The Extraction of Gold by Amalgamation and Chlorination

By RALPH W. BIRRELL
University of Melbourne

The gold ores found above the waterline in the Lachlan Fold Belt of south eastern Australia in the 1850s, were free milling, meaning that most of the gold could be easily separated from the quartz by crushing, followed by amalgamation with mercury.[1] The particles of gold were relatively large and separated cleanly from the quartz. Above the water line the sulphides of iron, arsenic, lead, silver, antimony, bismuth and copper deposited with the ore had mostly been oxidised over millions of years, leaving gold particles free of sulphides. This easily separated gold could be amalgamated with mercury without difficulty. If, after crushing, small amounts of these impurities had not been oxidised and were still attached to the gold particles, the mercury was often sickened, resulting in it being coated with a black scum. This prevented the gold amalgamating and both the mercury and some of the finer gold was washed away with the water if wet crushing was used. Ores from below the water line were not oxidised and the several mineral sulphides in the crushed ore caused sickening or flouring of the mercury when it was separated into very small droplets during crushing and these were also washed away in the water and lost.[2]

Historians of Australian mining have written little on the technical aspects of amalgamation of gold with mercury and the use of the chlorination process in the extraction of gold from its ores.[3] In her publication on colonial technology, Jan Todd criticised the slow acceptance of the chlorination process in Australia compared with the short time it took to utilise the process in South Africa and New Zealand, stating that:

> The transfer of cyanide gold extraction benefited from the sharing of common institutions, language and culture and from the steady flow of people. A multitude of colonial connections were able to smooth away early obstacles in the patent system. More difficult was the distances between the practices of Australian goldmining and the leading edge of the technology frontier which this chemical process represented: despite some pockets of experiment with chlorination, the vast bulk of the goldmining industry was ignorant of chemical extractive processes and the scientific principles which governed them. These were considered the province of the much maligned ‘theorist’.[4]

It is the intention of this paper to discuss the use of calcination as part of the process of amalgamating the gold with mercury, the problems of amalgamating pyritic gold ores, and the use of the chlorination process after the 1870s to improve the extraction rate of the gold from the ore. The validity of the comment by Jan Todd on the lack of knowledge in Australia about chemical extraction processes and chlorination will be assessed as part of this discussion.

Calcination

When quartz mining commenced in eastern Australia from about 1854, many miners believed that heating the quartz was beneficial in two ways: first, it made the quartz softer and friable and more easily crushed by the primitive machines then in use; second, if any sulphides were present they would be oxidised.[5] Ore was mixed with dry wood in piles or in simple kilns, the wood was ignited and the pile burnt, a process called calcination. This oxidised most of the sulphur present to sulphur dioxide, which combined with water vapour in the air to form sulphurous acid so that any arsenic and antimony sulphides present were sublimed as oxides. Although the sulphides of other metals present were oxidised, some of the oxides such as lead and copper remained with the ore and made amalgamation difficult as they coated the gold particles. These ores were said to be refractory.[6] In 1860, a Mr. Wilkinson demonstrated a furnace at Ballarat that used charcoal to decompose steam into hydrogen and oxygen that were then burnt in a cupola containing quartz ore. He claimed the fine gold in the ore was heated to a high enough temperature to form globules that amalgamated without trouble. The Ballarat miners conducted tests on the plant and declared it to be uneconomical.[7]

The Port Phillip and Colonial Mining Company was formed in London in 1852 by a group of men who owned other companies mining for gold in South America. After searching for a suitable mine in Victoria, the resident director, Rivett Bland, leased private land at Clunes in 1857 and established a successful quartz mine. By the early 1860s the company was mining sulphide ores from below the water line.[8] Some of the staff had treated gold ores in Brazil containing 15 per cent pyrites and although the Clunes ores contained less than one per cent pyrites they included a kiln as part of the first plant with which to heat all the quartz before sending it to the stampers. This was a large bottle shaped kiln with work platforms top and bottom. Ore and timber were thrown into the top of the kiln from trucks on rails, in alternate layers until the kiln was full.[9] Similar kilns had been used for many years for burning seashells to make lime.[10]

The timber was then ignited at the bottom and as the burnt quartz settled down to the hearth it was quenched with water and shovelled into trucks that were then wheeled to the stampers.[11] This was designed to be a continuous process to make the ore more friable for crushing, but as the output of the mine increased it became more difficult to continue this process due to volume and cost. It was abandoned in 1862 and replaced with a Chambers rock crusher that acted as a primary crusher before the stampers.[12] At many early quartz mines in Victoria the quartz ore was burnt in surface stacks or in kilns before crushing and this practice was still in use at Stawell in 1869.[13] The ratio of pyrites in Stawell ores was said to be one in a thousand, so it seems calcining was used there to make the ore more friable,[14] although it is difficult to decide from the literature whether the use of this practice was for that purpose or to alter minerals in the ore. It is possible that old methods persisted without justification, although one witness at the 1890 Royal Commission on Mining claimed that calcining Maldon ores increased gold production by 25 pennyweights per ton.[15] The second reason for calcining the quartz will be considered further when examining the treatment of pyrites.

Amalgamation of gold

On 21 December 1893, a meeting of the Institute of Mining and Metallurgy was held at the Museum of Practical Geology in Jermyn Street, London, at which the President, George Seymour called on a member, C.G. Warnford Lock to present his paper on ‘Gold Amalgamation’, commenting that there was no issue in mining that offered so large a field for controversy. The ensuing discussion recapitulated debates conducted over the previous forty years in California, Australia, South Africa and Great Britain but what nobody disputed was that nine-tenths of the gold produced worldwide was recovered by the amalgamation process.[16] Included in the discussion was a survey conducted in 1874 by the Victorian Mines Department, when a wide range of people involved in mining, plus people living near processing plants and doctors of medicine were interviewed.[17] The Board members directed their questions to amalgamating methods then in use and the problems of using those methods for the separation of gold from pyrites. The report also discussed a chemical method then in use in London that separated gold and silver from ores. Roasting of the pyrites after separation followed by amalgamation was recommended but no comments were made about the use of the chemical method.[18]

