Mixing between enriched lithospheric mantle and crustal components in a short-lived subduction-related magma system, Dry Valleys area, Antarctica: Insights from U-Pb geochronology, Hf isotopes, and whole-rock geochemistry

Graham Hagen-Peter1, John M. Cottle1, Andrew J. Tulloch2, and Simon C. Cox2
1DEPARTMENT OF EARTH SCIENCE, UNIVERSITY OF CALIFORNIA, SANTA BARBARA, CALIFORNIA 93106-9630, USA
2INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES, PRIVATE BAG 1930, DUNEDIN 9054, NEW ZEALAND

ABSTRACT

Granitoids associated with the Neoproterozoic–early Paleozoic Ross orogeny are extensively exposed in the Dry Valleys region of southern Victoria Land, Antarctica, affording an exceptional opportunity to gain insight into the temporal and spatial scales of continental arc magmatism. Samples spanning 150 km along strike and 50 km across strike were selected for isotopic and geochemical analysis. Zircon U-Pb geochronology and the first Hf isotope data for Dry Valleys granitoids, coupled with whole-rock elemental data, reveal mixing between enriched lithospheric mantle and Precambrian crustal components and indicate that the principal phase of magmatism in the Dry Valleys area was restricted to a period of 23 m.y., from ca. 515 to 492 Ma. This relatively short period of magmatism contrasts with other segments of the Ross orogen, in which magmatism spanned greater than 100 m.y. Most calc-alkaline intrusions spanned 515–500 Ma, while postkinematic granitoids with alkali-calcic geochemical signatures spanned 505–492 Ma, indicating a transitional shift to an overall extensional tectonic regime. Zircon $\epsilon_{\text{Hf}}$ values range between ~0.3 and ~72, with two-stage depleted-mantle model ages ranging from 1.5 to 1.9 Ga. Low $\epsilon_{\text{Hf}}$ values in mafic samples are consistent with derivation from an enriched subcontinental lithospheric mantle source, while the large-volume granitic intrusions show evidence for increasing assimilation of old crust over time. A broadening of the $\epsilon_{\text{Hf}}$ range to more negative values in the younger intrusions may reflect crustal thickening or underplating of fertile continental material into the source region of the arc.

INTRODUCTION

Subduction zones control the generation and recycling of much of Earth’s crust. Petrogenetic and geochronologic studies of magmatism at convergent margins play an important role in understanding the rates and relative importance of such processes. The structure of active continental arcs can be studied using geophysical techniques, and igneous processes through volcanism, but information about the dynamics of magmatic processes at deeper crustal levels is largely absent. It is also impossible to study the entire sequence of magmatism, from initiation to termination, in active systems. Extensively exposed midcrustal igneous rocks in the Dry Valleys area of southern Victoria Land, Antarctica, yield insights into the timing, duration, and source of an exhumed subduction-related magmatic system.

The Ross orogen in the Transantarctic Mountains forms the boundary between the Proterozoic and Archean East Antarctic craton and the amalgamated terranes of West Antarctica (Fig. 1; Dalziel and Elliot, 1982; Borg and DePaolo, 1991; Goodge et al., 1993b; Stump, 1995). A geochemically diverse suite of igneous rocks in the southern Victoria Land segment of the orogen records a history of magmatism that resulted from westward subduction of paleo–Pacific oceanic lithosphere beneath the East Gondwana margin during the Neoproterozoic–Ordovician (Borg et al., 1987; Borg and DePaolo, 1991; Dalziel, 1992; Smillie, 1992; Allibone et al., 1993a, 1993b; Stump, 1995; Encarnación and Grunow, 1996; Cox et al., 2000; Stump et al., 2006). Large volumes of plutonic rocks are especially well exposed in the Dry Valleys area of southern Victoria Land, which is the largest ice-free area on the continent.

Magmatism in the Dry Valleys is thought to have spanned ~45 m.y., from 530 to 485 Ma (summarized in Allibone and Wysoczanski, 2002), but with few broad geochronology studies, ages for plutons are currently limited, and thus our understanding of the timing and duration of magmatism in the Dry Valleys remains incomplete. Here, we present zircon U-Pb ages, hafnium (Hf) isotope compositions and model ages, and whole-rock major- and trace-element geochemistry for 31 samples spanning 150 km along strike and 50 km across strike of the Ross orogen (Fig. 1), including the ~1000 km² Bonney Pluton. Specifically, we aim to place further constraints on the timing and duration of magmatism as well as potential magma source(s) and their evolution through time. Our new data indicate that most of this batholith-scale intrusive system was constructed in only ~23 m.y. from 515 to 492 Ma. An enriched subcontinental lithospheric mantle may have been the primary source of the mafic intrusions, but recycling of Proterozoic continental crust played a significant role in the evolution of the larger granitic plutons.

GEOLOGIC BACKGROUND

The Ross orogen is a continental arc that is thought to have been constructed on the attenuated margin of the Archean and Proterozoic East Antarctic craton (Grindley and McDougall, 1969; Borg et al., 1990; Finn et al.,
Mixing between mantle and crustal components in subduction-related magmatism | RESEARCH

Mackay Glacier

Raft Valley

Taylor Valley

Ferrar Glacier

Ross Sea

Dry Valleys

McMurdo Station

Ross Ice Shelf

-central Transantarctic Mountains

northern Victoria Land

southern Victoria Land

central Transantarctic Mountains

Figure 1. Location map of the Transantarctic Mountains (inset) showing the different physiographic segments and the study area. The box surrounding the Dry Valleys area is enlarged in a geologic map modified from Cox et al. (2012). The geologic map shows the distribution of the three Dry Valleys (DV) igneous suites, with the metamorphic country rock and younger sedimentary and volcanic rocks omitted to emphasize the distribution of intrusive rocks. The locations of samples from this study are marked by stars, color-coded according to DV suite.
with contraction across the arc and amphibolite-facies metamorphism and postdate the DV1 suites, with a youngest U-Pb age of ca. 530 Ma and 490 Ma, whereas the DV2 intrusions largely postdate the DV1 suites, with a youngest U-Pb age of ca. 485 Ma (Encarnación and Grunow, 1996). Allibone and Norris (1992) concluded that relatively small volumes of anatectic melt (“microplutons” ≤ 50 m across) could not have contributed significantly to the larger-scale Granite Harbour plutons; however, it is possible that assimilation of anatectic melt(s) occurred at deeper, unexposed crustal levels.

