Sulfur- and lead-isotope signatures of selected middle Silurian to Carboniferous mineral systems of the Lachlan Orogen, eastern New South Wales — implications for metallogeny

By

Peter Michael Downes
BSc (AppSc), MAppSc,

Thesis submitted in fulfilment of the requirements of the degree of

Doctor of Philosophy (Geology)

Discipline of Earth Sciences
School of Environment and Life Sciences
Faculty of Science and IT
University of Newcastle
17 July, 2009
Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

I hereby certify that the work embodied in this Thesis is the result of original research, the greater part of which was completed subsequent to admission to candidature for the degree (except in cases where the Committee has granted approval for credit to be granted from previous candidature at another institution).

I hereby certify that where work embodied in this Thesis has been done in collaboration with other researchers, or carried out in other institutions. I have included as part of the thesis a statement clearly outlining the extent of that collaboration, with whom and under what auspices.

I hereby certify that the work embodied in this thesis contains a published paper/s/scholarly work of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publication/s/scholarly work.
Supervisor endorsement

Included in this thesis are sections drawn from published papers/scholarly works for which the candidate has been a joint author. The candidate has included, as part of the introduction to each chapter or section of the thesis, a written statement, attesting to his and his co-authors contributions to the specific joint publication/s/scholarly work. Copies of the relevant publications are included in Appendix 9 (on CD-ROM).
ACKNOWLEDGEMENTS

This study would not have been possible without the active support from my wife Fay who put up with me visiting old mines and was a constant companion for my rock-tapping trips as circumstances permitted. Also, I wish to thank Lindsay Gilligan, David Suppel, Dave Forster, Peter Buckley, Rob Barnes, Gary Colquhoun, Cameron Ricketts and others from the Geological Survey of New South Wales (GSNSW) for their support and encouragement over the last 6 years. In particular, Dave read the drafts of several of the chapters and provided useful feedback.

A number of people and companies provided access to samples collected for other studies. They include: Gary Burton, Roger McEvilly and David Suppel (GSNSW); Remy Dehaan, Dominik Spodniewski, Craig Parry, Kim Seberry and Steve Wood (University of New South Wales), Paul Ashley (University of New England), Ken McQueen (University of Canberra), Gordon McLean (Golden Cross NL) and Ian Chalmers (Alkane Exploration). As a result of this collaboration some analytical results generated as part of this study were also presented in other studies and reference is made to: Wood (2001), Spodniewski (2003) and Seabury (2003).

I wish to thank all those whom provided analytical support for my project. They include:

- Frank Whippy (GSNSW), Richard Bale, Yanyan Sun and Zhiyu Jiang (University of Newcastle) for thin sections and polished blocks.
- Simon Poulson — S-isotope analyses (Nevada Stable Isotope Laboratory, University of Nevada, Reno, USA).
- Anita Andrew, Brad McDonald, Geoff Denton and Barbara Gardner — lead and sulfur isotope analyses (CSIRO Exploration and Mining, North Ryde).
- Dave Phillips — Ar–Ar dating (University of Melbourne).
- Host Zwingmann — K–Ar age dating (CSIRO Petroleum division, Bentley, Perth).
- Dave Phelan — Electron Microscope and X-ray Unit (University of Newcastle).
- Cheryl Hormann, Phillip Carter, Robyn Sharpe (GSNSW) and Olivier Rey Lescure (University of Newcastle) for drafting figures included in published papers.
- Clint Gilmore for preparing the self loading template used in digital Appendix 9 (the CD-ROM).

Permission to use lead isotope analyses from previously unpublished studies by the CSIRO Exploration and Mining is gratefully acknowledged. I am also grateful to Michael Agnew, Graham Carr, Richard Facer, Dave Forster, Sue Golding, Jeffrey Hedenquist, David Huston, Shunso Ishihara, David John, Ken McQueen, Dave Phillips, Cameron Ricketts, Phil Seccombe,
Mike Solomon, Noel White and other un-named reviewers for reviewing papers arising from this thesis.

Last but not least, I acknowledge and wish to thank my supervisors Phil Seccombe and Bill Landenberger for their support and encouragement. Phil pointed out the advantages of enrolling as a PhD candidate while on a three-day bushwalk over Mount Bogong in Victoria. Without Phil’s support and encouragement, particularly after his retirement, I would not have completed this project. Phil also critically reviewed individual chapters and papers prior to submittal. Bill has provided administrative support for my project when Phil was unavailable and listened to my concerns.

