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New geochronological and isotopic constraints on granitoid-related gold mineralisation near Majors Creek, New South Wales

Abstract

Previous workers have variously interpreted the style of gold mineralisation in the Majors Creek area, southeastern New South Wales, as epithermal or granitoid-related. The epithermal model implies that the mineralising event occurred during the opening of the Eden–Comerong–Yalwal rift zone, several million years after assembly of the host Braidwood Granodiorite.

We present new $^{40}Ar/^{39}Ar$ dating of white micas intimately associated with gold-bearing sulfides. These analyses give an age of 410.9 ± 2.0 Ma (2σ) for the gold-bearing greisen at Dargues Reef and 410.8 ± 1.8 Ma (2σ) for vein-style gold mineralisation at the Great Star mine (Majors Creek). These ages lie within the error of previous U–Pb SHRIMP ages for the Braidwood Granodiorite, which strongly suggests that a single hydrothermal mineralising event occurred in the Majors Creek district.

Sulfur isotope data supports the interpretation that open-system ^{34}S–^{32}S fluid–mineral fractionation occurred during the mineralising event at Dargues Reef. By contrast, the data for base metal bearing veins at Majors Creek indicates that closed-system ^{34}S–^{32}S fluid–mineral fractionation was predominant.

A genetic model is proposed for mineralisation in the Majors Creek district. The mineralogy, intrusive relationships and physiography at Dargues Reef and other key vein systems in the area suggest that magmatic-dominated hydrothermal fluids exsolved from late-stage felsic phases of the Braidwood Granodiorite. These mineralising fluids were then focused into fractures and along pre-mineralisation mafic- to intermediate dykes, which may also have been the focus of post-mineralisation intrusive phases.

The mineralisation is similar to other intrusion-related gold provinces, but the causative pluton is comparatively more oxidised and unevolved. Granitoids with analogous characteristics are widespread in the Tasmanides of eastern Australia. The recognition of the mineral potential of such plutons highlights the exploration potential of the region.

Key words: *Braidwood Granodiorite, Majors Creek, Dargues Reef, gold mineralisation, sulfur isotopes, $^{40}Ar/^{39}Ar$ dating, deposit model, granitoid-related gold*

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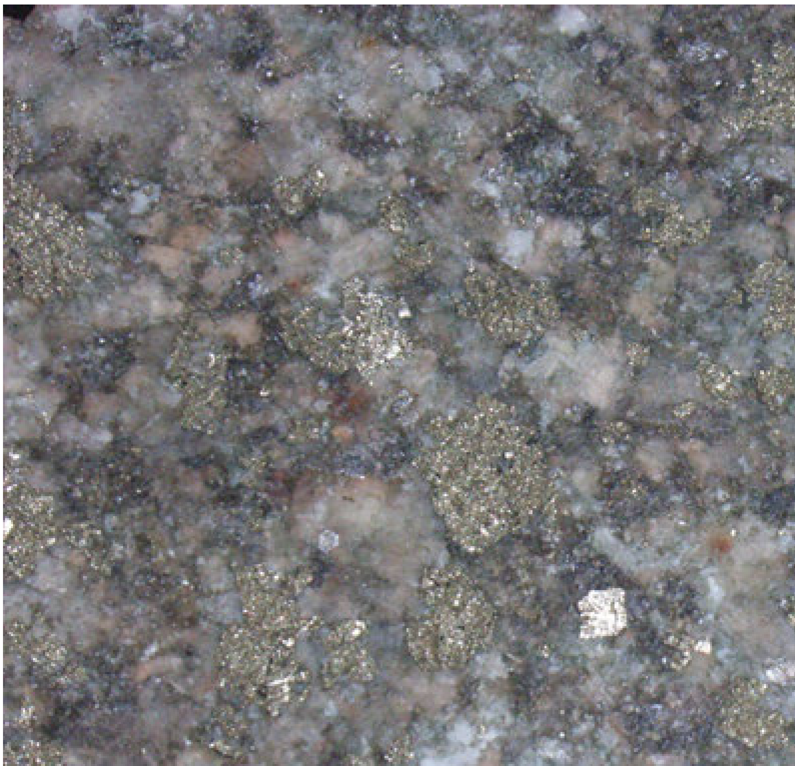

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Cover image: Drillcore sample from Dargues Reef of Braidwood Granodiorite with typical pyritic 'lode' gold mineralisation. Field of view is about 5cm. Photographer: O.D. Thomas.

Introduction

The Majors Creek district, located 14 km south of Braidwood in southeastern New South Wales (Figure 1), is host to two major styles of primary (hard-rock) mineralisation — auriferous greisen zones (e.g. Dargues Reef) and quartz-rich base metal–telluride–gold veins and disseminations (e.g. Majors Creek area). Dargues Reef is the largest deposit that has been identified; it contains a resource (measured, indicated and inferred) totalling 1.615 Mt and assaying 6.3 g/t Au (Cortona Resources Limited announcement to the Australian Stock Exchange dated 30/11/2010). The Braidwood Granodiorite and adjacent Long Flat Volcanics (Figures 2 & 3) host the primary gold mineralisation in the Dargues Reef–Majors Creek area. McQueen and Perkins (1995) suggested that this area was the main source of placer gold found in the alluvial deposits associated with the Shoalhaven and Araluen river systems. Past production from these alluvials exceeded 40 t of gold (Middleton 1970).

Two ore-forming processes have been proposed for the greisen- and vein-hosted mineralisation in the Dargues Reef–Majors Creek area. Wake and Taylor (1988) proposed that mineralisation at Majors Creek was epithermal in nature. They suggested that the veins formed during the extension event which resulted in the Eden–Comerong–Yalwal Rift Zone (ECYRZ) at around 376 Ma (based on dating of the Boyd Volcanics by Wyborn and Owen (1986) cited in Lewis et al. 1994). This implied that the mineralisation is ~40 Ma younger than the Early Devonian Braidwood Granodiorite host. Conversely, McQueen and Perkins (1995) presented sulfur-, oxygen- and carbon-isotope data for Dargues Reef and suggested that mineralisation in the Dargues Reef–Majors Creek area was related to late magmatic phases of the Braidwood Granodiorite. They also found that K–Ar dating of sericite from the Main lode at Dargues Reef gave an age of 411 ± 5 Ma, while sericite from the adjacent Big Blow lode (Dargues Reef) gave an age of 406 ± 4 Ma, which overlapped the K–Ar ages of 415 ± 4 Ma and 412 ± 4 Ma of biotite from the Braidwood Granodiorite reported by Wyborn and Owen (1986).

Direct dating of mineralisation can provide important information regarding the controls to ore-forming processes and improve our understanding of metallogenic events. Here we present new dating and isotopic data along with petrographic and geological evidence for gold mineralisation at Dargues Reef and the auriferous base metal vein-type mineralisation at Majors Creek. The Mineral Systems Group (MinSys) of the Geological Survey of New South Wales (GSNSW) undertook this work to better understand the mineralising processes associated with the Braidwood Granodiorite and to support the geological mapping and metallogenic assessment of the adjacent Braidwood 1:100 000 map sheet area (see Fitzherbert & Deyssing in press). The broad-based approach adopted in this study has enabled us to place pivotal constraints on the mineralising processes associated with the Braidwood Granodiorite, and to propose a new genetic model for deposits in the Majors Creek area.

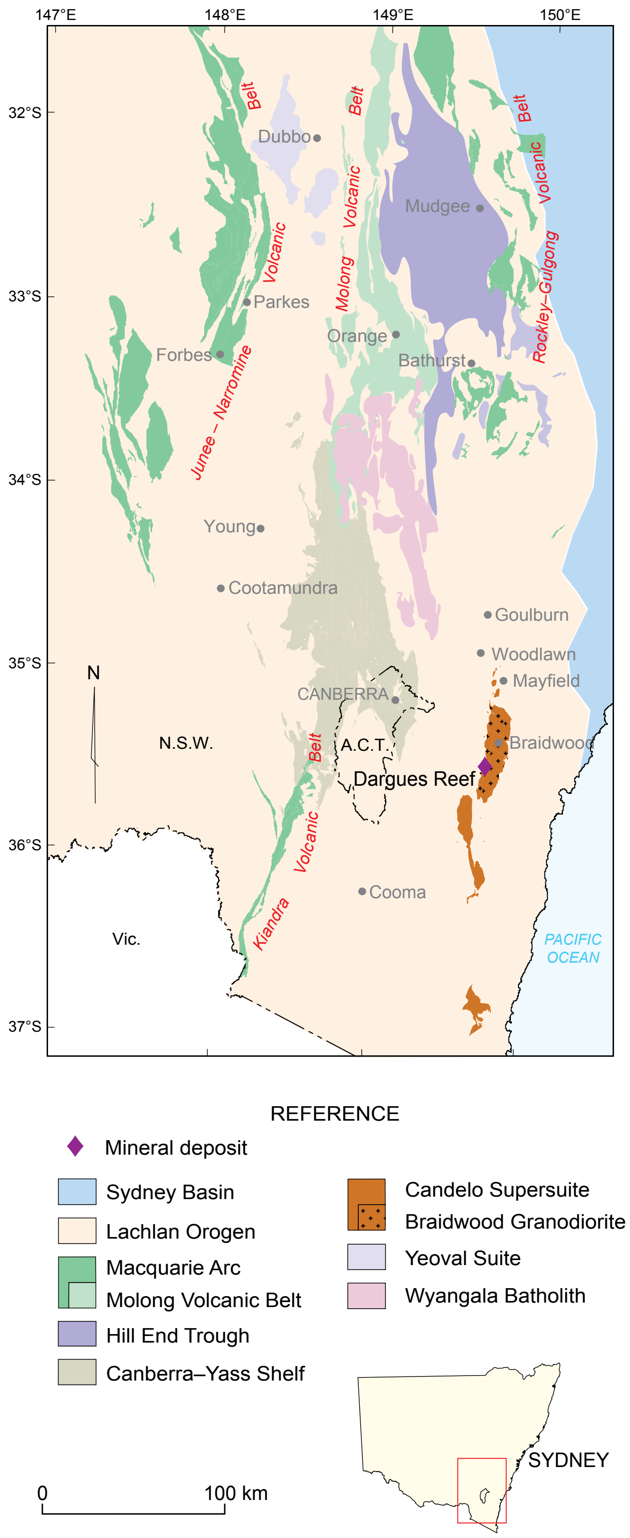


Figure 1. Location of the study area and major structural units of the Eastern subprovince of the Lachlan Orogen in N.S.W. Main deposits of the Candelo Supersuite are shown.

Geological setting and metallogeny

The Lachlan Orogen (formerly the Lachlan Fold Belt: Scheibner 1975) represents part of an extensive orogenic system — the Tasmanides (Scheibner & Basden 1996; Foster & Gray 2000; Glen 2005). The Tasmanides extends for more than 1000 km from east to west, and has a roughly north–south strike for about 3000 km, from Tasmania to Queensland. The Lachlan Orogen belt has three main subprovinces — the Western, Central and Eastern (Glen 2005).

The Majors Creek district is located within the Eastern subprovince of the Lachlan Orogen, which is dominated by Ordovician to early Silurian quartzose turbidites and mafic to intermediate volcanic rocks with related intrusions, early Silurian to lower Carboniferous volcanic, sedimentary and plutonic rocks, and rare Permian volcanic rocks. Glen et al. (1998) have suggested that this area was part of an outboard convergent continental margin terrane, dominated by stacked Ordovician turbidites of the Adaminaby Group and black shale units of the Bendoc Group. These rocks have been intruded and unconformably overlain by mafic to felsic igneous rocks, and by sedimentary rocks of middle to late Silurian–Early Devonian age (Foster et al. 1999; Collins 2002; 2003). Importantly, some of these late Silurian–Early Devonian volcanic rocks and volcanic-derived rocks were deposited in shallow to deep marine basins formed by rifting that possibly occurred in response to eastwards migration of subduction zones in the palaeo-Pacific Ocean (Collins 2002). In addition, middle Silurian to Early Devonian granitoids are widespread in the area (Chappell et al. 1988).

Four major styles of mineralisation are identified in the southeastern part of the Eastern subprovince of the Lachlan Orogen (see Downes 2009; Downes et al. 2011; Downes & Forster in Fitzherbert & Deyssing in press). These are: 1) volcanic-associated massive sulfide mineralisation associated with late Silurian volcanic rocks and related sedimentary rocks deposited in rift-related marine basins; 2) intrusion-related (including granite-related and skarn-type) mineralisation associated with late Silurian to Early Devonian granites; 3) deformation-related gold and base metal mineralisation related to the Middle Devonian (Tabberabberan) and early Carboniferous (Kanimblan) orogenies; and 4) epithermal mineralisation associated with volcanism in the ECYRZ. The ECYRZ is a 320 km-long belt of bimodal volcanic rocks and sedimentary rocks of Middle to Late Devonian age (late Givetian to Famennian — see Lewis et al. 1994) that hosts low sulfidation epithermal gold systems, including Pambula and Yalwal (both outside the study area — see Downes 2009; Downes et al. 2011).

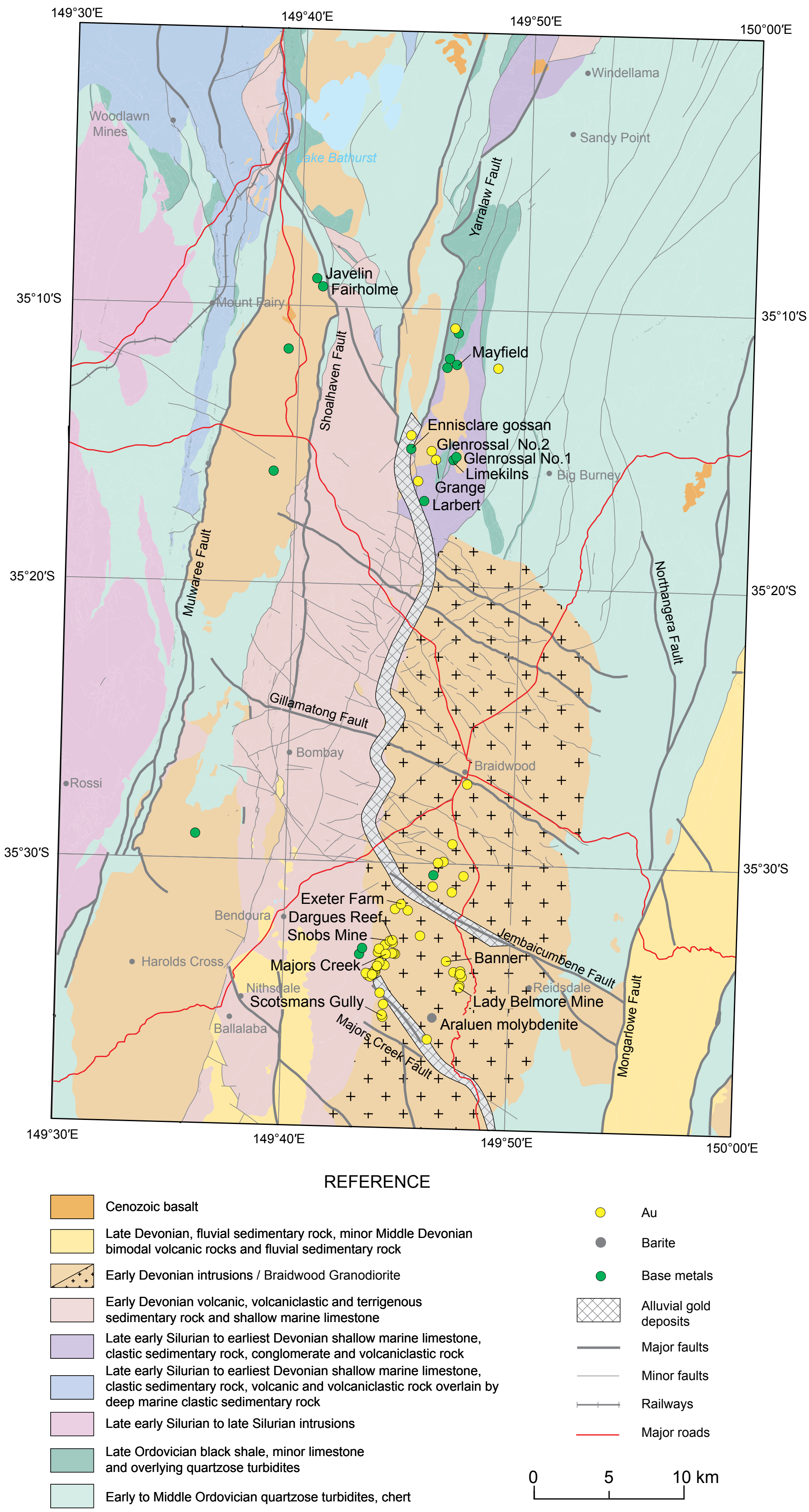


Figure 2. Geological map of the eastern part of the Canberra 1:250 000 map sheet.

