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AUSTRALIA'S GREATEST MINERAL DEPOSITS

EXTENDED ABSTRACTS OF THE 23RD ANNUAL CONFERENCE OF THE STATES' MINERALOGICAL SOCIETIES

BROKEN HILL, NEW SOUTH WALES, JUNE 2000

The following abstracts* are associated with the 23rd Annual Conference of the combined Mineralogical Societies of the various Australian States, held in Broken Hill in June, 2000. The theme of the Conference is epitomized in the above title. Eminent experts have agreed to speak on the geology, mineralogy and history of many important Australian deposits of international significance.

Of these, of course, Broken Hill itself is pre-eminent; a focus on "The Hill" is evident in the papers abstracted below. For this reason, if for no other, the setting of the Conference is significant. Reviews of the mineralogy of a number of major deposits are presented, as well as new science being announced for the first time in some instances.

The Conference has been supported by Pasminco Ltd and the City of Broken Hill. Their assistance is gratefully acknowledged. The Royal Society of New South Wales has agreed to the publication of the extended abstracts below as part of the Journal and Proceedings of the Royal Society of New South Wales. This is fitting in the sense that the Royal Society has in the past published many articles on Broken Hill, as well as other aspects of Australian mineralogy. The Royal Society of New South Wales is Australia's oldest learned Institution and its association with the Conference reflects its aims in promoting discourse on all aspects of scientific and cultural endeavour in Australia.

Professor Peter A. Williams
President, the Royal Society of New South Wales
President, the Mineralogical Society of New South Wales

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* Communicated to the Council of the Royal Society of New South Wales by Professor P.A. Williams

Mineral Occurrences in the Olary Domain, South Australia

P.M. ASHLEY

The Olary Domain forms part of the Curnamona Province, a large nucleus of Proterozoic rocks located in eastern South Australia and western New South Wales. The Olary Domain is contiguous to the Broken Hill Domain to the east and is dominated by metamorphic rocks of the Palaeoproterozoic Willyama Supergroup, together with significant amounts of Palaeoproterozoic and Mesoproterozoic intrusive rocks. Although large mineral deposits analogous to Broken Hill have not been discovered to date in the Olary Domain, there exists, nevertheless, a diverse range of mineralisation types, as well as metamorphic and metasomatic rocks, from which a wide variety of minerals, both common and unusual, may be obtained.

The Willyama Supergroup sequence in the Olary Domain displays regional correlations with that in the Broken Hill Domain, although there are numerous differences in detail. The lower part of the Olary Domain sequence is dominated by composite gneiss and migmatite. These rocks grade into the Quartzofeldspathic Suite. This contains the “Lower Albite” unit, dominated by ~1715–1700 Ma A-type metagranitoids and felsic metavolcanic rocks (Ashley *et al.*, 1996), the “Middle Schist”, dominated by psammopelitic schist and composite gneiss, and the “Upper Albite”, dominated by finely laminated albitite, as well as minor amounts of iron formation. The Quartzofeldspathic Suite grades up-sequence into the Calcsilicate Suite, dominated by laminated calc-albitites and minor calcsilicate and Mn-rich rocks. In turn, there is an up-sequence transition into the Bimba Suite, dominated by calcsilicate rocks and marble, locally with abundant Fe–Cu–Zn sulfides, and minor pelite and albitite. The Bimba Suite is overlain by a regionally sharp contact with the Pelite Suite, composed of pelite and psammopelite, psammite, tourmalinite and manganiferous iron formation (Page *et al.*, 1998).

Several intrusive suites occur in the Olary Domain and there have been at least five deformation and metamorphic events (Flint and Parker, 1993; Ashley *et al.*, 1997a). A-type granitoids were emplaced at ~1715–1700 Ma and co-magmatic rhyolitic volcanic rocks were erupted. Several small I-type granitoid bodies were emplaced into the central part of the Olary Domain at ~1640–1630 Ma. A major episode of deformation and amphibolite grade metamorphism occurred in the Olarian Orogeny at ~1600 ± 20 Ma, with subsequent emplacement of voluminous S-type granitoids and associated pegmatite bodies. Regional-scale retrograde metamorphism and alteration may have followed episodically between ~1580 Ma and ~1500 Ma, and there were further thermal perturbations during the Musgravian Orogeny at ~1200–1100 Ma. Mafic dyke emplacement at ~820 Ma was a precursor to development of the Adelaide Geosyncline and at least two episodes of low grade metamorphism and deformation occurred between ~500–450 Ma during the Delamerian Orogeny.

Regional-scale hydrothermal alteration has affected much of the sequence, as well as some intrusives, within the Olary Domain. Fluids have been high-temperature (~450°–600°C), commonly oxidizing and saline. They may have been derived by metamorphism of the host sequence, although there is a possibility of some magmatic fluid. Widespread metasomatism of.the Willyama Supergroup, and some of the intrusives, has occurred episodically between ~1630 Ma and ~1500 Ma, with development of Na–Fe assemblages (mainly albite ± Fe oxides, pyrite), with local strong Fe-metasomatism of iron formations and albitites and Ca–Fe(–Mn)-metasomatism of calcsilicate rocks (commonly in association with spectacular breccias), marble and quartzofeldspathic rocks.

Several styles of mineral deposits are recognised in the Olary Domain, including early syn-sedimentary or diagenetic types, various hydrothermal deposits related to intrusives, to metamorphic and alteration events, and to later weathering and redox-controlled processes (Ashley *et al*., 1997b). Syngenetic and/or diagenetic deposit styles are represented by Fe–Zn–Pb sulfides in the Bimba Suite, iron formations and barite in the Quartzofeldspathic Suite and Mn-enrichments in the Calcsilicate and Pelite Suites. Manganiferous iron formations in the Pelite Suite are closely analogous to iron formations associated with the Broken Hill ore bodies. In the Bimba Suite, stratiform laminated to massive and disseminated sulfides are common in calcsilicate, marble and pelitic rocks and have given rise, in part, to extensive, base metal-anomalous gossans. Epigenetic mineral deposits are represented by various types of hydrothermal replacements, vein/stockwork systems, and rare metal pegmatites and U–Th–REE deposits related to the ~1600 Ma S-type granitoids. Supergene oxidation and diagenetic processes from the Mesozoic to Recent has led to Cu–Co–Au enrichment deposits and redox-controlled U and Au deposits, especially to the north of the outcropping Olary Domain.

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The Iodine Puzzle at Broken Hill

BILL BIRCH

Almost from the time of discovery of the Broken Hill lode, the richness of iodine in the Broken Hill oxidized zone became apparent. Not only were large masses of silver iodide found, but a strong iodine smell was also reported when mining operations broke into cavities rich in the iodine minerals.

The main iodine-bearing mineral is the hexagonal polymorph of silver iodide, iodargyrite. It was found in rich patches in the upper levels of the oxidized zone, especially in the Proprietary Mine, and also in the Australian Broken Hill Consols Lode, a few hundred metres to the east (Birch, 1999). In the main lode, iodargyrite occurred in two main environments. In the outcropping portion, or gossan, iodargyrite was found with other minerals such as chlorargyrite, cerussite and smithsonite, in cavities in secondary manganese and iron oxyhydroxides. In the complex oxidized zone below the gossan, iodargyrite was concentrated in masses of kaolinite containing other silver and mercury minerals.

Minor to rare amounts of other iodine-bearing species have been found at Broken Hill, most notably in the series marshite-miersite (cubic CuI-AgI), whose crystals are small and rare. Small amounts of iodine are present in minerals of the chlorargyrite-bromargyrite series, and in the complex mercury silver sulfide halide species such as perroudite and capgaronnite.

Despite the abundance of iodine in the secondary zone, and the existence of several synthetic polymorphs of silver iodide, only iodargyrite and its cubic polymorph miersite have been recorded. Also, despite the aridity of the region, no minerals containing iodine in a higher oxidation state (iodates) have been found. The structural, geochemical and temporal complexity of the Broken Hill oxidized zone makes it impossible to model the distribution of iodargyrite and groundwater. It appears that the concentrations of iodide ions in groundwaters were anomalously high, but there are no data on these concentrations.

It is postulated that AgI precipitated in the oxidized zone from solutions containing excess iodine. These solutions became concentrated by evaporation accompanying capillary action with a fluctuating water table. The richness of iodargyrite in kaolinite masses suggests the clay mineral had properties which effectively lowered the solubility of AgI. It is likely that there has been episodic precipitation of silver iodide in the oxidized zone during climatic fluctuations over the past few hundred thousand years or more, although the exact timing is unknown. There are two main sources possible for the iodine. The first is the sulfide ore itself, which is known to contain trace amounts of the element, probably in either the galena or in silver-bearing tetrahedrite. It is not known whether the iodine is incorporated in the sulfide lattice or is present in fluid inclusions. The other possible source is from seawater which originally filled the so-called ‘Murray Sea’ (now the Murray Basin). Windblown spray, or possibly seaweed built up around ancient shorelines, may have provided a source of iodine for groundwaters to concentrate.

There are other occurrences of iodargyrite in or adjacent to the Murray Basin region. At the Iodide mine at Mineral Hill, north of Condobolin in New South Wales, iodargyrite occurred in the oxidized zone above primary silver-lead-zinc sulfides. At Lake Boga, near Swan Hill in Victoria, a few small crystals of iodargyrite have been found on supergene copper sulfides in granite. Elsewhere in Australia the mineral is almost unknown, so it appears there is a regional concentration in the Murray Basin. Weathering and erosion of the Broken Hill oxidized zone may have distributed iodine widely into the regional hydrogeological environment over millions of years.

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The Mount Lyell Mines, Tasmania

R. BOTTRILL

The Mt Lyell mining field is situated in the West Coast Range between Mt Owen and Mt Lyell, near Queenstown, in western Tasmania. The field comprises numerous workings, open cut and underground, on more than 20 separate orebodies, in an area of ~10 square km. The Mt Lyell Mine is one of the oldest significant mines in Australia and has been operating almost continually for nearly 120 years. The mines have produced about 1.5 Mt of copper, 50 t of gold and 850 t of silver from some 130 Mt of ore in their lifetime and, despite a chequered history, the present owners talk of the mine continuing for another fifty years or more (a vast age compared to most modern mines). The mine is mineralogically most important as the co-type locality for the rare copper-iron-tin sulfide mawsonite, named after Sir Douglas Mawson, the Antarctic explorer and geologist. However, many other rare minerals are also recorded from these mines, including betechtinite, florenceite, svanbergite-woodhousite, stannoidite, hessite, jalpaite and stromeyerite. At least 85 species have been reported from the mines, many being found as attractive specimens.

The first lease in the field was on the Iron Blow, an ironstone outcrop at the head of the Linda Valley, pegged for gold in 1883. This mine struggled as a gold mine for several years, until Bowes Kelly and William Orr, both successful investors from Broken Hill, tested samples at the Broken Hill smelters and showed they were buying a copper mine. The mining engineer Robert Carl Sticht (for whom stichtite was named) was brought over from America in 1895. He developed the revolutionary pyritic smelting process which turned the economics of the mines around, and was the most important metallurgical process for sulfide ores until the development of sulfide flotation at Broken Hill.

The Mt Lyell copper-silver-gold deposits are best considered as Cambrian volcanogenic sulfides partly remobilized by Devonian hydrothermal fluids (Solomon *et al.*, 1987; Arnold and Carswell, 1990). The mineralisation is mostly hosted by schistose, highly altered rhyolitic to andesitic lavas and tuffs of the Cambrian Mt. Read Volcanics, with minor occurrences in Ordovician conglomerates and limestones, and is controlled by the intersection of two major faults. The mineralized zone is up to about 800 m thick. There are five major styles of mineralisation:

1. massive pyrite-rich bodies, with colloform textures and high grade copper, gold, arsenic and silver-rich shoots, postulated to have formed at or near the Cambrian seafloor;
2. banded, thin, pyrite lenses with chalcopyrite, galena and sphalerite (volumetrically very minor), also generally considered to be deposited near the Cambrian seafloor, like many volcanogenic massive lead-zinc deposits (*e.g.*, Rosebery, Hellyer);
3. disseminated, low to moderate grade, chalcopyrite and pyrite (the major ore type in recent years), is highly deformed and also generally considered to be Cambrian in age, probably formed during early sub-seafloor alteration of the volcanics;
4. higher grade bornite-rich ores along the Great Lyell Fault appear to have been remobilized during Devonian syn-deformational, fault-related hydrothermal events, very common in Western Tasmania and often associated with Sn-W-Bi-Pb-enriched Devonian granites;
5. "copper-clay" deposits containing native copper, cuprite, chalcocite and other sulfides in clays derived from deeply weathered argillaceous Ordovician limestones. The origin is not clear but could be either related to Devonian hydrothermal activity, or Ordovician to Recent weathering.

High grade ore shoots in the massive pyrite bodies were the original ores mined (after working of the gossan cap for gold), particularly in the Mt Lyell (Blow) and South Lyell Mines. These shoots contained pyrite, chalcopyrite, tetrahedrite, tennantite, stromeyerite, jalpaite, arsenopyrite, molybdenite, enargite and 2-3 ppm gold. Gangue minerals include quartz, barite, haematite, sericite and pyrophyllite. The banded pyrite ores contain grades of up to 28% lead and 20% zinc. The disseminated mineralisation constitutes the principal ores mined in recent decades, particularly from the Prince Lyell Mine. The ores contain pyrite, chalcopyrite, and minor tennantite, molybdenite, galena, sphalerite and bornite, with traces of other sulfides, tellurides and selenides. The ores grade about 1-2% copper, 3 ppm silver and 0.3-0.4 ppm gold. Gangue minerals, in approximate order of abundance, include quartz, muscovite, chlorite, siderite, magnetite, haematite, rutile, pyrophyllite, apatite, barite, fluorite, calcite, ankerite, zircon and monazite. Bornite-rich mineralisation is characteristic of the North Lyell area but is somewhat variable in nature. The ores grade about 4-8 % copper, 30-50 g/t silver and 0.4-1 g/t gold. Ore minerals include bornite, chalcopyrite, pyrite, chalcocite, tennantite, galena, betechtinite, mawsonite, digenite, sphalerite, molybdenite, linnaeite, and stromeyerite. Gangue minerals are as above, but cherty quartz, barite, fluorite and haematite are typically more abundant. The "copper- clay" deposits are locally very copper rich but have only constituted a small part of production to date. They contain native copper, cuprite, chalcocite, digenite, bornite, covellite, chalcopyrite, galena, sphalerite and goethite in illite-kaolinite clays.

Massive chalcopyrite and bornite samples may be quite coarse and colourful, but most of the rarer minerals are microscopic. Gossans were poorly developed due to glaciation and erosion, but some good malachite occurred in them. Good copper and cuprite crystals occur in the "copper- clays," but most good collectable minerals (crystalline, mm to cm sized) occur within late, open veins and fractures, and include albite, barite, calcite, chalcopyrite, chlorite, cuprite, dolomite/ankerite, fluorite, fluorapatite, haematite (specular), pyrite, quartz (large crystals, some with stunning haematite and chlorite inclusions) and siderite.

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Minerals of the Cobar Mining District

J.R. CHAPMAN

The Cobar district has been a significant mineral producer since the discovery of copper in 1870 at what later became the Great Cobar Mine. By the turn of the century the district had become one of Australia's main copper producing areas. Significant gold, lead, zinc and silver production is associated with several deposits. The geology of the area comprises deformed sedimentary sequences of Early Palaeozoic age. Mineral deposits typically form steeply plunging sulfide lenses that extend to great depths. There has been much debate on the origin of the deposits but it is generally accepted that most formed from deep basinal hydrothermal fluids focussed along regional structures.

Primary sulfide minerals in the deposits include abundant pyrite, pyrrhotite, chalcopyrite, galena and sphalerite, with lesser amounts of tennantite, tetrahedrite, enargite and arsenopyrite. Cubanite is a common accessory and bismithunite is found in minor amounts in many of the deposits (Rayner, 1969). There was very little open space in the primary ores and, except for euhedral cubes of pyrite, sulfide minerals are mostly massive. The CSA Mine has produced well crystallized specimens of pyrite forming lustrous cubes to 1 cm and rounded aggregates to 15 cm in size. Rare chalcopyrite crystals to 3 cm, and small, unusual, acicular crystals of cubanite have also been collected at this mine. Secondary minerals derived from oxidation of primary sulfides are common on the field; weathering commenced in the Cretaceous to Middle Miocene period (97-16 Ma) and has continued to the present (Leah, 1996). The following occurrences are noteworthy.

Fine examples of azurite ($Cu_3(CO_3)_2(OH)_2$) were collected from Great Cobar, Gladstone and Mount Hope Mines. Recent mining at Girilambone exposed beautiful specimens of well-formed and lustrous crystals to 4 cm and stacked aggregates to 7 cm in length. Malachite ($Cu_2CO_3(OH)_2$) is ubiquitous in the copper deposits and was best represented in the Great Cobar Mine where it occurred as masses of acicular crystals forming velvety to dense laminar coatings and crusts.

Beautiful cone-shaped aggregates to 2.5 cm in length showing silky chatoyantcy were collected from the Great Cobar Mine and similar specimens are noted from the Nymagee Mine.Very fine examples of complete or partial pseudomorphs of malachite after azurite are common, particularly from Great Cobar and Mount Hope.

Native copper (Cu) forms thick, arboresent to delicate, dendritic masses, sometimes with well-formed crystals, particularly at Cobar and Mount Hope Mines. Cuprite (Cu_2O) is often associated with native copper as coatings or small octahedral crystals. Carne (1908) reported that it occurred at the Great Cobar Mine in '*massive bunches of great purity near the surface*' while Andrews (1913) claimed it to be common in all copper mines at groundwater level. The acicular form, *chalcotrichite*, was also encountered in the mines at Cobar. Copper phosphate minerals are prominent in some deposits. Mammillary masses of pseudomalachite ($Cu_5(PO_4)_2(OH)_4$) from the West Bogan Mine near Tottenham are among the finest examples of this mineral in the world. Pseudomalachite was abundant at Girilambone as crusts and coatings on gossan and other minerals, intergrown with malachite, as replacements after libethenite and as very small sprays of emerald green crystals showing an unusual helictite-type structure. Also at Girilambone, libethenite ($Cu_2PO_4(OH)$) occurred as light to dark green, stubby, prismatic and tetragonal bipyramidal crystals 1-6 mm in size, abundant in the upper parts of the oxide zone.

In the Elura lead zinc silver deposit, a zone of supergene enrichment that averaged 0.3% Ag was mined during the 1980s. This zone provided a treasure of mineral specimens.

Native silver (Ag) was abundant, occurring mostly as fine, delicate groups of small crystals dispersed through gossan. In places it formed spongy masses to thick dense wads many kilograms in weight. Coarser elongated crystals commonly referred to as wires were common, ranging up to 200 mm long and 5 mm thick. Mimetite ($Pb_5(AsO_4)_3Cl$) was the most prominent lead mineral. Larger crystals formed yellow to green, barrel-shaped hexagonal prisms, tending to flatter hexagonal prisms with increasing size. Spectacular specimens of large green crystals to 2.5 cm in length are among the best in the world. Cerussite ($PbCO_3$) occurred as delicately reticulated specimens or as crystals, often exhibiting a sixling habit. Native silver crystals grown on cerussite were reasonably common, an unusual association also noted from the CSA Mine.