The process of amalgamation of gold and silver by mercury (quicksilver) had been known for centuries. The Romans knew that gold would amalgamate with mercury but it is not certain they used the process to separate gold from ores. Agricola described the process of gold amalgamation in use in Europe in 1556 and it is likely that the process was first used by the Spaniards to separate silver from its ores in Peru in 1566.[19] The basic process as described by Agricola was to fine-grind the ore between two rotating flat stones, similar to flour mills at that time, and wash the pulp into a series of three barrels containing mercury. In each barrel the pulp and mercury were stirred by paddles, so the gold and mercury amalgamated in a continuous process. The amalgam, a lumpy grey mass, was later removed from the barrels, placed in a chamois, or fine cotton bag, and squeezed so that most of the mercury oozed out, leaving the gold and some mercury behind. He also described the collection of the gold by sluices, canvas strakes and buddles but said the use of the amalgamating barrel was the most efficient for collecting gold.[20] It is now believed that amalgamation is a physical process rather than a chemical one. The 'catching' of the gold is nearly instantaneous when the particle of free gold, liberated from the gangue by the stampers, is wetted by the mercury and because of its higher specific gravity sinks into the mercury.[21]

Just as the speakers at the meeting in 1893 had debated their preferred method of amalgamation, so every millman treating gold ores in the 19th century had his own preferred method, as he did on the best operating procedures for operating machinery to separate the gold from the ore. In the 1850s, in Victoria and New South Wales, Berdan pans, Chilean mills and stampers were tried for crushing. Berdan pans were circular bowls with a heavy steel ball rolling in the bowl to crush the ore. Chilean mills consisted of a heavy roller, rotated in a circular path in a shallow trough holding the ore. In both machines mercury was added to amalgamate the gold freed by crushing in a batch operation and this proved costly,[22] for Chilean mills were slow, and the balls wore rapidly in Berdan pans. By the end of the 1850s, the preferred method was to wet crush with stampers in a continuous process, then run the slurry through a pool of mercury or several pools in succession, on an inclined plane. The spongy amalgam was removed from the pools with a small scoop, at regular intervals. The variation between stampers was substantial as each millman sought to deal with different ores by empirical methods. William Kelly operated a stamper mill at Bendigo in 1855 and experimented with different types of deep wells after the mortar box so as to force the slurry to mix with the mercury to assist amalgamation.[23] Other millmen passed the slurry over copper plates coated with mercury that caught the gold and any silver particles.[24] Others followed Agricola and used blankets or cow hides to catch the gold, washing the blankets every few hours to collect the gold and sand particles that were then treated in an amalgamation barrel.[25] This was a small rotating barrel, up to four feet diameter by six feet long [1.22m x 1.83m], usually made of cast iron, containing small iron rods or balls for grinding. Blanket sand containing gold and pyrites, together with amalgam from cleaning up mortars and plates, was placed in the barrel with mercury and rotated for several hours until all the gold had amalgamated.[26] The amalgam, which contained 30 to 45 per cent gold, was then removed and most mercury was extracted by squeezing in a chamois bag. The remaining amalgam was then placed in an iron retort, heated to a dull red heat so the remaining mercury distilled off, and was then recondensed and collected.[27] The remaining gold cake containing some mercury was sold to a bank where it was refined. Some operators placed mercury in the mortar box for amalgamation to take place but others criticised this practice. They argued that it reduced the efficiency of the reduction of the ore and also reduced the mercury to very small particles that were poor amalgamators. It also caused flouring of the mercury which broke up into small droplets and was washed away with the water. The process worked best with free milling ores with no pyrites but by the 1860s, when mining was below the water line, the presence of pyrites at many mines caused problems with the sickening and flouring of the mercury and the loss of fine gold distributed in the pyrites. Amalgamation as an effective process of gold separation for free milling ores, after the removal of the pyrites, persisted in Australia into the second-half of the 20th century.[28] Because the process had been known for centuries it was never subjected to a scientific analysis of its properties as was later done with sodium cyanide as a dissolver of gold. Thus, millmen used empirical processes in determining the best way for its use - hence the continuous debate throughout the 19th century.

The solution of the pyrites problem

In the period after 1851 most advances in milling technology proceeded in small steps as managers and operators adjusted and improved equipment. For example, through rotating the stamps by altering the cam shape and increasing the weight of individual stamps. Occasionally, one mine would develop a change in technology that would have a major effect in improving the efficiency of the gold extraction process. Such a development occurred in the early 1860s at the Port Phillip and Colonial Gold Mining Company's mine at Clunes in Victoria.

By 1860 the quartz mines in Victoria and New South Wales were extracting ores from below the water line. Stampers were being improved and in the free milling ores at Bendigo, Ballarat, Castlemaine and Clunes much of the gold in the ore was separated cleanly from the quartz gangue during the crushing. It was then collected by mercury troughs, copper plates and canvas strakes that were washed to amalgamate the gold in barrels. The Port Phillip Company was one of the few companies that regularly tested their tailings for gold.[29] In 1861, the works manager, Henry Thompson and their chemist George Latta, realised the tailings contained six percent of the gold in the ore and proved that most of this gold was in the pyrites but could be separated by fine crushing after roasting the pyrites. The flow sheet was altered and a jaw crusher used to reduce ore from the mine to a uniform size. This was fed to a mortar box, the pulp exited from the screens and passed through mercury troughs for amalgamation, across blanket strakes to collect the pyrites, through a final mercury trough to catch any remaining free gold, and the tailings were then discharged into a creek. The initial roasting of all ore was abandoned as uneconomical. The small amount of pyrites mixed with sand from the blankets was treated in a Borlase buddle, modified by another member of the staff, John Munday, who patented a new type to finally separate the pyrites.[30] The sand was discharged to the tailings and the pyrites, about one per cent of the original ore, was roasted in a small reverberatory furnace. The arsenic oxide and sulphur dioxide were removed from the gases, leaving the furnace by water sprays before the gases were vented up the chimney. The oxidised pyrites was crushed finer by Chilean mills and amalgamated in steam amalgamating barrels.[31] The Company completed these experiments and built a reverberatory furnace to roast the pyrites in 1865.[32] Thomas Carpenter also experimented with pyritic ores at Bendigo in 1862 and after crushing he used canvas blankets to separate the pyrites and then calcined the pyrites in a reverberatory furnace before amalgamation.[33] His experiments do not appear to have been as comprehensive or influential as those of the Port Phillip Company.