Within the Dry Valleys area of southern Victoria Land, plutonic rocks of the Granite Harbour intrusives are hosted in metamorphic rocks of the Devonian–Triassic Beacon Supergroup (McKelvey et al., 1970; summarized in Barrett, 1981), and both are intruded by Ferrar dolerite sills associated with the breakup of Gondwana in the Jurassic (Heinmann et al., 1994; Encarnación et al., 1996). Rose-age crystalline basement is now exposed in the rift-shoulder of the Cenozoic extension-related Transantarctic Mountains (Gleadow and Fitzgerald, 1987).

Extensive geochronologic and isotopic studies of granitoids from northern Victoria Land and central Transantarctic Mountains have resulted in various tectonic models for the evolution of the Gondwana margin in the Neoproterozoic and early Paleozoic (e.g., Borg et al., 1990; Borg and DePaolo, 1991; Rocchi et al., 1998; Goodge et al., 2012). The Sr and Nd isotopic compositions of plutonic rocks and their host metasedimentary rocks in southern Victoria Land have been reported by various workers (Borg and DePaolo, 1994; Hall et al., 1995; Cooper et al., 1997; Cox et al., 2000; Read et al., 2002; Mellish et al., 2002; Cottle and Cooper, 2006a, 2006b). Extensive exposures of metamorphic and granitic basement in southern Victoria Land provide an opportunity for a more detailed geo-chronologic and isotopic study.

Plutonic rocks constitute ~70% of exposed pre-Devonian basement in the Dry Valleys (DV, Fig. 1). The granitoids, consisting of ~40–50 plutons over an area greater than 5000 km² (Fig. 1; Forsyth et al., 2002; Cox et al., 2012), have been divided into three magmatic suites based on intrusion characteristics, deformation style, and composition (Smillie, 1992; Allibone et al., 1993b). Based on field relationships and whole-rock geochemistry, these workers interpreted the DV1a and DV1b suites as subduction-related units, with the subsequent DV2 suite generated in an extensional regime after the cessation of subduction. Though the classification of all of the plutonic rocks in the Dry Valleys into three suites may be a simplification, the DV1a, DV1b, and DV2 suite divisions are a useful framework for the discussion of the samples from this study.

Limited geochronology suggests that the DV1a and DV1b suites overlap in age and were emplaced between ca. 530 Ma and 490 Ma, whereas the DV2 intrusions largely postdate the DV1 suites, with a youngest U-Pb zircon age of ca. 485 Ma (Encarnación and Grunow, 1996; Allibone and Wysockzanski, 2002). The largest DV1a pluton (Bonney Pluton) was emplaced at a midcrustal level (4.2 kbar or ~15 km depth), synchronous with contraction across the arc and amphibolite-facies metamorphism of the Skelton Group host metasediments (Allibone et al., 1993a; Cox, 1993). Subsequent emplacement of the DV2 suite occurred at progressively shallower crustal levels during extension and exhumation, with late-stage porphyry dikes recording pressures as low as 1.2 kbar (~4 km depth; Allibone et al., 1993a). The distinctive compositions and contrasting styles of deformation of various units in the Dry Valleys suggest that the Ross orogen probably developed through several distinct tectono-magmatic phases during the Neoproterozoic through Early Ordovician (Encarnación and Grunow, 1996).

METHODS

Thirty-one samples ranging from gabbro to granite were selected with an effort to target representative rock types for each suite and to sample the largest-scale intrusions. Here, we offer an abbreviated explanation of the methods employed in this study. A thorough description of the analytical details is provided in the GSA Data Repository.

Whole-rock major- and trace-element geochemistry was measured by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (ICP-MS) and used to distinguish samples based on composition and to correlate samples to the specific DV igneous suites of Smillie (1992) and Allibone et al. (1993b).

We employed zircon U-Pb geochronology by laser-ablation–multicollector (MC)–ICP-MS to determine the crystallization ages of individual bodies and constrain the duration of magmatism in the Dry Valleys area during the Ross orogeny. Zircon separates were mounted in epoxy disks, polished to reveal medial sections, and imaged by scanning electron microscope with a cathodoluminescence (CL) detector (Fig. 2). Images were used to guide the placement of spots for laser ablation, with care taken to avoid overlapping multiple growth domains or inherited cores, though in some cases it was impossible to avoid overlapping distinct CL domains (e.g., sample P49944 in Fig. 2). A Photon Machines short-pulse width (~4 ns), 193-nm-wavelength excimer laser was used to ablate spots of 24–30 μm diameter, and 238U, 232Th, 208Pb, 206Pb, and 206Pb( + Hg) were measured with a Nu Instruments Nu Plasma high-resolution MC-ICP-MS at the University of California, Santa Barbara. The Lu-Hf-Yb isotope compositions of the same zircons were measured by MC-ICP-MS in later analytical sessions. Laser-ablation spots for Lu-Hf-Yb measurements were 53 μm in diameter and overlapped those used in the U-Pb age determinations (Fig. 2). Age data were coupled to Hf isotopes and whole-rock geochemistry to identify temporal shifts in magma sources and evolutionary trends.

The Hf isotope system has become an important tracer for crustal evolution and magma source studies. Due to the stronger partitioning of Lu relative to Hf in the mantle during differentiation processes and the radioactive decay of 182Hf to 182W, over time, the 176Hf/177Hf of the depleted mantle increases relative to the crust (Patchett and Tatsumoto, 1980; Patchett et al., 1981; Patchett, 1983). In a way, this system is analogous to the Sm-Nd system. However, in situ analyses of Hf isotopes in individual growth zones of zircons may record processes such as magma mixing or country rock assimilation that changed the isotopic composition of the reservoir from which the zircons crystallized (e.g., Griffin et al., 2002; Hawkesworth and Kemp, 2006). Additionally, the physical robustness of zircon makes it less susceptible to the open-system behavior sometimes observed in whole-rock Sm-Nd (e.g., Moorbath et al., 1997), and commonly in Rb-Sr (e.g., Field and Råheim, 1979; Ramos et al., 2005).

