Early Developments in Treating Pyritic and Refractory Gold Ores in Australia

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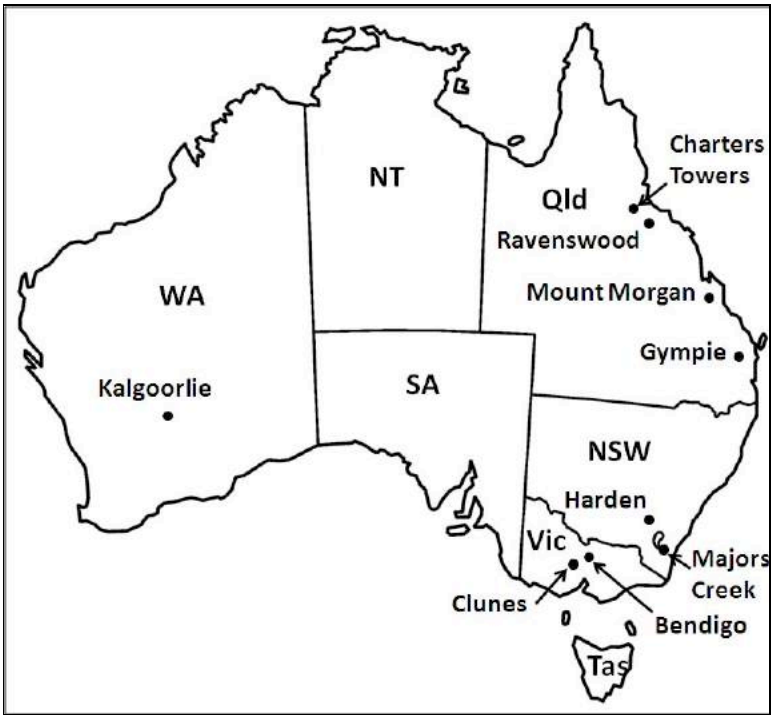
After quartz, pyrite (iron sulphide) is the mineral most commonly associated with gold.[1] In many pyritic gold ores significant gold occurs as intergrowths and small inclusions in the pyrite and probably in some cases in solid solution. Extracting this gold from pyrite presented a major challenge to early metallurgists, particularly when using traditional methods of crushing and gold extraction by mercury amalgamation. In the late nineteenth century new techniques were developed in an attempt to treat these refractory gold ores. In Australia experiments and developments were made at key pyritic gold deposits and gold mining centres including in: central Victoria; New South Wales at Harden and Majors Creek; in Queensland at Ravenswood, Charters Towers and Mount Morgan; and Western Australia mainly at Kalgoorlie (Fig. 1). Treatment processes evolved from concentration and finer grinding of the pyrite to release the gold for amalgamation, roasting to assist the release of the gold and chemical treatments, including chlorination and eventually cyanidation, to extract the very fine gold particles into solution. None of these techniques were developed in isolation; rather there was a vigorous transfer of ideas and information between mining areas in Australia and across the world, leading to improvements for local conditions and different ore characteristics.

Figure 1: *Location of some of the key gold mining centres referred to in this article.*



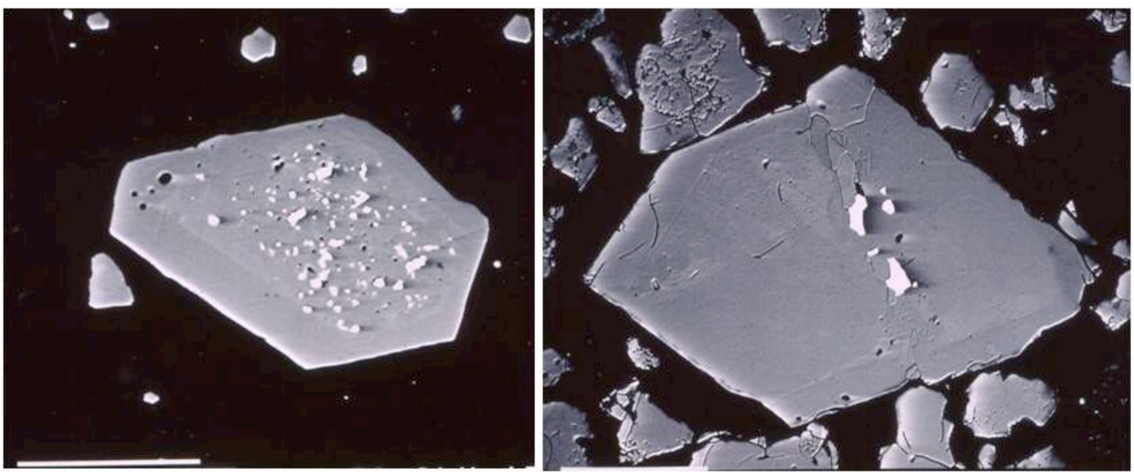
Source: Map compiled by the author from Google Earth.

