Chapter 2

The Mineralogy and Metallurgy of Copper

Both the mining of copper ore and its subsequent conversion to metal are dictated by geographical, geological and commercial constraints. The overwhelming bulk of commercially viable ore was raised from the mines of Cornwall, the general location of which were known from the reign of Elizabeth I.[1] The only other significant source of ore in the United Kingdom was located on the island of Anglesey. It also had been worked from an early date, although, unlike Cornwall, it was not until the third quarter of the eighteenth century that its full economic potential was realised.[2]

Locational constraints on the smelting and refining of the ore, its conversion into metal, were significantly more flexible. The prime requirement was a source of coal, and suitable reagents to liberate the unwanted constituent parts. The supply of coal was particularly important because of the considerable quantity needed to produce a single ton of copper. As a result the smelting industry evolved in close proximity to its source, although there were the exceptions. Thus transport became an issue following the functional separation of the two industries. During the eighteenth and early nineteenth centuries road transport facilities in Cornwall for bulk commodities were at the very best, primitive. Jenkin wrote in 1927: '… in 1797, one of the copper *(smelting)* companies refused to buy any more ore from Tresavean Mine on account of the cost of transporting it to the coast', and in 1754 a petition to Parliament stated: '… roads are become very ruinous, and many places thereof are so narrow that carriages cannot pass each other, especially in winter and the rainy season, when they are so deep and founderous that wheel carriages, horse laden, and even travellers pass in great danger.'[3] The result was the more or less universal movement of ore, as well as copper, by sea and canal, both requiring appropriate port facilities.

From the introduction of the reverberatory furnace in the late seventeenth century the copper industry has seen the separation of its two main functions, mining and smelting. In this chapter this separation is examined to determine the factors which resulted in geographic dislocation.

Mineral Deposits

Cornwall

Prior to the formation of the mineral bearing lodes, the geological structure of Cornwall comprised highly compacted sedimentary rocks, which over a period of time had become contorted and fractured.[4] During the carboniferous period, these rocks were subjected to major change as a result of the contraction of the surface and pressure from the underlying molten magma. The magma intruded into the sedimentary layers forming the granite bosses, the backbone of the two counties. These now eroded bosses comprise the high ground of Dartmoor, Bodmin Moor, St Agnes Beacon, Carn Marth, Carnmenellis, Carn Brea and the Land's End peninsula, all of which became associated with metalliferous mining (figure 2.1). The magmatic intrusion greatly altered the adjacent sedimentary rocks, causing numerous minerals to be deposited throughout the interface between the two regions, the metamorphic aureole, as well as in the fissures produced by the earlier movement of the earth's crust. This process was repeated intermittently throughout the next 50 million years, resulting in an ongoing deposition of minerals in an ever changing pattern of fissures and other voids, whilst at the same time distorting and displacing the lodes already formed. This dynamic situation terminated during the Triassic age.

This upward flow of mineralised material was found to originate from regions close to the source of the granite upthrust, locations known as emanative centres. As they neared the surface, pressure and temperature dropped to a point were the material solidified, forming the metalliferous lodes. Distribution was not uniform, resulting in the formation of a series of mineral zones. In general, tin and copper bearing minerals occurred close to the emanative centre, whilst others, such as silver and lead, were further removed.

Copper ore is found in many forms.[5] The two most common, both sulphide ores, found in Cornwall were chalcopyrite (Plate I), composed of copper, iron and sulphur, and chalcocite, composed of copper and sulphur. Other copper ores found in the county included the carbonates, malachite and azurite, the oxides, melanconite and cuprite, and native copper.

Copper mineral deposits became stratified over time, forming three merging zones. In the upper layer on and near the surface, the primary ore was modified following its reaction with rain water permeating the surface, the residual minerals comprising oxides and carbonates of copper and iron. The copper bearing sulphur components leached out by the rain water descended to the water table, forming a zone of secondary enrichment. In the third zone below the water table were the unaltered primary copper minerals. In later geological periods, Cornwall was subjected to glaciation which resulted in the erosion of much of the oxidised and secondary zones. Thus, although some of these enriched minerals have been discovered, the bulk of the ore raised has comprised the lower copper content mineral, chalcopyrite.

