Multiple felsic events within post-10 Ma volcanism, Southeast Australia: inputs in appraising proposed magmatic models

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INTRODUCTION

The late Cenozoic (<10 Ma) intraplate volcanic fields in Victoria and SE South Australia (Figure 1) have been extensively studied from a number of aspects. These include their volcanic land forms (Kershaw 2004; Joyce 2005; Boyce 2013), drainage and groundwater systems (Taylor & Gentle 2002; Bennetts et al. 2003), petrology (Price et al. 2003; Hare et al. 2005; Paul et al. 2005; Irving & Green 2008), inclusion suites (Graham et al. 2003; Powell et al. 2004; Sutherland et al. 2004); ages (Gibson 2007; Vasconcelos et al. 2008; Gray & McDougall 2009; Gillen et al. 2010; Matchan & Phillips 2011), magma sources (McBride et al. 2001; Demidjuk et al. 2007; Furrington et al. 2010) and volcanic-tectonic setting (Graeber et al. 2002; Sandiford et al. 2004; Lesti et al. 2008).
The genesis of Australian–Tasman Sea volcanism has been widely debated. Some researchers advocate a role for asthenospheric mantle plume-like inputs related to the age-progressive volcano migrations, especially in continental basaltic shields with evolved felsic cores (central volcanoes) and offshore basaltic seamount chains (Vasconcelos et al. 2008; Sutherland et al. 2012). Plume-like inputs, however, become less obvious where felsic activity is limited and basaltic lavas are widespread (Price et al. 2003). Some studies may support plume-like asthenospheric inputs, such as the Os-isotope and trace-element data on alkaline basalts that are consistent with an oceanic island basalt (OIB)-type mantle plume source or a veined lithospheric mantle source (McBride et al. 2001; Sutherland 2003). Other workers, however, downplay plume involvement and instead propose repeated long-term magmatic events triggered by regional tectonic causes with shallower asthenospheric/lithospheric sources (Price et al. 2003; Demidjuk et al. 2007; Lesti et al. 2008; Farrington et al. 2010). However, some Victorian volcanism such as the felsic rocks in the Macedon–Trentham area (K–Ar ca 6 Ma) and the leucite-bearing basalt at Cosgrove (40Ar–39Ar ca 9 Ma), lie close to the latitudinal expression of the East Australian Plume (EAP) trace through SE Australia (Cohen et al. 2008; Vasconcelos et al. 2008; Figure 2). Further evidence for a potential recent plume component in this area was advanced by Matsumoto et al. (1997), who identified a primitive neon component in apatite from a metasomatised mantle xenolith in young Victorian basalt. This interpretation was disputed by Gautheron & Moreira (2003), based on a different modelling of Ne isotope fractionation. The initial finding of a plume-like Ne-isotopic composition, however, remains as a robust conclusion after the isotope fractionation model was re-examined by Matsumoto et al. (2004).

The region where suggested plume-like magmatic interactions exist below Victoria has present surface expression through mantle signatures for He, Ne and CO2 detected in spring waters around Daylesford (Cartwright et al. 2002). The underlying mantle exhibits seismic velocities that reach their greatest reductions (slowest values) below the young basalt fields to depths of at least 200 km, suggesting anomalously high heat flows (Graeber et al. 2002). The depths and positions of asthenospheric thermal anomalies relative to the basalt fields may provide insights into the underlying magmatic processes. High surface heat flows in western Victoria may be linked to mantle and tectonic features (Purss & Cull 2001; O’Neill et al. 2003; Geothermal Heat Flow Atlas of Victoria 2010, www.dpi.vic.gov.au/minpet/geovic), while the young volcanic fields have been linked to high advective mantle–crust geotherms, the SE Australia (SEA) geotherm, based on xenolith-derived pressure–temperature data from the Bullenmerri and Gnotuk maars (O’Reilly et al. 1997; Sutherland et al. 2005a). In a wider context, high heat flow regions along the southern Australian margin were strongly correlated with present seismic and neotectonic zones, suggesting that thermal weakening has localised intraplate deformations (Holford et al. 2011a). The neotectonic deformations, including those in western Victoria, have been linked to enhanced stress fields related to Indo-Australian and Pacific Plate couplings (Sandiford et al. 2004; Robson & Webb 2011; Holford et al. 2011b).
Several models have been developed to explain the younger (post-10 Ma) volcanism in SE Australia. Models include a system of transpressive-faults and mantle melting (TFMM; Lesti et al. 2008); a lithospheric-step, mantle convection (LSMC) system (Demidjuk et al. 2007) and an irregular EAP interactive system (Sutherland et al. 2012). The TFMM model involves stress effects along deep crustal faults and the onshore termination of the oceanic Australia–Antarctica Tasman Fracture Zone (TFZ), as influences on Victorian basalt distribution. The LSMC
model invokes a known lithospheric-step north of the basalt fields (Fishwick et al. 2006), being a cause of trailing-edge mantle convection along the wake of Australian northerly plate motion. The convective cell enables uptake of asthenospheric components. The EAP model involves a deep asthenospheric ‘thermal’ anomaly detected under Bass Strait by seismic studies (Montelli et al. 2006; Ford et al. 2010; Kennett & Abdullah 2011), as a dormant but previously active site of a plume system. The plume site lies east of the TFZ and southeast of the young Victorian basalts and was not part of the older Tasmanian basalt province farther south. The plume inputs may include mantle plume upwelling deflected westward by asthenospheric flow (Sutherland et al. 2012). Such westerly mantle flow appears at the Australia–Antarctica depth anomaly, where Pacific-signature oceanic basalts have invaded Indian Ocean-signature basalts for at least 28 Ma (Whittaker et al. 2010).

Within the younger SE Australian basalt fields, further dating now suggests a wider distribution and age range of episodes than previously considered and allows a fresh approach into assessing the different petrogenetic models for this regional volcanism. Younger and more westerly trachyte than the dated Macedon–Trentham trachytes (6–5 Ma) was reported near Creswick with a K–Ar age of ca 2.4 Ma (Gibson 2007). Zircon megacrysts shed from central-western Victorian volcanic fields (Graham et al. 2003; Birch & Henry 2013) within the last 10 Ma (based on U–Pb formation and reset fission track ages) suggest widespread generation of felsic melt events under the volcanic fields.

This paper reports more precise ages on the wider range of felsic components within the late Cenozoic SE Australian basaltic volcanism. An updated, integrated inventory of felsic episodes has been assembled as a guide for assessing the prevailing models of magma generation below the volcanic fields. New results are based mostly on zircon U–Pb and alkali feldspar 40Ar–39Ar dating techniques for felsic mineral formation ages, supplemented by zircon fission track (FT) and feldspar K–Ar dating, which although subject to thermal resetting and Ar loss/excess effects, provide back up support. The U–Pb method now produces reliable results for quite young zircons (Cocherie et al. 2009), so can be extended to the youngest zircon sites. Minor discrepancies between zircon U–Pb and alkali feldspar 40Ar–39Ar ages from the same host rock owing to using different techniques and mineral standards can be reconciled with appropriate corrections (Sutherland et al. 2012) and are discussed further within this study.

Another aim is to provide representative major and trace-element analyses of the dated rocks, to facilitate discussion on potential processes of basaltic fractionation that evolved felsic magmas within these basalt fields. A final overall aim is to give a detailed picture of late Cenozoic SE Australian volcanism than was outlined in the broad study of Cenozoic eastern Australian volcanism.

**GEOLOGICAL SETTING**

The volcanic rocks studied here lie within the Macedon–Trentham and Western District Provinces of the post-10 Ma Western Victoria–SE South Australian volcanic fields (Price et al. 2003; Boyce 2013). The bulk of younger basaltic activity forms the Western Districts Province spread across the Central Highlands, western Plains and Mount Gambier subprovinces. At least 704 eruption points from 416 centres and possibly 785 eruptive points from 491 centres are mapped, with ~88% of centres being simple rather than complex volcanoes.

The felsic rocks along with some associated basalts lie in the Macedon–Trentham Province and represent at least 32 eruption points related to 24 centres (Boyce 2013). Two separate exposures (Figure 3) include an eastern group in the Romsey–Woodend area (6.0 ± 0.5) and a western group near Trentham (5.9 ± 0.1 Ma) and both lie within error in K–Ar age (Gibson 2007; Vasconcelos et al. 2008). The eastern sequence near Newham (VandenBerg 2005) presents a well-developed sequence, with some initial K–Ar dating. Here, intermediate basaltic and felsic lavas in the upper Neogene Smokers Creek Volcanic Subgroup are partly overlain by felsic basalt pyroclastic deposits of the Yungaburra Formation (VandenBerg 2006). The basalts in the Macedon–Trentham Province lie near an eastern sector of younger basalts that have elevated 87Sr/86Sr values compared with their counterparts west of the Mortlake discontinuity, which indicates that separate isotopic mantle domains underlie the basalt fields (Price et al. 2003). This eastern isotopic signature, however, is not a consistent feature, as more northeasteran basalts exhibit yet another set of isotopic signatures (Paul et al. 2006).

Victorian basaltic magmas were generated from partial melting of various asthenospheric and lithospheric mantle sources, with some modifications through crystal fractionation and crustal assimilation processes (Price et al. 2003). The felsic rocks include both Na-rich and K-rich types, with the more K-rich types developing higher 87Sr/86Sr ratios probably as a result of greater crustal contamination. Some evolved basalts were fractionated at mantle depths and experimental runs on such Victorian hydrous basanitic compositions suggest such magmas evolved into at least nepheline-mugearite compositions (Irving & Green 2006). Such fractionation proceeded by crystallisation of Mg-rich olivine, Ca-rich clinopyroxene, kaersutitic to pargasitic amphibole, Mg-rich, K-rich mica and ilmenite between 0.8 and 1.5 GPa. This may have implications for zircon formation from evolved magmas at mantle depths.

The volcanic and placer sample sites in this study mostly lie within the Bendigo and Stawell structural zones of the Paleozoic western Lachlan Orogen, bounded by the Mt William Fault on the east and Moyston Fault on the west and partly underlain by an emplaced extension of the Tasmanian Neoproterozoic–Cambrian crust, the Selwyn Block (Cayley 2011; Cayley et al. 2011). The fold belt is intruded by a range of Silurian–Devonian granites, from which Ba contents are a guide to the presence of the underlying Selwyn Block sequence (Rossiter & Grey 2000, as are Neoproterozoic crustal meta-xenoliths (ca 580 Ma in age) brought up in Neogene basalts (Allchurch et al. 2008).

The overlying Western District basalt fields exhibit unusual features for an intraplate basalt field (Gray & McDougall 2009; Müller et al. 2012), with maximum
compression directions at moderate angles to the eruptive axis (Demidjuk et al. 2007). The activity cuts across the grain of underlying mantle domains and crustal architecture, as revealed by deep seismic and teleseismic studies (Musgrave & Rawlinson 2010; Rawlinson et al. 2011).

The northern margin to the young western Victorian volcanic fields is bounded by the Murray–Darling Basin, where basement structures are obscured by a thick Paleocene–Holocene sedimentary sequence that extends into SW New South Wales and includes several late Cenozoic bentonite beds (Gardam et al. 2008; Rawlinson et al. 2008; Whitehouse 2009). The bentonites mark felsic ash fallouts (~3 Ma) into near-shore waters and at the Arumpo Mine, NSW, have compositions suggesting an intermediate trachyandesitic origin. The bentonites were first related to clusters of pipe-like bodies imaged along a 270 km E-W–W-SW swathe in the underlying basement (Gardam et al. 2008), but later geophysical modelling suggested the pipes were probably late Palaeozoic emplacements (Carlton 2009, 2010). The close correspondence between bentonite age and peak volcanism in western Victoria (Gray & McDougall 2009) will form a connective point in this paper.

MATERIALS AND ANALYTICAL METHODS

Sample sites

Zircon megacrysts were sampled for fission track (ZFT), U–Pb dating and geochemical analysis from trachytic pyroclastic deposits and lavas, sub-basaltic placers and basaltic plugs and maar deposits across the Macedon–Trentham and Western District provinces (Sample sites 1–9; Figure 1; Table 1). A composite mineral inclusion (~0.25 mm across) in a Bullenmerri zircon megacryst was studied by back-scattered imaging (BSE) and electron microprobe analysis, using a 3 spectrometer WDS JEOL JXA 8600 Superprobe in the School of Science, University of Western Sydney. Apatite megacrysts were sampled for FT dating from basaltic breccia at Brimbank Hill (Graham et al. 2003), 5 km NW of Blampied (Site 7; Table 1). Whole-rock samples were collected for 40Ar/39Ar dating and major/trace-element analysis of trachytes from Deep Creek, Newham (Locality 2) and Niggl Road, Creswick (Locality 8) and for analysing evolved alkali basalt from Brimbank Hill (Site 7).