The 'pyrites problem'

From a geological perspective gold ores can be divided into primary gold ores that have formed at various depths within the Earth's crust, generally by deposition from hot fluids, and secondary gold ores formed at and near the surface by the processes of chemical weathering and erosion. The latter include the upper portions of primary ores that have been weathered and chemically transformed *in situ*, as well as alluvial and placer deposits formed by the transport and gravity concentration of free gold. Primary gold ores can be subdivided into: 'gold only' ores containing predominantly native gold, typically in quartz, with only minor or trace amounts of metal sulphides; 'pyritic gold' ores where the gold is intimately associated with pyrite and in some cases arsenopyrite; and 'gold plus base metal' ores where the gold occurs with a range of more abundant metal sulphides, particularly of copper. There can be some overlap, and in 'gold only' ores additional gold can be held in the minor amounts of associated pyrite and other sulphides. For example, most of the deposits in the central Victorian goldfields are essentially 'gold only' in character, but many contain significant amounts of gold in pyrite and arsenopyrite. Pyritic ores, such as those at Ravenswood and in the Kalgoorlie lode systems, may also carry some free gold.

Pyrite can host gold in a number of forms including as particles and films on the pyrite surfaces or along grain boundaries and cracks, as well as tiny microscopic to sub-microscopic inclusions within the pyrite (Fig. 2).[2] Some gold may also be held in chemical solid solution within the pyrite. Extracting gold from pyrite involves treating the pyrite in some way that exposes the gold particles to amalgamation by mercury or chemical dissolution. The ease with which this can be done depends to a large extent on the particle size and the form in which the gold is associated with the pyrite (metallurgists generally describe ores in which it is very difficult to extract the gold as refractory).

Figure 2: *Scanning electron photomicrographs of polished sections showing zoned pyrite grains with gold inclusions (bright white), Lake View Mine, Golden Mile, Kalgoorlie. White scale bar is 50µm.*



Source: McQueen, et al., *Contributions of the Economic Geology Research Unit*, Department of Earth Sciences, James Cook University, No. 51, 1994.

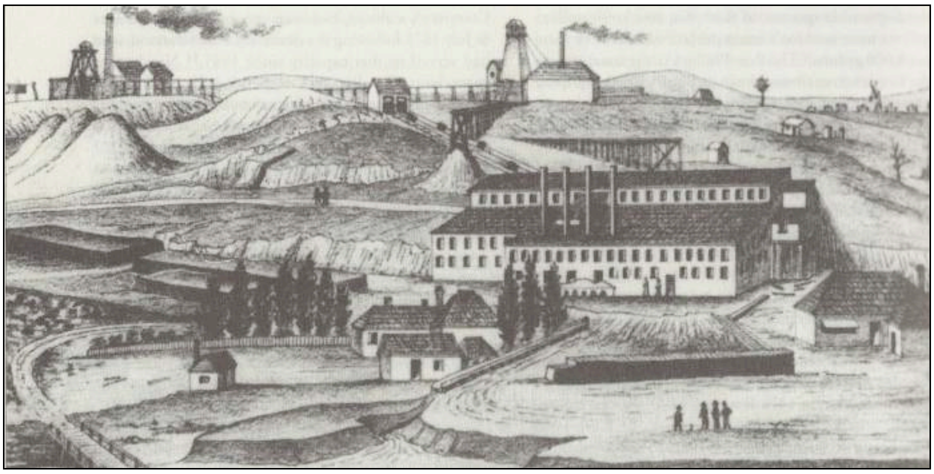
In secondary gold ores that have been exposed for long periods near the surface the pyrite has typically been broken down by natural chemical weathering processes to release the gold, rendering them non-refractory. Thus, early near surface mining in many Australian goldfields had the advantage of working oxidised ores in which pyrite or other sulphides had been naturally processed to release contained gold. Many of these secondary ores also had some degree of natural gold enrichment, related to residual concentration of gold following dissolution of other components. As workings extended deeper, particularly below the water table, more unaltered primary sulphide minerals, mostly pyrite or 'mundic', were encountered. Where these minerals hosted significant gold in a refractory fashion it was imperative to develop methods to effectively treat the 'pyrites'.

Early attempts to treat pyritic ores

The earliest attempts to treat pyritic gold ores in Australia were pioneered by the Port Phillip and Colonial Gold Mining Company at Clunes in central Victoria (Fig. 3). Clunes is generally considered the site of the first payable gold discovery in Victoria and was briefly worked as an alluvial field during July and August of 1851. However, the main wealth of the field lay in its gold-bearing quartz reefs, which would eventually yield over sixteen tonnes (514,814 ozs) of gold.[3]

In early 1852 the Port Phillip and Colonial Gold Mining Company was floated in London as one of more than fifty companies formed during the 'Gold Bubble' stock market boom triggered by the initial Australian gold rushes. The company was promoted by John Diston Powles, also a director of the St John d'el Rey Mining Company, which since 1834 had been successfully working the Morro Velho gold mine in Brazil. Just earlier, Powles had also floated the English and Australian Copper Company to smelt copper in Wales and South Australia. Interestingly, the Port Phillip Co. proposed to use a smelting process, the Longmaid's process, to extract gold, an approach that proved impractical for the quartz reef gold deposits of Victoria.[4] After a number of attempts to locate and work suitable mining claims, and against a general antagonistic attitude towards large scale company mining from individual diggers as well as a reluctance by the Victorian Government to grant mining leases or freehold title to companies, the Port Phillip Co. was able to secure leases on private land at Clunes in January 1857.[5] Here the company set up a quartz crushing plant and established a separate co-operative company, the Clunes Quartz Mining Company, to mine high grade quartz reefs running 3-10 ozs per ton.[6] Most of the gold was hosted in quartz, but a proportion was held in pyrite and other sulphides that made up about 1 per cent of the ore. In the upper, weathered parts of the reefs virtually all the gold was free milling and readily recovered by amalgamation, but once the water table was reached in about 1859 a significant proportion was lost with the pyrite. From the start of operations the Port Phillip Co. had instigated the practice, novel in Victoria at the time, of assaying the tails from the stamp battery, a critical step in determining how much gold was being lost.[7] This was found to be about 25 per cent and the battery manager, Joseph Robson, realised that if he could find a way to recover this gold it would improve the economic viability of the company's operation, particularly as a more pyritic reef had recently been discovered, in which much of the gold appeared to be in the pyrite.[8]

