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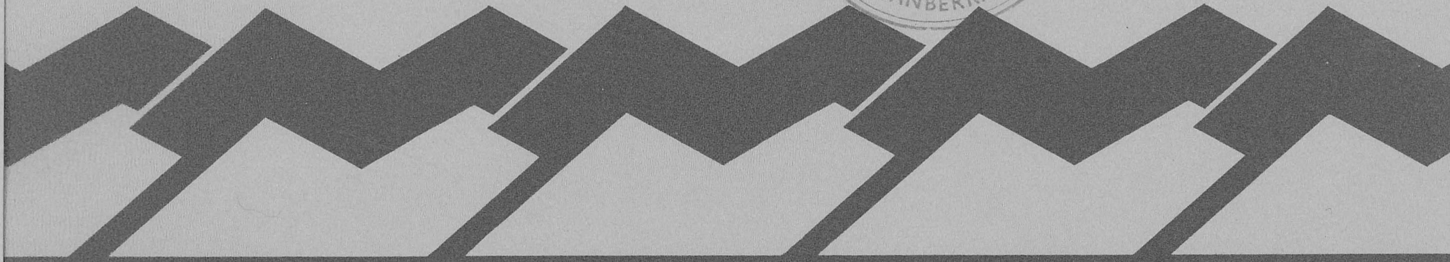

RECORD

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SGEG

ORE FLUIDS CONFERENCE

Canberra

1991

Abstracts for the Inaugural National Meeting of the Specialist Group in Economic Geology of the Geological Society of Australia

31 January/1-2 February, 1991
A. N. U., Canberra

"Ore Fluids - Their Origin, Flow Paths, Effects and Products"

Organising Committee: M. Solomon (Chairman), K. G. McQueen (Secretary), J. Angus, P.L. Blevin, S. Cox, H. Etminan, C. A. Heinrich, T. P. Mernagh, R. Skirrow, J. L. Walshe

Sponsors: Bureau of Mineral Resources, French Embassy in Canberra, Society of Economic Geologists, Société Géologie Appliquée aux Gîtes Minéraux

SGEG ORE FLUIDS MEETING 1991

Provisional Program

Wednesday 30 January

------- 1800 - 2000 Bruce Hall, A. N. U. Registration and welcome drinks

Thursday 31 January: Magma-related ore deposits (Convenor Phil L. Blevin) Venue: Chemistry Lecture Theatre

------- 0845 - 0900 Opening address by Peter J. Legge, President-elect, Geological Society of Australia and Manager, Project Generation, North Broken Hill Peko, Melbourne

Pollard, P., McNaughton, N.A. and Taylor, R.P.: A billion year history in the Bushveld granite at the Zaaiplaats tin mine - Pb and Sr isotopic evidence for a long-lived hydrothermal fluid system
Johnson, J.P. and Cross, K.C.: Geochronological constraints on the genesis of the Olympic Dam Cu-U-Au-Ag deposit, South Australia
Kleeman, J. and Plimer, I. R.: Isotopic studies on the Mole Granite and its related ore deposits
Poty, B. and Cuney, M. (CREGU): Uranium concentration mechanisms in granitoids. The example of the Variscan province of western Europe (late abstract)

------- Morning tea 1030 - 1100

Burnham, C. W. (Penn. State): The magmatic aqueous phase
Fu, M., Kwak, T.A.P. and Mernagh, T.P.: Characteristics of ore-forming fluids of some large carbonate replacement tin deposits of the world
Bajwah, Z.U.; White, A.J.R; Kwak, T.A.P. and Price, R.C.: Hydrothermal alteration associated with the Renison Granite, western Tasmania: Evidence for the evolution of hydrothermal fluids related to tin mineralization
Kitto, P. and Berry, R. F.: History of brittle deformation and related mineralisation at Renison Tin Mine, western Tasmania.

------- Lunch 1230 - 1400

Halley, S. and Walshe, J.L.: The genesis of tin-sulphide deposits in western Tasmania: a re-examination of the Mount Bischoff deposit
Clarke, G.W.: The involvement of fluids in the formation of pervasive alteration, microgranites and ore deposits in granites of the Herberton district, north Queensland
Blevin P.L. and Andrew, A.S.: Fluid evolution within an endo-exocontact greisen system: the Bamford Hill W-Mo-Bi greisen and pipe hosted ore deposit
Kent, A.: Contrasting styles of vein mineralisation in the Rockvale region, northeastern NSW.

------- Afternoon tea 1530 - 1600

Graham, I.T., Marshall, B. and Franklin, B.J.: Fluid-controlled formation and evolution of chromite, sulphides and PGE's in podiform chromitite in the Coolac Serpentine Belt, NSW
Keays, R. R., Wallace, M.W. and Gostin, V.A.: Mobilization of platinum metals by diagenetic fluids along the Lake Acraman meteorite ejecta horizon, South Australia

------- 1900 Informal meal at Bruce Hall, then SGEG Business meeting and Poster Session, Bruce Hall

Friday 1 February: Ore deposits and metamorphism (Convenors Steve F. Cox and Chris A. Heinrich) Chemistry Lecture Theatre

------- Commence session 0845

Sibson, R. H. : Fluid pressure reductions induced by faulting; their role as a precipitating agent at specific structural sites

Hobbs, B. E.: Mechanisms for generating wholesale downward flow in the crust.

Ord A.: Fluid flow in dilatant shear zones

Wilkins, C.: Microstructural timing of mineralisation at Big Bell Mine, Western Australia - a post-deformational, post-peak metamorphic Archaean hydrothermal deposit.

------- Morning tea 1030 - 1100

Groves, D. I. Barley M. E., Cassidy, K. J,. Mueller, A. G., McNaughton N. J., Perring, C. S., Ridley, J. R., Vearncombe, J. R.: Sub-greenschist to granulite-hosted Archaean lode-gold deposits of the Yilgarn Craton: A depositional continuum from deep-sourced hydrothermal fluids in crustal-scale plumbing systems

Gebre-Miriam M., Bennett J.M., Hagemann, S.G., Groves, D.I., Ho,S.E., McNaughton, N.J. Mikucki, E.J., Sang, J., Vearncombe, J.R.: Transitional mesothermal to epithermal-style Archaean gold mineralization in the Yilgarn Block, Western Australia

Hronsky, J.M.A., Mikucki, E. J, McNaughton, N.J., Groves, D.I.: Chemical processes of fluid-rock interaction at Lancefield, Western Australia: The role of redox changes in gold deposition in a basalt - carbonaceous shale/chert environment

Ridley, J.R., Heinrich, C.A,. Mikucki, E.J.: Fluid-rock reaction and imperfectly channelized fluid flow in hydrothermal systems: I Fundamental aspects. II Application to gold deposits.

-------- Lunch 1230 - 1400

Phillips, G.N.: Metamorphic fluids and gold

Wall, V.J.: Ironstone-hosted copper - gold mineralizations

Green, N, Changkakoti, A., Gray J., Krouse, H R. and Kwak,T.A.P.: A two stage fluid model for the Bendigo saddle reef system

Brown, P.E.: Infrared spectroscopic analysis of ore fluids.

------- Afternoon tea 1500 - 1600

Lawrie, K.C.: Metal zoning and fluids in the Elura orebodies, N.S.W. - implications for the formation of syntectonic massive sulphide orebodies

Hinman, M.: Paragenesis of a syn- to post-cleavage, multistage base- and precious metal ore system at Peak, Cobar, N.S.W

Perkins, W.G.: Mount Isa Ag-Pb-Zn orebodies: stratiform replacement lodes in a zoned hydrothermal alteration system

Waring, C.L.: The distinction between metamorphosed stratiform Pb-Zn-Ag mineralization and metamorphic syntectonic Cu mineralization at Mount Isa

------- Finish 1730

------- 1900 Buses to Conference Dinner, Canberra International Hotel, Northbourne Avenue. Award of A. B. Edwards Medal

Saturday, 2 February: VMS, Sedex (Convenors Mike Solomon and John L. Walshe) and epithermal (Convenor Roger G. Skirrow). Chemistry Lecture Theatre

------- Commence 0845

Gemmell, J. B.: Geology and geochemistry of the stringer zone underlying the Hellyer deposit, Tasmania

Seccombe, P. K., Godwin, C. I. and Krouse, H. R.: Multiple sulphur sources for seafloor exhalative mineralisation: Sulphur isotopic distribution in the Buttle Lake polymetallic massive sulphide deposits, British Columbia, Canada

Giles, A. D. and Marshall, B.: Microthermometry, petrography and morphological characteristics of fluid inclusions relating to a volcanic-associated massive sulphide orebody, Joma mine, Norway

Hill, A. P.: Structure and metal zonation of the Thalanga VMS-deposit, north Queensland

------- Morning tea 1030 - 1100

Raymond, O.: Pyrite paragenesis and trace element composition at the Prince Lyell copper deposit, Queenstown, Tasmania

Huston, D. L. and Large, R. R.: Distribution of gold in volcanogenic massive sulphide deposits: implications for ore genesis and metallurgical recovery

Large, R. R. and Davidson, G.: Controls of brine chemistry on the spectrum of Proterozoic sediment - hosted base metal deposits

Eldridge, C. S., Williams, N., Compston, W. and Walshe, J. L.: The H. Y. C. deposit at McArthur River, Northern Territory, Australia: a non-exhalative model

------- Lunch 1230 - 1400

McKibben, M. A.(Riverside): Brine diapirism and ore genesis in the Salton Trough

Solomon, M., Heinrich, C. A. and Swift, M.: Are high heat producing granites essential for the formation of giant sedex-type lead-zinc deposits?

Changkakoti, A., Kwak, T.A.P., Gray, J. and Krouse, H. R.: Fluid inclusions and stable isotopes of mineralized structures of the Emperor Mine, Vatukoula, Fiji -boiling or fluid mixing?

Cooke, D. and Losada-Calderon, A.: Low and high sulphidation epithermal systems - the dilution factor.

------- Afternoon tea 1530 - 1600

Henley, R.W., Browne, P.R.L. and Etheridge, M.A.: Tectonic controls on volcanism and active epithermal gold mineralisation in the Taupo Volcanic Zone, New Zealand

Jaireth, S.: Hydrothermal transport of tellurium and the genesis of telluride-bearing epithermal gold-silver deposits

McKibben, M. A. and Eldridge, C. S.: PGE and Au transport in geothermal systems

Morrison, G.W., Rose, W.J. and Jaireth, S.: Geological and geochemical controls on the silver content (fineness) of gold-silver deposits.

------- Award of Students Prize of the SGEG National Meeting.

POSTERS
Thursday Evening, Bruce Hall

Andrew, A.S.: Fifield PGE intrusions

Andrew, A.S.: Mount Leyshon/Kidston Au deposits

Bajwah, Z.U.: Geochemical evolution of the Proterozoic granitoids and related hydrothermal activity responsible for mineralization, Pine Creek Geosyncline, NorthernTerritory, Australia.

Cox, S.: The role of deformation processes in controlling fluid transport paths and fluid dynamics during ore genesis - Observations from nature and experiment.

Ewers, G.R.: The isotopic recognition of sinters in epithermal gold deposits.

Gemmell, J.B., Zantop, H. and Meinert L.D.: Genesis of the Aguilar Zn-Pb-Ag deposit, Argentina.

Hein, K.A.A.: An introduction to Batman.

McQueen, K.G.: Sulphide deformation and retrograde gold mobilisation at the Great Victoria gold deposit, Marvel Loch, W.A.

Mernagh, T.P.: Investigating ore fluids by laser Raman microprobe analysis of fluid inclusions.

Parr, J.: The Pb-Zn Pinnacles deposit, Broken Hill.

Sangameshwar, S.R.: Supergene processes in Archean nickel sulfide deposits and their significance in the low temperature stability relations of the Fe-Ni-S system.

Shi, Bielin: The geology and genesis of the Ximeng tin deposit Western Yunnan, China: A fluid inclusion, stable isotope and ore petrography study.

Skirrow, R.G. and Franklin J.M.: Silicification in a semiconformable alteration zone below the Chisel Lake Zn-Cu massive sulphide deposit, Snow Lake, Manitoba, Canada

Surmon and Kjolle, I. Browns Creek gold skarn

Trudu, A. G., Knittel, U.and Oliver, N.H.S.: The evolution of magmatic-hydrothermal fluids in the Tirad porphyry Cu-Au prospect (NW Luzon, Philippines), as inferred from biotite mineral chemistry data (late abstract)

GEOCHEMICAL EVOLUTION OF THE PROTEROZOIC GRANITOIDS, RELATED HYDROTHERMAL ACTIVITY RESPONSIBLE FOR MINERALIZATION, PINE CREEK GEOSYNCLINE, NORTHERN TERRITORY, AUSTRALIA

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The Pine Creek Geosyncline (PCG) was the site of intrusive activity during Early Proterozoic which led to the emplacement of granites in the western and central part of the region. In the western part (Litchfield Region) of PCG, granite intrusions appear to be syn-orogenic and coincided with the Top End Orogeny (1780-1870 Ma), whereas in the Central Region, they are predominantly post-orogenic and appear to have taken place at the culminating stages of the orogeny. In the Central Region, these granites cover an area of 5000 km^2 and occur as individual plutons e.g. Mt Bundy pluton or as a composite Batholith (Cullen Batholith) together with several satellite plutons in the area. Mt Bundy granite and several members of the Cullen Batholith are spatially related to gold, base metal and uranium mineralization in the adjacent meta-sediments.

K-feldspar megacrysts are the distinctive features of the majority of plutons along with quartz and plagioclase. Biotite and hornblende are the mafic minerals, whereas apatite, magnetite, sphene, allanite and zircon are the accessory phases. In a few cases quartz-muscovite greisens have developed along the margins of these plutons on a limited scale. An important feature of these plutons is the development of weak diffuse hydrothermal alteration throughout, represented by sericitization and chloritization.

The bulk chemical compositions of these granites vary considerably but each pluton is characterized by its own subtle geochemical patterns. SiO_2 contents as low as 64.4 to as high as 78.5 wt% have been observed. An increase in Rb and decrease in Sr and Ba contents are observed as a function of SiO_2 rise during the evolution of magma. Geochemically, PCG granites are distinctive and are characterized by the elevated levels of K, Ba, Rb, Sr, U and particularly LREE and are low in Ni and Mg.

Detailed geological, petrological and geochemical studies suggest that magma was derived from partial melting of accreted igneous rocks, during underplating event in North Australia. Low initial $^{87}Sr/^{86}Sr$ ratios (0.7058±0.0003) indicate that this accreted material to the base of the crust, source for the granite magma has short residence time. The melt derived by partial melting was probably anhydrous, as evidenced by the late precipitation of biotite and amphiboles. During ascent and fractional crystalization, the magma progressively became enriched in water and volatiles, responsible for the hydrothermal system within the cooling plutons and probably in the immediate host rocks. The range of chemical composition of biotite and amphiboles trends observed from the granite intrusions related to mineralization suggest that in the early stages of crystallization, fO_2 was high and it became progressively higher as magma went through the process of fractionation leading to the final stages of crystallization.

All these informations suggest that in the final stages of granite emplacement, the magma experienced differentiation, fractional crystallization which subsequently led to the emanation of hydrothermal fluids, responsible for mineralization in the adjacent meta-sediments.

HYDROTHERMAL ALTERATION ASSOCIATED WITH THE RENISON GRANITE WESTERN TASMANIA: EVIDENCE FOR THE EVOLUTION OF HYDROTHERMAL FLUIDS RELATED TO TIN MINERALIZATION

Z. U. BAJWAH*, A. J. R. WHITE, T. A. P. KWAK, AND R. C. PRICE.

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The Renison Granite in N.W. Tasmania, is genetically related to cassiterite-sulfide mineralization (carbonate replacement, distal skarn) at Renison Bell, one of the largest Sn deposits in the world. Fluids rich in metals were released during the magmatic hydrothermal stage from fractionated granite magma. The main phase of hydrothermal alteration related to the cassiterite-sulfide mineralization is also responsible for the development of three distinctive zones of alteration in the granite. The tourmaline zone (tourmaline + quartz + topaz + fluorite ± sericite ± cassiterite) forms the inner part (core) of alteration and is surrounded by a sericite zone (sericite + quartz ± tourmaline ± calcite ± cassiterite). An albite zone forms the outermost alteration envelope and is characterized by albite (hydrothermal) + quartz ± chlorite ± sericite along with primary plagioclase and K-feldspar.

Geochemically, it is characterized by a high SiO_2 (70.17 to 75.18 wt%), high K_2O (4.44 to 5.91 wt%) but low Na_2O,(2.52 to 3.67 wt%). Petrological and major and trace element geochemical data show that the granite was derived from meta-sedimentary rocks.
High Rb (up to 918 ppm) and Sr as low as 19 ppm, as well as other trace element abundances in the most felsic rocks, indicate that parts of the magma were highly fractionated and as a result enriched in volatile constituents, mostly aqueous. A magmatic hydrothermal system was responsible for extensive alteration of parts of the granite, and cassiterite-sulfide mineralization in the

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overlying meta-sedimentary rocks.

During hydrothermal alteration, B, Fe, and F were introduced into the tourmaline zone, while Na and K were removed. In the sericite and albite zones, chemical and petrographic effects of alteration are less conspicous and marked by changes in the concentrations of Na and K. Normal trace element concentrations defining fractionation trends of igneous origin, have survived the effects of alteration in the albite and sericite zone rocks as well as in weakly to moderately altered rocks of the tourmaline zone. However, depletion in Rb, Sr and Ba occurs in strongly tourmalinized rocks in which primary mineral fabric is completely replaced by secondary (hydrothermal) mineral fabric.

Fluid inclusion data, show that there are at least three phases of hydrothermal activity in the Renison Granite. The earlier phase (type I inclusions) is characterized by high salinity ranging from 30.0 to 38.41 equivalent wt% NaCl and this was followed by a second phase (type II inclusions) with comparatively lower salinities (8.80 to 22.52 equivalent wt% NaCl). Third generation fluids (type III inclusions) are marked by low salinities (4.5 to 12.30 equivalent wt% NaCl) and the presence of CO_2. Type I and type III inclusions are mainly restricted to the core of the alteration (tourmaline zone) whereas hydrothermal acitvity represented by type II inclusions appears to be widespread. Trapping temperatures recorded from type I and type II inclusions are essentially in the same range (343° to 455°C) in the core of alteration. A substantial overlap in temperature and salinity recorded from all the zones of alteration, suggests a continuous flow of fluids from core to the margin of alteration.

Petrological and geochemical information indicate that fractionation played a major role in the crystallization history of the Renison Granite which ultimately led to the evolution of a water saturated melt in the final stages of magma consolidation. These late stage fluids were enriched in metals and directed through the Federal-Basset structure and subsidiary faults to eventually react with Crimson Creek and Success Creek Formation where ore deposition took place due to a decrease in temperature and increase in pH.

FLUID EVOLUTION WITHIN AN ENDO-EXOCONTACT GREISEN SYSTEM: THE BAMFORD HILL W-Mo-Bi GREISEN AND PIPE HOSTED ORE DEPOSIT

Blevin, P.L. [1] and Andrew, A.S.[2]

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The Bamford Hill W-Mo-Bi deposit is located 5km north of Petford in north Queensland. It is hosted by the Carboniferous Bamford Granite which intrudes rhyodacitic ignimbrites of the Featherbed Caldera complex and a monzodiorite. The granite is I-type, fractionated and contains quartz, pink alkali and white sodic feldspars, minor Fe-Al rich and texturally late biotite, and minor allanite, magnetite, xenotime and zircon. Late stage phases of the granite include biotite micrograntites, fayalitic olivine bearing pegmatites and sodic leucomicrogranites containing REE rich Fe-Mn garnets. These phases are largely emplaced along the south-eastern contact zone of the granite which is also host to the alteration and mineralisation.

Hydrothermal alteration is distributed over the south and east apical and contact zones of the pluton and into the adjacent rhyodacite. The sequence of differing alteration styles can be organised into alteration stages common to both the endo- and exocontact systems: Stage 1 (>500°C; feldspars stable); Stage II (~500°-300°C; feldspar destructive); Stage III (<300°C; chlorite, sericite, base metal sulphides, Ca-phases). Within the exocontact system early formed cordierite occurs. This is interpreted to be hydrothermal rather than contact metamorphic in origin and is replaced by andalusite and Mg-biotite. Stage I represents potassic alteration where little chemical change has occurred to the rock other than addition of some K, Rb and Si. Greisenisation occurs during Stage II with biotite being stable. During Stage II wolframite and molybdenite are deposited over the temperature range 400-350°C within quartz rich pipe-like bodies and greisens within the granite. Stage III involves the replacement of wolframite by scheelite, biotite by chlorite, muscovite by sericite and kaolinite, precipitation of basemetal sulphides, replacement of pyrrhotite by pyrite, and later precipitation of comb quartz, fluorite, calcite, chalcedony and laumontite.

Alteration style changes from incipiently pervasive during Stage I to more focussed during Stage II to more focussed and fracture and vein controlled during Stage III. Alteration pathways during Stages I and II are largely parallel to the granite-rhyodacite contact. A fundamental change in structural style and orientation occurs between Stage II and III. During Stage III veining is vertical and orientated in a conjugate set so as to crosscut the contact zone.

Fluid inclusion data has been collected from both the exo- and endo-contact zones. Inclusion types recognised include: 1) vapour-rich, 2) liquid-vapour, 3) liquid-vapour solid, and 4) brine-liquid CO_2-vapour inclusions. Inclusion types 1, 2 and 3 occur in Stage I and II and homogenise at temperatures above 350°C to ~500°C for vapour-rich inclusions within the andalusite exogreisens. The close association of these inclusion types homogenising to about the same temperature is suggestive of boiling, a conclusion consistant with salinity, temperature and independant pressure estimates. Fluid inclusions rich in CO_2 are most common in greisens and exocontact samples. They are always secondary in nature and decrepitate at temperatures below 325°C. Laser Raman studies indicate that CO_2 is only present in inclusions where liquid CO_2 is visible, and is absent from the higher temperature fluid inclusion populations. Fluid inclusions from Stage III are invariably type 2, but with lower homogenisation temperatures (<~300°C), lower salinities (<10wt% NaCl equiv) and higher degrees of fill.

Stable isotopes have been measured on magmatic and hydrothermal minerals from Stages I to III. The unaltered portion of the granite shows little ^{18}O isotopic shift of alkali feldspars away from those expected for magmatic conditions ($\delta^{18}O_{qtz}$ = 9.9 per mil; and $\delta^{18}O_{kfs}$ = 7.4 per mil). With progressive hydrothermal alteration during Stage II magmatic quartzes remain undisturbed while the $\delta^{18}O$ values of the alkali feldspars decrease to 4.9 per mil. During mineralisation within the pipes $\delta^{18}O$ values for quartz and wolframite indicate that the $\delta^{18}O_{water}$ was 5.5 per mil, while δD was -70 per mil, as determined from water extracts of mineralised quartz. Unmineralised quartz pipes yield slightly lighter $\delta^{18}O_{water}$ values. Stage III minerals demonstrate a rapid decrease in calculated $\delta^{18}O_{water}$ values with temperature (= paragenetic time).

The present data for the Bamford Hill mineralising system suggests that re-orientation of the fracturing system between Stages II and III allowed the ingress of substantial quantities of unexchanged waters into the endocontact system. The influx occurred after precipitation of wolframite and molybdenite and indicates that other factors, such as cooling, were responsible.

INFRARED SPECTROSCOPIC ANALYSIS OF ORE FLUIDS

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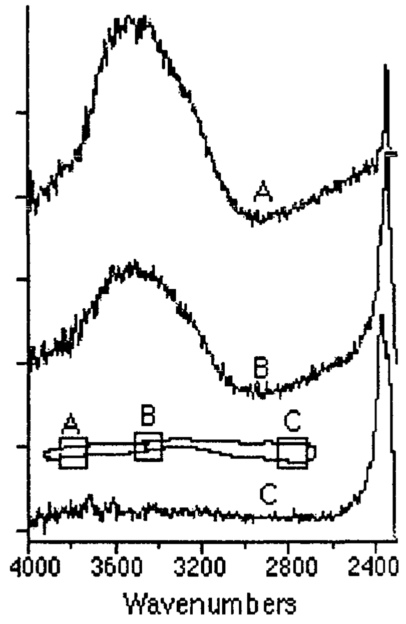
Analytical Fourier transform infrared spectroscopy (micro-FTIR) can be used to non-destructively analyze fluid inclusions for H_2O, CO_2, and other gases such as methane, in many mineral hosts. A systematic study is being undertaken to quantify such analyses and to determine detection limits for major fluid species in inclusions.

Our current analytical setup consists of a Bio-Rad FTS-40 spectrometer connected to a Bio-Rad UMA 300 microscope with a 100 µm square MCT detector and a 36X Cassegrain objective lens. A rectangular knife-edge aperture is used to select the area to be analyzed. The optimal 20 kHz scan speed for the interferometer allows 1024 scans at 8 wave number (cm^{-1}) resolution in 300 seconds. On-line data reduction is provided by a UNIX workstation built around a 68020 microprocessor.



Fluid Studies: The equipment permits routine analyses of inclusions larger than 10x10 µm. Spectral information can also be obtained from much smaller parts of large inclusions (Fig 1). The baseline corrected absorbance spectra in Figure 1 show the clear signals obtained from H_2O and CO_2 and demonstrate the spatial resolution of the system. The three spectra are serial 10 µm square sections (*A, B, C*) collected along the 75 µm long (3-5 µm wide) synthetic inclusion in quartz sketched on the Figure. *A* corresponds to the H_2O end and shows the characteristic sharp single peak for the dissolved CO_2 (near 2350 cm^{-1}) and the large well defined H_2O peak (between 3200 and 3700 cm^{-1}). *B* was collected straddling the meniscus between H_2O and CO_2 and *C* represents the CO_2 end. The broad, CO_2 peak in *C* is characteristic of dense liquid CO_2 as are overtones which may appear near 3600 and 3700 cm^{-1}. Spectra of many potential host minerals, including quartz, are noticeably free of peaks between 2300 and 4000 cm^{-1}.

[1] Millimeter-sized quartz grains have recrystallized from chert nodules in the Santa Elena Limestone in the contact aureole of the Christmas Mountains Gabbro, SW Texas. The quartz grains commonly have centers clouded by myriad submicron to 5 µm fluid inclusions. These clouded cores are surrounded by clear quartz containing relatively large (5-20 µm) low-density vapor-rich inclusions, and rarer mixed H_2O-CO_2 inclusions. Spectra from the clouded core area demonstrate the presence of both H_2O and also relatively large amounts of liquid CO_2. The mixed H_2O-CO_2 inclusions, by contrast, show a strong signal for H_2O, as well as a low peak suggestive of both liquid and dissolved CO_2. Spectra of the vapor-rich inclusions show only a small signal for H_2O. No CH_4 was detected. This preliminary work suggests an evolution of the dominant fluid present during prograde metasomatism from more CO_2-rich to more H_2O–rich compositions.

[2] Two chips of wairakite from the Los Azufres geothermal field in Mexico contain large, primary, aqueous fluid inclusions. The presence of several weight percent CO_2 (3-5%) has been inferred from apparent clathrate melt temperatures, expansion of the vapor bubble upon crushing, and the immediate disappearance of the bubble when crushed in alkaline $BaCl_2$ (Moore et al., 1990). The IR spectra of the wairakite, like spectra of many silicates, are clear of major interfering absorbance peaks in the region corresponding to CO_2. IR spectra of the aqueous inclusions failed to detect any species besides H_2O and have lead to an investigation of detection limits for dissolved CO_2 in water.

Solutions were made by dissolving reagent grade sodium carbonate (*NaC*) and sodium bicarbonate (*NaBiC*) in distilled water. The saturated *NaBiC* solution (≈7%) had an initial pH=8.4 while the *NaC* solution had pH=11. The pH was changed by titrating with either NaOH or HCl. The solutions were analyzed by trapping a 10-15µm film between two cleavage fragments of fluorite. The saturated *NaBiC* solution had an easily visible CO_2 peak at ≈2343 cm^{-1}. Lowering the pH increases the peak height until CO_2 begins to effervesce from the solution (pH≈7). Raising the pH causes the peak to decrease and vanish by pH≈9. More subtle but still predictable and systematic changes in the spectra occur between 2400 and 2900 cm^{-1} as the carbonate speciation changes in response to pH variations. The CO_2 peak was absent in the saturated *NaC* solution but could be generated by lowering the pH. Undersaturated *NaBiC* solutions had clearly visible CO_2 peaks down to 0.1% total dissolved carbonate. Titrating these solutions yielded similar results to those described above however it was possible to achieve somewhat lower pH's before the onset of effervescence. The IR spectra of the aqueous inclusions that failed to detect any species besides H_2O are interpreted here to suggest that the current in-situ pH of the inclusion fluids is sufficiently high that bicarbonate is the dominant form of the dissolved carbon species.

[3] Initial analytical results for a three-phase H_2O-CO_2 fluid inclusion whose long dimension is *inclined* to the microscope stage suggest that there is a serious focal position effect on the observed IR baseline. Theoretical calculations for the geometry of the IR microscope suggest an extremely small depth of field for the system as configured.

[4] Equant or negative-crystal shaped inclusions that contain multiple fluid phases may give particularly poor spectra. This is apparently largely due to refractive index contrasts between the host and liquid and gas phases. To understand and partially alleviate this problem, we have fitted the microscope with a heating stage that allows inclusions to be examined after partial or total homogenization.

Mineralogical Studies: Some daughter salts in inclusions can be identified by FTIR spectroscopy. Simple halides are IR transparent (KBr is used as windows and sample support media in the instrument). Both calcite and anhydrite have been positively identified as daughter salts (crystals <10µm in size) in several inclusions. The crystallographic orientation of the crystal effects the resultant spectra; the magnitude of this effect may be subtle or very pronounced.

Pressed KBr pellets of powdered *NaBiC* and *NaC* were made to help interpret the spectra in the pH-speciation experiments discussed above. The *NaC* spectrum has many features in common with the spectrum for calcite and is very different from the *NaBiC* spectrum; neither spectra has features that directly aid the interpretation of the solution results.

The quantity and composition of fluids present during metamorphism of a rock sequence hosting ore material will influence the deformation, recrystallization and preservation of the ore. In addition to fluid inclusions, minerals such as zeolites, beryl, and cordierite have structural channels that can trap and preserve ambient fluids. As shown in Vry et al. (1990), IR spectroscopy can provide an accurate determination of the relative amounts of CO_2 and H_2O present during the growth of cordierite. We have refined these results in light of further work and have shown that total CO_2 peak height is the *best* measure of the CO_2 content of cordierite.

Micro-FTIR spectroscopy promises to provide a new, relatively simple, non-destructive technique to gain compositional information from fluid inclusions. Continued development of this tool will define the problems of ore genesis to which it is applicable.

References

Moore J.N., Lemieux, M.M., Adams, M.C., 1990, The occurrence of CO_2-enriched fluids in active geothermal systems: Data from fluid inclusions.