The Deep Creek trachyte (Site 2) is poorly exposed in Sheltons Creek, within the Smokers Creek Volcanic Subgroup sequence. The flow that descends north from 660 to 500 m asl, overlies a porphyritic benmoreite flow at least 60 m thick and also trachytic tuffs of the Yangabulla Formation (Site 1). The Niggl Road trachyte (Site 8) was sampled from blocks of porphyritic trachyte up to several metres across in the weathered soil profile on a low hill. Some blocks exhibit patches of brecciated trachyte made up of angular fragments up to 2 × 1.5 m across, Ordovician slate and vein quartz. The exposure represents a trachyte body, partly brecciated by a later disruptive event, which has shed zircon into the weathered soil profile.
Table 1 Sample localities, material and analytical methods, central to western Victoria

| No. | Sample, material | Locality, map sheet | Sheet ref. E, N | Long. E lat. ° S | Source, nature | Methods, dating, analysis |
|-----|------------------|---------------------|----------------|-----------------|----------------|---------------------------|
| 1.  | W7, zircon conc. | Sheltons Road, Woodend | 289150, 5870150 | 144.6244 37.2598 | Pyroclastics, Felsic tuffs | Zircon U-Pb, LE |
| 2.  | DRI893, whole rock | Deep Creek, Romsey | 290000, 5885750 | 144.5500 37.3187 | Flow, Trachyte | 40Ar/39Ar feldspar, Zircon U-Pb, LE |
| 3.  | B97 zircon conc. | Rat Hole Track, Bullarto | 251300, 5898900 | 144.1667 37.4667 | Soil, Basalt plug? | Zircon PT |
| 4a. | 42524, zircon conc. | Leardons Hill, Barkstead | 245000, 5854000 | 144.1031 37.4500 | Basaltic soil, Alkalai basalt | Zircon FT |
| 5a. | D55261, zircon conc. | Trentham Falls, Coliban | 263000, 5860450 | 144.3167 37.3667 | Flow-base, Basaltic ash | Zircon FT |
| 5b. | T127, zircon conc. | Leonards Hill, Barkstead | 245000, 5854000 | 144.1083 37.4500 | Basaltic soil, Alkalai basalt | Zircon FT |
| 6.  | CG571-2, zircon crystal | Ridge Road, Daysylford | 245700, 5854000 | 144.1330 37.4667 | Xenocryst, Basalt flow | ZFT, U-Pb, LTE |
| 7.  | DR1546, whole rock | Brimbank Hill, Eganstown | 236900, 5862950 | 144.0033 37.3715 | Apatite, Alterred pipe | Apatite FT, ME, TE, REE |
| 8.  | DR1932, whole rock | Niggl Road, Creswick | 760450, 5853500 | 143.9167 37.4167 | Plug & soil, Trachyte | ZFT, U-Pb, LTE |
| 9.  | D1723, zircon conc. | Bullenmerri, Campedown | 665750, 5764150 | 143.1490 37.4667 | Tuffs, Basalt maar | Zircon U-Pb, ME, TE, REE |

1:25 000 Sheets: Woodend 7823-3-4, Romsey 7823-3-1, Bullarto 7723-2-1, Coliban 7723-2-3, Daysylford 7723-2-3, Trentham 7723-2-3, Eganstown 7723-3-4 (site now modified); Creswick 7823-2-2; Camperedown 7521-4-2 (in preparation). Cited E, N grid references are based on AMG66/84 and longitudes and latitudes are based on AGD 66/84. Relationships of Australian-generated location data and geographic datum systems are available on: http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/GDA.html; http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/historical-datums-of-australia.html; http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/historical-datums-of-Australia/Australian-geodetic-datum-agd.html LE, limited element analysis; FT, fission track analysis; ME, major-element analysis; TE, trace-element analysis; REE, rare-earth-element analysis.
The age analyses (Tables 2, 6; Supplementary Table 1) were performed using an Agilent 7500 csa quadrupole ICP-MS, modified at the University of Tasmania to date such young zircons (e.g. Meffre et al. 2007, 2008), and a 193 nm solid-state New Wave Laser with a custom low-volume ablation cell. A detailed run on a selected Bullenmerri zircon employed a Coherent excimer laser and Resonetics M50 ablation cell. The down-hole fractionation, instrument drift and mass bias correction factors for Pb/U ratios on zircons were calculated using two analyses on the primary standard and two analyses on the secondary standard zircons (Mud Tank and Temora; Black & Gulson 1978; Black et al. 2003) between samples.

The 91500 standard of Wiedenbeck et al. (1995) was used as the primary standard analysed at the same spot size, fluence (3 J cm⁻²) and repetition rate (5 Hz) as those used to analyse the zircons on the samples. A 32 μm spot size was used on all of the analyses except those on the Bullenmerri zircons where a 100 μm spot size was used. Uncertainty calculations were undertaken using techniques similar to those by used by Paton et al. (2010) where the variances in the ages of standards are taken into account to calculate the uncertainty. However, owing to the young age of the zircons, we used the ‘ratio of the means’ method for age calculations rather than the ‘mean of the ratios’ method (see Fisher et al. 2010), as it provides much more precise ages on Cenozoic zircons.

FT dating of zircons (Table 3) was performed at Geotrack International, Brunswick, Melbourne, with sample preparation, etching, track counting and statistical procedures following the methods outlined in Sutherland & Fanning (2001).

**FELDSPAR DATING**

The K–Ar isotopic age determinations were carried out at CSIRO ESRE and JdL, Curtin University, Western Australia (Table 4). Sample preparation, potassium concentration measurement (Heinrichs & Hermann 1990), argon extraction, isotopic Ar determinations using spiked Ar calibrated against biotite standard GA1550 and monitoring measurements (blanks and mass

**Figure 4** Photomicrographs of dated zircon-bearing rocks, Macedon–Trentham and Western District Provinces: (a) Deep Creek trachyte containing composite anorthoclase crystals, with reaction rim, in fine-grained matrix (crossed nicols); (b) Niggl Road trachyte containing alkali feldspar overgrowth on fine-grained trachyte core (crossed nicols); (c) Niggl Road trachyte, showing fluidal matrix containing abundant alkali feldspar laths, sparse oxidised Fe-rich olivine grains and scattered small pyroxene grains (plane polarised light); (d) Ridge Road basalt containing a mantled feldspar xenocryst containing a sieved alkali feldspar core (part view) and glomero-microphenocrysts of clinopyroxene in a fluidal basaltic matrix.
Table 2 Summary of U-Pb (Ma) and trace element (ppm) results, Victorian zircons.

| Locality sample | 206Pb/238U age range, mean age (n) | Hf range, av. Hf | Th range, av. Th | U range, av. U | Pb range, av. Pb | Ti range, av. Ti |
|----------------|-----------------------------------|------------------|------------------|----------------|-----------------|------------------|
| Sheltons Road, W7 (JDH) | 6.1-6.8, 6.28 ± 0.13 (12) | 7248-10013, 9443 | 236-1265, 618 | 536-1471, 781 | 0.6-1.6, 0.9 | 2-9, 3.7 |
| Deep Creek, DR17926 | 6.0-6.5, 6.15 ± 0.11 (11) | 6704-10412, 7332 | 273-9324, 4906 | 312-7796, 2888 | 0-11, 4 | 6-15, 10 |
| Rat Hole Tack, B97 (JDH) | 5.3-6.1, 5.74 ± 0.14 (12) | 5916-6362, 6073 | 42-2680, 874 | 93-1355, 659 | 0.1-1.8, 0.8 | 1-4, 1.7 |
| Ridge Road, D55261 | 1.70-2.0, 1.84 ± 0.19 (5) | 5859-6380, 6095 | 45-481, 223 | 92-521, 285 | 0.1-0.2, 0.1 | 1-2, 1.3 |
| Bullemerrri, D47123a | 0.14-0.29, 0.187 ± 0.022 (10) | 5090-6451, 5737 | 138-1536, 484 | 170-758, 368 | 0.0-0.0, 0.0 | 1-4, 1.2 |
| Bullemerrri, D47123b | 87.59-99.96, 93.78 ± 2.46 (2) | 5745-6206, 5976 | 5-15, 10 | 17-29, 23 | 6-7, 6.5 | 6 |

*206Pb corrected ages, with 2σ errors. Analyst S. Meffre.

The 40Ar–39Ar analyses were performed at the Western Australian Argon Isotope Facility at Curtin University (Table 5; Supplementary Table 4). From the Deep Creek trachyte sample (Site 2), hundreds of micrometre-sized sanidine crystals that were unaltered and transparent were handpicked under a binocular microscope after discrimination factor determined by airshots (followed procedures given in Sutherland et al. (2012). The error for the argon analysis is below 1%. The K–U calculation used constants after Steiger & Jäger (1977). The age uncertainty includes the errors during sample weighing, 40Ar/39Ar and 40Ar/38Ar measurements and K analysis.

Table 3 Fission track results, central to western Victoria, zircon/apatite.

| Grains | Ns | Ni | Na | pS (av.) | pI (av.) | Ratio | U (ppm) | Age (Ma) ± 1σ |
|--------|----|----|----|----------|----------|--------|---------|--------------|
| Sub-basalt beds, Trentham Falls (zircon) |        |    |    |          |          |        |         |              |
| Oldest Group (7.3–9.3 ± 0.7–2.0 Ma) | 11 | 788 | 2398 | 1040 | 1.267E + 06 | 3.875E + 06 | 0.329 | 97–995, av. 361 | 8.2 ± 0.5 |
| Younger Group (4.4–6.7 ± 0.8–1.9 Ma) | 5  | 235 | 1035 | 460  | 7.660E + 05 | 3.380E + 06 | 0.227 | 106–524, av. 313 | 5.7 ± 0.4 |
| Allens Creek pipe, Blackwood (zircon) | 9  | 588 | 6223 | 85   | 1.488E + 06 | 1.556E + 07 | 0.092 | 101–1610, av. 478 | 6.0 ± 0.3 |
| Trachyte soil, Niggl Road, Creswick (zircon) | |    |    |      |          |          |        |         |              |
| Oldest Group (>2.0 < 2.5 ± 0.4 Ma) | 3  | 108 | 1195 | 900  | 2.781E + 05 | 3.049E + 05 | 0.090 | 122–531, av. 276 | 2.3 ± 0.4 |
| Intermediate Group (>1.5 < 2.0 ± 0.2–0.4 Ma) | 4  | 175 | 2764 | 1000 | 1.531E + 05 | 2.143E + 06 | 0.063 | 153–274, av. 219 | 1.7 ± 0.3 |
| Youngest Group (>0.1 < 1.0 ± 0.0–0.02 Ma) | 7  | 86  | 5896 | 3840 | 2.627E + 05 | 9.219E + 06 | 0.015 | 55–4665, av. 835 | 0.4 ± 0.1 |
| Leonards Hill, Dayselford (zircon) | 7  | 230 | 6320 | 100  | 3.750E + 05 | 1.013E + 07 | 0.035 | 245–838, av. 492 | 1.8 ± 0.1 |
| Mafic breccia, Brimbank (apatite) | 4  | 34  | 1202 | 1675 | 8.604E + 03 | 3.012E + 05 | 0.029 | 2.7–3.2, av. 3.0 | 6.3 ± 1.1 |

Zircon ages calculated using a zeta of 87.7 ± 0.8 for U 3 glass (87.9 ± 0.8 for Leonards Hill). ρD = 5.755E + 05 cm–2 (1.199E + 06 cm–2 for Leonards Hill). Apatite ages calculated using a zeta of 385.5 for CNS glass. ρD = 1.31E + 06 cm–2. Summarised from Geotrack Reports #30 (1985), #571 (1995), #797 (2001), #822 (2001), #865 (2003). Determinations: P. F. Green.

Table 4 K Ar geochronology for central-western Victoria trachytes.

| Sample, locality | Material | %K a | 40Ar b (× 10 10 moles/g) | 40Ar b/40ArTotal | Age c |
|-----------------|----------|------|--------------------------|-------------------|-------|
| 1-182, Niggl Road | K-feldspar | 5.29, 5.28 | 0.2189 | 0.82 | 2.4 ± 0.1 |
| 4/134/8 Trachyte, Deep Creek, Newham, AMG 20026F6 58001740N (WOODEND 7823) | K-feldspar | 3.168, 3.165 | 0.45721 | 0.82 | 8.3 ± 0.1 |

*1Radiogenic 40Ar.

*aAge in Ma, with error limits given for analytical uncertainty at one standard deviation. Constants 40K = 0.01167 atom %, λD = 4.962 × 10^{-8} y^{-1}, λE = 0.581 × 10^{-10} y^{-1}. 

