A new $^{40}$Ar/$^{39}$Ar eruption age for the Mount Widderin volcano, Newer Volcanic Province, Australia, with implications for eruption frequency in the region

E. L. Matchan, E. B. Joyce and D. Phillips

School of Earth Sciences, The University of Melbourne, VIC 3010, Australia

ABSTRACT

The Mount Widderin shield volcano is located near Skipton, western Victoria, in the Western Plains subprovince of the monogenetic Pliocene–Holocene Newer Volcanic Province (NVP). Radiometric ages for lavas in the Hamilton–Skipton–Derrinallum area are few, owing to limited suitable outcrop for K–Ar or $^{40}$Ar/$^{39}$Ar geochronology studies. Existing age constraints for flows in this area have been inferred from Regolith Landform Units (RLUs), complemented by a small number of K–Ar studies on $\geq 1$ Ma flows. Although the RLU provides a valuable overview of relative eruption ages across the NVP, it is limited in use in eruption frequency studies. Additional radio-isotopic ages are required to refine age ranges for individual RLUs, and to validate previous assignment of individual flows to specific RLUs. We report a new, high-precision $^{40}$Ar/$^{39}$Ar age of 389 ± 8 ka (2σ) for a Mount Widderin basalt sample. Based on this age and geomorphic observations, we propose that both the Widderin and Elephant lava flows be reassigned from the Eccles RLU to the Rouse RLU. We use the 389 ± 8 ka (2σ) age for Widderin, along with published K–Ar ages, to anchor a stratigraphic sequence of 15 individual flows in the Hamilton–Skipton–Derrinallum area, demonstrating that intermittent volcanism has occurred in this area from $>3$ Ma to $\leq 0.389$ Ma. Within the limits of available data for the NVP, this time span of volcanic activity is second only to that of the Melbourne area. We consider the significance of the Widderin eruption age, in conjunction with published age constraints for maars and scoria cones of the Western Plains subprovince, building on previous studies that have focused solely on lava flow ages. The inclusion of the additional data weakens the argument for a decrease in volcanic activity after ca 0.9 Ma as implied by published ages for lava flows only. Additional detailed combined geochronology–geomorphology studies of lavas, scoria cones and maars in strategically selected small areas are advocated to better understand eruption frequency across the NVP.

Introduction

The Pliocene–Holocene monogenetic basaltic Newer Volcanic Province (NVP; sometimes spelled ‘Newer Volcanics Province’) of southeastern Australia covers an area of $>19$ 000 km$^2$ (Boyce, 2013), extending from Melbourne in Victoria, to the Mount Burr Range in South Australia (Figure 1). The NVP contains 416 recognised volcanic centres, comprising lava shields, scoria cones, maars and composite eruption centres (Boyce, 2013) with compositions ranging from tholeiitic to alkalic (Irving & Green, 1976, Vogel & Keays, 1997). The origin of the NVP is the subject of continued discussion, but isotopic data support derivation of melts from a shallow, heterogeneous, asthenospheric mantle source (Paul, Hergt, & Woodhead, 2005), consistent with thermal instability models (e.g. Davies & Rawlinson, 2014; Demidjuk et al., 2007; Lister & Etheridge, 1989).

The NVP has been subdivided into three subprovinces based on geomorphological characteristics (Joyce, 1975; Ollier & Joyce, 1964): Central Highlands, Western Plains and Mount Gambier (Figure 1). In the Central Highlands subprovince, volcanoes erupted within an already uplifted and dissected terrain (Boyce, 2013; Holdgate et al., 2006; Joyce, 1992, 1999). In the Western Plains subprovince, volcanic centres are more sparsely distributed. Here, thin but extensive lava flows mantle a low-profile gently undulating surface developed on weathered Cretaceous to Neogene sediments (Joyce, 1999). The Mount Gambier subprovince is separated from the Western Plains subprovince by some 50 km. It contains a cluster of volcanoes in the northwest (Mount Burr Range) that are stratigraphically constrained to be of Pleistocene age (Holt, Holford, & Foden, 2014), and the Holocene eruption centres of Mount Gambier and Mount Schank in the southeast.

As reviewed elsewhere (e.g. Gray & McDougall, 2009; Matchan & Phillips, 2011), available age data indicate that volcanism initiated at ca 4.5 Ma in the Central Highlands subprovince, with the most recent activity in the Mount Gambier subprovince; however, there is no apparent age progression across the NVP. Based on a comprehensive compilation of
K–Ar ages for lava samples from the Western Plains subprovince \((n = 44)\), together with a small number of volcanoes with inferred \(<0.1\) Ma ages \((n = 5)\), Gray and McDougall (2009) proposed a peak in volcanic activity at 3.0–1.8 Ma. Although this interval could represent a peak in effusive volcanism, it may also be an artefact of relatively low sampling density in the Western Plains subprovince. Furthermore, maars and scoria cones were excluded from consideration, presumably due to a paucity of age constraints at the time of publication. This is an important observation because if the relative frequencies of different eruption styles have varied over the lifetime of the NVP, this could lead to significant bias in eruption frequency studies based solely on the ages of lava flows.

There are at least 175 eruption centres in the Western Plains alone, of which approximately half are lava shields or complex centres that experienced some period(s) of effusive eruption activity (Boyce, 2013). The remainder are scoria cones or maars that did not produce any significant amount of lava (Boyce, 2013). Most maars and scoria cones do not have any published age constraints. Improving the geochronological record of the NVP is important for understanding the petrogenetic evolution of the province, testing models for its origin, as well as establishing eruption frequencies for geohazard evaluation. On a local scale, improved age constraints for key volcanic units provide a stratigraphic reference framework for Quaternary landscape evolution and paleoclimatic variation.