Of particular significance in this development work at Clunes was the first use of a jaw crusher in gold mining in Australia in 1862, the separation of pyrites by blanket strakes and later by buddle, and the trials of copper plates and mercury troughs for amalgamation.[34] Fortunately for the company, its ores contained a small percentage of pyrites but being largely iron sulphide this did not sicken the mercury after roasting. As the pyrites contained up to four ounces of gold per ton, the recovery of this gold could mean the difference between a profit or a loss for any company mining ores less than five pennyweights per ton of ore overall.[35] For this reason the experiments by the Port Phillip Company that were completed and publicised by 1867, had been watched closely by many other companies in Australia.[36] The Superintendent, Rivett Bland, welcomed inspection of the plant by other companies and published the results widely, leading to the adoption of similar methods by other mines.[37] Unfortunately, the results did not solve the problems of mines such as St Arnaud where there were highly refractory ores containing small amounts of silver, copper and lead, or those at Costerfield containing antimony that sickened the mercury. These mines continued to experiment with gravity methods of separating the components in their ores and with smelting.[38]

The Port Phillip Company treated pyrites concentrates from other companies in Victoria and New South Wales by amalgamation.[39] In the early 1870s, millmen who had worked at Clunes, and others, began to erect pyrites treatment plants on other gold mining fields where they treated parcels of concentrate either for a fee or by purchase. The mixing of the concentrates from various mines to give more efficient processing was also adopted.[40] In so doing, they were following procedures developed at Freiberg in Saxony and at Swansea in Wales, where ores from all over the world were purchased on the basis of assay and smelted to recover a wide range of minerals. Concentrates from St Arnaud were sent to Freiberg for treatment until well into the 1880s and those from Lucknow in New South Wales were sent to Swansea from 1880.[41] In eastern Australia plants were erected in most districts from 1871 for the contract treatment of pyrites, and individual mines built pyrites plants for treating their own ores.[42] The delay between the successful operation of the process by the Port Phillip Company and its general adoption by 1871 was probably because of water shortages caused by drought after 1865, but can also be put down to the conservative attitudes of the Cornish mine managers who were then becoming dominant in the local industry.[43]

Parallel with these developments in the treatment of pyrites during the 1860s and 1870s was continuous modification and improvement of stampers in California and Australia, leading to comparisons being made between machine efficiencies on various fields.[44] The efficient operation of a battery depended on several variables: the type of ore, the weight of the stamp, the rate of stamping, the distance the stamp fell, the size of holes in the screen and the position of the screens relative to the dies. If the ore was free milling and there was no pyrites in the ore, the time in the mortar box had to be kept short or energy was wasted. If the screen holes were too large, the pulp passing through the screen would have particles in which gold had not been separated from the quartz, resulting in no amalgamation. If the screen holes were too small, the slurry particles would remain in the mortar box and be crushed too fine, resulting in slimes from which it was difficult to separate the fine gold which floated off in the current of water. Heavy stamps gave rapid crushing but because of the inertia could not be raised too high because power would be wasted. Heavy stamps required slow speed, while light stamps allowed higher speeds. Despite the large number of variables, battery operators in California and Victoria reached similar conclusions on best practice by 1871. In that year, American writer, W. Raymond, presented comparisons of Australian and Californian practice:

Table 1: *Comparison of Californian and Victorian Battery performance c.1871.*

Goldfield	Wt. of Stamp lb.	Drops per Min.	Drop inches	Tons daily/H.P.
California District				
Tuolumne	500	40-80	6-10	1.26-2.2
Amador	600	70-79	9-11	1.07-1.9
Eldorado	300-650	65-80	7-10	1.24-3.93
Placer	600-800	60-75	7-12	1.24-1.53
Plumas	400-850	35-70	7-11	1.15-2.83
Shasta	300-600	60	6	1.83-2.75
Victoria District				
Ballarat	400-850	50-85	7-10	1.66
Beechworth	442-775	40-90	5-14	2.13
Bendigo	500-800	25-75	6-18	1.5
Maryborough	450-800	50-75	6-22	1.33
Castlemaine	450-800	35-75	6-15	1.7
Ararat	500-675	60-72	7.5-10	1.83
Gippsland	600-750	60-80	7-10	1.58
Pt. Phillip Co.	600-800	60-80	7-10	2.42-3.3

Source: R.W. Raymond, *Mines. Mills and Furnaces of the Pacific States and Territories*, J.B. Ford & Co., New York, 1871.

The final column can be considered a measure of the efficiency of crushing. As weighing was not very accurate at most mines in the 1870s and there is no guarantee that a ton measured in California was the same as in Victoria, the second decimal place in this column can be ignored. The Shasta and Port Phillip results are for individual mines while the others are averages for several mines. The figures show the averages of efficiencies were equal if not better at Victorian mines and the results at the Port Phillip Company were better than most. Later in the 19th century Rickard reported that at mines in Gilpin County in Colorado, the stamps weighed 500 to 600 pounds [226.8 to 272.2kg], the drop was 16 to 20 inches [40.6 to 50.8cm] while the speed was an average of 30 drops per minute. In California at that period the stamps weighed 750 to 1000 pounds [340.2 to 453.6kg], the drop 4 to 6 inches [10.2 to 15.2cm] and the average drop rate 90 per minute. The difference between the fields was that the Colorado mines had about 15 per cent pyrites in their ores and required fine crushing, while most Californian and Victorian ores contained less than two per cent pyrites and coarse crushing was sufficient to separate most of the gold.[45] Unfortunately, comparative statistics for Australian mines or mills treating high pyritic ores are not available.