1GSA Data Repository Item 2015047, detailed description of analytical methods, data tables, cathodoluminescence images, concordia diagrams, and U-Pb age distributions, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
Zircon readily incorporates Hf into its structure (routinely >1 wt%) and has a low Lu/Hf ratio (Ahrens and Erlank, 1969; Hoskin and Schaltegger, 2003; Hawkesworth and Kemp, 2006); thus (assuming no fractionation of Hf isotopes during crystallization), the Hf composition of a zircon approximates that of the reservoir from which it crystallized. Unlike trace-element patterns, which are affected by fractional crystallization/melting processes, Hf isotopes in zircon may reflect the composition of the source if open-system processes such as contamination and magma mixing are minimal during the evolution of the magma. In a gross sense, large positive $\varepsilon_{206}$Hf values (the $^{176}$Hf/$^{177}$Hf in the sample at the time of crystallization relative to the chondritic uniform reservoir) indicate a depleted-mantle source for the sample, while a negative $\varepsilon_{206}$Hf value suggests a significant recycled crust component (Vervoort and Blecht-Toft, 1999; Belousova et al., 2005, 2010).

Depleted-mantle model ages ($T_{DM}$) provide an estimated time of separation of a crustal magma source from a depleted-mantle reservoir. Details of the principles behind the calculation of depleted-mantle model ages ($T_{DM}$) and two-stage depleted-mantle model ages ($T_{DM}^{2}$) are described thoroughly in DePaolo et al. (1991), and, as applies to Hf isotopes, in Griffin et al. (2000, 2002). It is important to note that model ages involve several untestable assumptions that may significantly affect the calculated "crustal separation age." Two fundamental assumptions are: (1) that the crustal source of a melt separated from a reservoir that followed the $^{176}$Hf/$^{177}$Hf evolution curve by the depleted-mantle model parameters (present-day $^{176}$Hf/$^{177}$Hf = 0.28325; $^{176}$Lu/$^{177}$Lu = 0.0384; Griffin et al., 2000, 2002), and that (2) the crustal source evolved along the $^{176}$Hf/$^{177}$Hf trajectory of "average crust," with $^{176}$Lu/$^{177}$Hf = 0.015 (Griffin et al., 2002). The latter assumption is specific to $T_{DM}^{C}$. Model ages are often interpreted to represent a minimum age because any contamination from a more radiogenic (higher $^{176}$Hf/$^{177}$Hf) mantle component or younger crustal component would drive the resulting isotope composition toward a younger model age. Because of these major assumptions, the model ages presented in this study are considered only very general estimates of the age of crust underlying the Ross orogen.

RESULTS

Major- and Trace-Element Geochemistry

The XRF geochemical data for each dated sample (except for two, for which there was no additional material to analyze) are given in the GSA Data Repository (see footnote 1) and are displayed on discriminant diagrams in Figure 3. The whole-rock composition data presented here are a combination of those from Allibone et al. (1993b), Forsyth et al. (2002), and from this study. See Allibone et al. (1993b) for a comprehensive geochemical data set for Dry Valleys samples. Sample locations and brief descriptions of the rock types can be found in Table 1. Additional information on the samples from this study is available in the New Zealand Institute of Geological and Nuclear Science (GNS) rock and mineral database (www.pet.gns.cri.nz).

Considerable scatter on the Harker diagrams in Figure 3 precludes a simple cogenetic relationship of samples assigned to each suite, while there is also considerable overlap between the different suites. This demonstrates the need for caution when interpreting the samples in the framework of magmatic suites with distinct sources and evolutionary trends. It should also be noted that the original DV suite subdivision of Allibone et al. (1993b) was primarily for samples with >60 wt% SiO$_2$; therefore, the suite assignment of mafic (<60 wt% SiO$_2$) samples from this study should be considered tentative. However, the major conclusions drawn in this study do not change significantly when the data are interpreted independently of the suite framework.

$DV_{1a}$

The DV$_{1a}$ samples from this study range in SiO$_2$ content from ~50 to 70 wt%. On Harker diagrams, DV$_{1a}$ samples display steep negative slopes for Al$_2$O$_3$, MgO (not shown in Fig. 3), and CaO. The Na$_2$O contents are relatively constant, while K$_2$O increases with increasing SiO$_2$ content. The DV$_{1a}$ suite generally has higher Na$_2$O and lower K$_2$O than the DV$_{1b}$ and DV$_2$ suites. There is a wide range in the concentration of the trace elements Y, Sr, Rb, Zr, and Ba, with no strong correlation to SiO$_2$ content (except in Sr). DV$_{1a}$ samples have Sr/Y ratios (not shown in Fig. 3) similar to DV$_2$ samples and lower than most DV$_{1b}$ samples. The evolved DV$_{1a}$ samples typically plot near the boundary of the metaluminous and peraluminous fields, within the continental arc granitoid field (Fig. 3; Maniar and Piccoli, 1989). On tectonic discrimination diagrams (Fig. 3), the samples overlap the boundary of I&K-type and A-type granitoids on the diagram of Whalen et al. (1987) and plot within the "volcanic arc granitoids" (VAG) field on the diagram of Pearce et al. (1984).

$DV_{1b}$

The DV$_{1b}$ samples from this study are all highly evolved, with a restricted range in SiO$_2$ from ~70 to 75 wt% and major-element oxides that largely overlap with the evolved DV$_{1a}$ and DV$_2$ samples. These samples have greater K$_2$O/Na$_2$O ratios than most DV$_{1a}$ samples and are distinguished from evolved DV$_2$ samples by generally higher Ba and Sr and...
Figure 3. Composition data for the dated samples on variation diagrams compare and contrast the chemical characteristics of the Dry Valleys (DV) igneous suites. On some variation diagrams, samples show coherent trends (e.g., CaO vs. SiO₂), suggesting cogenetic relationships, but significant dispersion on others precludes a simple liquid line of descent for the evolution of the suites. Remelting, mixing of source components, and contamination are more viable mechanisms for the geochemical diversity of the suites. Only samples with greater than 60 wt% SiO₂ are plotted on tectonic variation diagrams of Maniar and Piccoli (1989), Pearce et al. (1984), and Whalen et al. (1987). Abbreviations for different fields are as follows: postorogenic granitoids (POG), continental arc granitoids (CAG), continental collision granitoids (CCG), syncollisional granites (syn-COLG), within-plate granites (WPG), volcanic arc granites (VAG), and ocean-ridge granites (ORG). Major oxide concentrations are in wt%; trace elements are in ppm.
low Zr and Y. The DV1b samples are weakly peraluminous and primarily plot within the I&S-type granitoid and volcanic arc granitoids fields on tectonic discrimination diagrams (Fig. 3).

