Lithos 206–207 (2014) 179–200

Contents lists available at ScienceDirect

Lithos

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

Lithospheric influences on magma compositions of late Mesozoic and Cenozoic intraplate basalts (the Older Volcanics) of Victoria, south-eastern Australia

Richard C. Price [a,*], Ian A. Nicholls [b], Arthur Day [c]

[a] Science and Engineering, University of Waikato, Hamilton, New Zealand
[b] School of Geosciences, Monash University, Clayton, Victoria, Australia
[c] PO Box 533, Corrimal, NSW, Australia

ARTICLE INFO

Article history:
Received 1 May 2014
Accepted 27 July 2014
Available online 7 August 2014

Keywords:
Basalt
Intraplate volcanism
Mantle metasomatism
Lithospheric mantle

ABSTRACT

Basaltic volcanism, ranging in age from Late Cretaceous to Holocene and extending across the southern part of the state of Victoria in south-eastern Australia was initiated during the earliest stages of rifting associated with opening of the Tasman Sea and Southern Ocean. Volcanism has continued sporadically since that time with major breaks in activity occurring between 77 and 62 Ma and 18 and 7 Ma. Basaltic rocks with ages in the range 95 to 18 Ma occur in small lava fields scattered across eastern and south-eastern Victoria and they have also been recovered from bore holes in the west of the state. They have been referred to as the "Older Volcanics" to differentiate them from more volumetrically extensive and younger (mainly < 4.6 Ma) lava fields comprising the "Newer Volcanics" of the Western District Province to the west.

Older Volcanics vary in composition from SiO_2-undersaturated nephelinites, basanites, basalts and hawaiites through transitional basalts to hypersthene and quartz normative tholeiites. Strontium, Nd and Pb isotopic compositions lie between depleted (DM) and enriched (EM1 and EM2) end member mantle components in Sr–Nd–Pb isotopic space. Trace element compositions are generally characterised by enrichment of Cs, Ba, Rb, Th, U, Nb, K and light REE over heavy REE, Ti, Zr and Y and the overall patterns of major and trace element behaviour can be explained in general terms by petrogenetic models involving partial melting of a complex spectrum of mantle compositions with subsequent but limited additional modification by fractional crystallisation with or without assimilation of crust.

Among basalts with relatively high Mg# [100 ∗ Mol. MgO/(MgO + FeO) > 65], two distinct end member compositions can be differentiated using primitive mantle normalised extended element patterns. Group 1 basalts have convex upward patterns with enrichment of light over heavy REE and depletion of Rb, Ba, Th and U relative to Nb. Group 2 basalts also have distinctive convex upwards patterns but are characterised by strong depletions of K, Rb and Ba relative to Nb. In both groups there is additional subtle variation with some samples having patterns with relative enrichments in Nb, Sr and Eu and/or depletions in Pb. Group 1 basalt compositions can be approximated by quantitative models involving 2 to 10% partial melting of an originally depleted mantle composition that has been metasomatised by the addition of 2 to 3% of an enriched component with a composition similar to EM1 intraplate basalt. The trace element patterns of Group 2 basalts can be modelled by 2 to 10% partial melting of an originally depleted mantle metasomatised by the addition of 1% of a calci-carbonatite composition.

When Sr isotope data for Older Volcanics are projected onto an east–west profile across the state of Victoria, they outline distinctive discontinuities in isotopic composition that appear to be related to surface and subsurface structural features within the basement. One such discontinuity has previously been identified using data for the Newer Volcanics of the Western District Province of Victoria. Lithospheric blocks present beneath southern Victoria range in age from NeoProterozoic or Cambrian to Palaeozoic and some of the lowest $^{87}Sr/^{86}Sr$ ratios are observed in basalts erupted above an older basement unit (the Selwyn Block). The inference is that there is some form of lithospheric control on basaltic magma chemistry and since a substantial proportion of Older Volcanics have the geochemical characteristics of primary magmas (high Mg# and moderate to high abundances of Ni and Cr), this could indicate that magmas have been sourced from regionally heterogeneous, variably metasomatised, sub-continental lithospheric mantle.