Chlorination of gold ores

The use of water containing dissolved chlorine gas as a solvent to dissolve gold from ores was first suggested by Dr John Percy of London as a result of experiments he made in 1846. His proposal was developed into an industrial process by Professor Plattner and his assistants at the Royal Freiberg Smelting Works in Saxony in 1848 to treat ores containing iron oxides and arsenic from which most of the arsenic had been removed. However, the residue contained about one ounce of gold to the ton, the separation of which proved intractable. The gold was dissolved from the pyrites at ordinary air pressure in earthenware pots, the liquid was run off into other earthenware jars and the gold precipitated from solution by hydrogen sulphide gas. Plattner later suggested the method would work on a greater scale using large wooden vats coated with pitch instead of earthenware jars and his method was introduced to Califonia by C. Deetkin in 1857.[46]

In August 1864, Alan Cameron Lyster De Lacey, a civil engineer living in Melbourne was granted Victorian Patent No. V 748 for ‘Improvements in machinery and processes for pulverising gangue and the extraction of gold from auriferous matters’. This was the eighth patent granted to De Lacy in Victoria since 1857, the others being related to the preservation of timber, iron and steel and to crushing of ores. An examination of patent records shows he was a prolific inventor, but few other references to his career have been found. He may have been ahead of his time and the foundries in Australia might not have been able to implement his ideas. Patent No. 748

related to the use of a solution of chlorine in water for extracting gold. Pressures above atmospheric were obtained by generating excess chlorine, with the crushed pyrites being placed in a barrel. This was dampened with water, chlorine gas injected and the barrel rotated to speed up processing. The liquid was then removed from the barrel and the gold precipitated by adding iron sulphide.[47] This was not the first barrel process for chlorination, for Duflos had used this method in Breslau in 1848.[48] No information on the use of De Lacy's patent has survived but the patent documents show it was well thought out and would probably have worked well, although it would have been expensive as it was a batch process treating four tons of pyrites per batch.

De Lacy was living in Bendigo and had a mine there in 1871[49] and suggesting he might have influenced local technology was the construction of a plant in 1876 by the United Pyrites Company at Pinchgut Gully. In 1879, the Bendigo mining registrar reported the company had replaced an amalgamation plant using arrastras (Chilean mills) for fine grinding, by a chlorination plant with a four ton vat, earthenware gas generators heated by steam and with a large number of earthenware vessels to hold the auriferous solution - a close description of De Lacy's patent.[50] The 1879 report said the company was treating sulphide ores from St Arnaud and Bourke's Flat successfully and could handle 40 tons per week.[51] In his *The Metallurgy of Gold,* Rose said this patent was tried and then forgotten.[52] No documentation has been found to prove that this installation at the United Pyrites Company used De Lacy's patent but it seems likely it did so. If true, it is a good example of the early efforts made to adapt an overseas invention to local ore processing in Australia in the second-half of the 19th century.

In 1880, Victorian patent cover was granted to James Howell Mears, an American inventor living in Philadelphia, for a process in which chlorine was used above atmospheric pressure. This was introduced under a law that allowed overseas inventors to be protected without a full submission if the patent was already approved in the country of residence.[53] De Lacy had covered the same process but his patent was now void due to effluxion of time. James Cosmo Newbery and Claude Vautin were awarded Victorian Patent No. 4484 in 1886 for a chlorination process which was similar to those of De Lacy and Mears, except that the excess pressure of four atmospheres above atmospheric was produced by compressed air.[54] The solution was heated to speed the process and charcoal was used as the precipitating medium.[55] Newbery and Vautin had worked closely with Joel Deeble and his staff at the United Pyrites Company plant at Pinchgut Gully, Bendigo and this was apparently the first time wood charcoal was used to precipitate the gold. The charcoal was then burnt at high temperature to recover the gold.[56] Newbery was Victorian Government Analyst, a graduate of Harvard University in the USA who worked for Professor McCoy at the National Museum in Melbourne, with the right to private practice, while Vautin was a metallurgist with experience at the Cobar copper mines.[57] Parcels of refractory gold ores from Australia and other countries were treated at Bendigo and at Ballarat until the second decade of the 20th century using this process.[58] Chlorination plants were built at Daylesford, Casillis, and Melbourne in Victoria, in the late 19th and early 20th century. Both Granya and Bethanga treated very refractory gold ores containing copper.[59] Although little documentation remains, there is evidence that the Oswald mine and the South German mine at Maldon, were operating chlorination plants up to World War I and there were most likely others.[60] A plant at Harden in New South Wales, the Carringar Chlorination Works, advertised its ability to treat refractory ores by chlorination and in 1899 there were two chlorination plants at West Wyalong, one at Wellington and one at Adelong.[61]

In Queensland, the Pyrites Works of Curtis and Company was established in Gympie around 1880 using the Plattner process to treat pyritic ores from local mines. Soon afterwards, the Aldershot Smelting Works commenced work in Maryborough to treat auriferous concentrates and pyrites and to smelt lead ores containing gold.[62] It is uncertain whether this plant used chlorination. The Summary of Gold Mining Statistics issued by the Queensland Mines Department in 1892 listed six chlorination vats at Cloncurry, 49 at Charters Towers, 48 at Ravenswood and 132 at Rockhampton (Mt Morgan). The Charters Towers field was discovered in 1871, the ore being found in quartz veins in fault fissures in grano-diorite. The ore contained lead, copper and iron minerals, the oxides of which caused no difficulties with the amalgamation process in the early years. The flowsheet for the rich 'brownstone' deposits of the oxidised zone was stampers, copper plates with mercury wells, Mundays buddle or Brown and Stanfield concentrator, Wheeler's pan (a modernised version of Agricola's stone grinders for fine grinding), and a tank to settle out any gold particles and amalgam. The lighter particles were stirred and run off to a Berdan pan and fine ground with mercury. When the water level in the mine was reached there was a tendency for the sulphides in the ore to slime in the attempt to fine grind. A modified flow sheet was introduced by D.A. Brown at the Charters Towers Pyrites Company. This saw a rockbreaker crush the ore for the stampers, followed by the concentrator, Wheeler's pan, settling tank, Berdan pan, and a second settling tank to collect the pyrites. These were then roasted with salt to oxidise the pyrites and to convert any zinc to zinc chloride in a three stage furnace built on a hillside. The roasted sand was fed into wooden vats with a filter of broken glass at the bottom, dampened with water and chlorine gas forced in from below. A weak solution of chlorine gas in water was added. When the gold had dissolved, the solution was run through a vertical column with counter current high-pressure steam to drive off the chlorine gas for reuse. The gold was precipitated with ferrous sulphate onto beds of charcoal and sawdust, which were burnt to smelt the residue. The method was a technical success but it was an expensive plant and was superseded after 1892 by the cyanide process.[63]

