Contrasting age and isotope characteristics of volcanic-hosted and skarn-type mineralisation near The Glen, Goulburn, in the Lachlan Orogen, New South Wales

Abstract

Felsic volcanic units of the middle Silurian–earliest Devonian Mount Fairy Group host mineralisation near The Glen, 23 km southwest of Goulburn. Two contrasting styles are present: volcanic-hosted massive sulfide-related mineralisation (Glen E prospect); and reduced gold skarn-type mineralisation (Collector prospect).

Glen E is a 500 m long, sulfide-rich zone hosted by the late Silurian Woodlawn Volcanics. Sulfides present include pyrite, chalcopyrite, galena and sphalerite. Sulfur-isotope compositions of sulfides from Glen E range from 5.9–9.5‰ (mean 8.5 δ¹⁰S‰). The sulfur is sourced from a reduced seawater sulfate reservoir with little or no sulfur from a magmatic reservoir. Lead-isotope data suggest that most of the lead and other metals were sourced from the host sequence.

The Collector skarn is about 350 m west of Glen E. The zone dips steeply to the west and is hosted by the middle to late Silurian De Drack Formation. Mineralisation includes zones of massive pyrrhotite, with pyrite and minor chalcopyrite; and bands of sphalerite with magnetite, pyrite, pyrrhotite, chalcopyrite and minor galena. Skarn (silicate) mineralogy includes andradite, actinolite, tremolite, diopside and wollastonite. The sulfur-isotope composition of sulfides from this skarn ranges between 5.8–8.5‰ (mean 7.7 δ¹⁰S‰), suggesting that sulfur has been sourced, by reduced fluids, from the adjacent host sequence. Lead-isotope data suggest that lead has been sourced from a slightly older reservoir than that for Glen E and is interpreted to be the De Drack Formation.

⁴⁰Ar/³⁹Ar dating of muscovite grains from a fracture filled with quartz–muscovite–sulfide (pyrite, sphalerite, chalcopyrite and galena) from Glen E gave an age range from 377.4 ± 5.2–422.3 ± 4.8 Ma. Multiple populations are present due to partial argon loss, however the weighted mean age obtained from four of the oldest grains from the high-temperature steps gave a 418.2 ± 2.2 Ma age, which is interpreted to be the timing of base metal mineralisation.

The Glen E deposit is the first VHMS-related system to be directly dated in the New South Wales part of the Eastern Subprovince of the Lachlan Orogen. The age confirms earlier interpretations that VHMS-related mineralisation associated with the Goulburn Basin formed in the late Silurian — synchronous with the middle to late Silurian felsic volcanic event.

Keywords: Lachlan Orogen, Lachlan Fold Belt, Goulburn Basin, lead isotopes, sulfur isotopes, ⁴⁰Ar/³⁹Ar dating, mineralisation, volcanic-hosted massive sulfide, skarn, Glen E prospect, Collector prospect, Woodlawn Volcanics
Introduction

Past exploration near The Glen, 23 km southwest of Goulburn (193 km southwest of Sydney) (Figure 1) identified sulfide-rich mineralisation containing elevated levels of lead, zinc, copper, silver and gold. The principal mineralised zones identified to date are the Collector and Glen E prospects (Figures 2 and 3). Additional sulfide-rich zones are also present at the Glen A (also known as Anomaly A), Glen C and Glen D prospects.

Exploration by Samedan Oil Corporation of Australia [Samedan], in the late 1970s, identified several bedrock geochemical anomalies — high in copper, lead and zinc — near The Glen (Figure 2). Samedan diamond-drilled three of these anomalies in early 1979, with seven holes being completed as part of their initial program (Kemezys et al. 1979). Jododex Australia Pty. Ltd. (subsequently restructured to become St Joe Australia Pty. Ltd.) entered into a
**Figure 2.** Location of mineral deposits and distribution of Silurian felsic volcanic and related sedimentary units within the northern part of the Goulburn Basin, eastern Lachlan Orogen. Geology adapted from Glen et al. (2007) and Johnston et al. (2008).
joint venture with Samedan in November 1979 and completed an additional six diamond drillholes (see Jododex Australia Pty. Ltd. 1981, 1982; De Ross 1983; St Joe Australia Pty. Ltd. 1983). In total, seven holes were drilled at the Glen E prospect with significant zones of base metal-rich mineralisation being intersected in DDH 3, DDH 7 and JSG 1 and minor mineralisation being intersected in the remaining four holes (Figure 3).

In addition, four diamond drillholes were completed at Glen A, with single diamond drillholes completed at Glen C and Glen D. However, only minor mineralisation was intersected at these three prospects.

Renewed exploration of the area in the early 1990s, by Platinum Search N.L. (later Platsearch N.L.) and Downmill Pty Limited, identified an additional zinc–copper–lead–gold bedrock geochemical and coincident ground magnetic anomaly, the Collector prospect (Richardson & Swingler 1992). The Collector prospect is 350 m west of the Glen E prospect (Figure 3). Diamond drilling of this anomaly intersected massive pyrrhotite–pyrite with minor lead–zinc–(copper–silver) sulfide mineralisation (N & K Swingler & Associates 1995; 1996). Subsequent to the initial discovery, further exploration of this zone was undertaken in joint venture with a number of companies including Fodina Minerals Pty Ltd (a subsidiary of Mining Project Investors Pty Ltd), Outokumpu Exploration Ventures Pty Ltd and subsequently Marlborough Gold Mines NL. In total seven diamond drillholes were completed with significant mineralised zones being intersected in P/DDH–2 (Richardson & Swingler 1992), DDH C–3, DDH C–4, DDH C–6, DDH C–7 and DDH C–8 (N & K Swingler & Associates 2000).

The aim of this paper is to outline the mineralisation styles at the Glen E and Collector prospects; to present reconnaissance sulfur- and lead-isotope studies for the two zones; and to report the results of \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of white mica from the Glen E prospect. These studies were carried out as part of the Goulburn 1:250 000 geological mapping project.

**Geological setting**

The Lachlan Orogen (formerly Lachlan Fold Belt — Scheibner 1975) represents part of an extensive orogenic system — the Tasmanides (Scheibner & Basden 1996; Foster & Gray 2000; Glen 2005) — that is more than 1000 km wide. The Tasmanides form the eastern third of Australia and record the breakup of the
Rodinian supercontinent, over a 200 Ma period from ~800 to ~600 Ma, and the establishment of a series of orogenic belts along the eastern (Pacific) margin of Gondwana (Glen 2005).