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Greenbushes: a 19th Century Mine Producing 21st Century Minerals

PETER CLARK

The Greenbushes rare-metal pegmatite in Western Australia is unquestionably deserving of inclusion in any list of Australia's greatest mineral deposits; its size, complexity, mineralogical diversity and production make it a world class mineral deposit. It is situated some 300 km south of Perth and 80 km SE of the Port of Bunbury and lies in the Western Gneiss Terraine of the south-west portion of the Yilgarn Block. The deposit is one of the world's largest lithium and tantalum resources. Currently the mine produces about 20% of the world's tantalum and is the world's largest lithium producer. Production has been continuous for over 100 years and reserves of tantalum are sufficient at the current mining rate to last a further 17 years. The pegmatite is notable for the occurrence of tantalite and spodumene as well as the rare tantalum minerals stibiotantalite, holtite, microlite, tapiolite, and wodginite (Hatcher and Clynick, 1990). The rare amphibole holmquistite (lithium glaucophane) is found in the exocontact zone (Witt, 1990).

Cassiterite was found in the area by a kangaroo hunter D.W. Stinton in 1888, although the Government Geologist E.T. Harding had a role in the discovery. Mining commenced in 1888 with tin being produced since that time. Early operations were small scale and in 1893, as a result of tin smelting problems, the presence of stibiotantalite and tantalite was confirmed. It was not until 1944 that markets for tantalum were established. More recently, tantalum and lithium have become the major revenue earners. In 1949, spodumene was identified by the Geological Survey of Western Australia in a specimen collected in 1928 and previously identified as feldspar. Until 1970 most production came from alluvial deposits and small underground and open pit operations. At that time, Greenbushes Ltd amalgamated all of the small mining tenements on the field and began production from the weathered pegmatite. Price increases in the late 1970s saw increased production and exploration in the weathered zone and the world significance of the deposit became apparent. Between 1977 and 1980, deep exploration drilling confirmed an extensive primary deposit below the weathered zone. The complex nature of the pegmatite was revealed and enriched Sn-Ta and Li zones were delineated. In 1990 Gwalia Consolidated Ltd took control of the operations of Greenbushes Tin and Lithium Australia; Sons of Gwalia Ltd are the current operators.

The Greenbushes pegmatite is part of a dyke swarm some 7 x 1 km in size intruded along a NNW shear zone within the Balingup Gneiss Complex (Witt, 1990). Pegmatites have intruded a sequence of metasediments and metabasic igneous rocks. The longest body, about 3.3 km long and up to 250 m wide, has been drill-tested to a depth of 500 m. The pegmatites dip at 40° to 50° W. Contacts are sharp but comprise mylonite zones while xenoliths occur within the pegmatites, which have been recrystallized with a grain size of generally less than 1 mm. Gneissic textures with mineral banding are common. It is evident that the genesis of the deposit is complex as is clearly shown by the multiple intrusion of pegmatite and dolerite dykes along a reactivated shear zone.The pegmatite is zoned and contains three internal asymmetric zones along with a discrete contact zone (Table 1).

The mineralogy of the deposit has been described by a number of workers (East, 1894; Simpson, 1952; Pryce, 1971; Pryce and Chester, 1978). Simpson (1952) described the occurrence of stibiotantalite ($SbTaO_4$) in detail and made the point that the mineral was found only in small quantities and in fragments generally < 3 cm in diameter. East (1894) described stibiotantalite thus: "*the mineral is essentially a tantalate of antimony, part of the tantalic acid being replaced by niobic acid and part of the antimony oxide by bismuth oxide.*" The mineral was described by the alluvial miners as "resin tin" and was a deleterious component of the ore. Pryce (1971) described the new mineral holtite ($Al_6(Ta,Sb,Li)[Si,As)O_4]_3BO_3(O,OH)_3$) occurring with tantalite and stibiotantalite. Both stibiotantalite and holtite form pseudomorphs after tantalite.

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Table 1. Zoning of the Greenbushes Pegmatite

Unit	Major minerals	Accessory minerals	Geochemistry
exocontact	biotite, holmquistite	tourmaline, garnet, arsenopyrite	Li (As)
contact	albite, quartz, Tourmaline	garnet, apatite, muscovite; Sn, Ta, and Nb oxide minerals	Na (Sn, Ta, Nb)
K-feldspar	quartz, microcline	tourmaline, spodumene	K. Rb (Cs) (B, Li)
albite	albite, quartz, tourmaline, Muscovite	apatite, spodumene; Sn, Ta, and Nb oxide minerals	Sn (B, Sn, Ta, Nb, Be)
spodumene	spodumene, quartz	albite, apatite	Li, Na (P)

The Nature and Significance of Colloform Textures in the Pernatty Lagoon Copper Deposits, South Australia

ROBERT A. CREELMAN

The most significant of the Pernatty Lagoon copper deposits occur along a major disconformity within Adelaidean rocks of the Stuart Shelf, a subdivision of the Adelaidean Supergroup. Adelaide Supergroup rocks form a middle to late Proterozoic apron around the older and deformed Gawler Craton The sediments were derived from the crystalline basement of the Gawler Craton to the west, but the Mt Painter and Willyama Inliers to the north-east were sources that made contributions to later rock units. Graben structures provided deep basins which accumulated thick blankets of sediment throughout Adelaidean time. On the Stuart Shelf the sediment wedges were thin following the deposition of the relatively thick Willouran Pandurra Formation. Post Pandurra Formation units lap onto the Pernatty 'Culmination', a major paleostructural high on the Stuart Shelf. The Cattle Grid orebody was the most significant of the deposits. The sulfides occurred along a disconformity between the Pandurra Formation, a quartzite, and the Whyalla Sandstone. There is evidence in other areas that breccias and disconformities – open spaces in the rocks, localize the mineralisation. A full description of the geology and the ore deposits can be found in Creelman (1984) and Tonkin and Creelman (1990).

Metal sulfides that deposit in the body of the rock can be early in the rock history, before diagenesis, or later than diagenesis. Whether consolidated or unconsolidated, deposition in a rock body requires open spaces, or if open spaces are not available, then the depositing minerals must create space for themselves. The accommodation can be accomplished in three ways:

1. the mineral grows in open fissures or cavities in the rock. The process is called 'secretionary growth' (Ramberg, 1952);
2. the mineral grows in a space by pushing aside other minerals as it crystallizes. The process is called 'concretionary' growth (Ramberg, 1952);
3. the mineral grows by replacing an older mineral or cluster of minerals occupying space in the rock mass. This is chemical replacement *sensu stricto*.

Although it is possible to isolate one of the three processes as dominant in any depositional situation, clearly all three can operate simultaneously and some situations are the product of the combination in whole or in part. There are many good examples of minerals that fill spaces in the Pernatty Lagoon copper deposits. The interstitial sulfide minerals in the arenites, vughs coated by sulfide crystals, and the colloform textures in the Pernatty Lagoon ores are all notable examples. Other examples are the carrollite-arseniferous pyrite spheroids, marcasite rosettes, and framboidal pyrite. It is the colloform textures that are of special interest in the Pernatty Deposits.

Colloform texture is defined as rounded reniform masses of mineral which result from colloidal precipitation. Ramdohr (1969) writes that according to the laws of physical chemistry all colloidal precipitates are metastable with a tendency to crystallize. This manifests in the loss of water as crystallization proceeds, perhaps with later increase in grain size and an exsolution-like precipitate of other minerals. Ramdohr notes that sphalerite and milnikovite-pyrite are the most common sulfides exhibiting colloform textures, although rotund and spherical forms of minerals, banding accompanied by syneresis cracking and pellet or oolitic structures are relatively common in oxides of iron, manganese and aluminium. Ramdohr's ideas are based on work by Rodger (1917) and Grigoriev (1928) who included all reniform shapes made up of fine crusts, spheroids, vesicular, bubble-like masses, concentrically banded radial spheroidal masses, and devitrified masses of various forms dominated by concentric or reniform structures. Grigoriev extended the definition to Liesegang rings and shells that included solid material more appropriately classified as concretionary growth.

The above ideas have left an indelible mark on the definition of what is colloform as it was a self-evident truth that colloform textures indicated the involvement of a colloid or gel stage during deposition. Roedder (1968) systematically examined the many textural criteria used to argue for gels and found them to be either ambiguous or invalid. Roedder considered that the dominant parameter controlling colloform texture formation is a high degree of super-saturation that results in many points of nucleation and rapid crystallization. The result is many small crystals coated on a flat surface, rather than a few large crystals that grow in the depositing fluid. Super-saturation is easy to achieve in solutions of substances that have low solubilities.

The balance between conditions that produce fine banding and those that grow large crystals is delicate. Roedder postulated that a flowing fluid becoming more saturated as it moved through a conduit could grow crystals, but stagnant solutions at very high levels of super-saturation produce colloform layers. It is noteworthy that large chalcocite crystals are directly associated with colloform textures in the Cattle Grid ores, which implies that conditions of colloform deposition have given way to those that produce crystals. The change from colloform deposition to crystal growth deposition is, using Roedder's criteria, indicative of changing hydrological conditions from stagnation to flow.

A change from one mineral phase to another in the fine bands is indicative of changing geochemical conditions. The majority of the bands seen in the Pernatty Lagoon ores are sulfur-rich bornite and chalcopyrite that represent low redox conditions relative to chalcocite (Garrels and Christ, 1965; Creelman, 1984). Redox levels are possibly the most variable parameter in the Pernatty groundwaters and are directly related to the activities of HS^- and S^{2-} in the solutions. At ambient temperatures the only demonstrated mechanism that produced sulfides is biogenic reduction of sulfate. Lambert *et al.* (1971) found sulfate-reducing bacteria in all groundwaters around Pernatty Lagoon, including the hypersaline playa lake waters themselves. An explanation of the banding must therefore involve variations in biogenic activity. Biogenic sulfate reduction is controlled by the supply of nutrient to the bacteria and, if the system is closed with respect to sulfur, it is possible that depletion of sulfur or oxygen will result in progressively lower levels of sulfide production, which can be redressed by recharge. It is then possible to have a series of bacterial blooms and decays which result in either excess sulfide or depleted sulfide supply.

The recharge is the temporal control. Roedder favoured the change in hydro- geochemical conditions as due to the annual fluxing of groundwater recharge, which would bring new nutrient and perhaps redistribute depleted elements and radicals. He consciously used the term "varve" to describe the bands. Annual recharges are not necessarily the only mechanism. Longer term aquifer recharges, *e.g.*, one in ten, twenty or even one hundred years are all possible redistribution-resupply events. What is necessary is the temporary removal of stagnation conditions in the groundwaters, *i.e.*, to periodically open the system.

The significance of colloform textures at Pernatty Lagoon is that they represent remobilization and redeposition of copper-bearing sulfides under special geochemical conditions. Normally, redeposition of copper-bearing sulfides results in covellite, but in the case of the colloform textures redox levels have been low enough to redeposit iron as well as copper. Such conditions can only be the result of active bacterial reduction in aqueous media. It is postulated that changing redox conditions, reflected by bands of different sulfide phases, represent blooms and decays of biogenic activity. Above all, colloform banding is the product of supersaturation in the aqueous media under hydrological conditions that are at, or approach, stagnation and the texture is evidence for 'supergene' enrichment under active reducing conditions. The fine banding is particularly fragile as copper and copper iron sulfides re-equilibrate, recrystallize and are easily replaced with only minor changes in physical and chemical conditions. The texture is consequently rare and only seen in ore deposits where the processes are close to or contemporary.

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The Origin of Fault Zone Minerals at Broken Hill, New South Wales

ANDREW GALLACHER & IAN PLIMER

The Palaeoproterozoic Willyama Supergroup comprising metasediments and meta-igneous rocks, is the host to the overturned Broken Hill orebody. The orebody underwent a number of distinct events of coeval deformation and metamorphism in the Palaeoproterozoic and metamorphism and deformation at 520 Ma. The orebody has a long history of both prograde and retrograde sulfide deformation, metamorphism, retexturing and new mineral formation. Late stage brittle deformation took place well after the 520 Ma event, probably in the Mesozoic or later (Stevens, 1999).

The brittle deformation zones, which transgress the orebody, are planar and vary from millimetres to metres in width and displace the Broken Hill orebody. The carbonate-rich fault zones commonly bifurcate, rarely contain vughs lined with terminated crystals in cavities metres in length and contain a diversity of clasts of high metamorphic grade sulfide rocks. The fault planes are strongly slickensided. The fault zones act as an aquifer and, closer to the surface, fault zones contain goethite, rare gypsum and supergene clay minerals.

The fault zones are mineralogically unusual because they contain no lead or zinc minerals yet are enclosed by a 280 Mt massive lead-zinc orebody. Furthermore, the Broken Hill orebody is unusual when compared with other massive sulfide deposits because it contains a paucity of iron sulfide minerals. By contrast, iron sulfide minerals are common in the fault zones. The fault zones have produced spectacular samples of manganoan calcite, kutnahorite, rhodochrosite, neotocite (*sturtite*), chlorite, inesite, fluorapatite, alabandite, pyrite, marcasite and amethystine quartz. There was a sequential deposition of minerals in the fault zones (Plimer, 1982).

Electron microprobe analyses of blocky, fibrous and terminated fault zone carbonates shows that there is a great variation in the Mn content of carbonate minerals. In places, this variation is repeated over a number of cycles. Fault zone minerals contain very small necked-down fluid inclusions along cleavage planes.

Attempts to date the fault zone apophyllite using Rb-Sr techniques failed. Recalculation of the model ages shows that mixing probably did not take place and, although fluorapophyllite is commonly the last phase precipitated in vughs, it is poorly Sr retentive. Loss of Sr was probably due to a long history of fluid flushing along fault zones. The high initial Sr values (0.811-0.872) for fault-zone carbonates compared to carbonates in the enclosing orebodies (0.716) suggests that fault zone carbonates derive from metasediments and that the fault zones are not in isotopic equilibrium with the orebodies.

Sulfur isotope studies on the Broken Hill orebody show a great consistency with a cluster around 0 per mil. Mylonite zone-hosted Thackaringa-type deposits emplaced at 520 Ma also cluster around 0 per mil. Pyrite from the fault zones is extremely isotopically negative suggesting kinetic fractionation of sulfur isotopes or highly fractionated sulfur isotopes derived from biological material. Carbon and oxygen isotope analyses of fault zone carbonates show extremely light carbon and variable but overall light oxygen. The carbon and oxygen isotope values of fault zone minerals are unlike the carbon and oxygen isotopes in the enclosing orebody.

It is concluded that the components in the fault zones at Broken Hill did not derive from the enclosing Broken Hill Pb-Zn orebody. On the assumption that the fault zone hydrothermal minerals formed from ascending and not descending fluids during and after brittle deformation, the source of the light stable isotopes can be determined. Because the Broken Hill orebody occurs on the downward facing limb of a recumbent fold, the upper part of the Willyama Supergroup stratigraphy has been beneath the orebody since Palaeoproterozoic folding. The uppermost part of the Willyama Supergroup is the Paragon Group, a sequence of carbonaceous (and rarely sulfidic) pelites with rarer psammopelites, pelites and calc-silicates. The carbonaceous and sulfidic material of the Paragon Group is of biological origin.

It is concluded that there was an episodic flushing of low temperature reduced carbon- and sulfur-bearing fluids up faults from the underlying Paragon Group in Mesozoic or younger times. Fault zone minerals were precipitated from fluids undersaturated to saturated in carbon dioxide; fluids associated with the final phases of mineralization were strongly acid. If any components in the fault zone could have derived from the enclosing Broken Hill orebodies, then it is possible that the minor amounts of manganese and fluorine in the fault zones may have derived from fluid-sulfide rock interactions.

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The Occurrence and Origin of Gold Nuggets in Victoria

DERMOT HENRY

Victoria has produced in excess of 2500 tonnes of gold (some 80 million ounces) since gold mining commenced in 1851. Exceptionally rich alluvial deposits attracted hopeful prospectors from overseas to the newly founded Colony in the early years of the rushes; later, quartz reef mining prolonged the industry. The occurrence of large gold nuggets throughout the alluvium provided the greatest fascination on the goldfields. Many large nuggets were discovered on or close to the surface while others occurred in buried auriferous alluvium in "shallow" or "deep leads". The allure of discovering a nugget and gaining instant wealth sustained many prospectors. Dunn (1912) noted however, *"there is a tragic side to nuggets also, for in the early digging days the sudden acquisition of more or less wealth in the form of a nugget* *often caused the mind of the finder to become unhinged".*

The Victorian goldfields have produced more and larger gold nuggets than any other goldfield. *A List of Nuggets Found in Victoria* published by E. J. Dunn (1912) listed some 1327 nuggets ranging from the largest, the Welcome Stranger, weighing some 2520 ounces down to nuggets of the order of 20 ounces. The *List* is not regarded as complete. In recent years with the ready availability of metal detectors nuggets continue to be unearthed with several examples greater than 200 ounces brought to popular attention.

Since the earliest discoveries of nuggets numerous theories were suggested to explain their origin. The theories polarised into two camps:

1. the nuggets were derived from adjacent auriferous quartz reefs.
   The proximity of many large nuggets to reefs was viewed as compelling evidence that they had been derived from these reefs. Many nuggets also contained large fragments of angular quartz or indentations from quartz crystals;
2. the gold had precipitated *in situ* from groundwater. Gold precipitated in timber found in deep leads or associated with pyrite which had replaced roots, branches and stems of recent trees was regarded as proof of the occurrence of gold in meteoritic waters (Newbery, 1868; Smyth, 1869). The purity of the nuggets in comparison to small fragments of gold in the reefs and the scarcity of large masses of gold within the reefs were also cited as evidence that the nuggets had formed *in situ*.

Supergene gold has been recorded from numerous deposits around Australia and overseas (Wilson, 1984; Boyle, 1979). Some gold nuggets from the Coolgardie region Western Australia contain concretionary iron oxides "limonite." The gold completely encloses the nodules and the iron oxide nodules contain finely disseminated gold. This has been cited as evidence that these nuggets accreted in the deposits and are associated with laterite horizons. Other nuggets in this field are intimately associated with quartz reefs.

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Mineral History of the Mount Morgan Copper-Gold Deposit, Queensland

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The Mount Morgan pyritic copper- gold deposit, 37 km south-south-west of Rockhampton in central eastern Queensland, was discovered in 1882 and over the ensuing eighty years produced 199,000 kg of gold and 295,900 tonnes of copper metal. The deposits occur within a sequence of rhyolites, diverse volcanoclastic sediments, jasper, chert, lava and limestone blocks and crystal-rich pumiceous breccia. These constitute the Mount Morgan Mine Corridor Volcanics which are divided into five units: Upper Mine Sequence, Banded Mine Sequence, Middle Mine Sequence, Lower Mine Siltstones and Lower Mine Sequence. These acid volcanics and their derivatives form the lower part of the mid-Devonian Capella Creek Group. The volcanics are intruded by the polyphase Mount Morgan Tonalite comprising tonalite, trondhjemite and quartz gabbro of about 380 Ma in age. The regional and local geology of Mount Morgan is quite complex with numerous differing accounts evident in the literature. The most comprehensive studies are those of Messenger and Golding (1996) and especially Messenger, Golding and Taub (1997).

The area is heavily faulted and the volcanics are further intruded by porphyries coeval with the acid volcanics and, in part, were emplaced in still wet sediments *i.e.*, synsedimentary intrusions (Golding *et al.*, 1993). The rocks of the Mount Morgan area, including the orebody, were then invaded by a series of conjugate dykes (NE-SW and NW-SE) of Triassic age with further faulting.