**DV2**

The DV2 suite samples range in SiO₂ content from ~48 to 75 wt%, with major oxides that largely overlap with DV1a and DV1b samples at high SiO₂ content. Two primitive DV2 samples have lower Al₂O₃ and CaO and slightly higher K₂O and Rb than DV1a samples of comparable SiO₂ content. Evolved DV2 samples are enriched in Y and Zr and depleted in Sr and Ba relative to most other samples. They typically have high K/Na₂O and low Sr/Y (not shown in Fig. 3) ratios relative to DV1a and DV1b samples, respectively. Evolved samples plot near the boundary of the metaluminous and peraluminous fields, within the overarching continental arc granitoid and postorogenic granitoid fields (Fig. 3). They plot near the boundary between the I&S-type and A-type fields and within the volcanic arc granitoids field on tectonic discrimination diagrams.

**Tentative DV2**

Three samples from Miers Valley, in the southern end of the study area (Fig. 1), are tentatively assigned to the DV2 suite based on composition and field characteristics (Simpson and Aslund, 1996; Cox et al., 2012). These samples are relatively primitive (49–56 wt% SiO₂), Ca-poor, and alkali-rich samples. They have high Ba, Sr, and Zr and low Y concentrations. They have some chemical characteristics similar to the DV1b suite, most notably very high Sr/Y ratios. These samples are all relatively primitive (49–56 wt% SiO₂) and are not plotted on the tectonic discrimination diagrams that were devised for granitoids. However, the alkali-rich nature of these samples is consistent with the other DV2 samples and the inter-

### TABLE 1. SUMMARY OF U-Pb AND Hf ISOTOPE RESULTS

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Pluton name*</th>
<th>Rock description</th>
<th>Location</th>
<th>Devonian age (Ma)</th>
<th>Uncertainty (m.y.)</th>
<th>n</th>
<th>MSWD</th>
<th>εHf(i)</th>
<th>TDM (Ga)</th>
<th>TDM (Ga) Lat</th>
<th>RESEARCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>P68760*</td>
<td>Discovery</td>
<td>Granite</td>
<td>76.93 162.47</td>
<td>500.1 6.6 18 1.6</td>
<td>-3.7 1.4 10 0.8</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P64403</td>
<td>Unassigned Homblende (hbl) gabbro</td>
<td>77.33 162.82</td>
<td>501.9 6.4 20 1.6</td>
<td>-0.6 1.5 10 0.5</td>
<td>1.1 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68770</td>
<td>Discovery</td>
<td>Weakly foliated granite</td>
<td>76.89 162.25</td>
<td>504.8 7.0 14 2.8</td>
<td>-5.2 1.4 9 0.5</td>
<td>1.3 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68782</td>
<td>Discovery</td>
<td>Weakly foliated granite</td>
<td>76.90 162.39</td>
<td>506.4 6.4 16 1.0</td>
<td>-3.5 1.7 8 1.2</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68681</td>
<td>Discovery</td>
<td>Massive hbl diorite</td>
<td>76.88 162.48</td>
<td>507.8 6.4 20 1.5</td>
<td>-0.3 1.5 12 0.8</td>
<td>1.1 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P49944</td>
<td>Bonney</td>
<td>Quartz monzodiorite</td>
<td>77.57 161.63</td>
<td>508.9 6.4 23 1.3</td>
<td>-2.0 1.3 10 1.2</td>
<td>1.2 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68860</td>
<td>Discovery</td>
<td>Folated hbl tonalite</td>
<td>76.88 162.48</td>
<td>509.4 6.6 17 1.9</td>
<td>-3.5 1.6 8 1.2</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P62321</td>
<td>Flint</td>
<td>Folated diorite</td>
<td>77.53 162.96</td>
<td>509.5 6.3 20 1.1</td>
<td>-1.1 1.2 12 0.4</td>
<td>1.1 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68787</td>
<td>Discovery</td>
<td>Hbl monzodiorite</td>
<td>76.87 162.35</td>
<td>511 6.4 28 2.2</td>
<td>-2.4 1.4 12 0.9</td>
<td>1.2 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68234</td>
<td>Denton</td>
<td>Folated diorite</td>
<td>77.54 162.90</td>
<td>515.4 6.6 28 1.3</td>
<td>-1.7 1.1 12 0.9</td>
<td>1.2 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P64422</td>
<td>Brownworth</td>
<td>Hbl diorite</td>
<td>77.48 162.82</td>
<td>493.2 6.1 35 0.8</td>
<td>-1.8 1.2 12 1.5</td>
<td>1.1 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68826</td>
<td>Darkowski</td>
<td>Pink granite</td>
<td>77.78 162.64</td>
<td>495.5 6.1 25 1.2</td>
<td>-5.9 1.1 12 0.5</td>
<td>1.3 1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P62101</td>
<td>Harker (?)</td>
<td>Granite</td>
<td>77.23 162.07</td>
<td>495.1 6.1 25 1.2</td>
<td>-5.9 1.1 12 0.5</td>
<td>1.3 1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68775</td>
<td>Gonville &amp; Caius</td>
<td>Granite</td>
<td>76.94 162.16</td>
<td>495.9 6.2 30 2.0</td>
<td>-4.6 1.2 12 0.9</td>
<td>1.3 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68844</td>
<td>Gonville &amp; Caius</td>
<td>Hbl granite</td>
<td>76.95 162.25</td>
<td>496.1 6.1 26 1.2</td>
<td>-4.5 1.3 12 0.8</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68442</td>
<td>Gonville &amp; Caius</td>
<td>Hbl granite</td>
<td>76.95 162.27</td>
<td>496.8 6.1 28 1.0</td>
<td>-5.6 1.3 10 1.3</td>
<td>1.3 1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P62293</td>
<td>Brownworth</td>
<td>Megacrystic granite</td>
<td>77.37 163.01</td>
<td>496.9 6.2 22 1.7</td>
<td>-4.2 1.5 12 0.7</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68802</td>
<td>Lion Island</td>
<td>Pink granite</td>
<td>76.81 162.44</td>
<td>497.1 6.2 29 1.4</td>
<td>-2.4 1.1 10 1.3</td>
<td>1.2 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68843</td>
<td>Gonville &amp; Caius</td>
<td>Porphyritic granite</td>
<td>76.95 162.29</td>
<td>504.2 6.4 19 0.9</td>
<td>-3.6 1.2 10 0.7</td>
<td>1.2 1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P68878</td>
<td>Mt. Perseverance</td>
<td>Porphyritic diorite dike</td>
<td>76.80 162.14</td>
<td>505 6.5 18 1.5</td>
<td>-2.1 1.5 8 1.4</td>
<td>1.2 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: MSWD—mean square of weighted deviates; TDM—depleted-mantle model age; TDM*—two-stage depleted-mantle model age.