The Eastern Subprovince of the Lachlan Orogen (cf. Glen 2005) (Figure 1), which hosts the study area, is considered to be an outboard, convergent-margin terrane dominated by mafic to felsic volcanic rocks and thick turbidite successions of Ordovician to Devonian age (Glen et al. 1998; Foster et al. 1999). This terrane underwent prolonged crustal extension during the middle Silurian to Early Devonian in response to slab rollback at the leading edge of the palaeo-Pacific oceanic plate and a retreating subduction boundary (Collins 2002; 2003). This formed a number of north-trending back-arc rift basins (Scheibner & Basden 1998) that include the Goulburn Basin and Hill End Trough (discussed below; Figure 1). These back-arc basins were filled by middle to late Silurian felsic volcanic and associated siliciclastic sedimentary rocks. Associated with the Goulburn Basin and the Hill End Trough are volcanic-hosted massive sulfide-type (VHMS) and skarn-type mineralisation. However, the timing of mineralisation associated with these troughs is poorly constrained.

Regional mapping by Johnston et al. (2008) has shown that the belt of middle to late Silurian–Early Devonian rocks located to the west of Goulburn (i.e. Campbells Group and overlying Crudine Group — not shown) is part of a continuous belt that extends northward to the Bathurst Batholith — where it links with the northern part of the Hill End Trough. Thomas and Pogson (in prep.), suggest that these units were initially deposited in a shallow-water environment that deepened to a deep-water environment. By contrast, the belt of middle to late Silurian–Early Devonian rocks that passes through Goulburn (i.e. the Mount Fairy Group and overlying Bindook Group — not shown), includes units that were deposited initially in a shallow-water environment, which then became deep and finally shallow again, with the final stage being sub-aerial. The differences in sedimentological and volcanic history between the two belts has prompted Thomas and Pogson (in prep.) to subdivide the former Captains Flat–Goulburn Trough into those units that form the southern continuation of the Hill End Trough and those units that form the Goulburn Basin (Figure 1). The age of inversion and deformation of these basins is poorly constrained. A Middle to Late Devonian age (380–370 Ma) for greenschist-facies regional metamorphism and cleavage formation is favoured for the northern Hill End Trough from radiometric dating of metamorphic mica (Cas et al. 1976; Lu et al. 1996; Packham 1999). Vassallo et al. (2003) suggested that the deformation in the Middle Devonian (i.e. Tabberabberan Orogeny) was thrust-dominated (thin-skinned tectonics). Following this, these basins were further deformed during the early Carboniferous Kanimblan Orogeny, with Vassallo et al. (2003) suggesting that this deformation was characterised by non-cylindrical thrust-related folding and was largely controlled by the reactivation of basement faults.

Within the Goulburn Basin, the principal unit hosting volcanic-hosted massive sulfide (VHMS) related mineralisation is the Mount Fairy Group (Figure 2). This unit also hosts significant skarn- and granite-related mineralisation.

Included in the Mount Fairy Group are the De Drack Formation, Woodlawn Volcanics and Currawang Basalt (Figure 2). The Woodlawn Volcanics and the overlying Currawang Basalt probably interfinger (Felton & Huleatt 1977). The Woodlawn Volcanics, which hosts the world-class Woodlawn VHMS base-metal deposit, as well as the Glen E, Glen C and Glen A prospects (Figure 2), includes a sequence of rhyolites, fine- to coarse-grained volcanioclastic sedimentary rocks, tuffaceous siltstones, grey to carbonaceous shales and minor quartzose sandstone (Thomas & Pogson in prep.).

The De Drack Formation is host to the nearby Collector deposit, with the mineralisation being located adjacent to the boundary between the De Drack Formation and the overlying Woodlawn Volcanics (Figures 2 and 3). In the study area, the De Drack Formation is hornfelsed, poorly exposed and includes massive fossiliferous marble, shales, fine-grained siltstones, quartzose sandstone, tuffaceous sandstones and crystal- and lithic-rich tuffs. Both units have been intruded by quartz monzodiorites and tholeiitic dolerites (Figure 2) of probable Early Devonian age (Thomas & Pogson in prep.) — shown as ungrouped Devonian intrusion.

Mineralisation
Scattered lead–zinc–(copper–silver) sulfide-rich zones have been intersected by diamond drilling near The Glen. The two major zones are: the Glen E prospect; and the Collector prospect (described below) (Figure 2). However, minor base metal-rich zones are also present at Glen A, Glen C and Glen D. Glen E and Collector prospects are approximately 350 m apart (Figure 3).

Glen E prospect
The Glen E deposit is a 500 m-long sulfide-rich zone hosted by pervasively altered and, in places, foliated tuffaceous siltstones and volcanic sandstones of the middle to late Silurian Woodlawn Volcanics. Sulfides
occur in quartz–sulfide–(muscovite) veinlets, sulfide-rich stringers and as disseminated grains. Sulfide mineralogy is dominated by pyrite, chalcopyrite, galena and sphalerite. Early euhedral pyrite grains often have skeletal-type textures and are partially replaced by galena and sphalerite. Sphalerite-rich zones include aligned blebs of chalcopyrite (chalcopyrite disease — cf. Barton 1978) and galena indicating that these two minerals have replaced sphalerite. Late pyrite-filled fractures cut earlier sulfides. Based on the observed textures, the proposed paragenesis is: early pyrite; then sphalerite; followed by chalcopyrite and galena; with late pyrite (Downes 2006).

A pervasive wall-rock alteration surrounds the base metal sulfide-rich zones. Based on a reconnaissance alteration study using petrology and the interpretation of short-wave infrared reflectance (SWIR) spectra, obtained using a Portable Infrared Mineral Analyser (PIMA), the alteration assemblage includes quartz, muscovite—phengite and Mg-chlorite—inter-chlorite (intermediate Fe/Mg-chlorite) with minor Fe-chlorite and actinolite (sericitic to chloritic assemblage). Minor biotite—phlogopite and hornblende are also present. However, these minerals are probably metamorphism-related.

**Collector prospect**

The Collector sulfide-rich zone is hosted by units of the De Drack Formation that Thomas et al. (in prep.) suggest is early Wenlock to mid-Ludlow in age. The sequence dips moderately to steeply to the west and includes massive fossiliferous marble, altered and foliated shales (including pyritic carbonaceous shale), fine-grained siltstones, tuffaceous sandstones and crystal- and lithic-rich tuffs. Those units have been intruded by porphyritic dolerites (Fander 1994) and quartz monzodiorites. Wall-rock alteration, associated with the mineralisation, includes calc-silicate hornfels, marble with a quartz–carbonate–actinolite–diopside-andradite assemblage and talcose marble (Richardson & Swingler 1992). Additional alteration-related minerals include chlorite, tremolite and wollastonite (N & K Swingler & Associates 2000).