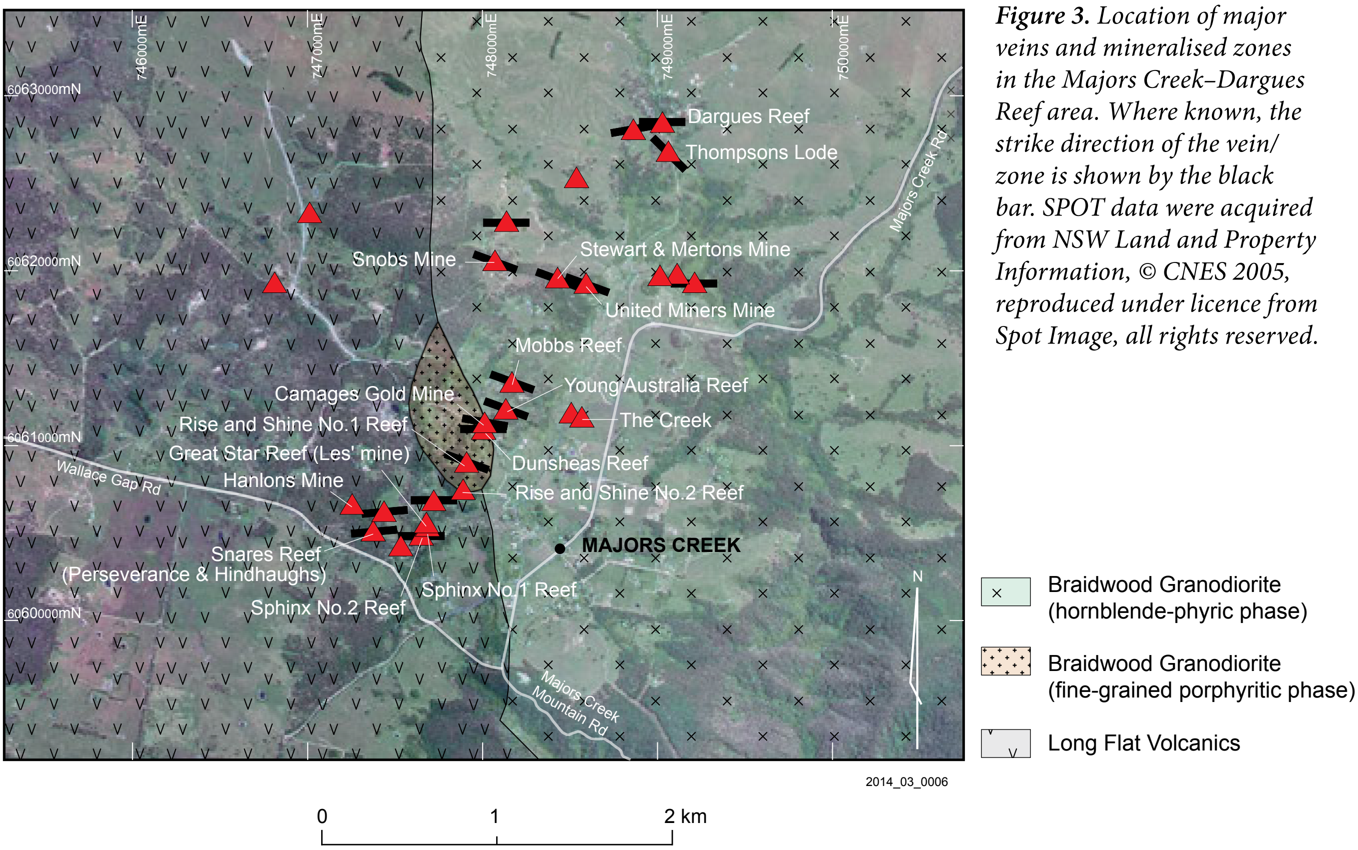


Figure 3. Location of major veins and mineralised zones in the Majors Creek–Dargues Reef area. Where known, the strike direction of the vein/zone is shown by the black bar. SPOT data were acquired from NSW Land and Property Information, © CNES 2005, reproduced under licence from Spot Image, all rights reserved.

In the Majors Creek area, most of the hard-rock gold mineralisation occurs close to the shallowly west-dipping contact between the Braidwood Granodiorite and the Long Flat Volcanics to the west of the village of Majors Creek (Figure 3). The Braidwood Granodiorite is part of the Braidwood Suite (Fitzherbert & Deyssing in press), which in turn is part of the Candelo Supersuite (Chappell et al. 1988; Chappell et al. 1991). Plutons forming part of the Candelo Supersuite extend from near Wangarabell in Victoria to Lower Boro, 15 km north of Braidwood (Figure 2). The Braidwood Granodiorite is a multi-phase (McQueen & Perkins 1995) I-type intrusion (Collins et al. 1982; Chappell et al. 1988). The main phases in the study area are the eastern and western phase (Wyborn & Owen 1986; McQueen & Perkins 1995). Fitzherbert and Deyssing (in press) named the western phase the 'hornblende–phyric phase' and the eastern phase the 'equigranular phase', noting that they are compositionally identical; their main distinguishing feature is the differing habit of hornblende. The Braidwood Granodiorite is predominantly a hornblende–biotite quartz monzonite or granodiorite to a hornblende–clinopyroxene–biotite microgranodiorite. It is metaluminous and unfractionated (Collins et al. 1982) with high K, Rb, REE, Ba and Sr (Wyborn & Owen 1986). It is rather oxidised (Fe_2O_3/FeO of 0.45 to 0.70) and consequently it is magnetite ± hematite-bearing (Blevin 2003). K/Rb values range between 148 and 262. Blevin (2003) argued that the batholith is moderately to strongly evolved (see also Fitzherbert & Deyssing in press).

Several age constraints are available for the Braidwood Granodiorite, which intrudes the Long Flat Volcanics to the west of Majors Creek, dated at 411.5 ± 3.1 Ma (Bodorkos et al. 2008: Figure 3). Wyborn and Owen (1986) dated the eastern (less mineralised) phase of the Braidwood Granodiorite by the K–Ar technique at between 401 ± 6 and 415 ± 4 Ma (on hornblende: 401 ± 6 Ma, 403 ± 4 Ma; on biotite: 412 ± 4 Ma, 415 ± 4 Ma). In addition, they reported whole-rock Rb–Sr pairs from that phase which yielded a 399 ± 6 Ma date (Wyborn & Owen 1986). More recently, U–Pb SHRIMP dating of zircons by Bodorkos et al. (2008) reported ages of 409.3 ± 3.0 Ma for the eastern phase and 409.9 ± 3.2 Ma for the western phase. These ages are interpreted as representing the crystallisation age for part of the host pluton, but the dated samples were not intimately associated with the mineralisation and may not reflect its age.

Metamorphism of the Braidwood Granodiorite in the Majors Creek district is of sub-greenschist to lower greenshcist facies (Fitzherbert & Deyssing in press). There is a 3 km wide cordierite ± andalusite–muscovite-bearing metamorphic aureole developed on the eastern margin of the pluton. No such aureole has been identified along the western margin, where a fine-grained variant of the Braidwood Granodiorite crops out near the village of Majors Creek (Figure 3). This supports Lackie and Flood's (1991) interpretation that the pluton has been tilted by about 20° to the west and has thus been unroofed to the east.

Geology and mineralisation of the Majors Creek district

McQueen and Perkins (1995) suggested that much of the hard-rock gold mineralisation in the Dargues Reef–Majors Creek area lies near the roof zone of the granite, and that it is hosted by the equigranular to locally porphyritic phases of the Braidwood Granodiorite and is close to the shallowly west-dipping contact with the host Long Flat Volcanics (Figures 2 & 3).

Based on field observation and interpretation of aeromagnetic data, several structural trends controlled the orientation of dykes, veins, lodes, faults and joints. Most of the mineralisation is hosted by two structural trends. One strikes approximately east–west and plunges very steeply. It includes auriferous phyllic lodes in the Dargues Reef area and a number of mineralised veins to the south near Majors Creek (e.g. Hanlons, Great Star, Sphinx No. 1, Dunsheas Reef and Mobbs Reef). The other trend strikes west-northwest–east-southeast and also plunges steeply (e.g. Snobs Reef, Snobs Lode–Stewart & Mertons–United Miners zone: Figure 3). Other structural trends that control the orientation of dykes and veins strike at ~055°, ~150° and ~075° (e.g. an aplite dyke that is closely associated with mineralisation at The Creek prospect — GR 748637 606156 near Snobs Reef).

Narrow (<10 m wide) mafic and intermediate to felsic dykes, microporphyritic inclusions, orthoclase–quartz ± muscovite pegmatites and orthoclase–quartz aplites (*sensu lato*) are present in the study area (see also Kennedy 1961; Duncan 1984; Wake 1985; Wake & Taylor 1988; McQueen & Perkins 1995). Their composition reflects markedly varying abundances of hornblende, quartz and plagioclase feldspar phenocrysts in a microcrystalline matrix. The largest dykes observed in this study are composed of diorite to quartz monzonite. They strike ~075–090° and occur within the mineralised zones at Dargues Reef and Exeter Farm (Figures 2 & 4).

Faults trend east–west and east–southeast, post-dating the mineralising events. They focus modern drainage and the distribution of alluvial gold deposits along Jembaicumbene Creek. The faults observed to contact the mineralisation in this study all have near-vertical displacements of 10 m or less.

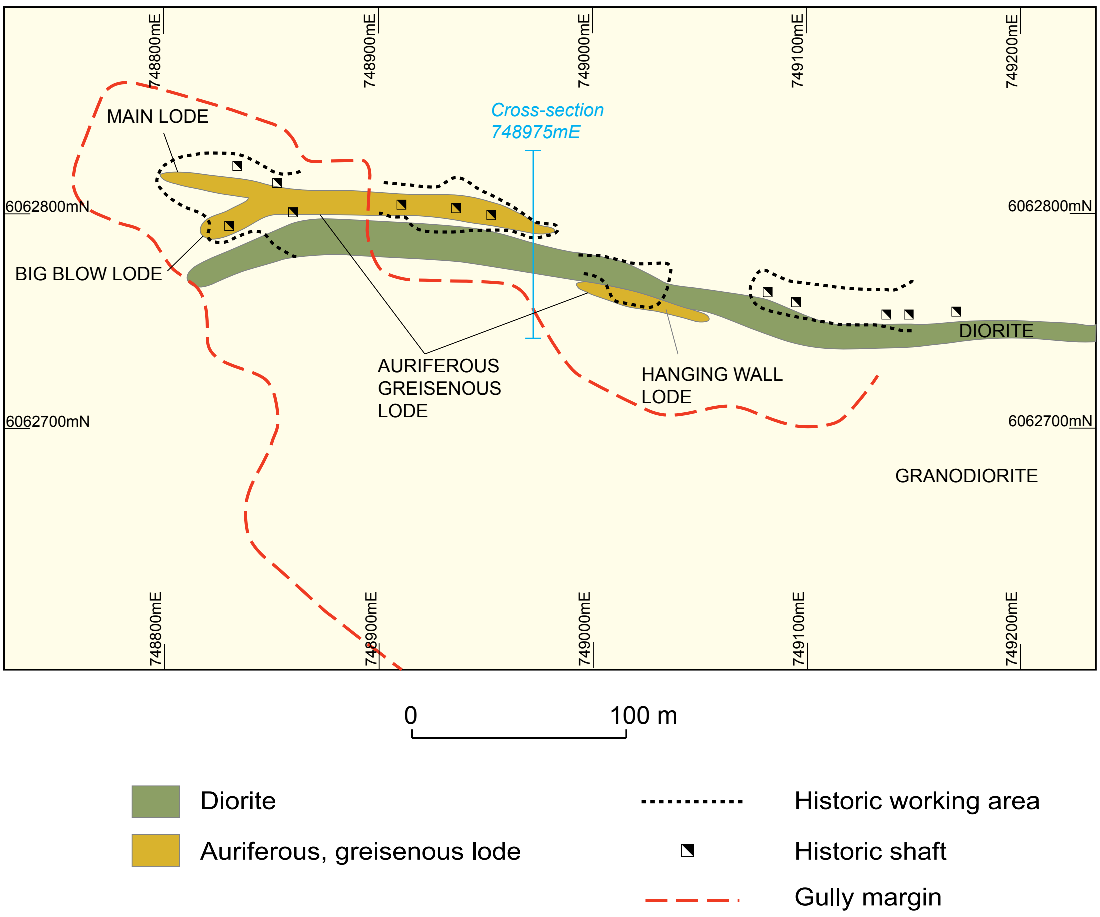


Figure 4. *Map of Dargues Reef showing the distribution of the mineralised (auriferous) lodes, diorite dyke and cross-section. Black boxes indicate historical shafts. (Dyke, lodes and shafts after Cortona Resources Limited ASX announcement, May 2008.) The mineralised lodes define a 2 ppm Au envelope and consist of albite–muscovite–pyrite–chlorite (replacing plagioclase and K-feldspar) or phengite–pyrite with minor other sulfides.*

Ore geology

The geology and gold mineralisation in the Dargues Reef–Majors Creek area has been described by Kennedy (1961), who established several important timing relationships for mineralisation, and by Gilligan (1975), Goleby (1977), Wake (1985), Wake and Taylor (1988), Ho et al. (1995), McQueen and Perkins (1995), McQueen (2003) and Fisher (2006). Three major mineralisation styles are present: auriferous, pyrite-rich greisenous zones such as those at Dargues Reef, Exeter Farm and Scotsmans Gully; gold–base metal-rich veins/lodes, including those adjacent to the Majors Creek village (Figure 3); and those deposits which have both greisen- and vein-type mineralisation, including those in the Snobs mine area, which takes in Snobs Reef (Snobs Lode–Stewart & Mertons–United Miners zone) and The Creek prospect.

Dargues Reef is the largest deposit in the study area (Figures 3, 4 & 5). The 'reef' was worked between 1875 and 1916, producing a reported 1.95 t gold (Goleby 1977; Table 1, p. 22). Smaller hard-rock gold–base metal veins and disseminations that were worked include the Snobs Reef (Snobs Lode–Stewart & Mertons–United Miners mines), Great Star Reef and Camages Reef (Figure 3). In total, the recorded hard-rock gold production from the area (excluding Dargues Reef) was 0.85 t (GSNSW data). Away from the Dargues Reef–Majors Creek area, minor hard-rock mineralisation is also present at Exeter Farm, the Banner and Lady Belmore mines (Figure 2), 5.3 km east of Majors Creek, and at Scotsmans Gully, 2.8 km south of Majors Creek.

Work undertaken and laboratory studies

As part of the present study, diamond drillholes DREX0027, DREX0028 and DREX0043 from Dargues Reef were logged in detail with additional information utilised from several of the 100+ diamond and reverse circulation (RC) drillholes at the deposit. In addition, field reconnaissance and sampling were conducted at a number of the other workings in the Majors Creek area. Core from diamond drillhole DREX0027, together with dump and surface samples from the Great Star mine and Snobs Reef, were systematically sampled using a portable infrared mineral analyser (PIMA) to obtain their short wave infra-red (SWIR) spectra to help identify alteration-related minerals associated with mineralised zones. Spectra were analysed using The Spectral Geologist version 4.0 software as described by Pontual et al. (1997). Thin sections for 18 samples were also prepared and examined by petrological microscope. Fourteen of these samples were from Dargues Reef (fresh Braidwood Granodiorite, diorite dykes and major alteration styles) and four were of vein-type mineralisation from Majors Creek.