Two differing genetic models have been presented as to the origin of the Mount Morgan orebody: (1) a structurally controlled breccia pipe with some replacement with ore derived from the intruding tonalite (Cornelius, 1967, 1969; Staff, Mt. Morgan Ltd., 1965), and (2) a volcanogenic massive sulfide pipe deposit (Paltridge, 1967; Frets and Balde, 1975; Lawrence, 1977; Golding *et al.*, 1993).

Although evidence for a large-scale replacement is scant, the orebody is pipe-like in structure (somewhat resembling a boot) with much of the ore as large brecciated masses. Toward the top of the open cut is a remnant of a stratiform pyrite-barite unit within black shales and considered to be of submarine volcanic exhalative origin. The model proposed by Messenger *et al.* (1997) and the similar model by Lawrence (1977) tends to reconcile the volcanic-exhalative and the breccia pipe concepts as being parts of a submarine mineralization process where black smoker chimneys are eventually disrupted by an ultimate explosive episode which produced the transgressive breccia pipe. The source of the ore, in this model, would be the acid volcanics and the associated porphyry of the Mine Corridor rocks.

The deposit had an expansive gossan which was extensively prospected but found to be mostly barren. Within this gossan was a smaller ore-derived gossan lying above the breccia pipe. The ore was mined underground initially and then by open cut, partly because of a mine fire in the 1920s. The ore at Mount Morgan did not generate

Table 1. Distribution of primary minerals at Mount Morgan.

Mineral	Composition	Relative abundance
Pyrite	FeS_2	dominant
Chalcopyrite	$CuFeS_2$	major
Magnetite	Fe_3O_4	semi-major
Pyrrhotite	$Fe_{1-x}S$	semi-major
Marcasite	FeS_2	accessory
Gold	Au	accessory
Molybdenite	MoS_2	accessory
Digenite	Cu_7S_4	minor accessory
Chalcocite*	Cu_2S	minor accessory
Hematite	Fe_2O_3	minor accessory
Calaverite	$AuTe_2$	minor accessory
Petzite	Ag_3AuTe_2	minor accessory
Sylvanite	$AgAuTe_4$	minor accessory
Tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$	minor accessory
Sphalerite	ZnS	minor accessory
Bismuthinite	Bi_2S_3	minor accessory
Covellite*	CuS	minor accessory
Galena	PbS	minor accessory
Arsenopyrite	FeAsS	minor accessory
Goethite	FeO(OH)	minor accessory
Cubanite	$CuFe_2S_3$	trace
Cassiterite	SnO_2	trace
Rutile	TiO_2	trace
Bismuth	Bi	trace
Bornite	Cu_5FeS_4	trace
Coloradoite	HgTe	trace
Hessite	Ag_2Te	trace
Silver	Ag	trace
Tellurobismuthite	Bi_2Te_3	trace
Tetradymite	Bi_2Te_2S	trace

*Mainly supergene.

many secondary minerals. Minor amounts of malachite and azurite were occasionally seen but little else though the gossan did provide some very colorful iridescent limonite. Thirty primary metallic minerals occur in the breccia pipe, Table 1 (Lawrence, 1974), but only pyrite, chalcopyrite and magnetite are readily visible macroscopically. Gold is rarely seen other than under the microscope as are most of the other minerals, many of which have been noted only once or twice. A particular feature of the pyritic ore is the differing textures ranging from aggregates of irregular grain shapes of very variable size (1 mm to 2 cm or so) to masses of granular sugar-like grains of a uniform 1 to 1.5 mm. The latter type is somewhat friable with individual grains having a polygonal shape.

It is evident that stress build-up, as a result of magma drag and compression resulting from sidewards spread during later dyke emplacement, affected the ore. Microscope study of a large number of polished sections shows that the granular pyrite has been annealed as has the associated magnetite, pyrrhotite and quartz. The pyrite of the irregular grain shape shows no such features.

In order to dissipate strain energy and to balance surface tensions, a movement of atoms in the grain exteriors occurs resulting in polygonally shaped grains whose sides, in two dimensions, are seen to meet in groups of three with triple-point junctions of 120⁰ in single phases – in this case pyrite. A histogram of triple-point angles plotted against frequency for annealed pyrite from Mount Morgan gives a bell-shaped curve with a 120⁰ maximum (Lawrence, 1972). Other features indicative of annealing such as the spreading of minor phases, such as chalcopyrite, along grain boundaries of major phases and to triple point junctions, and the spheroidization of minor phases in major phases *e.g.* pyrite in annealed quartz, are frequently observed under the ore microscope.

The effect of temperature elevation on a pre-existing ore subjected to strain has induced annealing–recrystallization within parts of the Mount Morgan deposit. Pyrite, which normally fails by brittle fracture, requires an extremely slow strain rate at relatively high temperatures to anneal; these conditions were operative at Mount Morgan. The particular influence of temperature elevation brought about by igneous intrusion into the already existing orebody has led to the concept of thermal metamorphism of a sulfide ore with Mount Morgan as an example.

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Minerals of the Harts Range, Northern Territory

DON McCOLL

The Harts and Strangways Ranges northeast of Alice Springs are parts of the Arunta Inlier, a group of Archaean age rocks which lie roughly east-west across Northern Territory just north of Alice Springs. In the more easterly sections, and particularly within the Harts Range, these rocks were originally intensely regionally metamorphosed to at least granulitic grade more than a billion years ago. Much of this alteration has however, been obscured by subsequent retrogressive changes, igneous intrusions, and an additional later profusion of pegmatitic, hydrothermal and metasomatic mineral veins introduced during relatively recent tectonism, perhaps only 300 million years ago. The mining history of the Harts Range area is quite insignificant, being limited to little more than prospecting and pitting of the pegmatites for mica during about thirty years in the early to mid-twentieth century. Many of the miners were first generation Italian immigrants, and they were aided in both prospecting and mining by the Aboriginal people of the Eastern Arrente tribal group. Even now the area is sparsely populated and pastoralism is virtually the only industry.

KORNERUPINE AND SAPPHIRINE

The geology of this deposit has been briefly described before (Warren & McColl, 1983; McColl & Warren, 1984). It consists of a single band within a quartzo- feldspathic gneiss which has been inter- laminated with mafic intrusives, which now appear as pyroxene granulites. The layer representing the host rock is believed to have been originally composed of felsic volcanics, tuffs and basalts in a section generally dominated by quartz-rich sediments, and all being about 1.8 billion years old. From the chemical composition and general local geology, it is suggested that the band might have originally consisted of soda-rich sediments deposited in a non-marine lagoon fed by hot volcanic springs. The formation of kornerupine and sapphirine, which are favoured by metamorphism at elevated pressure and temperature, infers that this band was downwarped to a depth, which may have been as much as 10 kilometres, about 1.5 billion years ago. This resulted in the formation of well shaped, eight sided prismatic crystals of kornerupine up to 20 cm in length and 5 cm diameter, and tabular crystals of sapphirine up to 3 cm in diameter and 1 cm thick. Later retrogressive alteration should have tended to destroy both of these minerals, but at this location and a few others in the Harts and Strangways Ranges, occasional cores of each pure mineral have survived within pseudomorphous idioblastic outlines.

CORUNDUM RUBY

Australian ruby was first recorded as well formed tabular crystals up to 5 cm diameter and 1 cm thick from a location south of Mount Brady in the Entia Creek headwaters of the Harts Range in 1978. The occurrence is restricted within and along the margins of irregular blocks of felsic amphibolite which are enclosed within schistose masses of dark green chloritic amphibolite. These host amphibolite blocks are best interpreted as former xenoliths or folded boudins of felsic aluminous amphibolite (anorthosite) which were incorporated, perhaps around a billion years ago, within ultramafic intrusive bodies having the probable form of sills or laccoliths (Lawrence *et al.*, 1987). Localised contact metamorphism of many of these xenoliths/ boudins would account for the formation of corundum, which would have the ruby colouring imparted by permeation of chromium from the ultramafic. Some of these crystals were exceptionally large, being as stated, up to 5 cm in diameter. They generally tended to a flat tabular habit however, with very short *c*–axes. Subsequent retrogressive alteration tended to develop sericitic and fuchsitic coatings on many of the crystals, and tectonic deformations have been noted, which may principally be ascribed to the later period of the Alice Springs Orogeny about 300 million years ago. Mining of this deposit was carried out during the late nineteen-seventies and early eighties, and although a considerable total weight of ornamental ruby was obtained, most of it was used to make cabochon gemstones, and virtually none of it was up to facetting grade. Operations were discontinued after about three years, and only minor work has been done at the site since.

SCEPTRE QUARTZ CRYSTALS

Large prominent veins of pegmatite and quartz, sometimes containing characteristic minerals such as muscovite, tourmaline, beryl, calcite and amethyst, along with veins of metasomatic crystals such as epidote, titanite and prehnite, mark the final phase of mineralising activity in the Harts Range. This probably took place at the same time as the Alice Springs Orogeny 300 million years ago (Shaw *et al.*, 1990). The sceptre-form quartz and amethyst mineralisation occurs almost exclusively within relatively small quartz- calcite veins (both minerals apparently being essential for the formation of some sceptre crystals), which transgressively cut particular bands of the Riddock Amphibolite member of the Arunta Inlier. These specific amphibolite bands have very distinctive outcrops, and may represent a metabasalt or other former lava of critical composition and with probably appreciable initial lime content. The crystal-bearing veins are most common in the near vicinity of massive pegmatites, which may have been the source of the hydrothermal mineralising fluids, which released the lime by hydrolytic alteration of the amphibolite. The best examples of the sceptre-form crystals have been collected by Aboriginal people from subsoil weathering accum-ulations, which are quite difficult to discover from the very meagre surface indications. The exact mechanisms which form these strangely distorted crystals are still a matter of conjecture, but the crystals themselves are frequently of very striking and beautiful appearance. Two mechanisms are suggested to explain differences seen in the many habits of the sceptre crystals collected. It is suggested that one be referred to as *co-crystallisation*, where the developing quartz and calcite produce the sceptre structure by regular physical distortions. The second mechanism is that of *point nucleation*, where there are two distinct phases of crystallisation, with the second initiated around the pointed apices of the initially formed crystals, which then become the stem of the sceptre structure.

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An Oxygen Isotope Thermometer for Cerussite: Applications at the Block 14 Mine, Broken Hill, New South Wales

ERIK MELCHIORRE, PETER A. WILLIAMS & RICHARD E. BEVINS

Slow precipitation experiments were used to determine the oxygen isotope fractionation between cerussite ($PbCO_3$) and water over the temperature range 20 to 60°C. Cerussite was synthesized at low temperatures, and analysed by methods similar to those described for malachite and azurite by Melchiorre *et al.* (1999, 2000) A 250 cm^3 glass bottle was filled with 3 g of calcite cleavage fragments, and 0.1 M $Pb(NO_3)_2$. Vessels were sealed and placed in a water equilibration bath set to the desired temperature of the experiment, and allowed to react for 8 to 12 weeks before the vesselwas removed from the bath, and the cerussite overgrowths harvested for isotopic analysis. The temperature dependent fractionation determined by these experiments is shown below,

$$1000 \ln \alpha = 2.63 (10^6/T^2) - 3.58$$

where T is in Kelvin (Figure 1). This new geothermometer has been applied to natural cerussite samples from the Block 14 Mine, Broken Hill, New South Wales, and other localities.

To assess the reliability of this new low temperature thermometer, cerussites that have formed in historical times of known water $\delta^{18}O$ and temperature were used to independently calculate fractionation values. These very low temperature (<25°C) samples, from the Bwlch Glas Mine, Wales, United Kingdom, and the Pinnacles Mine, Broken Hill, New South Wales, plot very

Table 1. Data for the Samples

Sample Type	**Location**	**Coll. By**	**Delta 18-O** (SMOW)	**Delta 13-C** (PDB)	**Calculated Temperature** (°C)
Cerrusite	Comet Mine, Tasmania	EBM 1999	20.24	-17.78	25
Cerrusite	Brown's Deposit, Rum Jungle, NT	EBM 1997	14.58	-13.69	58
Cerrusite	Pinnacle Mine Open Cut, Broken Hill District, NSW	EBM 1999	17.58	-7.31	39
Cerrusite	Block 14, Broken Hill, 1703N, 228E	PAW 1994	16.96	-14.90	42
Cerrusite	Block 14, Broken Hill, 1760N, 172E	PAW 1994	17.32	-19.16	40
Cerrusite	Block 14, Broken Hill, 1855N, 160E	PAW 1994	17.00	-18.87	42
Cerrusite	Block 14, Broken Hill, 1990N, 175E	PAW 1994	16.71	-14.56	44
Cerrusite	Block 14, Broken Hill, 1357N, 181E	PAW 1994	16.62	-15.65	44
Cerrusite	Block 14, Broken Hill, 360N, 180E	PAW 1994	16.82	-13.85	43
Cerrusite	Block 14, Broken Hill, 390N, 200E	PAW 1994	16.20	-13.53	47
Cerrusite	Block 14, Broken Hill, NSW "first level"	EBM 1997	15.98	-17.22	48
Cerrusite	Block 14, Broken Hill, NSW "first level"	EBM 1999	16.06	-16.85	48
Cerrusite	Block 14, Broken Hill, NSW "second level"	Austr. Museum	15.82	-18.34	49

close to the trend observed for our synthetic data (Figure 2). Similarly, the high-temperature experiments of O'Neil *et al.* (1969) are also in agreement with our thermometer (Figure 2).

The $\delta^{18}O$ and δ^{13} C values of both synthetic and natural cerussites were determined by the standard method of reaction with 100 percent orthophosphoric acid (H_3PO_4) at 25°C to release CO_2 gas. The resulting CO_2 gas was purified, and then analysed on an isotope ratio mass spectrometer. The cerussite-phosphoric acid fractionation factor of 10.08 was used in the correction of data.

Oxygen isotope data for 10 cerussite samples from the Block 14 Mine, and 3 cerussites from other localities, suggest formation from meteoric waters (Table 1). Both carbon and oxygen isotope delta values for these natural cerussites are consistent with values recorded for speleothems, soil carbonates, and copper carbonates, suggesting that cerussite commonly de-

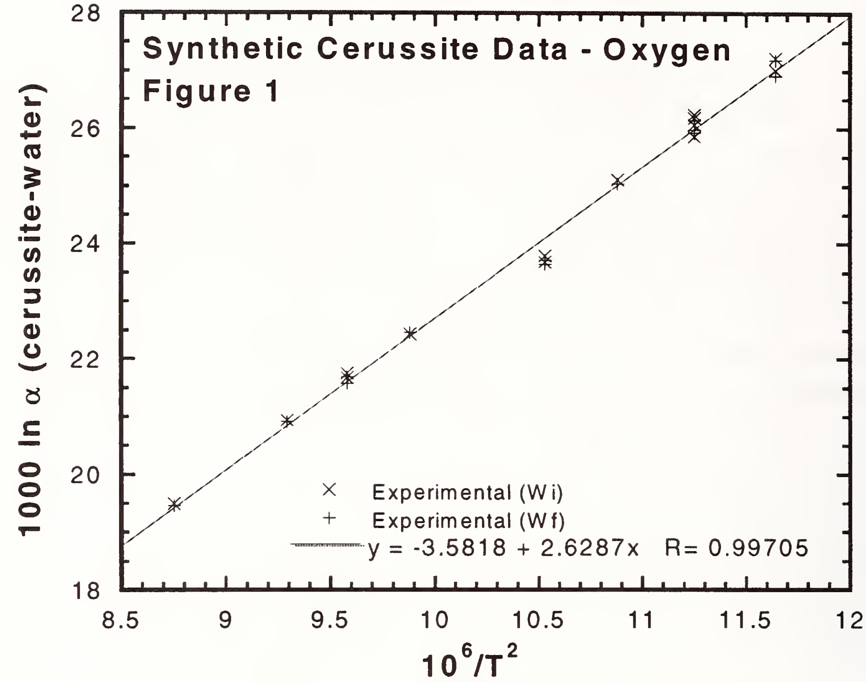

Fig. 1. Plot of experimentally derived data for the cerussite geothermometer (Wi and Wf refer to separate experimental runs).

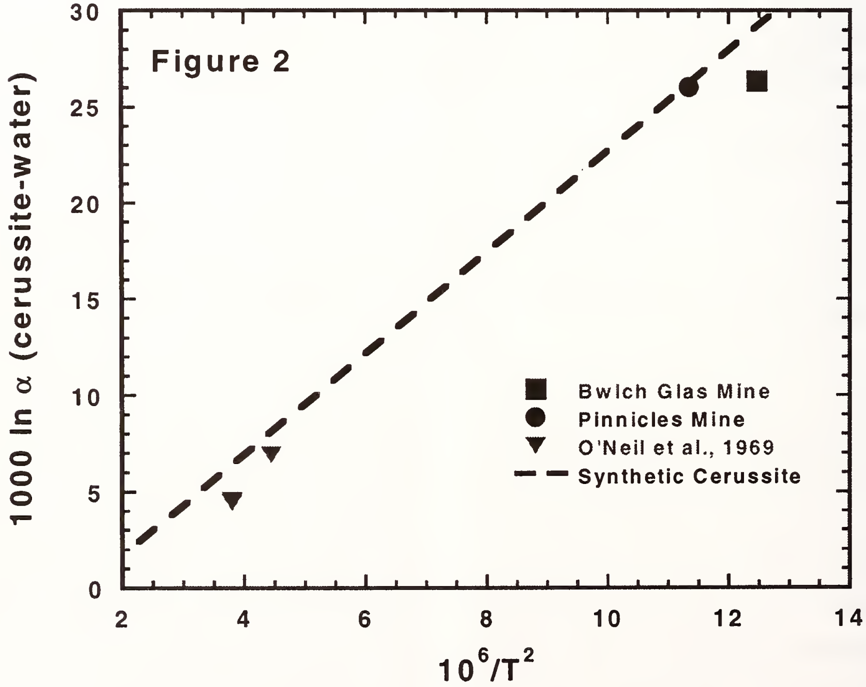

Fig. 2. Data for Bwlch Glas and Pinnacles Mines, together with the high temperature results of O'Neil *et al.* (1969). The dashed line is the experimentally determined. relationship of Figure 1.

rives much of its carbon from isotopically-light soil CO_2. Indeed, $\delta^{13}C$ values as light as -19‰ indicate a significant organic carbon source (Table 1). The new oxygen isotope thermometer indicates that natural cerussites at Block 14 formed at temperatures significantly greater than modern local air temperatures. This is consistent with malachite thermometry results at Broken Hill (Melchiorre *et al.*, 1999). We suggest that these higher apparent temperatures record the heat produced during oxidation of concentrated sulfides. Our results therefore indicate that exothermic oxidation of sulfides at Block 14 produced shallow subsurface temperatures up to at least 50°C.

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The Mineralogy of the Currently Producing Lodes, Broken Hill, New South Wales

JANE MURRAY

Broken Hill was first pegged in 1883 and within several years the extent and value of the 'Line of Lode' was realized.With an original resource of approximately 280 million tonnes averaging greater than 15% combined metal, Broken Hill is one of the greatest known mineral deposits. Now, in the second century of mining at Broken Hill, Pasminco is operating at the very extremities of the orebody in the combined underground workings of the Zinc Corporation (ZC), New Broken Hill Consolidated (NBHC) and Southern Cross mines. Despite the efficiencies of the modern mining methods, achieving the annual production target of 2.8 million tonnes becomes more challenging with every stope mined. The remaining *in situ* reserve is of significantly lower grade and more difficult to obtain than the ore for which Broken Hill is famous. Accurate geological interpretation with respect to the position of high grade ore is therefore becoming increasingly important. Mineralogy is a vital tool utilized by mine geologists to track individual lenses through the orebody.