*Pluton names are from Cox et al. (2012).

†Uncertainties on mean ages are quadratic additions of the internal 2 standard error (S.E.) and external uncertainty estimated from the reproducibility of the GJ-1 and Pleisiochrome reference zircons. Uncertainties on εHf(i) are reported as the 2 S.E. of the population of analyses used in the calculation. Hf(i) are weighted mean values of multiple measurements of a population from each sample.

‡Uncertainties on mean ages are quadratic additions of the internal 2 standard error (S.E.) and external uncertainty estimated from the reproducibility of the GJ-1 and Pleisiochrome reference zircons. Uncertainties on εHf(i) are weighted mean values of multiple measurements of a population from each sample.

*Samples with prefix “P” are housed in the New Zealand Institute of Geological and Nuclear Science (GNS) PETLAB database (www.pet.gns.cri.nz).

††A mean age could not be calculated for sample P64424, but individual spot ages were used to calculate εHf(i).

‡‡N.D.—no data.

εHf(i) are reported as the 2 S.E. of the population of analyses used in the calculation.

Mixing between mantle and crustal components in subduction-related magmatism | RESEARCH
pretation of Smillie (1992) and Allibone et al. (1993b) that the DV2 suite represents post-tectonic magmatism in the Dry Valleys area.

U-Pb Geochronology

The U-Pb ages and Hf isotope populations for all of the samples from this study are summarized in Table 1. The ages are presented as $^{206}\text{Pb}/^{238}\text{U}$ weighted mean ages. They are categorized by suite to emphasize the timing and duration of magmatism. For several samples, the mean square of weighted deviates (MSWD) of the analyses used in the age calculation is greater than that expected for a single population given the sample size. This indicates that either the uncertainties assigned to each individual data point are underestimated, or that the data used in the weighted mean may not be representative of a single population; that is, there is geologic significance to the scatter in the data (Wendt and Carl, 1991). Given that repeated measurements of secondary reference materials returned a mean age within uncertainty of the reference isotope dilution–thermal ionization mass spectrometry (ID-TIMS) age and an MSWD of near 1 (Fig. 4), we are confident that the uncertainty assigned to each data point is appropriate, and therefore samples with MSWD values $>1$ likely represent minor inheritance and/or Pb loss. We take the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages reported in Table 1 as the best estimates of the crystallization ages of the samples.

The samples range in age from 515.4 ± 6.6 Ma to 492.2 ± 6.1 Ma. Ages from the DV1a suite range between 515.4 ± 6.6 Ma and 500.1 ± 6.6 Ma (10 samples). Only one reliable age of 508.9 ± 6.4 Ma was obtained for a sample from the regionally extensive Bonney Pluton. Four of six DV1b samples yielded robust ages, ranging from 515.3 ± 6.4 Ma to 500.6 ± 6.6 Ma. Sixteen samples from the DV2 suite range between 505.0 ± 6.5 Ma and 492.2 ± 6.1 Ma. Concordia diagrams and $^{206}\text{Pb}/^{238}\text{U}$ age distributions of several samples are shown in Figure 5. These examples demonstrate the issue of Proterozoic and “young” (ca. 550 Ma) inheritance present in some samples, the origin of which is discussed further in a following section.

Hf Isotopes

The samples from this study have a restricted range of $\varepsilon_{\text{Hf}}$ values between $-0.3$ and $-7.2$ (Table 1; Fig. 6), with values overlapping for all of the suites. The DV1a suite ranges from $-0.3$ to $-3.7$. The DV1b suite ranges between $-1.4$ and $-7.2$. The DV2 samples range from $-1.8$ to $-5.9$. The oldest DV1a and DV1b samples have a restricted range of $\sim 3$ $\varepsilon_{\text{Hf}}$.

Figure 4. Results of the secondary reference zircons analyzed throughout the sessions when the Dry Valleys (DV) samples were measured spanning many months on concordia diagrams (left) and $^{206}\text{Pb}/^{238}\text{U}$ age distributions (right). These data provide estimates for the accuracy and external precision of our analyses. Both reference zircons were reproduced very accurately, within $<1\%$ of the “true” ages (GJ-1 = 601.7 Ma—Condon, personal commun.; Plešovice = 337.1 Ma—Sláma et al., 2008). The external reproducibility was $1.1\%–1.3\%$ (2 standard deviation [S.D.]); this was propagated into the uncertainty of the final $^{206}\text{Pb}/^{238}\text{U}$ weighted mean ages for the DV samples. MSWD—mean square of weighted deviates.
Figure 5. Examples of the U-Pb data from several representative Dry Valleys (DV) samples. The inverse concordia diagrams on the left show all of the analyses for each sample. The inverse concordia insets and $^{206}$Pb/$^{238}$U age distributions on the right show the analyses used in the calculation of the weighted mean ages reported in Table 1. $n$—number of analyses used in the age calculations (out of a total of 30–40 spots per sample). These examples are meant to demonstrate the occurrence of clear Proterozoic (P68770 and P68851) and likely “young” (P62293 and P68851) inheritance in some of the samples. There is also some evidence of common Pb and Pb loss in the first two samples. Note that inheritance is not ubiquitous among the samples from this study, though zircon cathodoluminescence domains that appeared to be inherited were generally avoided. Similar diagrams for all samples can be found in the GSA Data Repository (see text footnote 1). MSWD—mean square of weighted deviates.
DISCUSSION

Here, we discuss the interpretation of the U-Pb and Hf isotope data with respect to the timing and duration of magmatism and the potential source(s) for the Dry Valleys granitoids.