Two styles of mineralisation are present. These are massive pyrrhotite bands (to 5 m wide) with minor chalcopyrite in a chlorite–silica-rich gangue and zones of disseminated, aggregates, wispy stringers and bands of sphalerite with magnetite, pyrite, pyrrhotite, chalcopyrite and minor galena in an actinolite–chlorite–sericite–silica gangue (Richardson & Swingler 1992). Observed textures include colloform- and crustiform-type banded veins, suggesting that the mineralisation may have formed at relatively shallow depths. Pyrrhotite associated with the pyrrhotite-rich bands is partially replaced by pyrite.

Richardson and Swingler (1992) noted that the sulfide-rich zones at Collector have elevated levels of gold, silver and a range of other elements — including manganese, bismuth, molybdenum, antimony, cadmium and cobalt. Many of these elements are characteristic of intrusion-related mineralisation.

**Sample preparation**

Samples for the present study were collected from diamond drillcore, which is stored at the Industry & Investment NSW core facility at Londonderry, New South Wales. Initially, samples were described in hand specimen and using the binocular microscope. Then selected samples were prepared as polished thin sections for ore microscopy and petrology. In addition, a Portable Infrared Mineral Analyser (PIMA) was used to obtain short-wave infrared reflectance spectra to provide additional information about hydrous alteration mineralogy.

Twenty-six sulfide-rich powders were obtained using a microdrill and a binocular microscope and analysed for their sulfur isotope composition as part of the present study. Contamination of mineral separates by other sulfide species was minimised by selecting coarse-grained material. Isotopic analyses were undertaken at the Nevada Stable Isotope Laboratory, University of Nevada — Reno, USA, using the procedure outlined by Glesemann et al. (1994). Data are reported to an accuracy of ± 0.2 per million relative to Cañon Diablo Troilite (CDT) and a variety of secondary standards. The results of the sulfur-isotope analyses are included in Table 1, summarised in Figure 4, and discussed below.

Fifteen samples were analysed for their lead isotope composition at the CSIRO Exploration and Mining as part of the present study (Table 2). Carr et al. (1995) have described the preparation of samples for lead-isotope analyses at CSIRO Exploration and Mining. After crushing, whole-rock samples were digested using a mixed 7N nitric + 7N hydrochloric acid solution prior to ion exchange, whereas galena separates were dissolved using concentrated nitric acid. Lead from both sources was further purified by microelectrode deposition onto Pt electrodes. All samples were then analysed using a VG ISOMASS 54E solid source thermal ionisation mass spectrometer run in fully automatic mode. Ratios were normalised to accepted values of international standard NBS SRM 981. Precision estimates representing two standard deviations are 0.05 percent for the $^{207}$Pb/$^{204}$Pb ratio and 0.1 percent for all other ratios (Gulson et al. 1984). Analytical precision is shown in the upper left hand corner of lead isotope diagrams as a 95 percent confidence ellipses based on over 1400 analyses (Carr et al. 1995).
### Glen E prospect

<table>
<thead>
<tr>
<th>DDH &amp; depth (m)</th>
<th>Sample no.</th>
<th>Description</th>
<th>Mineral analysed</th>
<th>δ²⁸S ‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDH 5 102.60–102.67</td>
<td>DDH 5/1</td>
<td>Silicified chloritic rock with some sulfides [from 0.43 m zone @ 0.43% Cu, 3.67% Pb, 3.07% Zn, 26 ppm Ag — 102.52–102.95 m]</td>
<td>chalcopyrite</td>
<td>8.5</td>
</tr>
<tr>
<td>DDH 5 154.52–154.62</td>
<td>DDH 5/3</td>
<td>Foliated and chloritised rock with minor laminations filled by sulfides — altered intermediate volcanic rock [from 0.22 m zone assaying 0.42% Cu, 4.33% Pb, 8.24% Zn, 18 ppm Ag — 154.52–154.74 m]</td>
<td>galena pyrite sphalerite</td>
<td>5.9 7.9 8.4</td>
</tr>
<tr>
<td>DDH 7 187.75–187.87</td>
<td>DDH 7/1</td>
<td>Foliated and chloritised rock with minor laminations filled by sulfides — altered intermediate volcanic rock [from 0.22 m zone assaying 0.42% Cu, 4.33% Pb, 8.24% Zn, 18 ppm Ag — 154.52–154.74 m]</td>
<td>chalcopyrite galena</td>
<td>9.2 7.8</td>
</tr>
<tr>
<td>DDH 7 190.00–190.05</td>
<td>DDH 7/2</td>
<td>Foliated and chloritised rock with minor laminations filled by sulfides — altered intermediate volcanic rock [from 0.22 m zone assaying 0.42% Cu, 4.33% Pb, 8.24% Zn, 18 ppm Ag — 154.52–154.74 m]</td>
<td>pyrite</td>
<td>8.9 9.1</td>
</tr>
<tr>
<td>DDH 7 196.55–196.60</td>
<td>DDH 7/3</td>
<td>Foliated and chloritised rock with minor laminations filled by sulfides — altered intermediate volcanic rock [from 0.22 m zone assaying 0.42% Cu, 4.33% Pb, 8.24% Zn, 18 ppm Ag — 154.52–154.74 m]</td>
<td>chalcopyrite sphalerite</td>
<td>9.5 9.5</td>
</tr>
<tr>
<td>JSG1 297.15–297.19</td>
<td>JSG1/1</td>
<td>Mineralised zone with chalcopyrite and galena. [from 7.5 m zone assaying 0.43% Cu, 3.67% Pb, 3.07% Zn, 26 ppm Ag — 295–302.5 m]</td>
<td>galena</td>
<td>7.5</td>
</tr>
<tr>
<td>JSG1 298.40–298.44</td>
<td>JSG1/2</td>
<td>Mineralised zone with chalcopyrite and galena. [from 7.5 m zone assaying 0.43% Cu, 3.67% Pb, 3.07% Zn, 26 ppm Ag — 295–302.5 m]</td>
<td>chalcopyrite galena</td>
<td>9.7 8.1</td>
</tr>
<tr>
<td>JSG1 299.75–299.79</td>
<td>JSG1/3</td>
<td>Mineralised zone with chalcopyrite and galena. [from 7.5 m zone assaying 0.43% Cu, 3.67% Pb, 3.07% Zn, 26 ppm Ag — 295–302.5 m]</td>
<td>chalcopyrite</td>
<td>9.1</td>
</tr>
</tbody>
</table>