The largest chlorination plant in the world was erected at Mount Morgan to recover the fine particles of gold in ironstone.[64] In the oxidised zone, amalgamation recovered only about 40 per cent of the gold, the rest being washed over the plates without being caught. A Plattner process installed by A. Lymburner of Gympie was tried in 1884 but did not recover more than 75 per cent of the gold. The Newbery-Vautin patent was installed in 1885 and gave satisfactory results but was fragile for the quantity of ore to be handled. It was partly discarded later that year when a plant installed and designed by Henry Trenear, who had experience in Mexico, was installed to give 98 per cent recovery. Some of the Newbery-Vautin components were incorporated in the revised plant at the 'Lower Works', which was later enlarged to a capacity of 500 tons per week. It was then realised that the orebody was larger than anticipated and a new plant, the 'Upper Works', of 1000 tons per week was erected in 1887. After coarse crushing, drying and dry crushing between rolls, the fine ore was roasted for three hours in a reverberatory furnace, cooled and fed to hardwood chlorination barrels containing one ton of ore and mixed with water, calcium chloride and sulphuric acid, to produce chlorine (the Mears Process). After being rotated for three hours the barrels were discharged into leaching vats holding three tons where the mixture was drained with vacuum assistance for 36 hours. The residue was shovelled out while the gold chloride solution was passed through charcoal, which absorbed the gold. The charcoal was burnt and the gold smelted with appropriate fluxes to produce gold bullion. This plant was successful and the company paid substantial dividends but there was continual pressure to reduce costs. After much experimentation, the manager, Wesley Hall, and the chief metallurgist, George Richards, a graduate of the Ballarat School of Mines, developed what was called the Hall-Richard process. This involved the ore being crushed by orebreakers, dried in rotary furnaces (each 6ft 8inches diameter by 30ft 5inches long [2.3 by 9.3m]), fine crushed in No. 5 Krupp ball mills. Following this, the crushed material was passed through wire screens with 400 perforations to the square inch, was roasted in rotary furnaces, cooled and carried by small rail trucks to vats each containing 100 tons of ore. The ore in the vat was saturated with water and a solution of 80 grams of chlorine in a gallon of water was run in to the top and allowed to percolate through the ore to convert the gold to gold chloride, the solution being run into cement lined brick tanks from where it was passed over charcoal beds to precipitate the gold. The charcoal was removed periodically, burnt in a reverberatory furnace and then reduced in a smelting furnace to gold bullion. Mixing sodium chloride produced the chlorine, which was dissolved when manganese dioxide and sulphuric acid were passed up a scrubbing tower down which water was percolating. The total cost of treating the ore to extract the gold was just over 10 shillings per ton in 1911, including crushing, roasting and chlorination. This final plant, the West Works, with an initial capacity of 2,500 tons per month, was built progressively in four similar parallel sections in 1896-7 to a capacity of 10,000 tons per month. It was closed in 1911 when the ore for which it had been built was worked out.[65]

As the returns were overshadowed by the cyanide process after 1900, the chlorination process has been mostly ignored by mining historians but the use of the process was important in the development of gold mining technology in eastern Australia from 1876 when the process was first used on pyritic ores from Bendigo. Although the tonnages of pyrites treated and the gold recovered were not as large as that recovered by amalgamation, the revenue from chlorination was additional income not otherwise available to a company mining refractory ores. Often it was the difference between paying a dividend, or struggling to survive. As an example, the Lord Nelson Mine at St Arnaud began paying dividends in 1888, one year after Zebina Lane (Snr) was appointed manager. The company had previously sent pyrites concentrates to Freiberg at a profit but using Wheeler's pans, Lane introduced fine grinding followed by amalgamation.[66] By 1890 he was sending the residue from this process to Bendigo for further treatment by chlorination.[67] Early statistics of the mine production are not available but the Mines Department published some figures of the mine output between 1905 and 1914, the year the mine closed. These figures for 1905-14 have been collated as 75,203oz by amalgamation, 13,549oz by chlorination, 20,186oz by cyaniding old tailing dumps, and in 1905 a figure of 572oz by pan amalgamation of pyrites was given. Apparently, pan amalgamation was abandoned soon after 1905 and all pyrites treated by chlorination at the mine.[68] The percentage of pyrites in the ore was up to 20 per cent[69] and the figures show that 18 per cent of mine production in this period was produced by the chlorination process. In 1897, the South German mine at Maldon was also operating a chlorination plant for pyrites and recovering 97 percent of the gold and additionally used a cyanide plant to extract gold from tailings. Charcoal was used to precipitate the gold in both cases.[70] Figures printed in 1900 state that nearly 450,000oz of gold had been obtained from pyrites in Victoria up to that date. However, this figure apparently included gold from fine crushing, plus amalgamation, as well as chlorination and cyaniding. It also probably included pyrites sent from elsewhere in Australia and overseas for treatment at Ballarat and Bendigo.[71] Between 1884 and 1911, the major use of the process in eastern Australia was at Mt Morgan where it was used to separate fine gold not recoverable by amalgamation. During that period, the peak production there in one year was 300,000oz of gold.[72]

While in eastern Australia from 1876 there were a limited number of chlorination plants compared with the number of cyanide plants after 1900, the experience gained by metallurgists and mine managers who worked with the former process would have given them an understanding of how chemistry could be relevant to the efficient extraction of gold from complex refractory ores.