Table 2 Summary of U–Pb (Ma) and trace element (ppm) results, Victorian zircons.
Table 5: \(^{40}\text{Ar} / ^{39}\text{Ar}\) geochronology alkali feldspar fraction (1216), Deep Creek trachyte.

| Relative abundances | \(^{38}\text{Ar} [\%]\) | \(^{38}\text{Ar} [\%]\) | \(^{38}\text{Ar} [\%]\) | \(^{40}\text{Ar} [\%]\) | \(^{40}\text{Ar} / ^{39}\text{Ar} \pm 2\sigma\) | Age (Ma) \(\pm 2\sigma\) | \(^{40}\text{Ar} (\%)\) | \(^{38}\text{Ar} (\%)\) | K/\(\text{Ca}\) \(\pm 2\sigma\) |
|---------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 9A9063D             | 60.0% v        | 0.000334       | 0.000379       | 0.000415       | 0.01745         | 44.93529 \(\pm 0.51968\) | 60.14 \(\pm 0.15\) | 42.45           | 0.03           | 1.83 \(\pm 0.69\) |
| 9A9064D             | 61.0% v        | 0.000362       | 0.000397       | 0.000435       | 0.020105        | 2.74988 \(\pm 3.04159\) | 3.74 \(\pm 4.13\) | 13.57           | 0.23           | 1.07 \(\pm 1.30\) |
| 9A9065D             | 62.0% v        | 0.000356       | 0.000272       | 0.000314       | 0.023215        | 3.75427 \(\pm 1.6065\) | 5.10 \(\pm 2.25\) | 42.48           | 0.62           | 1.00 \(\pm 0.41\) |
| 9A9066D             | 61.0% v        | 0.000368       | 0.000377       | 0.000399       | 0.03348         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9067D             | 64.0% v        | 0.000311       | 0.000280       | 0.000318       | 0.03479         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9068D             | 65.0% v        | 0.000269       | 0.000245       | 0.000284       | 0.03354         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9069D             | 66.0% v        | 0.000113       | 0.000149       | 0.000173       | 0.12635         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9070D             | 67.0% v        | 0.000197       | 0.000253       | 0.000284       | 0.12897         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9071D             | 68.0% v        | 0.000108       | 0.000142       | 0.000176       | 0.13099         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9072D             | 69.0% v        | 0.000063       | 0.000087       | 0.000112       | 0.13399         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9073D             | 70.0% v        | 0.000276       | 0.000316       | 0.000351       | 0.13734         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9074D             | 71.0% v        | 0.000313       | 0.000263       | 0.000304       | 0.14039         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9075D             | 72.0% v        | 0.000225       | 0.000284       | 0.000327       | 0.14341         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9076D             | 73.0% v        | 0.000061       | 0.000091       | 0.000125       | 0.14642         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9077D             | 74.0% v        | 0.000110       | 0.000143       | 0.000176       | 0.14943         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| 9A9078D             | 75.0% v        | 0.000020       | 0.000023       | 0.000026       | 0.15246         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |
| Σ                   |                | 0.008200       | 0.012745       | 0.016323       | 0.15549         | 4.3943 \(\pm 0.47319\) | 6.10 \(\pm 0.64\) | 68.76           | 1.59           | 1.07 \(\pm 0.19\) |

Weighted plateau age = 6.14 \(\pm 0.08\) Ma (2\(σ\); \(P = 0.39\); MSD = 0.96). \(F\) value = 0.0007540 \(\pm 0.0000040\). Total fusion age = 6.20 \(\pm 0.08\) Ma (2\(σ\)). Fish Canyon sanidine (28.03 \(\pm 0.08\) Ma; Jourdan & Renne 2007). \(D = 1.001402 \(\pm 0.033\)\). Inverse isochron age = 6.27 \(\pm 0.16\) (MSWD = 0.96).
magnetic separation. The sanidine crystals were thoroughly rinsed with distilled water in an ultrasonic cleaner. The analytical details of the employed dating method are given in Appendix 2.

The Niggl Road (Site 8) K-feldspar determinations (Supplementary Table 4; Figure 5b) followed typical 40Ar–39Ar-dating procedures (Bonhomme et al. 1975; McDougall & Harrison 1999; Ludwig 2001). A concentrate of separated feldspar was cleaned and wrapped in aluminium foil along with biotite standard HD-B1 (24.21 ± 0.32 Ma; Hess & Lippolt 1994) to monitor the neutron flux gradient. The package was irradiated in the McMaster University Nuclear Reactor, Hamilton, Canada along procedures, analytical parameters and errors as given in Sutherland et al. (2012).

Geochemical analysis

ZIRCON MULTI-ELEMENT ANALYSIS

Selected elements were analysed by LA-ICP-MS during the isotope dating runs for comparisons of zircon compositions (Table 2; Supplementary Table 2; Figure 6). Each analysis on the zircon began with a pre-ablation (5 laser pulses) followed by a 30 s blank gas measurement followed by a further 30 s of analysis time when the laser switched on. Zircons were sampled on 32 micron spots using the laser at 5 Hz and a density of ~2 J cm−2 providing a drill rate of 0.5 μm s−1. A flow of He carrier gas at a rate of 0.5 L/min carried particles ablated by the laser out of the chamber to be mixed with Ar gas and carried to the plasma torch. Isotopes measured include 49Ti, 96Zr, 178Hf, 202Hg, 204Pb, 207Pb, 208Pb, 232Th and 238U with each element being measured sequentially every 0.14 s.

A more extended elemental array, including rare earth elements (REE) was analysed by LA-ICP-MS on a zoned Bullenmerri zircon megacryst, analysing the crystal at 8 spots on different zones along a traverse from its rim into its inner core (Table 7; Figure 7). The analysis

Table 6 Bullenmerri zircon ages with Th disequilibrium corrections.

| Sample, grain | Age (Ma) with error | 235Th/238U zircon | 235Th/238U whole rock | f(Th/U) | 206Pb/238U |
|---------------|---------------------|--------------------|-----------------------|--------|------------|
| D47123.1c     | 100.1 ± 2.5         | 0.31               | 4.4                   | 0.1    | 0.01564    |
| D47123.1r     | 87.7 ± 2.5          | 0.50               | 4.4                   | 0.1    | 0.01370    |
| D47123.2r     | 0.23 ± 0.05         | 0.94               | 4.4                   | 0.2    | 0.000004   |
| D47123.2e     | 0.25 ± 0.05         | 1.09               | 4.4                   | 0.2    | 0.000004   |
| D47123.3c     | 0.24 ± 0.05         | 2.03               | 4.4                   | 0.5    | 0.000004   |
| D47123.3r     | 0.22 ± 0.05         | 1.67               | 4.4                   | 0.4    | 0.000003   |
| D47123.4c     | 0.37 ± 0.06         | 0.80               | 4.4                   | 0.2    | 0.000006   |
| D47123.4r     | 0.31 ± 0.06         | 0.91               | 4.4                   | 0.2    | 0.000005   |
| D47123.5c     | 0.25 ± 0.14         | 0.81               | 4.4                   | 0.2    | 0.000004   |
| D47123.5r     | 0.26 ± 0.10         | 0.91               | 4.4                   | 0.2    | 0.000004   |
| D47123.6c     | 0.29 ± 0.06         | 1.20               | 4.4                   | 0.3    | 0.000004   |
| D47123.6r     | 0.27 ± 0.05         | 1.23               | 4.4                   | 0.3    | 0.000004   |

c, core; r, rim.

Disequilibrium and common Pb corrected.
Table 7 LA-ICP-MS analysisa (ppm), zircon megacryst, Bullenmerri

| Element | Range (n = 8) | Mean ± 2e (n = 8) |
|---------|--------------|------------------|
| Zr      | 44700-45414 ± 4475-5597 | 45 0015 ± 4861 |
| Hf      | 5795-6574 ± 50-71 | 5960 ± 61 |
| Y       | 239-1435 ± 4-15 | 871 ± 10 |
| Th      | 7-271 ± 0-3 | 109 ± 2 |
| U       | 24-231 ± 1-10 | 128 ± 3 |
| Nb      | 0.7-7.0 ± 0.1-0.3 | 3.8 ± 0.2 |
| Ta      | 0.5-2.3 ± 0.05-0.13 | 1.4 ± 0.10 |
| Al      | 2.7-5.3 ± 0.7-1.2 | 3.5 ± 0.90 |
| P       | 39-65 ± 7-9 | 56 ± 8 |
| Ti      | 1.2-2.7 ± 0.7-1.4 | 2.0 ± 1.0 |
| La      | 0.00-0.02 ± 0.01 | 0.01 ± 0.01 |
| Ce      | 1.0-12.4 ± 0.1-0.4 | 7.0 ± 0.2 |
| Pr      | 0.02-0.21 ± 0.01-0.04 | 0.17 ± 0.02 |
| Nd      | 0.2-3.4 ± 0.1-0.4 | 1.7 ± 0.3 |
| Sm      | 0.6-8.5 ± 0.2-0.6 | 4.3 ± 0.4 |
| Eu      | 0.6-6.4 ± 0.1-0.3 | 3.4 ± 0.2 |
| Gd      | 4.7-44.9 ± 0.5-1.5 | 24.5 ± 1.1 |
| Tb      | 1.9-15.6 ± 0.1-0.4 | 8.8 ± 0.3 |
| Dy      | 23.2-171.8 ± 0.8-2.8 | 98.9 ± 2.0 |
| Ho      | 8.4-54.7 ± 0.5-0.8 | 32.4 ± 0.6 |
| Er      | 35.5-199.6 ± 1.0-2.7 | 121.6 ± 1.9 |
| Tm      | 7.1-33.6 ± 0.2-0.6 | 21.4 ± 0.4 |
| Yb      | 59.2-242.4 ± 1.7-3.6 | 161.0 ± 2.8 |
| Lu      | 10.0-35.5 ± 0.2-0.6 | 21.4 ± 0.4 |
| Zr/Hf   | 68.6-77.4 | 75.40 |
| Th/U    | 0.31-1.17 | 0.72 |
| Ce'     | 11.39-26.57 | 21.06 |
| Eu'     | 0.75-0.85 | 0.81 |

aSi-normalised (15 284 ppm). Ce' = Ce/0.5; Eu' (= Eu)/0.5 (Sm + Gd).

employed a Resonetic M50 excimer laser combined with an Agilent 7500cs ICP-MS, using a duration time of 24.3 s, NIST 610 and zircon 91500 as standards to measure 25 elements, normalised to Si 15284 ppm.

WHOLE ROCK GEOCHEMISTRY

Major, minor and selected trace elements of the dated evolved rocks were analysed at the XRF and XRD Facility, University of Pretoria, Pretoria, South Africa (Maggi Loubser), using routine procedures. More extended trace and REE analyses on these rocks were made using inductively coupled plasma mass spectrometry (ICP-MS) at the Geology Department, University of Cape Town, Rondebosch, South Africa (Andreas Spath) along procedures given in Appendix 3. Additional trace-element analyses utilised ICP-MS facilities at AMDEL laboratories, Adelaide and the University of Melbourne for further comparisons of associated rocks. Representative analyses for the evolved rocks are listed in Table 8.

RESULTS

Geochronology

U–Pb Ages

The zircon U–Pb ages (6.3–0.2 Ma) fall within the eruptive span for young central to western Victorian volcanic fields (Tables 2, 6; Supplementary Table 1). The zircons from the Sheltons Road–Deep Creek trachytic sequence gave ages of 6.28 ± 0.13 (MSWD = 0.31, P = 0.98) and 6.15 ± 0.11 Ma (MSWD = 0.72, P = 0.71), which accord with their stratigraphic order (Sites 1 and 2), a K–Ar age of 6.19 ± 0.05 Ma on alkali feldspar from basal porphyritic benmoreite 6 km NW, and a sanidine 40Ar/39Ar plateau age of 6.14 ± 0.06 Ma (Sutherland et al. 2012), partly from recrystallisation of the 40K decay constants (Steiger & Jager 1977). Revised 40K decay constant and standard ages, calibrated directly against 207Pb/206Pb ages, show that 40Ar/39Ar ages should be ~+1% older for the Phanerozoic period (Renne et al. 2010). In addition, zircon can

Figure 7 Chondrite-normalised REE values for different zones within Bullenmerri zircon megacryst analysed at selected points in from the rim into the core (1–8).
Table 8 Major, minor and selected trace-element analyses, evolved Victorian rocks.

| Major oxides (wt%)<sup>a</sup> | CIPW norm (anhydrous)<sup>b</sup> | Major oxides (wt%)<sup>d</sup> | CIPW norm (anhydrous)<sup>b</sup> | Major oxides (wt%)<sup>e</sup> | CIPW norm (anhydrous)<sup>b</sup> |
|-------------------------------|--------------------------------|-------------------------------|--------------------------------|-------------------------------|--------------------------------|
| SiO<sub>2</sub>               | 57.95 Q                        | SiO<sub>2</sub>               | 59.07 Q                        | SiO<sub>2</sub>               | 47.60 Q                        |
| TiO<sub>2</sub>               | 0.37 Or                        | TiO<sub>2</sub>               | 0.68 Or                        | TiO<sub>2</sub>               | 3.19 Or                        |
| Al<sub>2</sub>O<sub>3</sub>   | 19.17 Ab                       | Al<sub>2</sub>O<sub>3</sub>   | 17.79 Ab                       | Al<sub>2</sub>O<sub>3</sub>   | 15.60 Ab                       |
| FeO<sub>2</sub>O<sub>3</sub>  | 1.32 An                        | FeO<sub>2</sub>O<sub>3</sub>  | 1.26 An                        | FeO<sub>2</sub>O<sub>3</sub>  | 2.42 An                        |
| FeO                           | 4.74 C                         | FeO                           | 4.55 C                         | FeO                           | 8.71 C                         |
| MnO                           | 0.65 Hy                        | MnO                           | 0.13 Hy                        | MnO                           | 0.10 Hy                        |
| MgO                           | 0.17 Di                        | MgO                           | 0.87 Di                        | MgO                           | 3.82 Di                        |
| CaO                           | 0.76 Ol                        | CaO                           | 2.24 Ol                        | CaO                           | 6.09 Ol                        |
| Na<sub>2</sub>O              | 4.78 Mt                        | Na<sub>2</sub>O              | 5.44 Mt                        | Na<sub>2</sub>O              | 4.59 Mt                        |
| K<sub>2</sub>O              | 5.48 Il                        | K<sub>2</sub>O              | 5.36 Il                        | K<sub>2</sub>O              | 2.76 Il                        |
| P<sub>2</sub>O              | 0.08 Ap                        | P<sub>2</sub>O              | 0.33 Ap                        | P<sub>2</sub>O              | 1.84 Ap                        |
| LOI                           | 2.50                            | LOI                           | 1.2                            | LOI                           | 1.91 Ne                        |
| Total                         | 97.39 D.I.                     | Total                         | 98.92 D.I.                     | Total                         | 99.23 D.I.                     |
| Mg #                          | 6.01 An%                       | Mg #                          | 25.20 An%                      | Mg #                          | 43.88 An%                      |
| Trace and REE (ppm)<sup>c</sup> | 7.84                            | Trace and REE (ppm)<sup>c</sup> | 15.28                          | Trace and REE (ppm)<sup>c</sup> | 29.80                          |
| Sc                             | 3.87 La                        | Sc                             | 7.2 La                         | Sc                             | <5 La                           |
| V                              | 1.85 Ce                        | V                              | 10.5 Ce                        | V                              | 80 Ce                          |
| Cr                             | 1.75 Pr                        | Cr                             | 34.5 Pr                        | Cr                             | 20 Pr                          |
| Co                             | 30.7 Nd                        | Co                             | 3.7 Nd                         | Co                             | 35.5 Nd                        |
| Ni                             | 8.77 Sm                        | Ni                             | 3.3 Sm                         | Ni                             | 56 Sm                          |
| Cu                             | 10.7 Eu                        | Cu                             | 12.3 Eu                        | Cu                             | 19.5 Eu                        |
| Cs                             | 0.41 Gd                        | Cs                             | 1.0 Gd                         | Cs                             | 0.9 Gd                         |
| Ba                             | 364 Tb                         | Ba                             | 417 Tb                         | Ba                             | 900 Tb                         |
| Rb                             | 130 Dy                         | Rb                             | 107 Dy                         | Rb                             | 43 Dy                          |
| Sr                             | 93.2 Ho                        | Sr                             | 217 Ho                         | Sr                             | 1500 Ho                        |
| Y                              | 26.7 Er                        | Y                              | 36.8 Er                         | Y                              | 21.5 Er                         |
| Zr                             | 11.0 Tm                        | Zr                             | 43.2 Tm                         | Zr                             | 370 Tm                         |
| Nb                             | 178 Yb                         | Nb                             | 107.7 Yb                        | Nb                             | 79 Yb                          |
| Hf                             | 19.7 Lu                        | Hf                             | 17.72 Lu                        | Hf                             | 6 Lu                           |
| Ta                             | 13.4 ΣREE                      | Ta                             | 6.50 ΣREE                      | Ta                             | 5 ΣREE                         |
| Pb                             | 9.59                            | Pb                             | 7.22                            | Pb                             | 3.5                            |
| Th                             | 15.1 Rb/Sr                    | Th                             | 13.19 Rb/Sr                    | Th                             | 6.5 Rb/Sr                     |
| U                              | 2.36 Zr/Nb                    | U                              | 3.71 Zr/Nb                     | U                              | 1.8 Zr/Nb                     |
| Ga                             | 36.0 Th/U                     | Ga                             | 36.0 Th/U                      | Ga                             | 36.0 Th/U                     |