PLATE I

Chalcopyrite

a. Parys Mountain, Anglesey

b. Carn Brea Mine, Camborne

Anglesey

The Anglesey copper mines were situated on Parys Mountain, approximately one mile to the south west of the associated port of Amlwch. The mineral zone lies on an approximate north east/south west axis, extending over some 3 km, and approximately 1 km wide. Unlike those of Cornwall, the Anglesey deposits were associated with an ancient volcanic event. Similar deposits have been discovered in Japan at Kuroko, which has given its name to this type of deposit. Its occurrence on Parys Mountain is unique in Britain.

The initial mineralisation on Parys Mountain was iron pyrite, an iron sulphide. A second stage was dominated by the copper sulphide, chalcopyrite, and a third by one comprising a mixture of sphalerite, an ore of zinc, and galena, an ore of lead, with only small amounts of chalcopyrite. This was know locally as "Bluestone"[6] In the first instance in working the mines, the ore was found freely distributed, and open cast methods were adopted. Only in the nineteenth century was the ore raised from lodes by conventional mining techniques.

Mining Technology

Cornish mines were characterised by their development on the lode (Figure 2.2). This was a natural evolution from the earlier surface workings in which the lode was followed both laterally and vertically until it became impossible to follow the open lode in depth with any degree of safety. At a convenient point on the lode a shaft would be driven which followed the alignment of the lode. This shaft was used for the raising of ore, access for the miners to the various work areas by means of ladder ways, and for the rods driving the pumps. As the mine became extended, so more shafts would be driven on the lode. Shafts were also vital in providing adequate ventilation. At intervals of between ten and twenty fathoms, the common unit of measurement used in the mines, a horizontal level would be driven, again on the lode, and ultimately linking up with one or more new shafts. As the level advanced, so miners would work from these levels either upwards or downwards, removing lode material. The former was known as overhand stoping, and the latter underhand stoping, the name deriving from the work place, the stope. Stoping would ultimately link the levels above and below, although not all material on the lode would necessarily be removed. At this point the lode was said to be stoped out. Material extracted from the lode would be rough sorted underground, only the better material being sent to the surface, or 'grass'. In addition to the stopes, intermediate shafts would be driven, the 'winzes', serving the purposes of communication and ventilation. At the same time as lode material was being removed from the stopes, shafts would be sunk to ever greater depths, new levels opened up, and existing ones driven forward. By these means further regions of the mine could be explored to ensure there was always a profitable reserve of ore available for future exploitation. Voids in the level floor resulting from underhand stoping would be bridged by timber platforms, known as 'stulls'. Amongst the first of the levels to be driven would be the 'adit'. This level would exit at the lowest point accessible above sea level, either a valley floor or cliff face. It would be to the adit all water from lower levels would be pumped. This water would be drawn from the deepest of the shafts, the bottom of which was known as the 'sump'.[7]

The continual inflow of water was a perpetual problem in the vast majority of Cornish mines. In earlier times, and amongst many of the smaller operations, all work would cease during the winter months. Simple bucket lifts were used to drain the shallower mines, using manually operated windlasses. The rag and chain pump, driven by a water wheel, was common. The height it could lift a column of water was limited, requiring a series of pumps, passing the water from one up to the next. In the deeper and wetter mines it was not unusual for more men and boys to be employed operating pumps than miners winning ore at the work face. At the onset of the copper era, the adit as a means of drainage was well established, but its value diminished as the mines developed and exceeded its depth. Water was never a problem if all activity occurred above the adit level.[8]

Notwithstanding the many improvements introduced by John Coster in drainage, haulage and dressing,[9] it was the introduction of steam power which was to provide the major stimulation to the industry. The earliest practical steam engine was developed by Thomas Newcomen (1663 – 1729), a Devonian,[10] the first being installed at Wheal Fortune in Ludgvan Lease in 1720. By 1727, a further five engines were thought to have been installed. Pryce writing in 1778 claimed this had risen to sixty, although very few were at work.[11]