Metal is currently sourced from the familiar Lead Lodes (2 Lens, 3 Lens) and Zinc Lodes (1 Lens, A Lode, B Lode, C Lode), but in recent years the relative contribution each lens made to production changed considerably. Marginal grade C Lode is now one of the major bulk-tonnage producing areas of the orebody. The shear zones of the Southern Cross area are being negotiated to access the sulfides of Southern A

Lode (SAL) and South Eastern A Lode (SEAL). Scattered remobilized pods of ore form the basis of the Western A Lode (WAL) stopes. Narrow blocks of A Lode and 1 Lens are being extracted from between the largely mined-out B Lode and Upper 2 Lens. Old sites of production are being revisited. Pillars of very high grade in Lower Lead Lode are being recovered from the sand-filled voids which surround them. The remnants of B Lode above its structurally-thickened, mined-out bulk are to be targetted in 2000.

The individual lenses of the Broken Hill orebody within the southern mine leases can be readily identified by the mineralogy of their ore and gangue and this classic lode individuality has been documented previously (Table 1; Johnson & Klingner, 1975; Haydon & McConachy, 1987). The essential mineralogical character of each lode is an invaluable aid to geological interpretation of the complex periphery of the orebody.

The Potosi deposit is one of only two deposits of significant (mineable) proportions discovered in the Broken Hill district. Potosi supplemented Pasminco's underground production with ore from its open pit from 1995 until its exhaustion in early 2000 (0.6 Mt mined). The Potosi orebody mineralogically and morphologically resembled Broken Hill, being comprised of discrete semi-conformable lenses of sphalerite and lesser galena associated with distinctive garnet, quartz and gahnite gangue. Some of the ore lenses were remobilized into the bounding Potosi shear zone. The study and mining of satellite Broken Hill-type deposits has become even more crucial with the depletion of the main orebody. The mineralogical character of the known Broken Hill 'hybrids' in the district provides direction for current exploration activity.

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Table 1. Gangue mineralogy of the Main Lode horizons, Broken Hill.

Ore lens	Gangue
Zinc Lodes	
A Lode	major: rhodonite, manganoan hedenbergite, quartz, garnet; minor: calcite, cummingtonite/grunerite, wollastonite
B Lode	major: quartz; minor: manganoan hedenbergite, garnet, apatite, gahnite, damourite (muscovite), rhodonite, calcite
C Lode	major: Quartz, garnet, biotite; minor: gahnite, manganoan hedenbergite, clinozoisite, feldspar
1 Lens	major: quartz, calcite; minor: wollastonite, bustamite, manganoan hedenbergite, epidote
Lead Lodes	
2 Lens	major: calcite, rhodonite; minor: bustamite, manganoan hedenbergite, fayalite-tephroite, quartz, garnet, fluorite, apatite
3 Lens	major: quartz, fluorite; minor: rhodonite, garnet

Copper Minerals from the Moonta and Wallaroo Mines, South Australia

ALLAN PRING

Moonta Mines at Moonta, Wallaroo Mines at Kadina and the smelting works at Wallaroo on the Yorke Peninsula, constitute the copper triangle of South Australia. In the 19th Century these mines were amongst the richest copper mines in the world and Moonta Mines was the first Australian mining company to pay a million pounds Sterling in dividends. The deposits of Wallaroo Mines were discovered in 1859 and those of Moonta Mines in 1861. The lodes at Moonta were fabulously rich and the profits from mining funded the development of the mines. The Wallaroo Mines required somewhat more faith and investment before they finally made a profit. Other small mines were also worked on the fields, the most important of these being the New Cornwall and Doora Mines at Kadina and the Yelta Mine at Moonta. Moonta and Wallaroo Mines were worked continuously for over 60 years, finally closing in 1923. Following the closure of the major mines at Moonta and Kadina, sporadic but unsuccessful attempts were made to re-open some of the mines on the fields. In the 1960s Western Mining Corporation and North Broken Hill Ltd intensively explored the field and found a number of additional lodes at Poona and Wheal Hughes, to the north of Moonta. These lodes were mined for copper and gold by the Moonta Mining Joint Venture between 1988 and 1993.

Detailed geological investigations of the Moonta-Wallaroo district are few, due to an almost total lack of outcrop. The principal works describing the geology and mineralogy of the mining area are Ward & Jack (1912) and Jack (1917), summarized by Crawford (1965), Parker (1990) and Pring (1988). The orebodies of the Moonta group of mines consisted of pegmatitic and quartzose veins filling fractures along faults in the feldspar porphyry. All the Moonta lodes lay within the boundaries of the Moonta Porphyry. The orebody extended over a distance of some 3 km with individual lodes to 1000 m in length. Principal ore minerals were chalcopyrite and bornite. The gangue consisted of quartz, feldspar and biotite with accessory hematite, schorl, molybdenite and fluorite. The geological setting of the Wallaroo group of mines is quite different from Moonta and this is reflected in the mineralogy of the lodes. At the Wallaroo Mines the host rocks are metamorphosed sediments, mainly biotite schists, which have been partly invaded by dykes and offshoots of the Moonta Porphyry. There were fewer individual lodes at Wallaroo Mines although they were more extended. The main lode was mined over a distance of 1000 m and to a depth of 850 m. The lodes were of a replacement-type rather than fracture filling. The mineral assemblage of the orebody consisted of chalcopyrite with pyrite and pyrrhotite; minor amounts of galena and sphalerite were also present. The gangue was quartz and carbonates; accessory minerals included schorl, apatite and scapolite. Theories of the origin and inter-relationships of the lodes at Moonta and Wallaroo are few and perhaps out-dated. Jack (1917) believed that the source of both ore bodies could be the Arthurton Granite, some 26 km south east of Moonta, and ascribed their differences in character to differences in base rock fracturing and distance from the source. Dickinson (1942) mentioned the possibility of mineral vein formation being a late phase of porphyry intrusion with the possibility that the porphyry also underlies the Wallaroo lodes. Parker (1990) provides an up-to-date review of the geological history of the field but little insight into their origins. The deposits at Moonta and Kadina are some 15 km apart and although the two deposits are hosted in different rock types the mineralization is thought to have a common history. The differences in geological setting are reflected in the mineralogies of the two deposits.

Both deposits appear to have had similar oxidized zones, which extended to a depth of between 30 and 50 m. The saline character of the ground waters in the area resulted in the formation of large masses of atacamite and this was the dominant mineral in the oxidized zones. Malachite and azurite were rare and in the lower portion of the oxidized zones, cuprite and chalcocite were the principal species. Several small pockets of uranium minerals were found at Moonta Mines associated with the amorphous organic compound thucolite. The Moonta-Wallaroo area is probably best known as a source of very fine atacamite crystals. The finest of these, over 10 cm in length, were found in the 1860s at the New Cornwall Mine, Kadina. Some early workers thought that these specimens came from Burra, South Australia, an error that was unfortunately perpetuated in parts of the literature. Moonta and Wallaroo Mines are also famous for producing exceptional specimens of cuprite, chalcopyrite, cobaltite, native copper and quartz.

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The Paragenesis and Spatial Distribution of Secondary Copper Minerals in the Eastern Mount Isa Block, Queensland

JAMES L. SHARPE

With few exceptions, the copper deposits of the Eastern Mount Isa Block are localised by faults. Economic mineralisation often occurs where faults or shears are intersected by cross-faults or tension gashes. Extensive brecciation in these locations provided the conduit for the injection of mineral-bearing fluids and the ingress of vadose groundwater bearing oxygen and ions capable of reacting with the primary sulfides to form an extensive suite of secondary copper minerals. In assessing the paragenesis and spatial distribution of secondary mineralisation it is necessary to consider not only the evidence revealed by examination of samples which may be representative of a particular part of the deposit, but also the geochemical processes that dictate the order of formation of the various species. In a natural system conditions of pH, oxidation potential, availability of reactants and naturally occurring catalysts or nucleators, *e.g.*, manganese oxides, and temperature and pressure variations all serve to create different local chemical conditions.

Native copper is found throughout the lodes but is most abundant near the water table, and historical records often refer to discoveries of native copper in the outcrop. Three distinct modes of occurrence have been noted. Throughout the shears containing the lodes and at all depths in the oxide zone it is common to find masses of highly siliceous goethite containing slugs and disseminations of native copper precipitated prior to silicification under conditions that were feebly reducing; cuprite (Cu_2O) is more likely to form with increasing Eh. At depth native copper becomes more abundant, usually as pods and stringers within cuprite and is often accompanied by nantokite (CuCl) (Sharpe and Williams, 1999). Native copper also occurs as nodules with successive cuprite, tenorite (CuO), and chrysocolla ($\sim CuSiO_3.nH_2O$) or malachite rinds.

Brochantite ($Cu_4SO_4(OH)_6$) distribution is noteworthy, the mineral being found in most deposits and at all depths, always tightly within the original lode limits. Antlerite ($Cu_3SO_4(OH)_4$) was confirmed from one deposit, the Monakoff mine. Stability relationship between antlerite and brochantite has been established showing that, compared with brochantite, antlerite forms at a higher sulfate ion activity and higher temperature (>35°C). Whole or partial replacement of antlerite by brochantite is common at Monakoff. Malachite ($Cu_2CO_3(OH)_2$) is present in all outcropping deposits. On the other hand, azurite ($Cu_3(CO_3)_2(OH)_2$) is abundant in very few deposits. Stability relationships between malachite and azurite have been established showing that a partial pressure of CO_2 above $10^{-1.36}$ is required to form azurite (Williams, 1990) consistent with the observation of azurite forming only at depth.

Secondary copper phosphates are more widespread than is generally realised. Pseudomalachite ($Cu_5(PO_4)_2(OH)_4$) can be found at all the operating open cut copper mines and on most of the dumps in the Cloncurry district. Libethenite ($Cu_2PO_4(OH)$) is also widespread but is much rarer. Cornetite, ($Cu_3PO_4(OH)_3$) is relatively rare, having been found in very small quantities in only three deposits. This is in accord with stability relationships for the suite (Magalhães *et al.*, 1986). A separate, but remarkable, observation in many deposits that have been examined is the zoning of the secondary copper phosphates in the supergene profile. In particular, libethenite is always found near the top of the oxide zone but is absent at depths exceeding 10 m. On the other hand, pseudomalachite is usually quite abundant near the surface and persists to the intermediate levels of the oxide zone. Stability phase data shows that libethenite forms at most concentrated phosphate activities and pseudomalachite from solutions with lower amounts of dissolved phosphate for a given copper ion activity. Phosphate ion is released from apatite as a result of weathering and the spatial distribution of the copper phosphates may be explained by differential weathering phenomena.

During field research relatively few deposits containing copper arsenates were found. In a few, arsenopyrite or cobaltite formed part of the primary ore thus providing the opportunity for the formation of secondary copper arsenates. Conichalcite ($CaCuAsO_4(OH)$) is by far the most common copper arsenate encountered. Olivenite ($Cu_2AsO_4(OH)$) occurs sparingly, while clinoclase ($Cu_3AsO_4(OH)_3$) is rare. Whilst it could be expected that the copper arsenates would have a similar species distribution as their phosphate analogues, this is not so, particularly when much calcium ion is available as is commonly the case. The area occupied by conichalcite in the appropriate stability field increases dramatically with increasing calcium ion activity, requiring a much higher activity of copper in order preferentially to precipitate olivenite or clinoclase in preference to conichalcite (Williams, 1990).

An interesting suite of copper chlorides from the Great Australia mine has been described including the rare minerals, connellite ($Cu_{19}Cl_4SO_4(OH)_{32}.3H_2O$) and claringbullite ($Cu_8Cl_2(OH)_{14}.H_2O$), (Day and Beyer, 1995). These occur very sparingly within masses of cuprite often associated with the very rare copper nitrate, gerhardtite ($Cu_2NO_3(OH)_3$). Atacamite ($CuCl(OH)_3$) is a common associate. Chrysocolla is as common as malachite, being present in numerous deposits in the district. Most chrysocolla is found near the surface often accompanied by copper phosphates.

Examples are given of each of these assemblages and of the detailed setting in which they are found.

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Exotic Secondary Copper Mineralization in the Eastern Mt Isa Block, Northwest Queensland

JAMES L. SHARPE & PETER A. WILLIAMS

Fault-hosted mineralization in the eastern section of the Mt Isa Block, north-west Queensland, is now thought to be of hydrothermal origin, associated with the Williams and Naraku granite complexes (Wyborn, 1998). In this setting, primary metalliferous mineral suites are remarkably simple. Pyrite (FeS_2), some bearing significant amounts of Co and Ni, and chalcopyrite ($CuFeS_2$) dominate. Arsenic-rich ores comprising arsenopyrite (FeAsS), cobaltite (CoAsS), alloclasite and glaucodot ((Co,Fe)AsS), together with varying amounts of pyrrhotite ($Fe_{1-x}S$), form a less common assemblage, invariably associated with high-temperature phases such as scheelite ($CaWO_4$), wolframite ($(Fe,Mn)WO_4$) and molybdenite (MoS_2). Oxidation zones of these deposits, however, are characterized by a bewildering array of secondary phases, especially for copper species, as a result of complex groundwater anion geochemistry.

Copper sulfate, carbonate and chloride minerals are ubiquitous in the oxidized zones, with the anions being supplied by the oxidation of sulfides, dissolution of gangue minerals, or supergene capillary action. Periodic fluctuations of the water table contribute to a recharge of anions in the weathering zone. Arsenate, derived from oxidizing sulfosalts, gives rise to olivenite ($Cu_2AsO_4(OH)$), clinoclase ($Cu_3AsO_4(OH)_3$) and especially conichalcite ($CaCuAsO_4(OH)$), in notable deposits including the Lorena, Poseidon and Desolation mines. Secondary copper phosphate mineralization is extremely common throughout the Mt Isa Block (Day & Beyer, 1995; Sielecki, 1988) and complex assemblages of copper arsenate-phosphate species are known in several deposits. Their chemistries are in accord with equilibrium models developed elsewhere (Williams, 1990). Elevated phosphate activities in oxidized zones derive from intense near-surface weathering of apatite. Allied to this is pervasive secondary silicification due to the weathering of susceptible rock-forming minerals. Chrysocolla ($\sim CuSiO_3.nH_2O$) is conspicuous in nearly all of the oxidized zones in the area.

Perhaps most intriguing is the remarkably abundant secondary copper nitrate mineralization of the Great Australia mine, Cloncurry. Large amounts of gerhardtite ($Cu_2NO_3(OH)_3$) enclosed in masses of cuprite (Cu_2O) and native copper were recovered from the B Tangye Lode, together with likasite ($Cu_3NO_3(OH)_5.2H_2O$) and magnificent, deep blue, acicular crystals of the connellite-buttgenbachite series ($Cu_{19}Cl_4(SO_4,NO_3)_2(OH)_{32}(H_2O,OH)_3$). In a similar setting in the Main Lode, the rare chloride mineral claringbullite ($Cu_8Cl_2(OH)_{14}.H_2O$) was fairly common, and the supposedly rare species nantokite (CuCl) was an important ore mineral (although unrecognized as such in early mining operations).

The origin of nitrate in supergene assemblages has puzzled geochemists for many decades. Suggestions for it include the leaching of nitrate-rich sedimentary strata, the formation of nitrogen oxides *via* electrical discharge during thunderstorms and photochemical processes in the atmosphere, and biological fixation of nitrogen in the soil. Stable isotope measurements of nitrate in caliche from northern Chile and California, USA, have established the probability of an atmospheric source for these deposits (Böhlke *et al.*, 1997). Very high levels of nitrate (to more than 50 ppm) in groundwaters of the Australian arid zone have been traced to bacteria in termite mounds which fix nitrogen as ammonia; this in turn is metabolized to nitrate by other organisms including cyanobacteria in the mounds and soil crusts (Barnes *et al.*, 1992). Both of the processes are likely to have played a role at Great Australia and probably still obtain. Analyses of 15 groundwater samples recovered from drill holes on the Main Lode at Great Australia, prior to the most recent phase of mining, gave nitrate concentrations of up to 11 ppm.

Finally, we note that several oxidation zones in the Block are still active. Silica-encapsulated goethite masses in the Main Lode at Great Australia, for example, contain sludges of poorly crystalline malachite/georgite ($Cu_2CO_3(OH)_2$), X-ray amorphous copper-silicate-phosphate polymers and soft, amorphous, hydrated chrysocolla-like material. This current chemical reactivity is in marked contrast to the oxidized zone of the giant Ernest Henry deposit, just north of Cloncurry, formed prior to and during Mesozoic times, and in which subsequent inundation led to the reduction of secondary copper minerals to arsenian native copper.

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The Richest Lode and the Silver City

ROBERT SOLOMON

Broken Hill and its mines are much distinguished for:

- the extent and richness of the mineral lode
- the volume and longevity of ore production
- the size and permanence of the town which the lode has supported
- the exceptional trades union influence on the life of the town
- the town's function as the centre for a uniquely extensive grazing region
- the long persistence of the mines and the settlement in a hostile environment.

MINING

Mineralogists are much taken by the wonderful variety of more than 100 minerals found in the Broken Hill lode. Lawrence (1968) wrote that for "*the variety and crystallographic perfection of its oxidised minerals the Broken Hill mining field finds a ready place as one of Nature's great museums. If the long list of primary ore minerals and gangue minerals be added, Broken Hill stands supreme in the mineral world.*" That, presumably, is why we are here.

The first Broken Hill ore produced 738 ounces of silver per ton in late 1885. It soon rose to thousands of ounces per ton, which confirmed the great value of the lode. The original syndicate of seven men must have regretted leasing their nearly 300 acres (120 ha) for five shillings per acre instead of purchasing the freehold for £2 (40 shillings), though disappointment was cushioned by the allocation in 1888 of new shares and profits to the value of £168/10/0 ($337) per share! The production of more than two million ounces (64.9 tonnes) of silver in the second half of 1888 was sufficient to establish the Hill's reputation as the world's leading silver field. It led A.C. Cooke to call his detailed 1894 drawing of the mines (reproduced in Solomon (1988)), the smelters and the town *The Australian City of Broken Hill showing the Proprietary and Principal Mines on the Richest* Silver *Lode in the World*, and for Ion Idriess to chose *The Silver City* for the title of his 1956 book (Idriess, 1956). In 1937 the gleaming "Silver City Comet" began its run between Sydney and Broken Hill.

