^{40}AR/^{39}AR DATING OF ALKALI FELDSPAR MEGACRYSTS FROM SELECTED YOUNG VOLCANOES OF THE NEWER VOLCANIC PROVINCE, VICTORIA

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The Newer Volcanic Province (NVP) in Victoria, with extension into south-eastern South Australia, represents the youngest chapter of Cenozoic volcanism in south-eastern Australia. However, most ages have been determined by the potassium–argon (K–Ar) method, and the age data are not comprehensive. In addition, few ages exist for the array of scoria cone volcanoes in the NVP. Seven alkali feldspar samples, mostly anorthoclase megacrysts, from volcanic centres in the NVP were used for ^{40}Ar/^{39}Ar dating in the present study. In geochronological order, with ages quoting 95% confidence limits, locations are Mount Franklin near Daylesford (0.110 ± 0.014 Ma), Red Rock near Alvie (0.116 ± 0.048 Ma), Lake Bullenmerri at Camperdown (0.116 ± 0.019 Ma), Ridge Road Quarry near Daylesford (2.01 ± 0.11 Ma) and Mount Kororoit near Diggers Rest (3.74 ± 0.26 Ma). Two samples from The Anakies, near Bacchus Marsh, produced discordant results suggesting a maximum age of ca. 1.9 Ma. The analyses and reported ages in the present study not only provide new geochronological data for the province, but also elucidate the difficulties in dating very young basalts using the ^{40}Ar/^{39}Ar dating method. These results are consistent with the erosion levels of the scoria volcanoes sampled, and indicate a major episode of explosive volcanic activity at ca. 100 ka. In contrast, the more eroded Mount Kororoit is considered to be ca. 3.7 Ma in age. The age of The Anakies is more equivocal owing to the indicated presence of excess argon and a maximum age of ca. 1.9 Ma is suggested for this locality. Given the latter results and lack of precision obtainable from the younger samples, the possibility remains that other samples contained extraneous argon and that the ages generated are thus maximum eruption ages. Analyses of additional samples from these and other localities will be required to further resolve this issue.

Key words: ^{40}Ar/^{39}Ar-dating, anorthoclase, Newer Volcanic Province, Victoria, young basalts, geochronology.

CENOZOIC volcanism in Victoria is related to regional tectonic events in south-eastern Australia, with the separation of Australia and Antarctica being the catalyst for the activity. Nevertheless, the precise cause of the volcanism is uncertain, although the younger activity may be associated with irregularities within the lithosphere–asthenosphere boundary (Demidjuk et al. 2007), coupling events on the southern Australian plate boundary (Sandiford et al. 2004) and deep thermal plume-like inputs (Sutherland et al. 2012). Volcanism occurred intermittently throughout the Cenozoic period and has continued to Recent times (Price et al. 1988, 2003). The volcanic rocks are mainly basaltic lavas with compositions ranging from tholeiitic to alkali (Wellman & McDougall 1974; Gray & McDougall 2009), although trachytic episodes are known (Price et al. 2003).

Cenozoic volcanism in Victoria has traditionally been divided into two groups, the 'Older Volcanics' of early Cenozoic age and the 'Newer Volcanics' of late Cenozoic age (Pliocene–Holocene; Wellman 1974; Price et al. 2003), representing some of the youngest volcanism in Australia. The replacement of the term 'Newer Volcanics' by 'Western District Province' was recommended by Price et al. (2003), however in this paper we have followed the terminology of Joyce and Webb (2003) and Joyce (2004) by using Newer Volcanic Province (NVP). The basalts of the NVP are well preserved and blanket large areas of western Victoria, extending into South Australia. They occupy over 15 000 km^2 of western Victoria, with approximately 450 eruption points presently recognized (Joyce 1988; Price et al. 2003), although there are likely to be many more. The province is subdivided into three subprovinces, namely the

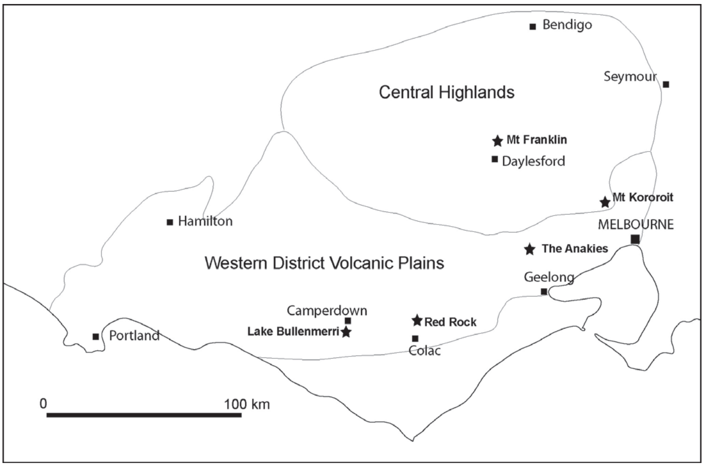

Fig. 1. Simplified map showing the localities of feldspar samples from eruption points in the Newer Volcanic Province selected for $^{40}Ar/^{39}Ar$ geochronology.