Figure 3: *View of the Port Phillip and Colonial Gold Mining Company works, Clunes in 1872, showing the treatment plant at right, directly below the south shaft, and north shaft at left.*



Source: Photo-engraving by N.W. Niven, Ballarat. Courtesy: Clunes Museum, Victoria.

The problem of gold 'locked' in pyrite was already well known for a number of gold ores around the world and various extraction methods had been tried, but generally all were too expensive or inefficient to apply on a commercial scale. Some operations, including that of the St John d'el Rey Mining Company at Morro Velho, stockpiled the pyritic tailings, allowing them to oxidise naturally in heaps before retreatment, after which the cycle was repeated several times. This 'low tech' approach was highly inefficient and probably only feasible in Brazil because of the slave labour employed.[9] At a number of mines in Victoria, a common practice was to roast the ore in kilns to fracture and soften the quartz before crushing.[10] This process also partially broke down any pyrite to release some gold, but it was ultimately found to be much more efficient to separate the pyrite after crushing and to roast or calcine the concentrate separately before further treatment.

From early 1861 the works manager of the Port Phillip Co. plant, Henry Thompson, together with Joseph Robson and the newly appointed company chemist, George Latta, began experimenting with pyritic tailings from the battery. They determined that most of the gold was present in the pyrite as separate particles, rather than chemically combined, so they initially applied finer grinding to expose the gold inclusions for contact with mercury and amalgamation. Microscopic observation also revealed that much of the gold was present as thin films and coatings along grain boundaries and fractures, requiring very careful treatment to prevent the thin flakes from floating away in the process water.[11] Samples of tailings were also sent to Britain for testing, including by Dr John Percy at the Government School of Mines, by metallurgist William Herepath in Bristol and by assayers Johnson Mathey and Co. of London. These experts tried various chemical dissolution methods to extract the gold, but concluded that these were not practical or cost effective, particularly in the remote wilds of the Australian colonies.[12] Further experiments on site trialled finer grinding of tailings in Mexican arrastras, and grinding of pyrite concentrate and roasted concentrate in a Chilean mill with mercury to amalgamate the gold. Grinding of roasted concentrates in the Chilean mill proved most successful and this was the method adopted for commercial scale operations. It was found that the Chilean mill had to be operated almost dry to prevent the mercury from quickly sinking to the base of the mill and the fine gold being washed away before it could amalgamate. After a sufficient period of grinding with the mercury, the waste could be flushed away by an increased flow of water.[13]

Tests were also made to determine the best method of concentrating the pyrite from the battery tailings that collected on the blanket strakes. Gravity separation using buddles proved to be the most effective method. Thompson and Latta then designed and patented an inclined roasting furnace to decompose the pyrite concentrate before treatment in the Chilean mills. By 1864 and after three years of careful experimentation, the Port Phillip Co. had a process and plant to efficiently extract gold from pyrite at Clunes. The average recovery of gold from the tailings was more than 4 oz per ton, representing about 95 per cent of the gold in the pyrite.[14] Other Victorian mines had been carefully watching developments and Rivett Bland, the Resident Director of the company, freely released information about developments in the local press. The Port Phillip Co. was soon recognised as a world leader in metallurgical research. Other mines sent their pyritic tailings to the company for processing, and their pioneering and later technologies developed at Clunes were adopted at other Victorian mining centres.[15]

Further experimentation and development of chlorination

Following the initial success of the Port Phillip Co., there were ongoing efforts in Victoria to improve the efficiency of pyritic gold ore treatment and to reduce its cost. Some ores proved more refractory than those at Clunes and gold continued to be lost with the pyrite. Thomas Carpenter, a Cornish mining engineer and assayer, who had come to Sandhurst (Bendigo) in 1854 from New South Wales experimented with pyritic concentrates from the Catherine Reef United Claimholders Company by roasting and amalgamation as early as 1862.[16] In 1864 Thomas Edwards, another Cornishman, also started roasting and amalgamation works near Clunes to treat battery tailings from one of the mines. By 1871 the grade of the ore and tailings from this mine dropped below economic values, so he moved to Bendigo to treat pyritic concentrates by the same method. In 1872 three companies built roasting furnaces at Bendigo including the Sandhurst Pyrites Company owned by J. Spargo, the Eaglehawk Pyrites and Gold Extraction Company and the United Pyrites Gold Extracting Company. Edwards was a one fifth owner of the latter.[17] The three companies developed expertise in treating the increasing volume of pyritic concentrates from the Bendigo reefs, which typically contained up to 5 per cent pyrite. In 1876 Edwards trialled dissolving gold in hot water containing chlorine gas, using an adaptation of the Plattner process first used in Silesia in 1848. This adaption was probably that devised and patented in 1864 by Alan De Lacy, a civil engineer living in Melbourne.[18] Although promising, the method did not prove fully practical or economically viable. Later, in 1899, Edwards developed a chlorine gas generation apparatus to provide a cheaper source of chlorine.[19]