Silver did not long continue as the mainstay of Broken Hill. The lode was described, when the Australasian Institute of Mining and Metallurgy met there in 1946, as "*a massive lead-zinc sulphide deposit forming a continuous arch...up to 300 feet in width...its...depth at the north and south ends is still unknown. The line of mineral-isation continues for at least eight miles north of the North Mine and two miles south of the Zinc Corporation workings, giving a known overall length of approximately 13 miles of mineralised belt, of which only 3.5 miles has so far been proved of economic value*" (Solomon, 1988). As you all will know, the proven ore-body runs for 7.5 km and in 1988 reached a depth of 1600 metres (just over one mile) at the north end. Before 1940, according to T.B. Dodds of North Broken Hill Ltd in 1947 (Solomon, 1988), three mining areas each produced 10-12 per cent of the world's lead: Broken Hill, whose ore contained 15 per cent lead and 12 per cent zinc; the Sullivan Mine at Kimberley, British Columbia (8.5 and 6.5 per cent); and the extensive, low-grade field of southeast Missouri (3.5 and 3.5 per cent). In the 69 years to the end of 1952, 71 million tons of ore were mined at Broken Hill, from which came 9.5 million tons of lead, 6 million tons of zinc and 572 million ounces of silver. The life of the lode was then expected to be about 50 years at the current annual extraction rate of 1.3 million tons (although proved reserves were only 15 M tons). That seems to have been a good guess, because, despite more than doubling production since the 1950s, the last mine is scheduled to close in 2006. Given the uncertainty which attended almost every stage of the mines' and town's development, its history has been quite extraordinary.

PEOPLE

The number employed to produce the impressive Broken Hill mining output grew greatly in a short time, as so often the case when valuable minerals are found. In 1887 there were about 1500 people in and on the mines. By 1890 there were 5,800 and in 1899 they passed 7,000. The peak was in 1907, when 8,820 people were employed. This was almost equalled in 1913, but World War I reduced the total to about 5,000, and the Great Depression took it down to 3,000. The post-World War II boom saw 6,000 reached again in 1953; then followed a gradual decline to the present 800 or so.

The population that supported the mining work force had a meteoric growth – from a handful in 1883 to 20,000 in 1891. This made Broken Hill the second urban centre in New South Wales, exceeded only by the State capitals in Australia. Many 19th Century mining camps around the world demonstrated this kind of growth, but more often to 10,000 than to 20,000 and few for long enough to become structured towns, let alone cities. The Hill's population graph continued to climb steeply to almost 31,000 at the 1911 Census, and then to 35,000 in 1915: most impressive for a mining settlement. The effects of war caused Broken Hill's population to plunge steeply to fewer than 27,000 at the Census of 1921. With the founding of the steel industry by Broken Hill Proprietary Ltd (BHP) in 1915, Newcastle soon pushed Broken Hill into third place among New South Wales towns, but there it stayed for almost half a century – more than 1100 km from the port city of Sydney and the New South Wales Parliament seated there. "On the edge of sundown", as Premier John Storey (in 1920) so colourfully described its location (BHP, 1920). In mid-1998 the population was down to 21,000, just above the 1891 mark, and the projection is for a little under 19,000 by 2006, when the Pasminco mine closes. The most serious aspect of the Hill's demography is the significant decrease of young people, with the under 20s falling from 38 per cent of the total in 1971 to 27 per cent in 1996. The birth rate is down and job opportunities elsewhere beckon.

MINING TOWN CULTURE

For at least its first 60 years, life at Broken Hill was tough. The climate was arduous, water was short, temperatures in uninsulated iron and timber houses were extreme (52 per cent of dwellings had walls of iron in 1933, still 34 per cent in 1954). Dust storms threatened the viability of settlement, and gave rise to the path-finding regeneration scheme. Food was basic and its variety limited. Typhoid and dust-caused lung disease were prevalent. Education was sound, with the contribution of the Technical College to the training of engineers and others well appreciated. Religion thrived, as did hard drinking and the temperance movement at one and the same time.

Union loyalty and control was the strongest known anywhere, with socialism actively embraced and the *Barrier Daily Truth* backing the workers against the bosses, but for most of the time the Barrier Industrial Council was in balance with the Mine Managers' Association, so that only three major strikes marred industrial relations on the line of lode: 1892, 1909 and 1919-20. The advent of the Lead Bonus, as a weekly wage bonus, in the 1920s did much to subdue thoughts of further strikes, for it rose from 3 shillings and sixpence in 1935 to £16/4/4½ in 1951, when the Australian Basic Wage was £12. From 1948 to 1960 the average weekly lead bonus did not fall below 75 per cent of the Basic Wage.

THE SOUTH AUSTRALIAN CONNECTION

If the mineral outcrop of "the broken hill" had been 50 km west when it attracted Charles Rasp's attention in 1883, Broken Hill's history might have been different. But, in my guess, not very. Its hundreds of millions in mining royalties would certainly have been welcomed by the South Australian economy, but trade and traffic were westward from the outset. There were 52,500 passenger border crossings in 1888 when the Silverton Tramway Co ran its first trains, and the large volume of ore was also shipped westward. By 1897 the smelters had moved to Port Adelaide and Port Pirie after a mere decade on the line of lode. The Zinc Corporation set up its holiday camp on the Adelaide seaside at Largs Bay in 1947.

Broken Hill has worked on Central Australian time for a very long time, and its STD telephone prefix is 08 while NSW's is 02. Only recently has the Hill been included in the ABC's NSW television weather summaries. Hillites have always followed Adelaide's Australian Rules competition and local stars have joined it over the years. The unions' 300-mile employment rule reinforced established connections by admitting Adelaideians and excluding Sydneysiders. There's no evidence that the city of churches influenced Broken Hill's Methodists to become even more temperate than they were, whereas the annual mid-summer Burra-Broken Hill barrow race undoubtedly created a great opening for West End beer.

THE REGION AND THE FUTURE

While Broken Hill's lifetime role of service centre to a vast agricultural region can be predicted to continue indefinitely, that is limited by the small population carrying on extremely low density grazing and by the bottom recently falling out of the always-reliable Australian wool market. The somewhat unexpected development of arable agriculture on Lake Tandou in the Menindee Lakes system in the late 1980s was a real morale-booster, but one which water availability will not allow to be substantially increased. So, it is to tourism that Broken Hill seems likely to link its future welfare (as I wrote (Solomon, 1988) in the final chapter of *The Richest Lode* in 1988). Who, in 1891 or 1920, would have imagined Broken Hill's mining base being replaced by tourism? But in those distant days the prospect was of mining's replacement by nothing, and much sooner than 120 years after it so strikingly began. And who would have thought, with the residents reduced to little more than half their 1915 peak, that their standard of urban amenity would be undreamed of by the pre-pipeline miners and townspeople?

Who would have imagined, in 1891, or in 1920, Broken Hill's mining base being replaced by tourism?

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Mount Isa: a Mineral Deposit of World Significance

GEORGE STACEY

Mount Isa in northwest Queensland is recognised as one of the world's great mines. Since its discovery in 1923, Mount Isa has produced over five million tonnes of copper, 21 million kilograms of silver, five million tonnes of lead, and five million tonnes of zinc. Silver and lead production is second only to Broken Hill and substantial reserves of copper and silver lead and zinc ores remain; large scale mining and processing operations will continue well in to the 21st century.

Mount Isa was discovered by a lone prospector, John Campbell Miles, in 1923 and Mount Isa Mines Limited was formed as a company in 1924 (Blainey, 1960). Mining and smelting of the oxidized lead ores, containing almost exclusively cerussite, began in 1931. It was not until 1935, when mining of primary sulfide ore began, that the first zinc concentrates were produced. During the 1930s the existence of copper ores was confirmed and in 1943 the mine ceased silver-lead-zinc production and switched to copper to help the war effort. Copper mining ceased from 1946 to 1953, then production from the copper orebodies began. Current underground ore production is approximately 32,000 tonnes per day, making it one of the largest underground mines in the world.

The silver-lead-zinc deposits at Mount Isa run in a northerly direction and occur in a sedimentary formation up to 1000 metres thick, the 1600 Ma Urquhart Shale. This consists of alternating sedimentary beds with carbonaceous siltstone rich in fine-grained pyrite and pyrrhotite. The parallel bedded silver-lead-zinc orebodies occur in close proximity to, but are geologically and spatially quite distinct from, breccia hosted massive to disseminated copper mineralisation. Virtually no copper occurs in the silver-lead-zinc orebodies and no lead-zinc in the copper orebodies. Some 20 km north of the Mount Isa mine, the silver-lead-zinc orebodies of the Hilton Mine are also restricted to the Urquhart shale and closely resemble the primary ores of the Mt Isa mine. The only primary copper mineral at Mount Isa is chalcopyrite associated with pyrite and pyrrhotite as disseminations and vein fillings situated within zones of brecciated and recrystallized Urquhart Shale known as "silica dolomite." The earliest discovered copper ore was that of the 650 Orebody. The deeper and larger 1100 Orebody at the south end of the mine was first intersected in the early 1950s (Sielecki, 1988).

Good specimens of oxidized lead minerals are relatively rare at Mount Isa. The only oxidized lead minerals of major significance to the collector are the fine specimens of *camphyllite* (arsenian pyromorphite) found near the surface in the vicinity of the Lawler Shaft and in the Black Star Open Cut during early mining operations. These are equal in quality to the best *camphyllite* found anywhere and occur as classically barrel-shaped crystals up to 10 mm in size, ranging in colour from bright lustrous orange red crystals of world class to yellow, caramel and greenish-yellow to green. The best crystals occur in association with surface clays and shales and fine specimens, over 30 cm long covered with large, lustrous semi-botryoidal crystals, were recovered in the early days.

The Black Star Open Cut, situated in the oxidized zone of the silver-lead-zinc orebodies, commenced operation in the 1930s. Since that time it has been mined intermittently as a source of siliceous flux for the lead smelter. In the early days a number of specimens were recovered from this source showing classic barrel shaped crystals of *camphyllite*. Since the second world war the deposit has been primarily noted for its attractive specimens of silicified shale displaying sharp, freestanding hexagonal prisms of yellow pyromorphite crystals. Individual crystals of pyromorphite range up to 5 mm across and 25 mm long. The Black Star Open Cut.is also noted for vughy limonite containing pure white, lustrous cerussite in fine dendritic sixlings up to 3 cm across, displaying reticulated twinning. Occasionally some prismatic crystals of opaque white anglesite to 5 mm in length have also been found. Very little zinc occurs in the oxidized zone but on occasions, smithsonite of fairly poor quality has been recovered; one small pocket of pink smithsonite, due to the presence of cobalt, was found in the late 1960s.

In 1957 production of copper at Mount Isa recommenced with the discovery of the Black Rock Orebody, which was found just underneath the surface about 500 metres south west of the old mine office. The deposit contained large quantities of secondary copper minerals and consisted of an oxidized sequence of Kennedy siltstone and shale resting upon Urquhart shale, which had been partly oxidized and kaolinized to variable depths. Open cut operations ended in 1965 with a pit some 165 metres deep. The Black Rock Open Cut was in the oxidized zone of the 500 Copper Orebody. The deposit contained no lead or zinc minerals.This deposit, when mined during the 1960s, produced some outstanding specimens of native copper, large gem-like cuprite crystals to 2 cm, red lustrous *chalcotrichite*, and chrysocolla often in association with tenorite, cuprite, and native copper. The Black Rock Open Cut produced some outstanding spinel twin crystals of native copper coated with a thin protective film of cuprite. Many of these crystals were from 4 to 10 cm in size with some specimens made up of superb crystal groups containing from 3 to 6 large crystals. A small number of notable specimens of native copper, some with lustrous transparent pale amber coloured barite crystals in association with skeletal silica were recovered from the upper levels of the 500 Orebody where drives on 4 level were used to access a ventilation shaft. Some good specimens of native copper crystals and crystals of calcite and barite were also recovered from cavities adjacent to fault zones and occasional vughs underground in the copper mining areas.

Over a 100 different mineral species have been reported from the Mount Isa mine but most of these are of minor or insignificant occurrence. During its operation Mount Isa produced only a few mineral species of significance on the world scene and, unfortunately, very few of these survive today.

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Geodiverse Gemstone Deposits, New England, New South Wales

F. LIN SUTHERLAND

The New England terrain provides a cornucopia of gemstones, an inheritance from a fold belt of Palaeozoic rocks, disrupted by granitic emplacement and veneered by volcanic and sedimentary deposits. This gemstone diversity (Webb and Sutherland, 1998) stems from three main rock associations. Continental volcanics supplied diamond, sapphire, ruby, zircon, garnet, feldspar, olivine and precious opal. Many gemstones were weathered out and flushed into alluvial deposits. Some did not form in their molten hosts, but rose up in melts that broke through metamorphic assemblages. Granitic bodies, veins and contacts supply topaz, beryl (including emerald), quartz, garnet and ruby-amber cassiterite. Again many crystals are reworked into abraded stones. The metamorphic fold belt supplies rhodonite, nephrite jade and a variety of cherts, jaspers and agates. These largely provide polished ornamental stones. New England began diamond mining in 1872 and in 2000 the Copeton and Bingara fields remain under exploration. The diamonds prevail in Cainozoic sub-basaltic deposits and their origin is problematic. Crystals show strong 'magmatic' resorption and are unusual, being made of heavy carbon and containing unusual inclusions (coesite, calcium-rich silicates) which yield 'young' formation ages. White (low nitrogen) and yellow (high nitrogen) diamonds are found. Their source remains controversial, whether derived from underlying diamond-bearing seafloor slabs (Barron *et al*., 1996) or transported from afar (Davies *et al*., 1999).

The Inverell-Glen Innes gemfield is a principal supplier of sapphires. Most stones are blue, green or yellow and often colour zoned. They are mostly shed from volcaniclastic deposits, but initial parentage is controversial, perhaps having formed from mid-crust interactions of carbonatitic and silicic magmas (Guo *et al*.,

1996) or from deeper feldspathic melts (Sutherland *et al.*, 1998a). Some fields yield 'fancy coloured' sapphires, grading into ruby (Sutherland *et al.*, 1998b). Zircon, an abundant associate of sapphire, adopts many crystal habits and colours. It is cut as a minor gemstone. Crystals range from pale, anhedral, lower-U types to more euhedral, darker coloured higher-U types. Radiometric dating indicates an origin closely, but not directly, related to basaltic volcanism (Sutherland *et al.*, 1993).

Beryls including emerald were mined from 1890. Yellow, green to blue and deeper coloured aquamarine and emerald varieties have been cut. The main material comes from pegmatite veins around the Mole Granite near Emmaville-Torrington (Brown, 1984). Recent finds of strongly banded beryl/emerald provide unusual cut stones. High grade gem quality topaz is widespread in granitic lodes and alluvial distributions (Smith, 1926). Large, limpid, colourless, green, yellow and blue crystals, some with pink brown tinges, provide flawless cut stones.

Abundant quartz varieties come from granitic bodies and related siliceous pipes. They include rock crystal, smoky quartz, brown quartz, amethyst, citrine, cairngorm, morion, rare rose quartz, as well as rutiled quartz, sceptre quartz and aventurine. Optically perfect quartz was mined from Kingsgate pipes. Deposits in foldbelt serpentinites southeast of Tamworth have produced export quality jade. It forms as bluish green to dark green lenses and the less sheared material takes a good polish. Lapidary grade rhodonite comes from manganese deposits within southern foldbelt sequences. Brownish to deep red and rose pink material has been mined. These old sea floor deposits became enhanced in colour by thermal effects near granite contracts. Pyrope-almandine garnets of gem quality are found in sporadic basalt associations. Faceting-quality peridot (olivine) and feldspar (labradorite) are found in rare basalt flows, while some precious 'volcanic' opal occurs in basalt and rhyolite lavas in northeastern areas. Green fluorite and ruby-amber cassiterite provide collectors gemstones from granitic deposits. A wide range of lapidary cherts, jaspers and agate pebbles can be fossicked in the fold belt drainages.

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Argyle Diamond Deposit, Western Australia

GAYLE WEBB

Argyle burst onto the world scene in the early 1980s and has since changed many aspects of diamond exploration and marketing. It is the largest diamond mine in the world, the largest producer of natural industrial diamonds and a significant producer of gem quality diamonds. The mine is in the East Kimberley region, about 2,400 km north-east of Perth, and is virtually one huge pipe with associated alluvial deposits. The Ashton Joint Venture identified diamonds at Smoke Creek in August 1979. Following the stream to its source, 20 kilometres away, geologists discovered the Argyle Pipe in October 1979. Named after nearby Lake Argyle the pipe was referred to as AK1. This pipe subsequently provided extremely rich diamond grades of 7 carats per tonne, 10 times higher than any known deposit. Argyle has proved unique in a number of areas: geological, mineralogical, and commercial.

The geology of the Argyle Pipe did not fit the existing model for diamond exploration and the normal suite of kimberlitic indicator minerals was absent. The main indicator proved to be diamond itself, with some chromite. Previously, kimberlite intrusions in old continental cratons, stable for billions of years, had been considered the primary source of terrestrial diamond. At Argyle, diamonds were found for the first time in an adjoining mobile zone. A further deviation from the accepted model was the olivine-rich lamproite in which the diamonds occurred. This was a new diamond-bearing rock and widened the range of potential diamond hosts. The Argyle Pipe is an olivine lamproite diatreme of Precambrian age with a surface area of 50 hectares. It is an elongated body, 2 km long, that varies in width from 500 m to 150 m. The pipe has been faulted and tilted before erosion. At depth, the diatreme is variable in shape. Like most diamonds, lamproitic diamonds are mantle xenocrysts transported and resorbed by their volcanic host. They come from depths of over 180 km in highly-explosive, rapidly-injected magmas. Diamond emplacement in the larger Kimberley region was sporadic, from Precambrian into Tertiary time (2000 to 20 Ma), but the Proterozoic Argyle pipe (1180 Ma) carried the only economic concentration of diamonds.

The Argyle Joint Venture estimated that the mine would supply more than 25% of the world's diamonds over 20 years. A two-stage mining program was formulated. Stage 1 began in 1983, with the short-term mining of alluvial deposits at Smoke and Limestone Creeks and scree overlying the AK1 pipe. From 1983–1985, 16.8 million carats of diamonds were produced. Stage 2 began in 1986 with the long-term mining of the main orebody. Production jumped to 29.2 million carats. Production reached over 30 million carats annually, about one third of the world's rough diamonds. In 1993, due to expansion and upgrading, a record 40.9 million carats was produced. Figures are still high, with 40.2 million carats produced in 1998.

In spite of its huge production figures, only about 5% of Argyle's total output is gem quality. The vast remainder is about 50% industrial grade and 45% cheap, near-gem quality. The quality of the alluvial diamonds is reputedly higher, with 10% being gem quality. This low gem ratio reduces the output to only 5 per cent, by value, of the world's gem quality diamonds, yet this small percentage generates 50% of the mine's revenue.

The majority of Argyle diamonds (95%) are eclogitic in type. They are dodecahedral or mixed crystal forms and are 1.2 to 1.6 billion years old, formed shortly before eruption. However, peridotitic, octahedral crystals also occur and these have a formation age of 3 billion years. Argyle diamonds provide many contrasts with African and Russian stones. They are typically small, averaging 0.10 carats. To date, the largest stones found have been between 40 and 50 carats. They are characteristically irregular in shape, with heavily etched surfaces attributed to their transport in corrosive potassic melts. Unusual hexagonal etch pits and trigons with truncated corners contrast with the sharply triangular etch features on many African crystals. The colour distribution of gem quality diamonds from the Argyle Mine is unique. They are dominantly brown, with less than 20 % being colourless or yellow shades. Less than 0.001% of total production is pink to red. Occasionally, blue and green stones are found. The pink and brown colours are due to plastic deformation of the crystal lattice. Argyle blue stones are unusual in being coloured by hydrogen, rather than a boron impurity. Argyle provides the world's only reliable supply of rare pink diamonds. A grading system was devised for these stones, which could include a range of colours from purplish pink to mixed shades, like *pink champagne*. Since 1984, Argyle Diamond Sales has held an annual Pink Diamond Tender in Geneva to sell its outstanding pink to red stones. Such stones have sold for $1,000,000 per carat.