Timing and Duration of Magmatism in the Dry Valleys

Previously reported U-Pb zircon ages for intrusive rocks from the Dry Valleys area suggest that magmatism spanned ca. 530–485 Ma (Encarnación and Grunow, 1996; Cox et al., 2000; Allibone and Wysockanski, 2002). On Mount Morning, ~70 km southeast of the Ferrar Glacier (Fig. 1), Martin et al. (2014) identified felsic granulite xenoliths (hosted in Cenozoic volcanic rocks) with DV suite geochemical affinities. They reported an age of ca. 545 Ma for one granulite xenolith with DV1b geochemical affinity, suggesting that subduction-related magmatism had commenced by this time in southern Victoria Land (Martin et al., 2014). Our samples do not represent the entire range of magmatism in this area during the Ross orogeny, with an oldest and youngest age of ca. 515 Ma and 492 Ma, respectively (Fig. 7). Allibone and Wysockanski (2002) reported ages of 531 ± 10 Ma and 516 ± 10 for small orthogneiss bodies with DV1b suite affinity. Encarnación and Grunow (1996) reported an age of 484 ± 7 Ma for a DV2 plagioclase-porphryry dike. These bodies are inferred to be volumetrically insignificant, composing <1% of the area of exposed basement rocks mapped in southern Victoria Land (Cox et al., 2012). All other U-Pb zircon ages for DV suite granitoids (summarized in Allibone and Wysockanski, 2002) fall within the 515–492 Ma range represented by the samples from this study. One sample from the large Bonney Pluton yielded a robust age of 508.9 ± 6.4 Ma, which is consistent with ages of samples from other parts of the pluton, including ca. 505 Ma ages reported by Encarnación and Grunow (1996) and Cox et al. (2000) and an age of 499 ± 6 Ma from Allibone and Wysockanski (2002). The four ages from this pluton agree within uncertainty, but the dispersion in the mean ages may reflect its composite emplacement. Our samples are not distributed evenly across the entire Dry Valleys area (Fig. 1), however; we targeted the largest plutons, including the Bonney and Discovery Plutons, and all the units dated in this study collectively represent over 40% of the exposed Granite Harbour intrusives in this area (Cox et al., 2012). We therefore interpret our data to record the largest pulse of subduction-related magmatism in the Dry Valleys area during the Ross orogeny.

Transient Initiation and Synchronous Cessation of Magmatism

In the northern Victoria Land segment, intrusions spanned ca. 545–485 Ma (Black and Sheraton, 1990; Tonarini and Rocchi, 1994; Rocchi et al., 1998; Fioretti et al., 2005; Bomparola et al., 2006; Tiepolo and Tribuzio, 2008). In the central Transantarctic Mountains, calc-alkaline magmatism may have initiated as early as 590 Ma, and persisted for over 100 m.y. (Goode et al., 2012). Immediately to the south of the Dry Valleys, alkaline intrusive rocks of the Koettlitz Glacier alkaline suite (Read et al., 2002; Cox et al., 2012) were emplaced ca. 557–517 Ma (Rowell et al., 1993; Encarnación and Grunow, 1996; Cooper et al., 1997; Mellish et al., 2002; Read et al., 2002; Cottle and Cooper, 2006a; Read, 2010). Although magmatism in the Dry Valleys area may have persisted for ~45 m.y. during the early Paleozoic (based on the ca. 530 Ma age from Allibone and Wysockanski [2002] and the ca. 485 Ma age of Encarnación and Grunow [1996]), the majority of granites were likely emplaced between ca. 515 and 492 Ma. This period was significantly abbreviated compared to other segments of the orogen, and it coincides almost exactly with the short period of deformation and magmatism recorded in the Delamerian orogen of...
southeast Australia (ca. 514–487 Ma; Foden et al., 2006). These results, compared with data from northern Victoria Land and central Transantarctic Mountains, highlight the transient nature of continental arc magmatism and deformation along the paleo-Pacific Ocean margin of Gondwana, with no clear trend of younging in one direction along the margin (Fig. 7).

Overlap in the ages of the subduction-related DV1 suites and the post-tectonic DV2 suite records a transitional shift in tectonic regime. Post-tectonic magmatism occurred within a relatively short period (ca. 495-485 Ma) along at least 1500 km of the arc from southeast Australia through southern Victoria Land, with the emplacement of mafic complexes and A-type granites in southeast Australia (Foden et al., 2006, and references therein), potassic Irizar granites and associated Vegetation lamprophyres in the southern Victoria Land coast.

The short period of subduction-related magmatism also contrasts with other well-studied continental arcs, for example, the Sierran Nevada batholith, in which Caaalkine magmatism persisted for over 160 m.y. (Saleebey et al., 2008, and references therein), albeit through high-flux episodes separated by relative magmatic quiescence (Barton et al., 1988; Barton, 1996; Ducea, 2001; Ducea and Barton, 2007). However, a picture of periodic magmatism in the Ross orogen emerges if the entire arc is considered (Fig. 7); the abbreviated magmatism in the Dry Valleys records only one major high-flux episode.