As early as 1864, Dr Ottway, an American chemist, was experimenting with lixiviation to separate silver from gold in the refractive St Arnaud ores and he later experimented with the Plattner process on Blackwood ores.[73] In the same year De Lacy patented a variation of the Plattner process.[74] By 1876, as discussed above, plants established in Bendigo and Ballarat to separate gold from pyrites by fine crushing and amalgamation indicate that this method failed to extract half of the gold. The Plattner process proved not very successful on the more complex ores. In the mid 1880s further experiments at Bendigo with the Newbery-Vautin patented variation of the Plattner process were more successful but the method was costly. This process was tried in 1885 at Mt Morgan on oxidised ironstone ore in which the gold was finely distributed, but the equipment could not process the amounts of ore to be treated and failed mechanically. Some of the equipment was incorporated in a modified barrel leaching process in 1887 and this was successful.

From about 1890 chlorination plants were distributed in strategic locations on the goldfields of eastern Australia to treat refractory ores. As the amount of pyrites in most ores was of the order of a few percent of the ore crushed, the number of plants did not need to be large to treat all the pyrites available. By the end of the 19th century some mines with very refractive ores were installing chlorination plants. The process replaced the system of fine crushing the pyrites followed by amalgamation, and sending the residue still containing gold to the pyrites plants for further treatment. At the same time, they installed cyanide plants to treat old oxidised tailings, and later fresh tailings were treated very cheaply by the newer method. On some fields, such as Charters Towers, cyaniding had replaced chlorination by 1897 because the ore was suitable for the cyanide process. However, very refractory ores found elsewhere were still being treated by chlorination until World War I.

Additionally, by 1890, most mines with refractory ores were crushing the pyrites fine enough to be experiencing a sliming problem and were experimenting with very sophisticated mechanical methods such as vanners to separate the pyrites and the contained gold from the quartz. These slimes were so fine that they 'packed' in the vats used for chlorination and cyaniding. In order to get the chemicals to attack and dissolve the slimes to recover the gold, Joel Deeble experimented in Bendigo with an agitator to stir the slimes in the vat. He later sold some nine of these plants to mines in the colonies, including two to Kalgoorlie and two to Maldon where they were fine crushing their ores for cyanide plants, although it is likely he first developed the plants for chlorination.[75]

Todd concedes that colonial Australia showed an ability to change course, to cross the divide between old and new trajectories and to transfer and adapt technologies.[76] Although there were undoubtedly some mine managers and others who were ignorant of the chemical methods, after 1890 it is unlikely they were the majority. In fact, chlorination and cyaniding were adapted in parallel, but with chlorination plants being somewhat earlier and distributed widely enough to educate mine managers and their staffs in chemical methods of ore treatment. In the first quarter of the 20th century, some mines with refractory ores operated both chlorination and cyanide plants - the chlorination plant to extract fine gold from pyrites and the cyanide plant to extract fine gold from tailings. Ignorance was not the reason the cyanide process was adopted slowly, more important was the complexity of many gold ores, the cost of the royalty, the uncertainty of the validity of the cyanide patents, the 1890s depression in Victoria that saw a squeeze on capital for new developments, and the need for time to adapt the cyanide process to complex ores. The sponsors of the cyanide process had to prove that their system was the cheaper, something they did not always succeed in doing.[77]

Endnotes

[1] R.M. Serjeant, 'Report of the Board to Investigate Methods of Treating Pyrites', Parliament of Victoria, *Papers Presented to Parliament 1874* [hereafter PPP Vic 1874], no. 96*,* Government Printer, Melbourne, 1874, p. 62. Appendix E includes the following data for gold recovered by simple amalgamation after crushing: Llanberris Co., Ballarat 93 per cent; Port Phillip Co., Clunes, 96 per cent; Walhalla Co., Walhalla, 97 per cent; Caledonian Co., Maldon, 81 per cent. At each mine the remaining percentage was recovered after treating the pyrites. Losses in the tailings are not included but would have been about one per cent or more.
[2] *Ibid*., p. 13.
[3] Exceptions are: D. Menghetti, 'Extraction Practices and technology on the Charters Towers Goldfield', *North Australia Research Bulletin*, September 1982; J. Kerr, *Mt Morgan, Gold, Copper and Oil*, J.D. Kerr and R.S. Kerr, 1982, pp. 55-58.
[4] J. Todd, *Colonial technology*: *Science and the transfer of innovation to Australia,* Cambridge UP, Hong Kong, Melbourne, 1995, p. 206.
[5]G. Agricola, *De Re Metallica*, 1556, translated by H.C. Hoover and L.H. Hoover, New York, Dover, 1950, pp. 118-20, 273. Agricola described how firesetting was used to heat hard rock underground to soften it. This firesetting technique was gradually superseded after gunpowder was introduced at Schemnitz in 1627 but it was still in use in English mines until about 1700. Agricola also discussed how burning ores made them easier to crush with stampers.
[6]Refractory ores were found at Maldon, St Arnaud, Bethanga and Granya in Victoria and at Harden, Lucknow and West Wyalong in New South Wales and at Ravenswood and Charters Towers in Qld.
[7] Mr. Wilkinson, 'Lecture on the Extracting Gold from Quartz,' *Colonial Mining Journal*, July 1860, pp. 175-6. This furnace was an early adaptation of science to gold mining technology.
[8] J. Woodland, *Sixteen Tons of Clunes Gold,* Clunes Museum, Clunes, 2001, pp. 15, 71.
[9] *The Mining Journal* (London)*,* 11 September 1858.
[10] J. Birmingham, I. Jack, and J. Jeans, *Industrial Archaeology in Australia - Rural Industry*, Heinemann Publishers Australia, Richmond, 1983, p. 74.
[11] *The Mining Journal*, 11 September 1858.
[12] Woodland, *Sixteen Tons of Clunes Gold*, pp. 68, 77.
[13]'Reports of Mining Surveyors and Surveyors, Victoria', Mines Department, Melbourne, 1869, p. 33.
[14] Serjeant, *Report of the Board to Investigate Methods of Treating Pyrites*, p. 59. It is odd that Stawell witnesses, members of the local Council, doctors and mining men said the percentage of pyrites in Stawell ores was very small and the fumes from roasting did not affect health, while recent geological studies state that the Cross reef, which was being worked in 1874 was sulphide rich. See D.C. Fredericksen and M. Gane, 'Stawell Gold Deposits,' in D.A. Berkman (ed.), *Geology of Australian & New Guinean Mineral Deposits*, Australasian Institute of Mining and Mineralogy, Melbourne, 1998, p. 538. Perhaps the locals were trying to protect the reputation of their town. Witnesses from Castlemaine were much more forthright about the detrimental effects of the fumes.
[15] *Report of the Royal Commission on Mining*, Government Printer, Melbourne, 1891, para. 9539.
[16] C.G.W. Lock, 'Gold Amalgamation,' *Transactions of the Institute of Mining and Metallurgy* vol. 1, 1893, pp. 205-37. Lock gave examples of practice in the Transvaal, Australia and the United States.
[17]The Board was set up on 28 June 1873 and submitted its report the following year. PPP Vic 1874, report no. 96. The membership was; four mine managers, the Government Analyst J. Cosmo Newbery, a geologist, and an industrial chemist.
[18]A written questionnaire was sent to each person called to give evidence and he was then questioned about his replies and other matters. The replies given in the record of the evidence show there was just as much difference in the 1870s about amalgamation as there was in the 1890s. Each manager or millman had a preferred method for treating the ore with which he was working.
[19]Agricola, *De Re Metallica*, pp. 293-99. See also the translators' note pp. 297-300 on the history of amalgamation.
[20] *Ibid.,* p. 298.
[21]T.T. Read, 'The Amalgamation of Gold-Ores,' *Transactions of the American Institute of Mining Engineers* XXXVII, 1906, p. 70. The specific gravity of gold is 19.32, that of mercury 13.55.
[22] Woodland, *Sixteen Tons of Clunes Gold*, pp. 8-9.
[23] W. Kelly, *Life in Victoria*, London, 1857, pp. 195-231.
[24] Read, 'Amalgamation of Gold-Ores,' p. 57. Read believed copper plates were developed in California but were not patented and the inventor is unknown.
[25] Woodland, *Sixteen Tons of Clunes Gold*, p. 66.