Pumps powered by the Newcomen engine were a significant improvement in draining the ever deepening mines when compared to earlier methods, yet they were thermally inefficient. On each cycle the cylinder had to be reheated and cooled, requiring an excessive input of fuel. Whilst not a problem for those engines installed on or near coal mines where coal was cheap or even free, where it had to be transported long distances, and initially subject to duty when delivered by sea, the engine was far from cost–effective.[12] Thus resulting from a combination of high fuel costs, and its inherent inefficiency, operation became spasmodic, and in many cases the engine was left idle unless deemed essential. Nevertheless, a breed of new engineers applied themselves to improving the engine, and significant advances were made.[13] Foremost amongst these were John Smeaton and Richard Trevithick, Snr, and latterly James Watt.

The lode material brought to the surface (Plate II) still contained a considerable amount of the host rock, or 'gangue',[14] and had to be dressed before the ore was rendered fit for sale. Hunt concisely defined the problem facing the dresser when he wrote: 'The more finely divided the stuff to be treated, the greater the amount of labour and care does the stuff require, and the more imperfect the separation.'[15]

PLATE II

Dolcoath Copper Mine, Camborne.

(T Allom, 1831

Minerals of Cornwall & Devon, Embrey, P G and Symes, R F. (1987))

The first task was to segregate the lode material in size and composition by visual inspection. All material that was clearly ore was removed to one side; all that was obviously waste discarded. The remaining larger material was sent for 'ragging', a simple process of breaking it down into smaller pieces. This again would be picked over and waste thrown away. Middling sizes resulting from the initial examination and ragging were further reduced in size, a process known as 'spalling', and again picked over and segregated. The middling sizes resulting from spalling were further reduced in size by the process of 'cobbing', and the resultant material further picked over. At each stage the material was sifted in a 'griddle', equivalent to a sieve, with an approximately one inch iron wire mesh. If necessary the material would be washed. These processes were entirely manual, the majority of the labour supplied by women and girls.

In each of these processes a quantity of undersize material would result, much of which was copper ore. A point would be reached where further reduction in size followed by visual inspection would be, as Hunt wrote, uneconomic.[16] Instead, a process of hydraulic separation was resorted to. This employed an inclined wooden trunk, some 18 feet long by 3 feet wide and 18 inches high, known as a 'strake', or 'stêke' (Figure 2.3). Water was introduced at the upper end, and allowed to flow rapidly down its length. The undersized material was shovelled in at the upper end, tossed and turned in the flow. The denser material, the copper ore was deposited towards the top of the strake, whilst the lighter material flowed through to a slime pit at the lower end. The material would be deposited along the floor of the strake according to its weight and density, the heavier and denser at the top, or head, and the lighter components at the bottom, or tail. If all the material was of equal size then the distribution would be entirely due to specific density. With copper ore having the higher density the majority of the ore would lie towards the head of the strake, and the waste at the tail. Once again the material from the upper end was removed, and sorted manually. The middle section may also have been removed for further processing and only that at the tail rejected as waste.

The picked–over denser lode material was cobbed to remove further waste, it being reduced 'to the size of a chestnut and less', and was considered ready for sale. Again the waste was subjected to further processing. It was cobbed once again, without any sorting, 'to the size of small beans or peas'. This material was then subjected to a further process known as 'jigging'. In a vat of water a coarse sieve was immersed, held by a dresser whose task it was to agitate the sieve in the water. Another person placed a quantity of the cobbed lode material in the immersed sieve, the motion causing the material to settle in layers in the sieve, the lighter waste material in the top layer and the mineral components in the under layer. The material remaining in the sieve was segregated and removed for sale or rejection as waste. The sieve was placed back in the water and the process repeated. This process was repeated until the vat was deemed full, at which point in the process the contents of the vat were removed, and rejigged using a finer mesh sieve. The jigging process could be repeated using ever finer mesh sizes until deemed no longer economically viable.