Mount Gambier subprovince in South Australia and the Western Plains and Central Highlands subprovinces in Victoria (Fig. 1; Joyce 1988; Price et al. 2003).

The flat basaltic lava plains of the Western Plains subprovince outcrop from Melbourne in the east to Hamilton in the west. Compared with other basaltic plains in the world, the volcanic succession of the Western Plains subprovince is relatively thin, generally <50 m (Joyce 1975), and overlies Otway Basin and Port Phillip Basin sedimentary successions (Hare et al. 2005). The lava flows in the plains are mostly younger than ca. 4.6 Ma, with the largest volumes being emplaced around 2 Ma (Price et al. 2003), although some basalt ages between 5 and 9 Ma have been recorded (Edwards et al. 2004; Gibson 2007). The most prominent volcanic features in the Western Plains subprovince are maars, lava shields and cones, and the rocks range from alkali basalt, transitional basalt and tholeiite to basaltic icelandite (Gray & McDougall 2009).

In contrast with the extensive basaltic plains, the Central Highlands subprovince hosts the highest concentration of eruption centres in the NVP (Hare et al. 2005), with approximately 250 small volcanoes identified in the region (Joyce et al. 1989). This subprovince contains valley flows on previously uplifted highlands that consist of folded Palaeozoic sediments and Devonian granitic rocks (Joyce 1988). The Mount Gambier subprovince occupies the far west of the NVP and is separated from the rest of the province by 60–80 km of predominantly Holocene sediments (Hare et al. 2005).

The basaltic outcrops of the NVP are widespread and well preserved, and the geochronology of the province is more comprehensive compared with the older basaltic outcrops from eastern Victoria (Day 1983; Graham et al. 2003; Price et al. 2003; Gibson 2007). However, obtaining high-precision and high-accuracy radiometric dates for young volcanoes (<500 ka) of the NVP is often difficult owing to the lower age limitations of many commonly used dating methods (e.g. U–Pb, Rb–Sr, K–Ar; Scaillet & Guillou 2004).

Most previous dating conducted on the NVP basalts used the K–Ar whole-rock method (e.g. Aziz-ur-Rahman and McDougall 1972; Wellman 1974; McDougall & Gill 1975; Ollier 1985; Gray & McDougall 2009) and, less commonly, radiocarbon (Gill & Elmore 1973; Gill 1978), cosmogenic (Stone et al. 1997) and zircon/apatite fission-track dating (Graham et al. 2003). However, the K–Ar method has limitations in terms of precision (>2%) and accuracy (argon loss or gain cannot be easily evaluated). In addition, the greatest challenge posed by very young rocks to the K–Ar method is the detection of low radiogenic argon contents from atmospheric argon (McDougall & Harrison 1999). Consequently, correction for trapped atmospheric argon is usually the main source of uncertainty in K–Ar ages measured on young volcanic rocks.

The primary aim of the present study was to determine new age data for younger NVP scoria cone volcanoes by using the $^{40}Ar/^{39}Ar$ dating method, a technique that overcomes many of the limitations of the K–Ar method (McDougall & Harrison

1999). The present study used alkali feldspar megacrysts for $^{40}Ar/^{39}Ar$ dating, rather than whole-rock samples typically used for K–Ar and $^{40}Ar/^{39}Ar$ dating (Matchan & Phillips 2011). Alkali feldspars are attractive targets for $^{40}Ar/^{39}Ar$ dating because of their elevated potassium content (usually >3 wt% K_2O cf. <2 wt% K_2O in whole-rock basalt samples), homogeneous chemistry and lower atmospheric contamination levels (due to reduced surface : volume ratios; McDougall & Harrison 1999). In addition, recent work by Upton et al. (2009) suggests that anorthoclase megacrysts associated with many alkali basalt provinces are not phenocrysts, but are formed from small-volume trachytic melts in the deep crust immediately prior to their entrainment by basaltic magmas. Therefore, a further aim of the present study was to test whether alkali feldspar megacrysts entrained in the NVP volcanoes can be precisely and accurately dated using the $^{40}Ar/^{39}Ar$ method.