### Collector prospect

<table>
<thead>
<tr>
<th>DDH &amp; depth (m)</th>
<th>Sample no.</th>
<th>Description</th>
<th>Mineral analysed</th>
<th>δ²⁸S ‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDH C3 93.75–93.90</td>
<td>PDC3/1</td>
<td>Massive pyrrhotite with minor zones of magnetite and chalcopyrite; silicified host rock; [from 1.05 m zone assaying 0.47% Cu, 20 ppm Pb, 0.19% Zn — 93.7–94.75 m]</td>
<td>pyrrhotite</td>
<td>7.9</td>
</tr>
<tr>
<td>DDH C3 100.65–100.80</td>
<td>PDC3/2</td>
<td>Massive pyrrhotite–magnetite-rich zone [from 1.0 m zone assaying 0.45% Cu, 50 ppm Pb, 0.57% Zn — 99.8–100.8 m]</td>
<td>pyrrhotite</td>
<td>7.9</td>
</tr>
<tr>
<td>DDH C3 120.50–120.70</td>
<td>PDC3/3</td>
<td>Disseminated magnetite with minor sulfides (pyrite) within a greenish white calc-silicate rock [from 0.89 m zone assaying 0.35% Cu, 64 ppm Pb, 1.94% Zn — 119.81–120.7 m]</td>
<td>pyrite</td>
<td>7.4</td>
</tr>
<tr>
<td>DDH C3 136.00–136.10</td>
<td>PDC3/4</td>
<td>Massive pyrrhotite with minor chalcopyrite [from 0.75 m zone assaying 0.56% Cu, 66 ppm Pb, 1.21% Zn — 135.65–137.4 m]</td>
<td>chalcopyrite pyrrhotite</td>
<td>5.8 8.0</td>
</tr>
<tr>
<td>DDH C3 143.50–143.65</td>
<td>PDC3/5</td>
<td>Massive vuggy pyrrhotite and massive magnetite with minor chalcopyrite and pyrite within the pyrrhotite-rich zone [from 1.0 m zone assaying 0.46% Cu, 156 ppm Pb, 840 ppm Zn — 143.0–144.0 m]</td>
<td>pyrrhotite pyrite</td>
<td>7.9 8.1</td>
</tr>
<tr>
<td>DDH C4 137.80–138.00</td>
<td>PDC4/1</td>
<td>Blackish partially weathered and silicified sulfide-rich calc-silicate rock with massive magnetite; sulfides include pyrite, pyrrhotite and minor chalcopyrite</td>
<td>pyrrhotite</td>
<td>7.8</td>
</tr>
<tr>
<td>DDH C4 158.20–158.40</td>
<td>PDC4/2</td>
<td>Massive sulfides with reddish garnet, magnetite and green calc-silicates; sulfides include pyrrhotite, Fe sphalerite and minor pyrite [from 0.15 m zone assaying 0.62% Cu, 0.39% Pb, 24.5% Zn — 158.2–158.35 m]</td>
<td>pyrrhotite</td>
<td>8.5</td>
</tr>
<tr>
<td>DDH C4 168.10–168.20</td>
<td>PDC4/4</td>
<td>Massive sulfide aggregates with greenish calc-silicate minerals; sulfides include abundant galena, reddish sphalerite, minor pyrite and chalcopyrite; zone is magnetic [from 1.0 m zone assaying 0.10% Cu, 1.17% Pb, 0.66% Zn — 167.5–168.5 m]</td>
<td>chalcopyrite galena</td>
<td>8.2 7.3 7.6</td>
</tr>
</tbody>
</table>
In preparation for \(^{40}\text{Ar}/^{39}\text{Ar}\) dating, muscovite grains were separated from a quartz–muscovite–sulfide (pyrite, sphalerite, chalcopyrite and galena)-filled fracture at Glen E prospect — using standard crushing, sieving, de-sliming and magnetic separation methods. Hand-picked single muscovite grains were then washed in deionised water and acetone. Prior to irradiation, the grains were wrapped in aluminium packets and placed into aluminium irradiation canisters with aliquots of the flux monitor GA1550 (Age = 98.8 ± 0.5 Ma; Renne et al. 1998). The samples were irradiated in position 5C at the McMaster reactor, Hamilton, Ontario, Canada. Following irradiation, grains were removed from their packaging and loaded into a copper sample holder. \(^{40}\text{Ar}/^{39}\text{Ar}\) analyses were undertaken at the University of Melbourne, using procedures described previously by Phillips and Miller (2006). Individual muscovite grains were step-heated by a Spectron CW Nd:YAG laser. Argon isotopes were analysed on a MM5400 mass spectrometer, equipped with a Daly detector. Mass discrimination was monitored by analyses of standard air volumes. Interference correction factors were: \((^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 2.63 (± 0.01) \times 10^{-4}; (^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 6.86 (± 0.03) \times 10^{-4}; (^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.0015 (± 0.007).\) Ca/K ratios were calculated from the following relation: \(\text{Ca/K = 1.9 \times ^{40}\text{Ar}/^{39}\text{Ar}}.\) The reported isotopic data have been corrected for system backgrounds, mass discrimination, fluence gradients and atmospheric contamination. Unless otherwise stated, errors associated with the age determinations are to one sigma uncertainty and exclude uncertainties in the J-value, age of the fluence monitor GA1550 and the decay constants. The decay constants are those of Steiger and Jager (1977). The \(^{40}\text{Ar}/^{39}\text{Ar}\) dating technique has been described in detail by McDougall and Harrison (1999).

### Results

#### Sulfur isotopes

Sulfur-isotope composition of sulfides from Glen E range between 5.9 δ\(^{34}\text{S}\)‰ and 9.5 δ\(^{34}\text{S}\)‰ (mean 8.5 δ\(^{34}\text{S}\)‰: 14 analyses, Figure 4, Table 1). Pyrite has δ\(^{34}\text{S}\) values of 7.9‰ and 8.9‰; chalcopyrite has δ\(^{34}\text{S}\) values between 8.5‰ and 9.5‰ (mean 9.2 δ\(^{34}\text{S}\)‰: 5 analyses); galena has δ\(^{34}\text{S}\) values between 5.9‰ and 8.1‰ (mean 7.2 δ\(^{34}\text{S}\)‰: 4 analyses); and sphalerite has δ\(^{34}\text{S}\) values between 8.4‰ and 9.5‰ (mean 9.0 δ\(^{34}\text{S}\)‰: 3 analyses).