Dressing of that batch of ore would then be considered complete. If the ore was known to be finely distributed it might be returned for further processing in a 'tye'. The tye was essentially identical to the strake but at a lower incline, combined with a slower water flow. Segregation occurred in the same way, the higher density material coming to rest at the top, and waste at the tail. Following the removal of the denser ore, it was more than likely dressing would be considered complete.

The preceding paragraphs describe a purely mechanical process. An alternative approach, although much less common was precipitation, a chemical procedure. This was employed in the Anglesey mines as a parallel process to mechanical separation. The water draining from the workings was highly acidic. As the water percolated through the bulk of the mountain and spoil heaps the mineralised copper deposits were dissolved. This chemically complex solution was drained into shallow tanks some 120 ft by 60 ft by 18 ins deep, in which had been thrown quantities of scrap iron. The acidic water dissolved the iron producing a sludge rich in copper sulphate and containing upwards of 40 per cent copper.[17] A contemporary example of the amount of copper that could be extracted by precipitation was '…one ton of iron bars immersed in the adit (of the Arklow mine in Ireland) in twelve months time produces one ton and nineteen hundred and a half weight of copper–mud, or dust; now, each ton weight of mud, when melted, produced sixteen hundred weight of the purest copper, selling at ten pounds *per* ton more than the copper made of the ore.'[18]

These methods would be reasonably typical of the process of dressing copper ore in the latter half of the eighteenth century. In all cases the basic principle that 'least is better' would always be applied.

METALLURGY

From its inception in South Wales the smelting of copper ores employed the coal fired reverberatory furnace to liberate the copper from the unwanted components which were bound and unbound in the ore. Only by employing this type of furnace could sufficient heat be generated to remove these components, especially arsenic and sulphur. Over time the smelting and refining of copper evolved to become standardised in a procedure known as 'The Welsh Process', particularly applicable to the sulphide ores commonly found in the copper mines of England and Wales.[19]

The Welsh Process of copper smelting comprised six discrete stages, each stage requiring one or more dedicated furnaces. These six stages are illustrated in figure 2.4. For optimum efficiency a mixture of ores was required. This was recognised from the earliest days of copper smelting . In 1585 Frosse, a German smelter, wrote from Neath to an agent, Richard Denham, in Cornwall: 'When you do send any more ore, if you can, send all sorts, the better it will melt and with more profit.'[20] A more precise example and typical of the practice in South Wales, although much later, of an ore mix was one comprising:

> Yellow Ore from Fowey Consols, Cornwall, mixed with copper and iron pyrites from Wheal Friendship, Devon, Cobre Ore from Cuba, comprising copper pyrites containing 28 per cent copper, Cobre Dust, also from Cuba, but only 12 per cent copper, cupriferous residues, a by–product of sulphuric acid production and deriving from Ireland, and known as Irish Ore, Vitreous Copper mixed with iron pyrites and hematite found in the Levant Mine, Cornwall, residues rich in iron oxide derived from the smelting of cupriferous Cornish tin ores, and finally a proportion of red oxide of copper combined with blue and green carbonate from Burra–Burra, Australia.[21]

THE SIX STAGES OF COPPER SMELTING[22]

STAGE 1: Referred to as calcination, the first stage was essentially a roasting of the ore to drive off the sulphur and other impurities trapped in the ores. A typical charge consisted of 3 to 3.5 tons of ore. Temperature was raised slowly to not more than 800°C, and the ore stirred at intervals, thus ensuring all ore was evenly exposed to the heat, and did not bind. The temperature reached was sufficient to vaporise the sulphide and sulphate components, and other contaminating agents, without melting the copper components. This process could take from 12 to 24 hours depending on the composition of the ore. On completion the calcined ore was deposited into chambers below the furnace, where it was quenched with water.