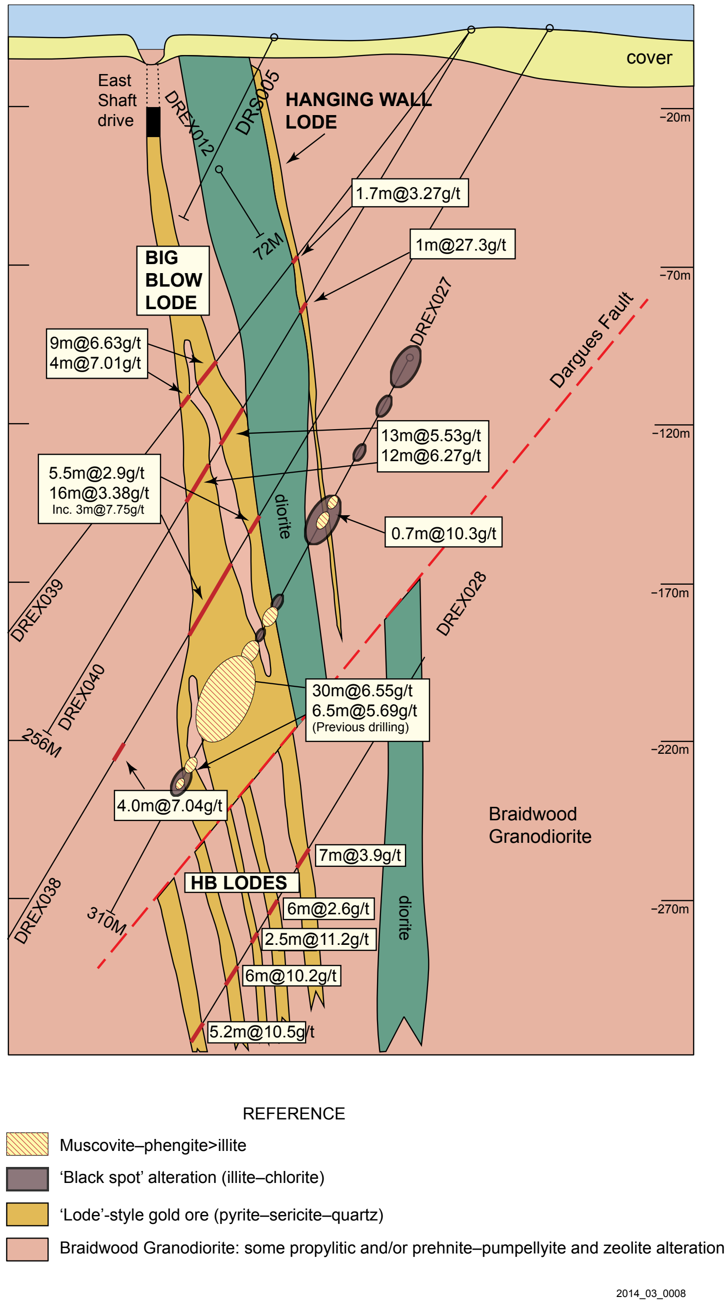


Figure 5. *Cross-section 748975E (looking east) of Dargues Reef deposit including significant intersections by Cortona Resources Limited. Alteration for drillholes DREX0027 and DREX0028, this study.*

In preparation for $^{40}Ar/^{39}Ar$ dating, muscovite grains were recovered from diamond drillcore sample DREX0027 220.2 m at Dargues Reef, and from rock chip sample PGDS01/8 from the Great Star mine using standard crushing, sieving, de-sliming and magnetic separation methods. Individual muscovite grains were hand-picked from the final concentrate for each sample and washed in deionised water and acetone, then shipped for irradiation in the McMaster reactor, Hamilton, Ontario, Canada. Grains were wrapped in aluminium packets and placed into an aluminium irradiation canister together with aliquots of the flux monitor GA1550 biotite (age = 98.8 ± 0.5 Ma; Renne et al. 1998).

Following irradiation, $^{40}Ar/^{39}Ar$ analyses were undertaken at the University of Melbourne, using procedures described by Phillips and Miller (2006) and Matchan and Phillips (2011). Individual muscovite grains were step-heated by a CO_2 laser. Argon isotopes were analysed on a MM5400 mass spectrometer equipped with a Daly detector. The reported isotopic data was corrected for system backgrounds, mass discrimination, fluence gradients and atmospheric contamination. Unless otherwise stated, the errors associated with the age determinations are 1σ uncertainties, and exclude uncertainties in the J-value, age of the fluence monitor GA1550 and the decay constants of Steiger and Jager (1977). The $^{40}Ar/^{39}Ar$ dating technique has been described in detail by McDougall and Harrison (1999).

Thirty-six sulfur isotope analyses were carried out as part of this study. Samples were selected from diamond drillholes DREX0027, DREX0028 and DREX0043 from Dargues Reef and drillhole EXE0014 at Exeter Farm, and from mine dump samples collected from Snobs Reef and the Great Star mine. Samples were described in hand specimen and using a binocular microscope. Sulfide-rich powders were obtained using a micro-drill under a binocular microscope, then crushed using an agate mortar and pestle. Contamination of mineral separates by other sulfide species was minimised by selecting coarse-grained material where possible. Any magnetic material (e.g. magnetite) or any possible micro-drill detritus (e.g. stainless steel) were removed using a rare-earth magnet covered by latex in a beaker of distilled water. The powders were then filtered and dried in an incubator at 60°C. Isotopic analyses were undertaken at the Nevada Stable Isotope Laboratory, University of Nevada, Reno, USA, using the procedure described by Glesemann et al. (1994), and also at the Environmental Isotopes Pty Ltd laboratory, North Ryde (Sydney) using the procedure outlined below. Sulfide samples (<0.1 mg) were combusted in a tin cup using a modified Roboprep elemental analyser attached to a Finnigan MAT 252 mass spectrometer. V_2O_5 was added to the sulfate samples and standards to enhance combustion. Samples were analysed relative to an internal gas standard and laboratory standards, including Ag_2S sample 3 = 0.4 ‰ (Vienna Canyon Diablo troilite, VCDT) and CSIRO S-SO_4 = 20.4‰ VCDT. The laboratory standards were calibrated using international standards IAEA-S1 ($\delta^{34}S$ = −0.3‰ VCDT) and NBS-127 ($\delta^{34}S$ = 20.3‰ VCDT) (A. Andrew, Environmental Isotopes Pty Ltd pers. comm. June 2011). Data from both laboratories was reported to an accuracy of ± 0.2/mL relative to Canyon Diablo troilite (CDT) and a variety of secondary standards.

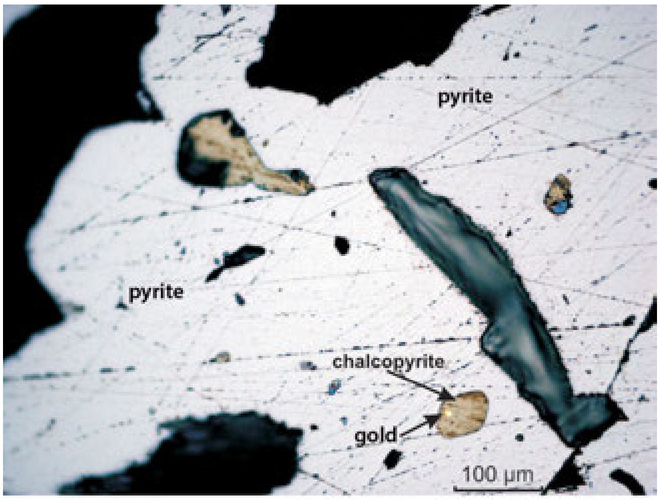
Results

Dargues Reef

Gold mineralisation at Dargues Reef is hosted by the Braidwood Granodiorite and is associated with sulfide-rich greisen-style alteration similar to that at Snobs Reef, Exeter Farm and Scotsmans Gully (Figure 2). Mafic to felsic dykes, microporphyritic inclusions, K-feldspar–quartz ± muscovite pegmatite dykes (Photograph 1) and vugs, as well as microcrystalline aplite dykes, are all features of the host Braidwood Granodiorite in the Majors Creek area, and were observed within 200 m of the Dargues Reef ore zone. However, only the Braidwood Granodiorite itself and the diorite to quartz monzonite 'mafic' dykes were altered and mineralised as part of the gold mineralising event.

The Dargues Reef deposit includes two main lodes, Main lode and Big Blow lode. Main lode dips steeply to the south and extends to a depth of 450 m (Figure 4). These lodes are in the immediate footwall of a major dyke and probably intersect with a plunge of about 70° to the east (Cozens et al. 2008). Recent drilling has shown that additional higher-grade ore zones are present within a lower-grade alteration envelope surrounding the Dargues Reef ore structure (e.g. HB lodes, Hanging Wall lode: Figure 5), and that additional auriferous greisen zones are present away from the main zone (e.g. Ruby lode).

Photograph 1. *Unaltered, apparently post-mineral pegmatite dyke with miarolitic quartz (Photographer D.B. Forster).*



Photograph 2. *Photomicrograph of sulfide-rich mineralisation from diamond drillhole DREX0028 (369.3 m, Dargues Reef) under reflected light. Although the area under the microscope is badly scratched, the image shows a bright yellow gold grain and dull brown chalcopyrite grains as micro-inclusions in pyrite (Photographer D.B. Forster).*

The auriferous greisens typically consist of a white mica (muscovite, phengite)–pyrite–albite assemblage. The ore assemblage is dominated by pyrite (up to 30% of the rock) with minor chalcopyrite, galena, tellurides (tellurobismuthite, rucklidgeite and Ag–bearing telluride), bismuthinite, bismuth, Bi-sulfosalts (aikinite, krupkaite, Ag-bearing aikinite–krupkaite and possible berrite), pyrrhotite, tetrahedrite and native gold also being present (McQueen & Perkins 1995). Gold correlates well with the abundance of pyrite, occurring as inclusions in pyrite (inclusions up to 50 µm were observed in the present study), in association with Bi-bearing tellurides and chalcopyrite (Photograph 2), as free gold along pyrite grain boundaries and in trace amounts within the feldspathic silicate–carbonate gangue (McQueen & Perkins 1995). Two forms of pyrite have been observed. Most pyrite is equant and may show minor embayment; however, Mason (2008) also identified a rare 'porous' and embayed form of pyrite and suggested that this may represent an earlier generation. Quartz veins are not abundant within the sulfide-rich greisens, although some minor pyrite-rich quartz veins were noted, including some that have formed along the margins of aplite dykes (Kennedy 1961).

Logging of diamond drillholes from Dargues Reef indicates that the system is zoned. Three main alteration zones were identified:

1. An unmineralised outer zone with bright pink feldspar (due to micro-inclusions of hematite: McQueen & Perkins 1995), dark chlorite, and minor epidote, illite, quartz, pyrite and prehnite–pumpellyite.
2. An intermediate zone with dark green to almost black clotted chlorite and calcite (replacing and nucleating on ferromagnesian minerals) and albite–illite–muscovite (replacing primary feldspars, particularly calcic-rich varieties) with minor quartz, sphene and magnetite. Gold grades in the zone of black, clotted chlorite are commonly anomalous but mostly well below 1 ppm.
3. A relatively intense, inner 'lode' assemblage with albite–muscovite–pyrite–chlorite (replacing plagioclase and K-feldspar) or phengite–pyrite with or without minor quartz, pyrrhotite, chalcopyrite and/or trace galena. Magnetite occurs in association with pyrite replacing mafic minerals but is generally less abundant in this inner zone than in the adjacent intermediate zone. In the deeper parts of some of the lodes, Cozens and Maher (2010) noted intense 'felsic lodes' that largely consist of K-feldspar–albite–pyrite ± chlorite. With less abundant mica than the typical lodes, gold grades are typically 3–7 ppm, although zones of ≥20 ppm Au were noted by Fisher and Glover (2006). Gold grades appear to correlate closely with pyrite abundance (Fisher & Glover 2006). Copper grades are generally <500 ppm, although a few zones of up to 5000 ppm Cu are also present (Fisher 2006). It appears likely that chalcopyrite abundance increases with depth. Calcite and prehnite weakly overprint mineralisation and probably reflect a late-stage cooling event. Diorite to quartz monzonite dykes within the mineralised zone are altered to a chlorite–epidote–pyrite assemblage, reflecting their more Fe- and Mg-rich composition.

The distribution and widths of the zones are shown in Figures 4 and 5. These are fairly representative of the system overall, although typically the inner, auriferous mica and pyrite-rich lodes are up to 5 m wide.

At Dargues Reef, the Braidwood Granodiorite outside the alteration zone is mostly equigranular and fresh with a weak prehnite–pumpellyite, chlorite and laumontite alteration assemblage being noted. Alteration fronts are mostly sharp and distinctive, but gradational fronts of fine-grained sericitic alteration were observed at Snobs Reef. Paragenetic associations of the alteration at Dargues Reef are restricted to overprinting of the outer, weaker and unmineralised propylitic zones by the relatively intense inner albite–muscovite-rich assemblage and localised remobilisation of chalcopyrite. The mineralisation is cut by aplite and externally nucleated pegmatite dykes and by clots that contain muscovite, but these are unaffected by the auriferous sulfide-bearing greisen assemblage (Photograph 1). Kennedy (1961) suggested that quartz–sulfide (sphalerite, galena, chalcopyrite, tetrahedrite–tennantite) veins at Majors Creek formed after the greisenous lodes. However, the few quartz veins that were observed in this study at Dargues Reef were physically associated with greisen lodes.

Majors Creek vein-style mineralisation

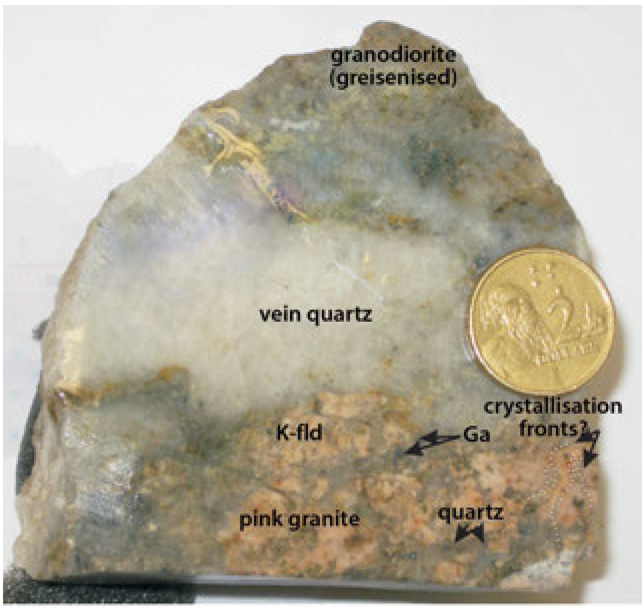
Hard-rock gold and base metal mineralisation occurs less than 2 km south of Dargues Reef at Majors Creek. These include the Great Star mine, Camages Reef and Rise and Shine Reef (Figure 3). The Braidwood Granodiorite also hosts mineralisation here. Only minor mineralisation is hosted in the adjacent Long Flat Volcanics, where the mineralisation is distinct from that at Dargues Reef. It exhibits a greater abundance of quartz veining, generally weaker alteration selvages with a predominance of illite over muscovite, and also a greater abundance of base-metal sulfides and Au–Ag tellurides. At the Great Star mine, Camages Reef and Rise and Shine Reef the mineralisation is associated both with veins and with illite–muscovite-rich alteration zones hosted by the Braidwood Granodiorite. The veins themselves are generally less than a few centimetres wide, although Duncan (1984) noted that some veins were up to 20 cm wide. Carbonate–quartz veins and infillings host galena, sphalerite, tetrahedrite with minor chalcopyrite, pyrrhotite, arsenopyrite, trace Au- and Ag-tellurides and native bismuth (see also Wake & Taylor 1988). Pyrite is 'healed' by later tennantite–tetrahedrite, sphalerite and minor chalcopyrite (see also Gilligan 1975). Wake and Taylor (1988) also suggested that pyrite occurred early in the paragenesis at Majors Creek, whereas sphalerite, chalcopyrite, tetrahedrite, galena, Au–Ag and Pb telluride minerals were deposited somewhat later.

