et al., 2006).