This study has been supported by funding from the Geological Survey of New South Wales — Department of Primary Industries, the University of Newcastle, a BHP Student Research Grant and a Hugh Exton McKinstry Fund grant both from the Society of Economic Geologists Foundation Inc.
Table of Contents

ACKNOWLEDGEMENTS iii
ABSTRACT xxi

CHAPTER 1 INTRODUCTION 1
  1.1 PREAMBLE 1
  1.2 PROBLEM AND OBJECTIVES 2
  1.3 SCOPE AND AREA OF THE THESIS 4
  1.4 PREVIOUS STUDIES 7
  1.5 PAPERS AND OTHER PUBLICATIONS ARISING FROM THIS THESIS 11

CHAPTER 2 GEOLOGICAL OVERVIEW 13
  2.1 INTRODUCTION 13
  2.2 BENAMBRAN CYCLE 15
  2.3 TABBERABBERAN CYCLE 18
  2.4 KANIMBLAN CYCLE 21
  2.5 POST-LACHLAN OROGEN EVENTS 23
  2.6 FINAL COMMENTS 24

CHAPTER 3 ANALYTICAL PROCEDURES 25
  3.1 INTRODUCTION 25
  3.2 S-ISOTOPE ANALYSES 27
  3.3 Pb-ISOTOPE ANALYSES 29
  3.4 SCANNING ELECTRON MICROSCOPE 35
  3.5 AGE DATING 36

CHAPTER 4 VHMS MINERALISATION IN THE MID TO LATE SILURIAN HILL END TROUGH AND GOULBURN TROUGH 41
  4.1 INTRODUCTION 41
  4.2 GEOLOGICAL SETTING 45
  4.3 MINERALISATION AND S-ISOTOPE RESULTS 50
    4.3.1 WESTERN HILL END TROUGH 50
    4.3.2 CAPERTEE ZONE 58
    4.3.3 SOUTHERN HILL END TROUGH 58
4.3.4 Goulburn Trough

4.4 NEW Pb-ISOTOPE DATA
   4.4.1 Northern Hill End Trough
   4.4.2 Southern Hill End Trough
   4.4.3 Goulburn Trough

4.5 DISCUSSION
   4.5.1 S-isotopes
   4.5.2 Pb-isotopes

4.6 SUMMARY

CHAPTER 5 OROGENIC GOLD–BASE METAL SYSTEMS
— S- & Pb-isotope signatures

5.1 INTRODUCTION

5.2 OROGENIC GOLD SYSTEMS
   5.2.1 Hill End Trough and Adjacent Areas
      5.2.1.1 Introduction
      5.2.1.2 Geological setting
      5.2.1.3 Mineralisation and results
         5.2.1.3.1 Northern Hill End Trough
         5.2.1.3.2 Molong High
         5.2.1.3.3 Capertee High
      5.2.1.4 Discussion
   5.2.2 Gilmore Fault Zone
      5.2.2.1 Introduction
      5.2.2.2 Geological setting
      5.2.2.3 Mineralisation and results
      5.2.2.4 Discussion
   5.2.3 Parkes Fault Zone
      5.2.3.1 Introduction
      5.2.3.2 Geological setting
      5.2.3.3 Mineralisation and results
      5.2.3.4 Discussion

5.3 OROGENIC BASE METAL SYSTEMS
   5.3.1 Introduction
   5.3.2 Geological Setting
8.1.3  **ORE GEOLOGY**  373
8.1.4  **S-ISOTOPES**  375
8.1.5  **Pb-ISOTOPES**  377
8.1.6  **DISCUSSION**  377

**CHAPTER 9  TIMING OF MINERALISATION AND DISCUSSION**  383

9.1  **INTRODUCTION**  383
9.2  **TIMING OF MINERALISATION**  383
9.3  **S-ISOTOPE ZONATION OF THE LACHLAN OROGEN**  400
9.4  **Pb-ISOTOPE RESERVOIRS**  404
9.5  **IMPLICATIONS FOR THE METALLOGENESIS OF THE LACHLAN OROGEN**  408