Considering the number of eruption centres and thicknesses of basalt sequences \((>100\) m in places; e.g. Hare, Cas, Musgrave, & Phillips, 2005), the existing geochronological record for the NVP is relatively sparse. This is primarily due to limited availability of suitable material for dating (unaltered holocrystalline outcrop/drillcore), and the difficulty in attributing flows to specific eruption points, many of which may have been fissures/low-profile shields that have been subsequently buried. The existing NVP eruption record is overwhelmingly constructed from K–Ar dating studies on lava flows aged \(\geq0.5\) Ma (e.g. Aziz-ur-Rahman & McDougall, 1972; Gray & McDougall, 2009; McDougall, Allsop, & Chamalaun, 1966). These data are complemented by a small number of relatively recent \(^{40}\text{Ar}/^{39}\text{Ar}\) geochronology studies (Hare et al., 2005; Ismail, Phillips, & Birch, 2013; Matchan & Phillips, 2011, 2014).

In the case of the very young \((<100\) ka) scoria cones and maars in the Western Plains subprovince, published age constraints are largely derived from radiocarbon analyses of underlying swamp material or crater lake sediments (e.g. Builth et al., 2008), complemented by several cosmogenic nuclide exposure dating studies (Gillen et al., 2010; Stone, Peterson, Fifield, & Cresswell, 1997), luminescence studies (Sherwood, Oyston, & Kershaw, 2004; Smith & Prescott, 1987), and \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of anorthoclase megacrysts entrained by basalt melts (Ismail et al., 2013).

\(^{40}\text{Ar}/^{39}\text{Ar}\) (and \(\text{K–Ar}\)) dating of basalts younger than \(ca 0.5\) Ma has historically been analytically challenging, owing to the difficulty in resolving extremely small radiogenic \(^{40}\text{Ar}\) signals (typically \(<5–20\%\) of total \(^{40}\text{Ar}\)) from atmospheric argon. However, recent advances in noble-gas mass spectrometry have improved the precision achievable with the \(^{40}\text{Ar}/^{39}\text{Ar}\) dating technique by an order of magnitude (e.g. Matchan & Phillips, 2014; Phillips & Matchan, 2013). Sample quality plays a critical role in the precision of individual ages, as any minor deficiencies in the key criteria (i.e. purity, lack of alteration and weathering, crystallinity, grainsize) have a measurable effect on the gas release profile during step-heating, and impact age precision and accuracy. Therefore, detailed
sample characterisation and careful evaluation of argon isotopic data are critical when evaluating the accuracy of eruption ages.

Adopting a similar approach to the K–Ar dating study of Gray and McDougall (2009), this study demonstrates how geomorphological observations can be used in tandem with radio-isotopic dating to unravel the eruption history of a complex region. We consider lava flows in the poorly documented Skipton–Derrinallum area, focusing on Mount Widderin (Figure 2).

Geological setting and existing age constraints

Basalt flows in the Skipton–Derrinallum area have been previously mapped as two units: undifferentiated Plains Basalts and Stony Rises (e.g. VandenBerg, 1997; Figure 2). Although this simple classification system is useful (and necessary) from a regional geology perspective, it masks the complex eruption history of this area. MacInnes (1985) identified and mapped 14 separate lava flow units in the Hamilton–Skipton area using a combination of aerial photograph interpretation, field observations, petrography and major-element chemistry. Relative ages were assigned on the basis of lava surface preservation, levels of soil development and field relationships, with a focus on flows to the west of Mount Emu Creek. The portion of the resultant map relevant to the Skipton–Derrinallum study area is reproduced in Figure 3, showing the nine basalt units identified in this area by MacInnes (1985): Terrinallum, Streatham, Caranballac, Vite Vite, Moorallah, Hamilton, Fyans (#1), Elephant and Widderin. The flow stratigraphy proposed by MacInnes (1985) is summarised below.

The oldest basalt units in this area are the deeply weathered Terrinallum and Streatham basalts, but their relative age relationship is unclear. The second-oldest unit is the Carranballac basalt, followed by the Vite Vite basalt, both of which have gently undulating surfaces with well-developed soil...

Figure 2 Geology and drainage of the Derrinallum–Skipton area. Geological data extracted from 1:100k and 1:250k GIS datasets (Geological Survey of Victoria, 2010). Hydrographic 1:25k data from VicMap Hydro (Department of Environment, Land, Water and Planning, 2015). Sampling locality for NVP26 indicated by star. Schematic inset map shows context of the study area within the Newer Volcanic Province (shaded region).
profiles (MacInnes, 1985). The Moorallah and Hamilton basalt units in the west of the study area exhibit degraded stony rises. The Moorallah basalt is considered to have diverted the Mount Emu Creek to its present location (Figure 3). On the basis of geomorphology alone, there is no obvious age difference apparent between the Moorallah and Hamilton basalts. The Fyans (#1) basalt exhibits stony rises and post-dates both the Moorallah and Hamilton basalts, having dammed the drainage network established on the southern margin of the Hamilton basalt (MacInnes, 1985). Minimal drainage pathways have developed on the Fyans (#1) basalt. The ages of the Elephant and Widderin flows, which both exhibit stony rises, relative to one another and the Fyans (#1) basalt, are unconstrained by stratigraphy.

The work of MacInnes (1985) was incorporated into the regolith landform map of Joyce (1999), refining earlier soil and regolith mapping schemes (Gibbons & Gill, 1964; Ollier & Joyce, 1986). In this classification system, the lava flows from Mounts Widderin, Elephant and Fyans are included in the Eccles Regolith Landform Unit (RLU) and assigned a nominal age of 200–0 ka (Joyce, 1999). The Mount Hamilton flows are assigned to the Rouse RLU (1.0–0.2 Ma), Mount Vite Vite flows to the Dunkeld RLU (3.0–1 Ma), and the remaining flows to the Hamilton RLU (5–4 Ma; Joyce, 1999).