Alteration surrounding mineralised veins at Majors Creek consists of an illite > muscovite–quartz assemblage (reflecting the replacement of feldspars) and an illite > muscovite–quartz–chlorite–calcite assemblage (reflecting the replacement of hornblende), based on petrology and short-wave infra-red (SWIR) data. This alteration tends to be of low to moderate intensity and is most strongly developed at the margins of the quartz–sulfide veins (see Goleby 1977).

Snobs mine (United Miners mine, Snobs Lode, Stewart and Mertons mine) and The Creek prospect occur to the south of Dargues Reef, close to the contact of the Braidwood Granodiorite with the Long Flat Volcanics, and are physically associated with diorite and aplite dykes along the main structural trends (Figure 3). Here, the mineralisation occurs as zoned sulfide-rich greisens with narrow quartz–carbonate–sulfide veins. Gilligan (1975) noted that the gold at Snobs Reef was mainly associated with the pyrite which is the dominant sulfide mineral, along with lesser galena, chalcopyrite, sphalerite and sulfosalts — analogous to that observed at the Great Star mine (see also Duncan 1984). In addition, pyrite is mainly resorbed, embayed and overprinted by needles of auriferous chalcopyrite, illite and comb quartz.

Snobs Reef has the clearest paragenetic associations observed in this study (see also Kennedy 1961 regarding Exeter Farm). Wake (1985) noted that mineralised quartz veins at Snobs Reef were commonly associated with a major northwesterly trending 'felsite' dyke (Wake 1985) along with narrow aplite dykes consisting of microporphyritic orthoclase and quartz. These dykes are both synchronous with, and cross-cut, the white mica–pyrite–quartz–sulfide greisens (e.g. at GR 748637 6061569). Weak sericitic alteration locally affects primary K-feldspar of the main hornblende–phyric phase of the Braidwood Granodiorite. A coarse-grained pink granite (consisting of pink K-feldspar, quartz and altered biotite) subtly cross-cuts the intensely greisenised hornblende-phyric phase of the Braidwood Granodiorite (sample PDSB01/1: Photograph 3). Also, at Snobs Reef, the pink K-feldspars are intergrown with fine-grained quartz, forming millimetre-scale intercrystalline fronts. The same generation of quartz occurs as veins and silica flooding of an earlier phase. Such silicified rock was reported to host grades of over 100 ppm Au and 2% Cu (Cluff Resources Pacific Limited 1986), suggesting that the emplacement of the pink granite resulted in upgrading the existing auriferous greisen and/or it was a key progenitor phase. Although this relationship has not been observed elsewhere at Majors Creek, similar (altered) dykes have been reported at Scotsmans Gully and at Exeter Farm (Wake 1985).

The Exeter Farm prospect is located about 2.5 km north of Dargues Reef (Figure 2). Although probably smaller than Dargues Reef, the greisen-hosted gold mineralisation here is developed adjacent to a diorite dyke and aplite and pegmatite dykes which cut across the mineralised zone (Duncan 1984). In addition, a quartz vein 1.8 m wide, which contained coarse-grained gold, was worked (see Canyon Resources Ltd 1986; Cozens & Maher 2010).



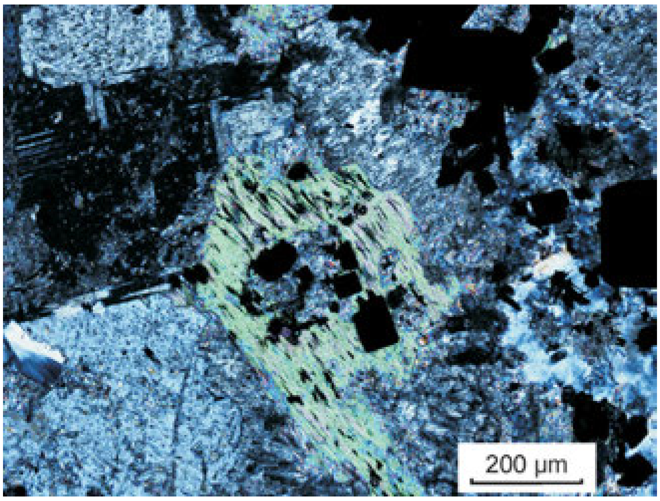
Photograph 3. *Pink granite at Snobs Lode. Shows greisenised Braidwood Granodiorite which is cut by pink granite with associated sulfide-bearing vein and interstitial quartz (Photographer D.B. Forster).*

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

As part of the present study, two samples (one from Dargues reef, the other from Majors Creek) were analysed using the $^{40}Ar/^{39}Ar$ technique to establish the timing of mineralisation in the Dargues Reef–Majors Creek area. The work was undertaken to determine if the Majors Creek vein-type mineralisation was contemporaneous with the Dargues Reef greisen-type mineralisation, and to establish whether the mineralising event overlapped the age of the western phase of the Braidwood Granodiorite based on U–Pb (SHRIMP) dating by Bodorkos et al. (2008).

Dargues Reef

Dargues Reef drillcore sample DREX027 220.2 m was analysed using the $^{40}Ar/^{39}Ar$ technique. This hole was collared at MGA 748993 6062862 (Zone 55) in 2005 by Moly Mines Limited and had a total depth of 309.5 m. The sample analysed was a 14 cm length of quarter-NQ core (from interval 220.20–220.34 m) collected from a high-grade ore zone containing 10.5 ppm gold. The analysed sample was a muscovite–phengite–chlorite-altered microgranodiorite typical of the mineralised lodes at Dargues Reef. This rock consisted of about 30% (secondary) albite, 15% secondary muscovite > phengite > illite ('sericite'), 20% pyrite, 15% quartz, 10% carbonate (mainly calcite), 5% relict K-feldspar, 1% chlorite, 1% magnetite and 0.5% chalcopyrite with minor galena, unidentified bismuth-bearing minerals, pyrrhotite, sphene and zircon. The muscovite–phengite grains (supported by SWIR data) were up to 500 µm long and undeformed. These white micas replaced earlier magmatic mafic minerals (Photograph 4) and feldspars. In addition, two forms of pyrite were noted — an equant crystalline form up to 5 mm and a ragged form (probably an earlier generation of pyrite: see also Gilligan 1975).



Photograph 4. Representative photomicrograph (crossed polars) of drill sample DREX027–220.2 m of sericitically altered Braidwood Granodiorite, which was dated by the $^{40}Ar/^{39}Ar$ technique. Note the muscvovite–phengite alteration developed as a pseudomorph after the large amphibole grain (Photographer D.B. Forster).

Eight individual muscovite grains from sample DREX027-220.2 m were step-heated in one or two increments. The analyses yielded a range of apparent ages, from 415.8 ± 3.9 Ma to 400.9 ± 7.5 Ma (Table 2, p. 24; Figure 6). In all but one case the low-temperature heating steps for individual grains gave marginally older apparent ages than the higher temperature steps for that grain, possibly due to minor recoil affects (Table 2). A weighted mean average age of 411.1 ± 2.9 Ma (95% conf.; mean square weighted deviate (MSWD) = 2.9) was calculated for the low-temperature steps (0 out of 4 rejected); 410.5 ± 4.1 Ma for the higher temperature and single fusion steps (95% conf.; MSWD = 4.6; 0 out of 9 rejected) and a weighted mean average of 410.9 ± 2.0 Ma for all steps (95% conf.; MSWD = 3.8; Figure 6). However, all weighted mean ages had MSWD values greater than 2.5. If the discordance is related to minor recoil artefacts, the weighted mean age of 410.9 ± 2.0 Ma (95% conf.) for all steps is considered to represent the timing of mineralisation at Dargues Reef.

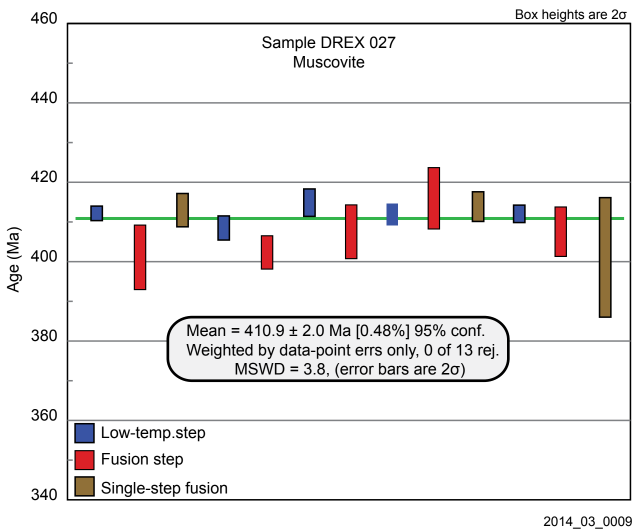
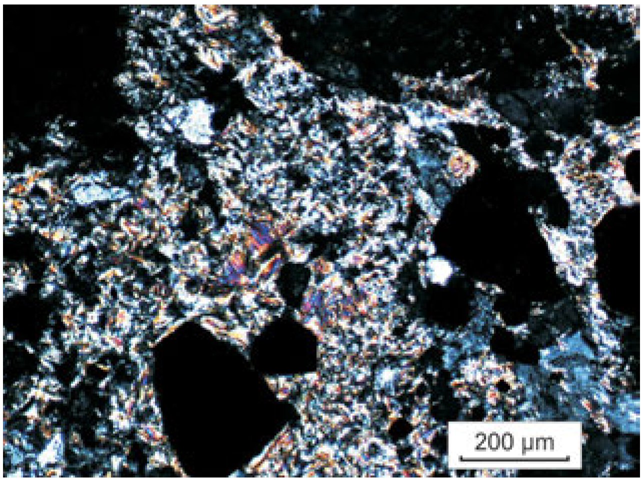


Figure 6. Calculated $^{40}Ar/^{39}Ar$ age results from heating steps for Sample DREX027-220.2 m.

Majors Creek (Great Star mine)

Sample PGDS0/18 was collected from near the main shaft at the Great Star mine (GR 748072 6062509) and is typical of the vein-hosted mineralisation found at Majors Creek. The sample selected for $^{40}Ar/^{39}Ar$ analysis was from a 3 cm wide sericite–sulfide–quartz–carbonate vein within sericite-altered microgranodiorite. The vein contains abundant radiating aggregates of illite–muscovite up to about 500 µm (Photograph 5), although most grains are smaller than those observed at Dargues Reef (Photographs 4 & 5). Sulfides within the vein include



Photograph 5. *Photomicrograph (crossed polars) of sample PGDS0/18 showing illite–muscovite-rich quartz–carbonate vein within altered Braidwood Granodiorite, which was dated by the $^{40}Ar/^{39}Ar$ technique (Photographer D.B. Forster).*

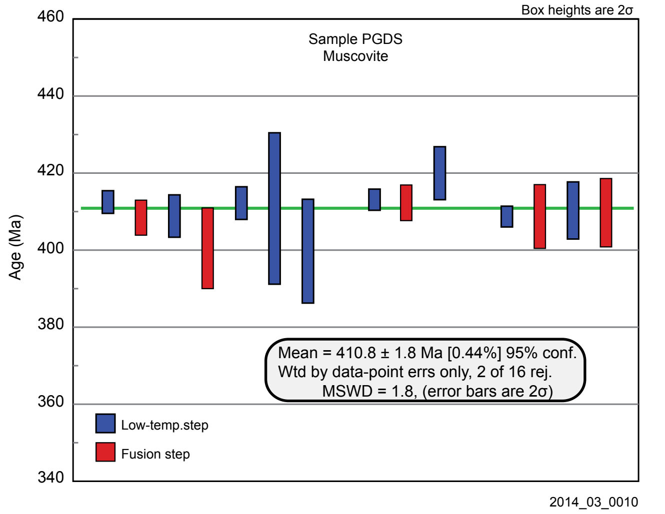


Figure 7. *Calculated 40Ar/39Ar age results from heating steps for Sample PGDS0/18.*

pyrite, galena and minor sphalerite. Alteration of the host granodiorite adjacent to the vein comprises a rather weak assemblage of illite > muscovite, chlorite and pyrite after mafic minerals, and a calcite > ankerite–illite assemblage after plagioclase feldspar and, to lesser extent, perthitic K-feldspar. There is no textural evidence of deformation such as kinking or recrystallisation of mica grains, nor undulose extinction of quartz.

Eight individual muscovite grains (each about 200 µm long) from sample PGDS0/18 were individually step-heated in two increments. The analyses yielded a range of apparent ages, from 433.9 ± 4.6 Ma to 274.4 ± 30.2 Ma (Table 2, p. 24). There was generally good correspondence between heating steps, with only two steps not within the error of all other steps (PGDS-4b and PGDS-6b; Table 2, p. 24). These two steps were rejected. The low-temperature heating steps for individual grains (8 analyses) gave a weighted mean average of 411.2 ± 2.5 Ma (95% conf.; MSWD = 2.4). The age estimate for the higher fusion steps (6 analyses; Table 2, p.24) gave a weighted mean average of 409.2 ± 2.7 Ma (95% conf.; MSWD = 0.98). The weighted mean average for all but the two rejected analyses was 410.8 ± 1.8 Ma (95%; MSWD = 1.8; Figure 7). This age is interpreted as representing the timing of gold mineralisation at Great Star mine.

Sulfur isotope results

Thirty-six sulfur isotope analyses were carried out on sulfides from mineralised zones as part of the present study (Table 3, p. 26). Ten S-isotope analyses are available from McQueen and Perkins (1995) for sulfides from Dargues Reef. Based on the combined dataset (Table 3), sulfur isotope values for pyrite from Dargues Reef averaged –1.2‰ (19 analyses; range –4.4 to 0.2‰) with a single analysis of chalcopyrite of –1.3‰. Pyrite from Exeter Farm gave generally higher results, averaging 1.9 δ^{34}S‰ (13 analyses — range 1.5 to 2.4 δ^{34}S‰). The data from Snobs Reef and Great Star mine generally gave lower δ^{34}S results than Dargues Reef and Exeter Farm, with pyrite from the Great Star mine averaging –2.6 δ^{34}S‰ (6 analyses — range –5.2 to 0.4 δ^{34}S‰). Pyrite from Snobs Reef averaged –4.3 δ^{34}S‰ (6 analyses — range –6.5 to 0.6 δ^{34}S‰). A single analysis of galena from Snobs Reef had a δ^{34}S value of –6.7 δ^{34}S‰.

Additional S-isotope data is available for the unmineralised Braidwood Granodiorite. McQueen and Perkins (1995) reported that values for finely disseminated pyrite from the host Braidwood Granodiorite range between 1.4 and 2.5 δ^{34}S‰ (average 2.0 δ^{34}S‰ — 3 analyses), similar to a whole-rock analysis for the Braidwood Granodiorite of 2.8 δ^{34}S‰ (unpublished data by Poulson and Arehart 2007, quoted in Downes 2009).

Discussion

The gold mineralisation in the Dargues Reef–Majors Creek area has many features characteristic of late-stage magmatic–hydrothermal processes (see Burnham & Ohmoto 1980; Lang et al. 2000; Lang & Baker 2001). However, the presence of tellurium-bearing galena, gold–silver and lead tellurides, and carbonate–base metal veins with open-space textures, along with low homogenisation temperatures from inclusion data, led Wake and Taylor (1988) to suggest that mineralisation in the Majors Creek goldfield was epithermal in character. They also inferred that mineralisation in the Majors Creek area was related to low-sulfidation epithermal gold mineralisation associated with the

ECYRZ, which developed during the Middle to Late Devonian (late Givetian to Famennian: see Lewis et al. 1994). However, the $^{40}Ar/^{39}Ar$ dating undertaken as part of this study indicates that the Dargues Reef greisen-type mineralisation formed at 410.9 ± 2.0 Ma (95% conf.) and that the vein-type mineralisation at Majors Creek is of a very similar age, forming at 410.8 ± 1.8 Ma (95% conf.). Both dates are within the error of a U–Pb SHRIMP date of 409.9 ± 3.2 Ma for zircons from the western phase of the Braidwood Granodiorite (which is host to the mineralisation) by Bodorkos et al. (2008).