STAGE 2: Following calcination, the ore was melted in the Ore Furnace, using slag produced at stage 4 as a flux. Any openings through which the ore was introduced were sealed, and the furnace brought up to a temperature of 1150°C, sufficient to melt the mixture. This took about 5 hours. Following a thorough raking, the slag was skimmed off. A second charge was added of a similar mix and the process repeated. Recharging and skimming continued until the furnace bed was filled with molten regulus, containing approximately 35 per cent copper. At this point, the furnace was tapped, and the molten regulus, or coarse–metal, allowed to drain into a stream of water, causing it to granulate. The slag was disposed of as waste.

STAGE 3: The granulated regulus underwent a further 24 hours of calcination, being regularly stirred, and open to the air. The temperature was slowly elevated throughout the period. This second calcination reduced the sulphur content from approximately 30 per cent to 15 per cent, for a typical charge of 2 tons.

STAGE 4: The output from the third stage was mixed with ores containing carbonates and oxides of copper, and slags from stages 5 and 6. This mixture was converted to a molten mass in the metal furnace as the temperature was raised, the slag being skimmed off, and retained for mixing at stage 2. The product, containing 75 per cent copper, was drawn off into sand moulds, and allowed to cool. The bulk of the balance was sulphur, plus a small residue of iron. The furnace charge was typically 2.5 tons, and the temperature reached approximately 1200°C. The output was known as white metal.

STAGE 5: The cast pigs were placed in the roasting furnace, and brought once again to a molten state, but in this case in the presence of air freely admitted, with the aim of driving off any remaining sulphur in the form of sulphur dioxide. The temperature was slowly raised over a period of 8 hours. On first reaching a molten state, and having been stirred, the floating slag was once again drawn off. A cycle of heating and cooling followed, during which sulphur dioxide was emitted, and drawn off through the flue. Just prior to tapping, the mixture was again skimmed. This slag was used as a flux in stage 4. The copper, now approaching a purity of 95 per cent was drawn off into sand moulds. The resulting material was known as blister copper, so called from its surface appearance.

STAGE 6: This final phase of refining resulted in marketable copper and refinery slag. The furnace was loaded with 6 to 8 tons of blister copper pigs, and brought to a molten state, maintained for between 15 and 24 hours. Air was allowed to enter freely to aid oxidation. Slag was drawn off. The molten metal was sampled, and depending on the nature of the fracture, the refiner determined when the metal had reached the state of refined, or dry copper. At this point anthracite, or similar free burning coal was thrown onto the surface, and a 'thick pole of green birch or oak wood' inserted in the molten mass. The action of the wood and coal caused the molten metal to be violently perturbed, and gaseous components to be liberated, the product achieving the state of toughpitch or cake copper. When deemed of marketable quality, the copper was ladled out into moulds. Alternatively it could be ladled into baths of cold water to form feathered shot.

This Welsh Process evolved during the eighteenth century, and was subject to only minor modification in the later years of the industry's life. The one improvement introduced, and shown in the flow chart, was the use of the Fine Metal Furnace, employed when oxide ores were not available at stage 4, or earlier oxidation was incomplete. In this case the output, known as blue copper, underwent a further process very similar to that undergone at stage 4.

Large quantities of slag resulted from the smelting and refining process, some of which, known as 'scoria' was converted into building blocks, readily identified by their black vitreous surface. The greater problem was the waste flue gases, particularly sulphur dioxide, which in the presence of rain was converted into sulphuric acid, an early instance of 'acid rain'.

Having established that within the larger copper industry there was, for a number of reasons, two subindustries it is appropriate to examine these in detail. It is self–evident there was a high degree of interdependency between the two, yet it will be shown as a result of its organisation the smelting industry achieved the dominant position. Furthermore, the simplicity implied in this division belies the complex interaction between mines, smelters and other agencies, as witnessed by the evolving pattern of monopoly and collusion resulting from changing economic and political conditions experienced over the years between 1760 and 1820. In the next chapter the evolution of the mining industry will be traced.