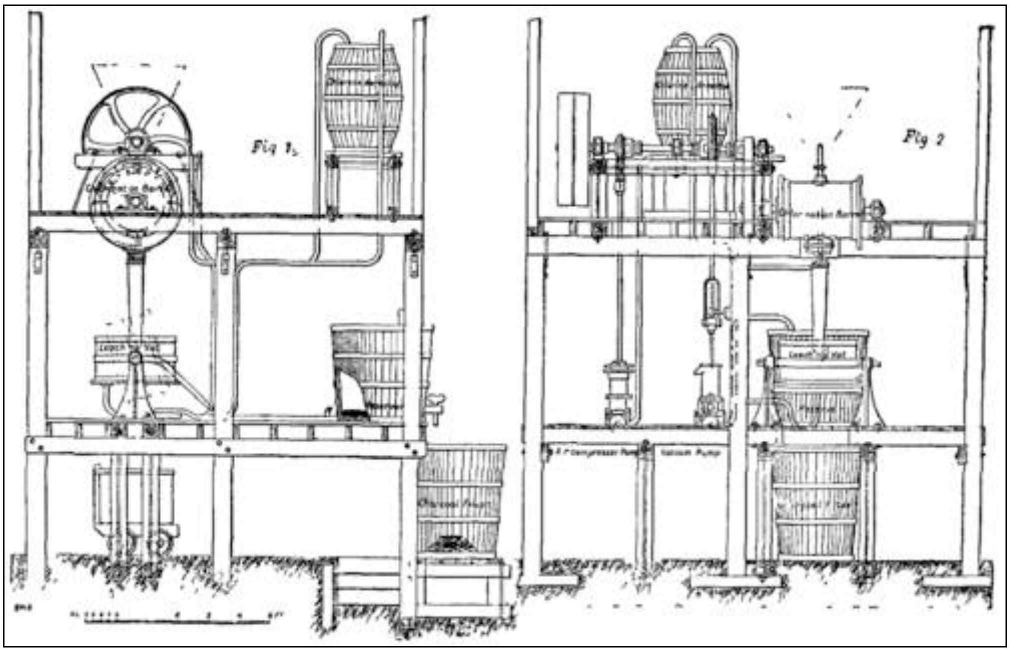
Around Australia other metallurgists and hopeful entrepreneurs were soon busy experimenting with various gold extraction processes for pyritic and refractory gold ores. These were generally split between either a mechanical approach, involving exposure of the gold by finer grinding and roasting, followed by amalgamation, or a chemical approach with dissolution of the gold. Chlorination seemed promising, but was expensive, as it was typically a batch process and also slow due to the time needed for the chlorine gas to permeate the ore.[20] It also required a chemically skilled metallurgist and the chemistry was finicky, particularly in relation to variable contents of calcium and magnesium minerals in different ores. Despite the difficulties many different chlorination methods and refinements were developed and patented between 1876 and 1886.[21] A disadvantage of most of these, compared to amalgamation, was that they did not recover the silver present and in some gold ores the silver values were significant.

Some more complex ores, including those with sulphides of copper, lead, zinc, silver and antimony, proved particularly difficult to process by roasting, fine grinding and amalgamation, for although the sulphur and arsenic could be driven off, sulphates of other metals were retained and tended to ‘sicken’ the mercury and reduce its efficiency. In 1882, Mrs Elizabeth Barnston Parnell of Sydney patented a method for processing concentrates of these ores involving two stages of roasting followed by treatment of the residue with boiling water to remove any sulphates. This was followed by amalgamation or alternatively extraction in a lead bath or smelting with lead ore. The process stirred interest with a number of potential investors and in November 1885 a trial was conducted at the Austral Foundry at Pyrmont in the presence of a ‘large number of gentlemen interested in mining pursuits’. The trial was successful, but the process does not appear to have been widely adopted, probably because it was too expensive. Mrs Parnell went on to patent modifications of her process in 1886, then known as the E.B. Parnell sulphur process, and also patented an improved furnace in 1898.[22] A similar approach to cleaning roasted concentrates was developed by L. O’Brien in 1889. This method used sulphuric acid generated from the pyrite roasting to dissolve iron oxide and other coatings on the gold to allow it to amalgamate. This method was adapted from a process for extracting cobalt from manganiferous cobalt ores in New South Wales.[23]

Smelting proved successful for some complex pyritic ores, for example those at Bethanga in northeast Victoria. The ore here was a mixture of pyrite, pyrrhotite, arsenopyrite and lesser copper, lead and zinc sulphides. Treatment included partial roasting in heaps to expel arsenic and some sulphur followed by crushing, smelting in a cupola furnace, formation of a copper regulus, fusion with lead to extract the gold and silver, and eventual recovery of the gold and silver from the lead by cupellation.[24]

In 1878, James Cosmo Newberry, an ex-government assayer who had lost his job when a large number of Victorian public servants were retrenched, and visiting London metallurgist, Claude Vautin began experimenting with chlorination at the United Pyrites Gold Extracting Co. in Bendigo. In 1886 they eventually patented a chlorination process that overcame many of the problems with the earlier methods. This involved placing roasted pyrite concentrates in a revolving barrel with water and adding calcium chloride and sulphuric acid to generate chlorine gas (Fig. 4). The barrels were sealed and the pressure increased to about four atmospheres using compressed air. After 1-4 hours the gold had formed a soluble gold chloride and was dissolved in the water, which was then passed through a vacuum assisted filter to remove the residue. The gold could then be precipitated from solution in a charcoal filter. When fully charged the charcoal could be burnt and the ashes fused with borax to produce gold bullion. This method had the advantage of being much faster than earlier chlorination processes due to the rotational mixing combined with high pressure.