**CHAPTER 10  CONCLUSION**  413

**CHAPTER 11  REFERENCES**  425

**APPENDICES**

APPENDIX 1  **PAPERS AND OTHER PUBLICATIONS ARISING FROM THIS THESIS**  469
APPENDIX 2  **SAMPLE LOCATIONS**  475
APPENDIX 3  **NEW AND UNPUBLISHED S-ISOTOPE DATA**  515
APPENDIX 4  **NEW Pb-ISOTOPE DATA**  569
APPENDIX 5  **MICROCHEMICAL ANALYSES OF SULFIDE MINERALS CARRIED OUT USING THE SCANNING ELECTRON MICROPROBE**  581
APPENDIX 6  **MICROCHEMICAL ANALYSES OF SILICATE MINERALS CARRIED OUT USING THE SCANNING ELECTRON MICROPROBE**  585
APPENDIX 7  **DETERMINATION OF TEMPERATURES USING CLORITE GEOTHERMOMETRY**  589
APPENDIX 8  **AGE DATING**  597
APPENDIX 9  **SUPPORTING STUDIES, PUBLISHED PAPERS AND PUBLISHED CD-ABSTRACTS**  CD-ROM
### FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Location of 1:250 000 geological map sheet areas referred to in the text.</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Major subdivisions of the Tasmanides.</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Key Ordovician terranes in the Eastern and Central Subprovinces of the Lachlan Orogen in southeastern Australia.</td>
<td>16</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Geological summary map showing the distribution of the major geological elements, discussed in the text, within the Central and Eastern Subprovinces of the Lachlan Orogen in New South Wales.</td>
<td>20</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Location of the Hill End Trough and the Goulburn Trough, Lachlan Orogen, New South Wales.</td>
<td>42</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Location of VHMS systems and distribution of Late Silurian to earliest Devonian felsic volcanic and related sedimentary units within and adjacent to the northern and central parts of the Hill End Trough.</td>
<td>46</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Location of VHMS systems and distribution of Late Silurian felsic volcanic and related sedimentary units within the southern Hill End Trough and Goulburn Trough.</td>
<td>47</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Distribution of S-isotope values ($\delta^{34}\text{S}$) for volcanic-hosted massive sulfide (VHMS) deposits in the northern Hill End Trough.</td>
<td>54</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Distribution of S-isotope values ($\delta^{34}\text{S}$) for volcanic-hosted massive sulfide (VHMS) deposits (Black Springs, Cordillera, Elsinora, Gurrundah, Kempfield, John Fardy, Mount Costigan, Peelwood) in the southern Hill End Trough.</td>
<td>60</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Distribution of S-isotope values according to ore type for the John Fardy deposit (including the Central Hill zone).</td>
<td>65</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Distribution of S-isotope values ($\delta^{34}\text{S}$) for individual ore types for the Elsinora VHMS deposit.</td>
<td>65</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Thin section photomicrographs of sample Glen DDH7/1 under transmitted light (crossed nicols) (left) and reflected light (right).</td>
<td>68</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Thin section photomicrographs of sample Glen DDH7/1 under transmitted light (crossed nicols) (left) and reflected light (right).</td>
<td>68</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$ age data for all heating steps from sample Glen DDH7/1 muscovite grains.</td>
<td>69</td>
</tr>
<tr>
<td>Figure 4.11</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$ age data for the high temperature steps from sample Glen DDH7/1 muscovite grains.</td>
<td>69</td>
</tr>
</tbody>
</table>
Figure 4.12  $^{40}$Ar/$^{39}$Ar age data for selected (older) high temperature steps from sample Glen DDH7/1 muscovite grains.

Figure 4.13  $^{40}$Ar/$^{39}$Ar age data for low temperature steps for muscovite grains from sample Glen DDH7/1.

Figure 4.14  Distribution of S-isotope values ($\delta^{34}$S) for VHMS mineralisation in the Goulburn Trough.

Figure 4.15  Distribution of S-isotope values according to ore and halo sulfides for the Currawang East deposit.

Figure 4.16  Distribution of S-isotope values for both sulfide and sulfate minerals according to ore type and massive sulfide lens for the Woodlawn deposit (114 analyses).

Figure 4.17  Distribution of S-isotope values for all sulfides according to sulfide-type and distance (in metres) from the top of C Lens for the Woodlawn deposit (114 analyses).

Figure 4.18  Distribution of S-isotope values for sulfides from the C Lens ore zone only (Woodlawn deposit), according to distance (in metres) from the top of C Lens.

Figure 4.19  Distribution of S-isotope values for disseminated pyrite from wall rocks of the Woodlawn VHMS deposit (23 analyses).

Figure 4.20  Distribution of S-isotope values for vein-hosted sulfides according to sulfide-type and distance (in metres) from the top of C Lens for the Woodlawn VHMS deposit (22 analyses).

Figure 4.21  Distribution of S-isotope values for all sulfides according to sulfide-type and distance (in metres) from the top of C Lens for the Woodlawn deposit.

Figure 4.22  Distribution of Pb-isotope data for the Calula, Lewis Ponds, Mount Bulga and Sunny Corner VHMS deposits (northern HET).

Figure 4.23  Distribution of new Pb-isotope data for the VHMS-related deposits in the northern Hill End Trough (Accost, Belara and Commonwealth).

Figure 4.24  Distribution of Pb-isotope data for VHMS-related deposits in the northern and central parts of the southern Hill End Trough.

Figure 4.25  Distribution of Pb-isotope data for VHMS-related deposits in the northern part of the southern Hill End Trough.
Figure 4.26 Distribution of new Pb-isotope data for VHMS-related deposits in the southern part of the southern Hill End Trough (Gurrundah and Wet Lagoon).

Figure 4.27 Distribution of Pb-isotope data for the Captains Flat, Currawang East and Woodlawn base metal deposits.

Figure 4.28 Distribution of Pb-isotope data for the Glen E prospect (The Glen — Goulburn Trough).

Figure 4.29 Block model for the Peelwood district to explain the development of distinct S-isotope signatures for four very similar VHMS deposits along a >11 km strike-length of host stratigraphy.

Figure 5.1 Location of project areas (highlighted by red boxes) and index to more detailed maps included in Chapter 5.

Figure 5.2 Regional geology of the northern Hill End Trough showing the distribution of structurally controlled gold mineralisation, major faults and major stratotectonic units.

Figure 5.3 Distribution of S-isotope values ($\delta^{34}$S) for orogenic gold systems within and adjacent to the northern Hill End Trough.