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Mine Geology and Mineral Localities at Broken Hill, New South Wales

TONY WEBSTER

Many of Australia's great ore deposits have produced mineral specimens of exceptional quality with the Palaeo- proterozoic Broken Hill lead-zinc-silver deposit in far western New South Wales being pre-eminent. At Broken Hill, the compositional complexity of the various orebodies, coupled with high grade regional metamorphism and the subsequent exposure of the orebodies to near-surface weathering processes has produced an exceptional variety of minerals.

The first recorded specimen from Broken Hill was collected by Charles Rasp in 1883. It was a heavy black material that contained minor silver and lead and was probably coronadite. The outcrop, from which it came, was a distinctive linear ragged hill, the "broken hill" which is often referred to as a gossan, but true gossan only becomes a significant proportion of the oxidized zone at depth. At Broken Hill, the oxidized ore types are all closely associated with a plunge culminating in the centre of the field. It is only here that the mineralisation was close enough to the surface to have been affected by surface oxidation. The geology of the upper Broken Hill Proprietary mine shows that most near-surface mineralisation was 3 Lens lying in the hinge of an antiform.This fold hinge only reached the surface over a maximum strike length of approximately 720 metres in MLs 12 and 13 and was just being exposed at the crest by erosion when mining commenced. Distribution of the minerals was not random in the oxidized zone since mineralogically distinct regions existed. Though opinions of various workers differ on the zones that they define, Jaquet (1894) recognised the following mineralogical zones: *manganiferous iron ore* formed the surface capping; *dry high grade ore* was "*chiefly kaolin with some garnets and quartz 30 oz to 300 oz Ag/ton, 5% Pb;*" *carbonate of lead ore* was "*a loose aggregation of crystals of cerussite and a quartzo-aluminous gangue impregnated with manganiferous iron oxide. 5 oz - 80 oz Ag/ton, 20 - 60% Pb/ton;*" *dry low grade ore* differed from carbonate of lead ore in containing a much smaller percentage of cerussite; it consisted of a mixture of carbonate of lead ore and dry high grade ore; *sulphide ore*.

Mine geology shows that the geometry of the oxidized zone and outcrop was controlled by the shape of the underlying garnetiferous lode rocks and mineralisation. The richest ore type of the oxidized zone was the kaolin-dominated mineralisation which Jaquet (1894) named "*dry high grade ore*" (*i.e.*, silver-rich). It was best developed in three southerly plunging shoots at the boundary of MLs 11 and 10. The southerly plunge of the shoots suggests that there was some geological control on its formation, other than the water table. Kaolin, the main constituent, would not be the product of the breakdown of sulfides and it is probable that this ore type formed within leached metasediments. Silver-rich solutions originating from the weathering of sulfides may have been channelled down the synformal keel with silver deposited as bromian chlorargyrite in the clay. A number of.large vughs ranging from 4.5 x 1.8 x 1.8 metres to 2.7 x 4.5 x 12 metres, was developed in the heart of the ironstone body, probably the equivalent of the oxidation collapse zone, in ML 11. Some vughs were spectacular sights, with smithsonite covering black stalactites of coronadite and carpeting the floor of the cavity. A silver-rich zone of supergene ore was developed between the sulfide and oxidized ores, up to 1 metre in thickness, composed mainly of secondary silver sulfides and large blocks of native copper.

The sulfide zone is dominated by sphalerite and galena, together with gangue minerals defining distinct layers and zones. The earliest minerals are the sulfides, pyroxenes, pyroxenoids and calcite. Some parts of the orebodies were subjected to slightly higher temperatures and pressures than others, and hence the northern end of the deposit was noted for the quality and abundance of rhodonite. The best rhodonite specimens were found in 3 Lens in the North Mine, because the temperature at the time of main deformation was slightly higher than in other regions of the deposit. Bustamite was best developed within calcite-rich parts of 2 Lens, within high grade shears zones, and was encountered in stopes between the 18 and 20 levels of the Zinc Corporation Mine (ZC). In 2 Lens, most of the rare specimens of fayalite and ilvaite occurred at the margins of large masses of rhodonite where it was in contact with banded calcite ore.This was especially the case between the 19 and 21 levels at the New Broken Hill Consolidated Mine (NBHC). Green feldspars are associated with large bodies of pegmatite that traversed the lode, or formed in small melt segments in adjoining metasedimentary wall rocks.

Many minerals specimens were found lining vughs and cavities associated with well-defined fault zones in the ore. The Central and Flat Faults at the ZC and NBHC Mines were major sources of inesite, manganoan calcite, rhodocrosite, sturtite and “dogstooth” calcite. Bannisterite and gem rhodonite were recovered from fractures that were possibly associated with the Central Fault on the 12 level at the ZC Mine. Lords Hill Fault was a source of these minerals in the North Mine. “Hairy” bustamite was discovered in faults and fractures in both the North Mine and the ZC-NBHC Mines. Such environments are very unusual places for pyroxenes and pyroxenoids to crystallize. Dyscrasite in the Australian Broken Hill Consols lode developed where a geologically late fault crossed an amphibolite layer adjacent to the main orebody. Similar veins were identified in the Browne Shaft workings (12 level). Even later were the brecciated fault zones that fractured and milled the ores but were then cemented and lined with pyrite, calcite and manganoan calcite.

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The Foundation of the Sydney School of Coordination Chemistry

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ABSTRACT. The so-called 'Sydney School of Coordination Chemistry' has had an immense, even definitive, influence on Australian inorganic chemistry. Australian coordination chemists have been at the forefront of developments in the area and the international influence of many of the key figures (eg. Dwyer and Nyholm) has been widely acknowledged.

The founders of the 'School' were E.E. Turner, an Englishman who briefly held an appointment at the University of Sydney (1919-1921) and George Joseph Burrows, who after Turner's return to England influenced colleagues and research students toward careers in coordination chemistry. The scientific backgrounds of the founders and the state of inorganic chemistry at the time of foundation have been considered in detail. World War I significantly changed university education and the attitude of governments to scientific research. The timing of these influences ensured that the new foundation would become firmly established.

INTRODUCTION

It is generally agreed that the first research in coordination chemistry in Australia was carried out at the University of Melbourne (Baker & Livingstone, 1985; Mellor, 1976). The legendary professor of chemistry, David Orme Masson and Bertram Dillon Steele, later to be professor of chemistry at the University of Queensland, demonstrated that copper was present as a cupritartrate anion in Fehling's solution (Masson & Steele, 1899). This work was revisited by Packer and Wark at Masson's suggestion some twenty years later (Packer & Wark, 1921). After this initial foray Masson did no further work in coordination chemistry (Weickhardt, 1989) and Steele also did no further work in this area, concentrating his energies on the development of a unique design of microbalance (Hardman-Knight, no date; Chiswell, 1986).

The leadership in coordination chemistry in Australia passed to the University of Sydney in the late 1910s and a 'school', as it is generally understood, was founded that was extremely influential in defining inorganic chemistry in this country, as well as having a significant impact on world chemistry. This school is often referred to as the Sydney School of Coordination Chemistry (Craig, 1987).

BACKGROUND TO FOUNDATION

Coordination chemistry was a relatively young and active field of chemistry in the 1910s. The development of the field had occurred mainly through the efforts of Alfred Werner in Zürich. In his work Werner contributed significantly to the understanding of valency through introducing the concept of auxiliary valencies (German: *Nebenvalenzen*) to explain the binding in coordination compounds (Werner, 1911a, p.57):

> 1. Principal valencies are manifestations of affinity, which permit their saturation capacities to be measured in terms of hydrogen atoms or groups equivalent to the latter.

> 2. Auxiliary valencies are manifestations of affinity which bring about stable union of radicles; the latter being able themselves to exist as independent molecules.

Werner went on to point out that for sodium nitroprusside it is practically impossible to decide to which class of valency the NO groups belongs. Having explained that the bonding can be represented similarly for both types of valency, he continued "Nevertheless, it appears desirable to preserve for the present the difference between principal and auxiliary valencies, for to-day the doctrine of valency is in a transition state, and hence it is judicious to construct sharply defined conceptions....." (Werner, 1911a, p.66). Werner's ideas were first published in the 1890s but it was only on the publication of his book *Neuere Anschauungen auf dem Gebiete der Anorganischen Chemie* in 1905 that significant attention was paid to his ideas. This work went through five editions in German [1905, 1909, 1913, 1920 (edited by P. Karrer) and 1923 (edited by P. Pfeiffer)] (Kauffman, 1966, p. 120). The second edition was translated into English (Werner, 1911a) with the title 'New Ideas on Inorganic Chemistry' by Edgar Percy Hedley, a Lecturer in Chemistry at the University of Birmingham. It is noted on the title page that the work is "translated, with the author's sanction, from the second German edition". This publication must have significantly assisted in bringing Werner's work to the attention of English-speaking scientists.

Werner was able to determine the structure of six-coordinate complexes by considering what isomers were possible for various combinations of ligands. This approach was an extension of the reasoning by Van't Hoff and Le Bel that led to the proposal of the tetrahedral arrangement of bonds for carbon (Jaques, 1993).

For six-coordinate complexes, four structures were considered possible: (i) hexagonal pyramidal, in which the metal atom sits above the plane of the six donor atoms which are arranged in a regular hexagon; (ii) hexagonal planar, in which the metal atom sits at the centre of a regular hexagon defined by the donor atoms; (iii) trigonal prismatic, in which the metal atom is at the centre of a trigonal prism defined by the donor atoms; and (iv) octahedral, with the metal atom sitting at the centre of a regular octahedron defined by the donor atoms. The first structure, hexagonal pyramidal, can be considered a special case of hexagonal planar (or *vice versa*) so only three structures need be considered.

For systems with only monodentate ligands only one isomer is possible for each of MA_6 and MA_5B for all structures. For MA_4B_2, the hexagonal planar and trigonal prismatic configurations would each result in three possible geometric isomers, whereas the octahedral configuration would result in only two possible geometric isomers (*cis* and *trans*). Again, for MA_3B_3, the octahedral configuration would yield two geometric isomers whereas for the other configurations three isomers would exist. Werner directed synthetic efforts at complexes of these formulae (MA_4B_2 and MA_3B_3) and other complexes containing bidentate ligands. His results strongly support the octahedral configuration but it was realised that failure to produce a third isomer was negative evidence and may have only reflected the inability to achieve the synthesis. Werner recognised that the resolution of optical isomers would confirm the octahedral configuration.

Werner wrote to his friend and fellow student Arturo Miolati on 20 February 1897 explaining that they were engaged in attempts to resolve cobalt complexes and in a paper published in 1899 on oxalatobis(ethylenediamine)cobalt(III) salts Werner discussed the possibility of the formation of asymmetric isomers, which he carefully distinguished from the optical isomerism displayed by carbon compounds in which one carbon atom has four different groups attached (Kauffman, 1981, p.122). Werner realised that complexes containing bidentate ligands would, for certain stoichiometries, yield resolvable optical isomers. Victor L. King spent a year trying unsuccessfully to resolve $[Co(en)_2CO_3]Br$ (en = ethylenediamine) and reasoned that working on a related compound $[Co(en)_2(NH_3)Cl]Cl_2$ might be more successful (Kauffman, 1981, p.125). The successful resolution was eventually achieved in June 1911 and the paper was dispatched that month for publication (Werner, 1911b). In what now would be considered an unusual convention, Werner was the sole author of the critical paper but at the head of the experimental section was "(Von V. L. King)". Werner's assistant, E. Scholze, was also acknowledged for collaboration on this paper (Werner, 1911b). Werner summarised (Werner, 1911b, translated in Kauffman, 1968, p.163) the importance of the results of this work as follows:

> (1) the proof that metal atoms can act as central atoms of stable, asymmetrically constructed molecules and thereby lead to phenomena which agree with those produced by the asymmetric carbon atom; (2) the proof that pure molecular compounds can also occur as stable mirror-image isomers, whereby the difference between valence compounds and molecular compounds, which is still frequently maintained, disappears entirely, and (3) the confirmation of one of the most far-reaching conclusions from the octahedral formula, by which the latter has found a new, important confirmation.

Subsequent to this important work, Werner was able to resolve further optical isomers of various complexes. The complexes contained ligands that included carbon atoms and it has been surmised that detractors suggested that the optical activity arose from asymmetric carbon atoms (Kauffman, 1966, p.37). Werner resolved the optical isomers of the carbon-free complex ion tris[tetrammine-μ-dihydroxocobalt(III)]cobalt(III), isolated as the bromide: $[Co\{(\mu\text{-}OH)_2Co(NH_3)_4\}_3]Br_6$, which dispelled these doubts (Werner, 1914). This remarkable achievement of a completely carbon free optically-active octahedral complex has only been repeated on a few occasions since (Kauffman, 1981, p.134).

Werner was awarded the Nobel Prize for Chemistry in 1913. In the presentation speech, Nordström, the President of the Royal Swedish Academy of Sciences stated (Nordström, 1913):

> By far the greatest interest in the field attaches also to the discovery he made in the last few years, that certain cobalt, chromium, iron and radium compounds with an asymmetrical metal atom in the complex radical can de divided into two forms which behave like mirror images and show differences of the same kind as those in organic mirror-image isomers, i.e. they are optical antipodes of each other. This discovery is a splendid support for Werner's theory. It has been called the most important discovery in chemistry in recent times, and his stereochemical work makes him the founder of inorganic stereochemistry.

Read, who completed his doctorate with Werner at Zürich (1907) and subsequently was Professor of Organic Chemistry at the University of Sydney (1916-1923), remarked later that the resolution of the salts of $[Co(en)_2(NH_3)Cl]^{2+}$ into optically active isomers "was a stereochemical achievement of the first order, confirming the octahedral environment of the central metallic atom" (Read, 1947, p.264).

Optical isomerism thus had a central role in the establishment of the structure of coordination compounds and the resolution of optical isomers of octahedral complexes has been a continuing theme in the history of coordination chemistry.

FOUNDATION

Credit for the founding of the Sydney School must go to Eustace Ebenezer Turner (1893-1966), who briefly held an appointment as lecturer at the University of Sydney from 1919-1921. Though Turner's time in Sydney was short, his influence was immense, particularly on George Joseph Burrows (1888-1950). It is through Burrows that the Sydney School was established.

Turner studied chemistry at East London College (now Queen Mary College), supported by an exhibition from the Drapers' Company, graduating B.Sc. in 1913 with first-class honours in chemistry. He found the professor of chemistry, J.T. Hewitt, a stimulating teacher who presented all areas of chemistry as equally interesting. After his B.Sc. Turner stayed one year at East London College, where he started a course on practical physical chemistry. In 1914 he was appointed as an Assistant Lecturer in Goldsmiths' College but spent most of World War I in war work. He worked on medicinals at Boots' Laboratories, Nottingham and Huddersfield Technical College for a few months at each location. Subsequently he worked on arsenicals as assistant to W.J. Pope at Cambridge. Interestingly, he published several papers in this period, including preliminary work on the structure of the biphenyls, an area in which he subsequently made a substantial contribution (Ingold, 1968).

Prior to his appointment at the University of Sydney, Turner had made some contribution to inorganic chemistry. His first publication (Bennett & Turner, 1914) opens with the statement: "The object of this investigation was to obtain organo-metallic derivatives of chromium." Anhydrous chromium(III) chloride was reacted with "the Grignard reagent" (phenyl magnesium bromide). The expectation was that $Cr(C_6H_5)_3$ (or perhaps $CrCl(C_6H_5)_2$ or even $CrCl_2(C_6H_5)$) would be obtained. The reaction was found to yield diphenyl ($C_6H_5{\cdot}C_6H_5$). The reaction was extended using other Grignard reagents to prepare α,α-dinaphthyl, dibenzyl and 4,4'-dimethyldiphenyl. Attempts to obtain asymmetric products (eg 4-methylphenyl-α-naphthalene) and products from aliphatic halides were not successful. Turner subsequently showed that copper(II) chloride could also be used as a coupling reagent, giving diphenyl from phenyl magnesium bromide (Krizewsky & Turner, 1919) and yielding 2,2'-dimethyldiphenyl from the appropriate Grignard reagent (Turner, 1920). It is to be noted that Turner's interest in the structure of diphenyl and related compounds was one of the principal lines of research that he pursued for many years. R.J.W. Le Fèvre worked with Turner at East London College in the 1920s and they co-authored eleven papers on the structures of diphenyl in 1926-8. It can be argued that Turner exerted an immense influence on chemistry at the University of Sydney, directly through his own time there (1919-1921) and indirectly through his student being appointed to a chair there from 1946-1970.

Turner's work on Grignard reagents and their reactions with transition metal compounds was only tangentially related to inorganic chemistry and was more in the sphere of organometallic chemistry rather than coordination chemistry. From his war work with Pope, he gained great experience in arsenic chemistry (Pope & Turner, 1920). In the paper it is acknowledged that "permission for its publication has been given by the General Staff."

Turner had made a strong contribution to the understanding of the structure of coordination compounds by a vigorous defence of Werner's theories. John Albert Newton

Friend published a series of papers (Friend, 1908a, 1908b & 1916) in which he proposed a cyclic theory for the structure of complexes. Friend was concerned that the "dissociable chlorine atoms hover in an indefinite manner" around the complex ion as a whole. He was also concerned that the valency (of six) proposed for cobalt was too high (Friend, 1916). Friend suggested that the chloride ions were attached directly to the cobalt atom thus exhibiting a valency of three and that the other groups were bound together in a hexagonal planar arrangement of donor atoms (in $[Co(NH_3)_6]Cl_3$, nitrogen would display a valency of five because it was bound to three hydrogen atoms and two adjacent nitrogen atoms). In his terms, "the cobalt atom lies in the ring from which it cannot easily escape for purely physical reasons". In the case of $[Co(NH_3)_5Cl]Cl_2$, one of the chlorine atoms would be in the ring, as well as bound to the cobalt, and the other two would be bound directly linked to the cobalt atom.

In his response to Friend's proposals, Turner demonstrated an understanding of the importance of optical isomerism in establishing the octahedral structure of six-coordinate complexes (Turner, 1916):

> The strong point of Werner's theory is the definite proof that the six-coordinated atoms or groups have a more or less well-defined octahedral orientation. Unless Friend's "shell" is identical with Werner's octahedral structure, there is no explanation on the cyclic theory of the existence of optical activity among certain types of compounds.

Clearly, Friend's proposal had, as an essential element, a tendency of nitrogen compounds to form ring structures. He suggested that the ammonia molecules can combine in the same way as "atmospheres" of water molecules surrounding ions as had been proposed by Kohlrausch to explain ion mobility in solutions (Friend, 1916). In modern terms, the formation of such "atmospheres" would depend on hydrogen bonding rather than a direct O-O bond as Friend claimed. Turner dismissed Friend's suggestion by reference to current understandings of nitrogen chemistry (Turner, 1916):

> Friend refers to the analogy between metalammines and ring compounds of carbon, but he seems to overlook the fact that unless some strong salt-forming influence is at work, nitrogen atoms do not combine together in the way that is so characteristic of carbon.

In the 1910s, Turner, coming from the synthetic tradition, had worked with Grignard reagents, in an attempt to prepare organometallic compounds, had gained experience in the chemistry of arsenic compounds and also had acquired a significant appreciation of the current theories of coordination compounds.