Gray and McDougall (2009) obtained the first K–Ar ages for basalts in this region, determining K–Ar ages of 3–2 Ma for basalts outcropping in the vicinity of Darlington (17 km SW of Derrinallum), previously assigned to the 5–4 Ma Hamilton RLU. However, Gray and McDougall (2009) noted that their reported ages are imprecise owing to high levels of atmospheric argon contamination resulting from analysis of weathered samples collected from the scant outcrop present.
in this area. These authors also obtained a single K–Ar age of 2.95 ± 0.16 Ma (2σ) for a tholeiitic basalt outcropping between Darlington and Derrinallum, corresponding to the ‘Terrinallum basalt’ unit of MacInnes (1985). Based on the stratigraphic age sequence of flows summarised above, an age of ca 3 Ma is regarded as a probable upper age estimate for volcanism in the Skipton–Derrinallum area, although we note that the undated Westmere and Streatham basalts may be older. Aside from a weighted mean K–Ar age of 0.99 ± 0.04 Ma (2σ) for the stony rises of the Stockyard Hill basalt (Gray & McDougall, 2009) 16 km NNW of Skipton, there are no further published age constraints for basalts in this region. Based on the flow stratigraphy outlined above, the Widderin, Elephant and Fyans (#1) basalts are classified as the youngest flows in the Skipton–Derrinallum area. No published age constraints exist for these flows.

**Mount Widderin**

The Mount Widderin shield volcano is located 6 km south of Skipton (Figure 2). A system of lava tubes near the summit of Mount Widderin (360 m elevation), commonly referred to as the Skipton Caves or Widderin Caves, includes one of the largest known chambers in the NVP (Ollier, 1963). These caves were once host to rare secondary phosphate minerals formed from guano, but these deposits have since been destroyed by human activity (Birch & Henry, 1993; Pilkington & Segnit, 1980). The Widderin basalt forms a gently undulating landscape (Figure 4a) that is typical of degraded stony rises in the Western Plains (Ollier & Joyce, 1964; Skeats & James 1937). The local topographic highs (stony rises) comprise rounded, vesicular lava blocks with development of shallow red soil (Figures 4a, 5). Soil is considerably thicker in the depressions between these stony rises, typically completely covering underlying basalt.

The Widderin lavas represent a considerable modification to the landscape and would have significantly reconfigured the local drainage system. The northwestern boundary of the basalt is now traced by the Mount Emu Creek, a major drainage feature in the Bolac–Skipton region (Figure 2). The Widderin lavas flowed predominantly to the southwest, channelled for approximately 25 km by a paleovalley (Figures 2, 3). To our knowledge, the contact between the Widderin and Elephant lava flows has not been documented previously.

**Comparison of Widderin and Elephant lava landforms and age implications**

Sediments in the vicinity of Lake Logan somewhat obscure the contact between the Widderin and Elephant lava flows. However, field observations reveal that the morphology and preservation of stony rises from these two volcanoes are significantly different, and allow a contact to be mapped to an accuracy of ∼100 m, coincident with the location of Vite Vite Road (Figure 3; Supplementary Papers Figure B2). We observe that the flows from Mount Elephant commonly form steep-sided mounds covered with angular lava blocks and thinly developed red soil (Figure 4b). The soil horizon is poorly developed and shallow in depressions, with small pieces of lava commonly breaking the surface. This contrasts with the rounded lava blocks of the undulating Widderin stony rises described above. In isolation, the difference in morphology between the Elephant and Widderin stony rises may be interpreted to chiefly reflect differences in lava viscosity, rather than significantly different erosional histories. However, the steep-sided and angular nature of the rises, taken together

![Figure 4](attachment:image)

**Figure 4** (a) Stony rises of Mount Widderin. Photograph taken approximately 800 m south of the NVP26 sampling locality, looking SE. (b) View of Mount Elephant with its stony rises in the foreground, looking south.
with the relatively limited soil development, suggests that the Elephant flows may be significantly younger than the Widderin flows. In turn, the Mount Elephant stony rises appear significantly more degraded than those of Mount Eccles/Budj Bim (Gillen et al., 2010), which have a reported cosmogenic \(^{21}\)Ne exposure age of 36 ± 6 ka (2σ; Gillen et al., 2010), in agreement with radiocarbon ages of 32–28 ka for Mount Eccles crater lake sediments and post-basaltic swamp deposits (e.g. Builth et al., 2008).

Sample collection and characterisation

determination of robust \(^{40}\)Ar/\(^{39}\)Ar ages requires holocrystalline, unweathered basalt samples with negligible glass in order to minimise excess argon contents, radiogenic argon loss and irradiation-induced recoil issues. Owing to the weathered and highly vesicular nature of the stony rises, lack of road-cuttings through the Widderin lava profile and the absence of significant quarrying activity, accessing material suitable for \(^{40}\)Ar/\(^{39}\)Ar geochronology proved challenging. For the current study, a 1 kg piece of apparently unweathered basalt with minimal vesicle content was carefully selected from a pile of rock extracted during construction of a >6 m-deep well on the Booriyalloak Homestead (37°44′25.2″S; 143°19′49.9″E; 204 m el.).

Petrographic inspection reveals plagioclase (laths up to 4 mm) and olivine phenocrysts set in a finely crystalline groundmass of interlocking plagioclase, clinopyroxene, olivine, magnetite and apatite (Figure 6); olivine is commonly altered to iddingsite, but plagioclase is unaltered. Late-stage feldspathic pools contain apatite and magnetite. Irving and Green (1976) classified the Widderin lava as an olivine tholeiite transitional to olivine basalt and reported a K\(_2\)O content of 1.09 wt%.

Methods

Sample preparation and irradiation

Mount Widderin sample NVP26 was crushed into gravel-sized fragments using a steel jaw crusher. Individual chips were then screened for alteration or large vesicles, and acceptable chips were crushed manually using a steel mortar. Crushed material was washed to remove dust and sieved to 180–250 μm. Following initial concentration by magnetic separation, approximately 500 mg of groundmass material was hand-picked under a binocular microscope. Grains were cleaned ultrasonically using the following procedure: 5% HNO\(_3\) (10 min), 2% HF (1 min), deionised water (10 min) and acetone (5 min). The sample was then loaded into an aluminium foil packet, placed in a quartz tube (UM#61), bracketed by packets containing flux monitor standard Alder Creek Rhyolite sanidine \(1.1811 ± 0.0011\) Ma (2σ; Phillips, Matchan, Honda, & Kuiper, 2016). Can UM#61 was irradiated for 25 min in the Cd-shielded CLICIT facility of the Oregon State University TRIGA reactor.