Figure 5.4 Distribution of all $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb data for Bodangora, Gulgong, Hargraves, Napoleon Reefs, Sofala—Wattle Flat, Stuart Town and Windeyer.

Figure 5.5 Distribution of $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb data for Hargraves (Big Nugget Hill mine and Hill End Shaft).

Figure 5.6 Distribution of $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb data for veins from Hill End.

Figure 5.7 Diagram showing the range in lead model ages for veins from Hill End.

Figure 5.8 Distribution of $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb data for Napoleon Reefs, Sofala (Big Oakey, Queenslander, Spring Gully), Stuart Town (Hughes Reef, Post Office Reef, Princess Reef) and Windeyer (Coronation, Eaglehawk Gully, Golden Lily).

Figure 5.9 Distribution of $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb data for Bodangora (Dicks Reward, Mitchells Creek) and Gulgong (Box Hill, Divide 4, Orchard, Springfield).

Figure 5.10 Geological setting of Adelong (Challenger deposit; O’Briens Shaft) and Sebastopol (Morning Star mine).

Figure 5.11 Distribution of S-isotope ($\delta^{34}$S) values for low sulfide orogenic gold vein mineralisation associated with the Gilmore Fault Zone.
Figure 5.12  Distribution of Pb-isotope data for the Morning Star mine (Sebastopol) and the Challenger and Gibraltar lode system at Adelong.

Figure 5.13  Geological setting of the Tomingley–Alectown–Parkes–Forbes gold district (Parkes district).

Figure 5.14  Distribution of S-isotope values ($\delta^{34}S$) for low sulfide orogenic gold deposits in the Parkes district.

Figure 5.15  Distribution of Pb-isotope data for the Calarie deposit, London–Victoria deposit (including BHP data) and the Wyoming One deposit.

Figure 5.16  Summary geology of the Goulburn 1:250 000 map sheet and northern part of the Canberra 1:250 000 map sheet areas.

Figure 5.17  Distribution of S-isotope values ($\delta^{34}S$) for sulfide-rich orogenic base metal deposits.

Figure 5.18  Distribution of Pb-isotope data for the Frogmore, Kangiara and Wallah Wallah base metal deposits.

Figure 5.19  Distribution of Pb-isotope data for the Lucky Hit–Merrilla area (Gurrundah base metal district).

Figure 5.20  Distribution of Pb-isotope data for Currawang South, Montrose and Mount Werong (including Ruby Creek).

Figure 6.1  Location of the Yerranderie, Yalwal, Pambula, Bauloora and Bowdens epithermal systems and the Eastern Subprovince of the Lachlan Orogen in New South Wales.

Figure 6.2  Location of epithermal and related mineralisation associated with the Bindook Volcanic Complex and with non-intrusive units (Yalwal Volcanics, Boyd Volcanic Complex, Comerong Volcanics and Merimbula Formation) of the Eden–Comerong–Yalwal Rift Zone.

Figure 6.3  Major mines and generalised geology of the Yerranderie silver–gold–lead district.

Figure 6.4  Location of the mines, extent of underground workings and main zones of stoping for the principal mines at Yerranderie.

Figure 6.5  A north–south section through the Duck House chute — Silver Peak mine showing the geometry of ore zones.

Figure 6.6  Proposed mineral paragenesis of sulfide and gangue minerals for zoned veins at Yerranderie combining the observations of Edwards (1953) and the present study.
Figure 6.7 Reflected light photomicrographs of quartz–sulfide filled fractures from Yerranderie.

Figure 6.8 Frequency histogram of S-isotope values (δ^{34}S) for the Yerranderie, Yalwal and Pambula epithermal systems.

Figure 6.9 Distribution of Pb-isotope data for Yerranderie.

Figure 6.10 40Ar/39Ar age data for single mica grains from PDY6–873.

Figure 6.11 Local geology and the location of the principal mines at Yalwal.

Figure 6.12 Distribution of alteration-related minerals within the Homeward Bound Low Level Tunnel and the Pioneer Tunnel (RL 89 m) at Yalwal.

Figure 6.13 Frequency histogram of S-isotope values (δ^{34}S) for pyrite compared to the presence of hydrous minerals within the same sample for Yalwal.

Figure 6.14 Distribution of Pb-isotope data for the Pambula and Yalwal goldfields.

Figure 6.15 Principal structures and the location of the mines at Pambula.

Figure 6.16 Crustiform banding in silica–sulfide veins and adjacent jigsaw-fit textured breccia from the Bauloora lead–zinc–(copper–silver–gold) deposit.

Figure 6.17 Thin section photomicrographs of sample PDBA03 under transmitted crossed polar light (upper) and transmitted crossed polar light (lower).

Figure 6.18 Thin section photomicrograph of sample PBBA03, from the Bauloora lead–zinc–(copper–silver–gold) deposit.

Figure 6.19 Frequency histogram of S-isotope values (δ^{34}S) for the Bauloora and Bowdens epithermal systems.

Figure 6.20 Distribution of Pb-isotope data for the Bauloora and Bowdens epithermal systems.

