

Tomnadashan—A re-examination of a 19th century copper mining and smelting operation in Perthshire, Scotland

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Abstract: This article presents an account of the efforts made by the 5th Earl of Breadalbane to develop a copper mining property during the mid-19th century on his Perthshire estate. During the twenty years from 1840, pyritic and copper-bearing ores of varying grade were produced. Following this period, limited amounts of sulphuric acid, phosphate fertilizer and copper matte were produced, but despite the high calibre of the consultants hired by the Earl, the operation made a heavy financial loss. Analysis of slag remaining by the shore of Loch Tay has permitted a description of the metallurgical process used, while by matching the information from the Breadalbane archives to the visible remains of the plant, the author offers an interpretation of the mining and manufacturing site as it exists today.

Introduction

In 1971 *Historical Metallurgy* published an article by John W Bainbridge describing copper-smelting operations at Tomnadashan, a small copper mine on the south shore of Loch Tay, which was owned by the Earl of Breadalbane in the middle of the 19th century (Bainbridge 1971, 12-14). This article followed his general discussion published in 1970 of the Tomnadashan enterprise in *Industrial Archaeology* (Bainbridge 1970, 60-74). Later, writing in the *Scots Magazine*, Bainbridge gave descriptions of both the mining and smelting operations and also of a sulphuric acid plant operated at the site (Bainbridge 1980, 38-45). Bainbridge's chief source materials were the Breadalbane Muniments, estate archives stored at the National Archives of Scotland, Edinburgh. However, when he was writing, these archives had not been fully indexed and were stored in a large number of boxes, thereby limiting their accessibility to the researcher. Today the muniments have been fully indexed and a more thorough perusal of them has been possible, and as a result of this the present author has prepared an updated account of the Tomnadashan operation. In particular, it is intended to show that the archaeological

remains of the operation which can be seen in the field, while slight, are considerably greater than previously believed; as well as remains of the copper smelting furnace, extensive traces of the flue systems in both the copper smelting and acid manufacturing circuits have been found.

Mining

Background 1825-41

In July 1825, a number of influential landowners established the Scottish National Mining Company, with a view to developing the natural resources of the Highlands (1/4/7—see List of Sources). Among those who attended the meeting were the fourth Earl (later 1st Marquis) of Breadalbane. He was accompanied by his son John Campbell, Lord Glenorchy. It was from this meeting that Glenorchy's interest in the minerals on his estates can be traced. In 1834 Glenorchy, then 38, succeeded to the Earldom (and Marquisate) on the death of his father.

The Tomnadashan deposit is located midway along the south bank of Loch Tay, Perthshire, in the central

Highlands of Scotland, (Fig 1). The former mine site is located approximately midway between the hamlets of Ardeonaig and Ardtalnaig, 800m NE of Wester Tullich farm at NGR: NN 692378. A small stream flows approximately W into Loch Tay from the N part of the mine site (Figs 2 and 4); the associated lochside plant site is found near where this burn enters Loch Tay, c NGR: NN 688380.

It seems that Breadalbane was aware of the existence of a deposit of pyrites at Tomnadashan from an early stage, for by June 1838 he had been in touch with Prof Thomas Thomson at Glasgow, who had outlined to him the method for extraction of sulphur from pyrites by heating in a restricted supply of air. Thomson had described the process as virtually obsolete, owing to the cheapness and availability of sulphur from Sicily, and pointed out that large quantities of pyrites were being put ashore at the mouth of the Thames or used as ballast for shipping (1/3/12).

However in that same year, the King of Sicily granted a monopoly of sulphur production to a French company,