Inheritance of ca. 550 Ma components (Fig. 5) records Ross-stage (margmatic?) zircon growth and/or recrystallization in the Dry Valleys area several tens of millions of years before the emplacement of the voluminous DV igneous suites. Several samples contain a range in concordant eHf(i) values: (1) eHf(i) values of all samples from this study are negative (−0.3 to −7.2); (2) more felsic samples have a wider range and lower eHf(i) values than mafic samples; and (3) the range of eHf(i) broadens with decreasing age. Several scenarios potentially explain the negative eHf(i) values: (1) Low-eHf(i) crustal reservoirs, which separated from the mantle at times indicated by the model ages of the samples, were the direct magma sources for the DV suites; (2) the DV suites were sourced from depleted mantle with a relatively radiogenic Hf isotopic composition and subsequently assimilated a significant proportion of low-eHf(i) crust; (3) melts sourced from an enriched (or primitive) subcontinental lithospheric mantle, with a subchondritic Hf isotopic composition, were contaminated by a subordinate amount of crust during magma differentiation. There are essentially three end-member components involved in these hypotheses: depleted mantle, subcontinental lithospheric mantle, and recycled crust (Proterozoic or older in this case), all of which are feasible constituents in the source of arc magmas. The contrasting hypotheses have bearing on the composition of the mantle wedge beneath the arc and on the relative roles of crustal growth versus recycling in the Dry Valleys area during the arc (Fig. 7). Various mechanisms have been proposed to explain the synchronous late-stage magmatism and extension across the orogen. Foden et al. (2006) suggested that the subducting slab beneath southeast Australia may have reached the base of the mantle transition zone (~660 km depth), resulting in hinge rollback, decoupling of the subducting and overriding plates, and exhumation of the upper plate. Hinge rollback, coupled with lithospheric delamination, was proposed to explain the late-stage lamprophyres and extensional collapse in Victoria Land (Di Vincenzo and Rocchi, 1999; Rocchi et al., 2009, 2011). There is also evidence for the suturing of discrete continental fragments in northern Victoria Land, though there is some debate over whether the fragments are exotic terranes (e.g., Borg et al., 1987; Kleinschmidt and Tessensohn, 1987; Borg and DePaolo, 1991) or autochthonous mobile belts (e.g., Rocchi et al., 2011). Allibone et al. (1993a) postulated that there could have been a similar collisional event in southern Victoria Land at approximately the same time, with remnants of the colliding terrane composing part of the Ross seafloor east of the southern Victoria Land coast.

Potential Magma Sources

Several prominent observations arise from the zircon Hf data in Figure 6: (1) eHf(i) values of all samples from this study are negative (~0.3 to −7.2); (2) more felsic samples have a wider range and lower eHf(i) values than mafic samples; and (3) the range of eHf(i) broadens with decreasing age. Several scenarios potentially explain the negative eHf(i) values: (1) Low-eHf(i) crustal reservoirs, which separated from the mantle at times indicated by the model ages of the samples, were the direct magma sources for the DV suites; (2) the DV suites were sourced from depleted mantle with a relatively radiogenic Hf isotopic composition and subsequently assimilated a significant proportion of low-eHf(i) crust; (3) melts sourced from an enriched (or primitive) subcontinental lithospheric mantle, with a subchondritic Hf isotopic composition, were contaminated by a subordinate amount of crust during magma differentiation. There are essentially three end-member components involved in these hypotheses: depleted mantle, subcontinental lithospheric mantle, and recycled crust (Proterozoic or older in this case), all of which are feasible constituents in the source of arc magmas. The contrasting hypotheses have bearing on the composition of the mantle wedge beneath the arc and on the relative roles of crustal growth versus recycling in the Dry Valleys area during the
Ross orogeny. However, the Hf isotope data alone do not uniquely fit any of these potential scenarios.

**Presence of Enriched Subcontinental Lithospheric Mantle Beneath the Ross Orogen**

The most mafic samples (~49–50 wt% SiO₂) have negative $\varepsilon_{\text{Hf}}$ values, from −0.6 to −2.7. A viable interpretation is that the gabbroic (sensu lato) rocks were derived from partial melting in the mantle wedge beneath the arc. Alternatively, they could have been sourced from mafic lower crust with 1.5–1.6 Ga depleted-mantle model ages; however, this would require total fusion of a gabbroic source. It is also possible that the gabbros are cumulates or the residuum of partial melting of an intermediate crustal source, and that the intermediate and felsic samples represent the extracted cumulates or the residuum of partial melting of an intermediate crustal source. It is also possible that the gabbros are sourced melt toward a negative $\varepsilon_{\text{Hf}}$ composition of the resulting melts, potentially driving a depleted mantle–derived melt to the Hf isotope composition observed in the most mafic DV samples. The $\varepsilon_{\text{Hf}}$ of depleted mantle in the model was fixed at +14.9 (the value at 500 Ma based on the parameters of Griffin et al., 2000), and the Hf concentration of a melt sourced from the depleted mantle is fixed at 2 ppm, based on the average of 12 samples of island-arc basalts from White and Patchett (1984). The conditions, and therefore derivatives, of partial melting beneath island arcs may be different from those produced in continental arcs, but these island-arc basalts, with highly radiogenic Hf ($\varepsilon_{\text{Hf}}$ ranging from +9.1 to +15.1; White and Patchett, 1984), are demonstrably sourced from the depleted mantle and are therefore an appropriate analog for this end member. The Hf concentration and isotope composition of the “old crust” end member are difficult to estimate because Precambrian cratonic rocks are not exposed in southern Victoria Land. The Hf isotope composition of the crustal component was estimated from the Nd isotope composition of Skelton Group metamictite rocks reported by Cox et al. (2000). The least radiogenic sample from that study has $\varepsilon_{\text{Hf}} = -10.2$, which corresponds to an $\varepsilon_{\text{Hf}} = -10.9$ ($\text{TDM} = 2.1 \text{ Ga}$) when it converted using the regression of the Hf-Nd “terrestrial array” of Vervoort and Blichter-Toft (1999): $\varepsilon_{\text{Hf}} = 1.36 \varepsilon_{\text{Nd}} + 3$). We chose the lowest $\varepsilon_{\text{Hf}}$ value in order to estimate a minimum amount of Proterozoic crust necessary to drive a depleted mantle–sourced melt to the negative $\varepsilon_{\text{Hf}}$ values of the mafic DV samples. The Hf concentration of the crustal end member was set at values of 1.9, 3.7, and 5.3 ppm, estimates for mafic lower crust, intermediate “bulk” continental crust, and upper crust, respectively (Rudnick and Gao, 2003).

The model demonstrates that ~35% by mass of Proterozoic crust in the source would be required to depress the Hf composition of a depleted mantle–derived melt to the negative $\varepsilon_{\text{Hf}}$ values observed in the DV samples (Fig. 8). An even greater proportion of crust would be required if mixing involved crust with a lower Hf concentration (~60% of crust with 1.9 ppm Hf; Fig. 8). Such a large proportion of crustal material in the source would have significantly affected the bulk composition of the resulting melt and, accompanied by fractional crystallization, would have shifted the melts to higher SiO₂ concentrations.