Figure 6.21 40Ar/39Ar Ar age data for composite fine-grained mica-rich separates from PDBA03 — Bauloora.

Figure 6.22 Geological setting of the Bowdens deposit and section along 10500 N showing the outline of >40 g/t silver in the Bundarra North Zone and Main Zone North.

Figure 6.23 Pb-isotope ratio plot comparing data for the Pambula and Yalwal goldfields (data: reinterpreted from Glaser 1988; present study) with the data for Yerranderie (data from the CSIRO Pb-isotope database).

Figure 6.24 Pb-isotope ratio plot comparing Pb-isotope data for igneous units associated with the Eden–Comerong–Yalwal Rift Zone with that for Yalwal, Yerranderie and Pambula and data for the Bega Batholith.
Figure 7.1 Distribution of granites in southeastern New South Wales and Tabberabberan-cycle intrusion-related mineralisation included in the present study.

Figure 7.2 Distribution of S-isotope values (δ34S) for skarn-type mineralisation, Eastern Subprovince of the Lachlan Orogen.

Figure 7.3 Distribution of all 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for skarn-type mineralisation, Eastern Subprovince, Lachlan Orogen.

Figure 7.4 Distribution of 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for the Browns Creek skarn deposit and related intrusions.

Figure 7.5 Distribution of 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for the Collector, Inveralochy (Ryans), Mayfield, Nasdaq, Red Hill, Rye Park and Tallawang skarns.

Figure 7.6 Distribution of S-isotope values (δ34S) for granite-related mineralisation, Eastern Subprovince, Lachlan Orogen.

Figure 7.7 Distribution of 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for Dargues Reef, Majors Creek, Phoenix, Whipstick and Yambulla.

Figure 7.8 Distribution of 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for Au mineralisation at Dargues Reef–Majors Creek and for the Braidwood Granodiorite.

Figure 7.9 Distribution of S-isotope values (δ34S) for granite-related mineralisation, Central Subprovince, Lachlan Orogen.

Figure 7.10 Distribution of 207Pb/204Pb vs 206Pb/204Pb and 208Pb/204Pb vs 206Pb/204Pb data for Ardlethan, Mineral Hill and Tara.

Figure 7.11 Distribution of S-isotope values (δ34S) individual mineralised zones at Mineral Hill.

Figure 7.12 Thin section photomicrographs of sample TRD8/7 (Tara) under transmitted crossed polar light (left) and reflected light (right).

Figure 7.13 Thin section photomicrographs of sample TRD8/7 (Tara) under transmitted crossed polar light (left) and reflected light (right).

Figure 7.14 40Ar/39Ar age data for all heating steps from TRD8/7 muscovite grains (Tara).

Figure 7.15 40Ar/39Ar age data for the high temperature steps from TRD8/7 muscovite grains (Tara).
Figure 7.16 Location of S-isotope analyses for middle Silurian to Early Devonian granites in the southeastern Lachlan Orogen.

Figure 7.17 Histogram showing the range of S-isotope data for granites, included in Table 7.5 classified by Batholith.

Figure 7.18 Histogram showing the distribution of S-isotope data for granites, included in Table 7.5 classified by granite type and with respect to the I–S line of White et al. (1976) and Chappell et al. (1988).

Figure 7.19 Distribution of $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ data for the Browns Creek for the area where $^{206}\text{Pb}/^{204}\text{Pb}$ lies between 17.50 and 19.00, showing the proposed secondary growth curve.

Figure 7.20 Distribution of least radiogenic $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ data for the Braidwood Granodiorite and the Dargues Reef, Majors Creek, Mayfield, Rye Park, Tallawang, Whipstick and Yambulla deposits for the area where $^{206}\text{Pb}/^{204}\text{Pb}$ lies between 18.05 and 18.35.

Figure 7.21 Distribution of least radiogenic $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ data for granites from the Cobargo, Kameruka, Candelo (including Braidwood Granodiorite and Yurammie Granite), Bemboka, Glenbog and Tonghi Supersuites of the Bega Batholith and those for the Berridale Batholith for the area where $^{206}\text{Pb}/^{204}\text{Pb}$ lies between 18.08 and 18.25.

Figure 7.22 Distribution of least radiogenic $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ data for granites from the Ardlethan, Mineral Hill and Tara for the area where $^{206}\text{Pb}/^{204}\text{Pb}$ lies between 18.05 and 18.25.

Figure 7.23 Distribution of Pb-isotope data for Browns Reef and Tara compared to the signatures for “Cobar-type” mineralisation as proposed by Lawrie and Hinman (1998).

Figure 8.1 Interpreted solid geology for the Cargelligo 1:250 000 map sheet area.

Figure 8.2 Interpretative plan of Browns Reef — adapted from Lees (1988).

Figure 8.3 Geological section 6300.0N through Browns Reef - showing +2% Pb–Zn mineralised zones — modified from Maniw (1983b).

Figure 8.4 Photograph of a quartz–pyrite–sphalerite–(galena)-filled fracture under reflected light from the Browns Reef deposit.