Figure 1: Location map

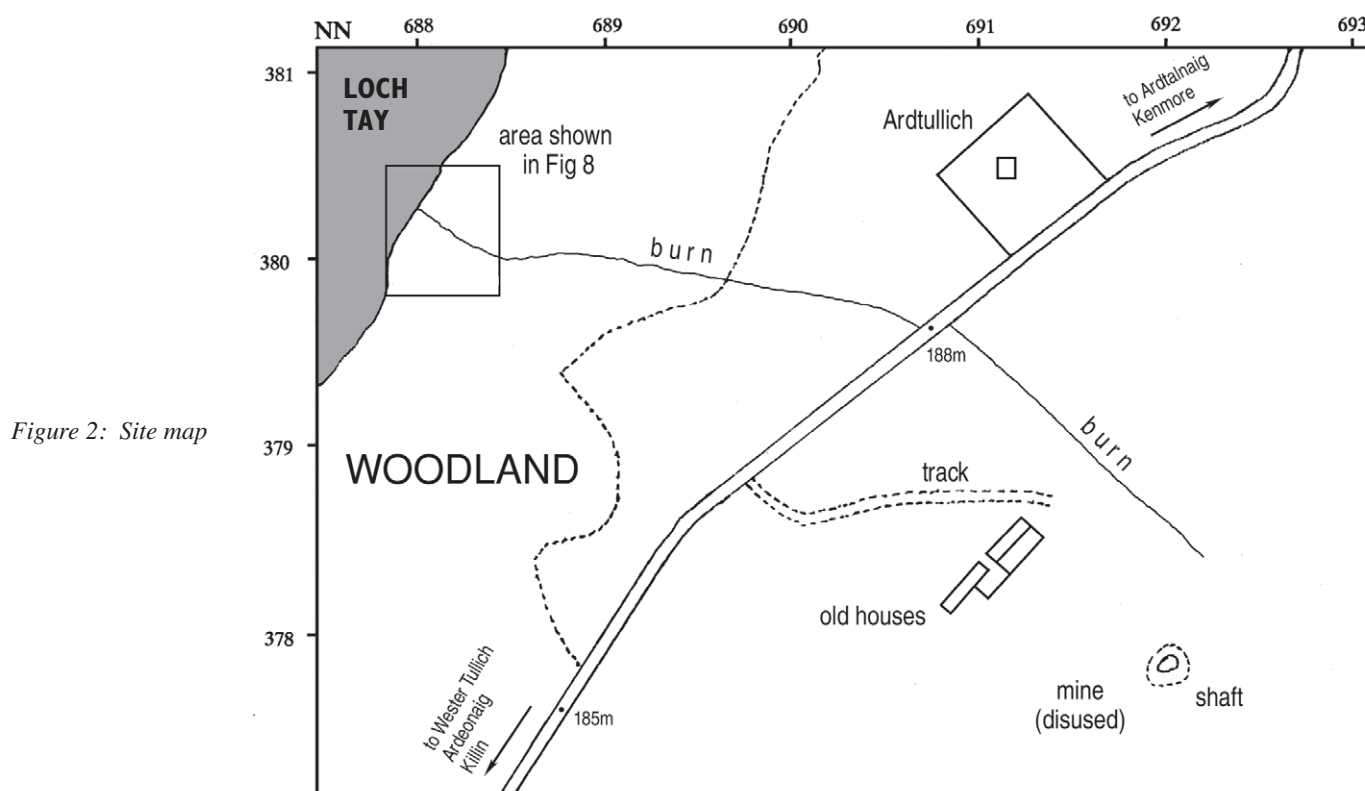
Faux-Aycard, who used their position to force the price upwards. From a previous price of £5 per ton, by 1839 the cost of sulphur was £12 per ton and rising, and United Kingdom manufacturers began to return to the idea of using pyrites as a source of sulphur (1/8/15; Bainbridge 1980, 43). By September 1838 Breadalbane clearly envisaged mining his pyrite deposit with a view to making 'sulphuric or vitriol' (1/7/1).

At the same time, the Earl had taken on as consultant a German geologist, F Odernheimer to prospect the deposit. Odernheimer identified chalcopyrite, iron pyrites and grey (As- and Sb- bearing) copper ores but said that 'no vein has been opened worth marking at this particular place' (4/1/25, October 1840). In 1841 Odernheimer published a description of the Tomnadashan deposit as well as the lead-bearing properties at Corriebuie, situated in the hills to the S, and at Tyndrum in Strath Fillan, 40km to the W (Odernheimer 1841, 541-56). Odernheimer's report was sufficiently optimistic to recommend to the Earl that mine development should continue on a trial basis but both the German and Lewis B Gordon, a consultant from Glasgow, advised Lord Breadalbane not to purchase any equipment for ore treatment until the future of the mine was 'assured' and the best use of the ore could be determined (4/1/66). It was also pointed out that simply to concentrate the ore to the grade required by the smelters in England or South Wales (8%Cu) would not be economic and Odernheimer indicated that dressing or smelting on site should eventually be considered, (4/2/1-3).