For the Collector skarn, the sulfur-isotope composition of sulfides range between 5.8–8.5‰ (mean 7.7 δ\(^{34}\text{S}\)‰: 12 analyses, Figure 4,
### Collector Prospect

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Sample location Drill name/depth sampled (m)</th>
<th>Description</th>
<th>$^{208}\text{Pb}/^{204}\text{Pb}$ ratio</th>
<th>$^{207}\text{Pb}/^{204}\text{Pb}$ ratio</th>
<th>$^{206}\text{Pb}/^{204}\text{Pb}$ ratio</th>
<th>Pb (ppm)/Sulfide analysed</th>
<th>Q Factor</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDC3/6</td>
<td>DDH C3 207.10–207.20 Magnetite-rich skarn, riebeckite–calcite and minor pyrite</td>
<td>38.1267</td>
<td>15.613</td>
<td>18.055</td>
<td>12400</td>
<td>Present study1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>PDC4/2</td>
<td>DDH C4 158.20–158.40 Reddish garnet, magnetite and greenish calc-silicate skarn</td>
<td>38.1065</td>
<td>15.646</td>
<td>17.946</td>
<td>883</td>
<td>Present study1</td>
<td>7</td>
<td></td>
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<tr>
<td>PDC4/3</td>
<td>DDH C4 166.15–166.30 Greenish calc-silicate-rich zone with minor reddish garnets and galena–sphalerite</td>
<td>38.1253</td>
<td>15.613</td>
<td>18.062</td>
<td>10200</td>
<td>Present study1</td>
<td>1</td>
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<tr>
<td>PDC4/4</td>
<td>DDH C4 168.10–168.20 Massive sulfide aggregates with greenish calc-silicate, abundant galena, sphalerite and minor pyrite</td>
<td>38.1259</td>
<td>15.613</td>
<td>18.058</td>
<td>945000</td>
<td>Present study1</td>
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<tr>
<td>P/DDH 2</td>
<td>P/DDH 2 231.1 Sulfides including galena</td>
<td>38.2200</td>
<td>15.637</td>
<td>18.109</td>
<td>galena</td>
<td>CSIRO</td>
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<td>P/DDH 2</td>
<td>P/DDH 2 231.1 Sulfides including galena</td>
<td>38.2175</td>
<td>15.638</td>
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**Notes:**

CSIRO = data from unpublished studies included in the CSIRO lead-isotope database; Present study1 = sample collected by P Downes as part of the present study; Present study2 = sample collected by R McEvilly and D Suppel as part of the ongoing Geological Survey of New South Wales lead isotope studies.

Quality Factor is an estimate of the quality of the data. Data with a quality factor of 0 represent the best data available; whereas, data with a quality factor of 9 are of poor quality and potentially unreliable — analyses with a quality factor $\geq 7$ are not shown on Figure 5.
Table 1). S-isotope values for pyrrhotite range between 7.8‰–8.5‰ (mean 8.0 δ34S‰: 6 analyses); chalcopyrite had values of 5.8‰ and 8.2‰; galena had values of 7.3‰ and 7.6‰; and pyrite had values of 7.4‰ and 8.1‰.

The Collector mineralisation contains primary pyrrhotite in addition to pyrite and base metal sulfides, whereas at Glen E, pyrrhotite is absent and the sulfide mineralogy is dominated by pyrite, chalcopyrite, sphalerite and galena. This indicates that ore-forming fluids at Collector were reduced compared with those for Glen E, where ore-forming fluids were relatively oxidised.

For reduced fluids, the isotopic composition of sulfides would correspond closely to the isotopic composition of total dissolved sulfur in the mineralising fluids (δ34S sulfide = δ34S ΣS fluid: Ohmoto & Goldhaber 1997). Thus, the sulfur isotope composition of sulfides from Collector will reflect the sulfur isotope composition of the sulfur source. By contrast, the ore-forming fluids for Glen E were more oxidised, with a relatively high content of aqueous sulfate, in addition to sulfur, in the hydrothermal fluids (i.e. ΣSO4^2−/H2S = 1). Under these conditions, and depending on factors such as the oxidation state of the fluids, their temperature, and the proportion of sulfur derived from the rock column relative to sulfate, 34S will preferentially fractionate into the oxidised sulfur species (i.e. SO4^2− — Ohmoto & Rye 1979). This will result in sulfides deposited from oxidised fluids being preferentially depleted in 34S (Rye 1993) and, depending on the availability of 34S (i.e. open vs. closed systems) and temperature, may have a wide range of isotope values. Thus, the S-isotope data for Glen E does not correspond closely to the isotopic composition of total dissolved sulfur in the mineralising fluid.

![Graphs](image.png)

**Figure 4.** Frequency histogram of sulfur-isotope values (δ34S) for the Glen E and Collector prospects (data from Table 1).

The range and average values for sulphur-isotope data at Collector and Glen E are very similar and suggest that the majority of sulfur included in these two deposits was sourced from the same or very similar reservoirs that were dominated by reduced seawater sulfate with little or no sulfur being sourced from magmatic reservoirs. In addition, average S-isotope values for the two deposits are very similar to those for sulfides from Group 2 VHMS deposits associated with the Hill End Trough (Downes & Seccombe 2004) and for average values for C lens and the upper massive sulfide zone at the nearby Woodlawn VHMS deposit (6.7‰ and 8.1‰, respectively — data from Ayres et al. 1979). Downes and Seccombe (2004) noted that pyrrhotite is generally absent or exists only as a minor to trace mineral for Group 2 VHMS deposits and Woodlawn. Moreover, some of these deposits contain massive barite indicating that the ore-forming fluids were relatively oxidised. The presence of massive pyrrhotite at Collector with similar sulfur-isotope values to that at Glen E suggest that sulfur incorporated into Collector was sourced, by the reduced ore-forming fluids through the dissolution and recycling of rock sulfide, from a very similar reservoir to that preserved at Glen E. This reservoir is likely to be the host sequence rather than a reduced seawater sulfate-bearing fluid, such as modified seawater, which is likely to be more oxidised.

**Lead isotopes**

Twenty-four lead-isotope composition analyses (including repeated analyses) are available for samples from the study area. Nine analyses are from unpublished studies by the CSIRO Exploration and Mining for the Collector skarn, with the remaining analyses being
Three quarters of the samples that were analysed (Table 2) contain galena, with the remaining samples being Pb-rich. Lead in galena and other Pb-rich and U- and Th-poor samples is, in general, assumed to have been separated from U and Th contained within the same reservoir prior to, or synchronous with, mineralisation and deposited as galena or other Pb-rich minerals — thereby preserving the initial Pb-isotope composition of the sample (see Faure 1986; Faure & Mensing 2005). Five samples have analyses included in Table 2 that have been discarded due to poor data quality (data quality Q ≥7) and are not shown in Figure 5 — although in some cases these analyses have ratios that are very similar to other initial ratio values. The discarded analyses include four from the Collector skarn (three of which were from earlier studies by the CSIRO) and one from Glen E.