Figure 8.5 Photomicrograph of part of a quartz–pyrite–sphalerite–(galena–chalcopyrite) vein under reflected light from the Browns Reef deposit.

Figure 8.6 Histograms showing the distribution of S-isotope data for Browns Reef.
Figure 8.7 Distribution of $^{207}$Pb/$^{204}$Pb vs $^{206}$Pb/$^{204}$Pb lead isotope data for Browns Reef.

Figure 9.1 Time–space plot for Tabberabberan cycle intrusion-related mineralisation in the Central and Eastern Subprovinces of the Lachlan Orogen, NEW SOUTH WALES.

Figure 9.2 Time–space plot for VHMS-related mineralisation located in the Hill End Trough and Goulburn Trough, Eastern Subprovince, Lachlan Orogen, New South Wales.

TABLES

Table 3.1 Summary of mineral deposits and systems for which new S-isotope data were collected as part of the present study. 30

Table 3.2 Summary of mineral deposits and systems for which new Pb-isotope analyses were carried out as part of the present study. 34

Table 3.3 Summary of mineral deposits/systems for which new age dating was carried out as part of the present study. 40

Table 4.1 Features of VHMS deposits in the Hill End Trough and Goulburn Trough, eastern Lachlan Orogen. 51

Table 4.2 Summary S-isotope data for the Lewis Ponds deposit. 53

Table 4.3 Summary S-isotope data for the Woodlawn deposit. 75

Table 4.4 Summary S-isotope data for ore sulfides from Group 1 deposits in the Hill End Trough and Goulburn Trough. 93

Table 4.5 Summary S-isotope data for ore sulfides from Group 2 deposits in the Hill End Trough and Goulburn Trough. 94

Table 5.1 Features of orogenic gold systems within and adjacent to the Hill End Trough, eastern Lachlan Orogen with an estimate of the contained gold for each field and summary sulfur isotope data. 117

Table 5.2 Summary of features for the Box Hill, Divide 4 Orchard and Springfield prospects, Gulgong. 133

Table 5.3 Summary of features that may be used to fingerprint the sources of gold included in the present study. 134

Table 5.4 Summary of S- and Pb-isotope results — northern HET. 136
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page no</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Features of low-sulfide orogenic gold vein systems associated with the Gilmore Fault Zone and Parkes Fault Zone included in this study.</td>
<td>147</td>
</tr>
<tr>
<td>5.6</td>
<td>Features of sulfide-rich orogenic-related base metal vein systems included in the present study.</td>
<td>176</td>
</tr>
<tr>
<td>5.7</td>
<td>Summary of $\delta^{34}$S results from this study and Roberts (1978) for the Kangiara base metal system.</td>
<td>184</td>
</tr>
<tr>
<td>5.8</td>
<td>Summary $S$-isotope data for ore sulfides from deposits in the Yass Shelf–Frogmore Fault Zone, southern Hill End Trough and Goulburn Trough.</td>
<td>195</td>
</tr>
<tr>
<td>6.1</td>
<td>Summary of the mine names, production and periods worked for the principal mines along the Yerranderie Fault.</td>
<td>211</td>
</tr>
<tr>
<td>6.2</td>
<td>Summary of mineral content of veins and shoots based on Edwards (1953) and the present study.</td>
<td>216</td>
</tr>
<tr>
<td>6.3</td>
<td>$S$-isotope data for individual mines and zones within the Yerranderie silver–gold–lead district.</td>
<td>222</td>
</tr>
<tr>
<td>6.4</td>
<td>Summary $S$-isotope data for sulfides from individual mines and drill hole DDD–Y6 for the Yerranderie area.</td>
<td>221</td>
</tr>
<tr>
<td>6.5</td>
<td>Summary of $^{40}K/^{40}Ar$ age dating of fine-grained sericite from the Pambula, Yalwal and Yerranderie epithermal systems.</td>
<td>230</td>
</tr>
<tr>
<td>6.6</td>
<td>Comparison of key features of the epithermal gold–silver systems (Pambula, Yalwal) and epithermal silver–gold–base metal system (Bauloora, Bowdens, Yerranderie) within the present study area compared to the geological and genetic characteristics of low- and intermediate-sulfidation deposits as summarised by Gemmell (2004).</td>
<td>234</td>
</tr>
<tr>
<td>6.7</td>
<td>Summary of $^{40}Ar/^{39}Ar$ furnace step-heating analytical results for sample PDBA03 — Bauloora.</td>
<td>267</td>
</tr>
<tr>
<td>7.1</td>
<td>Characteristics of major skarn systems of the Eastern Subprovince, Lachlan Orogen, included in the present study (adapted from Seccombe et al. 2005).</td>
<td>295</td>
</tr>
<tr>
<td>7.2</td>
<td>Summary of selected features for intrusion-related mineralisation associated with the Eastern Subprovince and Central Subprovince of the Lachlan Orogen, included in the present study.</td>
<td>318</td>
</tr>
<tr>
<td>7.3</td>
<td>Summary $S$-isotope data for Mineral Hill highlighting the $\delta^{34}$S range and mean for all sulfides within individual ore zones and the specific $\delta^{34}$S range and mean for specific sulfide minerals within each zone.</td>
<td>333</td>
</tr>
<tr>
<td>7.4</td>
<td>$^{40}Ar/^{39}Ar$ step-heating analytical results sample TRD8/7 — Tara.</td>
<td>338</td>
</tr>
<tr>
<td>Table 7.5</td>
<td>S-isotope composition analyses for plutons from the southeastern Lachlan Orogen.</td>
<td>341</td>
</tr>
<tr>
<td>Table 7.6</td>
<td>Summary of the S-isotope composition for individual batholiths from the southeastern Lachlan Orogen.</td>
<td>344</td>
</tr>
<tr>
<td>Table 7.7</td>
<td>Summary of features associated with skarn and intrusion related mineralisation included in the present study.</td>
<td>348</td>
</tr>
</tbody>
</table>
**ABSTRACT**