METHODS

Localities and samples

Megacrysts of anorthoclase, clinopyroxene, orthopyroxene and amphibole are relatively common at a number of the younger eruption points in the NVP (Irving 1974; Wass and Irving 1976). The megacrysts may also be found in some lava flows and in mafic dykes of uncertain age. Their origin has been discussed by several authors (Irving 1974; Chapman & Powell 1976; Stuckless & Irving 1976) but remains uncertain (see Discussion). Anorthoclase megacrysts are generally water-clear to white, occurring as rounded prisms up to 8 cm long and as fragments derived from the disintegration of crystals along cleavage planes during explosive eruptions. Former crystal faces generally show moderate degrees of rounding by magmatic resorption, suggesting that most crystals were subjected to a period of suspension in a magma, under conditions in which they were not stable, prior to eruption.

In the present study, sample locations were selected according to the availability of suitable feldspars and to obtain a broad coverage of younger volcanoes in the NVP. Feldspar samples (Fig. 2) were provided by Museum Victoria from eruption centres represented by Mount Franklin, Red Rock, Lake Bullenmerri, Mount Kororoit and The Anakies. A quarry in a basaltic lava flow on Ridge Road, near Daylesford, also provided a suitable feldspar sample. These localities are shown on Fig. 1.

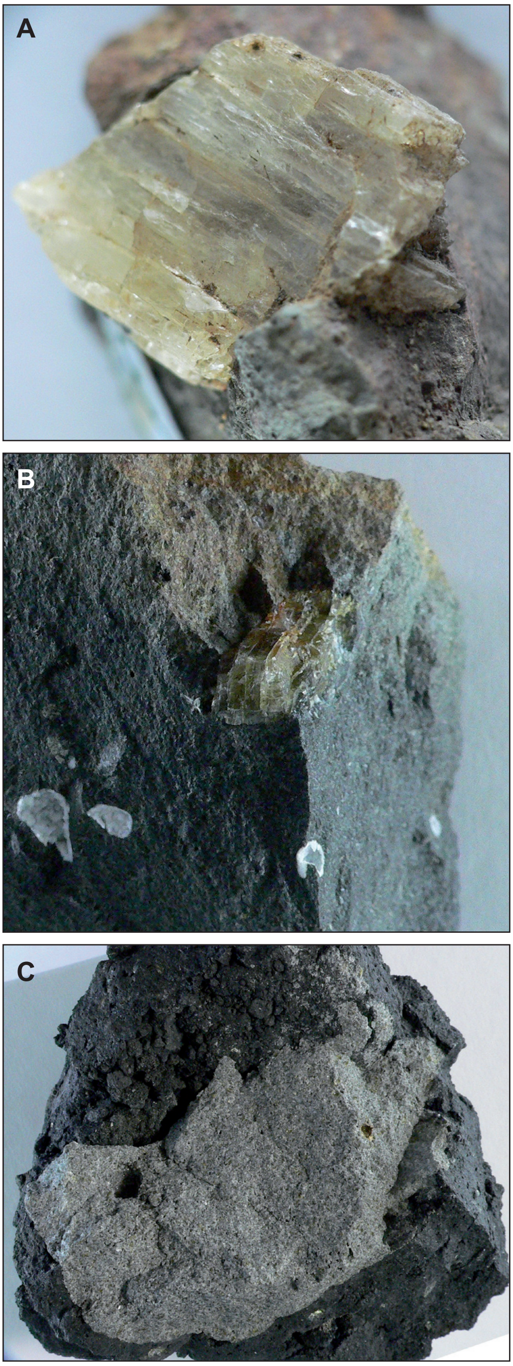

Fig. 2. (A) Anorthoclase megacryst (2 cm across) from Lake Bullenmerri (Museum Victoria sample M8775), (B) anorthoclase crystal fragment (1.5 cm) in basalt, Ridge Road Quarry (M43037) and (C) anorthoclasite xenolith (6.5 cm across) in scoria, Red Rock complex (M51259).

Mount Franklin, 9 km north of Daylesford (37º15´58´´S, 144º9´3´´E), is a scoria cone between 120 and 135 m high with a crater (Rosengren 1994). This locality is considered to be among the youngest eruption points in the NVP. The feldspar samples available from this site consisted of colourless cleavage fragments several centimetres across.

The Red Rock complex at Alvie, 12 km north of Colac (38º15´7´´S, 143º30´7´´E) consists of multiple maars, tuff rings and scoria cones, with nine intact craters up to 75 m deep, some containing lakes. The age of the complex is unknown. Feldspar megacrysts are not recorded from Red Rock, but an unusual xenolith consisting of a fine-grained aggregate of anorthoclase and olivine with minor pyroxene, collected from one of scoria quarries in the complex, was used in the present study.