[26] A. F. Taggart, *Handbook of Mineral Dressing*, John Wiley and Sons, New York, 1945, p. 149.
[27] T. K. Rose, *The Metallurgy of Gold,* Charles Griffin & Co., London, 1906, pp. 140-41.
[28]Australian Development Ltd., 'Amalgamation', in J.T. Woodcock (ed.), *Mining and Metallurgical Practices in Australasia*, Australasian Institute of Mining and Metallurgy, Melbourne 1980, pp. 484, 88, 517. The carbon in pulp process replaced amalgamation in the 1980s.
[29] Woodland, *Sixteen Tons of Clunes Gold*, p. 71.
[30] *Ibid.,* p. 74.
[31] *Ibid.* Woodland gives a comprehensive description of the work done by the Port Phillip Company in the development of improved crushing techniques and the treatment of pyrites of which only a brief outline is given here. Serjeant, 'Report of the Board to Investigate Methods of Treating Pyrites'. In the report the Board recommended the use of the modified Borlase buddle, of Cornish origin, to separate the pyrites from the sand.
[32] Woodland, *Sixteen Tons of Clunes Gold*, p. 73.
[33] Catherine Reef United Company, 'Mine Manager's Reports', 25 September, 9 October, 16 October, 11 December 1862. I am grateful to James Lerk for access to his files on mining in Bendigo.
[34] Woodland, *Sixteen Tons of Clunes Gold*, pp. 67, 73.
[35] In each 1 ton of gold ore of average grade of 5 dwt overall and containing 1 per cent pyrites there are 0.99 tons of ore with free gold which can be amalgamated and 0.01 tons of pyrites with attached gold which must be fine ground. The 0.01 ton of pyrites contains 4/100 ounces of gold = 80/100 dwts = 0.8 dwts. The free gold is therefore 5 - 0.8 = 4.2 dwts. When assumed all the free gold is amalgamated, the pyrites gold is 0.8/4.2 = 19 per cent of the free gold. By extracting the extra 19 per cent in the pyrites, a mine which had extracted the free gold and barely made a profit, could turn into a good profit maker.
[36] *Ibid.,* ch. 14.
[37] In 1868, several mine managers from Bendigo inspected the Port Phillip plant and soon afterwards requested the permission of the Sandhurst City Council to erect treatment plants to roast pyrites. See *Bendigo Advertiser,* 6 June 1868. Several people, including medical men, objected that the fumes from such plants were poisonous.
[38] *Report of the Royal Commission on Mining*, 1891, pp. 460-65. Many managers and owners, including Fred Stahl and John Rew, managers of St Arnaud mines, who appeared before this body, reported on experiments with vanners and other devices being tested.
[39] Woodland, *Sixteen Tons of Clunes Gold*, p. 76. Pyrites from the Amelia reef in the Blue Mountains of New South Wales were sent to the Port Phillip Company for treatment in 1867.
[40] These plants were erected outside municipal boundaries on leases granted by the Mines Department for this purpose. People living near these plants complained to the Board on Pyrites about the noxious fumes but several medical men said the fumes were not dangerous.
[41] *Report of the Royal Commission on Mining*, 1891, p. 460. 'The Lucknow Goldfield, Report No. 30', New South Wales Geological Survey, Sydney, 1920, evidence by Fred Stahl and L.F. Harper.
[42] *Victorian Mines Department Reports and Statistics 1859 - 1893,* Victorian Mines Department, Melbourne, 1859. These reports contained statistics on the tonnage of pyrites treated in each mining district from 1869. In most cases the returns were between two and five ounces of gold to the ton of pyrites. In the first quarter of 1869 the Port Phillip Company produced 87 tons and the New North Clunes Company 35 tons of pyrites respectively, with other districts producing negligible amounts. In the first quarter of 1872 the Ballarat mining district produced 414 tons mainly from Clunes, the Beechworth district 96 tons, the Bendigo district 396 tons, Maryborough district 108 tons and the Gippsland district 137 tons, respectively. In later years Bendigo was usually the largest producer and processor of pyrites.
[43] F. Cusack, *Bendigo a History*, Heinemann, Melbourne, 1973, p. 135.
[44] W.P. Blake, *Mining Machinery*, Charles Clasfield & Co., New Haven, 1871. Blake included excerpts from the Reports of Registrars and Surveyors of the Victorian Mines Department.
[45] T. A. Rickard, *Stamp Milling of Gold Ores*, Engineering and Mining Journal, New York, 1906, p. 2.
[46] Rose, *Metallurgy of Gold*, ch. XIII.
[47] A.C.L. De Lacy, 'Improvements in Machinery and Processes for Pulverising Gangue and the Extraction of Gold', in *Victorian Patent V748*, Victoria, 1864. The use of a rotating barrel appears to be a transfer from the amalgamation process.
[48] Rose, *The Metallurgy of Gold*, p. 257.
[49] *Register of Claims*, Victorian Mines Department. Claim no. 3976 for a residence licence associated with the Plantagent Gold Mining Company mine at One Tree Hill, Bendigo.
[50] W.B. Kimberley, 'Thomas Edwards', in *Bendigo and Vicinity*, Ballarat, 1895, pp. 246-7. Edwards had commenced roasting pyrites at Clunes in 1864. He probably learnt these skills at the Port Phillip works.
[51] 'Reports of Mining Surveyors and Surveyors, Victoria', Second Quarter 1879, Sandhurst Division.