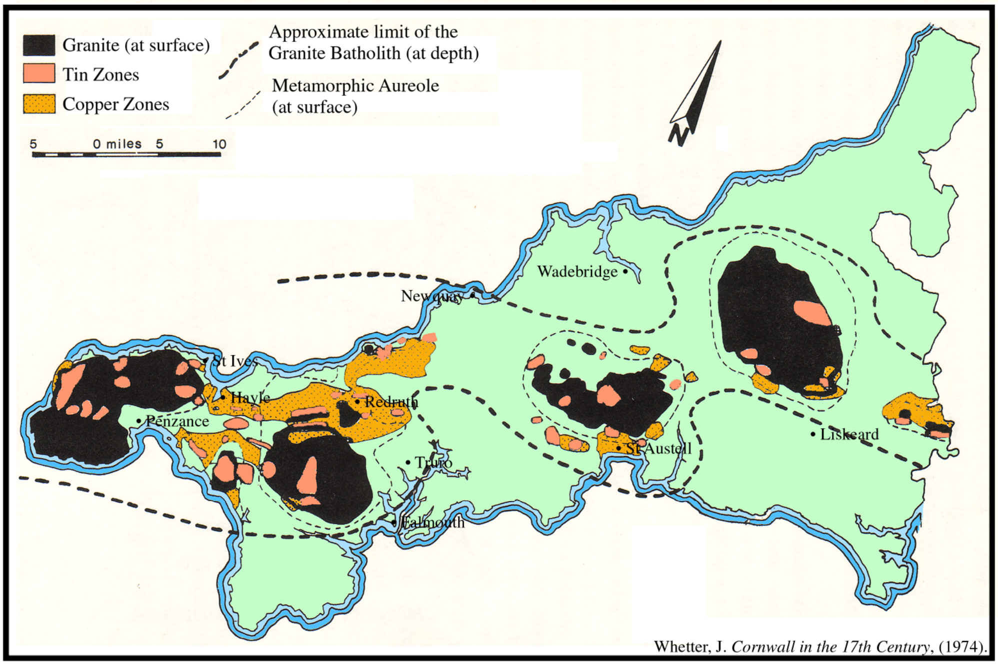


Figure 2.1. Mineral Distribution in Cornwall

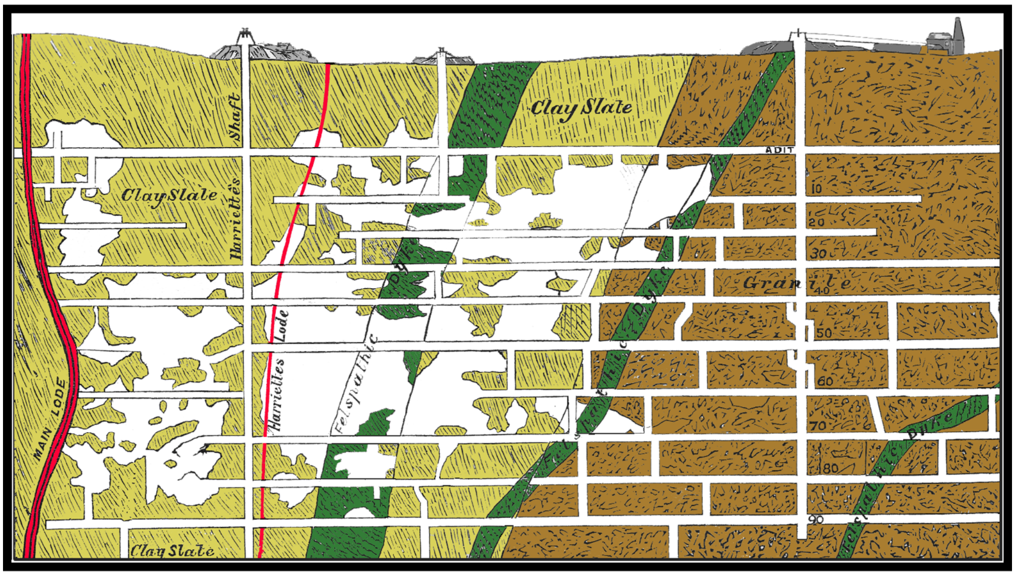
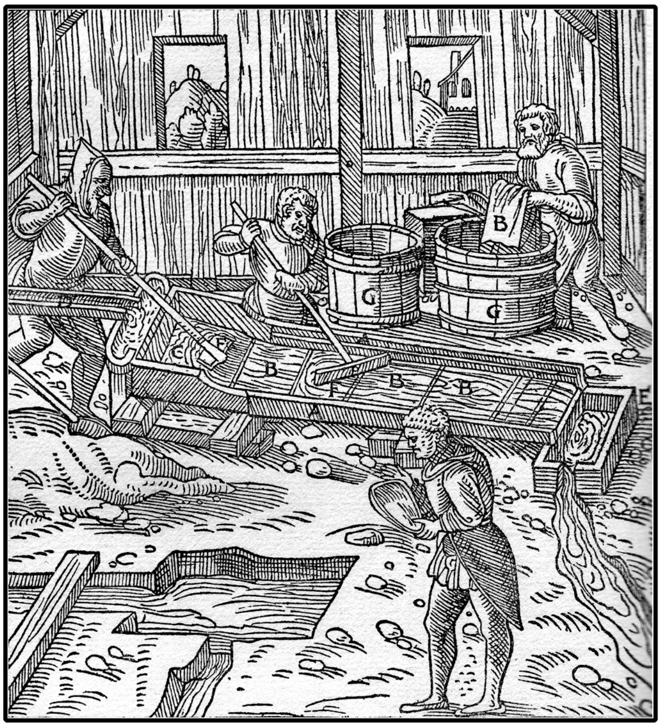