Vry J.K., Brown, P.E., Valley, J.W., 1990, Cordierite volatile content and the role of CO_2 in high grade metamorphism. Am. Mineral. 75, 71-88.

FLUID INCLUSIONS AND STABLE ISOTOPES OF MINERALIZED STRUCTURES OF THE EMPEROR MINE, VATUKOULA, FIJI

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Hydrothermal activity in the Emperor deposit took place predominantly in the temperature range of 150 to 250°C. The salinities of the fluids ranged from almost dilute meteoric water values (0 to 2 wt % NaCl equiv.) to brines (up to 15 wt % NaCl equiv.). Although the salinities of the fluids are higher than average epithermal deposits, it is not uncommon to find such high salinities. High salinities observed in the Emperor deposit could be attributed to derivation of the fluids from a cooling intrusive at depth. Alternatively, "boiling" or "effervescence" of lower salinity fluids could have also enhanced the salinities of the hydrothermal fluids.

The oxygen and hydrogen data suggest mixing of an evolved meteoric or formation water (with meteoric precursor) with a magmatic fluid, or mixing of dominantly magmatic fluid with meteoric or formation water (with meteoric precursor). Based on the fluid inclusion data the second model seems to be more viable.

Fluid flow was along the caldera contact. This is supported by the $\delta^{13}C$ of the carbonates. The $\delta^{13}C$ values of carbonates change gradually from magmatic values from the Crown structure to marine values towards the Prince-Dolphin structure. Initially the fluids had dominantly magmatic carbon, but as the fluids moved away, sedimentary carbon was leached from the country rocks and redeposited in the veins as carbonates.

LOW- AND HIGH SULFIDATION EPITHERMAL SYSTEMS - THE DILUTION FACTOR

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There are two major types of volcanic-hosted epithermal deposits recognised from around the world: the low sulfidation (adularia-sericite) and high sulfidation (alunite-kaolinite) deposits. Models for the formation of low sulfidation epithermal systems invoke the large scale circulation of meteoric fluids above plutonic igneous heat sources emplaced between 5 and 10 km below the surface (eg. Heald et al., 1987; White and Hedenquist, 1990). The heated meteoric fluids are localized within major permeable zones (typically faults) along which they ascend or migrate laterally, until they eventually undergo near-surface boiling and/or fluid mixing, resulting in the deposition of ore and gangue minerals. In contrast, high sulfidation deposits are thought to represent the near-surface extensions of porphyry systems (Sillitoe, 1983). The heat source in these systems is the porphyritic intrusion, which is generally considered to be situated much closer (proximal) to the developing epithermal mineralisation than in the low sulfidation (distal) case. Consequently, the contributions of magmatic volatiles are believed to be a significant source of metal constituents in high-sulfidation epithermal systems. In contrast, low sulfidation systems invariably have a more dubious magmatic connection; it is extremely difficult to prove that there has been any magmatic contributions to the meteoric-dominated hydrothermal fluids using the standard geochemical techniques (stable isotopes, fluid inclusions, etc.).

While there are rare examples of epithermal deposits which show some characteristics transitional between the two end-members of epithermal mineralisation, most epithermal systems are easily classified as one of the two aforementioned deposit classes. This suggests that there are strong controlling factors that inhibit the formation of epithermal systems with transitional characteristics, and these factors must be intimately linked to the genetic processes that operate during the development of both styles of epithermal mineralisation. Is it therefore possible to form a low sulfidation epithermal deposit proximal to a porphyry system both in space and time or is the inferred spatial relationship between mineralisation and heat source a sufficient control that prevents the occurrence of such an event? A key factor that has to be addressed when attempting to answer this question is the degree to which ascending magmatic hydrothermal solutions are diluted by circulating groundwaters. For example, if we consider an actively-forming porphyry system that has been emplaced near to the surface in a tropical setting with high annual rainfall and (consequently) high erosion rates (eg. Papua New Guinea, Philippines), this system has the potential to be rapidly inundated with meteoric fluids due to the combined effects of the potentially high rates of groundwater flow and the depths to which the groundwater table can penetrate. The rapid and overwhelming dilution of ascending magmatic-hydrothermal solutions by large volumes of circulating meteoric fluids in the upper levels of a porphyry system could easily obliterate any geochemical signature that would indicate a magmatic component for this fluid. That magmatic component can however still be a highly significant contributor of metals, sulfur, etc. In contrast, a porphyry system emplaced in an arid environment (eg. Peru, Bolivia, Chile, Argentina) with very restricted groundwater availability is more likely to preserve a magmatic signature and, therefore has a greater potential to form a high-sulphidation instead of a low-sulfidation systems. As a conclusion, it should not be rule out the possible presence of a porphyry-style mineralization nearby low-sulfidation veins. A good knowledge of the paleoclimatic condition and the paleohydrology of an area is essential in order to understand and properly evaluate the possibility of finding different styles of mineralization or to explain the co-existence of them in any particular place.

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THE INVOLVEMENT OF FLUIDS IN THE FORMATION OF PERVASIVE ALTERATION, MICROGRANITES, AND ORE-DEPOSITS IN GRANITES OF THE HERBERTON DISTRICT, NORTH QUEENSLAND

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The Permo-Carboniferous granitoids of the Herberton Batholith, northeast Queensland, are emplaced within penecontemporaneous volcanics and metamorphosed Siluro-Devonian sediments of the Hodgkinson Formation. The sequence of granitoid intrusion is broadly from the least silicic and fractionated granodiorites through to highly fractionated silicic granites. Internally, the latter are typically "reversely" zoned. All plutonic units contain, to a greater or lesser degree, suites of secondary minerals localised along grain boundaries, microfractures and within microscopic vughs. However, the relative abundance of the various pervasive alteration features is not constant either between or within individual plutonic units. In general, the younger granites are more affected, especially towards their outer zones. Comparisons between samples only slightly affected and those significantly changed by specific forms of post-magmatic alteration can therefore be used to reveal the geochemical changes involved.

Fractures which transected the plutonic intrusives during the course of their formation released and resited successive residual melt and fluid phases to form microgranite dykes, and alteration-bound pipes and veins. Within the younger granites some microgranite bodies contain textural variants such as saccharoidal aplite (± pegmatitic comb-layering), granophyres, miarolitic cavities, pegmatitic pods and pipe/vein mineralisation, all of which imply a discrete vapour phase was present during crystallisation. Variations in geochemistry associated with these features indicate that the volatile constituents involved included H_2O, F, Cl and CO_2. More particularly, these variations (along with the relative occurrence of specific minerals such as fluorite and Cl-bearing phyllosilicates) imply that the volatiles constituents considered responsible for post-magmatic alteration in individual plutons are also those which affected the geochemical evolution of microgranites enclosed within each of these plutons.

In addition, quartz pods/pipes and veins containing molybdenite and/or wolframite mineralisation are generally spatially associated with microgranite dykes of one specific pluton wherein F and H_2O are the volatiles inferred to have accumulated in the latter stages of crystallisation. Conversely, joint-/fracture-controlled alteration, which around Herberton commonly encloses cassiterite (± wolframite or sulphide) mineralisation typically occurs in association with the youngest granites wherein F, Cl, H_2O and CO_2 were the likely complexing agents in the residual fluids. Moreover highly fractionated microgranites from such granites are comparatively enriched in Sn, W, Zn and to a lesser degree Pb, while the small number of bulk low-grade "greisen-breccia-clay" tin mines around Herberton are centred on fine-grained granite/microgranites. Thus the active volatile species involved in microgranite fractionation are also implicated in the concentration of metals evident in ore deposits associated with specific granite units. In this respect the microgranites from a late magmatic link between the main intrusive units which post-magmatically "stewed" in their residual fluids, and the formation of rare-metals ore-deposits spatially related to these units.

THE ROLE OF DEFORMATION PROCESSES IN CONTROLLING FLUID TRANSPORT PATHS AND FLUID DYNAMICS DURING ORE GENESIS - OBSERVATIONS FROM NATURE AND EXPERIMENT

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During crustal deformation the establishment of fluid migration patterns which lead to the formation of ore deposits is dependent on interactions between deformation processes, fluid transport properties, and fluid pressure regimes. In particular, the development of linked systems of active transcrustal faults and shear zones can disrupt pervasive fluid migration patterns and establish channelised flow regimes.

Three important factors which influence fluid flow paths are spatial and temporal variations in permeability, fluid pressure and fluid pressure gradients. These variations develop in response to fluctuations in stress difference during the deformation of heterogeneous rock masses.

Experimental studies have demonstrated that when materials are deformed at low to moderate temperatures, frictional sliding on grain boundaries and cracks, and relative rotations between grains, can lead to volume increase or *dilatancy* (Nur,1975). In the absence of reactive pore fluids, deformation-induced increase in porosity and pore connectivity is strongly dependent on the applied stress difference, strain and effective confining pressure. At pore fluid pressures which approach the confining pressure, substantial increases in porosity and permeability occur, even at low stresses and elevated temperatures (Fischer and Paterson, 1989). At supralithostatic fluid pressures and low stress differences, the opening of macroscopic extension hydrofractures also enhances the permeability of deforming rock masses.

Recent experimental studies on quartz grain aggregates at elevated temperatures and pressures have demonstrated that the presence of reactive pore fluids during deformation can substantially influence the fluid transport properties and mechanical behaviour of rocks (Cox and Paterson, 1990). Stress-driven compaction that involves dissolution-precipitation reactions in hydrothermal regimes causes rapid porosity reduction and changes in pore connectivity. These processes act together with crack-healing and crack-sealing processes to compete with deformation-induced porosity-creation mechanisms such as grain-scale dilatancy.

Competition between porosity-creation processes and porosity-destruction processes governs the rate of change of permeability and porosity during deformation. This is a key factor which influences *fluid pressure gradients* and thus the dynamics of fluid migration (Cox and Etheridge, 1989). For example, if stress-induced dilatancy causes the local fluid pressure gradient to drop below a hydrostatic gradient, then transient, downwards fluid migration is possible, even in a suprahydrostatic fluid pressure regime. Similarly, if fluid supply rates to a hydrothermal system from deeper crustal levels are sufficiently high to develop suprahydrostatic fluid pressure gradients, then upwards fluid migration can be pressure-driven rather than buoyancy-driven.

The importance of time-dependent fluctuations in stress differences and competition between porosity-creation processes and porosity-destruction processes during the genesis of hydrothermal ore deposits is illustrated by the operation of fault-valve behaviour in fault zones such as those which host many mesothermal gold deposits (Sibson et al, 1988; Cox et al, in press). In such deposits, temporal variations in permeability and transient development of supralithostatic fluid pressures are related to the seismic cycle.

Fault failure causes a sudden increase in dilatancy and permeability, as well as loss of cohesion and partial to complete relief of shear stress in failure zones. Post-seismic compactional deformation of porous fault products, together with hydrothermal sealing and healing of gouges, breccias and fracture arrays, then leads to a progressive decrease in permeability within the fault process zone after failure events, and results in the development of very low permeability, or 'valved', fault segments. During post-seismic shear stress recovery in high fluid-flux regimes, the gradual development of near-lithostatic fluid pressures below valved fault segments promotes both grain-scale dilatancy and macroscopic hydrofracture dilatancy at low stress differences in wall-rocks adjacent to fault zones. This drives fluid migration out of the fault zone and into the wall-rocks. However, increasing fluid pressures also reduce the shear strength of fault zones and ultimately lead to renewed shear failure. Seismic failure, as well as attendant within-fault dilatancy and breaching of fault-valves, all cause a co-seismic drop in fluid pressure within the fault zone, and lead to collapse of hydrofracture networks in the adjacent host-rocks.

The spatial and temporal fluctuations in dilatancy and fluid pressure that are associated with fault-valve behaviour have important implications for the dynamics of fluid-rock interaction and fluid mixing during ore genesis in active fault zones. Immediately prior to failure, fluid pressures in the fault zone are higher than in the adjacent wall-rocks. This drives fluids out into the wall-rocks and promotes fluid-rock interaction. However the abrupt decrease in fluid pressure that is associated with failure drives reacted fluid back into the transiently lower fluid pressure regime in the fault zone. Fault-valve behaviour thus provides an extremely efficient mechanism for cyclic fluid mixing and ore deposition.

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THE H.Y.C. DEPOSIT AT McARTHUR RIVER, NORTHERN TERRITORY, AUSTRALIA: A NONEXHALATIVE MODEL

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The H.Y.C. mineralization at McArthur River, Northern Territory, Australia, has long been considered as a classic example of the sediment-hosted lead/zinc type deposit. The carbonaceous sedimentary host rocks at McArthur River are minimally deformed despite their age of around 1.7 by. The sulphide mineralogy is uncomplicated, comprising an early pyrite (py_1) and an overgrowth pyrite (py_2) as well as sphalerite and galena, with minor marcasite, arsenopyrite and chalcopyrite. Sulphide minerals are distributed along bedding and though some brecciation has occurred, the concentration of sulphides does not appear to be controlled by local reworking of material into graded beds like those commonly noted in Kuroko-type orebodies. To compensate for all of these straightforward characteristics of the deposit, the fine-grained nature of the sulfide minerals has made study of key genetic features, such as the mineral textural relationships and isotopic compositions, difficult. Consequently, several models for the formation of this important deposit have been advanced with the central point of contention being the relationship of py_1 to py_2 and whether or not one or both of the pyrite types is genetically related to the more economically interesting sulphides.

Petrographic examination of 26 standard polished sections prior to sulphur isotopic work supported the paragenesis set out by Williams (1978a,b) with the main points being: pyrite growth is typically as some variation of a framboidal structure; when both pyrite types are present, py_2 always directly overlies py_1; there is no evidence of deposition of other base metal sulphides between formation of the two pyrite generations or even during precpitation of py_2; the lead, zinc and copper sulphides often occur as overgrowths on py_2, or may cross cut both py_1 and py_2 framboidal structures. The question as to whether one or both of the pyrites might be associated with the lead/zinc sulphides could not be unequivocally answered from this work alone.

The sulphur isotopic compositions of py_1, py_2 and the lead, zinc and copper sulphides were investigated through more than 200 SHRIMP ion microprobe analyses. Analyses derived from areas as small as 25 μm in diameter and were performed directly on the material examined petrographically. In this way, the usual problems of conventionally analysing pure separates of each generation of material were avoided and the textural continuity of samples was preserved. Results indicate that both py_1 and py_2 may be biogenic in origin, with py_1 ranging in $\delta^{34}S$ value from -13 to 15 ‰ and py_2 reaching from -5 to 45‰. In a given sample, py_2 may be isotopically lighter than, the same as or heavier than the py_1 , though on average py_2 is 12‰ heavier than py_1 . It may be in many cases that precipitation of py_1 followed by isotopically heavier , and more isotopically variable, py_2 represents the transition from open system to closed system bacteriogenic sulphate reduction. In contrast to the sulphur isotopic systematics of the pyrite types, the lead, zinc and copper sulphides are of a relatively restricted isotopic range ($\delta^{34}S$ = -5 to 9‰). Moreover, the lead/zinc suphfides are typically too low in $\delta^{34}S$ value to be in isotopic equilibrium, at any temperature, with the pyrite they directly overlap (py_2).

It would appear then, from the sulphur isotopic data, that neither of the two pyrite types is genetically related to the lead/zinc mineralization. These data are entirely consistent with the textural information suggesting that the sphalerite and galena post-date pyrite precipitation and, therefore, both can be used to constrain the mineralization process as follows. (1) A lack of pseudomorph or caries textures, plus the isotopic distinctions between the sulphide groups, suggest that precipitation of the sphalerite and galena by replacement of pyrite did not occur. It seems unlikely, therefore, that the early pyrite was a local source of sulphur for precipitating metals from metal-rich, but sulphide-poor, brines. (2) The fact that py_2 is isotopically heavier than the later sphalerite and galena, indicates that it is unlikely that the sulphide reservoir used to preciptate py_2 was directly tapped to precipitate the lead and zinc sulphides. This, coupled with the differences between H.Y.C. mineral textures and those seen in sulphides known to have formed directly on the seafloor, eliminates models involving venting of metal-rich brines into an H_2S-rich pool already forming biogenic pyrite.

The least complicated mineralizing sequence, that accounts for these new constraints, may have involved steps like those proposed by Williams (1990): (1) precipitation of py_1 through open system biogenic sulphate reduction below the sediment/water interface; (2) formation of py_2, sometimes by continued biogenic reduction, but in a system now closed to further influx of sulphate; (3) permeability-controlled introduction of brines carrying iron, zinc and lead with CO_2 and H_2S. The main hydrothermal event also formed minerals below the sediment/water interface where iron precipitated as minor marcasite and as ankerite while the zinc and lead formed mainly sulphides.

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THE ISOTOPIC RECOGNITION OF SINTERS IN EPITHERMAL GOLD DEPOSITS

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Introduction

Surficial deposits of siliceous sinter are a common feature of present-day hot springs in areas of active volcanism, but they are rarely recognised in older, eroded volcanic terranes because of their low preservation potential. Recently, ancient sinters have been widely reported from gold prospects in the Devonian-Carboniferous Drummond Basin in northeast Queensland.

The importance of sinters to exploration for epithermal ore deposits is that they provide tangible and unambiguous evidence of a palaeosurface, and they indicate the possible presence of a significant mineralising system within 1000 metres of the earth's surface. Failure to recognise a sinter, or the incorrect interpretation of a siliceous rock as a sinter could lead to false assumptions in assessing an epithermal prospect, and perhaps to a misdirected exploration program.

Regional geologic setting

The Drummond Basin is a large (25000 km^2) intracratonic basin in northeast Queensland, which developed during the Late Devonian and Early Carboniferous (Fig. 1). It consists of thick units of predominantly terrestrial volcaniclastic sandstone and mudstone, and intermediate to felsic lavas and pyroclastic rocks. Primary volcanic rocks are widespread in the lowermost formations of the sequence, though the stratigraphy is complicated by numerous facies changes, internal disconformities, and poor age control (McPhie et al., 1990). Widespread Late Carboniferous igneous activity at around 300Ma resulted in a compositionally diverse sequence of ignimbrites and lavas intruded by co-magmatic granitoids (McPhie et al., 1990).

Epithermal gold mineralisation associated with this magmatic activity is widespread in the northern Drummond Basin, with significant deposits at Wirralie, Pajingo, and Yandan, and numerous prospects (Fig. 1). Mineralisation could be related to any or a combination of the major igneous events. However, most of the known gold deposits are hosted by the Drummond Basin sequence, which recent mapping has shown to be more extensive than previously recognised (Ewers et al., 1989).

Sinters

White et al. (1989) have described features in sinters from the Conway and Durah Creek prospects which are observed in modern sinters deposited in active hot-spring environments: they are conformable with subaerial, hydrothermally altered volcanic rocks, and preserve textures which are characteristic of modern sinters. Possible sinter has been noted also at Wirralie (Fellows and Hammond, 1988) and Verbena (Cunneen and Sillitoe, 1989), and many other prospects throughout the northern Drummond Basin (e.g. Yandan, Bimurra, Hill 273) are thought to contain them.

Oxygen Isotopes

Oxygen isotopes may provide an additional tool for characterising ancient sinters. Ideally, isotopic data should be used in conjunction with other criteria to verify the presence of a sinter, but where field and textural relationships are either ambiguous or lacking, they may be invaluable.

For currently active systems, Clayton and Steiner (1975) reported large ^{18}O-enrichments (22.2 and 23.6 per mil relative to SMOW) in siliceous sinter deposited at the surface at 55-60°C from water discharged from steam wells at Wairakei, N.Z. They noted that hydrothermal quartz deposited at depth at 250°C in the same system had a $\delta^{18}O$ value of 3.9 per mil. At the nearby Broadlands system, Blattner (1975) observed that the $\delta^{18}O$ value of vein quartz was generally in the range 3.9 to 12.3 per mil and decreased with both depth and increasing temperature.

Data for sinters from epithermal gold prospects in the northern Drummond Basin also indicate that they are isotopically heavy and that they can be characterised by their isotopic signature (Ewers, in press). For example, at the Conway prospect, sinters are consistently and significantly more ^{18}O-

enriched (+11.5±0.7 per mil) than nearby vein quartz (+6.3±1.9 per mil). These sinters are consistent with deposition at 90-100°C from a fluid having a value of about -9 to -8 per mil.

Such marked ^{18}O-enrichment relative to higher-temperature vein quartz can be explained by the rapid increase in the oxygen isotope fractionation factor for the quartz-water pair with decreasing temperature, particularly below 100°C (Friedman and O'Neil, 1977). Recrystallization of an originally amorphous sinter to cryptocrystalline quartz does not appear to have affected the isotopic signature of the sinter.

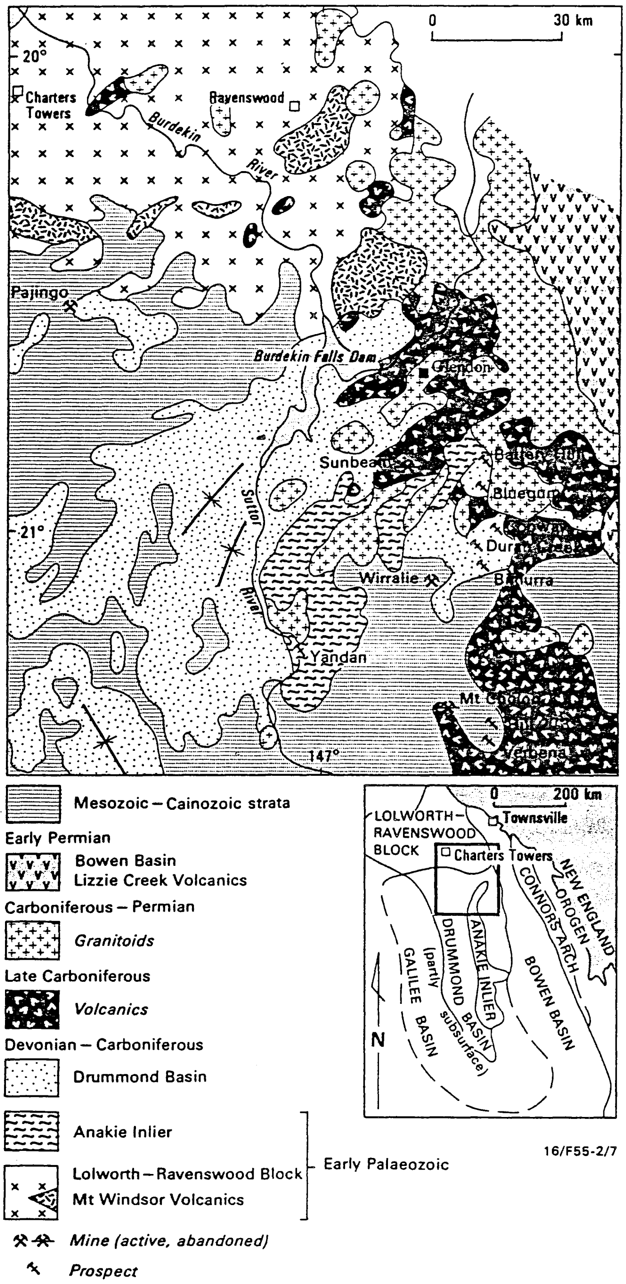

Figure 1 Epithermal gold deposits and prospects in relation to the geology of the northern Drummond Basin

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CHARACTERISTICS OF ORE-FORMING FLUIDS OF SOME LARGE CARBONATE REPLACEMENT TIN DEPOSITS IN THE WORLD

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Abstract

The Dachang and Gejiu deposits in southern China and the Renison Bell deposit in north-west Tasmania, containing 110, 100 and 42 million tonnes of ore at about 1% tin, are the three largest carbonate replacement tin deposits in the world. Detailed fluid inclusion studies show that these deposits were formed in similar geochemical and geological conditions.

Proximal skarns in these deposits were formed at high temperatures (450-660°C), high salinities (35-55 wt% total salts) and high pressures (650-1000 bars) while distal skarns were formed at low temperatures (170-490°C), low salinities (6-25 wt% NaCl equivalent) and low pressures (150-500 bars). Cassiterites in these deposits were formed at three main stages: tourmaline-quartz-cassiterite-(fluorite), sulphide-sericite-cassiterite and carbonate-sulphosalt-cassiterite stages.

Variations of the gas compositions of fluid inclusions in different stages found in these deposits is indicative of a gradual change in the geochemical environment of the ore-forming fluids. The primary fluid inclusions in the altered granites, proximal skarns and greisens are distinguished by high CH_4 content but no CO_2. During the formation of the distal skarns, the CO_2 content in the ore fluids increases with decreasing temperature and CO_2 becomes a predominant (except for water) gas at the sulphide-cassiterite stage. Thermadynamic calculations show that the change of the CH_4/CO_2 ratio in the ore fluids is related to the change of fO_2 that increasing fO_2 of the ore fluids caused the deposition of cassiterite.

TRANSITIONAL MESOTHERMAL- TO EPITHERMAL- STYLE ARCHAEAN GOLD MINERALIZATION IN THE YILGARN BLOCK, WESTERN AUSTRALIA

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Most well-described Archaean lode-gold ores may be classed as "mesothermal gold-only" deposits (Groves et al., 1988, 1989). They are characterized, where veins are present, by massive, bucky to well-laminated quartz veins within zoned wallrock alteration sequences that range from proximal ankerite/dolomite-muscovite-chlorite or ankerite/dolomite-biotite±albite assemblages to more distal calcite-chlorite assemblages. They show variable enrichments in Ag, As, Sb, W and B and background base-metal values, with Au : Ag ratios characteristically below 1.0 and gold grains with fineness about 900. Opaque mineral assemblages are dominated by pyrite and/or arsenopyrite with lesser pyrrhotite and magnetite. Tellurides may be locally abundant, but chalcopyrite, sphalerite and galena are rare. Gold was deposited by fluid-wallrock reactions or by phase-separation from low salinity, H_2O-CO_2 (XCO_2 = 0.1 - 0.2) fluids at T-P conditions ranging from 250 - 400 ^{o}C and 1 - 3 kbar (Ho, 1987). Stable isotope data indicate metamorphic or magmatic fluids, with no evidence for incursion of surface waters, and radiogenic isotope data provide evidence for fluid interaction with (or derivation from) lower and upper crustal rocks (McNaughton et al., 1990).

In some of the lower metamorphic grade settings (prehnite-pumpellyite to mid-greenschist facies), interpreted to be high crustal levels (Groves et al., 1990), there are a small group of deposits that show different characterestics. These deposits (including Wiluna, Racetrack, at Mt Pleasant, and specific lodes on the Golden Mile) are characterized by brittle structural settings, probably in large strike-slip fault régimes, in which hydraulic or implosion breccias are commonly the host to gold mineralization which may locally be very high grade. Although these deposits show similar, and spatially restricted, wallrock alteration styles to the typical "mesothermal" deposits (i.e. carbonate-white mica-chlorite), they show a variety of quartz vein structures and textures that are more typical of epithermal deposits. These include multiple cross-cutting quartz-carbonate veining and/or brecciation phases, cockade, comb, feathery and flamboyant quartz textures, and vughy vein fills. In addition, unusual mineral phases may include (not all present in one deposit): electrum (fineness <800), tetrahedrite-tennantite, Ag sulphosalts, Au-, Pb- and Hg-tellurides, stibnite, hematite and anhydrite. The fluids responsible for this style of mineralization are far more variable than those depositing the "mesothermal" lodes, with variable salinity (1->10 equiv. wt% NaCl), variable CO_2 content (XCO_2 <0.02 for Racetrack and Wiluna; >0.1 for Golden Mile), and T-P conditions also vary widely (150 - 300 ^{o}C, few hundreds bars - 1 kbar). In addition, calculated $\partial^{18}O$ values for the ore fluid are lighter (close to or less than 0‰) than those of most "mesothermal" deposits, and implicate incursion of surface (sea water or "equatorial" meteoric water) waters in the plumbing system (McNaughton et al., 1990). The Black Flag deposit at Mt Pleasant, although much richer in base-metals and probably younger than the other deposits, also has similar characteristics.

It is concluded that these deposits are a style of gold mineralization transitional between mesothermal and epithermal deposits, and that they represent the upper levels of vertically extensive hydrothermal plumbing systems that extended into the sialic crust beneath the hosting greenstone belts (Groves et al., 1990). Their mineralized brittle structures, vein structures and textures, ore mineralogy and variable fluid composition are a consequence of anomalously high Archaean crustal level with consequent hydrostatic or low lithostatic pressure and mixing of deep fluids with surface waters.

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GEOLOGY AND GEOCHEMISTRY OF THE STRINGER ZONE UNDERLYING THE HELLYER DEPOSIT, TASMANIA

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Underlying the Hellyer volcanogenic massive sulphide deposit is an extensive, well developed and preserved alteration zone and stringer vein system. The deposit is located in the Cambrian Que-Hellyer volcanics of the Mt Read Volcanic Belt. Lithologies in the footwall include andesitic and basaltic lavas and epiclastic debris flows. Footwall alteration occurs along the entire length of the deposit with dimensions of approximately 1000 by 350 m and is known to a depth of 550 m below the orebody. Mineralogical zoning exists within the footwall alteration pipe, with a central siliceous core giving way to zones of chlorite, chlorite-carbonate, sericite-chlorite, and finally sericite-quartz on the margins. However, the alteration zonation is not symmetrical around the central siliceous core; eastward the alteration zones are steeply dipping and terminate abruptly under the massive sulphide, while westward of the siliceous core the alteration zones extend past the edges of the ore body. Geologic evidence indicates that the pervasive alteration began with the development of sericite+quartz which was subsequently overprinted by chlorite and finally quartz+sericite±chlorite as the hydrothermal system became focused towards the centre of the alteration pipe.

Distinct differences in major oxide and minor element geochemistry, reflecting the alteration mineralogy rather than the original lithology, occur in the various alteration zones. The siliceous core is enriched in SiO_2, total Fe, and K_2O but depleted in all other major oxides. Total Fe, MgO, MnO are enriched while CaO, Na_2O, and SiO_2 are depleted in the chlorite shell. The chlorite-carbonate zone is characterised by enrichment in CaO, total Fe, MgO, and MnO but depleted in SiO_2 and Na_2O. SiO_2 and K_2O are strongly enriched but depleted in TiO_2, CaO, and Na_2O in both the sericite-chlorite and stringer envelope zones. The alteration index (K_2O+MgO/K_2O+Na_2O+CaO+MgO) value becomes progressively larger, with increasing intensity of alteration, from the unaltered andesite to the siliceous core.

Fluids responsible for the massive sulphide mineralisation flowed through a series of stringer veins that closely post-date the pervasive alteration. Eight stages of veining have been distinguished in the stringer zone, these include one stage of pre-mineralisation (Stage 1), three stages of syn-mineralisation (Stages 2A, 2B and 2C), and four stages of post-mineralisation veining (Stages 3–6). The greatest frequency of syn-mineralisation veining occurs in the siliceous core of the stringer zone. Stage 2A veins contain quartz, pyrite and carbonate (dolomite and calcite) and are commonly crustiform banded. Stage 2B veins are characterised by chalcopyrite, pyrite and galena with minor amounts of sphalerite, arsenopyrite, tetrahedrite and barite. Quartz and carbonate gangue are rare and crustiform banding is generally not well developed. Stage 2C veins contain barite with variable amounts of pyrite, galena, and carbonate.