---

**Figure 8.** Binary mixing models between depleted-mantle (DM) and crustal source components illustrate a wide range of mixing scenarios that could produce the Hf isotope values measured in the Dry Valleys (DV) samples. The parameters of the end members are explained in the text. Two hypothetical mixing scenarios that could explain the range of $\varepsilon_{\text{Hf}}$ in the mafic (<50 wt% SiO₂) DV samples are annotated and discussed in the text. The models demonstrate that a significant proportion of low-$\varepsilon_{\text{Hf}}$ crust in the source region would be necessary to “contaminate” the Hf isotope composition of a depleted mantle–derived melt to the values observed in the DV samples.
A qualitative assessment of Nd-Sr isotope data from along the Ross orogen supports the presence of an enriched subcontinental lithospheric mantle beneath the arc (Fig. 9). Parabolic trends of the Granite Harbour intrusive samples suggest mixing between old crust with low $e_{Nd(i)}$ and high $^{87}\text{Sr} / ^{86}\text{Sr}$ and a juvenile component with higher $e_{Nd(i)}$ and low $^{87}\text{Sr} / ^{86}\text{Sr}$. However, the juvenile component in each segment of the orogen only extends to moderately high $e_{Nd(i)}$ and low $^{87}\text{Sr} / ^{86}\text{Sr}$, far from the composition of depleted-mantle sources. This is consistent with the interpretation of Rocchi et al. (2009), that late-stage lamprophyres with low $e_{Nd(i)}$ in central Victoria Land were sourced from enriched subcontinental lithospheric mantle. The Vanda dike swarm (including lamprophyres and felsic porphyries) and DV2 suite in the Dry Valleys may be the equivalent of the Vegetation lamprophyres and Irizar granites of Rocchi et al. (2009).

Figure 10 shows Hf isotope evolution trajectories for several hypothetical mechanisms for the enrichment of the subcontinental lithospheric mantle beneath the Ross orogen. The metasomatism may have occurred at some time (or progressively) prior to the Ross orogeny, decreasing the Lu/Hf ratio of the subcontinental lithospheric mantle beneath the edge of the East Antarctic craton. Over time, this reservoir, with a low Lu/Hf ratio, could develop a low-$e_{Hf}$ composition that is indistinguishable from old crust in terms of radiogenic isotopes. Alternatively, "young" metasomatism may have occurred during the Ross orogeny, decreasing the $e_{Hf}$ of the subcontinental lithospheric mantle through the introduction of crust-derived Hf through fluid metasomatism, subduction of pelagic sediments, or subduction erosion of the overriding continental plate. Zircon oxygen isotope data could provide useful information about the nature of the mantle source but are currently unavailable.

**Crustal Recycling and Temporal Trends**

If the felsic DV samples were direct differentiates of the mafic samples, the data should fall on horizontal trajectories on the $e_{Hf(i)}$ versus $\text{SiO}_2$...
The broadening of the array of $\epsilon_{\text{Hf}}$ in younger samples (Fig. 6B) may reflect a thickening of the crustal column through which the magmas ascended or underplating of supracrystalline (low-$\epsilon_{\text{Hf}}$) material into the source region. Refertilization of the source region beneath continental arcs by periodic underthrusting of evolved continental material has been demonstrated in the North American Cordillera (e.g., DeCelles et al., 2009) and in the Australian Tasmanides (Kemp et al., 2009). Those periods were associated with negative excursions in $\epsilon_{\text{Hf}}$ in coconloutr intrusions. The pattern in Figure 6B seems to reflect a portion of one cycle of thickening and source refertilization. The conundrum here is that the earlier gneissic plutons in the Dry Valleys (including the Bonney Pluton), which have a more restricted range and higher $\epsilon_{\text{Hf}}$ (Fig. 6B), were likely emplaced during contraction across the arc (Cox, 1993). The younger, nonfoliated DV2 rocks were interpreted to have been emplaced in a post-subduction extensional regime (Smillie, 1992; Allibone et al., 1993b).

However, Allibone et al. (1993b) suggested that the DV2 suite plutons had various sources, and this suite has a wide range of $\epsilon_{\text{Hf}}$. The mafic samples with higher $\epsilon_{\text{Hf}}$ (Fig. 6A) may have been sourced from the lithospheric mantle, while the evolved samples with lower $\epsilon_{\text{Hf}}$ may have been sourced primarily from fertile lower crust.

**CONCLUSIONS**

Whole-rock geochemistry, U-Pb zircon geochronology, and Hf isotopic data for 31 samples from across the Dry Valleys area yield new insights into the magmatic processes that operated in the southern Victoria Land segment of the Ross orogen during the early Paleozoic. Geochronology reveals that the Dry Valleys segment of the arc was predominantly constructed in a relatively short pulse (~23 m.y.) of magmatism from 515 to 492 Ma. The style of magmatism transitioned from subduction-related to post-tectonic at ca. 505 Ma, which we interpret as a response to the cessation of subduction. Age spectra for individual samples suggest complex intrusion dynamics and inheritance within individual plutons. Mafic samples show geochemical and isotopic evidence for derivation from an enriched subcontinental lithospheric mantle source. Large granitic bodies may have had a similar source but involved crustal assimilation during their evolution. The crustal component in the DV suites increased over time, perhaps reflecting crustal thickening or the underthrusting of fertile continental crust into the source region. The isotopic composition of the Granite Harbour intrusives along the Ross orogen suggests the presence of enriched subcontinental lithospheric mantle beneath the entire arc. Melts derived from this source may be incorrectly interpreted as derivatives of crustal melting based on isotopic composition alone.

**ACKNOWLEDGMENTS**

Funding for this work was provided by National Science Foundation grant ANT-1043152 to J.M. Cottle. We thank New Zealand Institute of Geological and Nuclear Science (GNS), New Zealand, for providing samples for this study. We also thank Michael Flowerdew, Alan Cooper, two anonymous reviewers, and the editor, John Goodge, for providing many useful suggestions that significantly improved this article.

**REFERENCES CITED**