Trials 1841-58

In early 1841 an adit level was driven into the hillside. A group of four miners was recruited from Devon and Cornwall (4/2/1) and development of the level was continued S, splitting into SE and SW passages after 48 feet (14m) (1/9/15). Some 50m to the S of the entrance an open pit was excavated. By 1843 the SE branch had been extended underneath the open working, and a vertical shaft sunk which gave a connection between the open working and the level below (Fig 3). The vertical shaft was referred to on the plan as the 'sumpt'.

All these developments were regarded at the time as 'trials' and it was hoped to locate a vein of rich mineralization. The mine foreman, a taciturn man named Roberts, claimed he could do this on his own account but his offer was not taken up. Varying sized grains of yellow copper (chalcopyrite), grey copper, arsenopyrites



and mundic (iron pyrites) were found, while porphyritic greenstone with occasional felspar and quartz were the main gangue minerals (1/9/23, 24; March-April 1842).

During the succeeding years, the mine workings were extended to the E of the open pit. Production was intermittent; foremen Ewen MacGregor and Griffiths Roberts declared an output of 1½ tons of good copper ore per fortnight (4/2/16), and by the summer of 1846 70 tons of 'rich' ore had been won.

Early in 1846 the mine manager, Daniel Dewar, reported to the estate factor J F Wyllie that 14 men were employed at the mine, plus two boys 'breaking stones and sorting ore' (4/2/23). It would appear that the Cornishmen had left by this time, for at the end of May the men were given leave to cut peat, so presumably they were local (4/2/34, 30.5.46). By the end of 1847 there were 12 men 'blasting and wheeling' (4/2/41).

By the early 1850s it would have been obvious to all concerned that, as Odernheimer had reported, no rich vein existed and the distribution of the valuable minerals was very irregular. In 1850 the total money spent at the 'Ardtalnaig Mineral Trials' was £4,267 (4/1/46). Three years later the first delivery of high-grade copper ore was made to Swansea, South Wales. 71 tons of ore earned the estate £181 (1/3/29; Bainbridge 1970, 69),

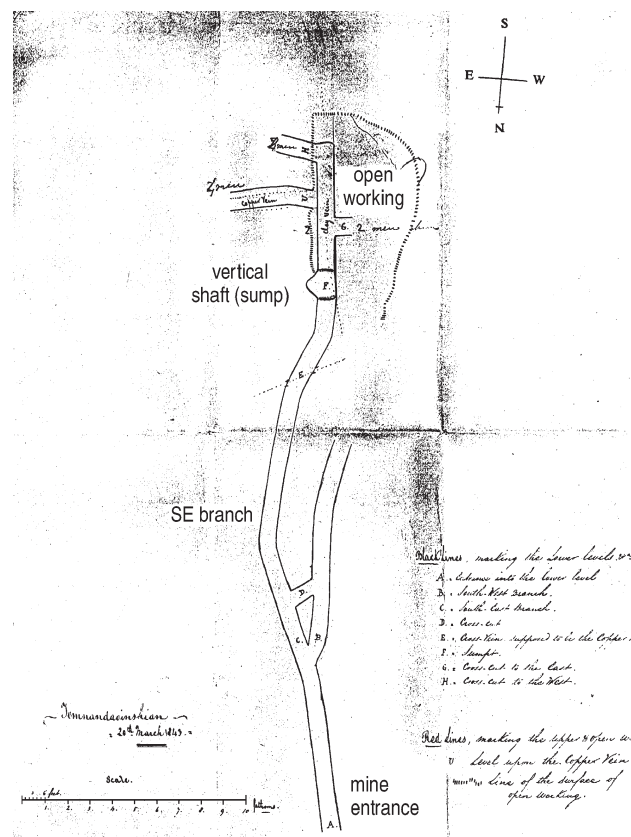


Figure 3: Tomnadashan underground mine as developed to 1843, plan reference GD/112/18/4/1/74, reproduced with permission of the Keeper of Records of Scotland.