Lake Bullenmerri occupies a spectacular, clover leaf-shaped maar crater, averaging 3 km across, near Camperdown (38º15´5´´S, 143º7´8´´E). A wide range of mantle and lower crustal xenoliths have been described from the tuff beds exposed in the crater rim and around the lake shoreline (Hollis 1981). The sample used in the present study consisted of fragments of anorthoclase up to 5 mm across collected from beach concentrates.

The quarry on Ridge Road, approximately 3 km southwest of Daylesford (37º22´9´´S, 144º13´52´´E), is in a basaltic lava flow along the former valley of Stony Creek, which is now entrenched along one edge of the flow. The basalt has been dated at 1.8 ± 0.1 Ma by zircon fission-track methods (J. Hollis, personal communication in Henry 1995; Graham et al. 2003). The feldspar sample selected for the present study consisted of a 2-cm long colourless, compositionally zoned crystal fragment enclosed in the basalt.

Mount Kororoit (also known formerly as Mount Misery) is a 60-m high eruption point made up mostly of pyroclastic material but with prominent summit lava ridges 5 km south-west of Diggers Rest (37º39´17´´S, 144º39´40´´E; Mitchell 1990; White et al. 2003). Its age is uncertain, but from its eroded nature it is likely to be the oldest of the sampled localities (Fig. 3). The feldspar used in the present study derives from a small selection of crystal fragments up to 3 mm across, labelled as having been collected from 'tuff'.

The Anakies are a cluster of three scoria cones, the largest being 170 m high, and a small maar 31 km north of Geelong (37º56´S, 144º11´50´´E). Quarries on two of the cones have yielded a range of xenoliths and megacrysts, with most, including the feldspar samples analysed herein, coming from the eastern-most cone.

Fig. 3. Mount Kororoit scoria volcano, near Diggers Rest.

Analytical methods

Mineral chemistry

Electron microprobe analyses were obtained for the feldspar samples to ensure that their potassium contents were sufficient (>2 wt% K_2O) for $^{40}Ar/^{39}Ar$ dating. Small chips from each feldspar megacryst were mounted in a resin block and polished to expose the grains. The sample block was then carbon coated, and major element analyses were conducted on the Cameca (Gennevilliers Cedex, France) SX-50 electron microprobe at The University of Melbourne's School of Earth Sciences (Parkville, Vic., Australia) using natural and synthetic mineral and elemental standards.

$^{40}Ar/^{39}Ar$ Geochronology

Feldspar megacrysts that were free from any visible alteration were crushed using a mortar and pestle to sizes ranging from 1 to 3 mm. Clean and fresh grains were then hand-picked microscopically to avoid any contamination or altered fragments, with each sample being approximately 300 mg. The samples were cleaned ultrasonically in deionised water and acetone for 15 min. Samples were then weighed and wrapped individually in aluminium foil packets, which were placed in a quartz vial stacked with aliquots of the irradiation standard GA1550 biotite, used to determine the amount of irradiation-induced ^{39}Ar derived from potassium. Samples were packed in package UM#40 and irradiated at the McMaster University Research Reactor (position 5C) in Hamilton, Ontario, Canada.

Table 1. Electron microprobe analyses of feldspar crystals used for $^{40}Ar/^{39}Ar$ dating

Locality	Lake Bullenmerri	Mount Franklin	The Anakies	The Anakies	Ridge Road Quarry	Mount Kororoit	Red Rock
MV no.	M8775	M11425	M11753	M22049	M43037	M49910	M51259
Sample no.	A4	A5	A3	A6	SD	A7	AC1
SiO_2	64.94	64.39	65.59	65.31	64.66	66.97	64.99
TiO_2	0.01	0.02	0.01	0.02	0.03	0.01	0.01
Al_2O_3	20.47	20.99	19.26	18.80	20.73	19.57	21.10
FeO	0.15	0.14	0.13	0.10	0.15	0.14	0.14
MnO	0.00	0.00	0.00	0.00	0.01	0.00	0.01
MgO	0.00	0.00	0.00	0.05	0.00	0.00	0.00
CaO	1.09	1.56	0.39	0.14	1.23	0.33	1.63
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	8.27	8.37	6.21	5.22	8.00	8.37	8.37
K_2O	3.92	3.23	7.81	9.27	3.85	4.60	3.19
Total	98.85	98.70	99.40	98.91	98.66	99.99	99.44
Cations							
Si	2.91	2.89	2.96	2.98	2.91	2.97	2.90
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.08	1.11	1.02	1.01	1.10	1.02	1.11
Fe^{2+}	0.01	0.01	0.00	0.00	0.01	0.01	0.01
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.05	0.08	0.02	0.01	0.06	0.02	0.08
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.72	0.73	0.54	0.46	0.70	0.72	0.72
K	0.22	0.19	0.45	0.54	0.22	0.26	0.18
Total cations	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Total oxygens	7.98	7.99	7.98	7.98	8.00	8.00	8.00
Endmember							
An	5.26	7.59	1.86	0.68	6.06	1.57	7.92
Ab	72.22	73.70	53.70	45.80	71.35	72.29	73.62
Or	22.52	18.71	44.44	53.52	22.59	26.14	18.46