Sulfur- and lead-isotope signatures for 64 deposits/systems located in the Central and Eastern Subprovinces of the Lachlan Orogen in eastern New South Wales were characterised in the present study. Here are presented four new $^{40}$Ar/$^{39}$Ar dates, 644 new sulfur- and 105 new lead-isotope analyses, plus a collation of 386 unpublished and 277 published sulfur isotope and over 560 unpublished and published lead isotope analyses for middle Silurian to Early Carboniferous mineralisation.

Measured $\delta^{34}$S values for 22 VHMS deposits range between -7.4‰ to 38.3‰. S-isotope values for Currawang East, Lewis Ponds, Mount Bulga, Belara and Accost (Group 1) range from -1.7‰ to 5.9‰ with the ore-forming fluids for this group of deposits likely to have been reducing and sulfur derived largely from magmatic sources. By contrast, S-isotope signatures for sulfides from Black Springs, Calula, Captains Flat, Commonwealth, Cordillera, Gurrundah, Kempfield, Peelwood mine, Sunny Corner, The Glen, Wet Lagoon and Woodlawn (Group 2) have average $\delta^{34}$S values between 5.4‰ and 8.1‰. These deposits appear to have formed from ore fluids that were more oxidising than those for Group 1 deposits, representing a mixed contribution of sulfur derived from partial reduction of seawater sulfate, in addition to sulfur from other sources. Four deposits, Elsinora, John Fardy, Mount Costigan and Stringers, have heavier average $\delta^{34}$S signatures (10.1‰ to 13.2‰) than Group 2 deposits, suggesting that these deposits included a greater component of sulfur of seawater origin. The S-isotope data for barite from Black Springs, Commonwealth, Stringers, Gurrundah, Kempfield and Woodlawn range from 12.6‰ to 38.3‰. Over 80% of the $\delta^{34}$S values are between 23.4‰ and 30.9‰, close to the previously published estimates for the composition of seawater sulfate during Late Silurian to earliest Devonian times, providing supporting evidence that these deposits formed concurrently with a Late Silurian volcanic event. New Pb-isotope data for eleven VHMS deposits included in the present study support earlier Pb-isotope studies which indicate that lead was largely sourced from the host sequence. However, the data for Black Springs, Elsinora and Commonwealth indicate that some lead, included in these deposits, was sourced from units forming basement to the Silurian troughs.

Sulfur isotope values for thirteen orogenic gold systems range between -7.5‰ and 16.1‰ (excluding outliers). The Wyoming One–Myall United system has an average $\delta^{34}$S value of -5.5‰ and a primitive mantle-derived lead isotope signature implying that sulfur and gold were sourced from a fractionated mantle-derived intrusion. The $\delta$-isotope data for Adelong, Bodangora, Calarie, Hargraves, Hill End, London–Victoria, Sebastopol, Sofala–Wattle Flat and Stuart Town are all very similar with average $\delta^{34}$S values close to 0‰ (range -2.8 to 3.4‰).
Sulfur in these deposits was derived from reduced fluids, sources from magmatic reservoirs either as a direct input or through dissolution and recycling of rock sulfide. For deposits hosted by the northern HET it is suggested that sulfur and gold were sourced from mantle-derived units located beneath the HET rather than the siliciclastic fill of the trough itself. Windeyer and Napoleon Reefs have heavier S-isotope signatures suggesting a greater contribution of sulfur derived from reduced seawater sulfate reservoirs. Springfield, located adjacent to the northern HET, has the heaviest S-isotope signature (15.4 $\delta^{34}$S‰) for orogenic gold deposits included in the present study. For this deposit it is suggested that HET-derived basinal fluids containing reduced seawater sulfate migrated along faults and leached gold from Ordovician mantle-derived units forming basement to that area.