In Figure 5, the majority of lead-isotope analyses plot in a relatively tight group, with all analyses plotting adjacent to and within error of the crustal growth curve and within the Silurian VHMS field of Carr et al. (1995). Although the majority of analyses lie within analytical error, lead-isotope analyses for samples from Collector plot to the left of analyses for samples from Glen E (see $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb graph — Figure 5) and thus are slightly less-evolved. This suggests that lead included in the Collector skarn was sourced from a slightly older reservoir. Using PbGraph, a lead-model age of 433 ± 11 Ma was calculated for Collector but the lead-model age for the Glen E prospect was 425 ± 11 Ma (Cumming & Richards 1975 model). It is suggested that lead included in the Collector zone was sourced from the De Drack Formation but that lead included in the Glen E zone was sourced from the Woodlawn Volcanics. The data for both Collector and Glen E are less-evolved than data from Carr et al. (1995) for the Woodlawn VHMS deposit (summarised on the $^{207}$Pb/$^{204}$Pb vs. $^{206}$Pb/$^{204}$Pb graph — Figure 5), suggesting that lead included in both Collector and Glen E was sourced from slightly older crustal lead reservoirs.

The lead-isotope analysis for Glen C is very similar to, and plots with, data for Glen E. By contrast, analyses for Glen A and Glen D plot to the right of data for Glen E and thus are slightly more evolved. This suggests that lead included in Glen A and Glen D may have been sourced from a slightly younger reservoir or that this zone includes lead sourced from both the host units and from a younger crustal reservoir (e.g. a younger intrusion).

**Figure 5.** Lead-isotope ratio plot comparing data from Collector skarn, Glen E, Glen A, Glen C and Glen D (Table 2) with the fields for major metallogenic events associated with the Lachlan Orogen as proposed by Carr et al. (1995). Also shown is the crustal growth curve from Cumming and Richards (1975). The ellipse in the upper left-hand corner of the ratio plot is the analytical precision at 95% confidence.
which has been partially replaced by chalcopyrite and sphalerite, and late pyrite-filled fractures that cut across the earlier sulfide assemblage. Chalcopyrite has a similar texture, under the reflected light microscope, to that for sphalerite and is interpreted to be replacing sphalerite. The veins contain abundant undeformed sheaths of coarse muscovite that are up to 0.2 mm long (Photographs 1 and 2).

Nine muscovite grains from sample Glen DDH 7/1 were individually step-heated in two increments. The analyses yielded a range of apparent ages, from 377.4 ± 5.2 Ma to 422.3 ± 4.8 Ma (Table 3). In all cases, the high-temperature apparent ages are older than

Photograph 1 a & b. Thin section photomicrographs of sample Glen DDH 7/1 under transmitted crossed polar light (a) and reflected light (b). The quartz–muscovite–sulphide-filled fracture includes coarse muscovite as intergrowths of unaltered grains up to 0.6 mm in length. The majority of muscovite grains are adjacent to quartz–sulfide grain boundaries. Thus, muscovite is interpreted to be synchronous with sulfide mineralisation. The dominant sulfide is chalcopyrite. However, minor sphalerite and corroded grains of pyrite are also present. (mus = muscovite; cpy = chalcopyrite; py = pyrite; qtz = quartz; sph = sphalerite). Photographer: P.M. Downes

Photograph 2 a & b. Thin section photomicrographs of sample Glen DDH 7/1 under transmitted crossed polar light (a) and reflected light (b). The quartz–muscovite–sulphide-filled fracture includes coarse sheaths of unaligned muscovite that occur as intergrowths of unaltered grains up to 0.6 mm in length that are intergrown with chalcopyrite, pyrite and sphalerite at the quartz–sulfide grain boundaries. Thus, muscovite is interpreted to be synchronous with sulfide mineralisation. The dominant sulfide is chalcopyrite. However, minor sphalerite and lesser corroded grains of pyrite are also present. (mus = muscovite; cpy = chalcopyrite; py = pyrite; qtz = quartz; sph = sphalerite). Photographer: P.M. Downes.
the lower-temperature steps, consistent with partial argon loss (Figure 6). The four highest temperature steps exhibit ages within error of one another, with a weighted mean age of 418.2 ± 2.2 Ma (2σ; MSWD = 0.74 — Figure 7) (MSWD = mean square weighted deviate). This age (418.2 ± 2.2 Ma) is interpreted to represent the timing of quartz–muscovite–sulfide vein formation. If the younger, low-temperature steps (~375 to 395 Ma) (Figure 6) were affected by thermal overprinting, then they provide a maximum estimate for the timing of that resetting event.

**Discussion**

Many workers have suggested that VHMS-related mineralisation associated with the Hill End Trough and the Goulburn Basin formed during the middle to late Silurian (e.g. Suppel & Scheibner 1990; Davis 1990). However, prior to the present study, no deposits had been directly dated. The timing of this VHMS event had been largely constrained by the age ranges for units hosting mineralisation and by the lead model ages for individual deposits (summarised by Carr et al. 1995), with estimates ranging from 450 Ma to 400 Ma.

A 418.2 ± 2.2 Ma date for the timing of base metal-sulfide mineralisation at Glen E is only slightly younger than the probable age of the host unit — the Woodlawn Volcanics. Felton and Huleatt (1977) and Abell (1991) suggested that the Woodlawn Volcanics are of late Silurian age. This is supported by U–Pb SHRIMP dating of zircon grains from the Woodlawn Volcanics which gave a 423.4 ± 2.5 Ma date (Black 2005), a 419.2 ± 3.2 Ma date (Bodorkos & Simpson 2008; rhyolite forming part of the hanging wall of the Woodlawn Volcanics — O. Thomas pers. comm., March 2009) and a 422.5 ± 2.3 Ma date (S. Bodorkos pers. comm., March 2009). Furthermore, Percival (I. Percival pers. comm., February 2007) suggested that the Woodlawn Volcanics are early to middle Ludlow in age based on palaeontological and stratigraphic constraints. These estimates are similar and largely within error. Thus, the available data support the interpretation that the mineralisation at The Glen formed at the same time as that for the host volcanism — during the late Silurian. In addition, a lead-model age of 425 ± 11 Ma for Glen E (present study) also supports the interpretation that the deposit formed during the late Silurian.