At the University of Sydney, he had the opportunity for sustained research. The work that he chose to do reflected his background and experience in that he worked on compounds of fundamental importance to the debate on bonding in coordination compounds and pursued further work on arsenic compounds. In this work on the constitution of coordination compounds and new organic arsenicals, Turner collaborated with Burrows. One of their principal triumphs was to demonstrate optical activity in an arsonium salt even though the racemisation was extremely rapid. The cation isolated was the phenyl-α-naphthylbenzylmethylarsonium ion, ie with an arsenic atom bound to four different groups. They also were able to clarify a controversy over the correct formulation of the nitroprussides by conductivity and cryoscopic measurements.

Turner returned to England to take up a research appointment at the Royal Arsenal, Woolwich and re-joined East London College as a Senior Lecturer in 1923. Eventually he retired in 1960 as the Professor and Head of Chemistry at Bedford College, having moved there in 1928. He was elected to the Fellowship of the Royal Society in 1939 (Ingold, 1968).

INTERLUDE: DEVELOPMENTS IN RESEARCH AND THE UNIVERSITY OF SYDNEY

World War I proved to be a great spur to scientific research in the British Empire as a means of supporting the development of technology-based industries. At the outbreak of the war Britain found that Germany was far in advance in the production of many goods relevant to the war effort (Currie & Graham, 1966, p.11):

> Great Britain was rudely awakened to the fact that she had been far too dependent on Germany for her supplies of manufactured articles, chemicals and raw materials. Optical glass, magnetos, drugs and pharmaceutical preparations, tungsten and zinc smelted from ores mined in the British Empire were among the many items processed in Germany and later imported by pre-war Britain.

Remarkably, Britain was paying royalties to Krupps for fuses in shells until 1915 and the stocks of chemical glassware were so low that a national inventory was established in case there was a need to commandeer university and other supplies (Rose & Rose, 1970, p.36).

The dyestuffs industry is particularly illuminating in emphasising the lead that Germany had taken in chemical manufacture. The aniline dyes had been discovered by the British chemist, W.H. Perkin, as a young man in 1856, and his family established a company to manufacture these dyes (Edelstein, 1961). The commercial potential of the discovery was realised by German manufacturers and there was a ready supply of well-trained chemists to support their endeavours. The German developments in the area were so effective that "by 1879, Germany was producing some £2 million-worth of coal-tar products and Britain only £450,000-worth of the dyes which had been invented in Britain by a British scientist." (Rose & Rose, 1970, p.28). A critical point was a technically-trained workforce, Britain's science in the nineteenth century had been largely in the hands of "amateurs and gentlemen" (Rose & Rose, 1970) but technical education in Germany was much better organised (Turner, J.W., 1909). Four German chemical concerns involved in the dyestuffs industry employed over 1000 chemists each in 1914, whereas the whole British industry employed only 1500 chemists (Currie & Graham, 1966, p.11).

As a result of concern expressed by the Royal Society, the British government established an advisory committee for scientific research. Australians were quick to realise the importance of this move with Professor Orme Masson expressing his relief that politicians had realised the parlous state of British science after much urging by scientists (Currie & Graham, 1966, p.12). These developments led in Britain to the establishment of the Department of Scientific and Industrial Research (Rose & Rose, 1970, p.40) and to the formation of an Advisory Council of Science and Industry in Australia in 1916, this body being the forerunner of the CSIRO (Currie & Graham, 1966, pp.43-56). In the discussions surrounding the formation of the Advisory Council, universities were strongly consulted and it was recognised that the stimulation and coordination of research in universities was an important aim. Some of the advice received in founding the Advisory Council had strongly urged that funding and organisation of research in universities should be the principal aim of the Advisory Council (Branagan & Holland, 1985, p.18), so scientific research in universities was very much 'on the agenda'.

There were parallel developments at this time at the University of Sydney that secured the future of research within the university. In the British tradition of science referred to above, workers often pursued their interests as a lone worker, for example Archibald Liversidge was the sole author on almost all of his many publications (Baker, 1997). In order to incorporate further research training in the science degree a four-year Honours degree was introduced in 1922 and the Master of Science degree was introduced in 1923 (Turney, Bygott and Chippendale, 1991, p.527). The other pressure which probably helped in the establishment of a research culture was the huge growth in numbers of students studying the sciences, possibly as a response to the important role science and technology played in World War I. First year Chemistry classes with an enrolment of 222 in 1909 had more than doubled by 1919 (Branagan & Holland, 1985, p.19). There was a sharp post-war increase in enrolments with the student enrolment jumping by 700 to a total of 2,764 (including 748 women) at the start of the 1919 academic year (Turney, Bygott and Chippendale, 1991, p.431). Because of the introduction of the Honours year and the research degree (M.Sc.), academic staff were able to pursue research in collaboration with research students. This probably led to an increase in output and the opportunity to disseminate influence through appointment of graduates to other institutions. Certainly, most of Burrows' publications after the early 1920s had a research student as a co-author (see Appendix).

ESTABLISHMENT

George Joseph Burrows graduated in science at the University of Sydney in 1910 with a double university medal in chemistry and in geology & mineralogy (Branagan & Holland, 1985). As an undergraduate he had undertaken a study of the water supply of Goulburn and made recommendations for the clarification of the supply (Burrows, 1909). There was a later publication on the analysis of natural waters (Burrows, 1926b) but the samples had been collected by Dr. W.G. Woolnough in 1911 and the analyses were also performed that year. He was appointed a lecturer at the University of Sydney and collaborated with Charles Edward Fawsitt, the professor from 1909 to 1946 (Branagan & Holland, 1985), on the corrosion of steel (Burrows & Fawsitt, 1911) and the decomposition of carbamide (Burrows & Fawsitt, 1914).

In his independent work Burrows appears to have shown a strong orientation toward physical chemistry, with several publications on the rates of reactions eg. inversion of sucrose (Burrows, 1914), hydrolysis of methyl acetate (Burrows, 1919b and 1921). The study of the hydrolysis of esters included a later paper on the equilibrium in such systems (Burrows, 1925). He also worked extensively on determining the volume changes associated with dissolution of solutes, eg. (Burrows, 1919a, Burrows & James, 1925 and Burrows, 1926a).

Burrows was appointed to a temporary lectureship in chemistry at the Royal Military College, Duntroon from August 1915 to April 1919. He was depressed about his academic prospects and considered resigning from his post at the University of Sydney (Mellor, 1976). Fortunately Turner arrived in 1919 and Burrows collaborated with him on coordination chemistry projects.

Their first work together was to study the composition of the nitroprussides. Turner had indicated that he intended to do some experimental work on these compounds in his response to Friend's theories of the structures of coordination compounds (Turner, 1916):

> In the case of the nitroprussides, Friend suggests a double formula. A molecular-weight determination or, better, a determination of the number of ions by the conductivity method, is necessary before such a formula can be accepted. The author hopes to examine these points when time is available for experimental work.

Presumably Burrows' skills as a physical chemist were of significant use in this initial study as there is no indication of such experience in Turner's background. Their experimental work confirmed that the nitroprussides were salts of an acid with the formula $H_2[Fe(CN)_5NO]$ as had been earlier assigned by Hofmann rather than salts of $H_4[Fe_2(CN)_{10}(NO)_2]$, as had been suggested by Friend. Rather archly the authors stated "Friend, apparently without further experimental work, proposed for potassium nitroprusside the formula ....." (Burrows and Turner, 1919). In subsequent work, they managed to isolate nitroprussic acid and alkyl derivatives of the acid (Burrows and Turner, 1921c). This work was of considerable significance and was still referenced in the major inorganic chemistry text-book in the early 1950s (Sidgwick, 1950).

As has been mentioned Turner had worked on arsenic compounds in the years of World War I and the collaborators now turned their attention to compounds of arsenic. In their first paper on arsenic compounds (Burrows and Turner, 1920) they reported work on the deeply-coloured "additive compounds" that are formed when tertiary arsines (RR'R"As) are reacted with diiodomethylarsine (CH_3AsI_2).

Burrows and Turner reasoned that the As-oxide of 1-methyl-1,2,3,4-tetrahydroarsenoline (the arsenic analogue of reduced quinoline) should be capable of resolution into its optical isomers. They prepared the compound but not in sufficient quantity to attempt the resolution of the isomers (Burrows and Turner, 1921a). They reported the successful resolution of a salt of the phenyl-α-naphthylbenzylmethylarsonium cation in the same paper. In these salts the arsenic atom is asymmetric in the same way that a carbon atom is considered asymmetric if all four groups attached are different. It was noted that racemisation was very rapid and only small molecular rotations were recorded (Burrows and Turner, 1921a). This was an important result and represented the first successful resolution for an arsenic compound. Burrows and Turner were too modest to make such a claim but mentioned that previous attempts were unsuccessful.

They also worked on additive compounds formed between tertiary arsines and the iodides of arsenic, bismuth, mercury, lead, tin, antimony and cadmium (Burrows and Turner, 1921b). The subject of their last collaboration was the preparation of certain tris(oxalato)ferrate(III) salts. They attempted to resolve the anion into its optical isomers through isolation of the cinchonine and strychnine salts but were unsuccessful (Burrows and Turner, 1921d). They noted that the resolution of tris(oxalato)ferrates had been achieved during the course of their study by Thomas.

Turner returned to England in 1921. Burrows, remaining at the University of Sydney, had been fired with enthusiasm to continue research in coordination chemistry but had not entirely lost interest in the physical chemistry of solutions he had pursued prior to Turner's arrival (Burrows & Eastwood, 1923; Burrows & James, 1925 and Burrows, 1926a). His first work in coordination chemistry, in the absence of Turner, was to study the dissociation of cyano complexes (Burrows, 1923) and oxalato complexes (Burrows & Walker, 1923) by conductimetric and cryoscopic methods.

The intention of this paper is to focus on the foundation of the Sydney School of Coordination Chemistry, so a detailed review of the subsequent work published by Burrows will not be attempted. A sense of this work will be gained from considering the full list of his publications included as an Appendix and through his Liversidge Lecture to the Royal Society of New South Wales (Burrows, 1940).

CONCLUSION

The Sydney School of Coordination Chemistry was founded because coordination chemistry was clearly a very active area in the 1910s. This claim can be substantiated by considering the activity of Werner's school in the 1910s and their marvellous achievements in elucidating the stereochemistry of coordination compounds. This work culminated in the award of the Nobel Prize in Chemistry to Alfred Werner in 1913. The importance of this decade in the development of coordination chemistry was summarised by Lawrence Bass in his preface to a book on coordination chemistry (Schwarz, 1923):

> So far as the writer is aware, there is only one monograph in English on the subject, viz., Hedley's translation (Longman's, 1911) of the Second Edition (1908) of Werner's "Neuere Anschauungen." Since the publication of this translation many fundamental contributions to the theory have been made which should be included in any study of the complex compounds.

Turner came from the synthetic tradition in chemistry and was clearly well aware of Werner's theory of bonding in coordination compounds as is demonstrated by his effective rebuttal of Friend's ideas (Turner, 1916). His expressed interest in the nitroprusssides was pursued in Sydney and his collaboration with a chemist from the physical chemistry tradition was fortuitous, given that conductimetric and cryoscopic methods were used to confirm the formula of the nitroprussides. Turner's wartime experience with arsenic compounds provided initial synthetic problems to pursue. Burrows and Turner had an early success in resolving the optical isomers of an arsonium salt, in which the cation has four different substituents (Burrows & Turner, 1921a). Having had experience in polarimetry Burrows was able to contribute to the work on the resolution of optical isomers. The study of arsenic compounds as ligands in metal complexes was a continuing theme in the Sydney School (Craig, 1972; Burrows, 1940).

Burrows had been pursuing independent research in physical chemistry until Turner's arrival in Sydney. As has been mentioned, his independent work included studying rates of reaction of hydrolysis of esters and inversion of sugars. After Turner's brief stay, and a few further physical chemistry papers, the character of Burrows' work changed to focus on the synthesis of coordination compounds. The matter of resolving optical isomers of coordination complexes that was pursued by Burrows has been a continuing theme in the 'Sydney School' with the work on complexes of sexadentate ligands by Dwyer and Lions being a highpoint (Baker, Xiao, Craig & Baker, 1999; Baker, 1999). Given that Burrows had no preparative experience in his research work, had little or no contact with coordination chemistry and had not previously dealt with arsenic compounds, Turner's influence was absolutely critical in recruiting Burrows to coordination chemistry. Burrows clearly learnt well and, as a proselyte, was effective in promoting coordination chemistry to students and colleagues.

Part of the reason for the vast influence of this school in Australian inorganic chemistry is that coordination chemistry itself was experiencing a vast resurgence on a world scale in the 1950s. Coordination chemistry was actively pursued in Australian chemistry departments after that time, so coordination chemists were in plentiful supply to take up academic appointments in the period of expansion in Australian universities in the 1950s and 1960s. An important conference on coordination chemistry was held in Sydney on 25th and 26th May, 1953. Sir Ian Wark opened the conference and his remarks serve as an excellent summary of the influence of Burrows (Wark, 1954):

> Sydney's proud position in coordination chemistry has sprung from the efforts of one man, G.J. Burrows, now dead. Probably, in the first instance, he owed something to E.E. Turner, but Turner returned to England after a short stay in Australia, and thereafter, for 25 years, Burrows devoted his whole working life to coordination chemistry. I collaborated with Burrows on a small piece of research on the aluminium salicylato complexes. One of us had expected to get salts of an acid $H[Al(C_7H_4O_3)_2]$, the other $H_3[Al(C_7H_4O_3)_3]$. Instead we got $H_2[Al(C_7H_4O_3)_2(OH)(H_2O)]$. Burrows was delighted that here was something new and unexpected.

ACKNOWLEDGEMENTS

I would particularly like to thank my daughters, Miss Elizabeth Baker and Miss Helen Baker for their assistance with Chemical Abstracts searching.

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APPENDIX

Following is a complete listing of the publications of George Joseph Burrows. All papers have been sighted in the original journal and confirmed through Chemical Abstracts.

1. G.J. Burrows, Notes on Goulburn water with some experiments on its clarification. *Journal and Proceedings of the Royal Society of New South Wales*, **43**, 394-8 (1909).
2. G.J. Burrows and C.E. Fawsitt, Observations on the corrosion of steel in water. *Journal and Proceedings of the Royal Society of New South Wales*, **45**, 67-75 (1911).
3. G.J. Burrows and C.E. Fawsitt, Decomposition of carbamide. *Journal of the Chemical Society*, **105**, 609-23 (1914).
4. G.J. Burrows, Inversion of sucrose by acids in water-alcohol solutions. *Journal of the Chemical Society*, **105**, 1260-70 (1914).
5. G.J. Burrows, Volume changes in the process of solution. *Journal and Proceedings of the Royal Society of New South Wales*, **53**, 74-99 (1919).
6. G.J. Burrows, The rate of hydrolysis of methyl acetate by hydrochloric acid in water-acetone mixtures. *Journal of the Chemical Society*, **115**, 1230-9 (1919).
7. G.J. Burrows and E.E. Turner, Constitution of the nitroprussides. I. Conductivity and cryoscopic measurements. *Journal of the Chemical Society*, **115**, 1429-35 (1919).
8. G.J. Burrows, The hydrolysis of urea hydrochloride. *Journal and Proceedings of the Royal Society of New South Wales*, **53**, 125-35 (1919).
9. G.J. Burrows and E.E. Turner, A new type of compound containing arsenic. *Journal of the Chemical Society*, **117**, 1373-83 (1920).
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20. G.J. Burrows and A.E. James, Molecular solution volumes and association. *Journal and Proceedings of the Royal Society of New South Wales*, **59**, 223-9 (1925).
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Thesis Abstract: Geology And Geochemistry of The Wallendbeen Area, N.S.W.

IAN COOPER

Abstract of a Thesis Submitted for the Degree of Master of Science,
University of Sydney 1998

The geology of the Wallendbeen area (400km south west of Sydney) is dominated by the Silurian Young Batholith and (?)Cambro-Ordovician Jindalee Group. The Jindalee Group consists of deformed and metamorphosed basalt, mafic volcaniclastic rocks, gabbro, ultramafic rocks, and banded quartz – Fe – Mn metachert defining an ocean floor

environment. Although samples are altered, whole rock major, trace and rare earth element data are consistent with a primary back-arc basin setting. A second association within the Jindalee Group is composed of finely bedded quartzose psammite and psammopelite that bear similarities to the Middle Ordovician Wagga Group. These quartzose rocks have been derived from a continental source and are part of an extensive turbidite fan covering the Lachlan Orogen in the Ordovician.

Both the mafic and quartzose rocks share a common metamorphic and structural history that involves two periods of tight to isoclinal folding. The first deformation event is correlated with the Early Silurian 'Benambran Orogeny' where peak metamorphic conditions are transitional to amphibolite facies at ~500°C and 300 MPa, indicating a depth of burial of 10 – 12 km. The second deformation involves tight to isoclinal upright folding with lower greenschist facies conditions. This event is ascribed to the 'Bowning Orogeny' that is constrained to the period ~420 to 417 Ma in the Wallendbeen area.

An 8 km long fault bounded wedge of andesitic volcanic rocks (Yandilla Volcanics) occurs within serpentinites at 'Fontenoy'. The Yandilla Volcanics comprise andesitic volcanic rocks, phyllite, banded chemical sedimentary rocks and a small hornblende diorite. The whole rock major, trace and rare earth element geochemistry display a continental arc signature and the Yandilla Volcanics are correlated with the Mid-Silurian Blowering Formation in the Cullinga area.

Both the Jindalee Group and the Yandilla Volcanics show the effects of contact metamorphism and boron-potassium metasomatism due to intrusion of the Young Granodiorite that postdates 'Bowning Orogeny' deformation. The Young Batholith is a large granitic body (210 km north-south by 40 km east-west) that is characterised by peraluminous S-type geochemistry. The intrusion is dominated by grey biotite granodiorite with rare alkali feldspar leucogranite. Metasediment xenoliths and tonalitic igneous enclaves that represent frozen droplets of a more mafic magma are abundant. Tectonic discriminant diagrams and palaeogeographic reconstructions indicate a volcanic arc setting for the pluton. The Young

Granodiorite is the product of partial fusion of Cambrian oceanic crust (Jindalee Group equivalents) and Ordovician metasediment with a mantle subduction component.

The tectonic development of the region commenced with the formation of a (?)Cambrian back-arc basin containing the Jindalee Group. This oceanic crust was covered by an enormous turbidite fan in the Ordovician, then both units were strongly deformed and metamorphosed in the Early Silurian 'Benambran Orogeny' that produced continental thickness crust. Mid Silurian back-arc transtensional rifting exhumed the Jindalee Group from ~12 km. Continental arc volcanism above the Young Granodiorite produced the Blowering Formation and Yandilla Voleanics. These units along with the Jindalee Group basement were deformed by the 'Bowning Orogeny' just prior to intrusion of the Young Granodiorite into the upper crust.

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Annual Report of Council

For the Year Ended 31 March 2000

PATRONS

The Council expresses its gratitude to his Excellency the Honourable Sir William Deane AC, KBE, Governor General of the Commonwealth of Australia, and to his Excellency the Honourable Gordon Samuels AC, CVO, Governor of New South Wales, for their continuing support as Patrons ofthe Society.