This supports the interpretation by McQueen and Perkins (1995) that the mineralisation was intrusion-related. In detail, the data supports the previous K–Ar age of 411 ± 5 Ma for Main lode, and is also within the error of the K–Ar date of 406 ± 4 Ma for Big Blow lode (both from McQueen and Perkins 1995). The narrow range of our Ar–Ar dates and close agreement with the U–Pb SHRIMP date for zircons from the western phase of the Braidwood Granodiorite (by Bodorkos et al. 2008) indicate that mineralisation formed at both Dargues Reef and Majors Creek during late crystallisation of the western hornblende-phyric phase of the Braidwood Granodiorite at ~411 Ma. The observed close association of the mineralisation with highly fractionated variants of the host pluton also supports this. An age of ~411 Ma for magmatism and mineralisation is significantly older than the likely opening of the ECYRZ (Downes 2009), which is constrained by geological and palaeontological evidence to a Givetian to middle Frasnian age (Lewis et al. 1994), and by U–Pb SHRIMP dating of zircons from two intrusions forming part of the Boyd Volcanic Complex at Bombala that gave ages of 366 ± 8 Ma and 365 ± 10 Ma (Sircombe & McQueen 2000).

The close agreement between the timing of magmatism and mineralisation, along with many of the features of the deposits (discussed below) indicate that only one tectono-hydrothermal mineralising event occurred in the Majors Creek district. However, different styles of mineralisation are present. Possible explanations for the difference include, firstly, that the two systems may have formed at different depths of emplacement whereby greisen-style mineralisation formed at greater depths and at higher temperatures, whereas vein-style deposits formed at shallow depths with cooler mineralising fluids; and secondly, that this may in part be due to changes in the oxidation state and/or pH of the ore-bearing fluids within the same gross mineralising system.

Insights into ore genesis from sulfur isotope systematics and petrology

The available sulfur isotope data places further important constraints on the mineralising process. McQueen and Perkins (1995) found that S-isotope values for pyrite from the mineralised zone at Dargues Reef range between −3.4‰ and −0.4‰ (average −1.3‰ — 10 analyses), whereas values for pyrite from the host granodiorite away from mineralised zones range between 1.4 and 2.5‰ (average 2.0‰; 3 analyses — Table 3, p. 26; Figures 8 & 9). Our data complements the earlier work, but also includes $\delta^{34}S$ values as low as −6.7‰. All the prospects included in the present study have values similar to or lower than those for unaltered and unmineralised Braidwood Granodiorite (~2 to 3‰ down to −6.7‰: Table 3). With the exception of a single result of $\delta^{34}S$ 0.6‰, Snobs Reef has the lowest $\delta^{34}S$ signature of all the deposits studied (Figures 8 & 9); Exeter Farm has the highest $\delta^{34}S$ signature, which is close to that of the bulk S-isotopic composition of the melt of ~2.5‰ (see McQueen & Perkins 1995; Downes 2009).

A number of factors can influence the variation of the sulfur isotope signatures for sulfide minerals within ore deposits. These include: the temperature, composition and oxidation state of the mineralising fluid; the size and nature of the hydrothermal system (i.e. the nature of the plumbing of the system and the permeability of the host rocks); and variations in the relative contributions of different sulfur reservoirs (Rye & Ohmoto 1974; Huston 1999). The sulfur isotope data is consistent with derivation from a magmatic source — the Braidwood Granodiorite. The observed variation

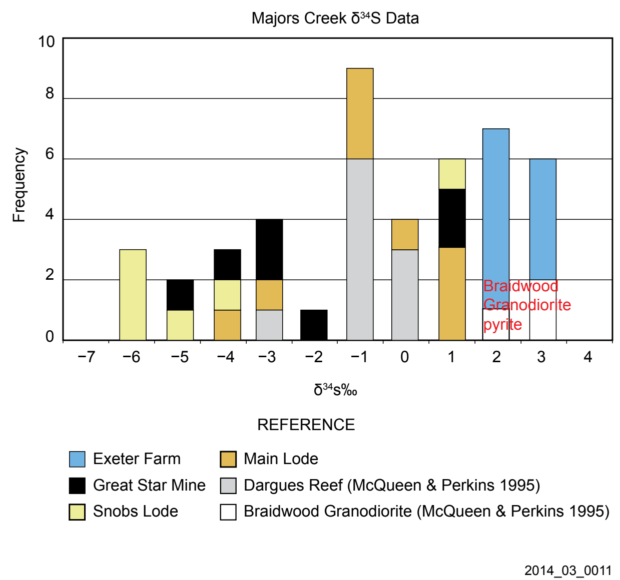


Figure 8. Histogram of sulfur isotope results for each mineral occurrence.

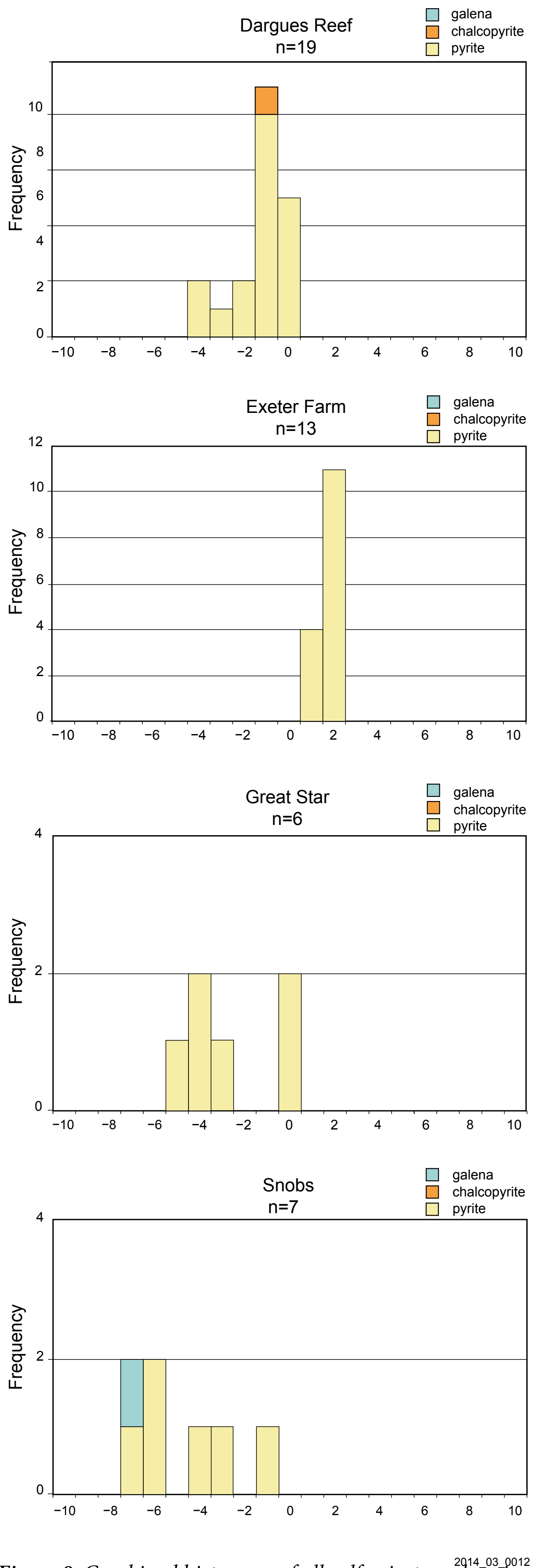


Figure 9. Combined histogram of all sulfur isotope data in the Majors Creek area.

in S-isotope values between deposits can be explained by limited fluid–mineral ^{34}S–^{32}S fractionation under open-system conditions for the larger greisen zones such as Dargues Reef (as suggested by McQueen & Perkins 1995). However, for the volumetrically less abundant veins analysed at Great Star mine and Snobs Reef that have the lowest $\delta^{34}S$, closed-system fractionation may have been important.

The unaltered Braidwood Granodiorite has a narrow $\delta^{34}S$ range, and is consistently rather oxidised, given that it is magnetite-bearing and has FeO/Fe_2O_3 ratios of 0.45 to 0.70 (Wyborn & Owen 1986). No anomalously light sources of sulfur (e.g. biogenic) or reactive rocks that may have affected the oxidation state of magmas or hydrothermal fluids are known to be present in the adjacent wall rocks of the Braidwood Granodiorite in the Majors Creek area (i.e. Long Flat Volcanics). Most of the deposits have ore zones that include magnetite–pyrite > pyrrhotite, which suggests that the greisen-forming fluids were fairly oxidised (near and above the fayalite–magnetite–quartz buffer, and above the pyrite–pyrrhotite buffer — see Ohmoto & Rye 1979, and phase equilibria by Lindsley 1991).

Constraints on the temperature of the mineralisation at Dargues Reef are approximate. The greisen mineralogy and observed features suggest a general range of fluid temperatures from ~260 to 400°C, taking into consideration the lack of both low-temperature clays and minerals such as hydrothermal biotite or garnet that would imply fluid temperatures above 400°C. Temperatures above ~280°C are interpreted, given the abundance of muscovite–phengite rather than illite towards the centre of the greisenous zones (see Montoya & Hemley 1975; Ulrich et al. 2001). The maximum temperature estimate of 350°C by McQueen and Perkins (1995), which was based on fluid inclusion microthermometry, is considered to be likely for much of the greisen formation. However, resorption textures in quartz were noted when logging diamond drillcore from the deeper albite-altered chalcopyrite-bearing 'felsic lodes' at Dargues Reef. Quartz stability declines markedly at temperatures greater than about 380°C in NaCl-bearing aqueous solutions at less than 1750 bars (Kennedy 1950; Khitarov 1956). The observed textures suggest that fluid temperatures may have exceeded 350°C in these (deeper) zones. Sulfide minerals deposited from H_2O-dominant, near-neutral to weakly acidic hydrothermal fluid under oxidising conditions at ≤350°C should have strongly depleted sulfur isotope values due to the mobilisation of ^{34}S to more distal parts of the hydrothermal system (Ohmoto & Rye 1979). However, McQueen and Perkins (1995) noted that there was no evidence of significant hydrolysis of SO_2 to produce H_2S and H_2SO_4 (which would strongly partition isotopically lighter S into volatile phases and would be likely to result in an intense acid–wall rock alteration reaction), nor is there evidence for the presence of significant sulfate-bearing minerals in the ore zones within the Majors Creek district. Therefore, near-neutral fluids and uniform $\Sigma S_{v\ \mathrm{fluid}}$ under near-equilibrium conditions are assumed. Following such an interpretation, the most intense quartz–sericite (muscovite-dominant)–pyrite alteration represents a body of rock that has undergone the most intense alteration. The centres of these major greisen zones are largely poor in primary magnetite, grading to magnetite-bearing greisen and then an outermost hematite-bearing alteration zone. This suggests that the mineralising fluids had lower initial fO_2 than the bulk pluton, and/or they evolved to lower fO_2 during greisenisation. The inner mineralised zones, which host the highest gold grades, were likely to be the loci of greatest fluid flow and had higher fluid temperatures (≥350°C) than the less-altered and less-mineralised outer zones (see Meyer & Hemley 1967; Rose & Burt 1979).

The sulfur isotope data for Dargues Reef is consistent with gold being precipitated along with sulfidation reactions, resulting in the deposition of pyrite and/or chalcopyrite due to fluid interactions with mainly Fe-bearing mafic minerals. The process was probably triggered by the weak reduction of gold-bearing bisulfide aqueous species (Cooke & Simmons 2000; see also Mason 2008). Precipitation of gold on sulfide mineral surfaces (Knipe et al. 1992) may also have been important, but further work is necessary to confirm this.

The extent of the greisenisation at Dargues Reef indicates that significant fluid flow must have occurred, and that it could have been diffuse and/or planar. Diffuse fluid flow could have occurred via interconnected pathways (including widespread grain-scale alteration of mafic minerals), or along grain boundaries and through interconnecting miarolitic cavities (not observed in this study — see Mustard 2001a; Candela & Blevin 1995). However, contraction of the host granite during late crystallisation may also produce planar fluid pathways (see Hart et al. 2002; Zaraisky 2004). Often these can form conjugate fracture sets according to the stress regime on the intrusion (Newberry et al. 1995; Lang et al. 2000; Hart 2005). At Dargues Reef, these zones were exploited initially by diorite to quartz monzonite dykes and later by hydrothermal fluids, with the dykes acting as a source of iron which triggered sulfidation reactions. Subsequently these zones may also have been exploited by post-mineralisation aplite and pegmatite dykes.

Sulfur isotope data for Great Star mine averages –2.6‰, significantly lower than the averages for Dargues Reef (–1.2‰) and Exeter Farm (1.9‰). In addition, there is a trend towards lower S-isotope values (≥–5.2 $\delta^{34}S$‰) than occur at Dargues Reef. The generally small size of these veins and their restricted alteration selvages suggest that they formed under hydraulic fracture conditions, with restricted fluid flow and only short-term interconnectivity between veins (see Forster & Downes 2008). Such an interpretation implies locally low fluid:rock ratios with a small exchange of bulk rock components, and supports the interpretation that closed-system S-isotope fractionation occurred at the Great Star mine. This model is supported by the greater volume of altered rock at Dargues Reef than in the Majors Creek vein-type deposits. Given the lack of chalcopyrite in many of these mineralised veins, the dominance of illite compared to muscovite and the generally lower fluid-inclusion homogenisation results (data from Wake 1985), we suggest that the gold–base-metal mineralisation at Majors Creek formed at generally lower temperatures than was the case at Dargues Reef — possibly below 260°C (see Montoya & Hemley 1975).

Overall, Snobs Reef has the lowest $\delta^{34}S$ signature (average –4.4‰), including the lowest individual $\delta^{34}S$ results for this study (Table 3, Figures 8 & 9). These values were obtained from galena (–6.7‰) and pyrite (–6.5‰) from a quartz vein adjacent to the coarse-grained pink granite that subtly cross-cuts and hence post-dates the greisenisation event (sample PDSB01/1: Photograph 3). Although narrow, the greisen alteration at Snobs Reef is equally or more intense than at Dargues Reef, suggesting high initial fluid flow. Although the dataset is limited, the wide range of $\delta^{34}S$ values and evidence of significant initial fluid flow suggest that open-system conditions were present initially along the Snobs Reef structure but, with more restricted fluid flow, *in situ* closed-system S-isotope fractionation occurred. Given the abundance of muscovite (with little illite) at Snobs Reef, it is likely that the initial fluid temperatures of the ore-forming fluids were higher than those in the nearby vein-type mineralisation at Majors Creek, and were probably roughly similar to those at Dargues Reef.