Figure 4: *Sketch of the Newberry-Vautin chlorination process. The rotating pressure barrel is on the top level with the air compressor, vacuum pump and filter on the second level. The washed residue from the filter was tipped into the truck below.*



Source: 'The Newberry-Vautin Chlorination Process', Scientific American Supplement, No. 620, 1887.

The rights to the Newberry-Vautin process were sold to a number of Australian and New Zealand gold mining companies, including the Mount Morgan Company in Queensland.[25] Bendigo became a recognised centre for treating pyrites by both the amalgamation and chlorination processes and concentrates were shipped to Bendigo from mines all over Australia. The United Pyrites Co. was the only ore treatment plant in Bendigo to adopt the chlorination process and it developed a reputation for being able to treat very refractory ores. Thomas Edwards eventually took a controlling interest in the plant and continued to improve processes for treating pyritic ores. He went on to establish a pyrite treatment plant at Ballarat in about 1895.[26] In the 1890s he developed a duplex ore roasting furnace and a portable tilting furnace, which were built in large numbers and sold to ore treatment plants all over Australia and also in America and South Africa. His furnaces were installed at the Great Boulder mine at Kalgoorlie, together with his innovation of a reciprocating ore conveyor to move the hot ore discharged from the furnaces.[27]

Significant gold deposits were found in Queensland at Gympie in 1867 and soon after at Ravenswood in 1868 and then at Charters Towers at the end of 1871. The Ravenswood gold ores were particularly refractory, containing in addition to pyrite, pyrrhotite and arsenopyrite, abundant sulphides of copper, lead, zinc and silver. Early attempts to treat the sulphides included concentration with buddles or a Brown and Stanfield concentrator, furnace roasting and crushing in Wheeler grinding pans with mercury to amalgamate the gold.[28] Several hundred tons of tailings from the richest ores were sent to Freiberg in Europe for treatment at a cost of 2 ounces of gold per ton. Smelting on site was tried, but proved too costly.[29] In 1883 it was proposed to introduce chlorination, based on the systems being trialled in Bendigo, although the assayer at the Gympie pyrites works, Henry Joseph, predicted that this would not work on the Ravenswood ores, because they were more complex with sulphides of copper, lead and zinc.[30] Eventually a chlorination plant was built in 1888. By 1892 the Ravenswood Gold Mining Company and the Australasian Gold Extraction Company were recovering over 90 per cent of the gold in their ores by using a combination of gravity separation of the coarse gold and chlorination of the fine gold by the Newberry-Vautin and Pollock processes respectively.[31]

At Charters Towers, as on most fields, the miners had little difficulty extracting the gold in the upper oxidised parts of the lodes using stamp batteries, copper plate amalgamation, concentration of residues and finer grinding and amalgamation in Wheeler and Berdan pans.[32] Below the water table the usual ‘pyrites problem’ appeared. The Charters Towers Pyrites Company, under the guidance of local engineer D.A. Brown constructed works on the side of Towers Hill with a three-stage furnace to roast the sands and a chlorination plant to extract the gold. During the design stage in 1885, Brown had visited England and South Africa to ‘investigate metallurgical procedures’ but it is not clear how this study tour influenced his design.[33] His chlorination plant predated the final development of the Newberry-Vautin process and involved treatment of dampened roasted concentrates with chlorine gas and then addition of a weak solution of chlorine in water. Once the gold was dissolved the solution was run through a vertical column against a counter current of high-pressure steam to remove and recover the excess chlorine. The gold was precipitated with ferrous sulphate on a filter of charcoal and sawdust, which were then burnt to recover the gold.[34] This plant operated successfully, but it was an expensive process and was superseded after 1892 by the cyanide process.

Gold extraction from sulphide ores by chlorination reached its zenith at Mount Morgan, where the world’s largest chlorination works were eventually constructed and operated successfully up until 1911. The ironstone of Mount Morgan was not recognised as a major gold deposit until 1882 when the Morgan brothers identified very fine gold in the gossan. Much of the fine gold was also coated with iron oxide so that even in the oxidised zone only about 40 per cent could be recovered by amalgamation. A Plattner type chlorination process was installed by A. Lymburner of Gympie in 1884 but did not recover more that 75 per cent of the gold. The Newberry-Vautin process was taken up and was technically satisfactory, but had difficulty in handling the large volume of ore. It was partly discarded and components incorporated into a new plant built by Henry Trenear to form what became known as the 'Lower Works', which were upgraded to handle 500 tons of ore per week. It was then realised that even larger works were required for the growing supply of ore, and so a new plant called the 'Upper Works' was constructed in 1887 to process 1,000 tons per week. This used reverberatory furnaces to roast the sulphides followed by chlorination using the Mears process, originally developed in the USA in 1880 and similar to the Newberry-Vautin process but employing higher pressures generated by the chlorine gas itself. After further experimentation, the manager, Wesley Hall, and chief metallurgist, George Richards, a graduate of Australia's first school of mines at Ballarat, developed a modified and simplified treatment scheme named the Hall-Richard process. A new plant known as the 'West Works' was built in four similar parallel sections in 1896-97 and had a total capacity of 10,000 tons per month. This employed Krupp ball mills to fine grind the ore, and rotary furnaces for roasting. The roasted ore was placed in large vats rather than chlorination barrels and saturated with water before a chlorine solution was allowed to percolate through the ore to dissolve the gold. The solution was then run to cement lined brick tanks from where it was passed over charcoal beds to precipitate the gold. Chlorine was generated in stone stills by the reaction of sodium chloride, manganese dioxide and sulphuric acid.[35] In 1899 a complementary plant, known as the 'Mundic Works', was set up to concentrate and separately treat the sulphide component of the ore. By this stage it was possible to recover 98 per cent of the gold at a low cost of about 10 shillings per ton. The Mount Morgan Gold Mining Company had thus developed over a thirteen-year period, an efficient, high capacity chlorination process for the Mount Morgan ores by experimentation and gradual evolution.