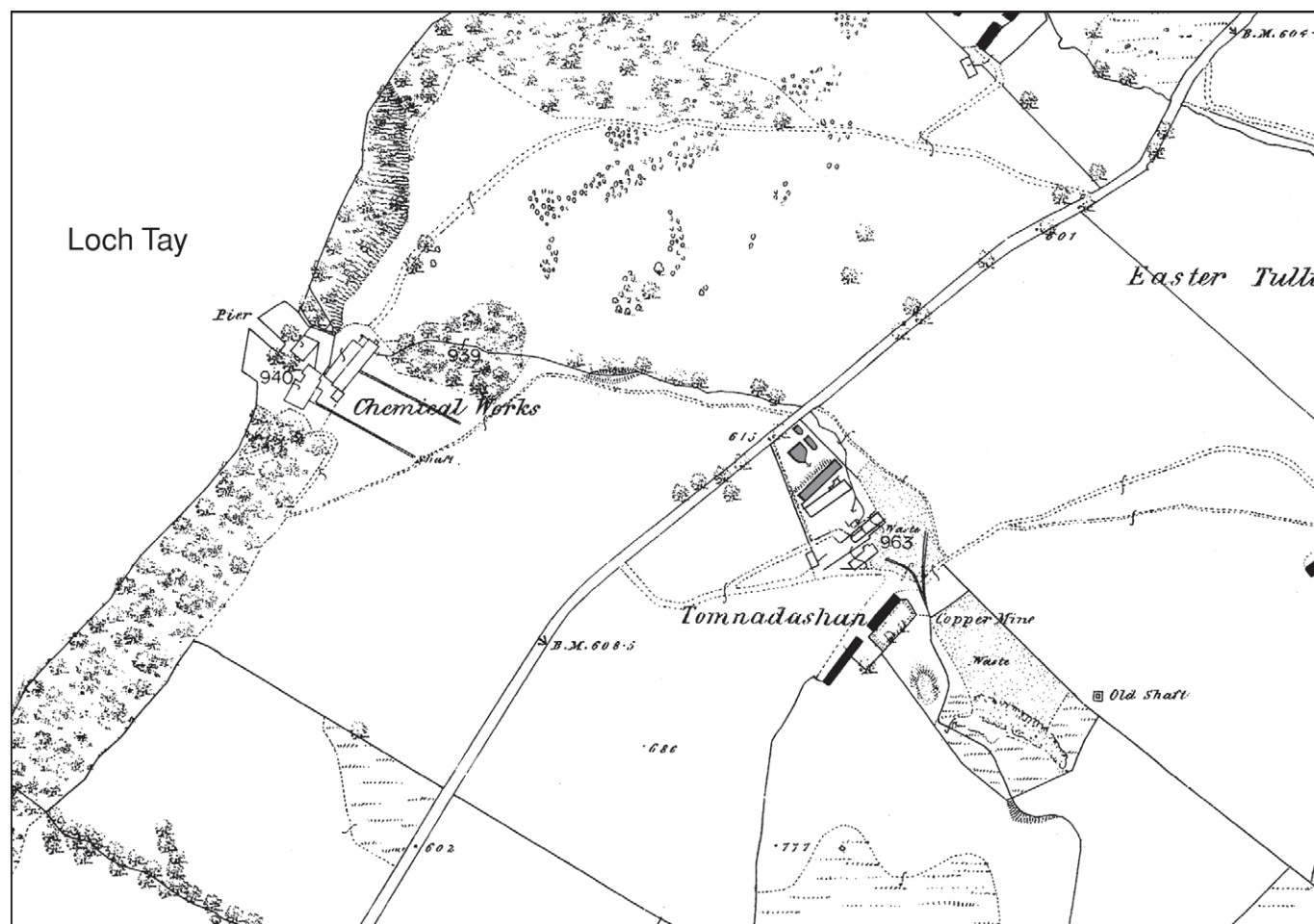


Figure 4: Extract from 1861 1:2500 OS Map of Perthshire, Sheet LXIX.7 Courtesy of Map Library, National Library of Scotland, Edinburgh

£82 having been deducted for transport costs.

Aware that only ores containing over 8%Cu would be directly saleable, and of the effect of his remote location on transport costs, Breadalbane attempted to use his copper and pyrite minerals on the spot. He also placed an advertisement to lease or sell the property, but without success (4/5/15, 5.7.58).

During these years, ore continued to be extracted at the mine. Work was on a smaller scale than before; the foreman, now Benjamin Gribble, reported three men working underground plus one man and a boy dressing ore from the 'stamps' (crushers) (4/3/18). Production was seasonal with waggoning and picking stopping for winter (4/5/38). However, an extensive underground network was developed and by November 1858, 200 tons of dressed ore had been stockpiled over the previous two years. Early the following year, the decision was taken by the then manager, Gustav Thost, and Gribble, to treat the orebody by open working, and not 'work the mine as if we were working on a vein' (4/6/1, 25 Jan 1859).