Analysis of metal zoning in the upper parts of the alteration zone indicates the presence of distinct feeder systems underlying the deposit. The main feeder is located under the middle of the deposit with several, small, secondary feeder systems underlying the southern portion of the deposit and a weakly developed feeder system below the far northern portion of the orebody. Distribution of metal values surrounding the feeder systems is related to the zonation of elements in response to changing physical and chemical conditions of the hydrothermal solutions. Iron and copper are concentrated in the cores of the feeders with zinc and lead, silver, gold and arsenic, and barium becoming increasingly dispersed away from the centres of the feeders.

A sulphur isotope investigation has shown distinct variations between vein stages in the stringer zone. Stage 2A veins have $\delta^{34}S$ values that are isotopically heavier (5.7–11.1 ‰, avg. 9.9 ‰) than the cross cutting Stage 2B veins (3.8–8.9 ‰, avg. 6.9 ‰). Stage 2A veins near the outer margins of the stringer zone and in the stringer envelope zone are isotopically very heavy (11.9–40.7 ‰, avg. 25.0 ‰).

A model is proposed to explain the fluid evolution of the Hellyer stringer and stringer envelope zones. Initially Cambrian seawater enters the convection system underlying Hellyer and progressively becomes reduced. In the early stages of the hydrothermal system the proportion of reduced seawater sulphate may have been high giving rise to fluids with heavier $\delta^{34}S$ values, such as those seen in the Stage 2A veins in the stringer and stringer envelope zones. As the convection system intensifies, and penetrates deeper into the footwall lithologies, rock sulphur begins to dominate the hydrothermal fluid. The resulting hydrothermal fluid is high temperature (300–350 °C), low salinity (< 3 equiv. wt. % NaCl) and metal-rich. This fluid passes up through the feeders of the stringer system towards the seafloor and is

GENESIS OF THE AGUILAR Zn-Pb-Ag DEPOSIT, ARGENTINA

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The Aguilar deposit, located in the Cordillera Oriental of northwestern Argentina, is the country's principal Zn-Pb-Ag producer. The deposit and several other prospects are are hosted by an Ordovician sedimentary sequence of interlayered sandstones and shales. These sediments are folded into a large, north-south striking syncline whose intensely folded and faulted eastern limb contains the deposits. Two major Cretaceous granitic intrusive complexes border the syncline and contact metamorphism has transformed the Ordovician sediments into quartzites, calc-silicate skarns and hornfels.

The Aguilar deposit consists of ten stratabound ore lenses in a thick quartzite, at or near its contact with an overlying hornfels. A distinctive ore stratigraphy is present in both strongly and weakly metamorphosed ore bodies of the district: sulphide-rich disseminated and stockwork ore is overlain by breccia ore, with either a sulphide or calc-silicate matrix, which in turn is overlain by massive to banded sulphide ore. Barite is present in the least metamorphosed deposit.

The economic minerals of the deposits consist of a fine to medium-grained intergrowth of sulphides and sulphosalts in quartzite and calc-silicate gangue. Sphalerite, galena, pyrrhotite, pyrite, and chalcopyrite are the most abundant phases. A series of semi-metal bearing sulphides and sulphosalts; arsenopyrite, pyrargyrite, polybasite, tetrahedrite, boulangerite, bournonite, gudmundite, and breithauptite occur in minor amounts. Other hypogene phases observed in trace amounts are marcasite, argentite, alabandite, cubanite, mackinawite, native lead, molybdenite, magnetite, hematite, and wolframite. The Aguilar deposit consists of a pre-metamorphic accumulation of sulphides that have been recrystallized and annealed during contact metamorphism and subjected to post-metamorphic deformation. The metamorphism and recrystallization is responsible for the addition of accessory sulphide and sulphosalt phases. The least metamorphosed prospect in the district, Esperanza, is not recrystallized or annealed.

The mineralized skarns at Aguilar have traditionally been interpreted as genetically related to the spatially associated granite. However, the skarn mineralogy, is inconsistent with this interpretation. In contrast to other Zn-Pb-Ag skarns, Aguilar garnets are sub-calcic with significant proportions of spessartine and almandine with varying proportions (mole percent) of almandine (Al_{5-23}), spessartine (Sp_{26-78}), grossularite (Gr_{8-52}), and andradite (Ad_{0-14}). Pyroxenes are moderately enriched in manganese but are relatively iron poor with an end member range of hedenbergite (Hd_{10-55}), johannsenite (Jo_{15-35}), and diopside (Di_{20-80}); more than 90 percent of pyroxene analyses contain more than 50 percent diopside. Late-stage skarn minerals include calcium-rich bustamite, sub-calcic actinolite, chlorite, and vesuvianite; all of which are enriched in manganese. Mineralogical and composition data indicate that Aguilar is different from any known zinc skarn and several of the minerals are unlike any skarn system in the world.

The deposits of the Aguilar district have $\delta^{34}S$ values that range from +12.5 to +26.8 ‰ for sulphide phases and +32.4 to +34.0 ‰ for barite. These strongly positive $\delta^{34}S$ values are consistent with fractionation from Ordovician seawater.

Lead isotope values from the stratabound mineralization in the Aguilar district are nearly identical with a mean of $^{206}Pb/^{204}Pb = 18.04$, $^{207}Pb/^{204}Pb = 15.64$, and $^{208}Pb/^{204}Pb = 38.03$. There is no significant variation in lead isotopic values between styles of mineralization, different Aguilar ore bodies, or between the Aguilar and Esperanza deposits. Potassium feldspar from the Cretaceous granite is far more radiogenic with values of $^{206}Pb/^{204}Pb = 19.28$, $^{207}Pb/^{204}Pb = 15.67$, and $^{208}Pb/^{204}Pb = 39.00$. These data suggest an early Paleozoic crustal source for the lead in the ore deposits that is unrelated to the lead in the granite.

Aguilar has been historically interpreted as a skarn deposit owing to its proximity to the granite and setting in the metamorphic aureole. However, overall geometry of the ore lenses, presence of banded mineralisation stratigraphically above breccias and stockworks, ore mineralogy and textures, unusual skarn mineralogy and sulphur and lead isotopic signatures indicate a different genesis. The Aguilar deposits are Ordovician sedimentary-exhalative accumulations of sulphides, silica, iron, and manganesethat have been metamorphosed and metasomatised into skarn deposits by intrusion of the Cretaceous Aguilar granite.

MICROTHERMOMETRY, PETROGRAPHY AND MORPHOLOGICAL CHARACTERISTICS OF FLUID INCLUSIONS RELATING TO A VOLCANIC-ASSOCIATED MASSIVE SULPHIDE OREBODY, JOMA MINE, NORWAY

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Joma Mine exploits a stratiform Cu-Zn, volcanic-associated massive sulphide deposit within the low-grade Koli Nappe system of the Norwegian Caledonides. Mesoscale and macroscale structural data from the mine region require four periods of deformation. D_1-D_2 generated a transposition schistosity and mineral elongation lineation, D_3 formed a crenulation foliation, and D_4 was associated with minor kinking and faulting. Microfabric interpretation indicates that the grade of metamorphism (biotite zone, intermediate pressure, greenschist facies) accompanied during D_2-D_3 and had fallen significantly by D_4 Fluid inclusions were studied in samples of vein quartz respectively formed during the D_1-D_2,D_3, and D_4 events within the ore zone.

P-T conditions inferred from fluid inclusions in metamorphic rocks commonly conflict with values obtained by other methods. This is because primary (rare) or secondary (fracture filled) metamorphic fluid inclusions are commonly masked by, and re-equilibrate to form other inclusion populations during subsequent metamorphic/deformation events, including uplift. Joma is no exception.

Microthermometric data were obtained from liquid-vapour type secondary inclusions in quartz formed in each of the four deformation events. Plots of temperature of homogenization (T_h) against the temperature of melting of ice (T_m ice) revealed two populations; with strictly similar characteristics in all four deformation events. This similarity in population distribution cannot be ascribed to the D_4 event overprinting preceding events. Detailed microfabric interpretation verifies that peak metamorphism occurred during D_2-D_3.

P-T plots of stability fields for metamorphic mineral assemblages at various grades of metamorphism against derived P-T conditions for liquid-vapour fluid inclusions can be used to determine whether fluids present were derived through metamorphism. Unfortunately for Joma, stability fields for greenschist facies are too broad and, at best, re-equilibration can only be suspected by use of this method.

Detailed study of the petrographic and morphological characteristics of the fluid inclusions provides an alternative method. This has been applied to the Joma quartz samples and reveals that there are no primary (i.e. growth zone) type inclusions within preserved, original quartz, or in the later strained and/or recovered quartz. All liquid-vapour type inclusions within Joma quartz occur within healed microfractures and are thus secondary in origin. Fluid inclusions at Joma cannot therefore record the ore forming event. However, a fluid history subsequent to ore formation has been derived by using inclusion morphologies and microfracture cross-cutting relationships.

The disparity between the timing of the metamorphic peak based on microfabric work and that derived by fluid inclusion data plots needed to be explained. Detailed petrographic studies of the fluid inclusions revealed decrepitation textures irrespective of which deformation episode or fluid event they represented. These textures are produced by rupturing of liquid-vapour type inclusions under conditions of large (~2kb) over or underpressure between the inclusion contents and host mineral, followed by resealing when pressure/temperature differences 'equalize'.

For Joma, the formation, resetting and then reformation (by decrepitation, necking-down or leakage) of fluid inclusions in vein quartz is due to regional uplift of the Joma district and has effectively destroyed or masked their capacity to record P-T conditions during earlier events.

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FLUID-CONTROLLED FORMATION AND EVOLUTION OF CHROMITE, SULPHIDES AND PGE'S IN PODIFORM CHROMITITE IN THE COOLAC SERPENTINITE BELT, NSW

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Podiform chromitite deposits occur within the Coolac Serpentinite Belt (CSB) N.S.W. The CSB mainly comprises harzburgite which is variably serpentinised and foliated without being intensely schistose. The podiform chromitites comprise massive fractured chromitite surrounded by poorly to unfoliated chromite-bearing dunite. Rodingite dykes cut the pods and harzburgite.

Chromites from differing podiform bodies show different intensities of fracturing and are chemically distinct. Further, although uvarovite and chromian clinochlore occupy fractures in all chromites, differences exist with respect to opaque minerals within the fracture-fill. Thus, the chromites in some pods only contain awaruite, whereas those in other pods also have heazelwoodite, polydymite and millerite.

Platinum group elements (PGE) are associated with the opaque minerals, particularly the sulphides, and differ from those in "normal" chromitites. The latter are enriched in Os, Ir and Rh whereas the Coolac chromitites show Os and Rh depletion and are enriched in Au and Pt. This suggests, a non-magmatic explanation for the present distribution of the PGE.

Field and chemical data are in keeping with the formation of chromitite bodies from high temperature (>500°C?) Cr bearing fluids. Emplacement and replacement was controlled by the pipe-like dunite metasomatites which mark extensional failure sites within the upper mantle. Much later, waves of relatively cool (<300°C) fluid associated with serpentinization invaded the now-fractured chromitites. These aqueous fluids resulted in a sequence of changes involving:

(a) formation of lizardite, chrysotile, secondary chromitite (ferritchromit) and titaniferous magnetite;

(b) crystallization of awaruite, heazlewoodite and polydymite, enriched in PGE's, within fracture-fill lizardite and chrysotile; and

(c) partial conversion of nickel sulphide minerals to millerite, concurrent with the conversion of fracture-fill silicates to magnesite and talc. Finally, the weathering regime resulted in the formation of hyalite, chalcedony and hydromagnesite.

Chromite in these podiform chromitites did not crystallize within a magma chamber. The initial formation and progressive modification of chromite and the associated sulphides and PGE's are fluid controlled.

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A Two Stage Fluid Model for the Bendigo Saddle Reef System

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Gold in the Bendigo Saddle Reef deposits is initimately associated with sulphides and quartz-carbonate veins. It occurs as blebs and stringers in partially or completely replaced carbonate (ankeritic) in the quartz. It in turn is intimately associated with graphitic fragments in the carbonate. It also occurs in sulphides.

The hanging wall of the east-dipping limb of the structure generally contain the highest gold values and are more deformed and carbonate rich than the corresponding west-dipping structures. West limbs do contain gold but were only economic if the west-dipping reverse fault was dominant.

Fluid inclusion study revealed that temperatures decrease moving into actual saddle structures or quartz thickening zones along the footwalls of the laminated legs and saddle. Salinities increase in these zones. Highest temperatures are found in the barren massive quartz of the saddle which corresponds to the crest of the anticline. Gold is found in the lower temperature and salinity zones of the east legs. This also corresponds to a higher concentration of methane in the fluid. This methane may be derived in situ by reaction with graphitic shales or from an external source.

Fluid movement into the hinge zones of anticlines involved a two stage process. In the first stage, a dominantly silica-rich fluid produced the saddle reefs with laminated legs. The second stage involved the introduction of a gold-rich fluid which precipitated sulphides, carbonates and possibly minor quartz.

Calculated $\delta^{18}O_{H_2O}$ (9 to 11 per mil) and δD (-38 to -55 per mil) of fluid inclusion waters indicate a metamorphic origin for the earlier stage quartz-fluids. The $\delta^{34}S$ of sulphides range from 0 to 6.0 per mil (CDT). The $\delta^{13}C$ of carbonates range from -6.5 to -2.5 per mil (PDB). The carbon and sulphur isotope data suggest a possible magmatic source.

SUB-GREENSCHIST TO GRANULITE-HOSTED ARCHAEAN LODE-GOLD DEPOSITS OF THE YILGARN CRATON: A DEPOSITIONAL CONTINUUM FROM DEEP-SOURCED HYDROTHERMAL FLUIDS IN CRUSTAL-SCALE PLUMBING SYSTEMS

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Most hydrothermal ore deposits from volcanic terrains were formed by fluid circulation in areas of local or regional high heat flow at relatively high crustal levels. There is commonly strong metal and/or wallrock-alteration zonation, with metal deposition over a limited crustal depth range due to fluid mixing, fluid boiling or discharge into seawater. Archaean gold deposits, however, depart from this pattern, with individual mines comprising 1 - 2 km deep ore systems with limited zonation of metals or alteration assemblages. They, therefore, warrant careful consideration in terms of fluid and solute source, crustal-depth range and gold depositional mechanisms.

It is now apparent that the majority of Archaean lode-gold deposits in the Yilgarn Block of Western Australia form a coherent genetic group of "gold-only" deposits, irrespective of setting, from the sub-greenschist to the lower-granulite facies. They apparently formed under a variety of structural régimes over a >15km crustal profile, at P-T conditions estimated to range from 250°C at 1kb to 700°C at 5kb. They represent a transitional group of structural styles of mineralization, ranging from dominantly breccias and planar quartz-vein sets at higher crustal levels to dominantly shear-zone hosted deposits with complex arrays of both deformed and undeformed quartz veins at lower crustal levels. Wallrock alteration assemblages show a consistent, but transitional trend in essential mineralogy from carbonate-white mica-chlorite, through carbonate-white mica- biotite±albite, to amphibole-biotite-plagioclase, and diopside-biotite±garnet with increasing depth, with textural relationships and their high thermodynamic variance indicating that they are primary high P-T assemblages rather than metamorphosed low P-T alteration assemblages. The extended P-T range of gold deposition implicates fluid-wallrock interaction as a gold-depositing mechanism common to all crustal levels, but phase separation may be responsible for the formation of high-grade ore shoots within alteration envelopes.

The crustal-depth spectrum exhibited by the deposits, when combined with recent Pb and Sr isotopic evidence for more radiogenic sources than contemporary mantle or greenstone lithologies , effectively eliminates derivation of the ore fluid solely from devolatilization of the hosting greenstone belts or from high-level porphyry dyke swarms. Instead, these data, together with the association of the gold deposits with crustal-scale deformation zones and the provinciality of isotopic compositions, implicate giant plumbing systems and a deep, sub-greenstone belt, source for the ore fluid. They point to either equilibration of lower crustal or mantle (subducted slab or mantle wedge)- derived fluids with older granitic crust, or exsolution of the fluids from granitic magmas derived from such crust. In addition, there is tentative evidence, from oxygen isotope studies of ore- and alteration-related carbonates, for the involvement of meteoric or sea water at upper crustal levels in the fluid plumbing systems.

THE GENESIS OF TIN-SULFIDE DEPOSITS IN WESTERN TASMANIA: A RE-EXAMINATION OF THE MOUNT BISCHOFF DEPOSIT.

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The Mount Bischoff tin deposit is located near Waratah in western Tasmania. It is one of three major stratabound, pyrrhotite-cassiterite, carbonate replacement deposits in this area. Mineralization at Mount Bischoff is hosted by a dolomite unit within structurally complex, late Precambrian rocks of the Oonah Formation. These sedimentary rocks were intruded by a swarm of narrow, vertical to steeply dipping, quartz-feldspar porphyry dykes of Devonian age. The dykes are distributed in a crude radial pattern resembling that developed over a diapiric structure. Previous workers have suggested that this pattern reflects an underlying cupola of the Meredith granite and that magmatic fluids from the granite were channelled up the margins of the dykes, reacted with the carbonate and deposited the cassiterite.

The dyke rocks have undergone an early stage of potassic alteration. This is overprinted to a variable degree by later greisenization. The alteration shows a zonation along and also across the dykes consistent with suggestions that the dykes were major fluid conduits. Within the replaced dolomite, different replacement assemblages, identified on the basis of the dominant silicate or carbonate gangue mineral, were formed in two separate and distinct stages of mineralization. The paragenesis was determined from petrographic information supported by mineral composition, fluid inclusion and thermodynamic constraints. During stage 1, serpentine and chondrodite assemblages formed at 400 to 460°C from hydrothermal fluids with 30 to 36 weight percent NaCl. A zonation from serpentine to chondrodite to magnesite reflects the lowering of the silica activity in the fluid as it reacted with the dolomite and precipitated magnesium silicates. During stage 2, quartz, talc, phlogopite and carbonate assemblages formed at about 350°C from hydrothermal fluids with about 2m NaCl, 1.5m CO2 and 0.3m CH4. The zonation in these assemblages from quartz to talc to ferroan magnesite also reflects decreasing silica activity in the fluid. The stage 2 assemblages extensively overprinted the earlier formed assemblages. Thermodynamic considerations suggest that talc was also an early product in stage 1 but it was not possible to identify the early formed talc texturally. Pyrrhotite is the dominant sulfide and textural studies suggest that pyrrhotite was formed early in stages 1 and 2 and was subsequently partially dissolved. Topaz, selliate and fluorite are locally abundant in the quartz assemblage. Cassiterite was precipitated predominantly within the quartz and talc assemblages during stage 2. Stage 1 assemblages are devoid of cassiterite. Sulfidic and sideritic greisenization in the quartz porphyry dykes also formed at around 350°C from the same type of fluid as the stage 2 mineralization. Fluid inclusions and textures within these rocks indicate that the fluid was boiling. In a gas-rich fluid, boiling is a likely consequence of decreasing temperature, due to the decreasing solubility of the dissolved gases. This would effectively precipitate any tin from the fluid.

The delta 18O values of the hydrothermal carbonates (+16.4 to +19.3 per mil) indicate that the hydrothermal fluid was isotopically heavy, and was probably highly exchanged with an O18 enriched sedimentary rock. Sulphur isotope data show a bimodal distribution with values for stage 1 samples ranging between -1.9 to 0.0 per mil and values for stage 2 between 1.5 to 4.5 per mil. The bimodal distribution indicates two sulfur sources. The near zero values for stage 1 sulfides suggest a primitive magmatic source for this stage. The heavier values for stage 2 suggests a sedimentary source; a conclusion consistent with the evidence from the oxygen isotope data.

To account for both the geological and the isotopic constraints we propose that the Mount Bischoff deposit formed by a two step enrichment-mineralization process. The first step involved the formation of tin-protore in an underlying apical zone of the Meredith granite. Enrichment of tin, flourine, boron and other incompatibles would have occurred during late-stage and essentially closed-system fractionation within the Meredith granite. The second step involved reduced, nonmagmatic fluids entering the solidified granite, altering and extracting tin and fluorine from the enriched zones.These fluids, driven by residual heat in the granite and focused by dykes and related faults, rose through these structures eventually encountering, altering and mineralizing the dolomite by a combination of wall-rock and boiling induced reactions. In the early, high temperature stage of this secondary leach of the Meredith granite the sulfur budget was dominated by residual magmatic sulfur in the granite. At subsequent stages the sulfur budget was apparently dominated by country-rock sulfur. At no stage after the formation of magnesite was the oxygen isotope budget dominated by the Meredith granite.

It is suggested that the tin-protore genesis model proposed for the Mount Biscoff deposit may be generally valid for the tin-sulfide deposits of western Tasmania and by extension tin-sulfide deposits elsewhere. It implies that factors such as the nature of the country rock into which the tin-granite is emplaced and the subsequent history of groundwater circulation are important in the genesis of tin-sulfide deposits in addition to the magmatic history of the tin-granite.

AN INTRODUCTION TO BATMAN

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The Early Proterozoic metasediments in the southern portion of the Pine Creek Inlier, Northern Territory, have been known to be prosepective for metals since 1889. Exploration for gold has been on-going since early this century and numerous small but significant mines have been developed, especially within the vicinity of Mount Todd. Exploration by the Mount Todd Joint Venture partners of Zapopan N.L. and Billiton Australia Gold Pty. Ltd. has identified a potentially mineable resource of 39 million tonnes grading at 1.5 g/t Au. This resource is the Batman prospect.

The Batman prospect lies some 45 km NNW of the township of Katherine and 3.5 km W of Mount Todd, at latitude 14° 08', longitude 132° 08'. The prospect is situated on the NE limb of a SE plunging F_1 syncline, and is hosted in an Early Proterozoic sequence of flyschoid and volcanogenic rocks termed the Tollis Formation. The Formation consists of laminated shales, poorly sorted sandstones, siltstones, and rare interbeds of tuff.

In the vicinity of the prospect, the Tollis Formation sediments were deformed by at least two folding events (Koerber, 1989) during the Top End Orogeny (1870-1800 Ma). The first event (D_1), coeval with lower greenschist facies metamorphism, produced N-S trending upright to slightly inclined, close to tight folds. The second event (D_2) produced E-W trending macroscopic upright, open to close folds, and was not associated with a marked increase in metamorphic grade. A third event (D_3) was associated with the development of kink bands.

The Tollis Formation has been intruded by syn- to post-orogenic plutons of the Cullen Batholith. The Tennysons Leucogranite and the Yenberrie Granite are those granitic intrusions of the Cullen batholith spatially associated with the Batman prospect. Contact matamorphism grades range from hornblende-hornfels facies (quartz-biotite-cordierite-muscovite-Fe oxide assemblage) to albite-epidote facies (quartz-chlorite-biotite assemblage). Cordierite, rather than andalusite, is the common mineral phase associated with the hornblende-hornfels facies in the prospect. The Batman prospect lies in the hornblende-hornfels zone within the inferred boundary between the two facies.

Gold mineralisation in the Batman prospect is contained within an intense zone of quartz-sulphide veins which trend predominantly 010° NNE· The easterly dipping zone is developed over a strike length of approximately 550 m and to a depth exceeding 400 m. Individual vein widths are predominantly 1-2 cm thick, although vein widths may range from a few millimetres to 10 cm. Sulphide minerals include pyrite and pyrrhotite, with minor occurrences of arsenopyrite and chalcopyrite. Bismuth, bismuthinite and sphalerite occur in trace quantities. Au grains up to 0.15 mm are found within quartz, however small blebs (2-5 microns) of Au have some association with chalcopyrite, arsenopyrite and bismuth. Retrograde alteration is typically restricted to within approximately 5 mm of the vein walls, and it is characterised by the sporadic development of an assemblage of biotite-chlorite-sericite-sulphide-carbonate. The development of crack-seal quartz preceded open space fill of quartz and sulphide.

The current conceptual model for the development of the prospect involves the emplacement of granite syn- to post-D_2 folding. The intrusion may have produced the favourable physiochemical conditions needed for the mobilisation of metals, and their subsequent deposition in dilatant fracture zones generated during folding of the competent lithologies.

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CHEMICAL IMPLICATIONS OF IMPERFECTLY CHANNELIZED FLUID FLOW IN HYDROTHERMAL SYSTEMS, II. APPLICATION TO GOLD DEPOSITS

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Ridley and Heinrich (this volume) have discussed some fundamental aspects of a chemical model for fluid-rock interaction along the contact of a fluid flow channel, such as a vein enveloped by a halo of hydrothermally altered wall rock. The model aims at quantifying the common observation in hydrothermal ore deposits, that the bulk of the hydrothermal fluid seems to have flowed relatively rapidly through a set of major channels and thus remained effectively out of chemical contact with the rock, while wall rock alteration is effected by relatively minor excursions of hydrothermal fluid into the wall and back into the main channels. This backflow of fluid towards the main channel will affect alteration zoning in the case of multiple alteration fronts, and it will influence how efficiently ore minerals are immobilised in vein haloes. Re-mixing of fluid packets modified by wall rock interaction with primary ore fluid in the main channel may be an important mechanism for the precipitation of minerals in veins. Repeated fluid excursions and backmixing will gradually alter the chemical composition of the vein fluid along its main flow path, and may thereby contribute to deposit-scale mineral zonations (e.g. 'telescoping') even in the absence of large-scale pressure or temperature gradients.

The Mount Charlotte vein stockwork at Kalgoorlie, Western Australia, is one of several Archaean mesothermal gold deposits for which a two-dimensional model for fluid-rock interaction is required to describe Fe-sulphide + gold alteration haloes at the centimetre-scale of individual veins, as well as the kilometre-scale zonation from multi-front pyrite-magnetite-pyrrhotite alteration haloes in the deepest exposed part of the mine to simpler pyrite-only haloes near the top of the deposit.

Throughout the mine, the bulk of the gold is associated with pyrite in wall rocks haloes. Reduction and/or desulphidation of gold(I) bisulphide complexes by formation of pyrite from Fe-silicates and oxides in the host metadolerite are believed to be responsible for gold precipitation (Neall, 1987). The veins are composed of quartz and variable proportions of carbonate, scheelite and minor sulphides but contain very little gold. One possible mechanism of scheelite depositon is the fixation of hydrothermally advected tungsten by reaction with calcium derived from the mafic wall rocks.

As a guide to future geological testing of the chemical mechanisms of ore deposition at Mt. Charlotte, and to explore the effects of back-mixing during imperfectly channelized fluid flow in general, a simplified 2-dimensional, finite-element, local-equilibrium model for mass transport and chemical reaction has been set up. The program MODEL of the CSIRO-THERMODATA software package (Turnbull and Wadsley, 1986) and a thermodynamic database building on published experimental data has been used. For lack of geological constraints and to simplify the numerical calculations to a minimum of species, a low-salinity $NaCl-KCl-H_2S-H_2WO_4-Au(HS)_2^-$ fluid was assumed to react with a wall rock composed of quartz + albite + ferrous chlorite + clinozoisite.

Preliminary results show that the mineral distribution resulting from a two-dimensional model describing fluid excursion and back-mixing is likely to differ grossly from the result of simple one-dimensional wall-rock infiltration away from a vein. Calculations for the latter model predict that gold as well as tungsten are deposited in the altered wall rock, primarily near the alteration fronts where calcium and ferrous silicates are consumed by Al-conservative Ca-Na-K-H-exchange reactions (to form $CaWO_4$) and Fe-conservative sulphidation reactions (to form FeS_2 + Au). In the more realistic two-dimensional model process taking into account fluid back-flow into the vein (but assuming otherwise identical starting compositions for the input fluid and wall rock protolith) the differential mobility of components and their concentrations in the returning fluid become the dominant factors determining spatial distribution of gold and scheelite. The effective immobility of iron in a low-salinity fluid causes *gold* to be immobilised at the site of pyrite formation in the *wall rock halo*. Calcium, being more soluble, is mobilised by alkali exchange during alteration of the wall rock, and fluid backflow into the vein channel followed by mixing with fresh tungsten-bearing fluid in the main channel may then lead to quantitative deposition of most of the *scheelite* inside the *vein*. The predictions of the latter model are clearly more consistent with gold and tungsten occurrence as observed at Mt.Charlotte. Multicomponent mass balance measurements, including the distribution of gold within the haloes, will be used to test and quantify the theoretical models.

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PARAGENESIS OF A SYN TO POST CLEAVAGE, MULTISTAGE, BASE AND PRECIOUS METAL ORE SYSTEM AT PEAK, COBAR. NSW.

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Mineralization at Peak has been microstructurally timed within a four stage tectonic history (Hinman, 1990). The first three stages at Peak are progressive elements of a single ductile shortening event whose effects are focused along the eastern margin of the Cobar Basin. They are: (S1) Folding associated with a weak S1 cleavage, (S2) a well developed regional slatey cleavage that postdates and transects folding and (S3) a locally developed and ore localizing, highly inhomogeneous, high strain reactivation cleavage. The fourth stage (S4) is a relaxation, post ductile, faulting event that locally crenulates earlier ductile fabrics.

Within this framework, a detailed multistage mineralizing paragenesis for the Peak system has now been established spanning in (micro)structural time: late-folding (late S1) through to post-ductile, late faulting (S4). Mineralization and alteration shows considerable and often dramatic evolution in (a) textural style, (b) silicate mineral chemistry, (c) base metal sulphide assemblages and (d) the type and amounts of precious and trace metals and alloys. This well constrained paragenetic evolution reflects a complex fluid-chemical evolution. Is this chemical evolution controlled by an evolving source environment? Is this linked to the tectonic/metamorphic history of the source region? Or is the chemical evolution controlled to some degree by the evolving structural regime at the actual site of deposition?

The main paragenetic stages, with intra-stage paragenetic details based on textural and microstructural criteria, are summarized below.

(1) **Late-Post S1; Pyrrhotitization of Sedimentary Py and Carbonate.** Disseminated po shows textures indicative of sedimentary py and CO3 replacement in an assymetric halo extending in the up-dip direction around the mineralized zone.

(2) **Late S1-Early S2; Coarse QZ-CO3-PY Veins.** Growth zoned and euhedrally terminated coarse qz, partially replacing earlier CO3, is indicative of open space infill vein growth.

(3) **Pre & Syn S2; Ag-poor, Veined and Replacive, Silica-CO3-SPN-GN.** Several varients of this stage exist. The earliest phase of veining contains coarse **QZ-CO3-Variable Fe SPH-GN.** Euhedral, zoned qz replaces earlier CO3 and the sph evolves from Fe-rich to Fe-poor. At its strongest this stage is represented by massive **Replacement zones of Silica-CO3-disseminated sph-gn** that core broader zones of 'Elvan' style sediment silicification. These are products of grain scale, crack-seal, silicification driven by ductile deformation during early S2. Veins and vein networks of **Ag-poor, Qz-CO3-sph-gn** generally contain Fe-rich sph.
Two stage veins show overprinting of (2) and (3) with textures showing qz of stage (2) being replaced by qz (and sulphides) of stage (3).