Mg # = 100 Mg/(Mg + Fe<sup>2+</sup>)

<sup>a</sup>XRF analysis, M. Loubser, University of Pretoria, South Africa.

<sup>b</sup>100 wt% anhydrous analysis, with Fe<sub>2</sub>O<sub>3</sub>/(Fe<sub>2</sub>O<sub>3</sub> + FeO) = 0.2

<sup>c</sup>ICP-MS analysis, A. Spath, University of Cape Town, South Africa.

<sup>d</sup>XRF analysis, I. Wainwright, University of New South Wales, Sydney.

<sup>e</sup>ICP-MS analysis, AMDEL, Adelaide.

<sup>f</sup>ICP-MS analysis, J. Woodhead, University of Melbourne.
retain Pb at magmatic temperatures, and thus can incorporate a residence time component of up to several hundreds of ka in the measured U/Pb age (e.g. Simon et al. 2009; Schoene et al. 2010). In the present case involving young rocks, the overlap in age suggests minimal (if any) residence time of the zircon in the magma chamber and rapid eruption rate. Altogether, these ages suggest a limited span of <1 Ma for benmoreite and trachytic eruptions in the Macedon area.

Similar zircon megacrysts derived from a fluidal hawaiite ‘plug’ at Rat Hole Track (Site 3), four km ENE of Spargo Creek township, have a slightly younger U–Pb age of 5.74 ± 0.14 Ma (MSWD = 0.63, P = 0.85). This suggests that felsic melts continued to generate at depth southwest of the Trentham felsic eruptive area (Figure 3). Other reconnaissance U–Pb ages (5.2–5.0 ± 1.0 Ma, SHRIMP data; Graham et al. 2003) on zircon megacrysts (Leonards Hill, South Bullarto) lie within error of the Rat Hole Track result and suggest subaqueous felsic bodies extended west into the Daylesford area. Two types of zircon megacrysts in the Ridge Road basalt flow (Site 5b) and at its eruptive vent at Leonards Hill (Site 5a), near Daylesford (Birch & Henry 2013) include an orange–yellow; slender prismatic type, which gave a U–Pb age of 1.84 ± 0.19 Ma (MSWD 0.40, P = 0.81; this study). Thus, the host flow is <2 Ma and is significantly younger than larger, red, more equant prismatic megacrysts, dated at ca 5 Ma at Leonards Hill and found in a syenitic xenolith in the Ridge Road basalt (Graham et al. 2003).

The youngest zircon U–Pb age has a mean age of 0.187 ± 0.22 Ma (MSWD = 1.08, P = 0.37) for five megacrysts (core and rim analyses) from Lake Bullenmerri maar (Supplementary Table 1). This result is within error of a U–Pb age estimate of 0.24 ± 0.04 on zircon from this locality obtained by isotope dilution mass spectrometry (Hiess et al. 2012). To refine the Bullenmerri zircon age on such young U–Pb ages, Th–U disequilibrium corrections are required (Cocherie et al. 2009). The results (Table 6) involve assumptions on the Th/U ratio in the original melt composition (f) that crystallised this zircon (Scharer 1984). Using an average younger western Victorian basaltic composition (f = ~0.26) gave a corrected age of 0.27 ± 0.06 Ma (MSWD = 0.64, P = 0.76). Crystallisation from a felsic magma, however, is more likely (f = ~0.17; Blundy & Wood 2003) and gave a corrected age of 0.28 ± 0.06 Ma (MSWD = 0.59, P = 0.80). Thus, melt activity that formed zircons below Bullenmerri took place at <0.3 Ma, with eruption sometime afterwards.

Older zircon is a rare component among the Bullenmerri megacrysts and is reported here. It has a mean age of 93.8 ± 2.5 Ma and distinctly lower U, Th and higher Ti content than in the young zircons (Table 2; Supplementary Tables 1, 2). Rare zircon groups with FT ages in the 106–70 Ma range appear in alluvial sequences in western Victoria, e.g. Stony Creek Basin, Daylesford (Willman et al. 2002) and gravels at Carrapooee (Birch et al. 2007), which with the older Bullenmerri zircon suggest minor felsic magmatic/volcanic events across western Victoria during that period.

ZIRCON/APATITE FT AGES

The oldest pooled FT ages came from red–orange (8.3 ± 0.5 Ma, n = 3) and pale pink (8.1 ± 0.5 Ma, n = 9) sub-basaltic zircon groups (Site 4) at Trentham Falls (Table 3). These ages resemble the 8.4 ± 0.5 Ma (n = 10) FT age found for zircon within the sedimentary infill in Stony Creek Basin to the west (Willman et al. 2002) and suggests an earlier zircon crystallisation event than that is defined by the 5–7 Ma U–Pb zircon ages in the area. A younger Trentham Falls red–orange zircon FT group at 5.7 ± 0.4 Ma (n = 4), however, falls within the later interval, within error of the K–Ar dating on the overlying Trentham Falls basalt sequence (Graham et al. 2003). The FT age of 6.0 ± 0.3 Ma (n = 9) for zircon in Allens Creek breccia pipe (Site 6) is within error of and probably genetically related to the nearby Trentham felsic intrusions (K–Ar ages, 5.8–6.0 ± 0.1 Ma; Graham et al. 2003). Apatite FT ages on crystals from breccia in the Brimbank vent (Site 7) with a mean age at 6.3 ± 1.1 Ma suggest that this is a relatively old centre related to the Macedon–Trentham Province (Table 3).

Significantly younger zircon FT ages characterise zircons recovered from vents in the Daylesford–Creswick region (Table 4). A FT age group at 1.8 ± 0.1 Ma (n = 7) from Leonards Hill (Site 5a) is matched by the U–Pb age of 1.8 ± 0.2 Ma for similar zircon in the Ridge Road basalt flow (Site 5b) from that vent, suggesting related generation and eruptive transport. Zircons recovered from soil formed on the Niggl Road trachyte plug (Site 8) gave three separate FT groups at 2.3 ± 0.4, 1.7 ± 0.3 and 0.4 ± 0.1 Ma. The older group matches the K–Ar age and the minimum 40Ar/39Ar age of >2.4 Ma obtained on the trachyte (Taylor et al. 2000; this paper) and presumably was derived from the trachyte. The intermediate FT age may relate to the later brecciated zones, in which zircon ages may have been reset. The very young FT group involves very small zircons that may represent airborne fall-out deposits from more distal eruption unrelated to the trachyte events.

40Ar/39Ar AGES

The dating of alkali feldspars from two representative trachytes gave significantly different ages (Table 5; Supplementary Table 4; Figure 5). The Deep Creek trachyte (Site 2) has a weighted plateau age of 6.14 ± 0.08 Ma (MSWD = 0.96, P = 0.49) within error of a zircon U–Pb age from this rock (Tables 2, 5; Figure 5a). The Niggl Road trachyte (Site 8) age lies within error of a feldspar K–Ar age and FT age of the oldest zircon group from this rock (Tables 3–5; Figure 5b). This result represents a perturbed age spectrum with increasing ages converging toward an apparent age of ca 2.4 Ma. This kind of profile is typical of 40Ar* loss by thermally active diffusion and suggests a minimum age of >2.4 Ma for crystallisation of the Niggl Road trachyte. The results suggest that felsic eruptive events not only characterise the older Macedon–Trentham Province but also form younger small-volume events within peak (ca 2.5 Ma) Western District Province basaltic eruptions.

Geochemistry

ZIRCON ANALYSES

Selected elements analysed in the young (<7 Ma, n = 50) zircon grains range noticeably in Hf (5000–10 600 ppm),
Th (40–8600 ppm) and U (90–7800 ppm) values (Tables 2, 6; Supplementary Table 2). In these determinations, the Ti values in the trachyte-derived zircons may incorporate potential contamination from abundant small rutile inclusions in many of the crystals.

The Hf values are highest in the trachytic Sheltons Road zircons (8443) and lowest in the young Bullenmerri megacrysts (5737). Average values (ppm) for Th (4305), U (2690) and the Th/U ratio (1.60) are highest in the trachytic Deep Creek zircons and lowest in the Ridge Road xenocryst in basalt (Th 225, U 285, Th/U 0.78). The young Bullenmerri maar zircons (–0.3 Ma, n = 10) differ noticeably in average Hf (5735), Th (485), U (370), Th/U (1.32) from an older zircon (94 Ma, n = 2) in the sample (Hf 5975, Th 10, U 25, Th/U 0.43), suggesting different parental melt compositions (Figure 6). Overall, the Zr/Hf ratios (Supplementary Table 2) form two fields (Figure 6). Trachytic-derived zircons show lower average ratios, between 55 and 75 (Sheltons Road, Deep Creek), while basalt-derived zircons show higher ratios, –80–85 (Rat Hole, Ridge Road, Daylesford, Bullenmerri). In Zr/Hf–Th/U plots (Claiborn et al. 2006), the trachyte-derived and basalt-derived zircon fields plot as separated areas, each with internal overlaps (Figure 6). Within the basalt-derived zircon fields, the young Bullenmerri field with much higher Th/U is well separated from the older Bullenmerri field.

DETAILED TRACE-ELEMENT TRAVERSE RIM TO CORE, BULLENMERRI ZIRCON

A Bullenmerri zircon, with well-developed part-oscillatory zoning around a sub-rectangular core zone was analysed at different spots across from its outer zones into the core area (Supplementary Table 3; Figure 7). The REE profiles are all similar with well-developed part-oscillatory zoning around a sub-rectangular core zone (Figure 7). The core is largely depleted in REE relative to the mantle-derived ne-mugearite from Victoria used for experimental studies on high pressure amphibole crystallisation from such magmas (Irving & Green 2008), although more depleted in Mg and slightly enriched in Ti and Fe relative to the experimental rock. An enriched P content produces 4.5% Ap in the norm and is presumably related to crystallisation of the large apatite megacrysts used in dating the host eruption. The Ol–Di–Ne-normative nature of the rock make it potentially a parent mantle magma for evolution into Ol-normative trachytic magmas of Deep Creek composition, after further crystal fractionation of suitable mineral phases at higher crustal levels (Irving & Green 2008).

In primitive mantle-normalised analyses (Figure 9), the trachytes are enriched in large ion lithophile (LIL) and high field strength (HFS) elements such as K, Rb, Nb, Ta, U, Pb, Zr and Hf, but are depleted in Sr and P, relative to moderate to strongly evolved western Victorian basalts (Brimbank mugearite, Newlyn hawaiite). The Brimbank mugearite is highly enriched in Ba, Th, Sr and middle REE (Ho to Lu), whereas the Newlyn hawaiite (Sutherland et al. 2004) is moderately evolved basalt of similar provenance to the Niggl Road trachyte. In chondrite-normalised REE plots (Figure 10), the trachyte arrays are higher in Pr and heavy REE and exhibit negative Eu anomalies compared with the basalt arrays.
Such Eu depletions are typical of considerable plagioclase/alkali feldspar fractionation during basaltic magma evolution, as found in the late Cenozoic bi-modal basalt/felsic sequences in central Patagonia (Espinoza et al. 2008). Such fractionation is only specific to the mantle, if supported by further data such as the presence of mantle xenoliths as found in the Brimbank mugearite.