Fieldwork

A plan of the mine drawn in 1843 is shown in Figure 3, referred to above. The mine is approached from the unclassified South Loch Tay road through a gate 760m NE of Wester Tullich farm. After ascending the track and approaching the top of the path, one finds a small burn which has recently been diverted to prevent further erosion. Facing the visitor and to the left are two short courses of drystone terracing, one above the other. Just to the right of these terraces the burn emerges from a pile of loose stones, and from the 1843 plan this would appear to be the collapsed entrance to the mine. To the right above the entrance lie the ruins of a row of stone cottages. These stone cottages are shown in the 1861 Ordnance Survey 1:2500 map, Perthshire sheet LXIX.7 (Fig 4), where they are marked with a black fill. It is believed that these are the cottages described as the 'old houses' by the factor, J F Wyllie in a letter to Breadalbane's lawyer, Lawrence Davidson, dated 3 June 1858, and in the author's opinion they probably predate the mine.

Approx 50m SE of this point one encounters the open working, with the sump sunk to connect the open working with the original level (Fig 5), although the sump is now choked with broken rock. Looking NW across the open working towards Loch Tay, the sump is a prominent feature in the middle distance. A patch of reeds can be seen on the left, which indicates the position of the small burn, and the burn's exit, already described, gives the evidence of the basic structure of the mine (4/1/74, 75). The cavity whose mouth can be seen on the right, as well as the open chimney (not shown in the photograph), would appear to have been created in the wake of Thost and Gribble's decision to treat the orebody by open working, quoted above (4/6/1).

Jefferis' Acid Plant

Operations 1857-58

The Marquis had an interest in the sulphur content of the deposits from the outset, and the manufacture of vitriol from pyrites was specifically referred to in the conditions of service offered to Odernheimer in September 1838 (1/7/1). There was no demand for sulphuric acid on the estate, but it was intended to react the acid with crushed animal bones to produce superphosphate, a valuable fertilizer (Derry & Williams 1993, 553).

Sulphuric acid was made at that time by the chamber process, in which elemental or pyritic sulphur was burnt in a chamber in the presence of sodium nitrate, which supplied oxygen and catalyzed the oxidation of SO_2 to the trioxide. The combustion products were then led into the lead-lined chamber, which had several inches of water on the floor and which absorbed the incoming gases to give dilute sulphuric acid. The acid was then



Figure 5: Looking across the open working to the north-west. The vertical shaft in the middle distance originally connected the openworking with the entrance adit (see Fig 3).

evaporated in a separate steamer to the required concentration. In 1854 the cost of an acid chamber, associated buildings and plant and working capital, was estimated at £6,500 (4/3/10-12; 25.7.54; Derry & Williams 1993, 534-6).

By the autumn of 1857 construction of an acid plant was proceeding under the management of a young chemist, James Jefferis (4/3/28, 10.10.57; 4/5/10). The plant followed the general lines described above with a 25ft chamber, but between the combustion furnace and the chamber he included a number of 12ft-high columns, for the purpose, he later explained, of condensing arsenic and nitrous gases. A long horizontal flue passed from the back part of the chamber underneath it (A Adriani, 4/4/14).

To judge by Jefferis' accounts, things went fairly well to begin with. On 5 December he reported that the acid plant was 'working extremely well' (4/3/33), but soon doubts began to creep in. A week later he reported only that acid production was progressing 'as well as might be expected with the present apparatus' (4/3/38, 14.12.57) and at the end of the month he said he would need two new chambers and an extra furnace to operate profitably (4/3/39, 26.12.57).

Jefferis' statement exemplified a growing realization that the Tomnadashan operation was losing money heavily. The financial details have been explained by Bainbridge (1970, 68-69), although in addition to the 1853 delivery of copper ore to South Wales, another shipment of lead and copper ores from Tyndrum and Lochtayside was sent to Liverpool in 1856. This had a combined value of £1,082, although how much came from the Tyndrum lead mines is not known (1/3/29). The factor, Wyllie, said that the mining operation had in effect been run on an experimental basis, and that while the aim of the estate was to 'turn the products (of the mine) to some profitable use by a cheap process', the general result was 'a great loss' (4/1/60).