(4) **Late S2-Syn S3; Veined and Replacive, Silica-(gn-Bi-Ag)-green chl-musc-PO-CPY-Au.** An early replacement mosaic of qz-gn with lesser po-cpy-sph is characterized by AgAu alloys, native Bi, CoNiSb alloys, bismuthinide and a AgSb sulpho-salt. This replacement phase exploits irregular fracture networks developed in brittly behaving, earlier veined and silicified material during ongoing ductile deformation of the sediment matrix. Coarse 'splashy' PO-CPY-cub occupies dilated qz grain boundaries lying at high angles to the L33 stretch direction. This sulphide precipitation anneals/recrystalizes the earlier qz, clearing adjacent inclusion-rich material. Even in discrete veins of this stage the coarse po-cpy postdates the largely replacive silica phase. A chl-musc assemblage, synchronous with or slightly post the po-cpy, spectacularly replaces the earlier qz and sulphide either along deformed grain boundaries or along S3 parallel subgrained zones. This replacement often upgrades the precious metals in size and fineness leaving a chl-musc-Au nugget-AuSb alloy assemblage.

A Au-rich, replacement assemblage with a much stronger base metal character probably represents a transitional mix of stages (3) and (4). **Veined and Replacive, Silica-PO-CPY-SPH-gn-chl-musc-Au** also exploits fracture networks in and around previously veined and silicified material, characteristically producing a 3-D irregular lattic work of semi-massive sulphide. Au within this sulphide matrix has finenesses betweeen 890 and 910. Similar chl-musc replacement of the qz-sulphide mosaic as in (4) refinens existing Au or precipitates new Au nuggets of fineness 980-990 along with a AuSb alloy. No native Bi, CoNiSb alloys or bisthmuthinide is associoated with the early silica-sulphide mosaic of this assemblage.

(5) **Late/Post S3-Syn S4; Replacive, Ag-rich, Banded, Black Chlorite-musc-SPH-GN-PO-PY-cpy.** This stage is characterized by post-ductile deformation, massive replacement of siliceous and mineralized assemblages. It is Ag-rich. Where replacement is strong, silica is absent from this assemblage. Irregular, disharmonic banding is controlled by jostling between remnant unreplaced blocks during the late (S4) faulting event.

Fluid inclusion work is in progress. Density, composition and temperature data coupled with geochemical modelling of the assemblages should rationalize much of the above and, in particular, explain: (a) the early qz-CO3 replacement relationships, (b) the pre-main stage qz-py veining, (c) the gross base metal evolution from Pb-Zn dominated through a Cu-Fe-Au dominated stage to a late, post-deformational Pb-Zn stage, (d) the precious metal evolution from none in the early Pb-Zn stage through a Au-rich, Fe-Cu stage to the late Ag-rich, Pb-Zn stage, (e) the rapid 'flips' from silica precipitating sub-stages to silica dissolving and chlorite-muscovite precipitating sub-stages especially during the latter part of the high strain (S3) phase of deformation and (f) the very variable, but possibly systematic, chlorite chemistries. Early indications are that some low temperature boiling is occuring. The possibility of a tectonically driven throttling system in the high strain zone at Peak that extensionally depressurises fluids drawn into the zone resulting in episodic boiling may explain some of the sub-stage evolutions noted. In addition, post ductile deformation relaxation may, speculatively, allow more oxidized fluids into the system and explain the unusual late stage replacive black chlorite stage.

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TECTONIC CONTROLS ON VOLCANISM AND ACTIVE EPITHERMAL GOLD MINERALISATION IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND.

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Despite extensive exploration for geothermal energy, the structural architecture of the Taupo Volcanic Zone is poorly understood. It has been generally believed that the Taupo Volcanic Zone comprises a relatively simple series of north-easterly trending normal faults and associated graben developed in response to back-arc extension during the last 2.1 Ma. A number of calderas and rhyolite dome fields have also been recognized and the extensive Holocene ashflow volcanism of the Taupo Volcanic Zone has been described in detail.

High resolution SPOT satellite imagery shows that in addition to the young north-easterly fault array a series of north striking lineaments of regional extent transect the Taupo Volcanic Zone . Assuming these northerly lineaments to be faults, the structural pattern they define suggests that the Taupo Volcanic Zone developed initially as a subsidence basin between the diverging right slip Hauraki Rift in the west and the Kaingaroa Fault - North Island Shear Belt in the east. A number of internal fault geometries are possible; one of these suggests that the location of the major rhyolite dome fields is controlled by divergent splays such as the Paeroa Fault which were reactivated or were developed *subsequently* along the fault array.

Hydrothermal activity occurs throughout the Taupo Volcanic Zone in response to the regional high heat flow, however the geochemistry of individual systems reflect a spatial control. The high gas, precious metal depositing systems are colinear and sub-parallel to the south-eastern margin of the Taupo Volcanic Zone. These systems are believed to be located on structures which penetrate deep below the volcanic basement and which may also localise andesite magmatism. Rotation of fault bound blocks developed within the original basin leads to dilation of earlier structures, linkage of fluid reservoirs and focussing of hydrothermal upflow and may, in equivalent older terranes, be responsible for the development of spectacular 'bonanza' gold vein deposits.

Recognition of the tectonic controls on magmatism and hydrothermal activity in an active volcanic belt provides a basis for evaluating controls on precious and base metal mineralisation in older volcanic terranes such as the Drummond Basin, N.E.Queensland, the 'Walker Lane' , Nevada and the well known VMS districts, and in turn provides a basis for defining deep exploration plays for high grade deposits.

STRUCTURE AND METAL ZONATION OF THE THALANGA VMS-DEPOSIT, NORTH QUEENSLAND

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Copper-zinc-lead mineralization is stratiform at the Thalanga volcanogenic massive sulfide deposit, 65km southwest of Charters Towers in north Queensland. The mineralization is hosted within the volcano-sedimentary terrane of the Late Cambrian - Early Ordovician Mt Windsor Subprovince (Henderson, 1986). The ore-horizon is just below the contact between rhyolite volcanics of the Mt Windsor Formation and the overlying dacite and andesite volcanics of the Troopers Creek Formation.

Cleavage, stratigraphy and mineralization are subvertical and trend east-southeast. The 5-8m thick, banded massive pyrite-chalcopyrite-sphalerite-galena mineralization is coarse-grained. Equilibrium textures suggest that this grainsize is the result of recrystallization during biotite-zone greenschist facies metamorphism (Wills, 1985). A zone of massive pyrite approximately 5m thick sits either directly, or 5-10m into the footwall of the economic mineralization. Zones of massive chalcopyrite occur at all stratigraphic levels within the ore-horizon. Interstitial chalcopyrite suggests that chalcopyrite remobilization has taken place.

The footwall rhyolites are strongly pyrite-sericite-chlorite altered with variable silica alteration. Pyrite occurs as disseminations and veins that are now subvertical and commonly parallel with the mineralization and local cleavage. There is a decrease in the percentage of pyrite and chalcopyrite with distance from the ore-horizon. Actinolite-chlorite alteration commonly occurs close to the massive pyrite. A zone of strong pyrite(5-30%)-chalcopyrite(<0.5%)-silica-sericite alteration that extends 120m into the footwall may represent a feeder zone. In Central Thalanga, this diffuse zone is broadly horizontal and perpendicular to the mineralization.

A change from southeast striking to east-west striking cleavage and mineralization at Central Thalanga is spatially related to a major subvertical east-west shear zone. Strong subvertical stretching lineations and cleavage-clast relationships within the shear zone indicate normal movement. The dacite-rhyolite contact is offset by about 40m and at depth the sulfide mineralization, or the lateral equivalent, is truncated by this shear zone.

Parallel steeply dipping sericite-chlorite alteration in the hangingwall to the east of the shear zone marks a second, smaller shear zone. Small-scale structures on the contacts of this shear zone suggest normal movement. A partly intrusive andesite is bound by the shear zones, with a wedge of andesite included in the major shear zone. Both shears anastomose and become parallel with the ore-horizon.

Immediately west of the sharp change in the strike of the cleavage and mineralization, the mineralization thickens to about 25m. In this zone, the mineralization has a kink-like form, with a shallow westerly plunge, that extends for about 40m before gradually dying out. Metal zonation studies suggest that this kink is mainly structural, it is likely to have formed during movement along the major shear zone. Some thickening may be primary and above a feeder zone. The pyrite-chalcopyrite-silica-rich alteration zone in the footwall is close to thickened mineralization.

Cross-cutting all structures and stratigraphy are late north-northeast trending brittle faults with predominantly dextral movement. Sub-parallel to these faults are a series of 0.5-4m thick microdiorite dykes that also cross-cut the stratigraphy and mineralization.

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MECHANISMS FOR GENERATING WHOLESALE DOWNWARD FLOW IN THE CRUST

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Fluid flow in the Earth's crust is controlled by gradients in the hydraulic head rather than by gradients in the pore pressure, as in models without gravity. The head is the height to which the pore pressure at a point of interest will support a fluid column plus the height of that point above some arbitrarily selected datum elevation. As a consequence of this, a lithostatic pore pressure gradient is always associated with overall upward flow and no flow occurs for a hydrostatic pore pressure gradient.

We have investigated the numerical coupling between fluid flow and deformation using the explicit, finite difference code FLAC (Fast Lagrangian Analysis of Continua, Cundall and Board 1988; ITASCA 1989). Using a model of the crust 10 kilometres long and 5 kilometres deep, we show that for sufficiently large dilatancy of the crust at depth, downward fluid flow may be induced during deformation.

We demonstrate this for a crust with Mohr-Coulomb material behaviour undergoing plane strain lateral compression with a lithostatic pore pressure gradient imposed on the boundaries. Within this model are three horizontal layers of more impermeable material. These layers buckle during deformation and over-pressured zones develop between the layers. Porosity and permeability change with the changing volume strain so that hydrofracing may be modelled, and we are able to study the history of pressure changes associated with these events.

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Chemical Processes of Fluid-Rock Interaction at Lancefield, Western Australia: The Role of Redox Changes in Gold Deposition in a Basalt-Carbonaceous Shale/Chert Enviroment.

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The Lancefield gold deposit (>25 tonnes Au produced) is located in the Archaean Yilgarn Block of Western Australia. Mineralization is largely hosted within bedding-parallel, brittle-ductile shear zones (lodes) confined to two strongly deformed, carbonaceous metasedimentary units intercalated within a mafic sequence. Adjacent to the lodes, the latter units are also the sites of minor economic mineralization and significant amounts of mineralization-related alteration. Structurally controlled, high grade ore shoots occur as discrete zones associated with undulations of the lode surfaces. These high grade ore shoots acted as dilatant zones and main ore fluid channelways (zones of high fluid-rock ratio), as evidenced by high vein densities and volume additions of >300% relative to sub-economic lode material. The absence of any cross-cutting structures and the finite nature of individual ore shoots suggest that the fluid flow involved the focussing of ore fluids from the flanking low grade zones into the ore shoots, rather than outward migration of fluids from the ore shoots themselves.

Silicification, sulphidation and carbonatization within the carbonaceous metasediments have resulted in the formation of alteration assemblages dominated by quartz, chlorite, ankerite, calcite, and muscovite with minor K-feldspar. Pyrrhotite, pyrite and arsenopyrite, the latter hosting most of the gold as sub-microscopic inclusions or in solid solution, comprise the major sulphide phases (typically 15-30% of the rock) and sphalerite and chalcopyrite are present in minor amounts. Graphite (<1-2 wt%) is also present in the lodes. Mineral assemblages within the shale/chert-hosted lodes are remarkably consistent, irrespective of gold grade. Differences between low grade (sub-economic) portions of the lode systems and high grade ore shoots are manifested primarily in variations in modal mineralogy and subtle changes in chlorite compositions. High gold grades are associated with increasing quartz, ankerite, total carbonate and arsenopyrite, and decreasing abundance of chlorite and graphite. These mineralogical changes with increasing gold grade are correlated with marked Si, Fe, S, and CO_2 addition (based on Gresens analysis), decreasing whole rock ($Fe^{2+}/\Sigma Fe$) ratios, and increasing Mg content in chlorite solid solution compositions. Isotopic compositions of coexisting carbonate minerals also show a trend, from $\delta^{13}C = -11‰$ to about -4‰, with decreasing graphite content and increasing gold grade. Petrographic and heating-freezing studies on fluid inclusions spatially associated with mineralization support phase separation of an initially CO_2- rich, low salinity (<4wt‰ NaCl equiv.) fluid into carbonic ($CO_2 \pm CH_4$)- and water rich phases at temperatures near 270-290°C.

In light of the above data, at least three possible depositional mechanisms must be considered. At present none of these models fully satisfy all of the geochemical and structural constraints noted above, and therefore must be considered as working models only.

i) Reduction of an ore fluid by graphitic host rocks (or fluids derived from them). This has long been proposed as a viable means of precipitating gold, and is consistent with both isotopic trends in carbonates, and the observed inverse correlation between graphite content and gold grade at Lancefield. Simple mass balance constraints, however, rule out graphite as the primary reductant responsible for ore deposition. If reduction was important, other, more abundant, phases such as chlorite must have acted as the primary reductant responsible for gold deposition.

ii) Progressive wallrock sulphidation. Coexisting chlorite-pyrite-pyrrhotite assemblages in both sub-economic lode and high grade ore shoots effectively buffer both f_{O2} and $a_{\Sigma S}$ in the Lancefield ore fluids, and are consistent with progressive wall rock sulphidation in the high grade ore shoots.

iii) Phase separation, either in response to decreasing fluid pressures caused by dilatant fracturing in high grade ore shoots or due to increased CH_4 contents in the ore fluid caused by fluid-rock interaction, could also be an important mechanism for gold deposition. At the redox states proposed for the Lancefield deposit (~ CO_2 - CH_4 redox buffer), gold deposition as a result of phase separation would occur primarily by reduction of a_{H2S} in the remaining ore fluid.

DISTRIBUTION OF GOLD IN VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS: IMPLICATIONS FOR ORE GENESIS AND METALLURGICAL RECOVERY

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Recent studies have demonstrated two styles of gold mineralisation in volcanogenic massive sulphide deposits, which relate to the complexes by which gold was transported: (1) the Zn-Au association in the upper portion of deposits ($Au(HS)_2^-$ transport), and (2) the Cu-Au association in the stringer zone and lower portion of deposits ($AuCl_2^-$ transport). Near neutral, low temperature (200-250°C) fluids promote high grade deposits of the Zn-Au association, whereas acid, high temperature (>300°C) fluids promote high grade deposits of the Cu-Au association (Huston and Large, 1989). Fluids with intermediate pH produce low grade deposits.

The mineralogical occurrence of the gold reflects depositional processes. In undeformed deposits of the Zn-Au association, gold occurs in auriferous pyrite and arsenopyrite in massive sulphide ore (Ramsden and Creelman, 1984), whereas it occurs as electrum in the overlying baritic zone (Shimazaki, 1974; Huston and Large, 1988). The occurrence of gold in sulphide minerals results from co-precipitation, whereas the occurrence of electrum in the barite zone relates to oxidation and removal of H_2S from the hydrothermal fluid upon interaction with seawater. In undeformed deposits of the Cu-Au association, gold occurs as coarser grained, high fineness electrum associated with chalcopyrite (Huston, 1988). This results from similarities in precipitation mechanisms of chlorocomplexed gold and copper in the pyrite stability field.

Deformation and metamorphism enhances metallurgical recoveries by increasing grain size and liberating gold from auriferous pyrite and arsenopyrite. However the effectiveness of these processes depends on the gold grade of the deposits. Owing to the small amount of available gold, a recrystallising electrum grain from a low grade deposit will have smaller grain size than one from a higher grade deposit.

In general, deposits of the Cu-Au association will have better recoveries than deposits of the Zn-Au deposits. In the Zn-Au association, the barite zone will have higher recoveries than underlying massive sulphide. Deformed deposits will have higher recoveries than undeformed deposits, and high grade deposits will have higher recoveries than lower grade deposits.

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HYDROTHERMAL TRANSPORT OF TE AND THE GENESIS OF TELLURIDE BEARING EPITHERMAL GOLD-SILVER DEPOSITS

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Thermodynamic mass-balance calculations in the Te-O-H and Au-Ag-Te-Cl-O-H-S systems show that in hydrothermal fluids characteristic of epithermal environment, HTe^- is the dominant aqueous complex of tellurium with $HTeO_3^-$ becoming dominant in more oxidizing fluids. A fluid buffered by the chlorite-magnetite-quartz (cmq) and potash feldspar-sericite-quartz assemblages can dissolve less than 0.1 ppb of tellurium at 300°C. In Au-Cl-S-Te-O-H and Ag-Cl-S-Te-O-H systems, tellurium and tellurides (hessite and calavarite) are the stable phases. Near-neutral fluids buffered by cmq or hm (hematite-magnetite) assemblages and containing 1 ppb of tellurium and 0.1 ppb of gold or silver are saturated with respect to tellurides at 300°C indicating limitations on the simultaneous transport of gold, silver and tellurium below 300°C. A possible alternative is the transport of these metals in two different fluids that mix at the site of deposition. Mixing trends reported in a number of such precious metal deposits where more oxidized meteoric fluids are postulated to be mixing with relatively more reduced fluids support this suggestion.

GEOCHRONOLOGICAL CONSTRAINTS ON THE GENESIS OF THE OLYMPIC DAM Cu-U-Au-Ag DEPOSIT, SOUTH AUSTRALIA

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The Olympic Dam Cu-U-Au-Ag deposit, which occurs within the Gawler Craton, South Australia, is one of the world's largest concentrations of Cu and U. It contains in excess of 30 million tonnes of Cu metal, 1 million tonnes of U, 1200 tonnes of Au, and 7000 tonnes of Ag. The deposit is hosted by the hematite-rich Olympic Dam Breccia Complex (ODBC - Reeve et al., 1990) which occurs wholly within the Roxby Downs Granite (RDG). It is concealed beneath ~300m of Late Proterozoic and Cambrian sedimentary rocks of the Stuart Shelf. The RDG is an evolved variant of a Middle Proterozoic anorogenic batholith (the Burgoyne batholith of Reeve et al., 1990) which, along with other granitoids of the Hiltaba supersuite, is interpreted to be an intrusive equivalent of the Gawler Range Volcanics (GRV). The Burgoyne batholith intrudes deformed granitoids and metasedimentary rocks correlated with the Early Proterozoic Hutchison Group.

The age of the Roxby Downs Granite (1588 ± 4 Ma; Creaser, 1989) constrains the maximum age of the Olympic Dam mineralisation. Constraints on the minimum age of the ODBC are provided by new ion microprobe U-Pb zircon dates on lithologies which intrude the breccias.

Laminated hematite-quartz sandstones, interpreted to have formed in a maar lake environment as part of the surficial facies of the hematite-producing hydrothermal system (Reeve et al., 1990; Oreskes and Einaudi, 1990), are locally intruded by felsic peperite dykes. One of these dykes yields an age of 1593±7 Ma (weighted mean $^{207}Pb/^{206}Pb$ age, 95% confidence limits). A more altered felsic dyke which intrudes unmineralised hematite-rich breccias has been dated at 1584±20 Ma. The fragmental nature of these dykes and the fluidal fabrics within their host rocks are interpreted to indicate that they intruded wet unconsolidated material, with resultant autobrecciation and mixing. The dykes are thus considered to be coeval with hydrothermal activity. Although some are significantly hematitised, few contain conspicuous Cu-U mineralisation, and it is likely that many (including those dated) intruded during the waning stages of the hydrothermal system.

Several zones of volcaniclastics occurring within the ODBC are interpreted to be diatreme structures (Reeve et al., 1990). One diatreme near the geographic centre of the deposit is exposed in mine workings, and zircons from a juvenile lapilli tuff horizon within it have an age of 1586±7 Ma. This lapilli tuff is intermingled with ash-fall tuffs and volcaniclastic conglomerates, all of which have undergone soft-sediment deformation and display sericite±hematite alteration of similar intensity to that in the surrounding hydrothermal breccias. The volcaniclastics have GRV affinities and are interpreted to have accumulated in the crater of the active diatreme. This crater-fill generally grades into tuffisitic breccias at depth, and much of the deformation and mixing observed within it probably occurred during its collapse towards the underlying root zone of the diatreme as a result of on-going phreatomagmatic activity. Because the volcaniclastics were poorly lithified at the time of deformation/collapse they are unlikely to be significantly older than the phreatomagmatic (mafic tuffisitic) activity that generated the diatreme itself. The degree and style of their alteration suggests that the hydrothermal fluids of the main hematite-producing system were still circulating at this time. The age of the lapilli tuff therefore dates diatreme activity and provides a minimum age constraint on the hematite-quartz breccias and heterolithic breccias that the diatreme intrudes. This date may also constrain the minimum age of a bornite-chalcocite ore zone which appears to be cross-cut by the diatreme.

From the data available the age of the ODBC cannot be resolved from the age of the RDG. This implies that the breccia complex and the diatremes within it formed soon after emplacement of the RDG, probably as part of the same overall thermal event (i.e.. the Gawler Range / Hiltaba volcano-plutonic event, the last major tectonothermal event on the Gawler Craton). This interpretation supports the genetic model proposed by Reeve et al. (1990) but is in contrast with the model proposed by Oreskes and Einaudi (1990) who suggested that the main brecciation event occurred approximately 200 Ma after emplacement of the granite (i.e. at ~1400 Ma).

The isotopic dates reported here effectively establish the age of the ODBC, but the timing of the Cu-U-Au-Ag mineralisation remains equivocal. Textural features and lithological relationships suggest that, although multi-stage, metal deposition and brecciation were broadly coeval. However, because of the deposit's physical setting below a major unconformity (and therefore the possible analogy with unconformity-type uranium deposits) there is a possibility that some metal deposition and/or remobilisation significantly post-dated the principal breccia-forming events.

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MOBILIZATION OF PLATINUM METALS BY DIAGENETIC FLUIDS ALONG THE LAKE ACRAMAN METEORITE EJECTA HORIZON, SOUTH AUSTRALIA.

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Discovery of Australia's largest impact structure and it's widely dispersed ejecta blanket in Late Precambrian shales in the Adelaide Geosyncline has provided an opportunity to document mobilization of the Platinum Group Elements (PGE), Au and Cu in 'red bed' environments by very low temperature, oxidized fluids.

It is estimated that the projectile which produced the structure had a diameter of about 4 kilometres and was travelling at a speed of 20-40 km/sec when it impacted the earth. The impact produced a widespread ejecta blanket, some of which fell into the shallow sea of the gulf-like Adelaide Geosyncline, some 300 km to the east, where Bunyeroo Formation shales were accumulating. Material also fell into the present Officer Basin, some 400 km to the northwest of the impact structure; recognition of ejecta material in the latter basin has made correlation of Late Proterozoic formations in the two sedimentary depositories possible.

The ejecta horizon occurs in the 600 million year old Bunyeroo Formation which consists of deep-shelf greyish red and somewhat deeper water greenish grey shales with minor concretionary carbonates. The impactite varies in thickness from 0 to 40 centimetres and consists of a basal breccia (not always present) consisting of poorly sorted, angular, sand and pebble sized fragments set in a mud matrix overlain by a coarse to medium sand unit grading upwards into a fine muddy sand. All coarse fragments and most sand sized grains appear to have been derived from a pink to red porphyritic volcanic rock, similar to that currently exposed at the Gawler Ranges impact site. The ejecta horizon, when hosted by the greyish-green shale facies, is encased by a pale green shale envelope that varies in thickness from a few millimetres to several metres (Fig. 1).

Diagenetic minerals occurring as cement and as replacements of clasts include chlorite, manganiferous radial and equant calcite, barite, albite, quartz, pyrite, chalcocite, covellite and chalcopyrite. The sulphides are generally weathered and are now represented by iron oxides, azurite, and malachite.

Whereas background values (44 samples) for the greyish red shales are 0.82 ± 0.40 ppb Pt, 0.44 ± 0.16 ppb Pd, 0.026 ± 0.020 ppb Ir, and 0.107 ± 0.068 ppb Au, ejecta horizon samples contain up to 274 ppb Pt, 7.7 ppb Pd, 5.2 ppb Ir, and 5.3 ppb Au. The pale green shales are variably enriched in Pt and Au which correlate strongly with Cu, reaching a high of 313 ppb Pt in a sample with 1.2 % Cu. They are also enriched in Ir, Pd, Ru, Ni, V, Co, and Zn and strongly depleted in Fe. In addition, pale green shale intercalations elsewhere in the Bunyeroo Formation are similarly enriched in Cu, Au, Ir and Pt. Hence, enrichment in the precious and base metals is not restricted to the ejecta horizon nor it's immediate environs.

It is suggested that the ejecta horizon acted as an aquifer for low Eh fluids derived from reduced facies, possibly the deeper water greenish-grey Bunyeroo Formation shales, deeper in the basin. Interaction of these fluids with high Eh, Cu-V-PGE bearing fluids circulating in the hematite-bearing greyish-red shales led to the precipitation of the ore metals. Although no ore grade PGE values have yet been documented, it is evident that highly oxidized fluids are capable of carrying appreciable quantities of the PGE even at very low temperatures. Focusing of such fluids into a low redox environment (e.g., in a red bed copper environment) should generate appreciable PGE enrichment.

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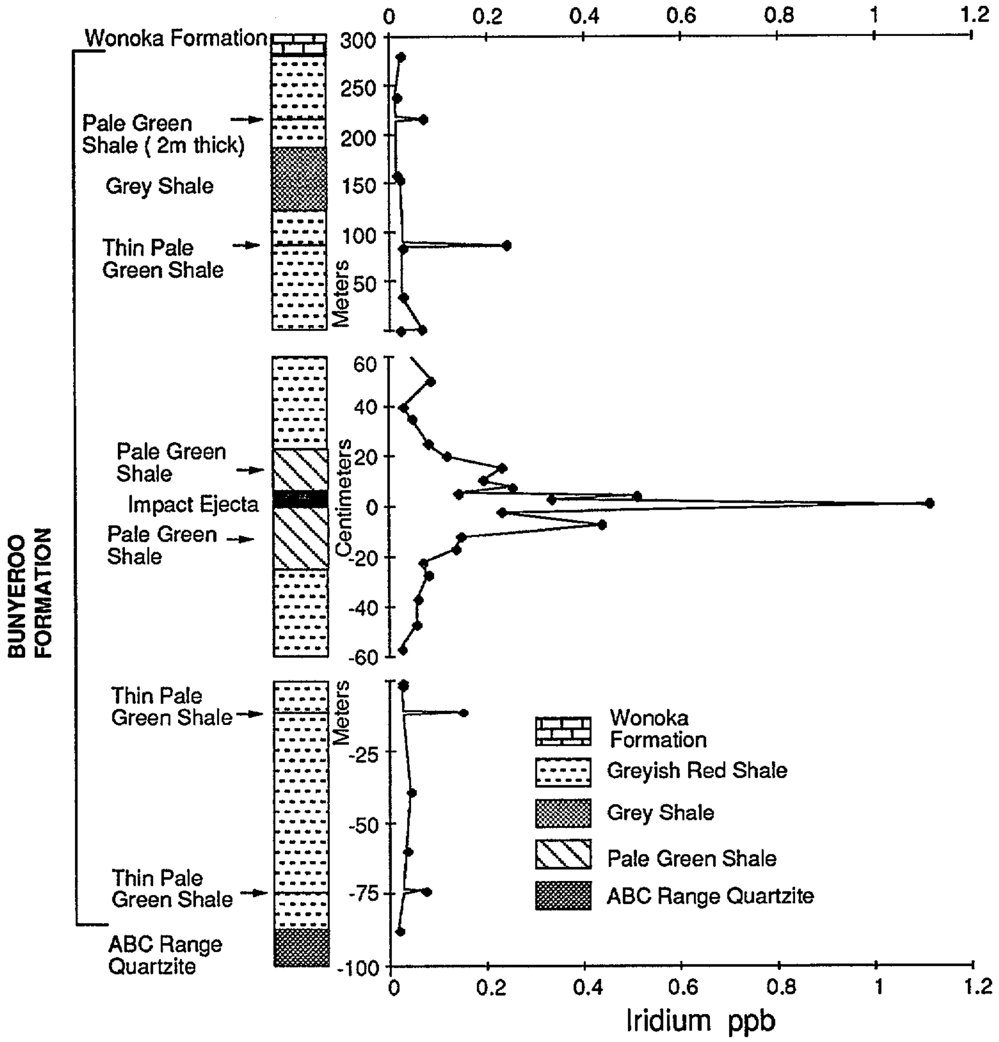
Figure 1. Iridium profile through the entire Bunyeroo Formation at Bunyeroo Gorge, Flinders Ranges. Note that in addition to an Ir anomaly at the ejecta horizon, several smaller Ir anomalies occur at thin green shale horizons.



CONTRASTING STYLES OF HYDROTHERMAL VEIN MINERALISATION IN THE ROCKVALE DISTRICT, NORTHEASTERN NEW SOUTH WALES.

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Within the Rockvale district 40km northeast of Armidale NSW, three distinct styles of hydrothermal vein mineralisation are hosted by regional brittle-ductile deformation structures. These are: (i) numerous small Sb-(As-Ag-Au) deposits, (ii) several rich Ag-As-base metal deposits, and (iii) a single, currently economic, Au-W-(Bi) deposit. Differences in mineralogy, chemistry and spatial distribution between deposit styles reflect differences in the hydrothermal fluids responsible for mineralisation.

Sb-rich veins (with or without accessory Au, As and Ag) form simple quartz-pyrite-stibnite-(arsenopyrite-berthierite) dominated vein systems hosted in siliceous flysch metasediments. Similar deposits to these occur throughout the Southern New England Orogen. Although no fluid inclusion data are available for the deposits in the Rockvale region, work on similar deposits at Hillgrove (Comsti and Taylor 1984), in the Nundle area (P.M. Ashley unpubl. data 1989) and elsewhere show these deposits were formed by low salinity (generally ≤5%eq.wt.%NaCl), CO_2 bearing fluids at temperatures less than 250-300°C. Current models for the genesis of this style of mineralisation involve deeply penetrating evolved meteoric water (Nesbit *et al.* 1989) or fluids released by metamorphic devolatilisation reactions at mid to deep crustal levels migrating into the upper crust via suitable structural conduits (eg. McKeag and Craw 1989).

Ag-As-base metal (with lesser Sn and Sb) rich vein systems are common within the central portion of the Rockvale region, and are hosted wholly within (or in two cases adjacent to) the Late Carboniferous Rockvale Adamellite, a member of the Hillgrove Suite of deformed S-type granitoids (Flood and Shaw 1977). Despite the obvious depositional control this pluton has had over Ag-As-base metal mineralisation, mesostructural, microstructural, geochronological and a variety of circumstantial geological evidence indicate that the Rockvale Adamellite was not the source of mineralising fluids. Instead it appears that the deformed adamellite provided an excellent structural and chemical host for the hydrothermal fluids responsible for Ag-As-base metal mineralisation.