DISCUSSION

The zircons and rocks studied here from this SE Australian volcanic region suggest a wider felsic distribution, particularly from underlying sources intersected by later basalts. This needs discussion within the overall context of the prevailing basaltic magmatism and its tectonic context. Previous modelling will be supplemented by further modelling involving the deeper mantle below the volcanic fields.

Zircon–felsic magmatic relationships

An older zircon U–Pb age group (6.5–5 Ma) represents high-level crystal types allied to Macedon–Trentham Province trachytic eruptions and magma chambers. Zircon chemistry suggests probable evolution within fractionating magma chambers (Clairborne et al. 2006), giving increasing Th and U, Zr/Hf and Th/U trends within the Shelton Road–Deep Creek sequence and among Rat Hole Track xenocrysts (Figure 6). An intermediate U–Pb age group (2.5–1.5 Ma), with typical elongated prism forms, characterises the Niggl Road trachyte, and xenocrysts in the Ridge Road basalt and Leardons Hill volcano. The Th and U contents and Th/U ratios are lower than in zircons from the Macedon Trentham trachytes and represent felsic fractionation within peak basaltic activity in the Western District Province. A young U–Pb age group (<1 Ma) is represented by Bullenmerri zircon from a minor felsic fractionation event where the zircons (av. Zr/Hf 55–85) do not attain the low Zr/Hf (<40) found in highly fractionated rhyolites in eastern Australian central volcanoes (Sutherland et al. 2012). The young Bullenmerri zircons formed from silicate magma (Figures 8, 11–12) and provide an important key to understanding any present felsic magma generation under the western Victorian volcanic field.

BULLENMERRI ZIRCON RELATIONSHIPS

The detailed multi-element traverse within a Bullenmerri zircon revealed oscillatory zoning around a core zone, more depleted in most REE elements (Table 7; Supplementary Table 3; Figure 7). In its REE profile, the depleted core mimics the enriched outer profiles, with positive Ce anomaly and negligible Eu depletion, although showing a distinct gap in absolute values. This suggests two-stage growth with the outer zones growing from more fractionated parental melt. The Ce anomalies are larger in the outer zones, with the La–Ce lengths twice those in the core, although the Ce–Pr lengths are similar.
Recent experimental investigation of Ce and Eu anomalies in zircon at 1 GPa and 800–1300°C (Trail et al. 2012) suggests that Ce/Ce³⁺ increases not only with rising oxygen fugacity but also with decreasing crystallisation temperatures. Although these factors interplay, a crystallising core of the zircon normally would grow at a higher initial temperature than the later growth zones within cooling melt. If the later growth forms from fractionating magma under higher oxygen fugacity, then both controlling factors would reinforce and increase Ce⁴⁺ entry in the crystallising zircon. Whether this applies to the Bullenmerri zircon is uncertain, as exact conditions of growth are difficult to establish for isolated megacrysts. The Bullenmerri zircon exhibits negligible Eu depletion core to rim and would discount high oxygen fugacities, inherited Eu depletions in the parent melt and any Eu-depleting processes such as plagioclase crystallisation, based on the studies of Trail et al. (2012).

The depth of origin of Bullenmerri megacrysts needs consideration. From the ⁴⁰K/⁴⁰Ar systematics, Hiess et al. (2012) assigned the high Bullenmerri ratio (137.86 ± 0.02) to a probable mantle origin, while Ce/Ce³⁺–Eu/Eu³⁺ plots for Bullenmerri zircons also match a mantle zircon array for Australian and other mantle-derived zircon (Figure 13). Nevertheless, the crystallisation T range based on the Pupin index and Ti-in-zircon thermometry (540–700°C) seems relatively low for a parental mantle melt evolved below Bullenmerri maar. In regard to a late Quaternary xenolith-derived geotherm here (O’Reilly et al. 1997; Sutherland et al. 2005a), the ambient geotherm T in a Moho transitional zone (25–35 km; Fichtner et al. 2010; Kennett et al. 2011) would range between ∼920 and 970 ± 100°C. This apparent T discrepancy for a mantle origin may involve uncertainties in initial Bullenmerri zircon growth. The Pupin T index results only reflect the final external crystal growth T, while the core Ti-in-zircon T estimates may need a P correction of 100°C upwards if it crystallised at mantle depth (∼1 GPa). Thus, initial age, growth from mantle melt then ascent to a crustal-level melt that had fractionated with trace-element enrichment, may explain the zircon characteristics. The parental melt probably had a significant hydrous content, as mantle xenoliths at Bullenmerri maar carry hydrous metasomatic phases (Powell et al. 2005).
that would generate cooler melts than for melts derived from anhydrous mantle. The average REE profile for Bullenmerri zircon is compared with those for other zircon megacryst suites from eastern Australia in Figure 12. Bullenmerri occupies a mid-range position, more enriched than low-U mantle zircon suites (Barrington, NSW; Mount McLean, Queensland) and similar in profile to the older Weldonborough, Tasmania and Yarrowitch, NSW megacryst suites. It is distinct from the high-U and REE-rich suites that exhibit Eu depletions (Barrington, NSW; younger Weldonborough, Tasmania). The REE profile and abundances for the Bullenmerri depleted core (Figure 7), however, are similar to these on low-U Mount McLean suite (Figure 12), which typifies mantle zircon.

Relationships of felsic components

The felsic events mostly stemmed from basaltic fractionation and assimilation processes (Price et al. 2003). The Brimbank ne-mugearite dated at ca 6.3 Ma suggests high-pressure mantle evolution based on its mantle xenoliths and xenocrysts that foreshadowed the nearby 6 Ma Macedon–Trentham felsic eruptions. Such evolution from hydrous basanitic magma probably took place by crystal fractionation at 1.43 and 1.35 GPa, based on experimental runs on similar Victorian basaltic compositions (Irving & Green 2008). A hydrous amphibole-metasomatised mantle was probably involved, as related xenoliths are common in Victorian basalts. Two types of amphibole in Victorian mantle samples carry trace-element signatures that suggest silicate melt and hydrous silicate fluid activity, from both earlier subduction and later intraplate magmatic events (Powell et al. 2004). While undersaturated mantle magmas potentially could evolve to ne-normative trachytes, fractionation beyond mugearite probably proceeded at crustal levels (<0.8 GPa) and involved feldspar fractionation (Irving & Green 2008). A crustal stage for Deep Creek trachyte generation is likely, as it overlies porphyritic benmoreite with abundant large phenocrysts of alkali feldspar (VandenBerg 2005). The Deep Creek trachyte is marginally sodic in composition, suggesting that crustal contamination effects were limited, based on Macedon area Na/K trachyte isotope studies (Price et al. 2003).

The Niggl Road trachyte with an age related to peak Western District volcanism (ca 2.4 Ma) and a K-rich, quartz-normative composition clearly differs from the Macedon–Trentham felsic eruptives. The magma probably fractionated from tholeiitic basalt progenitors, as evolved basaltic andesite and andesite appear in nearby basaltic sequences of similar age (Price et al. 2003). The andesitic sequences exhibit isotopic characteristics that suggest their magmas were derived from complex mantle subcontinental lithospheric and asthenospheric sources. In the Niggl Road region, these tholeiitic and transitional basalts carry higher 87Sr/86Sr isotopic ratios than basalt sequences derived from mantle sources west of the Mortlake Discontinuity (Price et al. 2003).

Felsic outcrop in the Western District Province at present is limited to the Niggl Road trachyte plug, within the Central Highlands subprovince, although other felsic bodies may be obscured by erosion and/or burial under later soils, sediments and basalts. Zircon megacrysts with reset PT ages matching peak Western District volcanism are common in alluvial deposits in basaltic areas east of the Mortdale Discontinuity (Graham et al. 2003; present authors’ unpublished data). Some may represent further felsic eruptions. The Spring Hill centre is of particular interest here with flows extending towards Coliban Dam and includes crustal meta-xenoliths (Allchurch et al. 2008). A minimum K–Ar age for the Spring Hill centre is 3.3 Ma (Graham et al. 2003) and suggests its fractionated lavas mark a more extended felsic eruptive span within Western District activity of at least a million years duration. Other potential felsic activity includes transitional to tholeiitic parental magma evolution towards felsic compositions within the Gisborne volcanic complex (Heyworth et al. 2005) where Fe-rich enstatite and quartz-bearing trachyandesite lavas require precise age-dating to confirm their Western District or Macedon–Trentham Province age-status (Price et al. 2003). Nevertheless, they add to the overall western Victorian felsic spectrum.

Alkali feldspar megacrysts (K-rich albite–sandine series) within Western District basaltic centres also need evaluating in terms of underlying felsic sources. These xenocrysts occur across the Central Highland and Western Plains subprovinces and some sites were recently studied using 40Ar–39Ar geochronology (Ismail et al. 2013). The precise origins of these megacrysts are debated, but they are widespread in eastern Australian and other intraplate alkali basalt fields, where some studies relate them to disaggregated, small-volume syenitic bodies (Zhang et al. 2002; Upton et al. 2009). If so, the dating of Western District eruptive events (<5 Ma) suggests young felsic crystallisation processes under the region are more widespread, than just represented by rare surface trachytes and zircon xenocryst distribution.

Outlying felsic ash beds are represented in the benotites in the upper Murray Darling sedimentary sequence in NW Victoria–SW New South Wales (Gardan
Within the lower Blanchtown Clay, ash bed stratigraphy suggests age limits between 2.6 and 0.8 Ma and most likely between 2.4 and 1.6 Ma (McLaren et al. 2009), a similar time frame to the ca 2.4 Ma Niggil Road trachyte. Bentonite volcanic bombs up to 15 cm long at Wemen Mine within the SW-end of the bentonite field suggest a proximal source with present considerations favouring a source near Mildura, Victoria, compatible with ash transport under a likely prevailing south-westly wind system. The many vents interpreted north of the Mount Gambier–Portland region by Lesti et al. (2008), if confirmed, would be ideally placed as a potential bentonite source region. Whatever the actual source, the bentonites add to the felsic inventory within the young volcanic fields of SE Australia.

**Origin of post-10 Ma volcanism, SE Australia**

Several models exist for the origin of young SE Australian basaltic volcanism since 10 Ma; they include plume-like asthenospheric upwellings, convective cells produced by lithospheric edge-driven plate motion and stress-field effects along major transform and onshore fracture systems (outlined in Introduction). The new data on ages of felsic components within the basaltic magmatism will assist appraisals of these models. However, the accompanying host petrological data, while locally relevant, is not detailed enough to delineate the complex asthenospheric and lithospheric sources producing the mantle melting. To further consider underlying inputs producing the magmatism, particularly plume-like processes, additional tomographic modelling was enlisted. This modelling uses geophysical parameters within the upper mantle to distinguish areas of seismically slower (hotter) upwelling below the Tasman–SW Pacific region and to construct time-depth slices applicable to eastern Australian volcanic fields (1 Ma intervals at selected depths from 113 to 655 km). Only time-depth slices relevant to the post-10 Ma and SE Australian–SW Tasman region are presented here. The modelling used recent lithospheric studies and plate tectonic reconstructions by the Earth Byte Group, University of Sydney, mantle density and seismic wave speed constraints from the GPySM tomographic model (Simmons et al. 2010), G-plate global tectonic reconstructions (Seton et al. 2012), and assumed long-term stability of the mantle upwelling regions within the Pacific region, shown to remain intact back to Mesozoic time (Conrad et al. 2013).

**EARLIER PHASES OF SE AUSTRALIAN MAGMATISM**

The felsic and basaltic activity accompanied changes in stress fields and late Cenozoic deformations arising from coupling effects along the East Australian–SW Pacific plate margins (Sandiford et al. 2004; Debayle et al. 2005; Quigley et al. 2010; Müller et al. 2012). Along the SW Pacific margin, after 11 Ma, Macquarie Ridge spreading ceased and the New Zealand–Antarctic plate boundary margin developed as a transpressive, strike-slip fault zone (Meckel et al. 2005). Convergence rates and directions along southern New Zealand increased and southeastern impacts on the SE Australian plate peaked at 6 Ma (Sandiford et al. 2004). Such stress field changes and associated uplifts and fault reactivations in SE Australia accompanied mantle thermal upwelling below northern, central Victoria and possibly SW Victoria, while conversely Tasmanian basaltic activity to the south had terminated at ca 9 Ma (Sutherland et al. 2012).

An age-progressive component extended from 9 Ma leucite-bearing basalt in northern Victoria southwards to the 8 to 6 Ma Macedon-Trentham basalt–trachyte sequences. The timing matches projected trends from migratory felsic centres erupted from 21 to 12 Ma in eastern-central NSW (Cohen et al. 2008). After underpinning the central Victorian felsic activity, with further north-easterly plate motion, the projected asthenospheric thermal anomaly (EAP) is presently sited within a 700 km-diameter, 150 km-deep dormant thermal anomaly now under Bass Strait (Figure 14). Initial northern Victorian activity involved low degrees of partial mantle melting within heterogeneous mantle (Paul et al. 2005), while succeeding central Victorian activity marked basaltic fractionation and a high level felsic surge typical of EAP line volcanism. The Macedon–Trentham felsic event compares closely in size and character with the small Belmore central volcano, NSW, where felsic eruptions dominated rare basalts (Sutherland et al. 2005b). A 10 km-diameter ‘gabbroic’ magma chamber injected into the crust below the Macedon feldspar area (Figure 3), based on thermal modelling would cool exponentially through its 80% solidus in the first million years of fractionation before becoming immobile, but would take 10 million years to cool to the pre-intrusion geotherm (R. B. Kitch, pers. commun., October 2013).