Analytical procedures

Individual groundmass aliquants of either ~70 or 100 mg were loaded into a custom-made copper sample holder, covered with a ZnS glass disc and loaded into the sample chamber of a gas-handling system connected to a new-generation multi-collector Thermo Fisher ARGUSVI mass spectrometer. This system has been described in detail by Phillips and Matchan (2013), but the line has since been modified to include two additional SAES Zr–Al getters for improved clean-up of gas released by hydrous phases. Following preliminary low-temperature out-gassing to remove the bulk of atmospheric argon, groundmass aliquants were incrementally heated in five to seven steps over the range of 4–30% laser power using a Photon Machines \(^{12}\)CO\(_2\) laser following procedures described by Matchan and Phillips (2014).

Argon isotopic results (Supplementary Paper Table A1) are corrected for system blanks, mass discrimination, radioactive decay and reactor-induced interference reactions. Isotopic results that exclude the interference corrections (as per the recommendation of Renne et al., 2009) are presented in the electronic appendix, alongside blank correction values (Supplementary Paper Table A2). Line blanks were measured after every third or fourth sample analysis. Mass
discrimination and detector bias were characterised via automated analysis of air pipette aliquots prior to the first analysis. Owing to the short irradiation time, it was not feasible to include Ca/K/Cl salts/glasses in the same package. Therefore, correction factors determined for K-glass and Ca-salts contained in another recent package irradiated in the CLICIT facility (UM#58) were used: $^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = (2.5713 \pm 0.0023) \times 10^{-4}$; $^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = (6.6200 \pm 0.0801) \times 10^{-4}$; $^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = (1.00 \pm 0.05) \times 10^{-10}$; $^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}} = (1.2136 \pm 0.0016) \times 10^{-2}$.

The J-value for sample NVP26 [0.0001070135 ± 0.0000000648 (0.061%; 1σ)] was calculated based on an age of 1.1811 ± 0.0011 Ma (2σ) for AC sanidine (Phillips et al. 2016) using the decay constants of Steiger and Jäger (1977) and the Lee et al. (2006) atmospheric argon composition ($^{40}\text{Ar}/^{39}\text{Ar} = 298.56 \pm 0.62$ (2σ)). Calculated uncertainties associated with weighted mean and plateau ages include uncertainties in the J-value, but exclude errors associated with the age of the flux monitor and the decay constant. Unless otherwise stated, uncertainties are reported at the 2σ or 95% confidence level. Plateau ages are defined as including >50% of the total $^{39}\text{Ar}$, from at least three contiguous steps, with $^{40}\text{Ar}^{*}/^{39}\text{Ar}$ ratios within error of the mean at the 95% confidence level (e.g. McDougall & Harrison, 1999).

$^{40}\text{Ar}/^{39}\text{Ar}$ age results

$^{40}\text{Ar}/^{39}\text{Ar}$ age results are summarised in Table 1 and Figure 7, with the full analytical dataset reported as supplementary information (Supplementary Papers Table A1). Step-heating spectra and isochron plots were generated using ISOPLOT/Ex v.3.75 (Ludwig, 2012). Errors associated with individual apparent ages are 0.5–2% (2σ). The age spectra for five aliquants show a general trend of decreasing apparent ages with increasing temperature, with calculated ages ranging from 403–394 ka for the initial step to 375–365 ka at fusion (Figure 7a; Supplementary Papers Figure A1). The exception is aliquant NVP26-2, which shows an initial decrease in apparent age from 402.6 ± 3.6 ka to 388.1 ± 3.8 ka, similar to the other step-heating experiments, before an increase towards 442 ± 17 ka at fusion. Radiogenic $^{40}\text{Ar}$ ($^{40}\text{Ar}^{*}$) yields were typically 35–45% of total $^{40}\text{Ar}$ measured in each experiment. The bulk of the $^{39}\text{Ar}$ (90–95%) was released during the low- to mid-temperature heating steps (4–14% laser power).

Plateau ages were calculated for three of the five aliquants: 391.1 ± 2.4 ka (NVP26-1), 394.4 ± 1.7 ka (NVP26-2), 387.1 ± 1.9 ka (NVP26-3). Calculated total-gas ages are identical, and indistinguishable from corresponding plateau ages at the 2σ level (Table 1). Inverse isochron data reveal a high degree of scatter and yield an apparent trapped $^{40}\text{Ar}^{*}/^{39}\text{Ar}$ ratio of subatmospheric composition ($^{40}\text{Ar}/^{39}\text{Ar} = 295.6 ± 1.6$ (95% CI; MSWD = 3.6); Figure 7b; Table 1). Inverse isochron ages tend to be slightly older than corresponding plateau and total-gas ages but, owing to relatively large associated errors, are not significantly different at the 2σ level (Table 1).
Discussion

Age of Mount Widderin basalt

Step-heating results were analogous for four of five aliquants, reflecting a homogenous groundmass composition. The exception to this was aliquant NVP26-2, where anomalously old apparent ages determined for the high temperature steps likely reflect the release of excess argon from inclusions in phenocrysts out-gassed at high temperature (e.g. olivine/pyroxene). Aliquot NVP26-2 is therefore excluded from subsequent discussion. The monotonic decrease in apparent ages from low to high temperature observed for all other step-heating experiments is characteristic of fine-grained samples that have experienced irradiation-induced recoil of 39Ar and 37Ar between phases with differing K- and Ca-contents (e.g. Jourdan & Renne, 2014; Koppers, Staudigel, & Wijbrans, 2000). This isotopic disturbance is reflected by the scatter of data in argon three-isotope space (Figure 7b; Table 1, MSWD values typically > 1) that precludes calculation of robust inverse isochron results.