Ag-As base metal deposits consist of rich sulfide dominated lenses within quartz-carbonate-sulfide vein systems hosted within solid state deformation structures produced by northeast trending sinistral strike slip faulting. Three distinct paragenetic stages of deposit formation can be identified:

(i) Initial deposition of quartz veins with disseminated euhedral pyrite-arsenopyrite (-argentite-cassiterite).

(ii) The main phase of ore deposition; this stage involved the formation of massive anhedral pyrrhotite-sphalerite-chalcopyrite-galena-stannite-tetrahedrite-pyrargyrite dominated lenses within areas already mineralised by stage (i). Numerous other rare sulfosalt and sulfide minerals are present in trace quantities within sulfide lenses (Lawrence and Chand 1962), and the highest grade regions in most mines were associated with this stage. Stage (ii) minerals often completely surround and/or infill cracks within euhedral stage (i) minerals.

(iii) Crosscutting quartz-sphalerite-carbonate veins are the last recognisable stage of mineralisation.

Numerous chemical, mineralogical, paragenetic and other similarities are evident between the Ag-As-base metal mineralisation of the Rockvale region and Ag-base metal deposits associated with distal deposits of mineralising felsic granitoids described from the northern parts of the New England Tablelands. Similar deposits are also described from elsewhere in Eastern Australia (eg. McQueen and Box 1989) and from other parts of the world (eg. Kelly and Turneaure 1970). Thus the Ag-As-base metal mineralisation of the Rockvale district is considered the distal product of a mineralising felsic granitoid despite the lack of an obvious source pluton within the region. This interpretation is supported by preliminary fluid inclusion evidence which shows these deposits to have formed from fluids of moderate salinity (5.5-12.5 eq.wt.%NaCl) at temperatures between 435-260°C. These fluid conditions are identical to those described by Sugaki et al. (1988) for Ag-base metal deposits from the Bolivian Andes.

The third style of hydrothermal vein deposit within the Rockvale district is Au-W(-Bi) mineralisation at the Comet Mine, located within the Rockvale Adamellite, adjacent to the northern contact of the pluton. This deposit is the most economically important of the region, and the mine has recently been reopened by Mount Gipps Ltd.; current estimates place reserves at 166,000 tonnes at 7.3g Au/tonne. Mineralisation consists of a single northeast trending laminated quartz-sulfide vein traceable for 1500m in surface outcrop. High grade portions appear restricted to about 300m of this strike length. As in Ag-As-base metal deposits, several paragenetic stages are recognisable:

(i) The initial and main stage of deposition consists of quartz-pyrite-arsenopyrit-pyrrhotite-wolframite (-gold-base metal sulfide-bismuthinite-telluride). Sulfides occur as both bands and disseminations within quartz.

(i i) Late quartz-ankerite veins and open space fillings.

The Comet mineralisation shares a similar structural position within the Rockvale Adamellite to that detailed for Ag-As-base metal deposits, ie. is hosted within solid state deformation structures. It is also interpreted to significantly postdate the Rockvale Adamellite. The chemistry and mineragraphy of this deposit is also characteristic of that formed by mineralising granitoids, although in these systems Au-W(-Bi) deposits occur in more proximal settings than Ag-As-base metal mineralisation (Kelly and Turneaure 1970, Sugaki et al 1988). Existing fluid inclusion data for the Comet Mine show fluid salinities less than 8 eq.wt.% NaCl and homogenisation temperatures between 350-200°C, and thus conflict with the proximal to distal zonation patterns associated with this style of granitoid related mineralisation. This may indicate that different source plutons are responsible for Au-W(-Bi) and Ag-As-base metal mineralisation, although this is somewhat conjectural at this stage. Further work to elucidate the relations between Au-W (-Bi) mineralisation at the Comet Mine and Ag-As-base metal deposits within the Rockvale region is currently underway.

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A HISTORY OF BRITTLE DEFORMATION AND RELATED MINERALISATION AT RENISON TIN MINE,WESTERN TASMANIA

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The Renison Tin Mine, on Tasmania's west coast is a world class primary tin deposit. It occurs within the central region of the Early Palaeozoic Dundas Trough bounded by the Proterozoic Tyennan and Rocky Cape blocks (Solomon, 1981). The deposit is hosted by the subareal to shallow marine, Late Precambrian to Early Cambrian Success Creek Formation (Corbett *et al.*,1987) and the shallow marine Early Cambrian Crimson Creek Formation (Kitto, 1990). The Renison carbonate replacement and vein style mineralisation occurs on the north-east limb of a broad south-east plunging anticline which in turn constitutes a horst block bounded to the north-east by the Federal-Bassett Fault (FBF). The dominant brittle deformation structures at Renison include the FBF together with the Western Boundary Faults (WBF) that occur west of and parallel to the FBF. A series of east-west trending Transverse Faults connect the FBF and WBF.

Cassiterite mineralisation at Renison was structurally controlled with mineralising fluids being focussed along fault planes and especially along the FBF. A detailed study of kinematic indicators was carried out on the mineralised faults to determine the stress field during mineralisation. Four phases of brittle deformation (Devonian to the Tertiary) were determined based on style and relative ages of fault striations.

First generation fibre growths have a mineralogy consistent with the host veins suggesting contemporaneous mineralisation. Second, and subsequent generations of striations are dominantly calcite or quartz fibre veins and striated pyritic polished surfaces occur on fault planes where fibre veins are absent. No striations pre-dating the mineralisation were found.The initial brittle deformation, (BD1), at Renison produced normal-dextral orientations of striations, grooves and undulations on fault surfaces (Fig. 1a). Modelled stress tensors predict a near vertical maximum compressive stress, $\sigma1$, and near horizontal minimum compressive stress, $\sigma3$, trending 84° (Fig. 1b). This stress regime is unique to Renison and initiated the FBF along a pre-existing monocline. The WBF and Transverse Faults were also produced by the BD1 event. Normal displacements of a few hundred metres on the FBF occurred during BD1 and the early stages of mineralisation were coeval to this event. A regional Devonian dextral wrench, (BD2), reactivated the earlier brittle deformation structures due to a near horizontal maximum compressive stress, $\sigma1$, trending 172° and a near vertical intermediate compressive stress,$\sigma2$ (Fig. c,d). BD2 opened a dilational jog on the FBF in which the Federal Orebody continued to form. A post-Devonian reverse-sinistral displacement, (BD3), with less than a few tens of metres movement overprinted the earlier fault striations. Modelled stress tensors indicate that the maximum compressive stress, $\sigma1$, was near horizontal trending 88° and the minimum compressive stress, $\sigma3$, was vertical (Fig. e,f). The BD3 event has not been previously reported. Minor Tertiary normal-sinistral reactivation, (BD4), is the last recognised brittle deformation at Renison and formed in a near vertical maximum compressive stress, $\sigma1$, and horizontal minimum compressive stress, $\sigma3$, trending 158° (Fig. g,h).

The syn-Devonian normal faulting at Renison contrasts with the compressional structures related to the Taberraberran Orogeny throughout the rest of western Tasmania. The horst structure is interpreted here as a result of modification of a pre-Devonian monocline by forceful emplacement of the Pine Hill Granite. The radial stress field added to the regional stress field, as reflected by BD2, during granite emplacement and caused the interchange of the σ_1 and σ_2 directions. This interchange initiated the normal fault movement on the FBF along a pre-existing monocline immediately above the granite. The local uplift led to N-S stretching of the uplifted block and this stretching produced the extensional Transverse Faults. The zone of largest uplift on the FBF was apparantly dilational and provided the major focus for granite related mineralising fluids and these fluids also focused along the extensional low angle Transverse Faults. During the later part of the mineralising event the granite-related stress field decayed and movement on the FBF reverted to dextral wrench movement consistent with the regional pattern. Mineralisation did not continue during the minor post-Devonian reactivations associated with the BD3 and BD4 brittle deformations.

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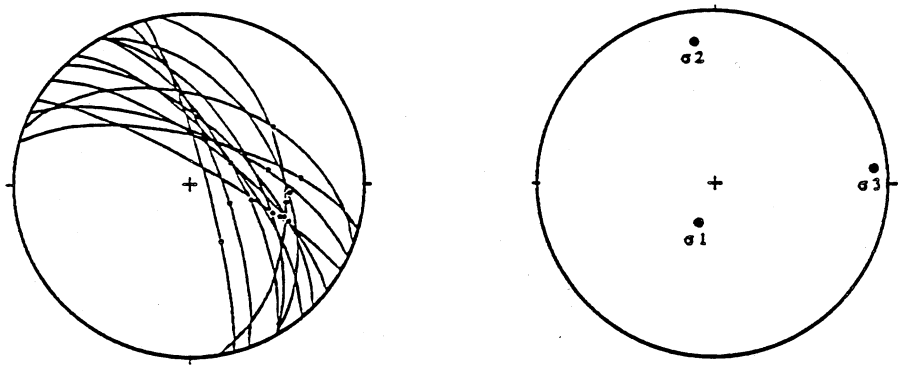
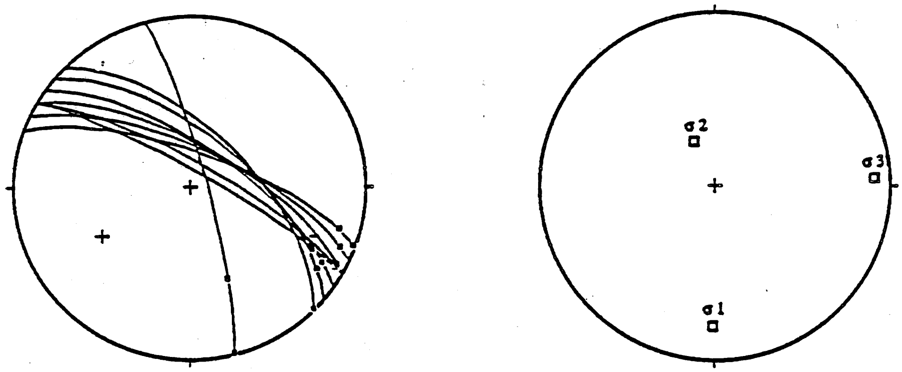


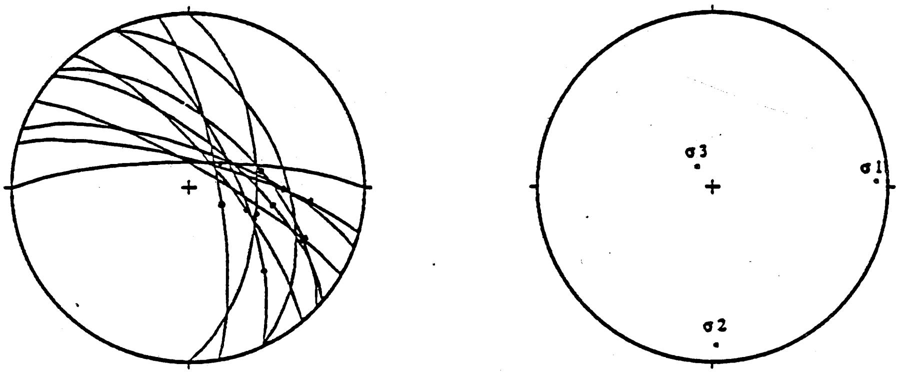
(a) BD1 - normal-dextral fault striatins for FBF.

(b) Principal compressive stress directions for BD1.



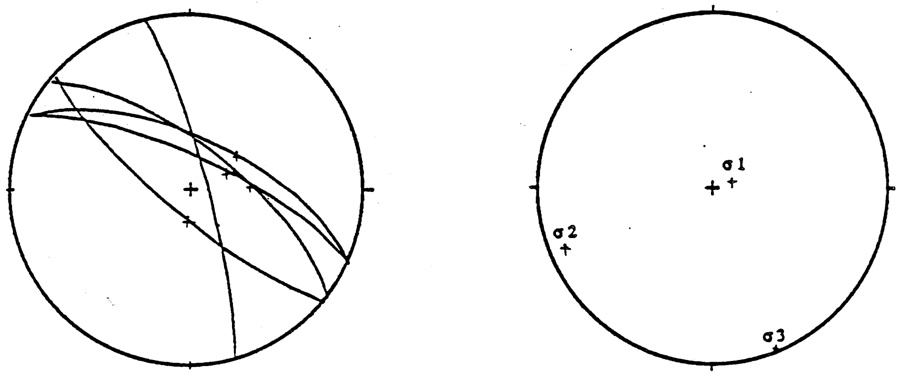
(c) BD2 - dextral wrench fault striations for FBF.

(d) Principal compressive stress directions for BD2.



(e) BD3 - reverse sinistral fault striations for FBF.

(f) Principal compressive stress directions for BD3.



(g) BD4 - normal sinistral fault striations for FBF.

(h) Principal compressive stress directions for BD4.

FIGURE 1 Lower hemisphere equal area projections illustrating the brittle deformation history for the Renison Tin Mine, western Tasmania.

ISOTOPIC STUDY OF THE SOURCE OF FLUIDS DURING TIN-TUNGSTEN MINERALIZATION

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The source and timing of granite-driven tin-tungsten mineralizing hydrothermal solutions is being investigated with stable and radiogenic isotopes.

The test case for the first phase of work is the intensively studied Mole Granite, north west of Glen Innes, NSW. There are three major, and at least two minor, stages of mineralization; their sequence established by field relationships.

It is difficult to precisely determine the emplacement age of the granite, because oxygen isotope data indicate a continued water-rock interaction as the granite cooled. The Rb/Sr biotite ages reflect the cessation of this activity, and even whole rock isochron data appear to correlate to some extent with the middle stages of mineralization. At this stage in the work, the emplacement age is within the range 242-246Ma.

The first, and most important stage of mineralization comprises cassiterite bearing sheeted veins, which follow emplacement almost immediately. Oxygen isotope data confirm that fluids, and therefore also the metals, are sourced from the granite, and deposited at a median 340°C (fluid inclusion data). Two minor stages follow: a complex pegmatite and a cross-cutting Mo-Bi stockwork, both possessing strongly magmatic stable isotopic character.

A wolframite-bearing quartz-topaz greisen ('silexite') is the most important middle stage. Wolframite occurs both in vughs and as fine to medium grained disseminated material. Both forms are in isotopic equilibrium with host quartz, and consistent with the fluid inclusion data (median 380°C). Fluids are sourced from the granite, and the phase of mineralization follows a thermal pulse initiated by microgranite intrusion. The age of this phase of mineralization is well constrained at 242.7±0.3Ma, by a Rb/Sr isochron.

The final stage of mineralization occupies fracture controlled veins, with distinctive sericite-chlorite wall-rock alteration. Quartz-chlorite-cassiterite vein mineralization (median 300°C) is followed by wolframite, and finally a galena-sphalerite-quartz, with secondary fluid inclusions down to 60°C. Oxygen isotope data are vey variable, and suggest that hydrothermal solutions in this stage are meteoric-water sourced but have undergone various degrees of fluid-rock interaction with the granite. Source of tin, and probably also the other metals, is most likely the result of this interaction. Rb/Sr data indicate that this final stage continued until at least 227Ma.

CONTROLS OF BRINE CHEMISTRY ON THE SPECTRUM OF PROTEROZOIC SEDIMENT HOSTED BASE METAL DEPOSITS

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The spectrum of sediment hosted base metal mineralisation in the Proterozoic basins of Australia includes four major ore types:

1) McArthur River type Pb-Zn-Ag mineralisation associated with pyritic shales (e.g. McArthur River; Hilton and Mt Isa Pb-Zn, Williams 1980).
2) Broken Hill type Pb-Zn-Ag mineralisation associated with silicate, carbonate and oxide facies banded iron formations (e.g. Broken Hill, Stanton 1972 and Pegmont, Stanton and Vaughan 1979)
3) Stratiform and/or breccia hosted copper mineralisation within a mixed oxidised/reduced sedimentary package (e.g. Redbank, Wall and Heinrich, 1990, and Mt Kelly, Williams, 1980).
4) Stratiform and stratabound copper-gold mineralisation associated with magnetite-rich iron stones and oxide facies BIF (e.g. Starra and Osborne deposits, Davidson et al., 1989).

All four styles of mineralisation develop within intra-continental or continental margin sedimentary basins which formed during major phases of crustal extension. The ore fluids are most likely to be high salinity sedimentary brines which have been expelled toward the margins of the rift basin during sedimentary compaction (e.g. Davidson, 1966; Gustalfson and Williams, 1981 and Large, 1983) or by episodic release along synsedimentary faults tapping overpressured zones (Sawkins, 1984). It is proposed here that temperature and fluid oxidation (fO_2) are the major chemical factors controlling which of the four styles of mineralisation will develop in a given sedimentary basin. Based on our understanding of metal transport in chloride-rich hydrothermal fluids (Helgeson, 1969; Large, 1977; Lydon, 1983; Huston and Large 1989), four different scenarios are possible depending on the fO_2 of the ore fluid and the fO_2 of the basin waters (Fig. 1).

Scenario 1 : Reduced/Reduced - a hot reduced brine entering a reduced marine basin will deposit lead-zinc mineralisation within a pyrite-rich sedimentary environment. This situation is applicable to the Mt Isa type Pb-Zn-Ag deposits and the Canadian Selwyn basin "Sedex" deposits (Carne and Cathro, 1982). These sedimentary basins characterised by reduced diagenetic environments are commonly not associated with significant volcanic or magmatic activity and the ore fluid is at the low end of the temperature spectrum (150 to 250°C) with a high concentration of H_2S. Under these conditions lead and zinc dominate the system, with negligible or minor copper in the footwall adjacent to the feeder fault. The ores commonly show a temperature related zonation of lead concentration adjacent to the feeder, passing to more zinc ± barium-rich ores in the distal location. Based on sulphur isotope evidence, there are at least two sources of sulphur; a) hydrothermal H_2S introduced with the metals, and b) sedimentary H_2S formed from reduction of marine sulphate (e.g. Smith & Croxford, 1973).

Scenario 2 : Reduced/Oxidised - a hot reduced brine entering a relatively oxidised marine basin will deposit lead-zinc mineralisation within a pyrite-poor but Fe-silicate or oxide-rich sedimentary environment. This situation is equivalent to the pre-metamorphic form of the Broken Hill or Pegmont deposits (Stanton and Vaughan, 1979). The footwall sedimentary package may contain significant volcanic components, however the ore fluid is again probably at the lower end of the temperature spectrum (150 - 250°C) and there is a general deficiency of H_2S in the fluid. Consequently the ores are copper-poor and show the reverse zonation to scenario 1, i.e. Zn-rich adjacent to the source feeder zone, and more Pb-rich toward the basin centre away from the feeder changing laterally to BIF's. An extensive Mn Halo is developed around the ore deposit within the host stratigraphy. Compared to scenario 1, there is only one source of sulphur; H_2S from the hydrothermal fluid.

Scenario 3 : Oxidised/Reduced - an oxidised brine entering a reduced marine basin or a reduced package of rocks will deposit copper and related elements such as silver, cobalt or uranium. This situation conforms to the typical stratiform copper environment (Maynard, 1983). Under these conditions copper may be transported at low temperatures (<200°C) in an H_2S deficient fluid. Precipitation of copper may take place below the basin floor at a sedimentary redox barrier (e.g. Redbank breccia pipes - Wall and Heinrich, 1990) or on the basin floor by sedimentary processes. There is commonly a zonation of copper minerals; chalcocite → bornite → chalcopyrite → pyrite in the direction of fluid flow (Maynard, 1983). Sulphur isotope data indicate that bacterial sulphate reduction on the basin floor is probably the major source of the sulphur. Although there are a number of small stratiform and breccia hosted copper deposits in the Australian Proterozoic, this scenario is less productive than the other three.

Scenario 4 : Oxidised/Oxidised - a hot oxidised brine entering an oxidised marine basin or oxidised sedimentary package will deposit copper and gold mineralisation in a magnetite-rich host such as an ironstone or magnetite BIF (Fig. 4). The Starra and Osborne Cu-Au deposits in the Mt Isa Eastern Succession (Davidson et al., 1989) are good examples of this scenario. Also the syn-metamorphic Tennant Creek Cu-Au (± U, W, Bi and

REES) deposits (Large, 1975 and Wedekind et al., 1989) form under a similar chemical regime, but are obviously epigenetic rather than syngenetic or syn-diagenetic deposits. Temperatures in excess of 300°C are generally required to transport significant amounts of copper and gold together as chloride complexes (Huston and Large, 1989) and therefore normal low temperature sedimentary brines are unlikely to be the ore fluid. Sedimentary brines heated by granitic intrusions or volcanic activity may suffice, however a magmatic input to the fluid by oxidised K-rich granites has been suggested in some cases (e.g. Wedekind et al., 1989). Lead and zinc are completely lacking in these systems owing to the high temperature of deposition (300 - 450°C) and the low levels of H_2S in the fluid and the sedimentary package. Some deposits show a zonation from gold-rich close to the feeder to copper-rich in a distal position. Only one source of sulphur is implicated by the S-isotope data: hydrothermal H_2S introduced with the metals.

Discussion and Summary - The four scenarios outlined above cover the spectrum of major types of base metal deposits hosted within sedimentary basins in the Australian Proterozoic. Interpreted fields of deposition in fO_2-T space for the four ore types indicate that the stratiform Cu-Ag type and the stratabound Cu-Au-magnetite type occupy the extreme ends of the temperature spectrum. In between there is considerable overlap between the fields of the Mt Isa and Broken Hill Pb-Zn-Ag types and between Starra Cu-Au and Pegmont BIF Pb-Zn indicating that intermediate styles are likely.

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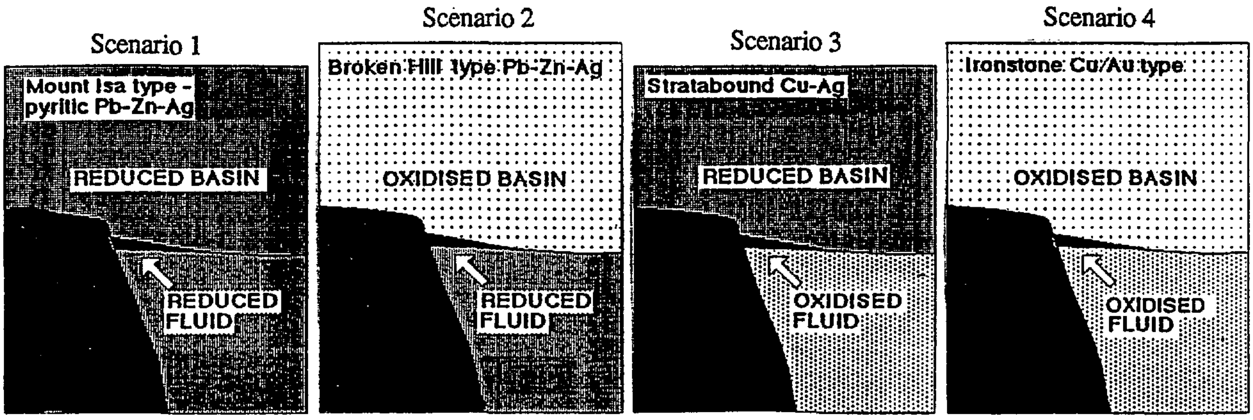

Figure 1: Schematic representation of redox environments for the four major types of Proterozoic sediment-hosted base metal ores.

METAL ZONING AND FLUIDS IN THE ELURA OREBODIES, N. S. W.: IMPLICATIONS FOR FORMATION OF SYNTECTONIC MASSIVE SULPHIDE OREBODIES

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The Elura deposit occurs in multiply deformed, lower greenschist facies metamorphosed distal turbidites in the Cobar Trough, N. S. W. At least seven massive sulphide Pb-Zn-Ag orebodies formed syntectonically in doubly-plunging fold hinges within a subvertical NW-trending D2 shear zone. Sulphides in the orebodies show the effects of at least two overprinting deformation events.

Structural studies have demonstrated that each massive sulphide orebody formed as a separate pod. Later deformation generally has partitioned around the orebodies, which were mantled by silicified envelopes. Visible carbonate and sulphide alteration define a 100-150 metre wide subvertical envelope that is at least 1.5 kms in strike length, and over 700 metres in vertical extent. Alteration inecreases in intensity with depth, and visible haloes die out rapidly above orebodies. Between individual pods minor sulphide veining and limited alteration is developed. NNE-trending D4 shear zones cause minor offset of the pre-existing mineralised structure, with replacement of the pre-existing alteration mineralogy with a chlorite-dominated assemblage.

Primary metal zoning patterns in Ag, Pb, Zn, As and Cu are preserved in the main orebodies. Modification is due to D2 effects rather than D3 deformation. With depth there is an increase in Zn, Pb and Cu contents, and a decrease in Ag and As. This trend is visible in all seven orebodies, and is provisionally interpreted as a function of physico-chemical gradients which probably controlled ore deposition.

Small Ag (and Au)-rich zones are present in the caps of the new northern lodes. These zones lie several hundred metres below the level of supergene development, and are interpreted as primary features. The Ag-rich caps in the main orebodies are characterised by development of a secondary sulphide assemblage and localised metal redistribution with secondary concentration of Pb, and locally Ag, Cu, Au, As, Sb, Hg, Sn, W and Ba, within true supergene layers at the base of oxidation (Schmidt, 1989). However, by analogy with the deeper pods, these enriched zones are considered to be primary features, *modified* by supergene processes.

Microstructural timing evidence indicates that the orebodies formed after lithification of the sediments, and during the first upright deformation event. Orebody compositions suggest that the fluids responsible for mineralisation were saline, whereas the presence of a carbonate alteration zone suggests fluids were also CO_2-bearing. However fluid sources remain problematic. There is no evidence of evaporites in the sedimentary sequence or of contemporaneous igneous activity in the area. It is considered likely that the fluids present during early metamorphism may have interacted with or be derived from relict basinal brines. This may explain the early syntectonic formation of Elura and other Cobar-style deposits. However, later shear zone-hosted base metal deposits occur, for example at the C.S.A. deposit, and further work is required to establish if these were derived from the same or similar fluid sources.

Brine Diapirism and Ore Genesis in the Salton Trough

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The Salton Trough of southern California is a sediment–filled continental rift formed by impingement of the East Pacific Rise spreading system on the North American continent. In deltaic and lacustrine sediment–smothered analogs of Guaymas Basin–type hydrothermal systems, pull–apart basins centered over spreading center fragments are sites of MORB–type dike intrusion at depths as shallow as 3 km. The resulting heat causes diapiric rise of deep basinal brines that accumulated within the last 5 Ma in the closed lacustrine environment of the northern Trough.

Within the well–studied Salton Sea system, the domal top of a brine diapir has been mapped out in three dimensions using fluid geochemical and temperature data from 50 commercial geothermal wells. The stable density–temperature structure of the young brine interface inhibits convective heat and mass transfer across the diapir interface, effectively separating deep convecting brine from shallow convecting low–salinity fluids.

The rising brine diapir has quantitatively stripped base metals from the volume of metasediments with which it has interacted. H_2S for ore genesis is generated by equilibrium reaction of the slowly rising Fe^{2+}–rich brine diapir with lacustrine anhydrite in the metasediments. Transient fluid mixing across the interface localizes incipient base metal oxide and sulfide ore genesis within transcending fractures.

The presently–exploited metalliferous brine volume is conservatively estimated at 7 km^3, and heat flow data imply that the brine is convectively upflowing at a rate of 0.02 km^3 per year. The exploited brine reservoir contains at least 13.2 Mt of Fe, 10.6 Mt of Mn, 3.3 Mt of Zn, 660,000 t of Pb, 66,000 t of Cu, 212 M oz of Ag, and 106,000 oz each of Au, Pt and Pd. If the currently unexplored brine volume at depths greater than 2 km is considered, the amount of metals stored in brine may be an order of magnitude higher.

In ancient lacustrine rift basins, similar intrusion–related brine diapirism may have served to localize ore mineralization along fluid interfaces. If sufficiently thick lakes or seas cover such brine diapirs, they may advect to the sediment–water interface to form "exhalative" stratiform ore deposits. Precise modeling of possible fluid flow scenarios will require more detailed knowledge of the temperature–density relations in complex Na–Ca–K–Cl brines at elevated temperatures.

PGE and Au transport in geothermal systems

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Studies of the Au and PGE contents of fluids, scales and drill cores from active geothermal systems of the western U.S. provide insight into the nature of complexes that transport PGE and Au in hydrothermal fluids. These studies also reveal important chemical linkages between gold deposition and sulfur isotopic zonation of sulfides deposited during fluid immiscibility (boiling).

Brines in the Salton Sea geothermal system (California, U.S.A.) are transporting up to 0.6 ppb Au and up to 2.0 ppb PGE at $\simeq 300^{\circ}C$ and pH 5–6. Scales deposited during flashing in the geothermal wellbores are enriched in Au, but not in PGE. These data imply that bisulfide complexes are the dominant aqueous gold complexes even in oxidized, saline brines at relatively low pH. The data also demonstrate that the brines transport PGE mainly as chloro complexes. The empirical data argue against significant chloro complexing of Au and against significant ammonia or bisulfide complexing of PGE under these conditions.

SHRIMP studies of sulfides deposited in boiling systems suggest that there may be a direct chemical link between fluid immiscibility (boiling), gold deposition (by destabilization of bisulfide complexes), and radical sulfur isotopic zonation of sulfide minerals in epithermal systems. Within a Au–enriched former boiling zone in the Valles Caldera (New Mexico, U.S.A.), pyrite crystals exhibit radical core–to–rim $\delta^{34}S$ zonations as high as 22 per mil. We propose a chemical linkage to boiling as follows. Oxidation of aqueous H_2S during boiling is promoted by the rapid loss of non–dipolar H_2 to the vapor phase relative to slower loss of dipolar H_2S. During oxidation of aqueous H_2S, ^{34}S is preferentially partitioned into SO_2 or SO_4. Therefore, residual aqueous H_2S can become progressively depleted in ^{34}S as boiling proceeds. If sulfide minerals grow during boiling, they may record this depletion trend in the form of intracrystalline sulfur isotopic zonation. The generality of these proposed relations should be tested by SHRIMP studies of sulfur isotopic systematics in other active and fossil epithermal gold deposits.

SULPHIDE DEFORMATION AND RETROGRADE GOLD MOBILISATION AT THE GREAT VICTORIA GOLD DEPOSIT, MARVEL LOCH, W.A.

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The Great Victoria gold deposit is unlike most known Archaean greenstone-hosted gold deposits in Western Australia. Gold mineralisation is associated with two large bodies of massive iron sulphides developed at the contact between metamorphosed greywackes and amphibolites. Stratigraphic, structural and geochemical evidence indicates that the deposit formed as a submarine exhalative sulphide lens, probably in the closing stages of tholeiitic, basaltic volcanism. It was buried and preserved by pyritic-carbonaceous shales and a thick sequence of distal turbidites before undergoing regional metamorphism. The distribution of gold in the massive sulphides, footwall rocks and associated siliceous meta-exhalites suggests an exhalative origin for the gold.