Seven sulfide-rich orogenic base metal deposits were included in the present study. Average $\delta^{34}$S values for Currawang South, Frogmore, Montrose, Ruby Creek, Wallah Wallah vary between 3.5‰ and 6.0‰ (Group 1), with Kangiara, and Lucky Hit–Merrilla, having heavier average $\delta^{34}$S values (10.0‰ and 8.2‰ respectively — Group 2). Group 1 deposits are small, and S-isotope signatures suggest significant sulfur was sourced from magmatic reservoirs; whereas, Group 2 deposits are larger and $\delta^{34}$S signatures indicate a larger component of sulfur was derived from reduced seawater sulfate reservoirs. The Pb-isotope data for these deposits suggest that the majority of the lead was derived from older Ordovician and Silurian crustal reservoirs. The data for Mount Werong and Merrilla support a Middle Devonian Pb-model age; whereas, those for Wallah Wallah point to an Early Carboniferous Pb-model age. Browns Reef, in the Central Subprovince, is now interpreted to be a syn-deformational orogenic base metal deposit, for which the S-isotope data are similar to Group 2 orogenic base metal deposits and Pb-isotope data suggest lead was sourced from the fill of the Rast Trough.

Five epithermal systems were included in the present study. Bauloora, Bowdens and those in the Yerranderie district are intermediate-sulfidation epithermal systems; whereas, Yalwal and Pambula are low sulfidation epithermal systems. Yerranderie, Yalwal, Pambula and Bauloora have $\delta^{34}$S values close to 0‰. Sulfur in these deposits was derived largely from a magmatic reservoir. The Yerranderie system is zoned with respect to S-isotope distribution and shows mineralogical zonation along the Yerranderie Fault. Yalwal is zoned with 0‰ S-isotope values correlating with sericitic alteration assemblages and heavier S-isotope values (up to 17.9 $\delta^{34}$S‰) correlating with assemblages that include minerals characteristic of argillic alteration.

Sixteen middle Silurian to Early Devonian intrusion-related deposits were included in the present study. Collector, Dargues Reef, Mayfield, Ryans, Tallawang, Whipstick and Yambulla are located east of the I–S granite line, with Dargues Reef, Majors Creek, Mayfield, Whipstick

- xxii -
and Yambulla hosted by or adjacent to their causative intrusion. These deposits have S-isotope signatures close to 0‰ (range -3.6‰ to 3.0‰) similar to that for granites east of the I–S line (range -1.5‰ to 4.9‰). The Pb-isotope data for these deposits includes both crustal- and mantle-derived lead. Deposits distal to their causative intrusions (Collector and Ryans) have heavier S-isotope signatures (7.7‰ and 4.3‰ respectively) indicating that some sulfur was probably sourced from the host sequence. The majority of lead, for these deposits, was sourced from the host sequence and/or older reservoirs. The S-isotope data for Tallawang suggest that the sulfur was largely sourced from the host sequence. Eight deposits are located to the west of the I–S line. Nasdaq, Phoenix, Tara, Rye Park and Mineral Hill have heavier S-isotope signatures (range: 2.6‰ to 7.3‰) which overlap with the range of values typical of granites located to the west of the I–S line (1.9 to 9.6‰) supporting the interpretation that the majority of sulfur was derived from the causative intrusion. The Pb-isotope data for Nasdaq, Mineral Hill and Tara suggest that lead originated from the host sequence or from older lead reservoirs; whereas, at Rye Park and Phoenix lead was probably sourced from the causative intrusion. Ardlethan and Browns Creek deposits have near 0‰ S-isotope signatures, lower than the range of δ²³⁴S values for granites west of the I–S line which is accounted for by mantle-derived volatiles and a possible biogenic sulfur component. The Pb-isotope data for these two deposits are consistent with a lead sourced largely from the causative intrusion; although, some mantle-derived lead is probably present. Red Hill has the highest S-isotope signature (13.7‰) indicating that the majority of sulfur was sourced from a seawater sulfate reservoir.

⁴⁰Ar/³⁹Ar dating showed that intrusion-related mineralisation at Tara formed at 420 ± 2 Ma; VHMS-related mineralisation at The Glen (Glen E deposit) formed at 418.2 ± 2.2 Ma; and that the Yerranderie and Bauloora intermediate sulfidation epithermal systems formed at 372.1 ± 1.9 Ma and 371 ± 13 Ma (respectively). New dating plus a review of timing constraints to Tabberabberan and Kanimblan cycle-related mineralisation highlighted metallogenic events at ~430 Ma (intrusion-related), ~420 Ma (intrusion- and VHMS-related) and a mid Devonian epithermal event. The timing of orogenic-related mineralisation is diachronous across the study area with the majority of orogenic gold systems in the west forming during the Middle Devonian Tabberabberan Orogeny; whereas, similar mineralisation in the northern HET formed during the Early Carboniferous Kanimblan Orogeny.

Keywords: Lachlan Orogen, Hill End Trough, Goulburn Trough, Gilmore Fault Zone, Parkes Thrust, lead isotopes, sulfur isotopes, volcanic hosted massive sulfide deposits, orogenic gold deposits, orogenic base metal deposits, low sulfidation epithermal deposits, intermediate sulfidation epithermal deposits, granite-related deposits, skarns, ⁴⁰Ar/³⁹Ar age dating