Meanwhile, Jefferis' plant was continuing to produce sulphuric acid, but much of the product was too dilute (10-15%) for the manufacture of fertilizer (4/5/1, 3). By February 1858 Breadalbane was having doubts about the manager's competence and he invited an experienced Dutch chemist, Dr A Adriani, to examine the operation (4/5/6, 7; 4.2.58). Four months later Adriani submitted his report. He strongly criticized both the design and operation of Jefferis' plant—the vertical columns were unnecessary and counter productive, starving the furnace of air; the horizontal flue under the chamber prevented

adequate draught; the site on a hill slope was most unsuitable; and several other points were made (4/4/14). Against these criticisms Jefferis defended himself as best he could. He claimed that the draught was adequate, except in calm weather, and the columns would allow separation of nitrous gas from chamber acid (4/5/28). Throughout the period, acid production continued and some gypsum and phosphate were produced (4/4/14), while a request was made for 50 tons of superphosphate 'manure' which would 'tie up acid production till May' (4/5/25). Whether the demand for fertilizer was ever met is not recorded, but by the end of June the chamber was full. Wyllie would not authorize any more carboys, and production was stopped (4/5/37, Jefferis 20.8.58).

By the time the acid plant was closed, morale at Tomnadashan was very low. As far back as 1851 Odernheimer had observed that 'the trials at Tomnadashan have not yet yielded a regular ore field' (4/1/44) and it was known that any sulphuric acid produced at the site could not bear the cost of its own transport (1/3/44). 'I have been in hopes year after year that (Lord Breadalbane) would give (the mines) up in part or in whole', wrote Wyllie in February 1858, '... up to this time they have been a very losing concern' (4/5/13). When in July the Earl offered the property to be let, Wyllie's relief was clearly shown: '... if the mines can be let for anything, however little... it is better to do so than continuing to work them ourselves at an annual loss of £2-3,000'. But no prospective tenant came forward, and the Earl reverted to his earlier policy of making manufactured products at the mine.

Fieldwork

The question arises whether any trace of Jefferis' plant is visible. One of Adriani's criticisms was that Jefferis did not use any drawings or plans in the construction of the acid plant, and no other estate drawings have come down to us. However the 1861 Ordnance Survey 1:2500 map, Sheet LXIX.7 already referred to (Fig 4) is available, and some information can be gleaned from the records. Adriani described the acid chambers as being 'on the slope of a hill on which the work at Tomnadashan stands' (4/4/14) and Wyllie wrote that the plant could only be extended by moving '30ft higher up beside the old houses' (4/5/32), (see Mining Fieldwork section above). A number of buildings are shown at the foot of the mine site, and these are tentatively identified as representing the 1857-58 acid plant, and are marked in grey on Figure 4. A modern view of the area is shown in Figure 6. This shows a parallel pattern of ridges on the ground below the mine.



Figure 6: Looking down from the mine site across Loch Tay, showing probable traces of Jefferis' acid plant. By comparison with Fig 4, the features on the ground running parallel with the road probably indicate the position of Jefferis' plant.

These features accord with those observed on the 1861 map, which are therefore provisionally ascribed as being the site of Jefferis' acid plant.

The two-tier copper roasting and smelting furnace

By March 1859, 200 tons of crushed and washed copper ore were stored on the floor of the site (4/1/38). Acting on the advice of the Parisian consultant Prof Frederic Weil, the Earl chose to upgrade the ore by roasting and smelting. Weil had also suggested roasting and leaching or alternatively chloridization, but the latter would have meant royalty payments to the holders of the patents and was not followed up (4/6/2,3, 26.3.59).

Before the advent of the Pierce-Smith converter, the conversion of matte to metallic copper was carried out by successive stages of roasting and smelting in which the copper content was gradually increased. This treatment reached its greatest success in the form known as the Welsh process, which led to South Wales becoming the world centre for copper metallurgy, although by this time it was beginning to lose its pre-eminence (Hopkins 1970, 6-8). Breadalbane's primary aim was to smelt to a saleable regulus (matte).

Breadalbane chose to build a double furnace, in which the roasting hearth is built directly over the smelting floor. Weil had recommended separate roasting and smelting furnaces, on the grounds that to operate the same furnace with different temperatures and conditions would require highly skilled and experienced operators

(4/1/40, 16.4.59). Thost, however, recommended a combined furnace as this would economize on fuel. Coal was extremely expensive on Loch Tay, £1 10s 0d per ton compared with 5s 0d in South Wales (Bainbridge 1971, 12).