Neither the temporal and spatial relationships of the magmatic activity that followed continental breakup nor the uplift history of the south-eastern Australian passive margin are readily explained in terms of deep mantle plume

* Corresponding author at: 13 Parkwood Street, Alfredton, Victoria, 3350, Australia.
E-mail address: rprice@waikato.ac.nz (R.C. Price).

http://dx.doi.org/10.1016/j.lithos.2014.07.027

tectonic models. Edge-driven convection across the irregular base of the southern Australian lithosphere, within the asthenosphere offers an elegant explanation for the longevity of the magmatic activity, its distribution, the small magma volumes involved and the uplift history as well as the geochemical variation observed in the eruptives.

1. Introduction

From late Jurassic time the eastern and south-eastern margins of Australia were affected by rifting and then slow spreading that heralded the breakup of eastern Gondwana and preceded rapid opening of the Tasman Sea and Southern Ocean (e.g. Gaina et al., 2003; Mutter et al., 1985; Veevers, 1986; Weissel and Hayes, 1977). Magmatism is commonly associated with lithospheric extension at evolving passive margins (Planke et al., 2000) and this was the case during the fragmentation of eastern Gondwana. From the very earliest stages of initial rifting, intraplate basaltic rocks were emplaced adjacent to the margin of the Australian continent (Holford et al., 2012) and this activity has continued to virtually the present day, Magmatic CO_2 in mineral springs of central Victoria (Cartwright et al., 2002) and low seismic velocities beneath western Victoria (Graeber et al., 2002; Rawlinson and Fishwick, 2012) could be indications that region still has the potential to be magmatically active. The products of this prolonged magmatic activity are lava fields, shallow intrusions and larger volcanoes and volcanic complexes ranging in age from Mesozoic to Cenozoic and these are exposed in a belt that extends for around 4400 km from far north Queensland to Tasmania (Johnson, 1989; Vasconcelos et al., 2008).

Active spreading that led to Gondwanan breakup was preceded by a period of faulting and rifting associated with lithospheric extension and when Australia began to separate from Zealandia and Antarctica, the rate of separation was initially relatively slow (~6 mm/year; Weissel and Hayes, 1977). Opening of the Tasman Sea was largely completed between 80 and 50 Ma (Weissel and Hayes, 1977). Along the Southern Ocean segment of the rifted Australian margin, the transition from rifting to spreading is likely to have taken place around 50 Ma (Mutter et al., 1985). Rapid spreading (average around ~5 to 6 cm/year) commenced in the Southern Ocean around 40 Ma ago and continues today.

In Victoria and into south-eastern South Australia, one of the consequences of this prolonged tectonic reorganisation was relatively low volume and intermittent magmatic activity over a wide area. Basaltic rocks, ranging in age from Late Jurassic to Holocene are distributed across the state of Victoria (Fig. 1) over an area covering more than 700 km from east to west and around 300 km north to south.

Jurassic aged igneous rocks have been identified as surface outcrops in far western Victoria (Day, 1983; McDougall and Wellman, 1976) and in drill holes and seismic profiles from onshore and offshore sedimentary basins (Holford et al., 2012). A breccia pipe with kimberlitic affinities at Meredith in central Victoria also has a Jurassic age (Day, 1983; Ferguson, 1980), as do alkalic dikes that have been found in outcrop and in the subsurface across central and eastern Victoria (e.g. McDougall and Wellman, 1976; Soesoo et al., 1999). This magmatic activity was related to the earliest, rifting stages of Gondwanan breakup.