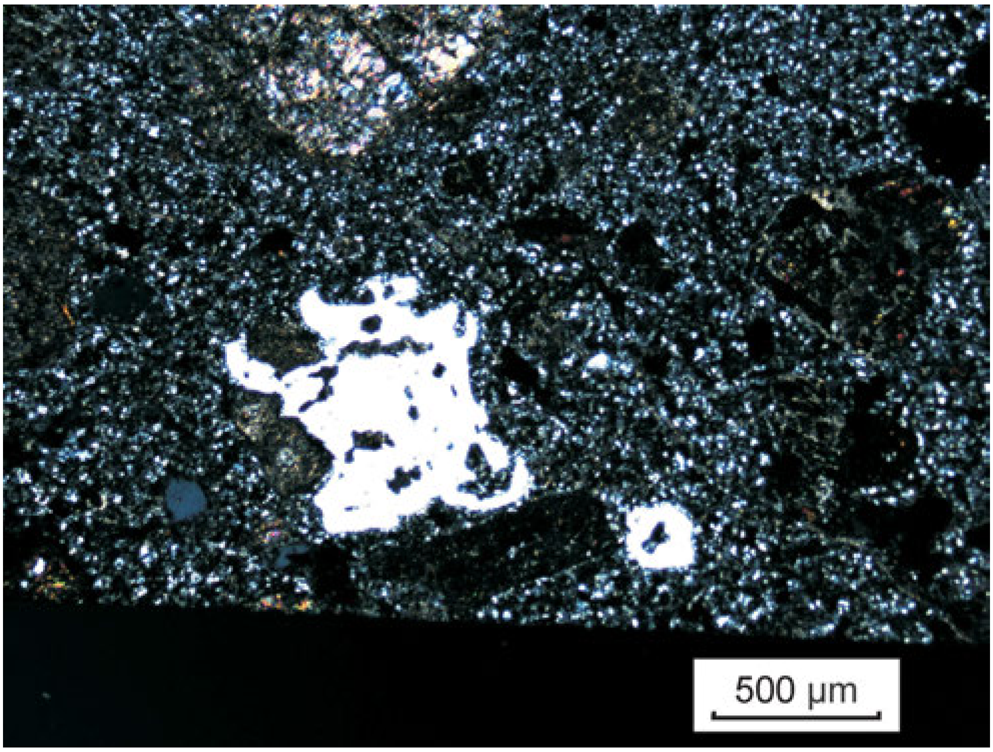
The S-isotope values for Exeter Farm (average 1.9‰) are higher than for the other deposits in the present study, and overlap the available data (S. Poulson unpubl. data, cited in Downes 2009) for bulk sulfur from the Braidwood Granodiorite. This implies that little S-isotope fractionation occurred and that little or no non-magmatic sulfur was contributed from sources external to the Braidwood Granodiorite. In addition, the number and size of historic workings in the area (Duncan 1984) and the intensity of alteration suggest that significant fluid movement occurred, implying that fluid movement was relatively unconstrained and resulted in limited fractionation. Unconstrained (open system) fluid movement would have limited fluid–wall rock interactions and sulfidation reactions, resulting in limited but widespread gold deposition.

Pre-mineralisation mafic–intermediate dykes

Mineralisation at Dargues Reef, Snobs Reef and Exeter Farm is developed adjacent to steeply dipping altered diorite to quartz monzonite dykes, but these are not interpreted to have contributed significant sulfur or fluid. The margins of the dykes vary from planar to contorted, gradational and chilled, with red hematite and pyrite developed on the margins. Considered together, such textures can indicate mixing and mingling of more mafic phases during pluton assembly (see Vernon et al. 1998). Within these dykes are large, partially resorbed anhedral quartz phenocrysts (Photograph 6) that are similar to those observed within the main Braidwood pluton, possibly suggesting a similar source/origin for both. Together, the observed textures are interpreted to reflect the rapid ascent and decompression of mafic magma into an oxidised, aqueous-rich environment, resulting in quench cooling and partial re-melting of the dykes and/or localised changes in the magma state (see Whitney 1975; Mair et al. 2003). The presence of hydrothermal epidote in the dykes may suggest that the fluids were not enriched in CO_2 (see Einaudi & Burt 1982).

Depth of formation

Estimates of the confining pressure and depth of emplacement during ore formation are problematic. Wake (1985) and Wake and Taylor (1988) suggested that the mineralised veins in the Majors Creek area were epithermal in nature, based on the observed vein mineralogy, the presence of open space textures, metal assemblage and a reconnaissance fluid inclusion study. They identified two-phase H_2O–CO_2 fluid inclusions from quartz–carbonate–sulfide veins, at Camages, Snobs, Banner and Scotsman Gully mines indicating that the ore-forming fluids were CO_2-bearing, low to moderate salinity (0.5–8 wt% NaCl) and low temperature (range 130–200°C; average 155°C). However, the homogenisation temperatures of the fluid inclusions are too low for the observed alteration and sulfide assemblages present at Majors Creek, suggesting either that they are secondary inclusions, or that pressure corrections were required (see Baker 2002). Wake (1985) and Wake and Taylor (1988) did not apply pressure corrections to their data, based on their assumption that boiling had occurred which would suggest that the system was emplaced at shallow depths. The presence of white micas (muscovite and phengite) and minor chalcopyrite in several mineralised zones suggest that the temperatures of the ore-forming fluids were close to 300°C or even higher, rather than averaging 155°C as proposed by Wake and Taylor (1988). Furthermore, carbonic fluids and fluid inclusions are common to many deposit styles (see Hart 2005) and therefore they are not diagnostic of epithermal veins. However, Wake and Taylor (1988) and McQueen and Perkins (1995) suggested that there was considerable evolution of magmatic-dominated fluids, so we do not rule out the possibility that some unroofing occurred during the mineralising event. Comparisons with other disseminated gold deposits related to granitoid intrusions, such as the Salave deposit, Spain (discussed below), suggest that the mineralisation at Dargues Reef formed at depths of about 3–6 km.



Photograph 6. *Photomicrograph of diorite sample DREX027–200.8 m (Photographer D.B. Forster).*

Intrusive history and sequence of mineralisation

Combining the data from this and earlier studies (e.g. Wake 1985; McQueen & Perkins 1995; Fisher & Glover 2006; Downes & Forster in Fitzherbert & Deyssing in press), we propose the following intrusive history for mineralisation in the Majors Creek area.

1. Formation of a high-level magma chamber containing magmas of granodioritic composition. This magma chamber probably underwent multiple injections of mafic to intermediate magmas along with significant assimilation of wall rocks, based on the abundance of xenoliths (see discussion of O- and C-isotope data by McQueen and Perkins 1995).

2. Intrusion of the western or monzogranite phase of the Braidwood Granodiorite including marginal porphyritic phases.

3. Emplacement of diorite to quartz monzonite dykes within planar, steeply dipping fracture zones in the partly crystallised Braidwood Granodiorite. These fractures probably formed due to the cooling and contraction of the host granitoid. Injections of mafic magma occurred at this time, accounting for the abundance of mafic enclaves within the hornblende–phyric phase (see Collins et al. 2000).

4. Further cooling and late-stage fractionation occurred with the exsolution of ore-forming hydrothermal fluids. These fluids fluxed through as much as several hundred metres of the host granodiorite and formed the main gold-bearing greisen zones. Fluid flow was focused along pre-existing fractures, which pooled and reacted to form greisenous alteration fronts within and adjacent to the cooling pluton. The initial temperature of the fluid may have been ~400°C, given the presence of quartz resorption textures. These fluids then cooled to ~300–360°C, with accompanying deposition of gold, auriferous pyrite, chalcopyrite and other sulfides. Vein deposits with illite-dominant alteration — such as at the Great Star mine — also formed in the roof zone of the Braidwood Granodiorite from very similar ore-forming fluids to those at Dargues Reef, but at lower temperatures since they were further from the primary heat/fluid source.

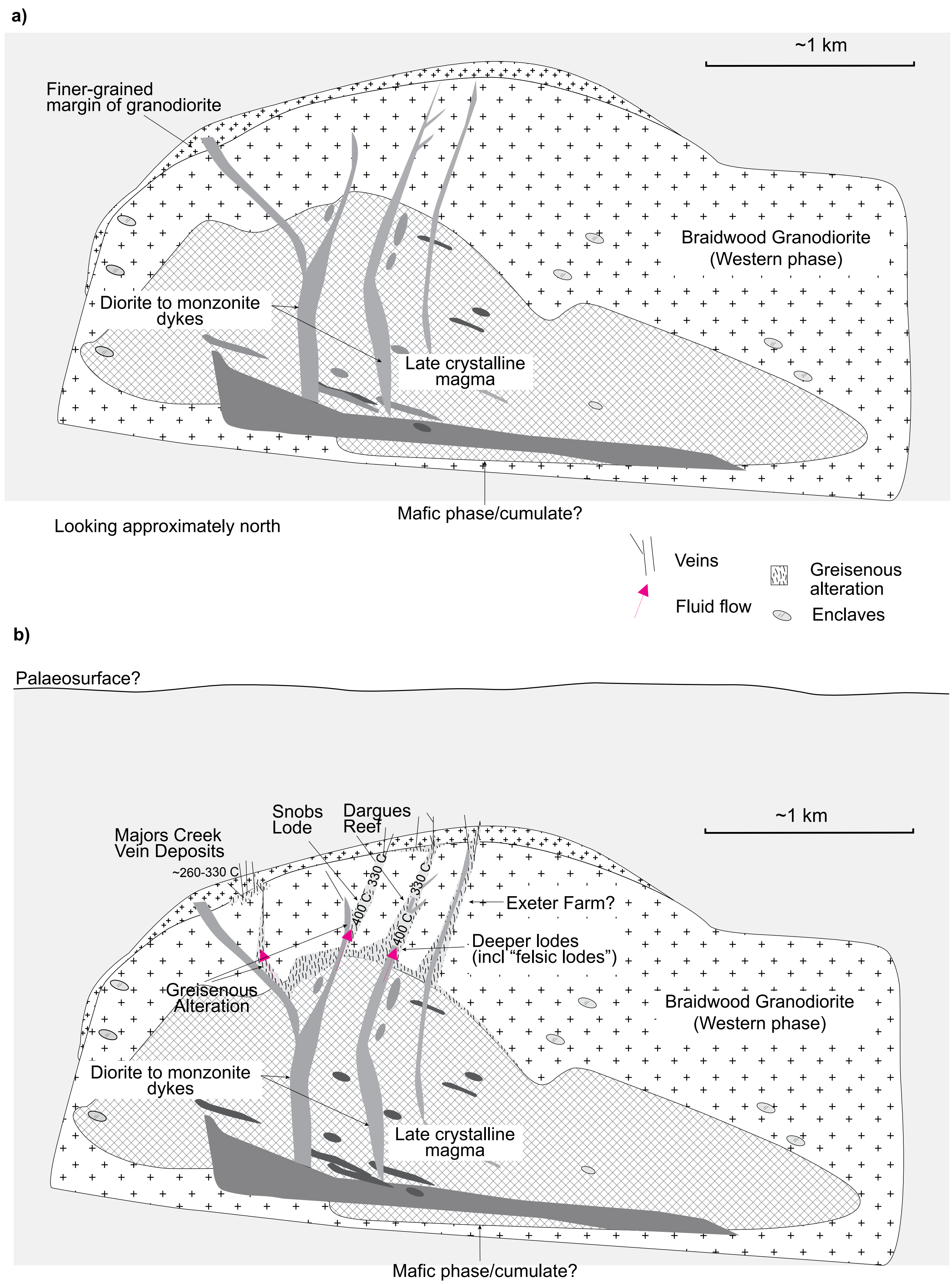
5. Emplacement of syn-mineralisation felsic dykes, ('felsite' of Wake 1985; 'aplite' of Wake & Taylor 1988; 'pink granite' this study) and minor granite and altered pegmatitic dykes at Snobs Reef and The Creek prospect along with dykes and sills at Scotsmans Gully.

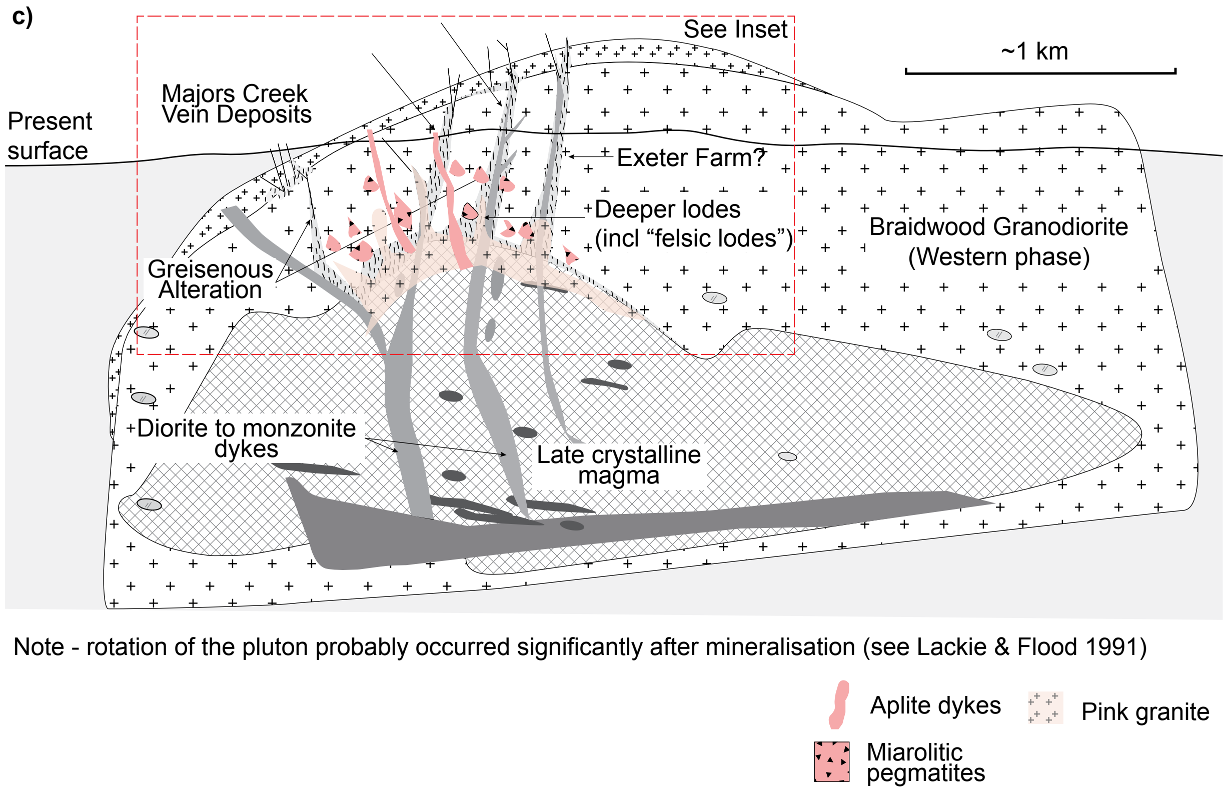
6. Continued, late-stage fractionation with the emplacement of: (1) externally nucleated post-mineralisation (orthoclase–quartz–muscovite) pegmatite dykes, veins and clots; (2) orthoclase–quartz–aplite dykes; and (3) veins and various miarolitic cavities developed in the host granodiorite and the adjacent wall rocks. All these phases post-date greisenisation, as they have only undergone propylitic alteration (see Photograph 1).

7. Cooling and additional fracturing of the granodiorite with the deposition of barren carbonate-rich veins and a zeolitic alteration overprint.

Many of the above relationships between the various intrusive phases, deposits and styles of mineralisation in the Dargues Reef–Majors Creek area are summarised in Figure 10.

Based on the above geological history, both the greisen-style and the vein-style mineralisation are interpreted to be related, having been deposited in a single mineralising event which produced a zoned hydrothermal system with the gold–base metal veins at Majors Creek possibly being deposited at lower temperatures further from the primary heat/fluid source. The close association of mineralisation and alteration with the pink granite at Snobs Reef supports the interpretation that late variants of the Braidwood Granodiorite acted as key progenitors. Alternatively or additionally, the intensely albitised 'felsic lodes' noted at Dargues Reef could have formed at ≥400°C, proximal to the loci of exsolution of magmatic-dominated fluid.


a)
~1 km
Finer-grained margin of granodiorite
Braidwood Granodiorite (Western phase)
Diorite to monzonite dykes
Late crystalline magma
Mafic phase/cumulate?
Looking approximately north
Veins
Fluid flow
Greisenous alteration
Enclaves
b)
Palaeosurface?
~1 km
Snobs Lode
Dargues Reef
Majors Creek Vein Deposits
~260-330 C
400 C- 330 C
400 C- 330 C
Exeter Farm?
Deeper lodes (incl “felsic lodes”)
Greisenous Alteration
Braidwood Granodiorite (Western phase)
Diorite to monzonite dykes
Late crystalline magma
Mafic phase/cumulate?