MV, Museum Victoria.

All $^{40}Ar/^{39}Ar$ analyses were conducted in the Noble Gas Laboratory in the School of Earth Sciences at The University of Melbourne, following procedures described by Phillips & Harris (2009). After the samples had cooled, each sample was weighed and further divided into approximately six aliquots, which were loaded into a copper tray for laser step-heating analyses. All samples were baked at approximately 120°C overnight. Laser step-heating (two to three temperature increments per aliquot) was performed using a 40-W CO_2 laser; isotopic analyses were performed on a VG5400 mass spectrometer (Fisons Instruments, UK) equipped with a Daly detector. J-values were calculated from the GA1550 biotite standard grains based on an age of 98.8 ± 0.5 Ma (Renne et al. 1998).

RESULTS

Mineral chemistry

The major element compositions for each feldspar sample are summarized in Table 1. Most of the feldspar analyses plot in the anorthoclase field of an alkali ternary diagram with K_2O contents ranging between 3 and 8 wt%. One sample from The Anakies (A6) contains 9.27 wt% K_2O and is classified as sanidine.

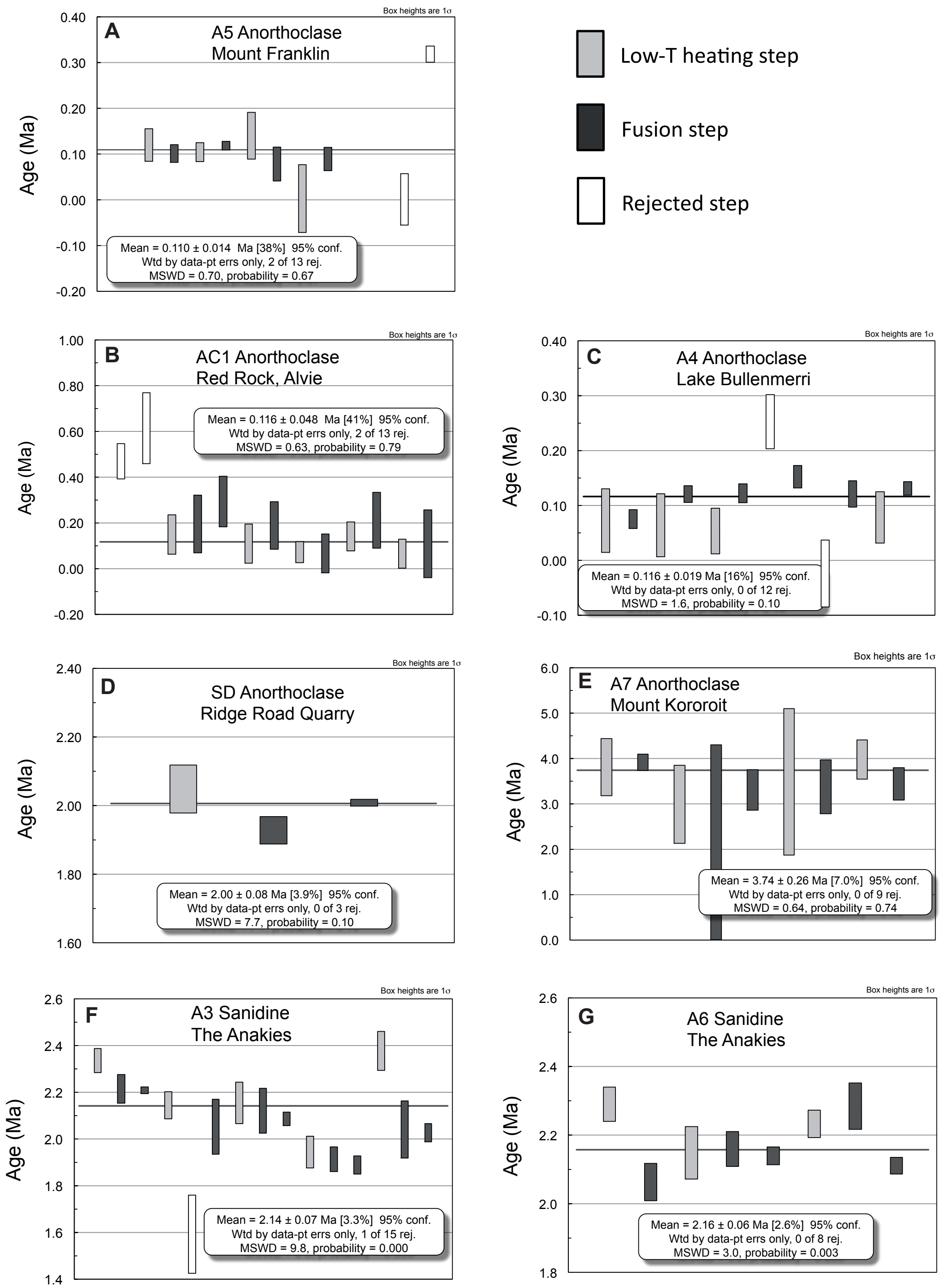

Fig. 4. Summary of $^{40}Ar/^{39}Ar$ age results obtained for feldspar samples from six Newer Volcanic Province locations, namely (A) Mount Franklin, (B) Red Rock, Alvie, (C) Lake Bullenmerri, (D) Ridge Road Quarry, Daylesford, (E) Mount Kororoit and (F,G) The Anakies. The boxes at the bottom of each graph include the mean age and statistical information. MSWD, mean square weighted deviation (a statistical measure of scatter about a line); Wtd by data-pt errs only, weighted by data-point errors only.

^{40}Ar/^{39}Ar dating

The ^{40}Ar/^{39}Ar step-heating datasets for all samples are shown in Figure 4. Samples with the highest potassium contents yielded more precise age results. Unless stated otherwise, errors are reported at the 95% confidence level.