Figure 2.2: A Section of the workings on the Counter Lode at Dolcoath, circa 1800.
(Davies, D C. *Metalliferous Minerals and Mining*, 1888)



A – Beams B – Canvas C – Head of Strake D – Small Launder
E – Settling Pit or Tank F – Wooden Scrubber G – Tubs

Figure 2.3. A Strake.
Agricola, G. *de re Metallica,* (1551, Trans.: Hoover, H C and L H; 1912), 308)

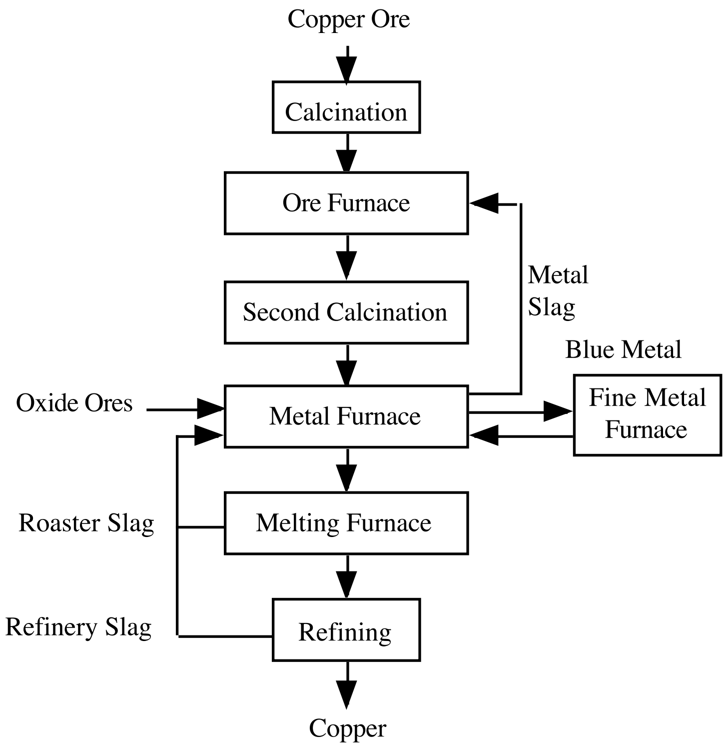


Figure 2.4: The Welsh Process of Smelting.