[52] Rose, *Metallurgy of Gold*, p. 257.
[53] See Victorian patent application no. 2814 by E. Waters, Patent Attorney, 14 April 1880.
[54] D. Clark, *Australian Mining and Metallurgy*, Critchley Parker, Melbourne, 1904, p. 269. Rickard, *Stamp Milling of Gold Ores*, p. 200. Clark said the patent was not sound scientifically as the amount of chlorine dissolved in the water was not increased by increasing the total pressure, but only by increasing the partial pressure of the chlorine gas. The patents of De Lacy and Mears did this. I am thankful to an anonymous referee for the information that Vautin later had a chequered career in England and South Africa and was imprisoned for six months for fraud in the latter country in 1899.
[55] See Victorian Patent Application, no. V4484, 29 March 1886.
[56] Joel Deeble had been a partner with Thomas Edwards in establishing the Pinchgut Gully plant in 1872 and later bought out his partner. He was the expert in metallurgy while Edwards concentrated on the furnace side of the business and in running his plant at Ballarat. In the 1890s Edwards built a new plant, near the Pinchgut plant and started chlorinating ores in opposition to Deeble who up to that time had had a monopoly in Bendigo. Unlike Edwards, Deeble was not a self publicist and there is little documentation on his development work.
[57] *Biographical Sketches*, Bulletin no. 23, Victorian Mines Department, 1910. W. Meyerriecks, *Drills and Mills*, Will Meyerriecks, Tampa, 2001, p. 162, states that the Newbery Vautin process was licensed for use in the United States.
[58] See *Supplement to the Weekly Times*, Melbourne, 10 September 1898, p. 57.
[59] *Reports to the Minister of Mines, Victoria*, Mines Department Victoria, Fourth Quarter, 1890, 1903. Clark, *Australian Mining and Metallurgy*, pp. 308-9, 316, 335.
[60] The Oswald Gold Mines NL at Maldon was operating a chlorination plant in 1913 on an intermittent basis to treat its pyrites (see Oswald Mine, Managers Reports, copy with author), and it is likely the Lord Nelson Company at St Arnaud had a plant working at the same time as it regularly reported on the amount of gold produced by chlorination. Clark, *Australian Mining and Metallurgy*, p. 327.
[61] *Australian Mining Standard*, 24 April 1889. *Reports to Minister of Mines, New South Wales*, Government Printer, Sydney, 1899.
[62] W. Lees, *The Goldfields of Queensland*, 1899, Reproduced by the Mines Department, Brisbane 1986.
[63] D. Menghetti, 'Extraction Practices and Technology on the Charters Towers Goldfield', *North Australia Research Bulletin*, September 1982.
[64] Rose, *Metallurgy of Gold*, p. 281.
[65] J. Kerr, *Mt Morgan, Gold, Copper and Oil*, J.D. & R.S. Kerr, Brisbane, 1982, pp. 55-58. R.F. Boyle, R.W. White, and O.A. Wilson, 'Mount Morgan, Queensland - Marvellous Mountain', paper presented at the AIMM Conference, 1993, pp. 330-31. C.H. Humphreys, 'West Works - Mount Morgan (Queensland) Chlorination', *Proceedings of the Australasian Institute of Mining Engineers,* vol. XV no. 2, 1911, pp. 363-77.
[66] Y.S. Palmer, *Track of the Years*, MUP, Melbourne, 1955, p. 263.
[67] *Report of the Royal Commission on Mining*, 1891, p. 455.
[68] *Reports to the Minister of Mines Victoria*, 1904 - 1914.
[69] *Report of the Royal Commission on Mining*, 1891, p. 456.
[70] J. Mactear, 'Notes on the South German Mine, Maldon, Victoria', *Transactions of the Australasian Institute of Mining and Metallurgy*, 1897, pp. 43-51.
[71] *Reports to the Minister of Mines, Victoria*, 1900, p. 10.
[72] Kerr, *Mt Morgan, Gold, Copper and Oil*, p. 62.
[73] G.H.F Ulrich, 'Gold and Silver Bearing Reefs of St. Arnaud', *Victorian Geological Survey*, Melbourne, 1864, p. 3. *Report of the Royal Commission on Mining*, 1891, para. 4619, p. 192.
[74] De Lacy, 'Improvements in Machinery and Processes for Pulverising Gangue'.
[75] Todd, *Colonial Technology*, p. 177. *The Australian Mining Standard*, 1 July 1897, p. 994, 5 August 1897, p. 2091, 1 June 1899, p. 120.
[76] Todd, *Colonial Technology*, p. 207.
[77] *Ibid.,* p. 133.