During amphibolite facies grade regional metamorphism (peak conditions of 545-590° C and 3-4 kb) the sulphide lens was folded, thickened and sheared into two steeply plunging pods. These are up to 60 m by 100 m in plan and the main pod extends down plunge for more than 580 m. At least three structural elements can be recognised in the ores including: a steep, NE dipping foliation, with a similar orientation to the schistosity in the overlying host rocks; a cross-cutting and N to NW dipping fracture direction containing pyrite veins; and a low angle, late-stage fracture set containing open-space fillings of calcite and crystalline pyrite. Deformation and recrystallisation of the massive sulphides during metamorphism also resulted in a sequence of superimposed ore fabrics reflecting:

1. Development of a tectonite fabric and retexturing of sulphides by prograde metamorphic mineral intergrowth;
2. A period of static recrystallisation, during which pyrite aggregates were reorganised into large porphyroblasts with outlines overprinting the earlier metamorphic fabric;
3. Late-stage, brittle deformation of pyrite and accompanying ductile deformation of pyrrhotite by dislocation-type mechanisms (dominatly kinking), concomitant with the formation of mini-shear zones through the massive sulphides; and
4. Very late fracturing of the sulphide mass, possibly related to late thermal contraction of erosional unloading of the deposit.

The present pyrrhotite-pyrite dominated mineralogy of the ores formed as a result of metamorphic recrystallisation and equilibration, followed by retrograde reequilibration along the pyrite-pyrrhotite buffer. Considerable fluid activity accompanied retrograde, brittle-ductile deformation of the sulphides. These fluids were CO_2-rich and relatively oxidising, as indicated by the development of carbonate-rich gangue assemblages in mini-shear zones and oxidation of pyrrhotite to magnetite. Textures also indicate that gold was locally mobilised or concentrated in the sulphides during the retrograde, brittle-ductile deformation event.

Conditions of retrograde alteration have been established from calcite-dolomite and arsenopyrite geothermometry, pyrite-pyrrhotite reequilibration compositions and intracrystalline deformation textures in the ores. These indicate a protracted retrograde history, with carbonate alteration commencing at 440° C and brittle ductile deformation of the sulphides and accompanying gold mobilisation/deposition at temperatures between 200° and 300° C.

INVESTIGATING ORE FLUIDS BY LASER RAMAN MICROPROBE ANALYSIS OF FLUID INCLUSIONS

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Fluid inclusions provide direct information on the composition of the fluids which form an ore deposit. However, the fluid composition is seldom fully constrained by microthermometry because the observed phase changes cannot be interpreted quantitatively due to the lack of appropriate thermodynamic data. This problem can be overcome by using the laser Raman microprobe which allows the V - X properties of the fluid to be directly deduced mainly from room temperature vibrational spectra of the solid, liquid and gaseous phases present within the fluid inclusions. The BMR's Microdil 28 laser Raman microprobe provides rapid analyses with a spatial resolution of 1µm.

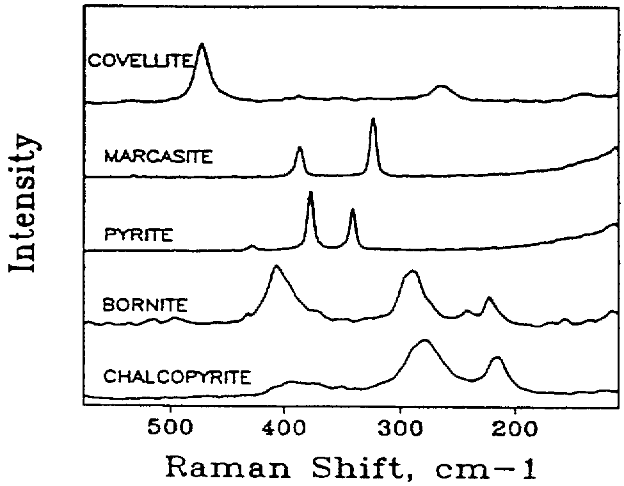

Fig. 1. Laser Raman microprobe spectra of some common sulfides.

The Raman microprobe can be used for the non-destructive identification of daughter minerals in fluid inclusions. Opaque daughter minerals which are particularly difficult to identify optically may be readily identified from their Raman spectra (see Fig. 1). Note also that the polymorphs, pyrite and marcasite can be easily distinguished by reference to their Raman spectra. Raman microprobe spectra have been successfully recorded from opaque daughter minerals (only a few microns in diameter) in fluid inclusions from the Tirad Porphyry Copper-Gold Prospect, NW Luzon, Philippines (Trudu et al., 1990). Chalcopyrite was identified by comparison with the spectra shown in Fig. 1.

The O-H stretching region (see Fig. 2) in Raman spectra of aqueous solutions is sensitive to changes in the salt concentration. This permits the determination of the total salinity in the aqueous phase (at room temperature) by calculating skewing parameters from the Raman spectra (cf. Mernagh and Wilde, 1989). The technique does not require detailed knowledge of the fluid composition and can be applied to most chloride solutions which commonly occur in fluid inclusions. Furthermore, the Raman microprobe can be used to determine the salinity of vapour-rich and other inclusions which because of their small size are difficult (at best) to analyze by conventional microthermometry.

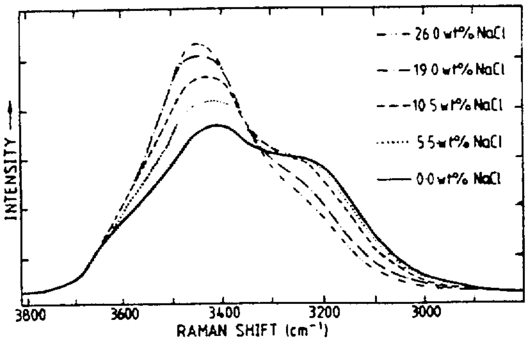

Fig. 2. Effect of NaCl concentration on the intensity and profile of the Raman O-H stretching bands of water.

Carbon dioxide, methane and nitrogen have been identified by laser Raman microprobe analysis of the vapour phases in fluid inclusions from the unconformity-related uranium deposits of Koongarra, Nabarlek and Jabiluka, Northern Territory, Australia (Wild et al., 1989). Four distinct gas mixtures were identified. The vapour rich inclusions could be divided into those containing over 95 mole % CO_2 with minor amounts of CH_4 and N_2, those containing only a CH_4 - N_2 gas mixture and those with only a CO_2 - N_2 gas mixture. No gases were detected in the aqueous inclusions containing only 5 vol. % vapour. The frequencies of the Raman bands of CO_2 were used to determine the densities of the vapour phases which ranged from 0.11 to 1.18 g/cm^3 at room temperature. The Raman band of methane is also sensitive to pressure and indicated that the methane rich inclusions had a mean partial pressure of 7.2 MPa at room temperature. The fluid was found to be hypersaline and calcium-rich (typically 35 equiv. wt % $CaCl_2$). Some of the saturated inclusions contain as many as eleven solid phases and anhydrite, calcite, dolomite and hematite were identified by Raman microprobe analysis.

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GEOLOGICAL AND GEOCHEMICAL CONTROLS ON THE SILVER CONTENT (FINENESS) OF GOLD IN GOLD-SILVER DEPOSITS.

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A compilation of microprobe fineness data and a re-evaluation of bullion production fineness data suggest that the major deposit classes are characterised by the overall average or range of deposit averages and total range of gold fineness values. The Archaean (including Witwatersrand), Slate Belt and Plutonic classes are characterized by high and consistent average fineness and narrow fineness range. Solubility calculations indicate that in all these environments, gold and silver form the same aqueous species ($AgCl_2^-$ dominating for silver and $Au(HS)_2^-$ for gold). In all the environments the fluids transport an equal amount of gold and silver in the form of their bisulphide complexes. Therefore the observed gold-fineness values can not be explained only by the transporting mechanism. Low silver in the ores and high gold-fineness values observed in the Archaean, Plutonic and Slate Belt environments can be attributed to sulphidation as the dominant mechanism of ore deposition in these environments. Sulphidation of wall rocks destabilises only the bisulphide complexes of gold and silver. In contrast Epithermal, Volcanogenic and Porphyry environments are characterized by a diversity of ore-depositing mechanisms (cooling, boiling, mixing) which act alone or in combination with each other and destabilise chloro and bisulphide complexes of gold and silver. The high silver concentration in the ores, low fineness values and large variation in the fineness values in these environments can be attributed to the complexities in the ore-depositing mechanisms.

IS THE MARY KATHLEEN FOLD BELT (NW QUEENSLAND) A GIANT MID-CRUSTAL FLUID FLOW SYSTEM ?

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There is a general lack of consensus on the scale of fluid/rock interaction in the mid crust, a topic of considerable interest to those attempting to identify metal source regions for a range of hydrothermal ore systems. Mass balance requirements for metal and other components in mesothermal orebodies (e.g. Western Australian and Victorian goldfields, Mount Isa copper) are extremely large. Based on the solubility of a range of components involved in mass transfer accompanying ore genesis, estimated fluid volumes required are similarly large. Despite this, there is uncertainty whether such giant hydrothermal systems are common at mid-crustal levels, or whether such systems are as "rare as hens' teeth", the "hens' teeth" being the large orebodies and their local environs.

A continuing aim of our research is thus to document and understand an extremely well exposed metamorphic hydrothermal system, the Mary Kathleen Fold Belt (Oliver & Wall 1987). This is a suite of heterogeneously altered amphibolite-facies metasediments, dominantly calc-silicates of the Proterozoic Corella Formation, in the central Mount Isa Inlier. Inspection of the BMR Mary Kathleen and Marraba 1:100 000 sheets reveals hundreds of small-scale copper, uranium, and limestone prospects, quarries, and mines. The 'limestone' prospects in the Corella Formation, and most of the copper prospects, are calcite-dominated vein-, pod-, and shear-related systems, which represent syn-peak to early-retrograde metamorphic fluid pathways. The few uranium prospects known to us are also hosted in syn-metamorphic shear zones. Associated with the calcite bodies are extensive zones of albitization, affecting metasediments, metavolcanics, metadolerites, and metagranites. There is a strong structural control on the distribution of these fossil fluid pathways, indicating structural control of fluid flow under amphibolite facies conditions (Oliver et al. 1990a). Although the modest Mary Kathleen U-REE deposit is the largest metamorphic orebody recognised in this suite of rocks, the abundance of the small calcite-chalcopyrite occurences, various vein/fold/foliation crosscutting relations, and detailed petrography all attest to intense, focussed syn-metamorphic fluid flow.

The ultimate aim of this research is to test whether the Mary Kathleen Fold Belt is a *large-scale* fluid migration system in mid-crustal rocks which are not particularly noted for large orebodies. Both stable isotopic and whole-rock geochemical studies are being utilized, in conjunction with petrological and structural studies. Preliminary stable isotopic results (Oliver & Wall 1987) indicate at least two distinct major isotopic reservoirs within the Fold Belt. The first is the reservoir of carbonate dominated rocks comprising the well bedded scapolitic Corella Formation rocks, which have $\delta^{18}O$ and $\delta^{13}C$ values characteristic of Protoerozoic carbonate-bearing rocks that have not been affected by pervasive infiltration of isotopically distinct fluids ($\delta^{18}O$ ~20‰ and $\delta^{13}C$ ~0‰, Valley, 1986). Secondly, there is the reservoir of oxygen contained within the abundant metadolerites ($\delta^{18}O$ ~6‰). The calcite pods and veins and related albitic alteration are distinct from either of these possible reservoirs, having intermediate $\delta^{18}O$ values (10 to 12‰) and depleted $\delta^{13}C$ values (-7 to -3‰).

Two simple hypotheses arise from this data (Figure): a) the calcite pods are derived by mixing of the two distinct isotopic reservoirs of the calc-silicates and the metadolerites (although no very light $\delta^{13}C$ source has been identified), or b) the calcite pods are derived from an external (fluid) source with $\delta^{18}O$ and $\delta^{13}C$ appropriate to be in equilibrium with the measured isotopic values of the calcite bodies (fluid $\delta^{18}O$ ~11‰ and $\delta^{13}C$ ~3‰ at 550°C). The former hypothesis implies cyclic fluid migration and progressive fluid re-equilibration at 100m-scales between calc-silicates and metadolerites, whereas the latter implies fluid migration at greater than kilometre scales to account for the unusual isotopic signature of the calcite. Geochemically, the alteration envelopes around the calcite bodies reflect infiltration of saline fluids (Oliver et al. 1990b), derived in part from dissolution of halite in the Corella Formation during metamorphism. An apparent conflict thus arises by comparison of the isotopic signature of the calcite (? external reservoir) and the albitic alteration around the calcite (? locally derived NaCl).

One of the methods being employed to resolve this problem is to test the relationship between the isotopic composition of the calcite pods, and the distribution of the local (100m) scale isotopic reservoirs. That is, if the isotopic composition of the calcite bodies represents local (100m) exchange between the dolerite and carbonate reservoirs, then the calcite isotopic values should represent averaged values of the local 100m-scale distribution of the dolerites and calc-silicates, or at least some other systematic relationship. If no such relationship is evident, then we will further assess the possibility of ≥ km-scale isotopic mixing, or other possible infiltration and disequilibrium isotopic models that could explain the data.

Our initial data suggest that 100m-scale equilibrium controls on the isotopic composition of these fluid pathways are not apparent. Extensive and regional testing is underway, in conjunction with modelling possible isotopic and chemical disequilibrium effects, in order to confirm our present model of very large scale fluid flow. This model involves isotopic and geochemical redistribution of components at 1- to 5-km scales, sufficient for example to satisfy the gigantic mass balance requirements the Mount Isa copper orebody.

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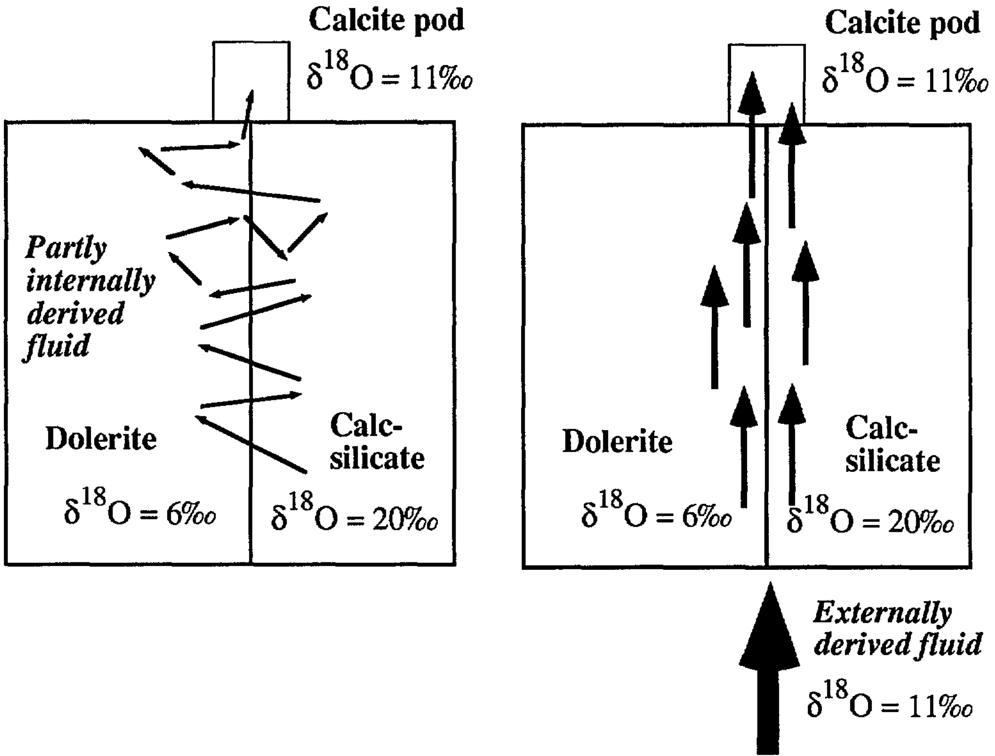

Figure: Two possible mechanisms for generating calcite vein and pod systems of observed isotopic composition

FLUID FLOW IN DILATANT SHEAR ZONES

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The initiation and evolution of dilatant shear zones are considered to be important to understanding the phenomenon of fluid focussing. We aim to understand why and under what conditions enormous volumes of fluid flow through a localised region such as a shear zone rather than in a homogeneous or more diffuse manner through the bulk of the deforming rock mass.

With this aim, Ord (1990) used the finite difference code FLAC (Fast Lagrangian Analysis of Continua, Cundall and Board, 1988) to examine the distribution of regions of high and low mean normal stress (or pressure) and of maximum dilation around deforming, quasi-periodic shear zones. In the absence of any fluid flow/mechanical coupling within the code, fluid flow was assumed to be favoured by large pressure gradients and to be enabled by regions of dilation.

Full fluid flow/mechanical coupling was incorporated in FLAC in 1989 (ITASCA, 1989). Ord (1991) was then able to test the earlier predictions on the behaviour of fluid flow around patterned shear zones under a variety of crustal conditions. Fluid flow was observed to be focussed into and along these shear zones for a hydrostatic pore pressure gradient, but to be upwards and unperturbed by the shear zones for a lithostatic pore pressure gradient. Also, under certain conditions of fluid flow rate and deformation rate, the presence of a fluid appears to have a stabilising effect, and the material continues to deform homogeneously. These results demonstrated that the simplified principles of effective stress do not sufficiently describe the possible complex inter-relationships. This is true despite the simple assumptions of homogeneous and constant material properties throughout deformation.

We present here some more geologically realistic situations in which the porosity and the permeability change with change in volume strain in the material during deformation and therefore with the formation of shear bands.

'Movies' of the changing fluid flow patterns and of the deforming numerical grid provide easy visualisation of the results and lead to greater understanding of the association between deformation and fluid flow in the Earth's crust.

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THE PB-ZN PINNACLES DEPOSIT, BROKEN HILL.

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The Pb-Zn Pinnacles deposit, 15km southwest of Broken Hill, NSW, is the second largest deposit in the Broken Hill area (approximately 400 000 tonnes) and the only working mine other than the Broken Hill mine itself. The stratabound massive sulphide ores form part of a mine sequence which includes garnet-rich rocks, quartz-gahnite rocks, quartz-magnetite rocks and garnetiferous pelitic schists. The ores can be subdivided into a main Pb lode and several subsidiary Zn lodes in both the footwall and hanging wall. The entire sequence has been subject to three phases of deformation associated with two prograde and one retrogressive metamorphic events.

Despite being two orders of magnitude smaller, there are many similarities between the Pinnacles and Broken Hill deposits and the former has been described as a Broken Hill-type deposit. It is important to relate the Pinnacles ores to those at Broken Hill, both for metallogenic exploration and for the implications to genetic models relating to this type of deposit. This poster explores that relationship and considers the timing of mineralisation at the Pinnacles deposit with respect to its larger cousin at Broken Hill.

THE MOUNT ISA AG-PB-ZN OREBODIES STRATIFORM REPLACEMENT LODES IN A ZONED HYDROTHERMAL ALTERATION SYSTEM.

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Mount Isa Mines Limited - Mount Isa

A range of interpretations of the origin of the Mount Isa Cu-Pb-Zn deposit have been put forward since the 1930's. Initially, all ore was ascribed to a telemagmatic hydrothermal process eg Blanchard and Hall, 1937. In the 1950's, a syngenetic origin for at least the Pb-Zn lodes began to be advanced. During the 60's and 70's a syngenetic origin for both Pb-Zn and Cu was generally accepted. A major research programme concentrating on the copper orebodies began in 1975 and evidence for a late-stage origin for them was presented. At that stage a syngenetic or early diagenetic origin for Pb-Zn was assumed. A re-examination of the Pb-Zn orebodies was prompted by the work of Neudert 1984, who presented cogent arguments against Pb-Zn ore being syngenetic.

Features of the Pb-Zn ores, at all scales, indicate that they are replacive, and closely linked in a zoned system with the copper orebodies. Rather than being controlled by residual sulphate in the sediments, (Neudert 1984), galena, sphalerite and pyrrhotite are interpreted to mostly replace metasomatic dolomite, as well as phyllosilicates and potash felspar. A zonal relationship of massive silica-dolomite alteration through a phyllosilicate/albite zone with elevated pyrrhotite to galena to sphalerite to pyrite can be shown both on cross sections, and a well-studied, stratigraphically constrained, longitudinal section in the hanging wall of No 7 orebody.

One of the obvious features of the Pb-Zn lodes are the`galena breccia beds,' cited as examples of solid state remobilization of galena-rich stratigraphy. On detailed examination, these layers are shown to be generally transgressive on at least one margin and the breccia texture to result from progressive digestion of a intrafolially folded and microfaulted sequence firstly by metasomatic dolomite, and subsequently by sulphides.A greater component of dilation than observed in the copper orebodies is shown by the `splitting' of beds and the development of fibrous bedded veins.

A textural continuity exists between these `galena breccia beds' and layer-parallel galena and sphalerite, where carbonate-replacement textures can be shown by the progressive destruction of laminations and extreme variations in the density of sulphide replacement either side of fractures which rotate the S_3 cleavage. In many areas finely laminated sphalerite is terminated by east-dipping veins developed synchonously with D_3 folding. The sulphides in the veins show the same textural relationships and timing as those in layer-parallel zones but grain sizes are controlled by the grain size of the precursor carbonate.

Fine-grained layer-parallel pyrite forms a `halo' to the ore system. Examination of this pyrite, often called `sedimentary pyrite', at high magnifications shows it to overprint carbonaceous S_3 cleavage seams in the same manner as bedding-parallel seams.

It thus appears to be part of the entire late-stage mineralizing system.

The Mount Isa Fold is a major structural feature which controls the disposition of the lead-zinc orebodies. Orebodies terminate quite abruptly within 30m of the anticlinal and synclinal hinges indicating that dilation through antithetic shear has been a gross control on orebody formation.

Similarities in textural relationships and timing criteria for mineralization between Pb-Zn and copper orebodies indicate that they are zoned parts of a single hydrothermal system rather that the Pb-Zn being a much earlier deposit which was later `remobilized'.

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METAMORPHIC FLUIDS AND GOLD

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Metamorphic fluids have been widely implicated in the transport of gold in Archaean greenstone, shale-greywacke and Witwatersrand gold deposits. Metamorphic fluids are here referred to as those fluids released by the devolatilization of crustal rocks undergoing regional metamorphism. In favour of such a metamorphic origin for the auriferous fluids are the broad synchroneity between metamorphism, deformation and gold introduction, the low salinity nature of the fluid, and the lack of significant vertical zonation in many deposits. Against a metamorphic origin for the fluid has been the detailed timing of mineralization relative to the metamorphic peak, and the isotopic signature of minor components of the fluid system.

The credibility of metamorphic fluids has gained substantial support recently from calculations of devolatilization processes during greenschist - amphibolite facies metamorphism that show large fluid volumes of appropriate composition must be evolved from many mafic piles (Powell et al., 1991). Critical to this argument are sequences comprising chlorite + calcite + quartz (very common in the greenschist facies) that can undergo devolatilization to yield amphibole + plagioclase +/- dolomite AND a fluid of low salinity rich in H_2O and CO_2. This reaction is not particularly dependent on Fe/Mg, and for a given composition and pressure most of the fluid is evolved over a very narrow temperature interval while the assemblage is tied to the invariant point involving the above phases. For 3 kbars, fluid release occurs around 460-480C, for 4 kbars it is closer to 500C: the evolved fluid has $X(CO_2) = 0.3$ and 0.2, respectively. That such a fluid so closely matches those recorded from many gold deposits can be no coincidence: the required assemblage is very common worldwide so it is not unexpected that such fluids should occur throughout many provinces and time intervals.

It follows from the above discussion that other lithologies with abundant chlorite, calcite and quartz might also produce similar fluids, and a possible candidate here is a graywacke pile. However, ordinary ultramafic and pelitic assemblages may not undergo the same metamorphic transformations as suggested for the mafic assemblages, so will produce fluids of different compositions over different temperature intervals. Through all this, the key to transporting gold is to have these fluids with sufficient reduced sulphur in solution and this probably requires having pyrite prior to peak metamorphism. The issue of having metamorphic fluids from depth rising into retrograde regimes appears a non-problem (Powell et al., 1991) as "deeper later" piles are easily explained by minor erosion.

The fate of metamorphic fluids after they form mesothermal gold deposits is rarely pursued, but intuitively they should migrate to higher levels in the crust and mix with nearer-surface waters. In places, both their timing and composition would make them prime candidates for a major role in forming many "epithermal" deposits (e.g. sediment-hosted examples, and those unrelated to volcanic activity): unfortunately this scenario is rarely developed by those working on such deposits. To illustrate the possible problem: most active and past epithermal systems reflect parts of the crust with high geothermal gradients. At relatively shallow depth beneath these epithermal systems, metamorphic reactions must be occurring given anywhere near "normal" crustal lithologies. The fluid products of these reactions should migrate upwards and eventually come into the zone of epithermal fluid activity and gold deposit formation: it should be of concern that such mixing has not been noted (e.g. in isotopes) nor even discussed in the extensive work on these systems.

A new twist to the metamorphic model postulates gold migrating from the mantle in lamprophyric melts, and the lamprophyre "devolatilizing" to release gold into the metamorphic hydrothermal system (Rock et al., 1989, fig. 4). Accepting for the moment the enthusiastic arguments that the lamprophyres represent gold-rich magmas (Rock and Groves, 1988 and several earlier papers; although noting that contrary ideas are held by other workers, Wyman and Kerrich, 1989), the lamprophyre hypothesis is still incompatible with the "metamorphic model" being discussed here (see Phillips and Groves (1983) and Powell et al. (1991)). For the lamprophyre ideas to be evaluated there needs to be confirmation of their primary igneous gold values, and outline of the transfer process of gold from the lamprophyre to the metamorphic fluid system. The metamorphic model being discussed here does not rely on lamprophyres as a significant source of gold, nor does it rely on lamprophyres to generate gold bearing fluid: the lamprophyre - gold association is seen to be one reflecting common structural control and thermal regime, rather than gold or fluid source.

Acknowledgements

Discussion with Russell Myers, Roger Powell and Thomas Will are greatly appreciated.

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A BILLION YEAR HISTORY IN BUSHVELD GRANITES AT THE ZAAIPLAATS TIN MINE - Pb AND Sr ISOTOPIC EVIDENCE FOR A LONG-LIVED HYDROTHERMAL FLUID SYSTEM.

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In magmatic-hydrothermal systems where widespread fracturing is not developed, the hydrothermal fluids occupy grain boundaries, microfractures and miarolitic cavities, where they interact with granite minerals to produce pervasive alteration. At the Zaaiplaats mine this has resulted in the development of zones of disseminated mineralization where cassiterite and other hydrothermal minerals occur as infilling components in miarolitic cavities within pervasively altered granite.

Ion microprobe study of zircons from a sample of mineralized Bobbejaankop Granite (unpublished data) suggests emplacement at 2.06 Ga, which is synchronous with other granites and mafic rocks of the Bushveld Complex. Ages for individual zircon grains in the sample range from the emplacement age to 1.08 Ga.

Measured $^{87}Sr/^{86}Sr$ isotope ratios for hydrothermal scheelite, fluorite and calcite from cavities in the Lease and Bobbejaankop Granites range from 0.71608 to 1.12627 and can be considered as initial ratios because of the very low Rb contents of these minerals. Initial Sr isotope ratios increase through the paragenetic sequence, usually in the order scheelite (early), green fluorite, purple fluorite, calcite (later). These extremely high initial ratios could be explained by mixing of magmatic fluid with an external fluid carrying highly radiogenic Sr, however large scale mixing is not compatible with fluid inclusion and stable isotope data (Pollard et al., in prep.). Instead, it is likely that these highly radiogenic hydrothermal minerals were precipitated from a magmatic fluid which evolved over an extended period of time, with an additional contribution of radiogenic Sr from Rb-rich minerals such as alkali feldspar.

Non-overlapping Pb-Pb isochrons for various rock units at Zaaiplaats consistently yield ages ca 1.1 Ga. The isochrons record an event where U and Pb ceased to be exchanged between rocks and minerals on the scale of sampling, but which did not result in homogenization and resetting of the U/Pb system at the mine scale. Instead, it appears that U/Pb systems of different granitic units evolved independently until exchange ceased at ca 1.1 Ga. This indicates a period of approximately 1 Ga of hydrothermal alteration and mineral precipitation at Zaaiplaats.

Pb-Pb ages of zircons from other Bushveld Granites display a similar range of ages to that observed at Zaaiplaats, suggesting that prolonged isotopic exchange affected most Bushveld Granites. It is likely that high levels of radioelements (K, U and Th) in Bushveld granites maintained high steady-state temperatures, preventing complete closure of U-Pb and Rb-Sr systems until uplift and erosion of the Kaapvaal Craton at ca 1.1 Ga.

PYRITE PARAGENESIS AND TRACE ELEMENT COMPOSITION AT THE PRINCE LYELL COPPER DEPOSIT, QUEENSTOWN, TASMANIA.

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The Prince Lyell copper deposit is a stratabound disseminated and stringer pyrite-chalcopyrite body. It is hosted by an overturned, steeply plunging sequence of quartz-sericite-chlorite altered volcanics within the mid-late Cambrian Mt Read Volcanics at Queenstown, Tasmania. The deposit is truncated at depth by the late Cambrian-early Ordovician Owen Conglomerate, along the Great Lyell fault. Current models of ore genesis invoke Cambrian volcanogenic replacement mineralisation along permeable horizons in a dominantly rhyolitic volcanic pile. Greenschist facies metamorphism during the middle Devonian Tabberabberan Orogeny resulted in local remobilisation of chalcopyrite and modification of primary ore textures. Although commonly fractured during the Devonian deformation, pyrite has not been significantly remobilised and internal growth structures have been preserved.

Polished sections of pyritic ore were etched in a solution of $KMnO_4$ and sulphuric acid to reveal the internal structure of individual pyrite grains. Early pyrite exhibits fine growth zoning and forms the cores of many pyrite grains. It is characteristically bounded by highly corroded margins, indicating dissolution by sulphur-undersaturated fluids. Later generations of pyrite are not zoned and occur as variably anhedral to euhedral grains and overgrowths on early pyrite. Any one pyrite grain may comprise up to five generations of pyrite growth, commonly separated by dissolution boundaries.

Electron microprobe analyses of individual pyrite generations demonstrates that homogenisation of trace elements has not occurred during metamorphism. Oscillatory zoning in the early pyrite (Pyrite I), is high in cobalt (generally 1,000 to 10,000 ppm) with erratic nickel concentrations between 0 and 4000 ppm (Fig. 1). Pyrite II, which commonly overgrows Pyrite I; contains cobalt and nickel at levels below detection limits (<100 ppm). Pyrite III typically contains > 5,000 ppm cobalt with variable nickel and occurs as thin anhedral overgrowths and small irregular inclusions. Repeated generations of Pyrite II and Pyrite III may overgrow each other.