The Australian progressive plume surges are variously attributed to plate motion changes or westerly deflections of an upwelling plume (Vasconcelos et al. 2008; Sutherland et al. 2012). The westerly location of the central Victorian episode within the asthenospheric source region may suggest plume deflection but deflection of a massive mantle mass has to overcome considerable gravitational and thermal inertia, so is unlikely to respond quickly or be driven by thin-skin crustal events and structures. Such mantle deflection, however, may reflect westward flow of Pacific asthenosphere, evident since 28 Ma within the Australian Antarctica Discordance (Whittaker et al. 2010), and possibly be reflected in the 6 Ma mantle upwelling structure modelled below central-western Victoria (Figure 15).

A western Victorian basaltic component may mark outlying activity that accompanied the central felsic episodes, based on a 9–5 Ma K–Ar ages for an emergent submarine volcano at Lady Julia Percy Island and flows near Hamilton and Linton (Edwards et al. 2004; Gibson 2007). Accepting these ages as reliable, this activity pre-dates most Western District activity (<5 Ma; Price et al. 2003; Gray & McDougall 2009) and would represent sufficient degrees of partial mantle melting to produce tholeiitic magmas, although their precise source affinities remain uncertain without detailed geochemistry. This melting event lies outside the present asthenospheric thermal anomaly confines, but will be examined in the mantle upwelling modelling (9–6 Ma slices).

The time-depth slices (Figures 15–17) show an intense upwelling region that underplume the original 65 Ma Coral Sea triple point rift zone, particularly along the...
The post-5 Ma components form the most prolific and extended basaltic volcanism in the region. Apart from minor basaltic eruptions at ca 4 and 2 Ma in eastern Victoria (Kershaw 2006), activity was concentrated west of 145°E, across W Victoria, SW New South Wales and SE South Australia (Figure 14). The activity marks a pronounced shift in the axis of volcanism from the earlier N-S plume-like volcanism and largely extends along an ENE–WSW-trending axis. The youngest Mount Gambier subprovince in SE South Australia forms a western outlier along this axis. The lithospheric trailing edge downstream convection cell model for the youngest volcanism (Demidjuk et al. 2007), based on U-series isotopic studies of the Mount Gambier field, favoured dynamic but moderate shallow asthenospheric upwelling. The identified lithospheric edge was a 125-km deep E–W shelf structure ~400 km north (Fishwick et al. 2008), lying across the plate motion direction and paralleling the Western District activity. Modelling of such convective cells, as proposed for SE Australian volcanism, supports a convective cycle of ca 10 Ma (Farrington et al. 2010) that matches the post-10 Ma Victorian volcanism but does not account for the early felsic phase and is twice the period of later Western District volcanism. Nevertheless, the Demidjuk et al. (2007) model provides a plausible starting-point for modelling Western District basaltic volcanism, as further examples of such lithospheric edge-driven basaltic lines were proposed from new dating in northeastern Brazil (Knesel et al. 2011). Aspects of the edge-driven convective cell model for Western District volcanism, however, need more explanation. How does the felsic magmatic activity, including Niggl Road trachyte and outlying bentonites, fit into the model? Also, why did Victorian activity have a longer eruptive period (by ca 4 Ma) than in the ca 1 Ma Mount Gambier subprovince, the area for the convection cell model?

The model of Lesti et al. (2008) may answer some of these questions. This study interpreted volcano distribution from Landsat 7 scenes using protocols for volcano recognition. It expanded volcano density, particularly north of the Burr Range–Mount Gambier and Portland areas, into domains not hitherto included in the younger basalt fields and linked all the post-10 Ma fields to magmatism triggered by onshore reactivations of transtensional structures through the dynamic role of the Tasman Fracture Zone in the Southern Ocean spreading process.

At 3 Ma, just prior to peak Western District and outlying bentonitic eruptive activity, the mantle thermal modelling (Figure 15) shows that at 113 km depth, the intense centre of the anomaly lies just south of western Victoria, but the northern part remains under central Victoria. The western side of Western District basalt fields overlies a less pronounced thermal zone, which intensifies at depths >250 km and merges towards the main anomaly at lower depths (384–655 km).

MODIFIED SE AUSTRALIAN MODEL

Based on the wider felsic interactions and underlying mantle upwelling story outlined in this paper, a modified genetic model is advanced to explain the causes of the underlying basaltic magma generation. Whether the magmatism involved edge-driven convection cells, tectonic fracture reactivations, or both processes, this modified model introduces greater interaction with a deep asthenospheric upwelling zone, now centred in the Bass Strait thermal anomaly. The previous suggested models, individually, may have limitations in their scope, to cover the full range of lithospheric–asthenospheric magmatic processes operating under this complex region. Many variables can produce shear-driven upwellings from asthenospheric situations, using wider modelling that also included young SE Australian volcanism.
Figure 15 Time-depth slices through upper mantle seismic profiles below the Australasian–West Antarctic region. Seismic wave speed gradients (fast to slow) are based on the GyPsuM tomographic model (Simmons et al. 2010). A boundary for seismically slow upwelling mantle (short dashed contour lines) mark seismic velocity perturbations above ~0.3%. Relative lithosphere to mantle upwelling perturbations are shown at 9 Ma, 6 Ma and 3 Ma (left to right) are based on plate reconstruction modelling by Seton et al. (2012). Mantle seismic zones are shown at 113 km, 384 km and 655 km depths (top to bottom). Initial sites of triple point rifts for the Coral Sea and South Fiji basins are shown as three rayed double lines and for the Tasman Sea rift is shown as double lines (light coloured lines). Their present triple point and rift positions lie to the north (black ridge lines). Other tectonic features include sea mounts and active intraplate volcanoes (triangles), present spreading ridges and plate boundaries (light coloured segmented lines) and plate motion velocity directions (black arrows).
(Bianco et al. 2011; Conrad et al. 2011). After activation of 9 to 6 Ma north to central Victorian magmatism as part of the EAP line, the trailing thermal aureole of this mantle-melting anomaly then passed under the eastern side of developing Western District activity. Extra inputs from this enhanced mantle-melting source would account for the plume-like OIB components, a young metasomatic xenolithic mantle plume signature and the prominent basaltic icelandite-felsic magmatic components, all features largely identified within eastern segment basalts, east of the Mortlake mantle discontinuity.

After peak activity, by 2 Ma northern plate motion would keep moving Victorian lithosphere away from the centre of main asthenospheric upwelling, although a peripheral part still persisted below the SE side of the volcanic fields, where a strong thermal anomaly was identified by seismic tomography (Graeber et al. 2002). A complex mix of magma source models, including input from a decaying EAP-like asthenospheric upwelling anomaly, may reconcile some points of previous debates on the precise nature of the sources contributing to Western District volcanism (McBride et al. 2001; Price et al. 2003).

The present mantle thermal regime modelled here under SE Australia is given in Figures 16 and 17. At 113 km depth, the main thermal anomaly resides within Bass Basin lithospheric mantle, but a segment underlies the young Western Districts basalt fields on their east side. A weak thermal region under the more western basalt fields forms a bridging ridge between the Bassian anomaly and a sharp thermal peak in SE South Australia. Below 200 km depth, the Bassian anomaly broadens to extend under the whole Western District volcanic zone, which continues into deep upper mantle (384–655 km depth).

The post-10 Ma SE Australian volcanic region emboilders the edge of a broad SW Pacific thermal upwelling below the north-migrating Australian plate and resides over a western lobe of the upwelling (Figures 15–17). This asthenospheric lobe not only cradled the initial Coral Sea–Cato Trough triple-point spreading rift, but also the plume-like sources for the subsequent migratory East Australia central volcanoes and Tasmanid seamount chains. Considerable debate now questions whether Lower Mantle plumes fed such ‘hot spot’ intraplate volcanism and rift zones, or whether other models apply (Anderson 2013; Smith 2013). This paper suggests that young SE Australian volcanism was influenced by Australian passage over ‘thermal’ asthenospheric upwelling from the base of the transition zone at ~650 km in depth. Support for injections of deep Lower Mantle ‘plumes’ would require more conclusive data than presently available. Nevertheless, the apparent western incursion into an increased upwelling zone after 5 Ma would probably enhance injections of enriched asthenospheric melts into the lithosphere, based on experimental petrological modelling of similar Australian basalts (Adam & Green 2011). This would aid a spread of basaltic volcanism across the Western District Volcanic Province.

**EPILOGUE**

Although basalts dominate these SE Australian fields, they differ from young Queensland basalt fields in a
greater record of felsic components, both in mapped centres and alkali feldspar/zircon megacryst distribution (~10^3) content. Both volcanic regions overlap asthenospheric thermal anomalies, which may contribute to the underlying melting (Sutherland et al. 2012; this paper). The Victorian magmatism, thus, differs from a passive, tectonically controlled predictable lithospheric mantle magmatism (e.g. Basin and Range region, USA; Valentine & Perry 2007).

Knowledge and modelling of the young Australian basaltic fields and their recent eruptive characteristics were advanced considerably in the last decade (Blakie et al. 2012; Boyce 2013; Holt et al. 2013; Jordan et al. 2013), assisting in understanding the volcanic evolution and potential volcanic risks (Joyce 2004, 2005, 2006). Basaltic eruptions are forefront in this modelling. Improved statistical re-analysis in such young intraplate basalt fields can modify inferred risk, as found for the <1 Ma Auck-land basalt field, New Zealand that gave a more random pattern (Beddington & Cronin 2011). Whether such randomness applies to the young Victorian activity remains for further testing, but the field has a greater magmatic input and recent dating suggests clustered activity at ca 100 ka (Ismail et al. 2013). Whether such randomness applies to the young Victorian activity remains for further testing, but the field has a greater magmatic input and recent dating suggests clustered activity at ca 100 ka (Ismail et al. 2013). The wider geographic and temporal spread in felsic episodes found in this study raises the stakes for new felsic outbursts, even in a waning magmatic system with dying hydrothermal activity (Cartwright et al. 2002; Gray & McDougall 2009). A future felsic vent would probably tap a Bullenmerri-like storage within the region. A prominent mantle thermal anomaly located under central Victoria (Aivazpourporgou et al. 2012) presents as a likely focus.

CONCLUSIONS

Combined zircon and alkali feldspar dating and host geochemical analysis in central-western Victorian volcanic fields suggest felsic magmas were generated over an 8-Ma period. Trachytic eruptions at ca 6 Ma and ca 2.4 Ma include prominent undersaturated (Macedon–Trentham) and saturated (Creswick) basaltic fractionation, with other zircon dating suggesting other felsic magmatism at ca 8, 5, 1.8 and 0.3 Ma. Zircon megacrysts at Bulleenmerri maar grew from a core with depleted mantle-like trace elements and then enriched silicate melt. A corrected U–Pb age of <0.3 Ma suggests future felsic eruption in Victoria remains feasible. New modelling of upper mantle regions, based on seismic wave speeds and tectonic plate motion parameters, suggest mantle upwelling contributed to magmatic processes. Upwelling asthenosphere and stress field changes from interactions on the bounding SW Pacific plate margins focused magmatism in SE Australia over the last 10 Ma.

Progressive N–S volcanism over a plume-like upwelling formed a felsic surge in north-central Victoria (9–5 Ma) and then peripheral inputs into younger E–W basaltic activity. Felsic activity remains a potential risk in the region.

ACKNOWLEDGEMENTS

Fons VandenBerg, Geological Survey of Victoria, supplied background data on the Trentham and Lancefield 1: 50 000 and Romsey 1: 100 000 mapping and stratigraphic notes. D. H. Taylor and C. E. Wilman and associates provided data from the 1: 100 000 Creswick and Castlemaine map sheet projects. Bernie Joyce, Geography Department, University of Melbourne provided data on Victorian volcano distribution, regolith and eruptive
risk. Astrid Carlton, Geological Survey of NSW, Maitland, assisted with airborne geophysical survey reports and unpublished data from SW New South Wales. Alan Reid and Anthony Mason, Arumpo Bentonite Pty Ltd, Mildura, provided data and discussion on the bentonite deposits. Hugo Corbella, National Natural Sciences Museum, Buenos Aires, Argentina assisted with fieldwork in central Victoria.

The Australian Museum Trust supported fieldwork, collection use and analytical work. Jo-Anne Wartho assisted with $^{39}$Ar/$^{40}$Ar dating for the Niggl Road trachyte sample (413) analysed at Curtin University. The geology departments of the University of Pretoria and the University of Cape Town, South Africa, assisted with analytical results through Maggie Louther and Andreas Spath. Greg Yaxley, Research School of Earth Sciences, Australian National University, Canberra, provided data on East Australian zircon megacrysts and Ti-in-zircon thermometry. The School of Biological, Earth and Environmental Sciences, University of New South Wales, helped with microscope photography and chemical analyses (Irene Wainwright, UNSW Analytical Centre). School of Science, University of Western Sydney provided EMMA access through Simon Hager. Ben Cohen, Earth Sciences, University of Queensland gave access to his 2007 PhD thesis on Ar–Ar dating of East Australian volcanic rocks.

Sabin Zahirovic, Earth Byte Group, University of Sydney, was instrumental in developing tomographic mantle models. Figure preparation was aided by Francesca Kelly, St Peters, Sydney. The manuscript was read by Graziella Caparella, School of the Environment, University of Technology Sydney. Constructive reviews were made by Bob Kitch of R. B. Kitch & Associates, Brisbane and Bill Birch, Museum Victoria, Melbourne.