MEMBERSHIP

The membership of the Society as of 31 March 2000 comprised; Patrons 2, Honorary Members 13, Members 258, Associates and Spouse Members 24. Two members resigned and 14 members were admitted during the year. The death of the following long standing members were announced [the year of their election to the Society is in brackets]: Mr Timothy K. Wright (1994), Dr E.D. McCarthy (1949), and Prof. S.C. Haydon(1965).

OFFICE

The Society continued during the year to lease for its office and library a half-share of Convocation House, 134 Herring Road, North Ryde, on the Campus of Macquarie University. Council is thankful to the University for continuing the lease. Mrs Chandler, Assistant Office Secretary, having provided excellent service to the Society for nine years, resigned in October.

MEETINGS

Eight General Monthly meetings, six Special Monthly Meetings and Events and the 132nd Annual General Meeting were held in Sydney during the year. Eleven meetings were held by the Southern Highlands Branch. None were held by the New England Branch. Council held eleven meetings at the Society's Office at North Ryde.

PUBLICATIONS

Journal

Volume 132, Parts 1 – 4, of the Journal and Proceedings of the Royal Society of New South Wales were published for the year 1999. The volumes contained the 50th Clarke Memorial Lecture, The Presidential Address, four peer reviewed research papers, eleven abstracts of higher Degree theses, a book review, the Council Report for 1998, the Financial Statement for 1998, biographical memoirs and citations for awards for 1998.

Council wishes to thank all the voluntary referees who assessed papers offered for publication. Several permissions for reproducing material from the Society's Journal were granted.

Bulletin

Nine issues of the Bulletin were produced. The Council wishes to thank the many contributors. Particular thanks are extended to Ted O'Keeffe for production of the Bulletin and to those who assisted with the mailing.

LIBRARY

Acquisition of literature and monitoring the exchange and gifts agreements was continued at the Society's office at North Ryde. Council thanks Mr Karl Schmude, University Librarian, University of New England and his staff for their continued efficient care of the Society's collection in the Dixson Library.

AWARDS

The following awards for 1999 were presented at the Annual Dinner in March 2000:

The Society's Medal: Dr Daniel J. O'Connor;
The Archibald D. Ollé Prize:
  A/Prof. Anthony T. Baker;
The Clarke Medal: Prof. Richard Shine;
The Edgeworth David Medal:
  Dr Merlin Crossley;
The James Cook Medal: Dr Peter Colman;

The Royal Society's Studentships:
Ms Alison Basden and Ms Sharon Downes.
The Walter Burfitt Prize was not awarded this year.

NEW ENGLAND BRANCH

The Branch reported that further efforts were made to create a focal point for local citizens interested in science.

SOUTHERN HIGHLANDS BRANCH

The Branch enjoyed another successful year using Frensham School's Lecture Theatre as its lecture venue, maintaining an average attendance of over 75 members and visitors. Ten monthly lectures were held during the period, one of them jointly with the local branch of the Federation of University Women, and an additional ecological lecture and field trip was arranged for the benefit of the Wingecarribee Bush Fire Brigade.

ABSTRACTS OF PROCEEDINGS

7th April 1999

The 1079th General Monthly Meeting and the 132ndAnnual General Meeting were held at the Australian Museum, Sydney. The President, Dr Dan O'Connor was in the Chair and 23 members and four visitors attended. The Annual Report of Council and the Financial Statement for 1998 – 1999 were presented. Mr B. E. Holden was elected Auditor for 1999-2000.

The following awards for 1998 were announced:

Society's Medal
Dr David F. Branagan
Clarke Medal (geology)
Em. Prof. Richard L. Stanton AO
Walter Burfitt Prize
Prof. Anthony K. Burrell.

The Archibald D. Ollé Prize , the James Cook Medal and the Edgeworth David Medal were not awarded for 1998.

The following members were elected to the 1999 – 2000 Council:

President	A/Prof. A.T. Baker
Vice Presidents	Dr D.J. O'Connor Dr E.C. Potter Prof. D.J. Swaine Dr D.F. Branagan Prof. W.E Smith
Hon. Secretaries	Dr M.R. Lake Mrs Krysko von Tryst
Hon. Treasurer	Dr P.R. Evans
Hon. Librarian	Miss P.M. Callaghan
Members of Council	Mr J.R. Hardie Prof. A. Shannon Dr F.L. Sutherland Prof. R.H. Vernon Prof. P.A. Williams Prof. M.A. Wilson
New England Representative	Vacant
Southern Highlands Representative	Mr H.R. Perry.

Dr O'Connor yielded the Chair to the incoming President A/Prof. A.T.Baker, who then thanked the outgoing Council for its contribution during the preceding year. Dr O'Connor then presented his Presidential Address; "The Australian Republic and the Royal Society ofNew South Wales".

5th May 1999

The 1080th General Monthly Meeting was held at the Faculty of Science, University of Technology, Sydney. Mr Colin Nicholson and Dr Peter Cox addressed the meeting on "Challenge in the Provision of Drinking Water for Cities — Risk Management and Clever Science". Twenty one members and visitors attended.

2nd June 1999

At the 1081st General Monthly Meeting the 50th Clarke Memorial Lecture was delivered by Prof. Richard J. Arculus, Department of Geology, Australian National University, on "Origins of the Continental Crust" at the Geoscience Department of Macquarie University at North Ryde.

7th July 1999
The 1082nd General Monthly Meeting was held at the School of Physics, University of Sydney as a joint meeting with the Australian Institute of Physics, NSW Branch. Dr Murial Watt of the Photovoltaic Special Research Centre, UNSW, addressed the meeting on "Photovoltaics in Buildings".

4th August 1999
The 1083rd General Monthly Meeting was held at the Faculty of Science, University of Technology, Sydney where Prof. Len Lindoy, Department of Chemistry, University of Sydney, addressed the joint meeting with the RACI, NSW Branch, on "Art, Architecture and Engineering". Thirty three members and visitors attended.

1st September 1999
The 1084th General Monthly Meeting was held at the Australian Museum, Sydney. Dr James Bell, Director of the Langton Centre, addressed the meeting on "Naltrexone – Faith, Hope but Little Clarity" and Dr Don Weatherburn, Director of the Bureau of Crime Statistics and Research, on "Drug Law Enforcement, Heroin and Harm Minimisation".

6th October 1999
The 1085th General Monthly Meeting was held at the Australian Museum, Sydney. Dr John Ramshaw, Chief Research Scientist, CSIRO, addressed the audience on "Collagen-Polymer Composites" and Prof. I. Klineberg, Professor of Prosthodontics, University of Sydney, on "Osseoperception in Oral Implant Restoration".

21st October 1999
The 1086th Meeting was held at the Frensham School in Mittagong in conjunction with the Southern Highlands Branch meeting to begin the process of implementing proposed changes to the Rules of the Society. This was followed by the 4th Poggendorff Memorial Lecture on Agriculture delivered by Professor Peter Cullen, President, Federation of Australian Scientific and Technological Societies, and Director, Cooperative Research Centre for Freshwater Ecology, on the topic "Water and Limitations to World Agriculture". Thirty four members and several visitors attended.

3rd November 1999
The 1087th General Monthly Meeting was held at the Australian Museum, Sydney. Two prizes for student achievement were announced; Alison Basden, Department of Geoscience, Macquarie University, and Sharon Downes, School of Biological Sciences, University of Sydney. Both recipients spoke about their work: A. Basden about "Early Devonian Fish Faunas, SE Australia" and S. Downes about "Predator-Prey Coevolution in Rock-dwelling Reptiles".

8th February 2000
The Joint Meeting of Four Societies Talk was given by A/Prof. M.J. Fulham on "511 keV Photons in Medicine".

17th February 2000
The 1088th General Monthly Meeting was a joint meeting with the Southern Highlands Branch at the Frensham School in Mittagong. The proposed changes to the Rules of the Society were passed. The evening lecture was by Emeritus Professor Dr D.J. Mulvaney on the Archeology of Kakadu and Southwest Tasmania. Twenty six members and several guests attended.

SOUTHERN HIGHLANDS BRANCH

18th March 1999
At the Anual General meeting of the Southern Highlands Branch, the following Office Bearers were elected:

Chairman:	Mr Clive Wilmot
Vice Chairmen:	Dr K.G. McCracken, AO Mr Roy Perry
Hon. Secretary:	Mr David Robertson CBE
Hon. Treasurer:	Miss Christine Staubner

Committee Member:
Miss Marjorie Roberts
Liaison Officer: Mr Roy Perry.

Mr Dale Budd, Director, Public Affairs, Speedrail Group Pty Ltd, spoke on "The science of very fast trains".

15th April 1999
Mr Allan Cavanagh, a registered surveyor, Fellow and President of the Institution of Surveyors, Australia, and his wife, Mrs Delma Cavanagh, a science/maths teacher, spoke on "Mine Surveys among the Pyramids of Egypt".

20th May 1999
Dr David Malin, Principal Research Scientist, anglo-Australian Observatory, addressed the Society on "A Universe of Colour".

17th June 1999
Densey Clyne, noted naturalist and writer, spoke to a joint meeting of the Branch with the local branch of the Federation of University Women on "The Lives and Behaviour of Minibeasts".

15th July 1999
Professor John Charles Kelly, Visiting Professor of Physics at the University of NSW' spoke on "Cold Fusion and the Alchemists Dream".

19th August 1999
Paul Dyer, Artistic Director of the Australian Brandenburg Orchestra gave a talk on "The Structure of Music".

16th September 1999
Associate Professor Ahmad Shboul, of the Department of Semitic Studies at the University of Sydney, spoke on "Arabic Science and the European Renaissance".

21st October 1999
For this meeting, chaired by the President of The Society, Associate Professor A.T. Baker, see the record of the 1086th General Monthly Meeting, above.

29th October 1999
Dr Malcolm Gill of the CSIRO Division of Plant Industry's Centre for Plant Biodiversity Research at the Australian National Herbarium, addressed a joint meeting of the Branch with the Wingcarribee Bush Fire Brigade on the subject of "Cycles of Fire, Cycles of Life".

18th November 1999
Dr Paul Redding, A/Professor in the School of Philosophy at the University of Sydney, presented a lecture titled "Freud's Continuing Relevance for Theoretical Psychology". At this meeting the Branch's 1999 Science Award was presented to the winner, Miss Clare Roxburgh of Frensham School, Mittagong.

17th February 2000
Professor D.J. Mulvaney, AO, CGM, spoke on the "Archaeology of Kakadu and Southwest Tasmania and Lake Mungo".

16th March 2000
Dr Kirsten Benkendorff (University of Wollongong) spoke on 'Biodiversity in the Sea and its Vital Importance to Medicine".

CITATIONS FOR AWARDS

The Society's Medal 1999

Daniel John O'Connor

Daniel John O'Connor, the recipient of the Society's Medal for 1999, graduated Bachelor of Science in Chemistry at the University of Melbourne in 1949. Focussing on Mineral Chemistry, he was awarded the degree of Doctor of Philosophy, Melbourne in 1954 for a thesis on Electrical Double Layers at Mineral Solution Interfaces. Further research at Harwell, UK, and at Lucas Heights, NSW, notably on direct fluorination, produced more published work, culminating in his co-editorship of a book on the handling of radioactive materials.

In 1962 he moved into applied research, joining Colonial Sugar Refining Company at Roseville, NSW. His career there was reinforced by Bachelor and Master of Economics degrees at the University of Sydney in 1966 and 1968, Before leaving CSR in 1983, he had risen to manager of Research Laboratories.

He then returned to University life and chemical engineering at Sydney, publishing his innovative work on alumina extraction in 1988. Afterwards he was appointed Executive Director of ANZAAS (The Australian and New Zealand Association for the Advancement of Science), but it was four years later and nearing his normal retirement that ourRoyal Society began to benefit directly from his remarkably broad range of skills.

Dr O'Connor was the Society's Honorary Treasurer from 1995-1998 and our President 1998/99. He held these exalted positions with authority and distinction, and continues, through the Society's executive Council, to steer and foster the profile of the Society with his restrained but inspiring manner.

By virtue of his sustained contributions to scientific research and its management, together with his continuing role in furthering the traditional ideals of the Society, Dr Daniel O'Connor is a worthy recipient of the Society's Medal.

E.P.

The Clarke Medal for 1999

Richard Shine

Richard Shine is Professor of Evolutionary Biology at the University of Sydney. He is one of Australia's most distinguished scientists and is universally acknowledged as the leading authority on the biology of indigenous reptiles. He has made seminal contributions to his discipline both in Australia and overseas. His research on reptilian ecology has been ground-breaking, and his work has substantially clarified the ways in which microevolutionary processes determine major life-history transitions and has illuminated the ecological role played by reptiles in natural ecosystems. Two classic texts on herpetology bear witness to his expertise. Both have received Whitley awards from the Linnean Society of New South Wales.

Professor Shine has received numerous awards and has acted on several government bodies, including the Australian Research Council. A plethora of invitations to lecture at prestigious international research conferences attest his standing.

Aside from these distinguishing marks, Professor Shine has left an enduring legacy in terms of his influence on the many postgraduate students he has guided in their research. Much of their work has concerned fundamental studies of the biology of poorly-characterized Australian ecosystems and has had a major bearing on issues relating to future planning relevant to conservation and management of Australian herpetofauna.

Professor Shine is an outstanding recipient of the Clarke Medal of the Royal Society of New South Wales.

P.W.

Edgeworth David Medal for 1999

The Edgeworth David medal for 1999 is a Awarded to Dr Merlin Crossley, BSc, DPhil, Senior Lecturer in the Department of Biochemistry, The University of Sydney.

During is Honours year at The University of Melbourne, Crossley became interested in aspects of gene expression in bacteria. His postgraduate work at Oxford University and postdoctoral work at Harvard University produced important seminal findings in the area of gene transcription in mammalian cells. His study of clotting factor genes resulted in the identification of mutations that prevented the binding of two proteins to DNA. At Harvard, Crossley became interested in understanding how protein transcription factors recognise their target sites and collaborate with other proteins to control transcription. A significant outcome was the identification of another factor (FOG) that interacts with GATA-1. Dr Crossley's research has led to new insights into the molecular mechanism of promoter control in eukaryotes. It is commendable that a scientist of Dr Crossley's calibre is continuing such fundamental research in Australia.

Dr Crossley received a Rhodes Scholarship and many research grants. He teaches undergraduate courses, has Honours and PhD students and is in demand as a speaker at Conferences and research meetings. He is clearly a very active member of his Department.

Dr Crossley's contributions, especially in the field of molecular mechanisms that control the expression of human genes, confirm him as one of Australia's top molecular biologists, whose work is recognised internationally. There is no doubt that he is a very worthy recipient of the Edgeworth David Medal for 1999.

D.J.S.

James Cook Medal

Peter Colman

Dr Peter Colman is the Director of the Biomolecular Research Institute, located at Parkville Victoria. He was educated at the University of Adelaide, doing his initial research work in design of crystallographic instruments and small molecule crystallography. His introduction to protein crystallography was in Brian Matthew's laboratory, working on the structure of thermolysin, among other problems. His next theme of structural work was directed a understanding, at near atomic resolution, how the immune system functions through studying the three-dimensional structure of antibody fragments. Peter also spent some time at the University of Sydney where he worked in

Professor Hans Freeman's group on the structure of the copper-containing protein particle. The first neuraminidase structure was solved in 1983. Subsequent progress included the solution of the structure of influenza virus neuraminidase complexed with an antibody fragment. A major result of the neuraminidase work was the recognition that there is a conserved structural feature on the surface of the enzyme that could serve as a target for drugs. This led to the design of new chemical entities one of which, known commercially as Relenza, is approved in many countries for treatment of human influenza. Peter was awarded the Australia Prize in 1996 for this work.

The James Cook Medal is awarded for outstanding contributions to science and human welfare in and for the Southern Hemisphere. it is for his work on the structure of the antibodies, his fundamental work on the structure of the influenza virus neuraminidase and the subsequent development of anti-influenza drugs that Dr Peter Colman is awarded the James Cook Medal of the Royal Society of New South Wales for 1999.

A.T.B

Senior Research Studentships

This is the first time we have awarded Senior Research Studentships, which are given on the basis of doctoral research in progress.

There are two winners, namely Alison Basden from the Department of Geology, Macquarie University, for her research on "Early Devonian micro- and macro-fish faunas from south-eastern Australia", and Sharon Dpwnes from the School of Biological Sciences, University of Sydney, for her research on "Sedentary snakes and gullible geckos: predator prey in nocturnal rock-dwelling reptiles". Sharon Downes cannot be present this evening, but it is a pleasure to invite Alison Basden to come forward to receive a presentation.

A.T.B.

'Australia's Greatest Mineral Deposits' Extended Abstracts of the 23rd Annual Conference of the States' Mineralogical Societies. Broken Hill, New South Wales, June 2000

NOTICE TO AUTHORS

Manuscripts should be addressed to the Honorary Secretary, Royal Society of New South Wales, PO Box 1525, Macquarie Centre, NSW 2113. Manuscripts submitted by a non-member (through a member) will be reviewed by the Hon. Editor, in consultation with the Editorial Board, to decide whether the paper will be further considered for publication in the Journal.

Manuscripts are subjected to peer review by an independent referee. In the event of initial rejection, manuscripts may be sent to two other referees.

Papers, other than those specially invited by the Editorial Board on behalf of Council, will only be considered if the content is substantially new material which has not been published previously, has not been submitted concurrently elsewhere, nor is likely to be published substantially in the same form elsewhere. Well-known work and experimental procedure should be referred to only briefly. Short notes and letters to the Editor may also be submitted for publication.

Three, single sided, typed copies of the manuscript (double spacing) should be submitted on A4 paper.

Captions to illustrations and a Table of Contents should be prepared on separate sheets.

Spelling should conform with "The Concise Oxford Dictionary"or "The Macquarie Dictionary" usage. The Système International d'Unites (SI) is to be used, with the abbreviations and symbols set out in Australian Standard AS1000.

All stratigraphic names must conform with the International Stratigraphic Guide and new names must first be cleared with the Central Register of Australian Stratigraphic Names, Australian Geological Survey Organisation, Canberra, ACT 2601, Australia. The Codes of Botanical and Zoological Nomenclature must also be adhered to as necessary.

The **Abstract** should be brief and informative.

Tables and Illustrations should be in the form and size intended for insertion in the master manuscript - 150 mm x 200 mm; column width 72 mm. If this is not readily possible then an indication of the required reduction (such as 'reduce to 1/2 size') must be clearly stated.

Maps, diagrams and graphs should generally not be larger than a single page. However, larger figures may be split and printed across two opposite pages.

The **Scale** of maps or diagrams *must* be given in bar form.

Half-tone illustrations (photographs) should be included *only* if essential and should be presented on glossy paper.

All Tables and Illustrations should be numbered serially with Arabic numerals and each must have a caption.

References are to be cited in the text by giving the author's name and year of publication. References in the Reference List should be listed alphabetically by author and then chronologically by date. Titles of journals should be cited in full - not abbreviated.

MASTER MANUSCRIPT FOR PRINTING

The journal is printed from master pages prepared by a desktop publishing computer program. When a paper has been accepted for publication, the author(s) will be supplied with a guide to acceptable electronic format for the submission of the revised manuscript. Galley proofs will be provided to authors for final checking prior to publication.

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An author who is a member of the Society will receive a number of reprints of his/her paper free. Authors who are not members of the Society may purchase reprints.

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