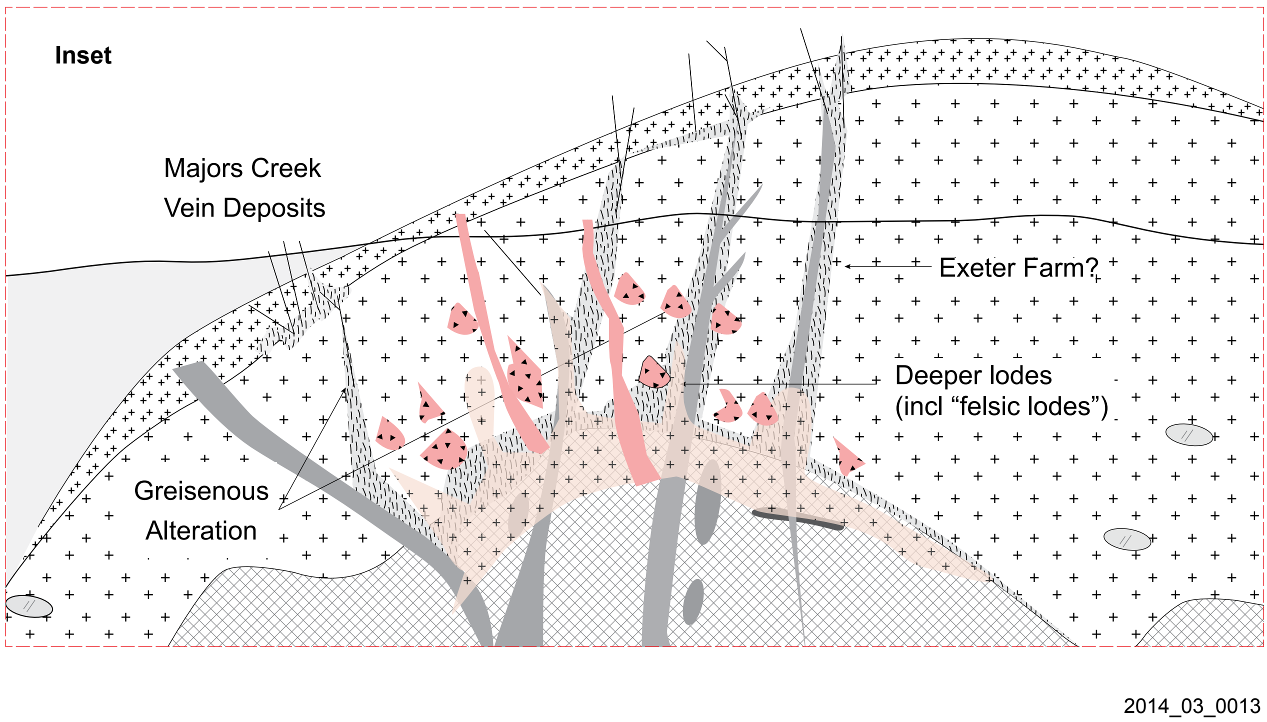


Figure 10. Interpretative genetic model for mineralisation in the Majors Creek district. a) Crystallisation of the Braidwood Granodiorite with finer-grained margins in the Majors Creek area with contemporaneous emplacement of relatively mafic dykes along structural weaknesses. b) Further fractionation of the Braidwood Granodiorite and exsolution of magmatic-dominated fluids which were focused along the same structures. The fluids pooled and reacted with the host unit to form alteration fronts about the cooling pluton. Gold–base metal veins at Majors Creek (e.g. Great Star mine and Camages Reef) probably formed due to hydraulic fracturing associated with very similar ore-forming fluids that further cooled with increasing distance from the primary heat/fluid source. Fractionation of the granite continued. Pink granite at Snobs was emplaced, overprinting the greisens associated locally with high-grade gold. c) Aplites, miarolitic pegmatites were then emplaced.

Definitions and analogues

Several terms are currently in use for gold deposits that are genetically related to granitoid intrusions similar to those found in the Dargues Reef–Majors Creek area. They include 'granite-related gold' (GRG — see interpretations by Wilton and Strong 1986) and 'intrusion-related gold' (IRG — Lang et al. 2000; Lang & Baker 2001; Mair et al. 2003; Mair 2004; and review by Hart 2005). Overall, these deposits are less well described than some other deposit styles, but nonetheless have emerged as an important class of gold deposit (Blevin 2003; Lang & Baker 2001**,** Hart 2005). However, given the association of mineralisation with intrusions that are not strictly granites (according to Streckeisen 1976), the term 'granitoid-related gold' (GdRG) as used by McQueen and Perkins (1995) is more appropriate for mineralisation in the Majors Creek district. Several lines of evidence support such a classification for the Dargues Reef–Majors Creek system, as follows.

1. High-precision $^{40}Ar/^{39}Ar$ data for Dargues Reef and Majors Creek is in close agreement with independent age constraints for the age of the Braidwood Granodiorite, suggesting an empirical relationship between the two.
2. Greisen-style disseminated mineralisation is hosted within and adjacent to the roof zone of the host granitoid.
3. The mineralisation is associated with highly fractionated phases of the Braidwood Granodiorite, including pegmatites and aplites.
4. A series of planar, sub-vertical joint zones (probably related to cooling and contraction within the pluton) control the location of the mineralised dykes, greisens and veins.
5. A strong gold–bismuth–tellurium association with strongly anomalous Mo, Pb and As.
6. Higher Au/Cu, Ag/Cu and Zn/Cu values are associated with veins that are narrower than those in the larger, gold-dominant greisens such as Dargues Reef.
7. Sulfur isotope data is consistent with fluid-mineral fractionation of sulfur derived primarily from the host intrusion.

A porous form of pyrite is present in weakly altered granodiorite at Dargues Reef. Such textures are consistent with ore-forming fluids being undersaturated in sulfur, and suggest that the source melt was undersaturated with respect to H_2S prior to exsolution of the mineralising fluids. This is in keeping with IRG and GRG deposits worldwide (Blevin 2003; Lang & Baker 2001).

The styles of mineralisation within the Dargues Reef–Majors Creek area are analogous to those described in a number of other IRG/GRG deposits, including those in the Tintina gold province (e.g. Scheelite Dome, Canada; Donlin Creek, Alaska (McCoy et al. 1997; Lang & Baker 2001; Maloof et al. 2001; Mair et al. 2003). The gold-dominant, steeply dipping greisens at Dargues Reef and Snobs Reef, with few veins and elevated Bi–Te geochemistry, are similar to the deeper parts of the Timbarra system in northern NSW (the Big Hill deposit: see Mustard 2001a, b; 2004) and the Salave gold deposit, Spain (Sillitoe 1991). The quartz–carbonate–illite veins with Zn–Pb–Te–Bi–Ag–Mo–As-rich minerals, such as those at the Great Star mine and Camages Reef (Figure 3), are analogous to those at Keno Hill in Canada, where vein-type mineralisation occurs peripherally to the greisens and to the likely progenitor intrusions (Mair et al. 2003). Weak zones of illite-rich alteration, such as the apparently shallowly dipping roof-zone hosted greisens noted near the Hanlons mine (GR 747534 6060428) are reminiscent of the Kori Kollo deposit in Bolivia (Thompson et al. 1999).

Nonetheless, there are important distinctions between deposits in the Dargues Reef–Majors Creek system and other GdRG deposits worldwide. Mineralised breccias and veins such as those at Kidston, Mt Leyshon and Fort Knox (Baker and Andrew 2001; Orr & Orr 2004) have not been identified in our study area. The Braidwood Granodiorite is more oxidised, with higher Fe_2O_3/FeO ratios (Wyborn & Owen 1986) than most granitoids known to be associated with 'reduced intrusion-related' mineralisation of the Tombstone plutonic suite, such as at Fort Knox (Newberry et al. 1995; Mair 2004). As a result, the pluton has relatively low tungsten and bismuth geochemistry (Blevin pers. comm. 2008) but lacks sulfate minerals such as those at Kori Kollo (Thompson et al. 1999). The Majors Creek vein-style mineralisation, which we interpret to have formed at lower temperatures than the greisen-style mineralisation at Dargues Reef and Snobs Reef, locally contains chalcopyrite; however, since it does not have a strong mercury association, it is likely to have formed at higher temperatures than those interpreted during formation at Donlin Creek (McCoy et al. 1997; Lang & Baker 2001). Finally, Rb/Sr and Rb/Sr vs SiO_2 are distinctly lower than for the intrusions associated with mineralisation at Timbarra and Kidston (Blevin 2003).

The recognition of high-grade, granitoid-related gold mineralisation of a rather oxidised character in the Majors Creek district highlights the exploration potential for similar deposits in the Tasmanides of eastern Australia where many large, I-type plutons are present.

Conclusions

Dating of white micas using the $^{40}Ar/^{39}Ar$ method indicates that mineralisation in the Dargues Reef–Majors Creek area is temporally related to late-stage crystallisation of the Braidwood Granodiorite. The sulphur isotope data for Dargues Reef supports the interpretation that open-system fluid–rock fractionation occurred there. The data for the base-metal–telluride veins at Majors Creek indicates that closed-system sulfur isotope fractionation was predominant. The physiography and mineralogy of the Dargues Reef and Snobs Reef mineralisation suggest that magmatic-dominated hydrothermal fluids first exsolved from late-stage felsic phases of the Braidwood Granodiorite and then formed gold-bearing greisens at Dargues Reef and Snobs Reef — in part adjacent to pre-mineralisation mafic to intermediate dykes — along with vein-hosted mineralisation nearby. The mineralisation is analogous to that in other IRG or GRG provinces. However, the causative pluton is more oxidised and unevolved than other, better-described gold provinces, such as the Tintina gold province in North America.

Acknowledgements

Simon Poulson of the Nevada Stable Isotope Laboratory and Dr Anita Andrew of Environmental Isotopes Pty Ltd, North Ryde, NSW, are thanked for undertaking the sulfur isotope analyses used in this study. Cortona Resources Limited (now Unity Mining Limited) is also thanked for access to Dargues Reef, drillcore and helpful discussions.

Tables

Table 1. Summary of ore mineralogy. Data from Kennedy (1961), Gilligan (1975), Goleby (1977), Wake (1985) and this study.

Mine/reef (including workings)	Production periods	Recorded production (kg)	Mineralogy major (minor)	Dykes, veins and gangue mineralogy	Comments
Banner mine	1870–1934 (intermittent)	41.83	asp (ga, tet, cpy, ba, py, au)		Workings to 85 m lode 0.3 m wide
Camages Reef	1907–1918 1931–1942	61.7	py>sph, ga, cov (syl, hes, pez, arg, mar, eng, mag, ang)	Quartz, calcite, greisens, 2 cm vein of nearly pure gold	Strike 280°, dip 86°S with the ore shoot plunging west at 40°–50°
Dargues Reef	1875–1916	1950	py (up to 30% of the rock), minor cpy, ga, tellurides (tellurobismuthite, rucklidgeite) and Ag–bearing te, bi, Bi-sulfosalts (aikinite, krupkaite), Ag-bearing pyr tet and native gold	Gold-bearing pyritic greisens, a1 m-wide quartz vein all near mafic to intermediate dykes. Pegmatite and aplite dykes and clots	Strike of lodes mainly about 100° dipping steeply. Big Blow, HB lodes and Ruby lodes adjacent to diorite dykes. Main Lode was worked to at least 150 m. Gold grades typically 1–5 ppm, copper <500 ppm and appears to increase with depth.
Dunsheas	Intermittent through gold rushes	6	py, cpy>sph (au)	2.5 cm wide quartz vein	52 m deep shaft; E–W trending
Great Star mine	1903–1936 (intermittent)	6.29	py>>cpy, sph, tet, ga, (au, cav)	1.3 cm to 20 cm veins	152 m deep shaft, vertical reef
Hanlons (inc. Hanlons, Heazlitt & Crandell; Hindhaughs, Persever-ance)	1890–1898 ~1900		ga, sph tet, py, ga, cav, cpy, au, syl, cav		Worked to 30 m. Vein strikes 265°, dips 85°S with higher-grade shoots plunging steeply westwards
Mobbs Reef			py, sph, cpy, ga (tet, hes, arg, au)	Gold grades to 94 ppm to 44 m, then below 24 ppm	Approximately E–W-trending mineralised zones
Rise & Shine No. 1 & 2	1882–1888 1909		sph, py, cpy, ga (ten–tet, cav, au)		
Scotsmans Gully	Late 1800s	30.4	py (sph, cpy, mag, pyr)	Greisens, altered stocks and sills	Southern zone 100 m long and up to 1.5 m wide. Extensive underground workings
Snobs Mine (inc Stewart & Mertons, United Miners)	1870–1916	365	py>cpy, tet, ga, sph (au)	10 cm wide quartz vein, pyritic, greisen, mineralised aplite dyke	Reef 760 m long, 152 m deep, strike 290° dip 85°N, reef 0.1–1.8 m wide, at least 150 m deep
Sphinx No. 1 & 2	Until 1909		sph, py, ga (cav, cpy, arg, tet, au)	Au-bearing lode and narrow quartz-carbonate veins	Sphinx No. 2 reef worked to 43 m; shoots on No 1 reef plunge steeply east
Stalkers			py, ga, sph, cpy (au)		
Young Australian			py (sph, au)		20 m long and worked to 18 m
Exeter Farm	Several small pits and shafts on an E–W trend		py, cpy, ga (au)	E–W-trending microdiorite dyke. Pyrite–sericite greisen N–S trending altered and unaltered aplite dykes. Quartz > carbonate veins with coarse Au	300 m long, up to 8 m wide; 2 m at 4.7 g/t Au. 15 m at 1.92 g/t Au (Duncan 1984).

Abbreviations: asp = arsenopyrite, ang = anglesite, arg = argentite, au = native gold, ba = barite, cav = calaverite, co = covellite, cpy = chalcopyrite, eng = enargite, ga = galena, hes = hessite, krp = krupkaite, mag = magnetite, mar = marcasite, pez = petzite, pyr = pyrrhotite, py = pyrite, sph = sphalerite, syl = sylvanite, tel = tellurides (not specified), ten = tennantite, tet = tetrahedrite

Table 2. $^{40}Ar/^{39}Ar$ step-heating analytical results for white mica from samples DREX027 220.2 m (Dargues Reef) and PGDS0/18 (Great Star mine).