REFERENCES

ABBOTT A., SUTHERLAND F. L. & BELDICHSA E. B. 2012. U–Pb age and origin of gem zircon from the New England nepheline fields, New South Wales, Australia. Australian Journal of Earth Sciences 59, 1067–1081.

ADAMS J. & GREEN T. H. 2011. Trace element partitioning between mica- and amphibole-bearing garnet ilmenolite and hydrous basaltic melt: 1. Tasmanian Conodonic basalts and the origins of intraplate basaltic magmas. Contributions to Mineralogy and Petrology 161, 883–889.

ALLENCHEUR S., DACEZIO N. & GRAHAM I. 2008. Petrographic, geochemical and geochronological characteristics of crustal xenoliths from Coliban Dam, central Victoria, with implications for the early evolution of the Lachlan Orogen. Geological Society of Australia Abstracts 89, 40.

AVAPPOULOU S., THIEL S., HAYMAN P., MORIES L. & HIRN J. 2012. Thermal structure of the Newer Volcanic Province, Western Victoria, Australia from a long period Magnetotelluric (MT) array. Geophysical Research Abstracts 14, p. 16. EGU 2012–249.2. EGU General Assembly 2012, Vienna, Austria.

ANDERSON D. L. 2013. The persistent mantle plume myth. Australian Journal of Earth Sciences 60, 657–673.

BEDFORDTON M. S. & CORNIN I. S. J. 2011. Spatio-temporal hazard estimation in the Auckland Volcanic Field, New Zealand, with a new-event order model. Bulletin of Volcanology 73, 55–72.

BELYAKOVA E. A., GRIFFITH W.L. O’REILLY S. Y. & FISHER N. I. 2002. Igneous zircon: trace element composition as an indicator of source rock type. Contributions to Mineralogy and Petrology 143, 662–672.

BENNETT D. A., WEISS J. A. & GROF C. M. 2003. Distribution of Plio-Pleistocene basalts and regolith around Hamilton, western Victoria and their relationships to groundwater recharge and discharge. In: Reach I. C. ed. Advances in Regolith, CRC LEME, Bentley, Perth, WA. pp. 11–15.

BIRCH W. D. & HOFF D. A. 2013. Gemstones in Victoria, Museum Victoria, Melbourne.

BIRCH W. D., BARRON L. M., MAGEE C. & SUTHERLAND F. L. 2007. Gold–diamond-bearing gravels Whiles Hills Gravel, St. Arnaud district, Victoria: based on U–Pb dating of zircon and rutile. Australian Journal of Earth Sciences 54, 609–628.

BLACK L. P. & GULSON B. L. 1978. The age of the Mud tank Carbonatite, Strangways Range, Northern Territory. BMR Journal of Australian Geology and Geophysics 3, 237–232.

BLACK L. P., KAMIS L., ALLEN C. M., ALIEKHOV J. N., DAVIS D. W. & KORSH R. J. & FOUCOULS C. 2003. TEMORA 1: a new zircon standard for Phanerzonic U–Pb geochronology. Chemical Geology 200, 155–170.

BLACK L. P., KAMIS L., ALLEN C. M., DAVIS D. W., ALIEKHOV J. N., VALLEY W. J., MUNDRI, CAMPBELL I. H., KORSH R. J., WILLIAMS I. S., & FOU DOUTS C. 2004. Improved $^{206}$Pb/$^{207}$Pb$^{208}$ microprobe geochronology by the monitoring of a trace-element related matrix effect: SHRIMP–ID TIMS, ELA–ICP–MS, and oxygen isotope documentation for a series of zircon standards. Chemical Geology 205, 115–140.

BLASKE T. N., ALLENDER L., CAS R. A. P. & BETTS P. C. 2012. Three-dimensional potential field modelling of a multi-vent magmatic diatreme – The Lake Corangamite maar, Newer Volcanics Province, southeastern Australia. Journal of Volcanology and Geothermal Research 235–236, 70–83.

BLUNDY J. & WOOD B. 2003. Mineral melt partitioning of uranium, thorium and their daughters. Uranium-Series Geochemistry. Reviews in Mineralogy & Geochemistry 52, 59–123.

BONOMME M. G., THUEYER P., PENALTY Y., CLAVER N., WEIDLING R. R. & WEDDE R. 1975. Methode de datation potassium–argon. Appareillage et Technique, University of Strasbourg, Strasbourg.

BOYCE J. 2013. The Newer Volcanics Province of southeastern Australia: a new classification scheme and distribution map for eruptive centres. Australian Journal of Earth Sciences 60, 449–462.

CARLTON A. 2009. Carboniferous–Recent Cretaceous volcanic rocks in the Balranald region, NSW. ASEG Extended Abstracts 2009 (1), 7 pp. CSIRO Publishing, Melbourne.

CARLTON A. 2010. The latest geological/ geophysical interpretation of the NSW Murray Basin basement. ASEG Extended Abstracts 2010, 4 pp., CSIRO Publishing, Melbourne.

CARTWRIGHT L., WEAVER T., TWEED S., AMEURN B., COOPER M., CIANK K. & TRANTER J. 2002. Stable isotope geochemistry of cold CO$_2$-bearing mineral spring waters, Daylesford, Victoria, Australia: sources of gas and water and links with waning volcanism. Chemical Geology 185, 71–97.

CARTLEY R. A. 2011. Exotic crustal block accretion to the eastern Gondwanaland margin in the Late-Cambrian – Tasmania, the Selwyn Block and implications for the Cambrian–Silurian evolution of the Ross, Delamerian and Lachlan orogens? Gondwana Research 19, 628–649.

CARTLEY R. A., ELLIS R. J., MOORE D. A., CASTELLONE R. D., NAGAMURA A., WILLIAMS C. E., RAWLING T. J., MORANDV. J., SKYLADENS P. B. & O’SHEA P. J. 2011. Crustal architecture of central Victoria: results from the 2006 deep crustal reflection survey. Australian Journal of Earth Sciences 58, 113–156.

CDRICH L. L., MILLER C. F., WALKER B. A., WOODEN J. L., MAZDA F. K. & BEA F. 2006. Tracking magmatic processes through Zr/Hf and $^{206}$Pb/$^{207}$Pb/$^{208}$Pb ratios from the 2006 deep crustal reflection survey. Australian Journal of Earth Sciences 58, 113–156.

COHEN B. E., KNEEL K. K., VASCONCELOS P. M. & THECTOR J. M. 2008. $^{40}$Ar/$^{39}$Ar constraints on the timing and origin of the Miocene leucitite volcanism in southeastern Australia. Australian Journal of Earth Sciences 55, 407–418.

CONRAD C., P. STEINHUBER B. & TORSKUV S. 2013. Stability of active mantle upwelling revealed by net characteristics of plate tectonics. Nature 498, 479–482.
F. L. Sutherland et al.

Conrad P., Brando T. A., Smith I. E. & Wessel P. 2011. Patterns of intraplate volcanism controlled by asthenospheric shear. Nature Geoscience 4, 317–321.

Deblauwe E. B., Kenna K. B. & Priestley J. 2005. Global azimuthal anisotropy and unique plate-motion deformation of Australia. Nature 433, 509–512.

Demets Z., Turner S., Sandford M., George R., Foden J. & Etheridge M. 2007. U-series isotope and geostratigraphic constraints on mantle melting processes beneath the Newer Volcanic Province in South Australia. Earth and Planetary Science Letters 261, 517–533.

Edward J., Carley R. A. & Joyce E. B. 2004. Geology and geomorphology of Lady Julia Percy Island, a Late Miocene submarine and subaerial volcano off the coast of Victoria. Proceedings of the Royal Society of Victoria 116, 15–31.

Espinoza F., Morata D., Polivy M., Lagaubrielle Y., Maury R., Guel C., Cotton J., Bellon H. & Saurez M. 2008. Bi-modal back-arc magmatism after ridge subduction: Pliocene felsic rocks from central Patagonia (47°S). Lithos 110, 191–207.

Farquharson R. J., Stimpson D. R., Moore L. N., Sandford M. & May D. A. 2010. Interactions of 3D Mantle flow and continental lithosphere near passive margins. Tectonophysics 483, 20–28.

Ferrier E. D. A., Essene E. J. & Becker U. 2008. Computational study of the effect of pressure on the Ti-in-zircon geothermometer. Earth and Planetary Science Letters 270, 745–755.

Fisher J. M. & Watson E. B. 2007. New thermodynamic model and revised calculations for the Ti-in-zircon and Zr-in-rutile thermometry. Contributions to Mineralogy and Petrology 154, 429–437.

Fletcher A., Kenna K. B. L., Ied H. & Bengt H. P. 2010. Full wave form tomography for radially anisotropic structure: New insights into present and past states of the Australasian upper mantle. Earth and Planetary Science Letters 290, 270–280.

Fischer C. M., Longhicer H. P., Jackson S. E. & Hanschin J. M. 2010. Data acquisition and calculation of U–Pb isotopic analyses using laser ablation (single collector) inductively coupled plasma mass spectrometry. Journal of Analytical Atomic Spectrometry 25, 1905–1920.

Fishwick S., Heintz M., Kenna K. B. L., Reading A. M. & Yoshizawa K. 2008. Steps in lithospheric thickness within eastern Australia, evidence from surface wave tomography. Tectonics 27, TC09, 17.

Ford H. A., Fischer K. M., Abt D. L., Rychert C. A. & Elkins-Tanton L. 2011. Provenance of a primitive plume under Australian based on neon isotope fractionation during step heating. Terra Nova 23, 47–49.

Gardner M., Mason A. J., Reda A. P., Churchman G. J. & Raven M. 2008. Arumpton bentonite deposits: distinctive indicators of past volcanic events in the Murray Basin, southeastern Australia. Australian Journal of Earth Sciences 55, 183–194.

Gaithersburg C. & Moreira M. 2000. Re-interpretation of the existence of a primitive plume under Australia based on neon isotope fractionation during step heating. Terra Nova 15, 36–39.

Gibson D. L. 2007. Potassium–argon ages of Late Mesozoic and Cainozoic igneous rocks of eastern Australia. CRCEMLE Open File Report 193, pp 1–53. CSIRO Exploration and Mining, Bentley, Western Australia.

Gillen D., Honda M., Chivas A. R., Yatsushiri I., Patterson D. I. & Cas P. F. 2010. Cosmogenic 26Al exposure dating of young basaltic lava flows from the Newer Volcanic Province, western Victoria, Australia. Quarterly Journal of Geology 51, 517–521.

Gravelle F. M., Houseman G. A. & Greenough S. A. 2002. Regional tectonics of the Newer Volcanic Province, Victoria. Australian Journal of Earth Sciences 49, 245–258.

Hansen A. G., Cas R. A. F., Mosegrave R. & Phillips D. 2005. Magnetic and chemical stratigraphy for the Werribee Plains basaltic lava field, Newer Volcanic Province, southeastern Australia: implications for eruption frequency. Australian Journal of Earth Sciences 52, 41–57.

Hartley S. L. & Kelly N. M. 2007. Zircon: Tiny but timely. Elements 3, 13–18.
Lester C., Giordano G., Salvin F. & Cas R. 2008. Volcano tectonic setting of the intraplate, Pliocene-Holocene, newer volcanic province (south east Australia): Role of crustal fracture zones. Journal of Geophysical Research 113, 1–11.

Lewis K. F. 2001. Isotopic E/49v2-49, A Geochronological tool kit for Microsoft Excel. Berkeley Geochronology Centre Special Publication 1a, 56 p.

McBride J. S., Lamberty D., Nicholls I. A. & Price R. C. 2001. Osmium isotope evidence for crust mantle interaction in the genesis of continental intraplate basalt from the Newer Volcanic Province, Southeastern Australia. Journal of Petrology 42, 1179–1213.

McDougall I. & Harrison T. M. 1999. Chemical and isotopic systematics of Earth's mantle by the 40Ar/39Ar method (2nd Edition). Oxford University Press, New York.

McLelland S., Wallace M. W., Pillans B. J., Galloway S. J., Miranda J. A. & Wade M. T. 2009. Revised stratigraphy of the Blanchant clay, Murray Basin: age constraints on the evolution of palaeo Lake Bungunnia. Australian Journal of Earth Sciences 56, 239–270.

Matchet E. & Phillips D. 2011. New 40Ar/39Ar ages for selected young (<1 Ma) basalt flows of the Newer Volcanic Province, southeastern Australia. Quaternary Geochronology 6, 356–368.

Matsuzoto T., Honda M., McDougal I., Yatsuyich I. & O'Reilly S. Y. 1997. Plume-like neon in a metasomatic apatite from the Austra-

lian lithospheric mantle. In: Proceedings of the 26th Annual Conference of the European Geophysical Society, pp. 372–377.

Meckel T. A., Mann P., Mosher S. & Coffin M. F. 2005. Influence of cumulative convection and lithospheric thrust development and topography along the Australian-Pacific Plate boundary south of New Zealand. Geochemical Letters, Geosystems 6, P20, Q1001. doi: 10.1029/2005GC001094.

Meissner S., Scott R. J., Glyn R. A. & Squire R. J. 2007. Re-evaluation of the existence of a prim-}

ary plume under Australia based on neutron isotope fractionation during step heating' by Gautheron and Moreira (2003). Terra Nova 18, 23–26.

Meikle A., Mann P., Mosher S. & Coffin M. F. 2005. Influence of cumulative convection and lithospheric thrust development and topography along the Australian-Pacific Plate boundary south of New Zealand. Geochemistry, Geophysics, Geosystems 6, P20, Q1001. doi: 10.1029/2005GC001094.