A feature of the 40Ar/39Ar data is that the high-temperature ages are older than the lower temperature steps. This is consistent with partial argon loss. If the younger, low-temperature steps (Figure 6 Table 3) were affected by thermal overprinting, then they may provide an estimate for the timing of this resetting event. The weighted mean average for all low-temperature steps is 391 ± 3.5 Ma, however, this has a MSWD value greater than 2.5 (2σ; MSWD = 3.5) and thus is not statistically robust (cf. Baksi 2006) and should be rejected. Although a date and error estimate for argon loss cannot be stated with confidence it is suggested it suggested that argon loss occurred as a result of greenschist facies metamorphism and subsequent cooling as a result of the Tabberabberan Orogeny. Glen (2005) suggested that the Tabberabberan Orogeny occurred during the Eifelian (397.5 ± 2.7 Ma to 391.8 ± 2.7 Ma — based on the later timescale of Gradstein et al. 2004; or 391.9 Ma to 388.1 Ma — based on the later timescale of Pogson 2009).

Important features of the Glen E mineralisation include:

- mineralisation timing is coincident with, or is
Table 3. $^{40}$Ar/$^{39}$Ar step-heating analytical results sample Glen DDH 7/1 — Glen E deposit.

| Grain no. | Step no. | Cum. % $^{39}$Ar (x10$^{-13}$ mole) | ± $^{39}$Ar (x10$^{-14}$ mole) | ± $^{38}$Ar (x10$^{-16}$ mole) | ± $^{37}$Ar (x10$^{-16}$ mole) | ± $^{36}$Ar (x10$^{-16}$ mole) | Ca/K ± %40Ar* 40Ar*/$^{39}$Ar ± Age Ma ± Ma |
|-----------|----------|---------------------------------|------------------|------------------|------------------|------------------|----------------|------------------|
| 1         | 1        | 75.0 ± 0.1532                   | 0.0002 ± 0.0073  | 0.0002 ± 0.0144  | 0.0003 ± 0.0179  | 0.0006 ± 0.0179  | 0.0011 ± 0.0323 | 0.0037 ± 87.5  |
|           | 2        | 100.0 ± 0.0477                  | 0.0001 ± 0.0035  | 0.0001 ± 0.0049  | 0.0002 ± 0.0095  | 0.0005 ± 0.0095  | 0.0016 ± 0.0513 | 0.1108 ± 95.8  |
| 2         | 1        | 58.8 ± 0.0811                   | 0.0001 ± 0.0053  | 0.0001 ± 0.0073  | 0.0001 ± 0.0107  | 0.0002 ± 0.0107  | 0.0011 ± 0.0035 | 0.0015 ± 90.7  |
|           | 2        | 100.0 ± 0.0551                  | 0.0001 ± 0.0037  | 0.0001 ± 0.0050  | 0.0002 ± 0.0080  | 0.0005 ± 0.0080  | 0.0013 ± 0.0074 | 0.1096 ± 96.8  |
| 3         | 1        | 43.5 ± 0.0568                   | 0.0001 ± 0.0035  | 0.0001 ± 0.0048  | 0.0001 ± 0.0063  | 0.0002 ± 0.0063  | 0.0014 ± 0.0053 | 0.0031 ± 85.2  |
|           | 2        | 100.0 ± 0.0681                  | 0.0001 ± 0.0046  | 0.0001 ± 0.0051  | 0.0001 ± 0.0080  | 0.0004 ± 0.0080  | 0.0011 ± 0.0041 | 0.0014 ± 99.8  |
| 4         | 1        | 39.2 ± 0.0694                   | 0.0001 ± 0.0043  | 0.0001 ± 0.0056  | 0.0001 ± 0.0080  | 0.0004 ± 0.0080  | 0.0012 ± 0.1203 | 0.0259 ± 85.2  |
|           | 2        | 100.0 ± 0.0988                  | 0.0002 ± 0.0068  | 0.0002 ± 0.0089  | 0.0003 ± 0.0127  | 0.0006 ± 0.0127  | 0.0025 ± 0.1586 | 0.0649 ± 97.2  |
| 5         | 1        | 30.8 ± 0.0173                   | 0.0000 ± 0.0010  | 0.0000 ± 0.0013  | 0.0000 ± 0.0019  | 0.0000 ± 0.0019  | 0.0001 ± 0.0109 | 0.0005 ± 83.0  |
|           | 2        | 100.0 ± 0.0344                  | 0.0001 ± 0.0023  | 0.0001 ± 0.0036  | 0.0001 ± 0.0036  | 0.0001 ± 0.0036  | 0.0001 ± 0.0041 | 0.0004 ± 96.3  |
| 6         | 1        | 51.7 ± 0.0456                   | 0.0001 ± 0.0029  | 0.0001 ± 0.0040  | 0.0001 ± 0.0049  | 0.0001 ± 0.0049  | 0.0008 ± 0.1163 | 0.0851 ± 86.1  |
|           | 2        | 100.0 ± 0.0407                  | 0.0001 ± 0.0023  | 0.0001 ± 0.0033  | 0.0001 ± 0.0031  | 0.0001 ± 0.0031  | 0.0001 ± 0.0010 | 0.0017 ± 99.7  |
| 7         | 1        | 61.7 ± 0.0291                   | 0.0000 ± 0.0018  | 0.0000 ± 0.0024  | 0.0000 ± 0.0011  | 0.0000 ± 0.0011  | 0.0001 ± 0.0103 | 0.0183 ± 85.8  |
|           | 2        | 100.0 ± 0.0180                  | 0.0000 ± 0.0011  | 0.0000 ± 0.0016  | 0.0000 ± 0.0016  | 0.0000 ± 0.0016  | 0.0000 ± 0.0109 | 0.0158 ± 94.5  |
| 8         | 1        | 35.7 ± 0.0398                   | 0.0001 ± 0.0022  | 0.0001 ± 0.0034  | 0.0001 ± 0.0034  | 0.0001 ± 0.0034  | 0.0001 ± 0.0034 | 0.0109 ± 94.5  |
|           | 2        | 100.0 ± 0.0589                  | 0.0001 ± 0.0039  | 0.0001 ± 0.0054  | 0.0001 ± 0.0054  | 0.0001 ± 0.0054  | 0.0001 ± 0.0038 | 0.0076 ± 96.0  |
| 9         | 1        | 47.2 ± 0.0243                   | 0.0001 ± 0.0016  | 0.0001 ± 0.0027  | 0.0001 ± 0.0055  | 0.0001 ± 0.0055  | 0.00015 ± 0.1536 | 0.1675 ± 88.2  |
|           | 2        | 100.0 ± 0.0268                  | 0.0000 ± 0.0018  | 0.0000 ± 0.0020  | 0.0000 ± 0.0020  | 0.0000 ± 0.0020  | 0.0000 ± 0.1580 | 0.1127 ± 99.1  |

Notes
i) Errors are one sigma uncertainties and exclude uncertainties in the J-value.
ii) Data are corrected for system backgrounds, mass discrimination, fluence gradients and atmospheric contamination.
iii) Interference corrections: ($^{39}$Ar/$^{37}$Ar)$_{Ca}$ = 2.63 ± 0.01 × 10$^{-4}$; ($^{39}$Ar/$^{37}$Ar)$_{K}$ = 0.0015 ± 0.0007
iv) J-value is based on an age of 98.8 Ma for GA-1550 biotite.
shortly after, (host) volcanism

- a reduced seawater sulfate sulfur-isotope signature — associated with a relatively oxidised sulfide assemblage (pyrite with chalcopyrite, galena and sphalerite but no observed pyrrhotite or arsenopyrite)

- a mineralisation-related alteration assemblage of quartz, muscovite and chloride — consistent with slightly acidic to near neutral fluid chemistry

- a crustal lead isotope signature with a middle Silurian lead-model age consistent with lead being sourced from the host sequence.