Sample ID	Grain No.	Step No.	Cum.% ^{39}Ar	^{40}Ar ($\times 10^{-13}$ moles)	±	^{39}Ar ($\times 10^{-14}$ moles)	±	^{38}Ar ($\times 10^{-16}$ moles)	±	^{37}Ar ($\times 10^{-16}$ moles)	±	^{36}Ar ($\times 10^{-16}$ moles)	±	Ca/K	±	%$^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	±	Age (Ma)	±
Sample DREX027																				
J-Value = 0.013775 ± 0.000026																				
DREX-1a	1	1	13.5	0.3824	0.0006	0.1900	0.0002	0.0052	0.0080	0.0285	0.0068	0.0969	0.0019	0.0026	0.0006	92.5	18.62	0.04	412.0	0.9
DREX-1b		2	16.0	0.0755	0.0001	0.0351	0.0002	0.0171	0.0022	0.6914	0.0952	0.0411	0.0021	0.3450	0.0475	83.9	18.07	0.20	400.9	4.0
DREX-2b	2	2	23.2	0.2235	0.0003	0.1001	0.0002	0.0244	0.0050	0.0285	0.0042	0.1243	0.0029	0.0050	0.0007	83.6	18.66	0.10	412.8	2.1
DREX-3a	3	1	44.3	0.5541	0.0007	0.2970	0.0008	0.0002	0.0103	0.4223	0.0719	0.0242	0.0026	0.0249	0.0042	98.7	18.42	0.06	407.9	1.2
DREX-3b		2	49.0	0.1337	0.0002	0.0651	0.0002	0.0086	0.0031	0.7995	0.0914	0.0528	0.0017	0.2149	0.0246	88.3	18.13	0.10	402.2	2.1
DREX-4a	4	2	57.5	0.2342	0.0003	0.1194	0.0003	0.0033	0.0042	0.4556	0.0603	0.0347	0.0025	0.0668	0.0088	95.6	18.76	0.09	414.7	1.7
DREX-4b		2	61.6	0.1408	0.0002	0.0575	0.0001	0.0201	0.0031	0.4754	0.0555	0.1191	0.0032	0.1448	0.0169	75.0	18.39	0.17	407.4	3.4
DREX-5a	5	1	73.8	0.3584	0.0005	0.1714	0.0004	0.0120	0.0049	1.0606	0.2106	0.1335	0.0025	0.1083	0.0215	89.0	18.61	0.07	411.8	1.3
DREX-5b		2	75.8	0.0689	0.0001	0.0280	0.0001	0.0137	0.0035	1.3091	0.1957	0.0548	0.0017	0.8180	0.1223	76.5	18.82	0.20	415.8	3.9
DREX-6b	6	2	84.7	0.3024	0.0005	0.1244	0.0002	0.0476	0.0051	0.3188	0.0579	0.2355	0.0033	0.0448	0.0081	77.0	18.71	0.09	413.7	1.8
DREX-7a	7	1	96.0	0.3053	0.0005	0.1591	0.0003	0.0002	0.0050	0.1863	0.0285	0.0308	0.0015	0.0205	0.0031	97.0	18.62	0.06	411.9	1.1
DREX-7b		2	98.7	0.0807	0.0002	0.0381	0.0002	0.0146	0.0017	0.2933	0.0223	0.0358	0.0016	0.1347	0.0103	86.9	18.39	0.16	407.4	3.1
DREX-8b	8	2	100.0	0.0491	0.0001	0.0178	0.0002	0.0088	0.0014	0.0291	0.0056	0.0571	0.0020	0.0286	0.0055	65.6	18.07	0.38	400.9	7.5
Sample PGDS0/18																				
J-Value = 0.013797 ± 0.000024																				
PGDS-1a	1	1	12.1	0.2178	0.0003	0.1105	0.0003	0.0349	0.0059	0.2872	0.0421	0.0410	0.0013	0.0455	0.0067	94.4	18.61	0.07	412.4	1.4
PGDS-1b		2	19.2	0.1477	0.0002	0.0642	0.0002	0.0233	0.0030	0.4523	0.0962	0.1001	0.0019	0.1234	0.0263	80.0	18.41	0.12	408.2	2.3
PGDS-2a	2	1	26.8	0.2226	0.0003	0.0693	0.0001	0.0579	0.0049	0.0026	0.0005	0.3212	0.0030	0.0007	0.0001	57.4	18.43	0.14	408.6	2.7
PGDS-2b		2	32.2	0.1640	0.0002	0.0489	0.0002	0.0465	0.0039	0.0072	0.0009	0.2571	0.0040	0.0026	0.0003	53.7	17.99	0.26	399.9	5.2
PGDS-3a	3	1	38.5	0.1233	0.0002	0.0579	0.0001	0.0060	0.0024	0.2215	0.0515	0.0531	0.0018	0.0670	0.0156	87.3	18.60	0.11	412.1	2.1
PGDS-3b		1	41.2	0.1004	0.0002	0.0248	0.0001	0.0314	0.0060	0.0308	0.0146	0.1842	0.0041	0.0217	0.0103	45.8	18.52	0.50	410.5	9.9
PGDS-4a	4	1	44.0	0.0621	0.0001	0.0249	0.0001	0.0138	0.0035	0.4502	0.1300	0.0596	0.0031	0.3167	0.0915	71.7	17.89	0.37	398.1	7.5
PGDS-4b		2	44.8	0.1344	0.0002	0.0074	0.0001	0.0805	0.0030	0.6889	0.0552	0.4251	0.0035	1.6337	0.1321	6.5	11.90	1.41	274.4	30.2
PGDS-5a	5	1	56.5	0.2048	0.0003	0.1073	0.0003	0.0002	0.0039	0.0309	0.0153	0.0162	0.0012	0.0050	0.0025	97.7	18.64	0.07	412.9	1.4
PGDS-5b		2	60.0	0.0771	0.0002	0.0319	0.0001	0.0028	0.0017	0.0309	0.0107	0.0602	0.0010	0.0169	0.0059	76.9	18.60	0.12	412.1	2.3
PGDS-6a	6	1	63.3	0.0651	0.0001	0.0293	0.0001	0.0119	0.0029	0.0309	0.0098	0.0318	0.0016	0.0184	0.0059	85.6	19.00	0.18	419.9	3.5
PGDS-6b		2	64.9	0.0459	0.0001	0.0146	0.0001	0.0114	0.0020	0.0309	0.0206	0.0580	0.0009	0.0370	0.0247	62.7	19.70	0.23	433.9	4.6
PGDS-7a	7	1	75.2	0.1846	0.0003	0.0939	0.0002	0.0021	0.0030	0.7097	0.0979	0.0393	0.0013	0.1323	0.0182	93.7	18.42	0.07	408.5	1.3
PGDS-7b		2	80.1	0.1200	0.0002	0.0450	0.0001	0.0229	0.0035	0.0309	0.0054	0.1254	0.0032	0.0120	0.0021	69.1	18.42	0.21	408.5	4.2
PGDS-8a	8	1	90.9	0.2969	0.0005	0.0983	0.0003	0.0747	0.0027	0.0309	0.0139	0.3899	0.0058	0.0055	0.0025	61.2	18.49	0.19	410.0	3.7
PGDS-8b		2	100.0	0.4405	0.0006	0.0829	0.0002	0.1880	0.0053	0.4834	0.0600	0.9725	0.0059	0.1020	0.0127	34.8	18.47	0.23	409.6	4.5

Table 3. Sulfur isotope data for sulfides from the Dargues Reef–Majors Creek study area.

Deposit Location sampled	Description	Sample no.	MGAE (Z55)	MGAN (Z55)	Mineral	S-isotope value (per mil)	Reference
Dargues Reef							
Main Lode — DREX027-228 m	Pyrite from main quartz–sericite–pyrite lode; from zone assaying 10.3 ppm Au	DBF2B	748818	6062677	pyrite	0.2	present study
Main Lode — DREX028-369.3 m	Pyrite from Cu-bearing quartz–sericite–pyrite lode	DBF2C	748862	6062606	pyrite	−1.1	present study
Main Lode — DREX028-369.3 m	Chalcopyrite from Cu-bearing quartz–sericite–pyrite lode	DBF2D	748862	6062606	chalcopyrite	−1.3	present study
Main Lode — DREX027-233 m	Pyrite from Main quartz–sericite–pyrite lode	DBF2E	748818	6062677	pyrite	0.1	present study
Main Lode — DREX-283.85 m	Pyrite from Main quartz–sericite–pyrite lode	DBF2F	748818	6062677	pyrite	−1.0	present study
Main Lode — DREX027-283.7 m	Pyrite from Main quartz–sericite–pyrite lode	DBF2G	748818	6062677	pyrite	−0.1	present study
DREX027-200.8 m	Pyrite from diorite dyke, margin with cubic porous pyrite	DBF3B	748818	6062677	pyrite	0.1	present study
DREX027-200.8 m	Pyrite from diorite dyke, margin with cubic porous pyrite	DBF3B	748818	6062677	pyrite	0.1	present study
DREX043-212 m	Whole-rock: fine-grained silicified, sericitised granite with fine interstitial pyrite	DBF4N	748862	6062606	pyrite-rich rock	−3.6	present study
DREX043-212 m	Whole-rock: fine-grained silicified, sericitised granite with fine interstitial pyrite	DBF4O	748862	6062606	pyrite-rich rock	−4.4	present study
Dargues Reef		6S10	748950	6062700	pyrite	−1.3	McQueen & Perkins (1995)
Dargues Reef		6S11(A)	748950	6062700	pyrite	−0.8	McQueen & Perkins (1995)
Dargues Reef		6S11(B)	748950	6062700	pyrite	−1.4	McQueen & Perkins (1995)
Dargues Reef		6S11(B)	748950	6062700	pyrite	−1.5	McQueen & Perkins (1995)
Dargues Reef		7S5	748950	6062700	pyrite	−0.4	McQueen & Perkins (1995)
Dargues Reef		DR3	748950	6062700	pyrite	−1.0	McQueen & Perkins (1995)
Dargues Reef		DR4	748950	6062700	pyrite	−1.2	McQueen & Perkins (1995)
Dargues Reef		DR5	748950	6062700	pyrite	−3.4	McQueen & Perkins (1995)
Dargues Reef		DR6	748950	6062700	pyrite	−1.5	McQueen & Perkins (1995)
Dargues Reef		DR7	748950	6062700	pyrite	−0.5	McQueen & Perkins (1995)
Exeter Farm							
EXE014-96 m A	Sericitically altered granite with cubic pyrite	DBF4A	749502	6065079	pyrite	2.3	present study
EXE014-96 m B	Sericitically altered granite with cubic pyrite	DBF4B	749502	6065079	pyrite	1.8	present study
EXE014-96 m C	Sericitically altered granite with cubic pyrite	DBF4C	749502	6065079	pyrite	2.4	present study
EXE014-96 m D	Sericitically altered granite with cubic pyrite	DBF4D	749502	6065079	pyrite	2.1	present study
EXE014-99 m A	Sericitically altered granite with cubic pyrite	DBF4E	749502	6065079	pyrite	1.5	present study
EXE014-99 m B	Sericitically altered granite with cubic pyrite	DBF4F	749502	6065079	pyrite	1.9	present study
EXE014-99 m C	Sericitically altered granite with cubic pyrite	DBF4G	749502	6065079	pyrite	2.3	present study
EXE014-99 m D	Sericitically altered granite with cubic pyrite	DBF4H	749502	6065079	pyrite	1.5	present study
EXE014-100 m A	Sericitically altered granite with cubic pyrite	DBF4I	749502	6065079	pyrite	1.8	present study
EXE014-100 m B	Sericitically altered granite with cubic pyrite	DBF4J	749502	6065079	pyrite	2.1	present study
EXE014-100 m C	Sericitically altered granite with cubic pyrite	DBF4K	749502	6065079	pyrite	1.6	present study
EXE014-100 m D	Sericitically altered granite with cubic pyrite	DBF4L	749502	6065079	pyrite	1.7	present study
EXE014-100 m E	Sericitically altered granite with cubic pyrite	DBF4M	749502	6065079	pyrite	2.2	present study
Great Star mine							
dump	Intensely sericitically altered granite with 1% pyrite and narrow quartz veins	PDGS01/1	747568	6060386	pyrite	−4.1	present study
dump	Sericitised granite with ~2% euhedral and disseminated pyrite	PDGS01/10	747568	6060386	pyrite	0.4	present study
dump	Strongly silicified granite with grey quartz veins after sericitisation, ~2% pyrite	PDGS01/2	747568	6060386	pyrite	−3.8	present study
dump	Sericite–chlorite-altered granite ~1% cubic pyrite	PDGS01/6	747568	6060386	pyrite	0.1	present study
dump	Sericitically altered granite with disseminated pyrite. Barren linear carbonate vein not later than alteration.	PDGS01/7	747568	6060386	pyrite	−5.2	present study
dump	Intensely sericitised granite, 1% pyrite assoc. with chlorite, v. minor residual reddening of feldspar.	PDGS01/8	747568	6060386	pyrite	−3.1	present study
Snobs Reef							
dump	Quartz vein with pink granite one side and quartz–sericite–pyrite alteration on other	PDSB01/1	747960	6061885	galena pyrite	−6.7 −6.5	present study
dump	Quartz veins with strongly sericitised granite clasts, minor pyrite and galena to 1 mm.	PDSB01/5	747960	6061885	pyrite	−5.5	present study
dump	Silicified and phyllically altered granite with quartz veins <<1% pyrite	PDSB01/6	747960	6061885	pyrite	−2.8	present study
dump	Strongly silicified granite with grey quartz veins after sericitisation, ~5% pyrite	PDSB01/7	747960	6061885	pyrite	−4.1	present study
dump	Quartz with pyrite	PDSB01/8	747960	6061885	pyrite	0.6	present study
dump	Quartz with pyrite and some brecciated, sericitically altered granite.	PDSB01/9	747960	6061885	pyrite	−6.1	present study

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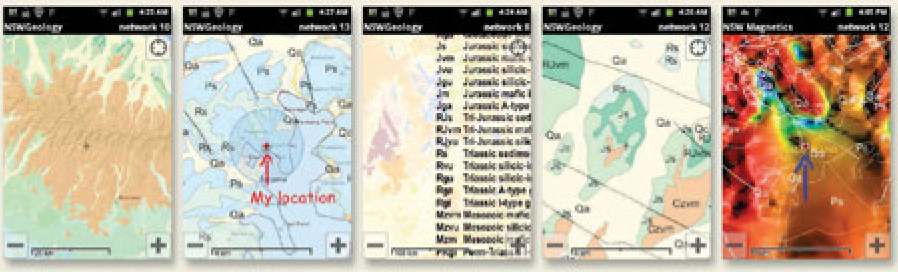

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Bouguer gravity, isostatic Bouguer gravity, greyscale isostatic Bouguer gravity tilt filter and isostation Bouguer gravity over isostatic Bouguer gravity tilt filter

Radiometric data

Ternary K/Th/U

Additional data

DEM, Landsat-7 principal components 1, 2 & 3

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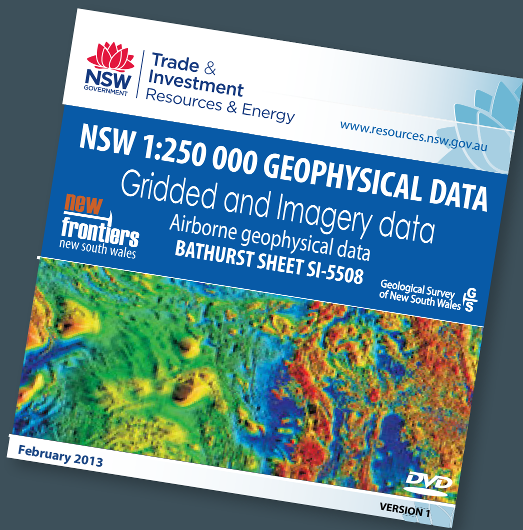

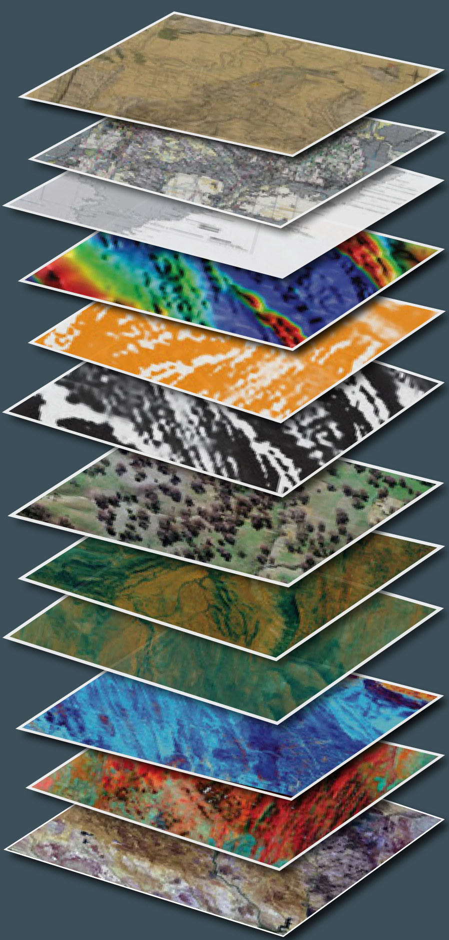

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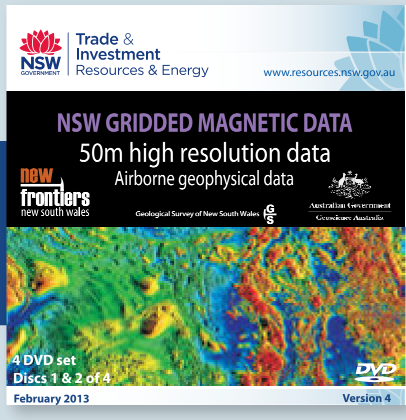
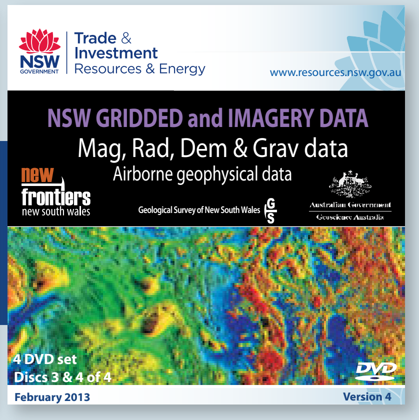
dvds





Pricing

- Statewide grids and images for aeromagnetic, radiometric, gravity and SRTM (elevation) data are available as 4 DVD set $110
- Hardcopy statewide images $19.80 each

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