Irradiation-induced argon recoil and its implications for the 40Ar/39Ar dating technique has long been recognised (e.g. Huneke & Smith, 1976; Onstott, Miller, Ewing, Arnold, & Walsh, 1995; Turner & Cadogan, 1974). The reaction that produces 39Ar (40K(n,p)39Ar) involves neutrons of sufficiently high energy that the daughter 39Ar atom may be recoiled on the order of 0.1–0.2 μm from the parent 39K atom position (Onstott et al., 1995). The average recoil distance for 37Ar is slightly longer (~0.5 μm) owing to the greater activation energy required for the 40Ca(n,p)37Ar reaction to proceed (Onstott et al., 1995). Although these distances are small, the recoil loss/redistribution of 39ArK and 37ArCa in fine-grained samples can have a significant effect on 40Ar/39Ar apparent ages, especially in the case of Ca-rich samples (e.g. Jourdan & Renne, 2014; Koppers et al., 2000).

The impact of irradiation-induced recoil on argon isotope systematics in basalt groundmass has been studied in detail by Koppers et al. (2000). The redistribution of 39Ar from relatively K-rich phases (e.g. plagioclase/feldspathic mesostasis), which outgas at low temperatures, into K-poor Ca-rich phases (e.g. clinopyroxene), which outgas at higher temperatures, results in lower 39Ar/40Ar ratios for low-temperature steps and concomitantly higher 39Ar/40Ar ratios for high-temperature steps (Koppers et al., 2000). Similarly, the recoil redistribution of 37Ar from Ca-rich to Ca-poor sites results in elevated 39Ar/40Ar and 36Ar/40Ar ratios owing to amplified interference corrections (Koppers et al., 2000).

Taking the simple case of a sample with a uniform trapped component, these competing effects essentially serve to decrease concordancy between data for high and low-temperature steps, affecting calculation of 40Ar/36Ar and 40Ar/39Ar isochron intercept values. It is noted that subatmospheric 40Ar/36Ar values have been reported for some basalts and attributed to isotopic mass fractionation during lava emplacement (e.g. Matsumoto & Kobayashi, 1995; Ozawa, Tagami, & Kamata, 2006). However, in the case of NVP26, the shape of the age spectrum, together with the degree of scatter apparent in argon three-isotope space, implicates recoil-induced isotopic disturbance, such that the absolute 40Ar/36Ar values calculated by inverse isochron analysis are unreliable. Importantly, the inverse isochron data show no evidence for excess argon aside from NVP26-2, such that assumption of a trapped atmospheric composition is valid for calculation of total gas ages.

Assuming that all 39Ar and 37Ar have been retained in the sample, but redistributed between phases (i.e. no net loss), the total gas age should approximate the groundmass crystallisation age (e.g. Jourdan & Renne, 2014). We note that if a slightly subatmospheric 40Ar/36Ar ratio of 295 is assumed, this results in a decrease in apparent ages of 1–3% for the low- to mid-temperature steps (< 14% laser power, containing 90–95% of the 39Ar released) and 5–10% for the higher-temperature steps. Excluding aliquant NVP26-2, a weighted mean total-gas age of 389.0 ± 2.1 ka (0.5% 2σ; MSWD = 1.1)
is calculated. Given the uncertainty surrounding the true composition of the trapped component, which may be slightly subatmospheric, we propose that the error associated with the total-gas age be expanded to 2% to accommodate this uncertainty. Therefore, we propose an age of 389 ± 8 ka (2%; 2σ) for the Widderin basalt.

**Implications for the timing of other volcanism in the region**

The Widderin basalt was previously assigned to the Eccles RLU (Joyce, 1999). However, detailed field observations from the current study suggest that the Widderin lava landform is better classified as part of the Rouse RLU (1–0.2 Ma). The age of the Mount Rouse basalt [284.0 ± 1.4 ka (2σ); Matchan & Phillips, 2014] is closer to the age presented here for Mount Widderin (389 ± 8 ka, 2σ) than cosmogenic exposure ages reported for probable primary lava surfaces for Mounts Eccles, Napier and Porndon in the Eccles RLU (Joyce, 1999), which range from ca 60 to 30 ka (Gillen et al., 2010; Stone et al., 1997).

The stony rises from Mount Elephant appear better preserved than those in the Widderin lava landform, suggesting Mount Elephant significantly younger. Therefore, the Widderin basalt is interpreted to have dammed the northward flowing Elephant basalt, consistent with a topographic cross-section constructed along the Widderin—Elephant basalt outcrop (Supplementary Papers Figure B1). On the basis of field observations, the eruption age of Mount Elephant can be loosely constrained to 390–40 ka (i.e. older than Mount Eccles and younger than Mount Widderin lavas), but future direct \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of ejecta is warranted to better constrain the eruption age of Mount Elephant lavas.

As mentioned earlier, proposed peaks in volcanic activity in the NVP (e.g. Gray & McDougall, 2009) may be an artefact of relatively low sampling density and/or bias owing to consideration of only lava-producing eruptions. We propose that if the eruption histories of specific regions are considered in detail, with attention given to numbers of eruptive units and provenance, together with stratigraphic constraints (e.g. Hare et al., 2005), this may improve understanding of eruption frequency across the province as a whole. We establish a relative age framework for flows in the Hamilton—Skipton—Derrinallum area (Figure 8) using the flow stratigraphy summarised above, referred to the \(^{40}\text{Ar}/^{39}\text{Ar}\) age of 389 ± 8 ka for Mount Widderin reported here, and the \(K–\text{Ar}\) ages of 0.99 ± 0.04 Ma and 2.95 ± 0.16 Ma reported previously for Stockyard Hill and the Terrinallum flow, respectively (Gray & McDougall, 2009). It is readily apparent that in this relatively small area volcanism has been sporadic since ≥3 Ma to 0.389 Ma. This duration of intermittent activity rivals that of the Melbourne area where basalt ages span 4.6–0.7 Ma (Gray & McDougall, 2009).