Based on those four features, the Glen E deposit is classified as a VHMS-type deposit following Large’s usage (1992). Such deposits can consist of stratiform to stratabound base-metal massive sulfide-rich lenses, related stringer zones and/or massive replacement pipes that occur in a sequence dominated by submarine volcanic rocks — the sulfide-rich mineralisation having formed at about the same time as the host volcanic rocks (Large 1992). It is likely that the Glen E zone is either part of a sub-seafloor replacement or stringer zone, rather than being part of a mound- or brinepool-type deposit. The VHMS-related mineralisation at Glen E was deformed in the Middle Devonian during the Tabberabberan Orogeny and the zone is distinct from the Collector massive pyrrhotite–pyrite mineralisation, 350 m to the west.

Important features of the Collector deposit include:

- a reduced sulfide assemblage that contains pyrrhotite, other sulfides including pyrite, sphalerite, chalcopyrite and minor galena — also with magnetite

- a calc-silicate assemblage with quartz, carbonate, actinolite, diopside, andradite (Richardson & Swingler 1992), chloride, tremolite and wollastonite (N & K Swingler & Associates 2000)

- sulfide-rich zones with elevated levels of gold, silver, bismuth, molybdenum, antimony, cadmium and cobalt (Richardson & Swingler 1992), some being typical of intrusion-related mineralisation

- a lead-isotope signature indicating that lead incorporated into the deposit was sourced from a slightly older lead reservoir than that for the adjacent Glen E deposit

- a sulphur-isotope signature that is very similar to that preserved in the Glen E deposit which, when combined with a reduced sulfide assemblage, suggests that the reduced fluids sourced sulfur from the adjacent sequence.

Based on those five features, the Collector zone is classified as a reduced sulfide-rich skarn. Richardson and Swingler (1992) suggested that Collector is a distal iron-rich exoskarn with minor base metals or possibly a hybrid zinc skarn as outlined by Einaudi et al. (1981). Those authors also recognised the possibility that the zone may have been a feeder to a VHMS-style system. However, the features for Collector are more typical of skarn-type mineralisation and are distinct from those for the adjacent Glen E VHMS mineralisation.

Massive pyrrhotite is unusual in iron- or zinc-rich skarns and more common in reduced skarn systems. The presence of andradite, diopside and wollastonite, together with elevated levels of gold, silver, bismuth, molybdenum and antimony in addition to zinc, lead and copper, suggest the zone may be a polymetallic molybdenun skarn as outlined by Einaudi et al. (1981), or a reduced gold skarn as outlined by Meinert (1989, 1998). Both molybdenun and reduced gold skarns can be zoned. Einaudi et al. (1981) noted that significant sphalerite can be present in the distal part of the molybdenun skarn systems, although Meinert (1998) noted that reduced gold skarns are commonly zoned with respect to garnet–pyroxene ratio and geochemistry (increased gold, antimony, bismuth, cadmium, manganese, lead and zinc in the distal part of the skarn system). In addition, Meinert (1998) noted that reduced gold skarns often contain arsenopyrite and löllingite, as well as minor chalcopyrite, pyrite, sphalerite, hedleyite, native bismuth and gold. The presence of andradite, diopside and wollastonite suggests that Collector is intermediate to, rather than distal to, the causative intrusion.

It is proposed that the Collector massive sulfide mineralisation is part of a zoned reduced gold skarn system rather than being part of an iron skarn or hybrid zinc skarn as proposed by Richardson and Swingler (1992). The absence of significant molybdenite suggests that the deposit is not a molybdenum skarn.

The timing of skarn formation at the Collector prospect is poorly constrained. Based on the available data it is likely that Collector formed as a result of the intrusion of a pluton related to the Bega Batholith during the Early Devonian or as a result of the intrusion(s) of similar age — such as quartz monzodiorites and tholeiitic dolerites which crop out within the study area (Figure 2) — shown as ungrouped Devonian intrusions. U–Pb SHRIMP dating of zircons from the Boro Granite, which is associated with the Terry Hie and Astrids skarns near Inveralochy (11 km southeast of The Glen — Figure 2), gave a 411.5 ± 3.1 Ma age. The Braidwood Granodiorite, which is host to the Dargues Reef intrusion-related gold deposit (McQueen & Perkins 1995), is only very slightly younger at 410.2 ± 3.1 Ma and 410.8 ± 3.2 Ma (Bodorkos & Simpson 2008). Some of these dates overlap with selected high-temperature step-heating results for muscovite grains from the Glen E deposit that are interpreted to have undergone
partial argon loss during the Early Devonian (i.e. grain 2 step 2, grain 8 step 2 — Table 3).

**Conclusion**

Multiple mineralising events have been identified near The Glen, 23 km southwest of Goulburn. These include VHMS-related mineralisation at the Glen E base-metal prospect at approximately 418.2 ± 2.2 Ma and a reduced gold skarn at the adjacent Collector prospect. The area was subsequently deformed during the Tabberabberan Orogeny in the Middle Devonian.

Dating of the Glen E deposit supports earlier suggestions that VHMS mineralisation associated with the Hill End Trough and the Goulburn Basin is late Silurian in age — with the base metal mineralisation being contemporaneous with or formed shortly after volcanism. Sulfur-isotope data suggest that the majority of sulfur included in this deposit was sourced from a reduced seawater sulfate source. Lead-isotope data suggest that the majority of metals were sourced from the host sequence — the Woodlawn Volcanics.

It is suggested that the Collector mineralisation is part of a zoned reduced gold skarn system. Isotope data suggest that the majority of sulfur and lead incorporated into the Collector deposit was sourced from the host sequence.

This study has highlighted The Glen area as an area in which multiple mineralising events have occurred. This has enhanced the prospectivity of the area and highlighted the need for additional exploration.

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Lu J., Seccombe P.K., Foster D. & Andrew A.S. 1996. Timing of mineralisation and source of fluids in a slate-belt auriferous vein system, Hill End goldfield,
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