Through the 1880s and 1890s numerous other chlorination plants were constructed around Australia to handle pyritic and refractory gold ores. Plants were built at Ballarat, Daylesford, Cassilis, Maldon, Walhalla and Melbourne in Victoria and at Norton and Cloncurry in Queensland. In New South Wales there were plants at West Wyalong, Wellington, Adelong, McMahons Reef near Harden, Parramatta in Sydney and at Dargues Reef, Majors Creek.[36] These plants employed various local modifications of the main patented processes with varying degrees of success. During this period there was also much experimentation with devices to grind ore and produce pyritic concentrates, including Huntington mills, Duncan concentrators and Frue vanners.

Thomas D. Merton was a leading developer of chlorination in New South Wales who constructed an innovative plant at McMahons Reef for the Cunningar Proprietary Gold Mining and Chlorination Company. This plant was built in about 1887 at the site of an earlier smelting works that had treated pyritic ores by extended roasting, smelting and concentration of the gold into molten lead. The modified plant employed multi-stage roasting and treatment of the residue with acid before chlorination by the Newberry-Vautin process. Refractory pyritic ores were sent to the Cunningar Co. Plant from other mines in New South Wales. In 1888, Merton, with partners, built a similar plant at the Clyde Ore Crushing, Amalgamation and Chlorination Company of Sydney, near Parramatta, and in 1889, another plant at Dargues Reef, where he was the manager of the Majors Creek Proprietary Gold-Mining Company.[37]

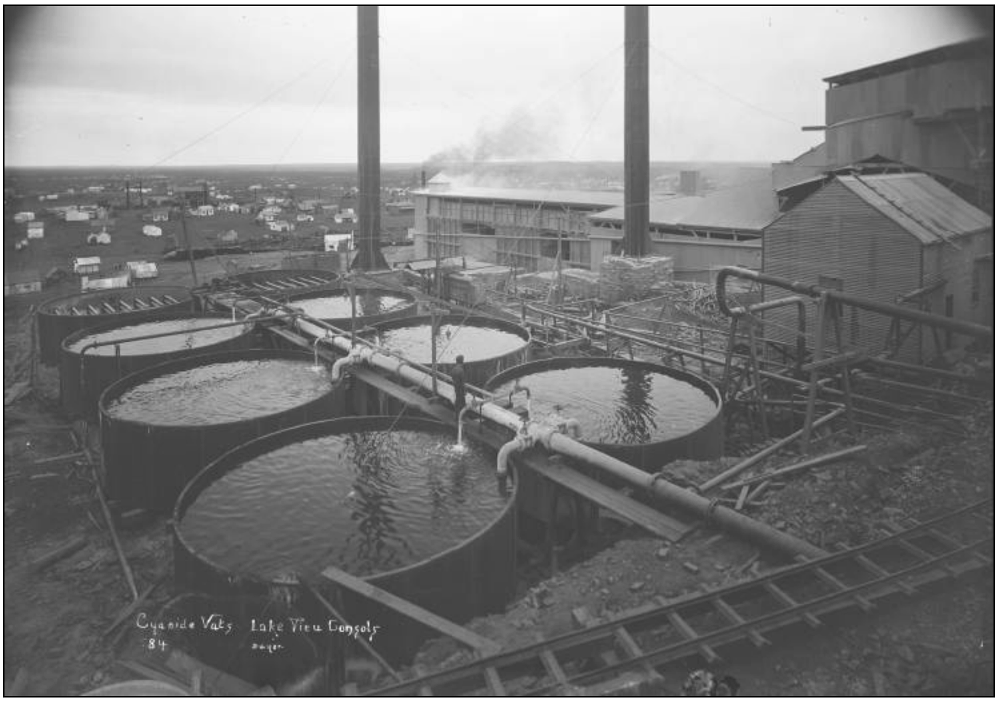
Major advances with cyanidation

A major breakthrough in the treatment of pyritic gold ores came with development of the cyanide process. The ability of a potassium or sodium cyanide solution to dissolve gold had been known for some time and Julio H. Rae had taken out an American patent for a cyanide process as early as 1867, although the process was never used commercially.[38] In 1887, John Stewart MacArthur and William and Robert Forrest patented a process in the UK that was efficient and economical and soon adopted around the world. It could be applied to pulped ore and roasted pyrite concentrates and dissolved the gold in an aerated potassium cyanide solution with subsequent precipitation on zinc shavings. Initial field trials of the MacArthur-Forrest process were conducted at Ravenswood in Queensland by one of MacArthur's assistants, Peter McIntyre, and his brother Duncan. The trials proved successful, but the McIntyres had difficulty obtaining sufficient tailings. They shifted the trials to Mount Morgan in 1891, but by this time that mine was committed to chlorination. Tests were then conducted on tailings at Charters Towers and in 1892 the process was adopted and adapted at the Excelsior Mill. This became the first plant in Australia to commercially employ the cyanide process.[39] The cyanide process worked a treat at Charters Towers, due to the particular nature of the ores and the established fine grinding practices of the millmen. It was not so successful for ores with a high copper content, for example at Mount Morgan, due in part to the costly consumption of cyanide by the copper.