**Eruption frequency in the Western Plains subprovince**

The age compilation of Gray and McDougall (2009) includes only five eruption centres <0.5 Ma: Mount Rouse, Mount Porndon, Mount Napier, Mount Eccles and Red Rock. Of these, only Mount Rouse has been dated directly (Gray & McDougall, 2009; Matchan & Phillips, 2011, 2014; McDougall & Gill, 1975), with the remainder assigned ages of <0.1 Ma, owing to preservation of lava landforms, an interpretation supported by cosmogenic nuclide exposure dating studies (Gillen et al., 2010; Stone et al., 1997). Interpreting eruption frequency information solely from histograms (e.g. Gray & McDougall, 2009) is not ideal, as slightly altering bin values or adding a small number of data points can dramatically affect the apparent age distribution, especially if the number of data points in each bin is low. We suggest that a more meaningful approach may involve consideration of kernel density estimation (KDE, e.g. Vermeech, 2012) in conjunction with a corresponding probability density plot (PDP). A KDE gives essentially the same frequency summary information as a histogram, but is continuous and thus avoids the under-smoothing issues inherent to histograms (Vermeech, 2012). However, like the histogram, the KDE does not take into account the precision of each datum, and may in fact over-smooth the true age distribution. In contrast, the PDP incorporates age uncertainties and is routinely used for evaluating unimodal geochronological data. However, interpreting a PDP constructed with data from multiple age populations must be done with caution as individual high-precision ages may obscure the true age distribution. Therefore, we propose that the KDE and PDP be considered in tandem to obtain an accurate sense of eruption frequency.

**Figure 8** Summary of relative ages for lavas in the Hamilton—Skitpton—Derrinallum region. Flows with direct age constraints are italicised. The \(K–\text{Ar}\) age for Widderin is from the current study; \(K–\text{Ar}\) ages for the Stockyard Hill and Terrinallum flows are from Gray and McDougall (2009) as reported in the text. Minimum and maximum ages as stratigraphically constrained by MacInnes (1985). The estimated age limits are based on the geomorphological observations of the authors and MacInnes (1985).

---

**Figure 9** shows the KDE and PDP for eruption age dataset reported by Gray and McDougall (2009) for lava flows in the Western Plains subprovince. From the KDE, a peak in activity from ca 3 to 1.4 Ma is apparent, consistent with the conclusion of Gray and McDougall (2009), with an apparent waning in activity after ca 0.9 Ma. However, the addition of a small number \((n=9)\) of published age constraints for maars and scoria cones, together with the new age for Mount Widderin, results in a significant change to the age distribution pattern (Figure 9). Within the limits of the updated dataset, eruption frequency appears to have increased since ca 0.5 Ma (Figure 9). However, the proportion of maars and scoria cones...
with published age constraints is small, and the age distribution may be affected by a bias from studies generally focusing on better-preserved, younger eruption centres. Regardless, we stress that consideration of ages for lava flows alone may give a skewed impression of true age distribution if the dominant eruption style has varied over time (i.e. from effusive to more explosive) as has been suggested in previous studies (e.g. Price, Gray, & Frey, 1997).

Use of volcanic chronology in Quaternary landscape evolution studies

There is scope to extend early ideas based on regolith and drainage mapping undertaken in the 1960s and 1970s (Gibbons & Gill, 1964; Ollier & Joyce, 1964) in the context of neo tectonism and volcanic chronology in the Western Plains. Although the historical seismicity of western Victoria is relatively subdued (e.g. Clarke & McCue, 2003), there is evidence for significant neo tectonic activity (e.g. Joyce, 1975; Paine, Bennetts, Webb, & Morand, 2004; Sandiford, 2003). While most of this activity is considered to have occurred prior to the onset of NVP volcanism (e.g. Paine et al., 2004), there is geomorphic evidence in southwestern Victoria for ~200 m of fault-related uplift of Pliocene shoreline deposits during the Late Neogene, with subsequent faulting between 2 and 1 Ma, as constrained by K–Ar dated lava flows (Sandiford, 2003). There is also evidence for several phases of vertical movement on the north—south-trending Rowsley Scarp (near the Anakies), warping of basalts by monoclonal movement (e.g. Lovely Banks Monocline), and local uplift/faulting related to individual eruption points (Joyce, 1975). Therefore, refining age constraints for <2 Ma eruption centres may improve understanding of the timing of neo tectonic activity in western Victoria. Furthermore, as NVP basalts significantly modified regional drainage patterns (e.g. Raiber & Webb, 2008; Taylor & Gentle, 2002), determining well-constrained eruption ages for key flows may provide useful stratigraphic markers for changes in paleo-environment (e.g. Baker, 2008).

Conclusions

A groundmass sample from the Mount Widderin basalt yields an 40Ar/39Ar eruption age of 389 ± 8 ka (2σ). This age, together with geomorphic observations, reassigns the Widderin lava landform from the Eccles RLU (<0.2 Ma), to the Rouse RLU (1–0.2 Ma). On the basis of field observations, Mount Elephant is inferred to be younger than Widderin and is also reassigned to the Rouse RLU. Construction of a stratigraphic sequence of 15 individual basalt flows in the Hamilton–Skipton–Derrinallum area, anchored to the 40Ar/39Ar age of Mount Widderin and previously published K–Ar ages for two older flows in the area, reveals that volcanism has been intermittent from ≥3 Ma to ≤0.389 Ma. Incorporating the Widderin eruption age and published constraints for scoria cone and maar ages into the compilation of basalt ages presented by Gray and McDougall (2009) for the Western Plains subprovince reveals a significantly different age distribution for volcanic activity in the past 1 Ma from that apparent from lava flow ages alone.