A spot close to the shore of the loch, just to the NE of the small burn which flows from the mine site, was selected for the smelter. From the late summer of 1859 the ground was prepared, and three tiers of terracing and a wooden pier were constructed. Following continental practice, Thost built the furnace of brick with an outer cladding of stone. Much material—brick, building stone, bar iron and wood—were salvaged from the former acid plant but firebricks and a mason were brought up from Swansea (4/6/7).

During the winter, furnace construction was delayed for several weeks by a collapse of the first arch, (4/7/3, 2.2.60). More men were brought from Swansea and in April Gribble reported that the furnace was ‘drying well, with no sign of a crack of any kind’ (4/7/6; 4/7/10).

A cross-sectional drawing of the furnace by Thost was published by Bainbridge (1971, 13). According to Thost’s description, the first arch was levelled by a bed of clay followed by two horizontal courses of bricks, each 3in. deep, which formed the sole of the upper or calcining hearth (4/7/1, 3.1.60). The flue was built of stone with a brick lining (4/6/12). A special arrangement of horizontal and vertical chimneys was built, recommended by Weil to ensure a suitable draught, and the furnace had a quartz bottom (4/1/32, 4/7/15).

To convey the ore from the mine to the smelter, Thost proposed a series of cast iron troughs (4/6/7, 1.8.59). Presumably these were operated by hosing down; in January he reported that ‘the troughs have been tried and set agoing. One of the gathering ponds has been nearly filled at the end of the week’ (4/7/2). A hopper charging from the E is shown on Thost’s drawing; it must have been of strong construction, for by March it held 85 tons of ore (4/7/8). Another component of the charging system was referred to by Thost as the ‘railway line to combine the hoppers with the top of the furnace’ (4/7/2).

The furnace campaign began on 28 April 1860 using low-grade ore to begin with, later using four charges of 1.1 tons of ore plus 2.9 tons of coal per day. Starting with poor ore, the charge was increased to 20% stamped, 80% dressed ore and after a week two tons of matte had been produced (4/7/15). Thost sought to upgrade the regulus by partial conversion, using calcination and

remelting (4/7/16). This was done by means of an ‘open calciner’, a frame in which the broken matte was placed, mixed with some pieces of ore and fuel, and burnt. Calcination was said to take four weeks (4/7/18).

After trying various mixtures, Gribble gave as the best feed blend a mixture of:

16cwt (800kg) dressed ore
10cwt (500kg) burnt ore from the vitriol works
2cwt (100kg) calcined regulus.

A little lime was also used (4/7/24, 2.6.60). Thost was clear that the formation of FeO was necessary to form the base for a slag. At the end of May he reported that better calcining was giving rise to a more fluid slag. On 28 June Thost described an operation in which all doors of the furnace and calciner were closed and the main flue closed by a damper. This would maximize the flow and retention of heat from the smelting compartment in the calciner. After three to four hours the damper was withdrawn from the main flue and the calcine smelted. A large quantity of excellent slag was skimmed, and the regulus was diminished in bulk. Thost observed that ‘ore better calcined melts far more readily than otherwise’ (4/7/28).

It is clear that the higher temperature of calcination would lead to greater sulphur removal from the pyrites, while restricting the air flow would tend to maintain iron oxides in the ferrous state. This would give rise to a greater quantity of fluid slag, together with a correspondingly smaller quantity of higher grade matte.

By mid July the firebridge and part of the furnace arch needed repair. The furnace was shut down, taking a week to cool. The smelter operators left to visit their families. The total results of the 12-week campaign were as follows:

Charge	Quantity (tons)
dressed ore	184.7
undressed ore and burnt cinder	125.7
calcined regulus	2.45
lime	15.0
total:	327.85
Coal	179.25

The smelter feed assayed $7/8\%$ copper, and 85 tons 1cwt (50kg) regulus was produced containing $31/2\%$ copper (4/7/30,31).

Operations under Napier

In May 1860 a proposal for a new acid plant, this time by the side of Loch Tay, was made by Thost (4/7/16,18). The Marquis then commissioned a report from James Napier, one of the leading metallurgists in the country. Napier offered a plant design based on a raw material with a sulphur content of 26%. In July Napier was appointed to the position of 'Superintendent and Manager of the intended Chemical Works at Lochtayside' (4/7/32).