Meissner S., Scott R. J., Glyn R. A. & Squire R. J. 2007. Re-evaluation of the existence of a prim-

ary plume under Australia based on neutron isotope fractionation during step heating' by Gautheron and Moreira (2003). Terra Nova 18, 23–26.

Meissner S., Large R. R., Scott R., Woodhead J., Chiang Z., Gilberry S. E., Danyshevskiy L. V., Maekenrovn V. & Heirt J. M. 2008. Age and pyrite Pb-isotope composition of the giant Sukhoho Log sediment-hosted gold deposit, Russia. Geochimica et Cosmochimica Acta 72, 2077–2101.

Meszler K., Mundel R., Renne P. R. & LeDoux K. R. 2000. A test for system-

atic errors in 40Ar/39Ar archeochronology through comparison with U-Pb ages of a 1.1 Ga rhyolite. Geochimica et Cosmochimica Acta 64, 73–98.

Montet-White N., Gerya T. & Masters G. 2006. A catalogue of deep mantle plumes: New results from finite-frequency tomography. Geochemistry, Geophysics, Geosystems 7, 1–69.

Muller R. D., Dynekhelev V. & Roy P. 2012. Australian palaeo-stress fields and tectonic reactivity over the last 100 Myr. Australian Journal of Earth Sciences 59, 13–28.

Munslow R. & Rawlinson N. 2010. Linking the upper crust to the south of New Zealand. Australian Journal of Earth Sciences 58, 259–270.

Schoene B., Latkoczy C., Schaltegger U. & Gurnis M. 2012. New 40Ar/39Ar geochronology with zircon trace element analysis (U-Pb, TIMS-TEA). Geochimica et Cosmochimica Acta 74, 7144–7151.

Seton M., Muller R. D., Zandberg S., Guba C., Torsvik T., Shephard G., Gurnis M., Turner M., Marx S. & Chandler M. 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth-Science Reviews 113, 212–270.

Sherby C., Schmidt A. K., Davis H., Chen F., Meier S., Weis S. & Ego-

li S. 2009. Prolonged residence of zircon xenocrysts from the western Eiger rift. Nature Geoscience 2, 886–889.

Simmons J. L., Vaquez J. A., Renne P. R., Schmidt K. C., Bacon C. R. & Reid M. R. 2009. Accessory mineral U-Th-Pb ages and 40Ar/39Ar eruption chronology and their bearing on rhyolite magma evolution in the Pleistocene-Cenozoic volcanic field, California. Contribution to Mineralogy and Petrology 158, 421–446.

Simmons N. A., Fonte M. A., Bosch L. & Grand S. P. 2010. A joint tomographic model of mantle density and seismic wave speeds. Journal of Geophysical Research 115 B12310, doi: 10.1029/2010JB007631.

Smith A. D. 2013. Recycling of oceanic crust and the origin of intra-

plate volcanism. Australian Journal of Earth Sciences 60, 675–680.

Steiger R. H. & Jager E. 1977. Subcommission on Geochronology: convention on the use of decay constants in geo- and cosmochronol-

ogy Earth and Planetary Science Letters 36, 158–159.

Stephenson A., Rubatto D., Hermand J. & Klimas A. 2011. Tracing ultrahigh-pressure metamorphism and melting using zircon trace element composition. Biennial Conference of the Specialist Group in Geochemistry, Mineralogy and Petrology, November 20–25, Marrara-

marang, NSW Geoscience Society of Australia, Sydney, pp. 52.

Sun S.-S & McDonough W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle compositions and pro-

cesses. In: Saunders D. A. & Norty M. J. eds. Magmatism in the Ocean Basins, pp. 313–345. Geological Society of London Special Publication Volume 42.

Sutherland F. L. 1996. Alkaline rocks and xenoliths, Australia: a review and synthesis. Australian Journal of Earth Sciences 43, 323–343.

Sutherland F. L. 2003. ‘Boomerang’ migratory intraplate Cenozoic volcanism, eastern Australian rift margins and the Indian– Pacific mantle boundary. Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372, 203–221.
SUPPLEMENTARY PAPERS

Supplementary Table 1 Zircon U–Pb age analyses, central to west Victorian magmas.

Supplementary Table 2 Analyses of selected elements (ppm) on age-analysed zircon spots.

Supplementary Table 3 Analyses (LA-ICP-MS, ppm)$. Bulleenmerri zircon (core to rim).

Supplementary Table 4 $^{40}$Ar/$^{39}$Ar geochronologyfeldspar fraction (h13), Niggld Rd trachyte

APPENDIX 1: THIN-SECTION MICROSCOPY OF AGE-DATED ROCKS

Mafic trachyte, DR 17926, Deep Creek, Newham.

Euhedral laths of alkali feldspar and rarer clinopyroxene phenocrysts, along with microphenocrystic opaque iron oxide and rareapatite grains, form a flow-orientated porphyritic component (15–20 vol%) in a fine-to medium-grained, fluidal to granular groundmass (80–85 vol%) of alkali feldspar, clinopyroxenes, opaque iron oxides, dark mica, amphibole and apatite.

The alkali feldspar phenocrysts (1.3–5.5 mm across) are mostly zoned anorthoclase with undulose extinction and form 70–80 vol% of the phenocrystic fraction. Some feldspar crystals include, or show reaction rims, with opaque Fe-rich spinel, clinopyroxene,apatite and rare zircon with radiation haloes. The clinopyroxenes range into purple coloured (Ti-rich augite) and green coloured sodic (aegirine-augite and aegirine). Incipient alteration of central Victoria, Seamless Geology Project. Geochronology of the Australian Cenozoic: a history of tectonic and igneous activity, weathering, erosion and sedimentation. Australian Journal of Earth Sciences 55, 185–914.

Vosper D., D allan L., Fioretto A.M. & Fanning M. 2006. Zircon megacrysts from basalts of the Venetian Volcanic Province (NE Italy): U–Pb ages, oxygen isotopes and REE analyses. Lithos 94, 168–180.

Whittlehouse J. 2009. Mineral systems of the Murray Basin, New South Wales. Quarterly Notes Geological Survey of New South Wales 132.

Whittaker J. M., Muller R.D. & Gurfus M. 2010. Development of the Australian–Antarctic depth anomaly. Geochemistry. Geophysics, Geosystems 11, P25, Q11068, doi:10.1029/2010GC00327.

Wiedenbeck M., Alle P., Corfu F., Giffen W.L., Meier M., Oehl F., Vosquet A., Roddick J.C. & Speigle, W. 1995. 3 natural zircon standards for U-Th-Pb, Lu-Hf, trace-element and REE analyses. Geostandards Newsletter 19, 1–23.

William C.E., Biffy L.M., Radovic M.A., Macker S.J., Haydon S.J., Hollis J.D. & Osborne C.R. 2002. Castlemaine 1: 100 000 map area geological report, Geological Survey of Victoria Report 121.

Zhang Z., Feng C., Li Z., Li S., Xie Y., Li Z. & Wang X. 2002. Petrochemical study of the Jingpohu Holocene alkali basaltic rocks, North-eastern China. Geochimical Journal 36, 153–153.

Received 9 September 2013; accepted 20 December 2013
Trachyte, DR 16932, Niggi Road, Creswick,

A mixed porphyritic trachytic texture is defined by unaligned equant alkali feldspar euhedra (up to 20 mm, but rarely >10 mm in size) and smaller (1.2–2.5 mm) flow-aligned, subhedral to euhedral crystals of alkali feldspar and hornblende amphibole. Phenocrysts form –25 vol% of the modal mineralogy (~80 vol% alkali feldspar; 20 vol% amphibole) and contain common needles of minute apatite prisms (<0.01 mm long). They are contained in a fine-grained base composed of partly aligned, interlocking grains of alkali feldspar and opaque Fe-rich spinel (<0.2 mm across) and <1 vol% micro-phenocrysts of altered olivine (up to 0.5 mm across) and rare prismatic zircon (<0.8 mm long).

Some larger alkali feldspar phenocrysts include a core of an earlier-crystallised, granular-textured chryscase assemblage and are rimmed by strongly zoned alkali feldspar, partially embayed against the main trachyte groundmass. The inner enclosed trachyte forms a fine-grained (0.1–0.2 mm), equigranular, subhedral interlocking assemblage of alkali feldspar, amphibole and Fe-rich opaque spinel grains. The smaller, simply twinned alkali feldspar phenocrysts include some fractured and slightly bent (by up to 20°) grains and embayments against the ground mass are rare. The amphibole phenocrysts form strongly pleochroic (pale tan to dark brown), subhedral to euhedral, equant to prismatic grains and show well-developed reaction rims of fine-grained magnetite aggregates, which in cases completely surround and form more extensive areas than the amphibole cores.

Pale-brown Fe-rich chloritic material. Almost all the olivine is altered to fine-grained mixtures of colourless Mg-rich chloritic material and aggregates of magnetite largely altered to red-brown goethite. All the alkali feldspar appears relatively free of alteration, making the rock suitable for 40Ar–39Ar dating of feldspar extracts.

APPENDIX 2: 40Ar–39Ar DATING METHOD, DEEP CREEK TRACHYTE

Samples were loaded into a large well of one 1.9 cm diameter and 0.3 cm depth aluminium disc and were bracketed by small wells that included Fish Canyon sanidine used as a neutron fluence monitor using an age of 28.03 ± 0.08 Ma and good in-between grain reproducibility (Jourdan & Renne 2007). The discs were Cd-shielded to minimise unwanted nuclear interference reactions and irradiated for 25 h in the Hamilton McMaster University nuclear reactor (Canada) in position 5C. The mean J-value computed from standard grains within the small pits is 0.0007540 ± 0.0000040, determined as the average and standard deviation of J-values of the small wells for each irradiation disc. Mass discrimination was monitored with an automated air pipette and gave a mean value of 1.001402 (± 0.0000040) per dalton (atomic mass unit). Correction factors for interfering isotopes were (40Ar/37Ar)Ca = 7.30 × 10⁻⁴ (± 11%) and (36Ar/38Ar)Ca = 2.82 × 10⁻⁴ (± 1%) and (38Ar/36Ar)K = 6.76 × 10⁻⁴ (± 32%).

The sanidine crystals were wrapped in a 0-blank Nb foil and step-heated using a 110 W Spectron Laser Systems, with a continuous Nd-YAG (IR; 1064 nm) laser rastered over the sample during one minute to ensure a homogeneously distributed temperature. The gas was purified in a stainless steel extraction line using a GP50 and two AP10 SAES getters and a liquid nitrogen condensation trap. Ar isotopes were measured in static mode using a MAP 215-50 mass spectrometer (resolution of ~500; sensitivity of 4 × 10⁻¹⁴ mol/V) with a Balzers SEV 217 electron multiplier mostly using 9 to 10 cycles of peak-hopping. The data acquisition was performed with the Argus program written by M. O. McWilliams and run under a LabView environment. The raw data were processed using the ArArCALC software (Koppers 2002) and the ages were calculated using the decay constants recommended by Steiger & Jäger (1977). Recent more accurate 40K constants (Renne et al. 2010) shift the age by ~ +1% for the Phanerozoic, a relatively minor correction for the young ages of these rocks, which do not affect the interpretations in this study.

Blanks were monitored every 3 to 4 steps and typical 40Ar blanks range from 1 × 10⁻¹⁵ to 2 × 10⁻¹⁴ mol. Ar isotopic data corrected for blank, mass discrimination and radioactive decay are given in Table I. Individual analytical errors in Table 1 are given at the 1σ level. Our criteria for the determination of plateau are as follows: plateaus must include at least 70% of ³⁸Ar. The plateau should be distributed over a minimum of 3 consecutive steps agreeing at 95% confidence level and satisfying a probability of fit (P) of at least 0.05. Plateau ages (Figure 5a) are given at the 2σ level and are calculated using the mean of all the plateau steps, each weighted by the inverse variance of their individual analytical error. Inverse isochrons include the maximum number of steps with a probability of fit > 0.05. The uncertainties on the 40Ar/³⁹Ar ratios of the monitors are included in the calculation of the integrated and plateau age uncertainties, but not the errors on the age of the monitor and on the decay constant (internal errors only; see discussion in Min et al. 2000).

APPENDIX 3: WHOLE-ROCK TRACE-ELEMENT ANALYTICAL PROCEDURE

Dissolution of 50 mg of each sample with a standard acid digestion procedure used ultra-clean HF and HNO₃ solutions. Standards were made up from artificial multi-element standard solutions. The samples were analysed on a Perkin Elmer Sciex Elan 6000 ICP-MS. The instrument operating conditions were typically: nebuliser gas flow of 0.81 L/min; main gas flow of approx. 15 L/min; auxiliary gas flow of approx. 0.75 L/min; autolots voltages were ¹⁰⁶Be = 8.6 V, ¹⁰⁷Co = 9.2 V, and ¹⁰⁴In = 9.8 V; the ICP RF forward power was 1100 W. The instrument operating conditions were optimised to minimise the formation of doubly charged ion (Ba²⁺/Ba⁺ < 0.03) and oxides (CeO/Ce < 0.03). The instrument sensitivity for ¹⁰⁶Rh was approx. 25 000 cps/ppb. Three replicates of each sample were analysed with 20 sweeps per replicate. The dwell times were 35-50 ms per mass peak and the analytical time for each sample was 1:41:58 min. Internal standardisation utilised ¹⁰⁶Rh, ¹¹⁵In, ¹⁷⁵Re and ¹⁸⁷Bi. Interference corrections were made for isobaric interferences and for the most severe doubly charged ion and oxide interferences (particularly on the REE).

Post-10 Ma felsic volcanism, SE Australia 267