Acknowledgements

This study is supported by Australian Research Council Discovery grant DP130100517 awarded to D. Phillips. S. Szczepanski is thanked for technical assistance in the Noble Gas Laboratory at the University of Melbourne. John and Judith Dawson of Booriyalloak are thanked for their hospitality and assistance with sample collection. The authors acknowledge the constructive comments from A. Chivas and an anonymous reviewer.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

E. L. Matchan http://orcid.org/0000-0003-3098-3039

References

Aziz-ur-Rahman, A., & McDougall, I. (1972). Potassium–argon ages on the Newer Volcanics of Victoria. Proceedings of the Royal Society of Victoria, 85, 61–69.
Baker, H. (2008). 40Ar/39Ar Dating of the Newer Volcanics: Reducing Uncertainties in Victoria’s Sedimentary Record. B.Sc. (Hons) thesis, University of Melbourne, Melbourne (unpubl.).
Birch, W. D., & Henry, D. A. (1993). Phosphate minerals in cave deposits. In W. D. Birch & D. A. Henry (Eds.), Phosphate minerals of Victoria (pp. 121–152). Melbourne Vic: The Mineralogical Society of Victoria Inc., Special Publication No. 3.
Boyce, J. (2013). The Newer Volcanics Province of southeastern Australia: a new classification scheme and distribution map for eruption centres. Australian Journal of Earth Sciences, 60, 449–462.
Ismail, R., Phillips, D., & Birch, W. D. (2013). 40Ar/39Ar dating of alkali feldspar
Irving, A. J., & Green, D. H. (1976). Geochemistry and petrogenesis of the
Gray, C. M., & McDougall, I. (2009). K
Holdgate, G. R., Wallace, M. W., Gallagher, S. J., Witten, R. B., Stats, B., &
Huneke, J. C., & Smith, S. P. (1976). The realities of recoil: 39Ar recoil out of
D
Gillen, D., Honda, M., Chivas, A. R., Yatsevich, I., Patterson, D. B., & Carr, P. F.
Paine, M. D., Bennetts, D. A., Webb, J. A., & Morand, V. J. (2004). Nature and
Ollier, C. D., & Joyce, B. (1976). Geochemistry and petrogenesis of the
Newer Volcanics Province, southeast Australia: implications for eruption frequency.
Australian Journal of Earth Sciences, 52, 41−57.
Harle, K. J., Kershaw, A. P., & Heijnis, H. (1999). The contributions of uranium/thorium and marine palynology to the dating of the Lake Wangoom pollen record, western plains of Victoria, Australia. Quaternary International, 57/58, 25−34.
Holdgate, G. R., Wallace, M. W., Gallagher, S. J., Witten, R. B., Stats, B., & Wagstaff, B. (2006). Cenozoic fault control on ‘deep lead’ palaeoeruvor systems, Central Highlands, Victoria. Australian Journal of Earth Sciences, 53, 445−468.
Holt, S. J., Holford, S. P., & Foden, J. (2014). New insights into the magmatic plumbing system of the South Australian Quaternary Basalt province from 3D seismic and geochemical data. Australian Journal of Earth Sciences, 60, 797−816.
Huneke, J. C., & Smith, S. P. (1976). The realities of recoil; 39Ar recoil out of small grains and anomalous age patterns in 40Ar−39Ar dating. Proceedings of the 7th Lunar Science Conference, Houston, Texas, 15−19 March 1976, pp. 1987−2008.
Irving, A. J., & Green, D. H. (1976). Geochemistry and petrogenesis of the new basalt of Victoria and South Australia. Australian Journal of Earth Sciences, 23, 45−66.
Ismail, R., Phillips, D., & Birch, W. D. (2013). 40Ar/39Ar dating of alkali feldspar megacrysts from selected young volcanoes of the Newer volcanic Province, Victoria. Proceedings of the Royal Society of Victoria, 125, 59−68.
Jourdain, F., & Renne, P. R. (2014). Neutron-induced 39Ar recoil ejection in Ca-rich minerals and implications for 40Ar/39Ar dating. Geological Society, London, Special Publications, 378, 33−52.
Joyce, B. (1975). Quaternary volcanism and tectonics in southeastern Australia. In M. M. Cresswell & R. P. Suggate (Eds). Quaternary studies: selected papers from IX INQUA Congress, Christchurch, New Zealand, 2−10 December 1973, pp. 169−176. Wellington, NZ: Royal Society of New Zealand.
Joyce, E. B. (1992). The West Victorian Uplands of southeastern Australia: origin and history. Earth Surface Processes and Landforms, 17, 407−418.
Joyce, E. B. (1999). A new regolith landform map of the Western Victorian volcanic plains, Victoria, Australia. In G. Taylor & C. Pain (Eds.), Regolith ’98, Australian Regolith & Mineral Exploration, New Approaches to an Old Continent, Proceedings, 3rd Australian Regolith Conference, Kalgoorlie, 2−9 May 1998, pp. 117−126. Perth: CRC LEME.
Koppers, A. P. A., Staudigel, H., & Wijbrans, J. R. (2000). Dating crystalline groundmass separates of altered Cretaceous seamount basalts by the 40Ar/39Ar incremental heating technique. Chemical Geology, 166, 139−158.
Lee, J.-Y., Marti, K., Seeringhaus, J. P., Kawamura, K., Yoo, H.-S., Lee, J. B., Kim, J. S. (2006). A redetermination of the isotopic abundances of atmospheric Ar. Geochimica et Cosmochimica Acta, 70, 4507−4512.
Lister, G. S., & Etheridge, M. A. (1989). Detachment models for uplift and volcanism in the Eastern Highlands and their applications to the origin of passive margin mountains. In R. W. Johnson (Ed.), Intraplate Volcanism in Eastern Australia and New Zealand (pp. 297−313). Cambridge: Cambridge University Press.
Ludwig, K. R. (2012). User’s Manual for Isoplot 3.75. A Geochronological Toolkit for Microsoft Excel, Spec. Publ. No. S. Berkeley, California: Berkeley Geochronology Center, 75 pp.
MacInnes, K. J. (1985). The Newer Volcanics of the Mt Hamilton region in western Victoria. B.Sc. (Hons) thesis, University of Melbourne, Melbourne (unpubl.).
Matchan, E., & Phillips, D. (2011). New 40Ar/39Ar ages for selected young. Quaternary Geochronology, 6, 356−368.
Matchan, E. L., & Phillips, D. (2014). High precision multi-collector 40Ar/39Ar dating of young basalts: Mount Rouse volcano (SE Australia) revisited. Quaternary Geochronology, 22, 57−64.
Matsumoto, A., & Kobayashi, T. (1995). K−Ar age determination of late Quaternary volcanic rocks using the ‘mass fractionation correction procedure’ application to the Younger Ontake Volcano, central Japan. Chemical Geology, 125, 123−135.
McDougall, I., Allsop, H. L., & Chamalaun, F. H. (1966). Isotopic dating of the Newer Volcanics of Victoria, Australia, and geomagnetic polarity epochs. Journal of Geophysical Research, 71, 6107−6118.
McDougall, I., & Gill, E. D. (1975). Potassium−argon ages from the Quaternary succession in the Warrnambool-Port Fairy area, Victoria, Australia. Proceedings of the Royal Society of Victoria, 87 (1−2), 175−178.
McDougall, I., & Harrison, T. M. (1999). Geochemistry and thermochronology by the 40Ar/39Ar method (2nd edition). New York: Oxford University Press.
Ollier, C. D. (1963). The Skipton lava caves. Victorian Naturalist, 80, 181−183.
Ollier, C. D., & Joyce, B. (1964). Volcanic physiography of the Western Plains of Victoria. Proceedings of the Royal Society of Victoria, 77, 357−376.
Ollier, C. D., & Joyce, E. B. (1986). Regolith terrain units of the Hamilton 1:1 000 000 sheet area, Western Victoria. Canberra: Bureau of Mineral Resources, Geology and Geophysics.
Onstott, T. C., Miller, M. L., Ewing, R. C., Arnold, G. W., & Walsh, D. S. (1995). Recoil refinements: Implications for the 40Ar/39Ar dating technique. Geochimica et Cosmochimica Acta, 59, 1821−1834.
Ozawa, A., Tagami, T., & Kamata, H. (2006). Argon isotopic composition of some Hawaiian historical lavas. Chemical Geology, 226, 66−72.
Paine, M. D., Bennetts, D. A., Webb, J. A., & Morand, V. J. (2004). Nature and extent of Pliocene strandlines in southwestern Victoria and their application to Late Neogene tectonics. Australian Journal of Earth Sciences, 51, 407−422.
Paul, B., Hergt, J. M., & Woodhead, J. D. (2005). Mantle heterogeneity beneath the Cenozoic volcanic provinces of central Victoria inferred from trace-element and Sr, Nd, Pb and Hf isotope data. Australian Journal of Earth Sciences, 52, 243−260.
Phillips, D., & Matchan, E. L. (2013). Ultra-high precision 40Ar/39Ar ages for Fish Canyon Tuff and Alder Creek Rhyolite sanidine: new dating standards required? Geochimica et Cosmochimica Acta, 121, 229−239.
Phillips, D., Matchan, E. L., Honda, M., & Kuiper, K. (2016). Reassessment of key 40Ar/39Ar dating standards using high-precision, multi-collector (ARGUSV) mass spectrometry. Geochimica et Cosmochimica Acta (submitted).
Pilkington, E. S., & Segnit, E. R. (1980). Taranakite from the Skipton Caves, Victoria, Australia. *Australian Mineralogist*, 30, 141–143.