Notes

[1] Donald, M B. *Elizabethan Copper*, (Michael Moon, Whitehaven; 1989), 301.
[2] Rowlands, J. (1966), 20.
[3] Jenkin, A K H. (1927), 173.Michell, F. *Annals of an Ancient Cornish Town – Redruth*, (Frank Michell, Redruth, 1978), 39. For a more detailed account of the roads of Cornwall see Jenkin, A K H. *Cornwall and the Cornish*, (J M Dent & Sons Ltd, London; 1933) 21 – 37. This contrasts with the rest of England which experienced a significant increase in road transport in the eighteenth century with the growth in the network of turnpikes and the emergence of the stage coach. Chartres J A and Turnbull G L, 'Road Transport" in Aldcroft, D and Freeman, M. (eds). *Transport in the Industrial Revolution*, (University Press, Manchester; 1983). Briggs, A. *A Social History of England*, (Penguin Books Ltd, Harmondsworth; 1985), 207.
[4] The geology of Cornwall has been widely investigated over a considerable period of time. The following are a sample: de la Beche, H. *Report on the Geology of Cornwall, Devon and West Somerset*, (HMSO, London; 1839). Dines, H G. *The Metalliferous Mining Region of the South West*, (HMSO, London; 1956). Barton, R M. *An Introduction to the Geology of Cornwall*, (Truro Bookshop, Truro; 1964). Selwood, E B, Durrance, E M and Bristow, C M. *The Geology of Cornwall*, (Exeter University Press, Exeter; 1998).
[5] Dines, H G. (1956), 22.
[6] Barrett, T J., Tennant, S C and MacLean, W H. *Geology and Mineralization of the Parys Mountain Polymetallic Deposit, Wales, United Kingdom*, (Unpublished Report for Anglesey Mining plc; 1999), <www.oresystems.com/global/geominparys.html> [30 Jul 02]. Jenkins, D A. *Geology of Parys Mountain*,(Research Papers, Anglesey Mining plc; 21 April 1998) <www.copperkingdom.fsnet.co.uk/geology.htm> [30 Jul 02].
[7] Earl, B. (1968). Burt, R. (1982).
[8] Pryce, W. (1778), 145 – 50. Burt, R. *A Short History of British Metal Mining Technology*, (de Archæologische Pers, Nederland; 1982), 60 – 69.
[9] Barton, D B. (1961), 12 – 13. Day, J. (1973), 50 – 51. Hamilton, H. (1967), 146.
[10] For the history of the steam engine in Cornwall see Barton, D B. *The Cornish Beam Engine*, (D Bradford Barton, Truro; 1965). For a contemporary description of the steam engine's development see Pole, W. (1844) and Farey, J. (1827)
[11] Rolt, L T C, (1968), 122.
[12] Duty on coal consumed in draining the mines was remitted following the passing of the Supply Act of 1741. Brown, B. 'The Duty on Coal 1698 – 1831', *Journal of the Trevithick Society*, 26, (1999), 32.
[13] Rolt, L T C, (1968), 142.
[14] Pryce, W. (1778), 233 – 46. Hunt, R. (ed). *Ure's Dictionary of Arts, Manufacturers and Mines*, vol 2, 6th ed., (Longmans, Green & Co, London; 1867), 62 – 120. Burt, R. *A Short History of British Ore Preparation Techniques in the Eighteenth and Nineteenth Centuries*, (de Archæologische Pers, Eindhoven, Nederland; 1982).
[15] Hunt, R. (1887), 710.
[16] Hunt, R. (ed). (1867), vol 2, 65.
[17] Rowland, J. (1966), 45.
[18] Borlase, W. (1752), 207.
[19] Percy, J. (1861), 314. Newell, E. (1988), 11 – 15.
[20] Ulricke Frosse to Robert Denham, 4 July 1585.
[21] Percy, J. (1861), 322.
[22] Percy, J. (1861), 322 – 326.