In 1893 gold was discovered at Kalgoorlie, initially near Mount Charlotte and later to the south at what was to become the famous Golden Mile. Primary ores at depth on the Golden Mile contain much of their gold in pyrite and, in some lodes, chemically bound up in telluride minerals. Once these were reached, methods had to be developed to treat another variety of pyritic gold ore. By this time the cyanide process was well established and the treatment of these complex ores was initially attempted by modification of the standard combined amalgamation and cyanide methods. Gravity concentration was applied to produce a concentrate but this approach was unable to achieve a sufficient recovery, and both the concentrate and residue still required cyanidation. The next approach tried dry milling and roasting of the total sands, followed by cyanide extraction (Fig. 5). This had the advantage of decomposing the pyrite and gold tellurides, but was costly because all the ore rather than a concentrate had to be roasted.[40] Tube or ball mills were gradually introduced to replace stamp batteries and Chilean mills. Experiments were conducted in finer grinding of the ore to improve recovery, but created the additional problem of sliming, which consumed tons of precious water and created problems in the cyanide circuit. Filter presses, adapted from the sugar processing industry and first used at Karangahake in New Zealand, were progressively introduced to extract most of the water from the slimes and assist in containing the fine material during leaching. John Sutherland, a young metallurgist who had also studied at the Ballarat School of Mines has been credited with their introduction at the Lake View mine in 1897, although a Johnson filter press had been used at the Hannans Brownhill oxidised ore plant earlier that year.[41]

In 1900, Dr Ludwig Diehl, a German metallurgist employed by the London and Hamburg Gold Recovery Company and working at its laboratory on the Hannans Brown Hill mine in Kalgoorlie, developed a new method that utilised two stages of grinding, with fine grinding in Krupp ball mills (down to 74 µm), to convert all the ore to slimes.[42] The slimes were then treated in an agitated solution of potassium cyanide with added bromo-cyanide to break down the gold tellurides. The treated slimes were separated from the gold-bearing solution by filter pressing and the gold precipitated on zinc shavings. The Diehl process overcame the telluride and pyrites problem without the expense of roasting the bulk of the ore and it achieved the highest recovery rate of better than 93 per cent for the complex ores. The new process was trialled in various forms and taken up by the Lake View Consols, Hannans Star and Hannans Brownhill operations between 1897 and 1901.[43] Different modifications were included, such as the use of Wilfley tables to collect a sulphide concentrate after the first stage of grinding, which was then roasted, finely ground and treated in the same way as the bulk of the ore.[44] With its large number of separate mines and mills all experimenting and adapting to improve the efficiency of gold extraction, Kalgoorlie was by then the leading centre of gold metallurgy in Australia and probably the world.[45]

Figure 5: *Plant and cyanide vats Lake View Consols mine ca. 1896. Note worker inspecting vats (centre).*



Source: Photo by J.J. Dwyer. Courtesy: State Library of Western Australia.

By the early 1900s some type of cyanide process was typically the preferred option for processing most gold ores across Australia and in other parts of the world. It did not work well with all ores, particularly those high in copper and in some ores it was still more cost effective to use traditional methods. At many plants in Australia cyanidation was used in conjunction with standard amalgamation extraction. A good example was the Mount Boppy gold mine in western New South Wales. In 1905 Mount Boppy was considered the leading gold mine in the state and processed its ore by a 60 head stamp battery, followed by amalgamation, concentration of the tailings on Wilfley tables and treatment of the concentrate sands and tailings slimes in a cyanide plant. Pyritic concentrates were shipped for custom smelting at Cockle Creek north of Sydney, but in 1908 an Edwards duplex roaster was installed so that these could be treated in the cyanide circuit. In 1912 the process was further improved by finer grinding in tube mills, along the lines of the Diehl process, but the gold was still extracted with a two-stage process involving amalgamation of the coarser gold and treatment of the slimes by cyanidation.[46]

The development of flotation processes from 1902, initially designed to separate different sulphide minerals in the ores of base metal deposits like Broken Hill, also had a profound benefit for the processing of pyritic gold ores. It provided a much more efficient method to separate the pyrite into a concentrate that could be selectively roasted at a lower cost. The basic metallurgical scheme for pyritic ores then became, selective flotation, roasting of the concentrate and cyanidation to extract the gold.[47] The Diehl process no longer had an advantage and disappeared.