Mount Franklin

Analyses were performed on six aliquots of sample A5, with two heating increments used (Fig. 4A). The resulting average ages were 0.106 ± 0.034 Ma (A5-1), 0.116 ± 0.017 Ma (A5-2), 0.100 ± 0.059 Ma (A5-3), 0.08 ± 0.34 Ma (A5-4), 0.99 ± 0.71 Ma (A5-5) and 0.30 ± 1.20 Ma (A5-6; Fig. 4B). If the last two aliquots are omitted, the remaining steps yield a preferred weighted mean age of 0.110 ± 0.014 Ma. The older ages obtained for aliquots A5-5 and A5-6 could again be due to contamination; alternatively, some fragments may contain extraneous argon.

Red Rock

Analyses were performed on six aliquots of sample AC1, with two heating increments used on all aliquots except for AC1-2, which underwent three heating increments (Fig. 4B). All analyses are characterized by relatively large associated uncertainties due to the limited sample material available. However, within analytical uncertainties, the low and high temperature steps yielded indistinguishable age results. The average ^{40}Ar/^{39}Ar ages for each aliquot are 0.50 ± 0.14 Ma (AC1-1), 0.20 ± 0.12 Ma (AC1-2), 0.14 ± 0.13 Ma (AC1-3), 0.070 ± 0.079 Ma (AC1-4), 0.16 ± 0.11 Ma (AC1-5) and 0.07 ± 0.11 Ma (AC1-6; Fig. 4A). Excluding the analyses from aliquot AC1-1, the remaining temperature steps give a weighted mean age of 0.116 ± 0.048 Ma. Aliquot AC1-1 produced distinctly older ages, possibly due to sample contamination or the presence of extraneous argon.

Lake Bullenmerri

Step-heating analyses were performed on six aliquots of sample A4 from Lake Bullenmerri (Fig. 4C). The aliquots yielded average ^{40}Ar/^{39}Ar ages of 0.074 ± 0.033 Ma (A4-1), 0.116 ± 0.029 Ma (A4-2), 0.11 ± 0.31 Ma (A4-3), 0.17 ± 0.46 Ma (A4-4), 0.10 ± 0.63 Ma (A4-5) and 0.13 ± 0.17 Ma (A4-6). If the more anomalous steps (A4-1 and low-temperature step A4-4) are omitted from further consideration, a weighted mean age of 0.116 ± 0.019 Ma is calculated for the remaining four aliquots.