Price, R. C., Gray, C. M., & Frey, F. A. (1997). Strontium isotopic and trace element heterogeneity in the plains basalts of the Newer Volcanic Province, Victoria, Australia. *Geochimica et Cosmochimica Acta*, 61, 171–192.

Raiber, M., & Webb, J. A. (2008). Tectonic control of Tertiary deposition in the Streatham Deep-Lead System in western Victoria. *Australian Journal of Earth Sciences*, 55, 493–508.

Renne, P. R., Deino, A. L., Hames, W. E., Heizler, M. T., Hemming, S. R., Hodges, K. V., … Wijbrans, J. R. (2009). Data reporting norms for 40Ar/39Ar geochronology. *Quaternary Geochronology*, 4, 346–352.

Sandiford, M. (2003). Geomorphic constraints on the Late Neogene tectonics of the Otway Range, Victoria. *Australian Journal of Earth Sciences*, 50, 69–80.

Sherwood, J., Oyston, B., & Kershaw, A. (2004). The age and contemporary environments of Tower Volcano, South West Victoria, Australia. *Proceedings of the Royal Society of Victoria*, 116, 69–76.

Skeats, E. W., & James, A. V. G. (1937). Basaltic barriers and other surface features of the Newer Basalts of western Victoria. *Proceedings of the Royal Society of Victoria*, 49, 245–278.

Smith, B. W., & Prescott, J. R. (1987). Thermoluminescence dating of the eruption at Mt Schank, South Australia. *Australian Journal of Earth Sciences*, 34, 335–342.

Steiger, R. H., & Jäger, E. (1977). Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, 36, 359–362.

Stone, J., Peterson, J. A., Fifield, L. K., & Cresswell, R. G. (1997). Cosmogenic chlorine-36 exposure ages for two basalt flows in the Newer Volcanics Province, western Victoria. *Proceedings of the Royal Society of Victoria*, 109, 121–131.

Taylor, D. H., & Gentle, L. V. (2002). Evolution of deep-lead palaeodrainages and gold exploration at Ballarat, Australia. *Australian Journal of Earth Sciences*, 49, 869–878.

Turner, G., & Cadogan, P. H. (1974). Possible effects of 39Ar recoil in 40Ar–39Ar dating. *Proceedings of the Fifth Lunar Science Conference*, 1601–1615. Houston Texas, 18–22 March 1974.

VandenBerg, A. H. M. (1997). *Ballarat SJ 54-8 Edition 2, 1:250 000 Geological Map*. Melbourne: Geological Survey of Victoria.

Vermeesch, P. (2012). On the visualisation of detrital age distributions. *Chemical Geology*, 312–313, 190–194.

Vogel, D. C., & Keays, R. R. (1997). The petrogenesis and platinum-group element geochemistry of the Newer Volcanic Province, Victoria, Australia. *Chemical Geology*, 136, 181–204.

Wagstaff, B. E., Kershaw, A. P., O’Sullivan, P. B., Harle, K. J., & Edwards, J. (2001). An Early to Middle Pleistocene palynological record from the volcanic crater of Pejark Marsh, western plains of Victoria, southeastern Australia. *Quaternary International*, 83–85, 211–232.