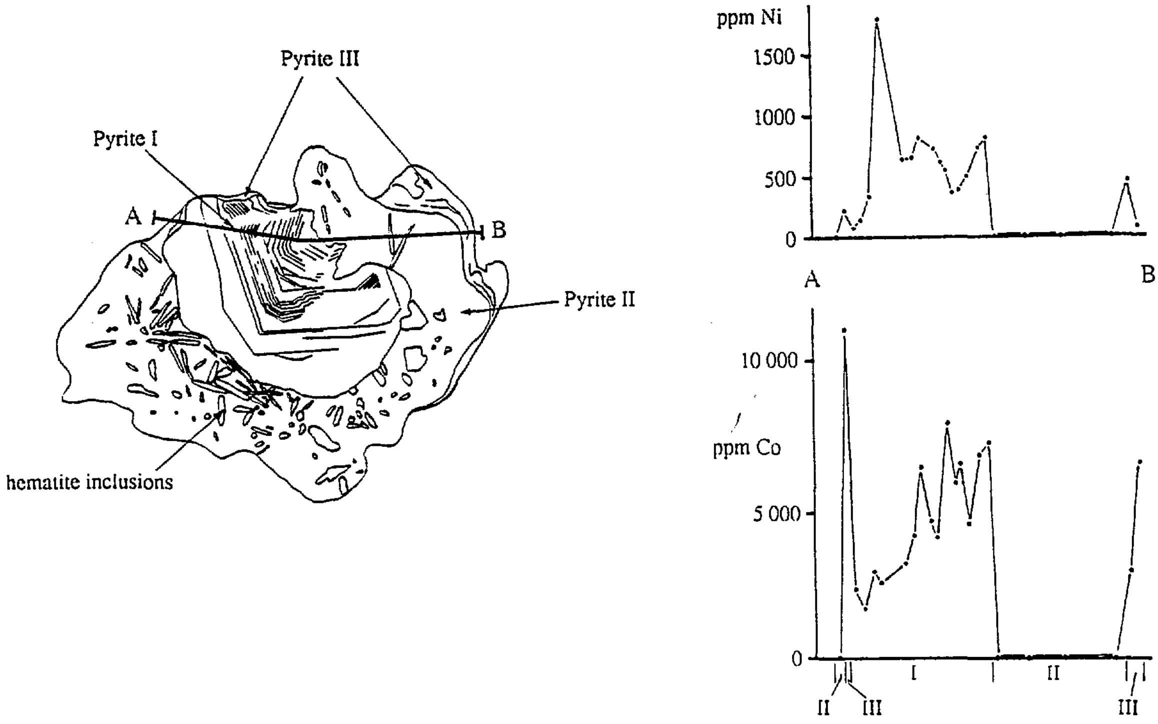

Figure 1. Cobalt and nickel distribution across a composite pyrite grain containing hematite inclusions.

The strong positive correlation of cobalt in pyrite with copper mineralisation in the Prince Lyell deposit (Walshe and Solomon, 1981) suggests that the cobaltiferous pyrite is coeval with chalcopyrite mineralisation. Similar cobalt- and nickel-rich pyrite is associated with Cambrian volcanogenic mineralisation elsewhere in western Tasmania (Loftus-Hills and Solomon, 1967). The cobalt-poor Pyrite II is interpreted to reflect sulphide deposition by a Devonian metamorphic fluid. Pyrite II is chemically similar to pyrite in Devonian vein deposits in western Tasmania where trace elements such as cobalt and nickel have been expelled from the pyrite structure (Loftus-Hills, 1968). However, the intimate association of Pyrite II and the cobalt-rich Pyrite III strongly suggests that Pyrite II has been deposited prior to Devonian metamorphism and is of Cambrian volcanogenic origin.

Pyrite II also contains inclusions of hematite not found in early pyrite. Hematite occurs in a zone where fluids circulating through the hematitic Owen Conglomerate have migrated across the Great Lyell fault and deposited hematite in the footwall volcanics. If Pyrite II is of volcanogenic origin, the inclusions of hematite imply that volcanogenic mineralisation continued during Owen Conglomerate deposition, and raises the possibility of the interaction between volcanogenic fluids and oxidised sedimentary basin fluids along the volcanics-conglomerate contact.

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FLUID-ROCK REACTION AND IMPERFECTLY CHANNELIZED FLUID FLOW IN HYDROTHERMAL SYSTEMS, I. FUNDAMENTAL ASPECTS

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It has recently been recognized that hydrothermal systems associated with Archean lode-type gold deposits are vertically extensive, predominantly single fluid-pass systems, involving channelization of upward fluid flow in the crust (Colvine, 1989; Perring et al., 1989). The presence of alteration haloes around deposits implies movement of a portion of the fluid into and through the wall-rocks. Maintenance of overall channelization requires that fluid that infiltrates the wall-rock must also undergo return flow back into the conduit. It is suggested, therefore, that fluid flow should be pictured as being 'imperfectly channelized' - being dominantly along the conduit, but with excursions into the wall-rock.

Return flow of fluid back into the conduit has important consequences for the chemical evolution of a hydrothermal system. It provides the major cause of changing fluid composition along the conduit, and, as is discussed by Heinrich et al. (this volume), mixing between returned fluid and conduit fluid may promote mineralization reactions.

A quantitative analysis of chemical evolution in an imperfectly channelized hydrothermal system may allow constraints to be placed on a number of parameters that are potentially important in the understanding of gold mineralisation. These include:
i) An assessment of the reliability of various geochemical markers of the source rock of the fluids.
ii) An assessment of possible relationships between the extent of fluid–rock reactions and the grade of mineralisation. Does the proportion of fluid that makes excursions into the wall-rock vary between different points along the conduit?
iii) An indication of the depth of the source rock beneath any mineralised system.

Mathematical analysis is available for the case of channelized fluid flow with diffusion-controlled exchange of a single component with the wallrock (Grisak and Pickens, 1980; Tang et al., 1981). This may also provide an adequate description of exchange, e.g. of an isotopic tracer, between fluid and wall-rock in the case of a gold lode system, in which movement of the tracer into the wall-rock is dominantly through fluid advection along secondary fractures rather than by diffusion.

A different approach is required for modelling of reaction zones and reaction fronts. In an ideal case, the fluid downstream of a reaction front will be in equilibrium with the assemblages on both sides of the front (Bickle and Baker, 1990). Consideration of a simplified history involving infiltration of a fluid packet into the wall-rock followed by return flow shows that: a) where there is only one reaction front, return flow will not alter the position of this front; b) where there are multiple reaction zones, return flow will cause back reaction at the fronts closer to the conduit.

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SUPERGENE PROCESSES IN ARCHEAN NICKEL SULFIDE DEPOSITS AND THEIR SIGNIFICANCE IN THE LOW TEMPERATURE STABILITY RELATIONS OF THE Fe-Ni-S SYSTEM.

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Supergene processes in nickel sulfides are important because they result in enriched nickel deposits as at Kambalda. However, a review of literature on the low temperature stability relations of the Fe-Ni-S system reveals that there are obvious differences between those based on extrapolation of experimental data from 200° C to lower temperatures, and those based on analytical data of natural assemblages. The main differences are in the stoichiometry and stability of violarite compositions. Synthetic violarites are stable below between 461°C and are always stoichiometric, with a maximum iron content corresponding to $FeNi_2S_4$, whereas natural supergene varieties are always non-stoichiometric, generally with metal excess. The compositions of the latter are quite variable apparently ranging from polydymite to gregite.

Furthermore, extrapolation of experimental data suggests that pyrite-millerite is the stable low temperature assemblage whereas data on natural supergene assemblages suggests that violarite-pentlandite is the stable assemblage. Re-evaluation of the published analytical data of the supergene assemblages from the Archean Lunnon Shoot at Kambalda, combined with other published data on supergene violarites also suggests that violarite-pentlandite is the stable low temperature assemblage. The data further implies that there is a miscibility gap in violarite compositions between Ni-rich and Fe-rich varieties. The present study explains the differences in the stoichiometries of natural and synthetic violarite compositions. It is believed that these studies are instructional in understanding the compositional characteristics of carrolites.

MULTIPLE SULPHUR SOURCES FOR SEAFLOOR EXHALATIVE MINERALISATION: SULPHUR ISOTOPIC DISTRIBUTION IN THE BUTTLE LAKE POLYMETALLIC MASSIVE SULPHIDE DEPOSITS, BRITISH COLUMBIA, CANADA

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The massive sulphide orebodies at Buttle Lake in central Vancouver Island, British Columbia, comprise a world-class resource of Zn, Cu, Pb, Au and Ag. Four mines, representing several unit orebodies, define a six kilometre-long favourable horizon within calc-alkaline, mafic to felsic volcanic and volcaniclastic rocks of island arc derivation. Hostrocks are of Devonian, Frasnian age (370Ma).

Sulphur isotope determinations for sulphides (pyrite, sphalerite, pyrrhotite, chalcopyrite, bornite and galena) and sulphate (barite) demonstrate major variation. $\delta^{34}S$ values for sulphides from the ore zones range from 9.0 to -6.7 ‰ (mean = 2.3 ‰; n = 63). Isotopic disequilibria is common among sulphide pairs, particularly those involving pyrite, and may be attributed to rapid precipitation from a quenched plume, mechanical mixing of sulphides or subsequent replacement.

Five samples of syngenetic pyrite and pyrrhotite, taken from the felsic tuffs and graphitic metasediments distant from mineralisation are characteristically depleted in ^{34}S (mean = -20.3 ‰; range -14.3 to -34.0 ‰). The biogenic nature of this sulphur is unequivocal. $\delta^{13}C$ values ranging from -19.6 to -24.8 ‰ (mean = 21.2 ‰; n = 4) for the accompanying graphite attests to the anoxic nature of the environment in which organic matter and syngenetic sulphide accumulated, distal from the hydrothermal vents.

$\delta^{34}S$ for baritic sulphur ranges widely from 26.2 to -6.3 ‰ (mean = 18.6 ‰; n = 52). The data indicate two isotopic groupings for baritic sulphur. Abundant 'heavy' barite ($\delta^{34}S$ ranging from 26.2 to 20.5 ‰) matches almost exactly the isotopic composition of Frasnian seawater sulphate. This barite is likely to have formed when vented, barium chloride-bearing hydrothermal fluids mixed with oxygenated open ocean water. Unusual 'light' barite ($\delta^{34}S$ ranging from 17.6 to -6.3 ‰ formed when vented hydrothermal sulphide was oxidised in the plume and mixed with ocean water sulphate. The mixing proportions for sulphate of hydrothermal and seawater origin determined the resulting $\delta^{34}S$ value of the 'light' barite.

Late-stage calcite veins that crosscut sulphide mineralisation have $\delta^{13}C$ values which range from -3.0 to -8.2 ‰ and unusually 'light' $\delta^{18}O$ compositions ranging from -17.1 to -18.8 ‰. The carbon isotope data from these samples are not definitive but the oxygen isotope compositions may indicate the rôle of meteoric water in their formation.

The contributions to mineralisation of three sulphur reservoirs in the submarine environment are defined by the isotopic study. These are (1) hydrothermal sulphide of magmatic or rock sulphide derivation, (2) seawater sulphate and (3) biogenic sulphide. Sulphur isotope systematics and the interaction of these sulphur reservoirs are illustrated in Fig. 1. Venting of hydrothermal fluids led to metal sulphide precipitation by mixing with cold, anoxic bottom waters. The sulphide appears to be principally of hydrothermal derivation. Most barite formed when the venting hydrothermal plumes rose above the anoxic bottom water and encountered sulphate available from normal, oxidising ocean water. Sulphur in some barite is of a hybrid origin and represents variable proportions of oxidised hydrothermal sulphide and seawater sulphate, mixed in the upwelling plume. The contribution made by biogenic sulphur may be limited to syngenetic sulphides encountered away from the ore zones, however a biogenic signature could be apparent in ^{34}S-depleted sulphide and sulphate from some ore samples.

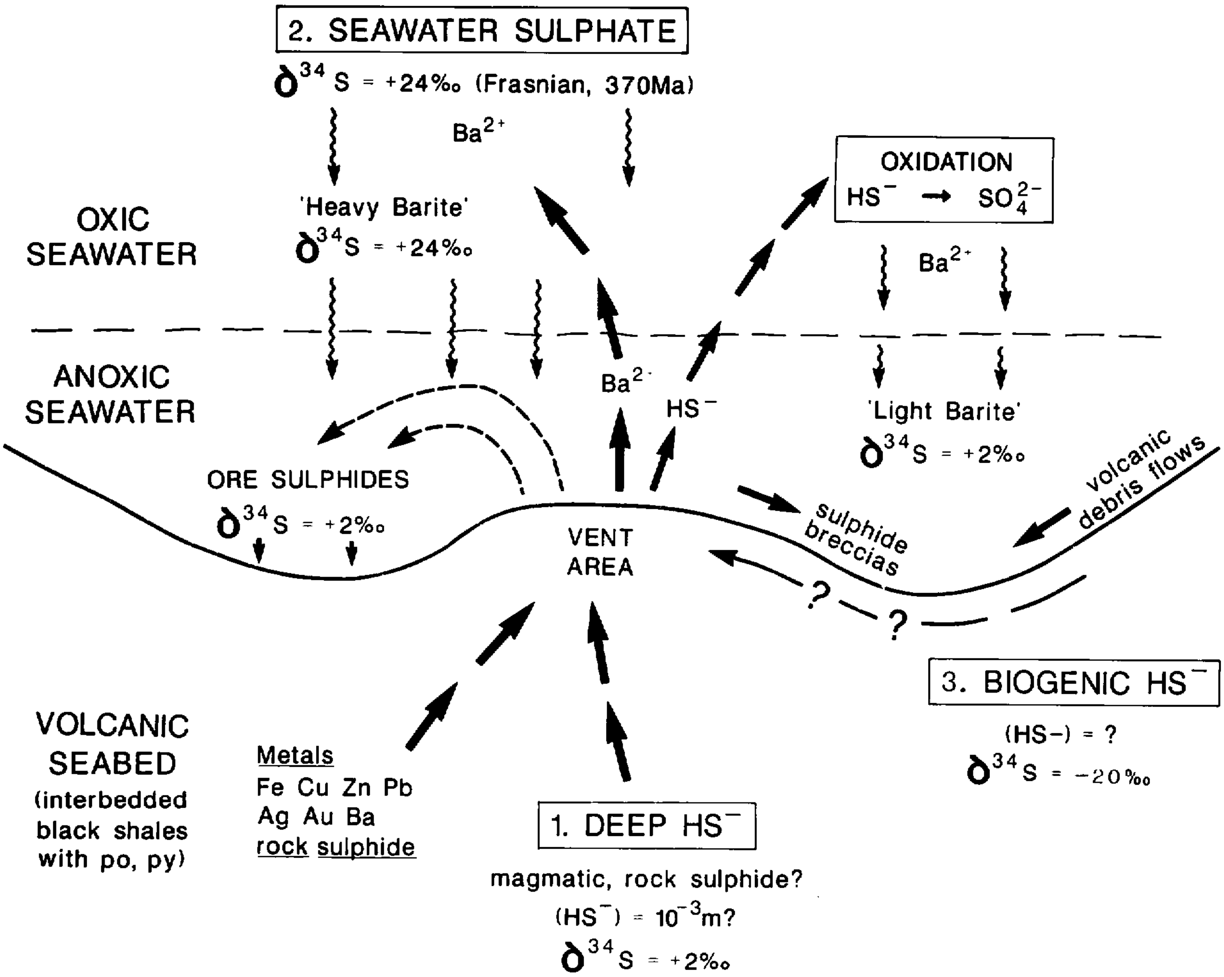

Fig. 1. Sulphur reservoirs and sulphur isotope systematics in the submarine environment, Buttle Lake orebodies, Canada.

THE GEOLOGY AND GENESIS OF THE XIMENG TIN DEPOSIT WESTERN YUNNAN, CHINA: A FLUID INCLUSION, STABLE ISOTOPE AND ORE PETROGRAPHY STUDY

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The Ximeng tin deposit is located in Ximeng County, of Western Yunnan Province, China. The deposit lies in the southern part of the Lan Chang River polymetallic mineralization belt, in the centre of the Changnin-Ximeng-Meng Lian magmatic mineralization zone. This represents the northern extension of the Southeast Asian tin province including Burma, Thailand, Malaysia and Indonesia. Cassiterite mineralization at Ximeng is spatially and temporally related to the Xiaomasa Granite and occurs in schists and leptites of probable Precambrian age. The metamorphosed country rocks consist of a lower and upper succession separated by an unconformity. The lower succession includes banded migmatite, augen migmatite, leptite, marble and skarn. The upper succession consists of mica-schist, quartz-schist, plagioclase-schist and quartzites.

Cassiterite mineralization occurs as stratabound replacement bodies in schists of the upper metamorphite succession and as veinlets in fissures. The generalized paragenetic sequence at Ximeng Tin Mine is:

Stage 1: cassiterite, tourmaline, quartz, microcline - tentatively inferred as an early stage of replacement ore formation;
Stage 2: cassiterite, quartz, fluorite, minor sulfides and iron oxides - the main stage of tin mineralization;
Stage 3: cassiterite, arsenopyrite, pyrite - forming veinlets in major fault zones;
Stage 4: major veining by pyrrhotite, sphalerite, minor galena and silicates.

Temperatures of 420°C and 350°C are inferred for stages 1 through to 3, from the investigation of fluid inclusions and stable isotopes.

Bulk fluid inclusion analyses indicate that fluids during stage 1 to 4 were Na-K-F-Cl brines with a total salt concentration of about 5 to 38 eq. wt% NaCl and a Na/K ratio of about 2. Variable Ca and Mg concentrations may be partly due to contamination during sample leaching. The fluids are gas rich, with average CO_2+ CH_4/H_2O molal ratios of about 3. The CO_2/CH_4 ratio varies from 0.6 to 26.

Oxygen isotope ratios of the mineralizing fluids, calculated from analyses of cassiterite, tourmaline and quartz, suggest that the fluids were derived from a magmatic aqueous phase. Sulfur isotope values are consistent with the Xiaomasa Granite being the major or sole source of sulfur for the ore-forming fluids.

Precipitation of cassiterite occurred at low fO_2 (about 10^{-28} atm), low fS_2 (10^{-10} to 10^{-13} atm) and low pH(5). The main control on ore deposition is the intersection of a fracture zone and the unconformable contact between the two metamorphic successions. Boiling of the ore-bearing fluids played an important role in development of the main orebodies.

FLUID PRESSURE REDUCTIONS INDUCED BY FAULTING; THEIR ROLE AS A PRECIPITATING AGENT AT SPECIFIC STRUCTURAL SITES

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Gold-quartz vein systems with textures recording incremental histories of deposition are often hosted in faults and shear zones. Epithermal deposits tend to develop at shallow depths (<1-2 km) in the vicinity of extensional or transtensional fault systems. In contrast, many mesothermal gold-quartz lodes are associated with high-angle reverse or reverse-oblique shear zones of mixed discontinuous-continuous character, developed under greenschist facies metamorphic conditions at ~10 km depth. These different environments for hydrothermal deposition therefore bracket the continental seismogenic regime. A feature common to both settings, however, is that mineralization tends to be localised at structural sites where increments of slip lead to reductions in fluid pressure.

Abrupt reductions in fluid pressure induced by rupturing thus seem likely to play a key role effecting mineral precipitation in both settings, although the mechanisms differ in detail. In the epithermal environment, especially, rapid slip transfer across dilational fault jogs and bends during rupture propagation causes abrupt local reductions in fluid pressure below ambient (hydrostatic?) values. At high crustal levels in geothermal systems, such pressure reductions may induce boiling, triggering mineral deposition throughout the phase of aftershock activity. Dilational fault irregularities thus act essentially as ***suction pumps***.

In the mesothermal environment at the base of the seismogenic zone, high-angle reverse faults play a different role as ***fluid-pressure activated valves*** capping over-pressured fluid systems, and promoting cyclic fluctuations between lithostatic and hydrostatic levels of fluid pressure. Frictional shear failure can initiate only when supralithostatic fluid pressures are attained. Rupturing through the upper crust then allows sudden drainage of the over-pressured reservoir along the reactivated fault, with fluid pressures dropping rapidly towards hydrostatic values. Discharge is accompanied by phase separation of carbon dioxide, rapid mineral precipitation and hydrothermal self-sealing. Fluid pressures then rebuild towards the supralithostatic values needed to trigger the next episode of fault slip, and the cycle repeats.

SILICIFICATION IN A SEMICONFORMABLE ALTERATION ZONE BELOW THE CHISEL LAKE ZN-CU MASSIVE SULPHIDE DEPOSIT, SNOW LAKE, MANITOBA, CANADA.

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Regionally extensive semiconformable zones of silicified, Fe-Mg-metasomatised and epidotised, dominantly mafic, volcaniclastic strata and lava flows are exposed 0.5-2 km stratigraphically beneath the Chisel Lake Zn-Cu massive sulphide deposit in the Snow Lake district, Manitoba, Canada. The alteration zones occur within a Lower Proterozoic medium grade regional metamorphic terrane of felsic and mafic volcanics and marine sediments. In the 2x2 km study area there is a crude zonation of alteration from relatively distal, deeper silicification and epidotisation (clinozoisite alteration) to Fe-Mg-metasomatised, garnet-chlorite± biotite±staurolite rocks nearer the Chisel Lake deposit. The discordant footwall 'pipe' alteration directly beneath the Chisel Lake sulphide deposit appears to meet the semiconformable Fe-Mg-metasomatised zone; a similar relationship of discordant and semiconformable alteration zones was documented at the Anderson and Stall Lakes massive sulphide deposits by Walford & Franklin (1982).

Silicification resulted in partial to complete replacement of lithic clast margins in volcaniclastic rocks, pillow interiors in flows, and of zones adjacent to some felsic dykes, by quartz and sodic plagioclase. Mass-balance calculations of elemental gains and losses in silicified rocks and equivalent least altered parts of pillows, dykes and volcaniclastic beds indicate that up to 50% (by weight oxide) Si and as much as 30% Na were added, and up to 80% of the Fe, Mg, Ca and Zn were removed during silicification. The magnitude of Mn, V and Cr losses generally are similar to those of Fe. Several elements including Cu, K, Rb, P, Ba and Sr show variable gains and losses in silicification. Cu contents, however, are commonly below 50ppm and in places are less than 10ppm in both least altered and silicified mafic volcanic rocks, suggesting widespread partial removal of Cu in the area.

Elemental fluxes in Fe-Mg-metasomatism are generally opposite of those characterising silicification and are of comparable magnitude, whereas clinozoisite alteration resulted in depletion of Na, total Fe (but increased the Fe_2O_3: FeO ratio), Mg, Mn, K, Zn and Ba and enrichment in Ca and Sr, relative to least altered rocks.

Almost constant interelement ratios of Ti, Zr and Al in altered and less altered rocks indicates that these elements were essentially immobile during metasomatism and subsequent medium grade regional metamorphism, except possibly where large gradients of P_{CO_2} or extremely high fluid/rock ratios existed. Limited data suggest that the heavy REE were also immobile and were simply diluted during silicification.

A model of hydrothermal alteration is proposed in which Si-saturated Na-rich evolved seawater(?) fluids were locally heated above the temperature of the silica solubility maximum (approx. 350-400°C at pressures below 500 bars) in two distinct semiconformable environments: (a) in a near-seafloor zone where unfocussed hydrothermal discharge interacted with hot lava, and (b) where felsic dykes intruded hot (200-300°C), 'wet', highly permeable, country rocks at subseafloor depths of 0.5-2 km. A portion of the leached Fe, Mg and possibly Zn and Cu are proposed to have been transported upwards and laterally away from the semiconformable silicified zones of environment (b), and produced the semiconformable Fe-Mg-metasomatised zones

The detailed relationship of silicification to massive sulphide deposits in the area remains unclear, but there is textural and geochemical evidence that silicification associated with felsic dykes occurred coevally with deposition of the felsic volcanics directly beneath the Chisel Lake Zn-Cu deposit. The semiconformable alteration therefore may have developed just prior to and/or during massive sulphide deposition on the seafloor. It is speculated that some of the Fe, Zn and Cu(?) leached from the semiconformable silicified zones of type (b) was transported to the seafloor to form sulphide deposits, as also proposed for massive sulphide genesis at Matagami, Quebec, by McGeehan (1978). Silicified zones of type (a) may have acted in a more passive role as relatively impermeable 'cap' rocks, similar to the role of the silicified Amulet Rhyolite at Noranda, Quebec (Gibson et al., 1983).

Large pervasively silicified zones, particularly those in association with Fe-Mg-metasomatised and/or epidotised rocks, provide potentially important guides for locating favourable environments of volcanic-associated massive sulphide deposition.

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ARE HIGH HEAT PRODUCING GRANITES ESSENTIAL FOR THE FORMATION OF GIANT SEDEX-TYPE LEAD-ZINC DEPOSITS?

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Giant, sediment-hosted lead-zinc deposits in northern Australia formed during development of mid-Proterozoic extensional basins. All the definitively dated deposits are about 1680 to 1670 Ma old (Page 1988; Page and Laing 1990). The basins overlie basement of Early Proterozic and Archaean age. In the McArthur Basin this basement is largely obscured but in the Mount Isa area it is exposed by folding and faulting, and is seen to contain fractionated, high heat producing (HHP) granites (Jackson et al. 1987; Blake 1987; Wyborn et al. 1988). These granites are younger than those of the 1880 to 1840 Ma magmatic event which do not display marked fractionation. Examples of the HHP granites dated by stratigraphy or isotopic methods as younger than 1840 Ma but older than the lead-zinc ore deposits include the Yeldham granite, the Wonga microgranite and the Naraku microgranite. The Sybella microgranite was supposedly emplaced about 1670 Ma but this age requires updating (or downdating) by ion microprobe methods. Only the Sybella appears to have any spatial relationship to known lead-zinc deposits. Indirect evidence that uranium-rich granites exist beneath the McArthur Basin is given by the uranium deposits and nearby basement composition of the Westmoreland area. The HHP granites have U, Th and K contents capable of generating thermal fluxes of about 6 mW m^{-3}. Our preliminary modelling indicates that a granite of this type, 10*10 km in area and 5 km thick, lying benath 5 km of relatively impermeable sedimentary cover, can generate temperatures within the granite of up to 250°C.

The thermal output of the HHP granites would significantly raise the temperature of fluids travelling laterally in the basin sediments under the influence of a hydraulic head (the MVT model of Bethke, 1986). Alternatively the heat input may be sufficient to initiate buoyancy-driven fluid convection in the granite and basin sediments, if vertical permeability is established by extensional fracturing. Our hydrodyamic modelling of the favoured convection model is not sufficiently advanced to predict whether the mass and thermal fluxes would be suffient to generate giant lead-zinc deposits by this mechanism. Earlier modelling by Fehn (1985) and Strens et al. (1987) based on granites with similar heat output (e.g. Cornwall) suggests that a degree of optimism is justified. However, the outlook for the compaction dewatering model (Sawkins 1984), or the downward excavating convection model of Russell (1978), is less hopeful.

Galena and spalerite solubilities, which increase exponentially with temperature, place a severe limit on the minimum fluid flux required to form a giant sedex deposit. The simplest interpretation of textural and sulphur isotopic data from the H.Y.C deposit (Smith and Croxford, 1973; Williams, 1978; Eldridge et al., 1988) indicate that the ore metals were transported together with reduced sulphur in the same ore fluid. A Na-K-Cl (Ca-CO_2-HCO_3) brine equivalent to 4m NaCl, buffered by quartz, muscovite and K-feldspar requires a minimum temperature of about 235°C to transport 10 ppm Pb and Zn each plus an equivalent molal concentration of reduced sulphur. Sulphide deposition could result from simple cooling, or may be enhanced by reaction with carbonate. To accumulate 10 Mt Pb from such a brine requires a mass flux of at least 10^6 Mt of fluid (or ten times more if the temperature is only 200^oC). These fluid quantities exceed the likely total pore volume of fluids available from simple basin compaction, unless perfect fluid focussing over hundreds of kilometers is invoked. Also, the required temperatures are higher than expected within a sediment package at normal geothermal gradients. These considerations suggest that energy, rather than metal availability, is the likely limiting factor for the formation of giant sedex deposits. If HHP granites are indeed vital as a source of thermal and/or mechanical energy, then exploration strategies for these deposits may require reexamination.

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GEOLOGY OF THE BROWNS CREEK COPPER-GOLD SKARN DEPOSIT, BLAYNEY N.S.W.

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The Browns Creek copper-gold skarn deposit is situated 8 km west of Blayney N.S.W., and is estimated to have produced about 60,000 oz of gold in the mining period 1870-1914. The current phase of mining began in 1980 and known reserves will allow open cut production until the end of 1992, by which time total mine production will have been approximately 2 million tonnes at 4 g/t gold and 0.3 % copper. The deposit is located within the northern part of the Molong-South Anticlinorial Zone, an Ordovician-Silurian tectonic unit within the Lachlan Fold Belt. The host rocks include the Blayney Basalt (a new name replacing the old term Blayney Andesite/Angullong Tuff (D. Wyborn, pers. comm.)); the Cowriga Limestone which occurs as a localized unit within the Blayney Basalt; and the Long Hill Granodiorite intruding the volcanics and limestone. Gold and copper mineralization occurs in skarn and clay zones developed at volcanic-limestone or granodiorite-limestone contacts, or in structurally favourable zones of shearing and faulting within these lithologies. The character of the skarn varies widely laterally, but less vertically. Which of the major skarn minerals wollastonite, grossular-andradite and diopside-hedenbergite dominate, and their textural relationship, seems mainly to depend on which host rock has been replaced. Gold is intimately associated with the major sulphides, bornite and chalcopyrite, and less commonly in microfractures through the skarn without sulphides. The clay ore comprised nontronite clay and clay breccias containing weathered fragments of all lithologies. It occurred within 70 metres of the surface, clearly associated with major shear zones and maybe related to karst weathering of the limestone. It has recently been mined out.

Petrography and geochemistry currently being undertaken by Idunn Kjølle, as part of a Ph.D.-study at ANU on the genesis of the Browns Creek deposit, will be presented during the poster session in the context of detailed mapping carried out by mine staff and will comprise the following: Petrography of host rocks integrated with C. Perkins' dating work on the deposit; geochemical analysis by XRF of ore, altered and relatively unaltered intrusive phases in the pit, and of the Long Hill and Carcoar Granodiorites, both of which from mapping appear to belong to the same intrusive phase.

THE DISTINCTION BETWEEN METAMORPHOSED STRATIFORM Pb-Zn-Ag MINERALISATION AND METAMORPHIC SYNTECTONIC Cu MINERALISATION AT MT ISA

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Co-genetic models for Pb-Zn-Ag and Cu mineralisation ore formation imply that both ore styles formed from the same hydrothermal fluid. Other poly-metallic ore deposits (for example granitoid-related vein systems and VMS deposits) which form zonal metal distribution patterns display systematic changes in style and mineral zonation that are consistent between individual deposits for a particular deposit type. At Mt. Isa, Pb-Zn-Ag mineralisation and Cu mineralisation are separate chemical and morphological entities. There is no progressive change between these two distinctive ore styles. Nearby Native Bee and Stony Ck. Cu mineralisation is indistinguishable from parts of the Mt Isa Cu system, and yet there is no Pb-Zn-Ag mineralisation present. Similarly, the outer upper margin of the main 1100-1900 Cu orebody does not display any progression from sparse vein-hosted dolomite-chalcopyrite mineralisation to Pb-Zn-Ag mineralisation. Stratiform Pb-Zn-Ag mineralisation interdigitates with lobes of the vein network Cu system alteration at the northern end of the 1100-1900 Cu orebody, but does not form a continuum.