Influence of the world wide web of metallurgy

In the successful treatment of pyritic gold ores many innovations and developments were undoubtedly made in Australia; however there was a strong transfer of expertise and exchange of ideas with mining centres around the globe.[48] From the very beginning the Port Phillip Co. benefitted from expert knowledge and experience gained by the St John d'el Rey Company at Morro Vehlo in Brazil. Ideas were initially imported from Britain, although these were often influenced by mining experience in other centres, particularly in the Americas. Many Cornish immigrants who had come to the Australian colonies before and during the gold rushes had experience in mining and ore processing, particularly of copper ores. Once company mining of gold reef deposits developed, hard rock Cornish miners and millmen were in great demand, contributing significantly to local mining and processing technology. Welsh smeltermen also brought their furnace skills, particularly after the development of copper mining at Burra Burra, Moonta and Wallaroo in South Australia.[49]

In the early days, when most mining was in the oxidised zone and the ores were relatively rich, many Australian gold mines were unconcerned, or even oblivious, about gold losses in their tailings. When highly refractory ores became a problem the initial tendency was to send these overseas for treatment at established ore processing centres, for example in Britain and Germany. These shipments, as well as trials of samples by overseas laboratories, provided a connection and a conduit for technology transfer from the centres of metallurgical expertise. As a substantial home-grown body of metallurgical knowledge and experience developed, it was concluded that treatment could be just as effective in Australia, and without the additional cost of shipping material half way around the world. Distance and the tyranny of transport were probably key factors in promoting local invention and innovation.

From the mid 1870s the continued influx of overseas experts to the various developing Australian goldfields provided ongoing stimulus to innovation. Many metallurgists, particularly consultants, travelled widely and were in touch with their professional colleagues in Europe, the Americas and South Africa, but ideas had to be adapted to local conditions. Australian conditions required the technology to be robust, portable, easy to repair in remote locations and forgiving of limited scientific knowledge. Some equipment and plant were still imported from overseas, but a local manufacturing industry had developed and was supporting innovative processing technology. Custom processing plants were also set up across Australia to service mines too small to have their own plant or with particularly difficult ores. They also played an important role in developing new techniques.

As larger gold mining centres such as Charters Towers and Kalgoorlie expanded, foreign capital flooded in, together with overseas companies and their metallurgists and engineers. American experts, particularly from the western United States, began arriving in Australia and contributing to local developments in ore processing from the 1880s.[50] Successful innovations and adaptations were transferred back to other parts of the world. Chlorination plants using the Newberry-Vautin process were built at Thames in New Zealand, in Denver Colorado, Vancouver in Canada, at Johannesburg and Barberton in South Africa and even at the Morro Velho mine in Brazil, where the Port Phillip Co. had derived some of its early ideas for treating pyritic ores.[51] Following successful trials at Ravenswood, Queensland, the MacArthur-Forrest cyanide process was introduced to South Africa and was in general use on the Rand by 1892. Combined with fine grinding using the tube mills introduced with the Diehl process, it saved many of the mines from the 'pyrites problem'.[52]

By the early twentieth century effective treatment was available for most pyritic gold ores. This achievement was truly an international one, but Australian and Australian-based metallurgists, engineers, chemists, inventors and even the particular ores themselves had played a key role.

Acknowledgements

I am grateful to Mel Davies who provided comments on an early draft of the article. The Clunes Museum, Clunes, Victoria and the State Library of Western Australia provided some of the illustrations. The article has benefited from the helpful comments and suggestions of two anonymous reviewers, particularly in relation to the history of ore processing at Kalgoorlie. The research reported formed the basis of a presentation to the 9th International Mining History Congress held in Johannesburg in April 2012.

Glossary of some terms used in the text

Arrastra - a grinding device in which one or more large stone masses are dragged around a prepared stone base by rotating arms generally driven by a horse or mule.

Buddle – a device for separating particles based on their specific gravity. Material is distributed across a circular concave surface with rotating sweeps pushing the material up slope and a water current washing material downwards. The heavier minerals concentrate on the upper, outer slope of the buddle and the lighter material is washed down to the centre and removed.

Berdan pan – a hemispherical iron pan that revolves on an inclined axis and contains a heavy iron ball (in some cases a large ball and a small ball). Tailings or concentrates placed in the pan are crushed by the ball rotating against the lower part of the pan and mercury is added to amalgamate the released gold.

Chilean mill – a large wheel (originally of stone) erected vertically, which rotates on a horizontal axle while being revolved around a central pivot in a circular trough. Later models had two wheels arranged at opposite ends of the revolving axle. Effective crushing resulted from the rotation of the heavy wheel combined with the twisting action of the wheel as it revolved around the trough. Typically driven by horsepower or a steam engine.
Frue vanner – a rotating belt with adjustable slope onto which crushed material is placed and a flow of water maintained. The heavier particles settle on the belt and are carried up slope by its movement and the lighter material is washed down slope.
Grinding Pans – various designs, but basically consist of a horizontal fixed annular plate and an overlying rotating annular plate. Sands introduced to the pan through a central spindle are ground as they move outwards between the two plates. Wheeler's Pan have raised dies in the fixed plate and shoes in the rotating plate.
Huntington mill – a vertical cylindrical mill containing a rotating plate with a series of four suspended rollers. Centrifugal force causes the rollers to swing against the side of the pan to grind the ore.
Krupp mill – a tube mill adapted from cement manufacturing and consisting of a rotating cylindrical drum in which broken ore and grinding balls are placed. Initially stone or flint balls were used, but these were superseded by steel balls. The forerunner of modern ball, rod, SAG and FAG mills.
Wilfley table – a sloping vibrating table with riffles, used in the gravity separation of dense minerals.

Endnotes

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