Ridge Road Quarry

Because of the limited amount of feldspar available from the Ridge Road Quarry sample, step-heating analysis was performed on just one aliquot of sample SD (Fig. 4D). The three heating increments yielded slightly discordant ^{40}Ar/^{39}Ar ages of 2.05 ± 0.07 Ma, 1.93 ± 0.04 Ma and 2.01 ± 0.01 Ma, in order of increasing temperature (Fig. 4D). The weighted mean age for all steps is 2.00 ± 0.08 Ma. If the second step is excluded, the mean age becomes 2.01 ± 0.11 Ma. This result is broadly consistent with previous fission-track zircon data for this locality (Graham et al. 2003).

Mount Kororoit

Step-heating analyses were performed on four aliquots of sample A7 from Mount Kororoit (Fig. 4E). Individual age results are relatively imprecise owing to the small sample size, but low- and high-temperature steps yielded indistinguishable age results. The weighted mean age for all steps is 3.74 ± 0.26 Ma.

The Anakies

Step-heating analyses were conducted on five aliquots of sample A3 and three aliquots of sample A6 from The Anakies (Fig. 4F,G). In contrast with other anorthoclase samples, these aliquots produced discordant results, averaging 2.142 ± 0.070 and 2.157 ± 0.057 Ma, respectively. In some cases, high-temperature steps exhibit younger ages than low-temperature steps. This pattern suggests the release of excess argon, possibly from fluid inclusions. As a result, all ages obtained from this sample are considered maximum estimates for the time of host volcanic eruption. The youngest ages recorded from individual fragments are close to 1.9 Ma, and this age may represent the closest approximation for the eruption age of The Anakies.

DISCUSSION

There are three possible circumstances in which the ^{40}Ar/^{39}Ar age data obtained for the feldspar crystals may be interpreted as eruption ages of their respective host rocks: (1) the feldspar megacrysts are phenocrysts that crystallised from the basalt magma and contain no excess argon; (2) the feldspar crystals are xenocrysts that formed immediately prior to basalt volcanism and contain no excess argon; and (3) the feldspar crystals are xenocrysts formed prior to basaltic magmatism, but were isotopically reset by the hot basalt magma.

A limited number of studies on the origin of feldspar megacrysts has been undertaken. Irving (1974) analysed a wide variety of megacrysts from NVP volcanic centres and suggested that anorthoclase megacrysts from The Anakies could have formed from hydrous, differentiated near-solidus basaltic magmas at pressures <12 kb. Irving (1974) concluded that the megacrysts may have crystallised from the host basalt magma and/or related magmas. Stuckless and Irving (1976) showed that anorthoclase megacrysts from the NVP exhibit minor disequilibrium in Sr isotopic ratios compared with their host magmas. They suggested that the megacrysts and basaltic magmas were broadly cogenetic, but that the megacrysts are, in fact, xenocrysts entrained in later magmas of different isotopic composition. This model was supported by Chapman and Powell (1976), who concluded that anorthoclase megacrysts (and associated cumulate nodules) formed from high-level differentiated magmas and were subsequently transported to the surface by later more basic magmas.

Upton et al. (2009) investigated megacrysts and xenoliths, including an anorthoclasite suite, from alkali basalts in Scotland. They concluded that the majority of anorthoclase megacrysts (compositions in the range $Ab_{80–90}Or_{20–10}$) are not phenocrysts, but crystallized from small-volume trachytic melts in the deep crust before being disaggregated and entrained by their host basaltic magmas. Based on the common association of these megacryst suites with alkaline basalt provinces, the presence of euhedral megacryst crystal forms and (limited) K–Ar and U–Pb data that suggest a close timing relationship between megacryst formation and host basalt magmatism, Upton et al. (2009) suggested that the trachytic and basaltic magmas were broadly contemporaneous. However, some uncertainty remains about the exact location and nature of the host magma for the anorthoclase megacrysts.

In summary, previous work suggests that the anorthoclase megacrysts associated with the NVP are xenocrysts formed from deep crustal, most likely trachytic melts, which are compositionally unrelated to regional basalts, but were generated in response to the basaltic magmatic event. This synopsis implies that $^{40}Ar/^{39}Ar$ ages obtained from anorthoclase megacrysts will be maximum ages for the time of host basalt magmatism, but may approximate the time of this magmatism if the megacrysts formed immediately prior to basalt eruption (within the analytical precision limits of the method) and contain no inherited or excess argon.

Comparisons with previous age results

Of the six megacryst occurrences dated in the present study, only four have been dated previously. No or limited prior age constraints are available for Mount Kororoit and The Anakies, respectively.