Widespread volcanic activity commenced ~95 Ma ago and continued intermittently through the Cenozoic with the youngest rocks being emplaced < 10 ka ago. A major hiatus occurred between 77 and 62 Ma and another in the time interval 18 to 7 Ma with major peaks in activity at 45 to 37 Ma, 22 Ma and 3 to 2 Ma (Figs. 1 and 2) (e.g. Gray and McDougall, 2009; McDougall et al., 1966; Price et al., 2003b; Wellman, 1974; Wellman and McDougall, 1974). These volcanic rocks have traditionally been subdivided into chronological and spatially different groups (e.g. Edwards, 1938; Hills, 1938; Singleton and Joyce, 1969). Basaltic rocks with ages in the range 95 to 18 Ma have been referred to as the "Older Volcanics" to differentiate them from more volumetrically extensive and younger (<4.6 Ma) basaltic lava fields and cones of the "Newer Volcanics" or Western District Province (Fig. 1), 7 to 5 Ma felsic volcanoes and associated mafic lavas of the Macedon-Trentham Province (Fig. 1) (Price et al., 2003b) and leucitites and basalts of the Cosgrove–Euroa area (Fig. 1) in central Victoria, which are estimated to have been emplaced 10 to 5 Ma ago (Paul et al., 2005). Outside the Western Districts Province, Newer Volcanics have been identified at only one locality in eastern Victoria; isolated outcrops of basalt with an age estimated at 4 to 2 Ma have been assigned by Sutherland et al. (2003) to a separate Uplands Province (Fig. 1). The Western District Province, which covers over 15,000 km^2 of Victoria, comprises an extensive plain of thin (<50 m) basaltic lava flows on which basaltic cinder cones, lava shields and maar volcanoes have been emplaced (Boyce, 2013; Hills, 1938; Price et al., 1997; Singleton and Joyce, 1969; Sutherland et al., 2014). The "plains" basalts range in age from 4.6 Ma to < 1 Ma with a volumetric peak in eruptive activity occurring between 3 and 1.8 Ma (Gray and McDougall, 2009). "Cones" basalts are generally less than a few hundred thousand years old and some were erupted < 5 to 10 ka ago. Although this paper is concerned primarily with the older, 95 to 18 Ma eruptives (Older Volcanics), where appropriate and relevant, data for these have been integrated with those available for the plains and cones of the Western District Province (Newer Volcanics), the basalts of the Cosgrove–Euroa area and the Uplands Province of eastern Victoria and this information has been used to evaluate petrogenetic models for the complete suite of Victorian late Mesozoic and Cenozoic basaltic eruptives.

Using geochemical data for the Western District Province, Price et al. (1997) suggested that magma chemistry has been influenced by lithospheric structure (see also Price et al., 2003b) and new analyses for the Older Volcanics presented in this paper provide the opportunity to extend both the spatial and temporal scope for assessing the relationship between magma geochemistry and lithospheric influence in the petrogenesis of Victorian intraplate basalts.

2. The Older Volcanics: intraplate basaltic volcanism in Victoria between 95 and 18 Ma

On the basis of geographic distribution, geochronology and petrology the Older Volcanics of Victoria have been grouped into a number of provinces and sub-provinces (Day, 1983, 1989; Price et al., 2003b; Wellman, 1974; see Fig. 1). Each of the sub-provinces is a geographic entity comprising the remnants of lava fields, monogenetic cones and/or shallow intrusions. Age ranges within individual sub-provinces vary from 1 to 19 Ma (Fig. 2).

The physical volcanology and petrography of basaltic rocks of the Older Volcanics have been described by Day (1983, 1989) and a summary is provided in Table 1 (see also Price et al., 2003b). The rock classification scheme used here is that of Johnson and Duggan (1989). Older Volcanics vary in composition from nephelinites, SiO_2-undersaturated basanites, basalts and hawaiites through transitional basalts to hypersthene and quartz normative tholeiites. In contrast, Newer Volcanics are dominated volumetrically by tholeiitic and transitional types but the youngest eruptives tend to be SiO_2-undersaturated (Frey et al., 1978; Irving, 1971; Irving and Green, 1976; Price et al., 1997, 2003b).

3. Geological and tectonic context of Mesozoic and Cenozoic intraplate basaltic volcanism in Victoria

The intraplate basalts of Victoria were emplaced on Palaeozoic basement rocks that are part of the Tasman Orogenic system (Glen, 1992; Gray et al., 2003), which is in turn made up of three accreted belts or