A stratabound biotite/stilpnomelane/magnetite assemblage, and a white-mica/chlorite/albite assemblage occur amongst stratiform pyrite and Pb-Zn-Ag mineralisation, but they do not occur in dolomitic Urquhart Shale adjacent to the southern margins of silica-dolomite Cu alteration. The biotite/stilpnomelane/magnetite assemblage is interpreted to be a metamorphic product of Fe-carbonate/K-feldspar-rich, Pb-Zn-Ag related portions of the Urquhart Shale. The white-mica assemblage pseudomorphously overprints the biotitic assemblage, and is interpreted to be the product of metasomatism related to the interaction with highly evolved, syntectonic hydrothermal fluids associated with Cu-mineralisation. The description of the analagous unmetamorphosed McArthur River Pb-Zn-Ag deposit (Williams 1978 a b, Walker *et al.* 1977, Logan 1979) does not include similar non-sulphide mineral assemblages. McArthur River does however, have ferroan carbonates (Fe-dolomite and Ankerite, ± Siderite?) associated with Pb-Zn-Ag mineralisation (Logan 1979).

For general non-ferroan dolomitic Urquhart Shale during D_2-D_3 deformation (Swager 1983, Bell *et al.* 1988) there has been some recrystallisation of sulphides, with an attendant increase in grain size (McDonald 1970, McClay 1979) but little apparent metamorphic reaction. Localised intense S_3 cleavage overprints all stratiform sulphides, and is axial planar to small scale parasitic folding. Chemical data on the maturation of organic matter within ore show that Mt. Isa ore has a higher metamorphic grade than the McArthur River ore (Saxby and Stephens 1973, Saxby 1981). Mt Isa rocks have evolved past the stage of kerogen cracking resulting in hydrocarbon generation, and approach the graphite structure (Saxby and Stephens 1973, Saxby 1981). By analogy, the Mt. Isa non-sulphide mineral assemblages are interpreted to be metamorphic (biotite/stilpnomelane/magnetite assemblage), or Cu metasomatic in origin (white-mica/chlorite/albite assemblage), rather than a primary Pb-Zn-Ag metasomatic feature.

Other features attributable to metamorphism are present beyond the Mt. Isa mine environs in Mt. Isa Group rocks. The most distinctive of these features is calcitic banding formed from the reaction of ankerite and K-feldspar. A simulation of this metamorphic reaction using a K-feldspar-bearing dolomitic shale with 1wt% H_2O has been used to determine the minimum temperature of phlogopite formation, by means of a series of calculated temperature stepped mineralogical equilibrations. Phlogopite does not form at temperatures less than 330°C. Peak metamorphic temperatures probably exceeded 330°C. This is the upper limit of the wide range (~120°C) of corrected fluid-inclusion temperatures for Cu mineralisation (Heinrich *et al.* 1989).

Vein related syntectonic Cu mineralisation consistently overprints stratiform Pb-Zn-Ag mineralisation, stratiform pyrite, the biotite/stilpnomelane/magnetite assemblage, and the calcitic bands. Some dolomite veins cross-cutting Pb-Zn-Ag mineralisation show sphalerite dissolution halos surrounding the vein. If sufficient sphalerite is dissolved, minor sphalerite may be locally reprecipitated within or adjacent to the vein. These unusual veins representing localised dissolution and reprecipitation of sphalerite only occur in areas marginal to Cu alteration, within the Pb-Zn sequence, and at relatively low fluid/rock ratio. They do not represent an intermediary between the two styles of mineralisation. At high fluid/rock ratio sphalerite and galena are dissolved and do not cause a sufficient increase in aqueous Zn and Pb concentration to reach saturation and possible reprecipitation. Most Pb and Zn dissolved is lost from the system with the hydrothermal fluid.

Chemical modelling of the Cu hydrothermal fluid interaction with Urquhart Shale has reproduced the observed longitudinal mineralogical zonation of the Cu system. Albitisation of K-feldspar is expected to occur in the high K-feldspar-Pb-Zn-Ag-Fe sequence adjacent Cu mineralisation. Similarly, if iron silicates or carbonates have interacted with the Cu fluid they are predicted to become more magnesian. Some observational evidence supports these effects of Cu fluid metasomatism, which do not occur unless the host rock changes from dolomitic Urquhart Shale to an unusual ferroan rock (approximating the Pb-Zn-Ag sequence).

The metamorphosed stratiform Pb-Zn-Ag mineralisation is folded and overprinted by a locally intense S_3 cleavage. Pseudomorphous, and cross-cutting evidence indicates that Cu mineralisation is distinctly later than Pb-Zn-Ag mineralisation, and retrogressive, relative to peak regional metamorphism.

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Microstructural timing of mineralization at Big Bell Mine, Western Australia - a post-deformational, post-peak metamorphic Archaean hydrothermal gold deposit

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Previous studies proposed that gold mineralization at Big Bell - an enigmatic low-grade, large-tonnage deposit hosted in an upper amphibolite facies greenstone belt sequence - occurred by hydrothermal alteration synchronous with volcanism or hydrothermal alteration prior to peak metamorphism (Chown et al., 1984; Phillips & De Nooy, 1988).

As the previous workers admitted that they were unable to find any suitable timing criteria, this study is supported by an extensive detailed structural/microstructural analysis of the mine sequence, the greenstone belt hosting the orebody and the structural history of the Cue region as a whole. The following conclusions have been drawn:

1) Prior to mineralization: D1-D5 and M1 metamorphism to Staur-And zone of the amphibolite facies for pelites.
2) Granite emplacement post-dates the final fold phase, D5, and caused M2 thermal metamorphism that peaked at the Mu + Q breakdown reaction for pelites on or close to the And-Sill transition, but below the onset of partial melting, characterized by the narrow non-degenerate divariant field involving 7 KFMASH phases for pelites: Q + Mu + Bi + Crd + Kf + Als + H_2O. M2 hornfelsing consumes, cross-cuts and post-dates S5 cleavage.
3) Prograde Q + And + Sill veins replace the above M2 assemblage (and also clearly replace S5 cleavage) and are a product of volatile escape at depth and hydraulic fracturing coincident with a reduction in bulk rock permeability resulting from post-deformational hornfelsing.
4) Rehydration and mineralization: Disseminated gold-related mineralization in the lode schists is undeformed, cross-cutting and replaces all previously described structures and assemblages 1) - 3).
Stage 1 mineralization is typically associated with widespread retrograde muscovite plates:
Py - Po - Cpy - Ilm - Mag - Au
Tourm - Scheelite - Rutile - Sphene - Zircon
Mu (Bi) - Epi-clinozo - Q
Stage 2 mineralization is characterized by pervasive sericitic alteration that can be developed to an extent where all pre-existing mineralogies, including quartz, are totally destroyed within sericitic domains:
Aspy - Stib - Sb - Molb - Sphal - Au
Py - Po - Ilm - Mag - Cpy
Sericite - Chlorite - Carbonate - Epi-clinozo - Q

The gold mineralization at Big Bell is post-deformational and post-peak metamorphic. No shear zones are involved in the genesis of the deposit! The retrograde character of the mineralization has been deduced from detailed structural and microstructural observations and demonstrates the emplacement of this gold deposit is very late in the overall orogenic story in the Yilgarn Murchison Province.

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Late Abstracts

URANIUM CONCENTRATION MECHANISMS IN GRANITOIDS THE EXAMPLE OF THE VARICAN PROVINCE OF WESTERN EUROPE

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The metallogenic province concept is based on the occurrence, in the same area, of numerous ore deposits of the same metal or metal association of different ages. This has been attributed to high concentration of the metal(s) in a crustal segment compared to average crustal abundances. Geophysical, geochemical and isotopic data indicate that the pre-Variscan crust was enriched in some metallic elements. This enrichment mainly results from a first cycle of partial melting and magma fractionation during late Proterozoic to early Paleozoic times.

(1) Heat flow/heat production distribution and correlation in Brittany, (Vigneresse et *al.*, 1989) delineate an elongated crustal segment (about 17 km thick) enriched in radioelements, especially in U. This enrichment does not concern only Variscan granitoids (their thickness estimated from gravimetric data being between 2 and 8km), but also the surrounding metamorphic formations.

(2) Geochemistry of the pre-Variscan metamorphic formations of NW French Massif Central (FMC) and Brittany, (Cuney et *al.*., 1990) indicate that acid meta-igneous rocks of late Proterozoic to early Paleozoic age are enriched in metals (U, Sn, W...) compared to average upper crust estimates.

(3) Nd and Sr isotopic signatures of the late Variscan peraluminous leucogranites associated with U, Sn, W mineralizations is compatible with their derivation from these meta-igneous formations (Turpin et *al.*, 1990). Late Variscan peraluminous leucogranites cannot derive from outcropping pre-Variscan metasedimentary formations because their Nd isotopic signatures differ strongly.

The formation of ore deposits associated with granitoids needs either an anomalously high content of metals in the granite or efficient hydrothermal fluids to dissolve, transport and precipitate the metal from an average granitic or metamorphic source. In the case of intragranitic uranium deposits an enriched source is necessary. The three granite types associated with uranium mineralization in Europe or elsewhere in the world, present uranium contents (10-30 ppm) significantly higher than clarke estimates (3-4 ppm).

In the Variscan belt four main granite types have been distinguished from their major element geochemistry (La Roche et *al.*, 1980; Stussi, 1990) mineralogy and trace element content.

(1) *Alkaline to peralkaline granitoids* : They are characterized by a peraluminous index (Al/Na+K+2Ca) close to or lower than unity. They are rich in U, Th, Nb, Zr and REE and these elements are strongly enriched during magmatic fractionation. In the Variscan they are only located in Corsica and are not associated with any significant mineralization. However elsewhere in the world they can be associated with U, Th, REE (Bokan Mountain, Alaska) or Sn (Younger granite from Nigeria) mineralizations generated by extreme magma and magma/magmatic fluid fractionation.

(2) *Subalkaline (high K-calcalkaline) granitoids* : They are characterized by a peraluminous index around one. The less evolved terms (i.e. gabbroic to dioritic) are much richer in K_2O than equivalent calcalkaline terms. These granites are also rich in U, Th, Nb, Zr, REE but these elements present variable fractionation trends. U, Th, Nb, Zr and REE are generally enriched with differentiation but to a lesser extent compared to alkaline granites. Minor Mo, Cu, U mineralizations are associated with these granites.

(2) *Peraluminous granitoids* : They represent the most widespread magmatism in the Variscan belt. They are characterized by a high peraluminous index, but show distinctive mineralogical, geochemical and genetic characteristics when compared to the typical Australian S-type granites (Chappel and White, 1974). Two subgroups have been distinguished :

- G-type granites (the large Guéret batholite in the North FMC is taken as a reference) contain abundant Mg-rich biotite, An-rich zoned plagioclase ± cordierite. Th, Zr and REE content decrease slightly with differentiation. They do not present any metal enrichment. No significant metal deposit is related to them. The mineralizations locally observed are related to late leucogranite intrusions.

- L-type granites (because they are widespread in Limousin, Western MCF and Leucocratic: less than 10% biotite) are muscovite±sillimanite±andalusite±garnet bearing. Their peraluminous index increases with differentiation. Zr, Th and REE content strongly decrease with magmatic fractionation. Most Variscan economic U, Sn, W, Li, Ta, Be deposits are related to this type of granite. Most of the Variscan Au deposits are located in the metamorphic rocks a few kms from these granites.

The potentiality (fertility) of uranium rich granitoids to generate uranium deposits depends strongly on the nature of their accessory mineral paragenesis which holds most of the whole rock uranium content. The nature of the accessory mineral paragenesis depends on the physical and the chemical characteristics of the magma (Cuney and Friedrich , 1987). The nature of the major mineral host for uranium controls its availability for the ore forming hydrothermal solutions.

The Saint Sylvestre peraluminous granitic complex contains one of the largest vein-type uranium district in Europe (40 000 metric tons U at 2‰, already mined and proved reserves). The coarse-grained granites (g^1) are emplaced, during the last Variscan thrusting episode (325±5 Ma). During Westphalian (310±5 Ma), g^2 and g^3 fine to medium grained granitic stocks are emplaced. The Stephanian-Permian transition (270 Ma), corresponds to the formation of the main hydrothermal uranium deposits (Cathelineau et al. 1989), some 40 Ma after the emplacement of the magmas.
Detailed structural analysis of the magmatic structures associated with petrographic and geochemical studies in the Saint Sylvestre complex have evidenced several steps of magmatic fractionation for U. The most favorable U sources are late stage "endogranitic" intrusions. Their emplacement is structurally controlled into large magmatic shear zones. U-enrichment approaches with a factor of 100 to 10 the economic grade of the ore deposits in narrow shear zones. In these late intrusions U is essentially located in low Th uraninite which represents a metal preconcentration easily leachable by oxidizing hydrothermal solutions. The good spatial overlap between the structures developed at a magmatic stage, and those developed much later at a brittle stage controls the efficiency of the hydrothermal remobilization of the metal.
The successive movements occurring in a geometrically well defined area, and during a rather long time interval, are localized in structural boundaries between crustal blocks. These structural boundaries are interpreted as large and deep lineaments (Cuney, 1990) developed in crustal domains enriched in metals (Vigneresse et *al.*, 1988; Cuney et *al.*, 1990). They control the different steps of metal enrichment from partial melting in the crust to the last hydrothermal processes leading to the formation of the main ore bodies.
The emplacement of specialized granites correspond to an important thermal event in the Variscan belt. This thermal event is synchronous with the development of low pressure granulites in the lower crust of FMC (Pin and Vielzeuf, 1983). The U, Sn, Li, F, Rb, Cs, Be (W) enrichment of the most "specialized" granites is attributed the dehydration of the lower crust during late Variscan granulitization of the FMC lower crust. The volatile and metal rich fluids are channeled by the lineaments and promote partial melting in the intermediate continental crust.

In conclusion the U and probably also Sn specialization of peraluminous leucogranites in the Variscan orogen results from a multistage process, beginning with Late Proterozoic partial melting in the mantle (lower Paleozoic subalkaline orthogneisses) followed by one or several stages of partial melting of metal enriched parts of the continental crust enhanced by granulites devolatilization, magmatic fractionation and finally hydrothermal remobilization and concentration mainly focused in metallogenic lineaments.

CHARACTERIZATION OF MAGMATIC-HYDROTHERMAL PROCESSES IN THE TIRAD PORPHYRY CU-AU PROSPECT (NW LUZON, PHILIPPINES), AS INFERRED FROM BIOTITE MINERAL CHEMISTRY DATA

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The purpose of this comunication is to present mineral chemistry data of four texturally distinct types of biotites associated with porphyry copper-gold mineralization. Model calculations are used to infer chlorine and fluorine fugacities, as derived from the mineral chemistry of biotites, during the early stages of mineralization and a magmatic episode postdating the mineralization.

The Tirad porphyry Cu-Au prospect is one of the largest (500 m.t. grading 0.4% Cu and 0.4 ppm Au), undeveloped deposits of its type in the Philippine island arc. The geology of the Tirad prospect, which is located within the Central Cordillera of NW Luzon, consists of the remnants of a mid-Miocene stratovolcano unconformably overlying a volcano-sedimentary sequence of Cretaceous-Paleocene age. These rock units were intruded by a porphyrytic quartz diorite stock during the Pliocene. A complete alteration suite typical of porphyry copper environments is associated with characteristic ore minerals and developed synchronously with the intrusion of this stock. Subsequently, the rocks were intruded by an unmineralized dacitic complex.

Detailed petrographic studies have shown that four texturally distinct types of biotite are present. Biotite I occurs as relict phenocrysts of igneous origin in the quartz diorite. Biotite II is observed at depths in excess of 950 m below surface in a unit of the volcano-sedimentary sequence adjacent to the granitoid intrusive. It occurs as relict grains characterised by irregular margins and bright green pleochroism: its origin is inferred to be contact metamorphic. Biotite III is fine-grained, displays brown pleochroism and can occur in any rock type at depths in excess of 600 m below the surface within the area of mineralization: at Tirad it is the main silicate phase of the K-silicate alteration. Biotite IV occurs as phenocrysts in one of the porphryry dacite phases of the diatreme complex postdating the mineralization; this type of biotite shows brown pleochroism and saussuritized margins. Electron microprobe analyses of major and minor elements plus halogens (Cl and F) were carried out with a CAMECA SX50 electron microprobe set in wavelength dispersive mode. For each type of biotite we selected grains from samples which showed the least possible overprinting effects by subsequent alteration stages (e.g. chloritic and sericitic). For each type of biotite we have calculated structural formulae, mole fractions of phlogopite, annite and siderophyllite, relative halide enrichment factors and halogen acid fugacities relative to H_2O, according to Munoz (1984 and references therein).

Octahedrally coordinated major elements, i.e. Al(VI), Ti, Al, Mg and Fe(tot), and halogens (F, Cl) show the most interesting variations. Biotite I is characterized by relatively high Ti, Mg and halogens, but low Fe and very low Al. Biotite II displays a relative enrichment of Al and halogens, but relative depletion of Ti and Mg. Biotite III is relatively high in Ti and halogens. Biotite IV is characterized by relative Ti and Fe enrichment coupled with relative Mg, Al and halogen depletion. Here we list a set of representative analyses recalculated on the basis of 20 oxygens:
Biotite I - $[K_{1.7}, Na_{0.1}]_{1.8}$ $[Mg_{3.8}, Fe_{1.6}, Ti_{0.4}]_{5.8}$ $[Si_{5.7}, Al(IV)_{2.3}\ O_{20}]$ $(OH_{1.82}, F_{0.13}, Cl_{0.05})$
Biotite II - $[K_{1.9}, Na_{0.1}]_{2.0}$ $[Mg_{3.6}, Fe_{1.7}, Al(VI)_{0.6}, Ti_{0.1}]_{5.8}$ $[Si_{5.2}, Al(IV)_{2.8}\ O_{20}]$ $(OH_{1.83}, F_{0.12}, Cl_{0.05})$
Biotite III - $[K_{1.8}, Na_{0.1}]_{1.9}$ $[Mg_{3.7}, Fe_{1.7}, Al(VI)_{0.3}, Ti_{0.3}]_{6.0}$ $[Si_{5.4}, Al(IV)_{2.6}\ O_{20}]$ $(OH_{1.80}, F_{0.14}, Cl_{0.05})$
Biotite IV - $[K_{1.7}, Na_{0.3}]_{2.0}$ $[Mg_{3.5}, Fe_{1.8}, Al(VI)_{0.1}, Ti_{0.4}]_{5.8}$ $[Si_{5.5}, Al(IV)_{2.4}\ O_{20}]$ $(OH_{1.94}, F_{0.05}, Cl_{0.01})$.

The halide content of a biotite is controlled by crystallochemical parameters, temperature and relative halide concentration in the fluid reacting with this mineral. Linear trends in elemental distributions indicate that the crystallochemical parameters (mainly the octahedral site occupancy) predominate. Non-linear trends suggest that the halide content of biotite is a function of temperature and/or relative concentration of the coexisting fluid. Crystallochemical effects on halogen site occupancy (i.e. the Fe-F and Mg-Cl avoidance of Munoz, 1984) are apparent in some of the biotite types. Biotites I and II follow the Fe-F avoidance trend predicted by Munoz (1984) and confirmed by biotites from the Santa Rita porphyry Cu deposit (USA). Biotite III shows no such trend, or, at most, an opposite one, suggesting thermal or fluid compositional controls on halogen site occupancy, such as those developed in other large hydrothermal systems (e.g. Sisson, 1987). Biotite IV shows an unusual Mg-F avoidance trend, similar to the one reported by Munoz (1990) for the phlogopites from the Stillwater Complex (USA). This is also observed on an IV(F)-IV(F/Cl) plot, in which IV stands for the halogen intercept value, a concentration parameter which reflects the concentrations of both the different cations present in the biotite and the halide(s) of the fluid reacting with it (Munoz, 1984 and references therein). Van Middelaar and Keith (1990) use an X(Mg) vs. log[X_F/X_{Cl}] for the biotites with contours of log[*f*(HF)/*f*(HCl)] in the fluid for the CanTung W skarn (Canada) to infer that the different types of biotites had re-equilibrated with a fluid of constant temperature and chemistry. Their plot shows that the biotite analyses follow a trend parallel to log[*f*(HF)/*f*(HCl)] contours. The same distribution appears on Figure 1 for Biotites I, II and III of this study, suggesting that these minerals have re-equilibrated with a fluid of constant temperature (T=408°C, as calculated from the mean of the halite-saturated fluid inclusions of Trudu et al., 1990) and a log[*f*(HF)/*f*(HCl)] of -0.5 to 0. However, we observe that Biotite IV, at an estimated crystallization temperature of 740°C (inferred from the experiments of Conrad et al.,1988, on rocks of similar composition), shows a completely different trend compatible with a different T-fluid regime during this later stage.

We have found that the most effective way of discriminating amongst the different types of biotite are the Fe vs. Ti, X(Mg) vs. X(Sid) and X(Mg) vs. X(Sid) vs. X (An) plots: in all these plots the four types of biotite fall in fields which do not overlap. These coupled substitutions between cations in the biotite structure do not appear to have been affected by the hydrothermal overprint that affects the halogens. Plots of Ti/F vs. Mg/F (Fig. 2) show well defined linear trends for each biotite type, although X(Mg) vs. halogens plots do it to a very limited extent only. Such broad scatter of the data in the latter plots suggest that halide contents were controlled by fluid halide ratios (and/or temperature). However, the linear trends in Figure 2 and in a companion Ti/Cl vs. Mg/Cl plot suggest partly independent coupled substitutions amongst these components. The latter observation also indicates that the halide ratios in the fluid may not have been the dominant control on the compositions of the biotites. Therefore, calculations defining the effect of halide variations in hydrothermal fluids may not be valid if complex coupled substitutions (e.g. Mg-Fe-Ti-Al-Cl-F in biotites) are ignored.

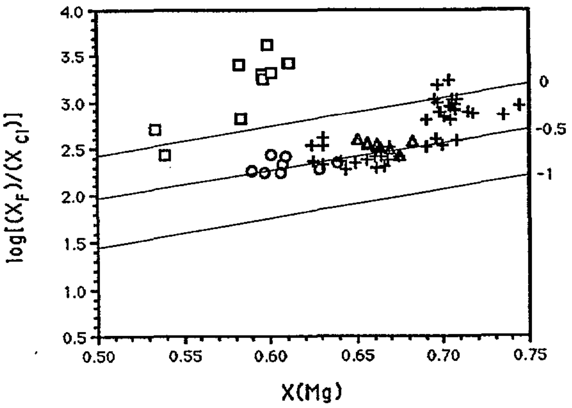

Figure 1 - Plot of X(Mg) vs. log[*f*(HF)/*f*(HCl)]. Contour lines refer to log[*f*(HF)/*f*(HCl)] for a fluid in equilibrium with Biotites I, II and III at 408°C; they do not relate to Biotite IV which is inferred to have crystallized at 740°C. Triangles represent Biotite I (magmatic from the quartz diorite porphyry), circles Biotite II (contact metamorphic), crosses Biotite III (hydrothermal) and squares Biotite IV (magmatic from the dacitic complex).

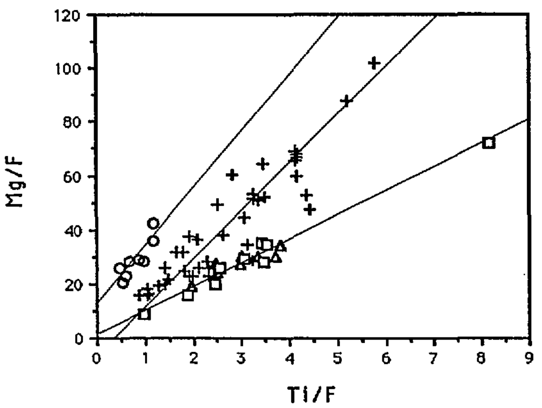

Figure 2 - Plot of Ti/F vs. Mg/F. The symbols are the same as those in Figure 1. Note that the linear regression lines for Biotites I and IV (both of magmatic origin) have been traced as one line, due to their very similar slopes.

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THE IRONSTONE - RELATED COPPER - GOLD (U,REE) ORE ASSOCIATION

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Copper-gold deposits associated with iron oxide rich rocks (ironstones) form a distinctive and significant ore association which occurs widely, though not exclusively, in the Proterozoic. The ironstone association is geochemically distinct from the BIF-hosted gold association (e.g. Phillips and Groves, 1983). Not only is the ironstone association higher in its copper and commonly uranium, REE, bismuth, molybdenum contents, but also the ironstones in many cases do not originate as chemical sediments. Although both associations form in metamorphic environs, they reflect differing tectonostratigraphic settings and with consequent differences in ore-forming fluids and ore-forming mechanisms. This paper discusses the nature and origin of the ironstone-related copper-gold association, utilising examples fromTennant Creek and elsewhere in Australia to clarify the chemical and mechanical systems involved in ore genesis. The genetic model developed emphasises the two stage (or more) origin of mineralization has significant implications for other ore-bearing environments.

Characteristic of the ironstone-related ore association, the Tennant Creek ironstones formed in the first major paragenetic stage, play both chemical and mechanical roles in the localisation of the gold-copper-bismuth mineralization of the district which forms during the second major paragenetic stage (Wall & Valenta,1990; cf Large, 1975 and later).

The ironstones appear to have formed before and during the regional deformation which formed the EW cleavage of the Warramunga Group and exhibit a broad range of orientations and shapes. Ironstone geometries are, however, kinematically consistent with north-south shortening and related flattening and steep extension, early-formed ironstones have undergone progressive deformation in this event. The ironstones are localised in dilational regions (e.g. fault jogs) in more laterally continuous, steeply dipping chlorite-rich zones where these zones intersect hematite-bearing metasediments. Formed during the low grade regional metamorphism (and granitic intrusion?) of the Warramunga Group, the ironstones appear to have resulted from precipitation of the mixing of regionally throughgoing saline fluids with highly oxidised fluids which had interacted with the hematitic facies of the Warramungas. The saline fluids may have been derived from meta-evaporites deeper in the metamorphic pile and/or from granitoid intrusives of Tennant Creek Granite age.

The gold-copper-bismuth mineralization and associated magnesian- and sulphide-bearing alteration formed in small scale and broader dilational zones within and around the ironstones (e.g. Nguyen et. al.,1989). The dilatant zones developed during deformation of the ironstones in phyllosilicate-enriched shear zones. Their distribution is controlled by the shape of the ironstone, strain incompatibility and stress reorientation effects due to the mechanical contrast between the ironstones and their more ductile envelopes. The broader dilational zones focussed fluid flow around the ironstones and fracture-veining of the ironstones allowed ingress of the mineralizing fluids. Shear zone deformation contemporaneous with the gold-copper-bismuth mineralization stage involved reverse to oblique (but small) displacement resulting from reactivation of these structures in the Warramunga Group during regional deformation and low grade metamorphism of its unconformably-overlying cover-rock succession.

Progressive infiltration of oxidised brines into and their reaction with magnetite-Fe chlorite assemblages (comprising the ironstones and surrounds) resulted in progressive reduction of these fluids and the precipitation of chalcopyrite, pyrite, and, more locally uraninite, bismuthinite and gold. Hematite-bearing magnesian alteration zones contiguous with mineralization reflect more advanced metasomatism and precipitation in dilatant zones. The mineralizing brines were sourced within or above the Warramunga cover sequence. Tennant Creek-style mineralization is thus similar in many respects to the unconformity-related uranium-gold-platinoid association.

Although Tennant Creek-style mineralization appears to be uncommon in other terrains, several important features of this ore association are shared by other ore deposit styles, suggesting that the model developed in this paper has broader application to ore genesis and exploration.

The ironstone-associated gold-copper deposits hosted by Proterozoic rocks of the eastern Mt. Isa Inlier (e.g. Davidson, 1990; Davidson et al., 1989,; Switzer et al., 1988; Kary and Harley,1989) are also anomalous in U, LREE, Bi. A two-stage model outlined by Switzer et al. (1988) for the Starra deposit examples of this mineralization has strong parallels with the model suggested here for Tennant Creek mineralization. Apparently precipitated from saline fluids, the Selwyn ironstones were localised in dilatant zones of a fault-controlled, metamorphic-hydrothermal plumbing system attending an early extensional deformation (Pearson et al., 1987) Mechanical contrasts between the massive ironstones and their schistose host rocks localised brittle fracture in the ironstones during later regional deformation and metamorphism, at the gold-copper stage. These fractures facilitated the ingress of the relatively oxidised, hypersaline fluids which effected ore formation.

Oliver, Wall and Pearson (1987, 1990) inferred analogous processes were responsible for the formation of the Mary Kathleen U-REE deposits (which also occur in the eastern Mt. Isa Inlier) under metamorphic conditions and timing relative to the regional deformation history broadly similar to those operative during the formation of the Starra mineralization. However, in the case of Mary Kathleen, a massive iron-rich, pre-regional metamorphic skarn played mechanical and chemical roles comparable to those of the ironstones. The Mary Kathleen ore-forming fluids were also hypersaline and strongly oxidising, due to their interaction with evaporitic successions during metamorphism. The strong REE enrichments and REE mobility that characterise the Selwyn, Mary Kathleen, Tennant Creek deposits and also the unconformity-related uranium ore association appear to reflect the agency of the high salinity fluids in these environments.

Olympic Dam style mineralization also exhibits strong geochemical similarities with the ironstone-related ore association. Hosted by Proterozoic iron oxide rich breccias, the Olympic Dam copper-gold-uranium mineralization is highly anomalous in LREE and at least some of the mineralization postdates the formation of its iron-rich host (e.g. Roberts and Hudson, 1983, 1984; Reeves et al., 1990; Oreskes and Einaudi, 1988, 1990)). We suggest that the evolution of Olympic Dam style mineralization may have more in common with that of the ironston - related association, than just similar geochemistry.

What are the key factors in the evolution of the ironstone - related Cu-Au-U-REE ore association?

At Stage I

- A supply of moderate temperature (greater than 300 C) saline fluids from evaporitic and/or magmatic sources.

- A regional (fault) plumbing system with associated dilational regions facilitating mixing with more oxidised/dilute fluids or interaction with reactive rocks to form iron-rich bodies.

At Stage II (and later)

- Later deformation of these ironstones in a regionally connected plumbing system.

- A supply of oxidised, saline hydrothermal fluids (greater than 200 C) and interaction of these with ironstones in the latter system.

In view of these factors it may be clear that the tectonostratigraphic evolution of the Proterozoic, particularly the middle Proterozoic, provides a range of settings in which the ironstone - related association may develop at different times during the tectonic history of such terranes.

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