Wallace and Ollier (1990) reported a K–Ar age of 0.47 Ma (error unknown) on a hawaiite sample from the Mount Franklin scoria cone. This age is distinctly older than the $^{40}Ar/^{39}Ar$ anorthoclase age of 0.110 ± 0.014 Ma obtained in the present study. The difference in these age results suggests that the samples dated by Wallace and Ollier (1990) may have contained inherited material and/or excess argon; alternatively, the analytical uncertainty associated with the K–Ar age exceeds ±77%.

Red Rock has not been dated directly, although Gill (1978) obtained a radiocarbon age of 7.81 ± 0.01 ka for a fossil soil found within the volcanic succession. The $^{40}Ar/^{39}Ar$ age of sample AC1 from Red Rock is significantly older, at 0.116 ± 0.048 Ma. Given the difficulties in relating radiocarbon fossil ages to the timing of associated basalts, we suggest that this result represents a minimum estimate.

Hiess et al. (2012) recently reported a U–Pb age of 0.24 ± 0.04 Ma for zircon megacrysts from Lake Bullenmerri. This age is distinctly older than the current anorthoclase $^{40}Ar/^{39}Ar$ age of 0.116 ± 0.019 Ma, suggesting that the zircons are earlier-formed xenocrysts. If the zircon and anorthoclase megacrysts formed from the same melts, this would imply partial to complete resetting of the feldspar argon isotopic systematics.

The concordance of $^{40}Ar/^{39}Ar$ ages for Red Rock, Mount Franklin and Lake Bullenmerri (0.110–0.116 Ma) suggests that they represent a period of enhanced volcanic activity within the overall intermittent eruption history in the NVP. The concordance in $^{40}Ar/^{39}Ar$ ages is also consistent with the similarity in erosion levels exhibited by these three localities.

The single zircon fission-track age of 1.8 ± 0.1 Ma reported for the Ridge Road Quarry basalt is broadly consistent with the $^{40}Ar/^{39}Ar$ anorthoclase age of 2.01 ± 0.11 Ma, although more dating is required to resolve the small difference between the two independent results.

The older ages determined for Mount Kororoit and The Anakies are consistent with their more eroded appearance. Mount Kororoit is within a group of eruption points in the Sunbury–Diggers Rest–Gisborne region that show similar features, in the form of lava 'cappings' that may represent basaltic dykes (Edwards & Crawford 1940). An age of 3.74 Ma for Mount Kororoit provides the first age information for this group of distinctive volcanoes. It is considerably older than the 0.75 Ma age for Mount Kororoit estimated by Mitchell (1990) based on magnetic reversal data.

For The Anakies, there are no immediate eruption points in the vicinity for comparison. As noted above, it is concluded that the age of this locality is ca. ≤1.9 Ma. Gray and McDougall (2009) listed K–Ar ages of 1.50 ± 0.02 and 1.55 ± 0.02 Ma for basalts from 'Anakie', but these come from a locality some 4 km south of the eruption points (F.L. Sutherland, personal communication), so the relationship of these lavas to The Anakies volcanoes is uncertain.

Using remote-sensing techniques, Ollier and Joyce (1986) mapped five broad regolith–landform units in the Western Plains subprovince and assigned broad age ranges to each unit. The five regolith–landform units recognized were Eccles (0.0–0.2 Ma), Rouse (0.2–1.0 Ma), Dunkeld (1–3 Ma), Clay (3–4 Ma) and Hamilton (4–5 Ma). The new ^{40}Ar/^{39}Ar ages place Mount Franklin, Red Rock and Lake Bullenmerri within the Eccles unit, and those of the Ridge Road Quarry and The Anakies within the Dunkeld unit. The older Mount Kororoit volcano has the most eroded profile, consistent with the Hamilton unit.

CONCLUSIONS

The new feldspar ^{40}Ar/^{39}Ar ages for Mount Franklin (0.110 ± 0.014 Ma), Red Rock (0.116 ± 0.048 Ma), Lake Bullenmerri (0.116 ± 0.019 Ma), Ridge Road Quarry lava flow (2.01 ± 0.11 Ma), Mount Kororoit (3.74 ± 0.26 Ma) and The Anakies (<1.9 Ma) are consistent with recognised periods of volcanism in the NVP of Victoria. The ^{40}Ar/^{39}Ar ages for Mount Franklin, Red Rock and Lake Bullenmerri are concordant, suggesting an episode of enhanced explosive volcanism at ca. 0.11 Ma.

The new ^{40}Ar/^{39}Ar ages provide more robust geochronological results than previous data and illustrate the potential of the ^{40}Ar/^{39}Ar method to date young volcanoes using potassium-rich feldspar megacrysts. Further dating is required on additional localities in the NVP to enhance the geochronological database, which would provide an improved understanding of eruption frequency and duration.

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