In his report, Napier proposed three pyrites furnaces, a lead chamber 100ft long, a small boiler to supply steam to the chamber, and one evaporating lead pan. The chambers were to be erected on pillars of brick or trap (a compact fine grained igneous rock). Napier's estimate also included provision for a wooden framework, pipes, flues and tools. Despite construction being delayed by the remoteness of the site and by frequent rain, early in November Napier was able to report that 'with the return of good weather and (the arrival of) additional men, the chamber was progressing much more rapidly, with the sides up and work on the ceiling beginning' (4/7/44).

The chamber began operating on 17 December and ran for eight days before the run was stopped by frost. 7.9 tons pyrite ore were burned producing an estimated 1.7 tons of acid (4/8/7). Breadalbane then expressed the view that the acid-manufacturing operation should be conducted using as low a percentage of sulphur as possible, to save the work and expense of concentration and to use more ore. The Earl criticized such things as Napier's choice of burners, and he then appointed Gribble to 'watch over' the other managers and advise him accordingly. This effectively promoted Gribble over Napier himself. In spite of an offer of a job with James 'Paraffin' Young, the oil-shale pioneer, Napier stayed on, but the resulting acrimony was only brought to an end when the Earl promised to transfer Gribble to Tyndrum (4/8/6, 11). Acid production resumed on 24 January 1861, in Napier's words 'knowing what was going in and coming out', (4/8/7).

From then until the end of February, 57.5 tons of ore were burnt, along with a ton of sodium nitrate. The ore contained an average of 13.5% sulphur (*cf* 37% at Avoca, Wicklow and 42% at Wheal Jane), and 13.8 tons of acid were produced, (4/8/7, 1.3.61). After burning, the pyrite cinders were thrown in a heap to decompose in air. Napier carried out several experiments to recover copper and silver from the calcine but was unable to develop an economic method. Trials were also carried out to use

Thost's regulus as a source of sulphur, but the matte only oxidized to a depth of 1/16in. (1.5mm) from the surface. Thost was able to burn off only 10% of the contained sulphur after roasting for nine weeks (*ibid*).

A persistent problem was the treatment of fines. The ore treatment system consisted of stamps for crushing the run-of-mine ore, followed by hand-picking. Slimes were treated by up to 12 self-acting buddles, located, it is believed, immediately below the mine area. Weil had pointed out that the methods used were giving rise to heavy losses and that a high proportion of undersize material had ended up in Loch Tay. In addition, the fines were higher in sulphur than the coarser material. From a run-of-mine ore of 28%S, after ore-treatment 40wt% appeared as fines assaying 28-31% sulphur, while the 60wt% oversize, which went on to acid manufacture, contained 19-20%S (these back-calculate to 23.5%). The fines were too small to pelletize with clay. Napier ordered a halt to stamping and washing to allow an investigation, but he was overruled (4/8/6, 7, 10). For the next production run Napier was able to present a sulphur balance:

February-March 1861	kg S
59.3 tons ore burnt @ 20.6% S	12,212
Sulphur in cinder 3.4%*	2,015
Sulphur in acid	9,010
Draught loss	1,187

* based on weight of ore

32 1/2 tons of vitriol were manufactured, corresponding to 84.8% H₂SO₄, and a sulphur recovery-to-acid of 73.7% was obtained.

By May 1861 a water wheel and 1 ton/day pan mill had been installed for the purpose of grinding the bones. Despite difficulties due to shortages of water, 17.4 tons of fertilizer were made, which was judged to meet the current needs of Breadalbane's farms (4/8/17, 18, 21). The plant ran for a further two weeks in May, but was shut down for want of ore (4/7/21).

After effecting repairs due to malicious damage to the chamber (two carboys of acid were also broken), production was restarted on 8 July. The feed included regulus and pelletized clay balls, but with an ore which fell to as low as 10% sulphur. By 16 August the chamber was full, while the carboys Napier had ordered had not arrived (4/7/26, 27).

The rebuilding of the furnace was begun during the latter

part of May, and a roof with iron pillars was built over the site. Towards the end of the following month the operators began gradually heating the furnace. A quartz smelting floor was installed which was fused and cooled to harden and fix the base. The furnace began operation on 10 July 1861, charged with a mixture of ore, uncalcined and calcined regulus from the previous year. The newly-formed matte contained 10-11% copper (4/8/18, 20; 4/8/21, 26). The feed grades were as follows (4/6/21):

	Wt%S	Wt%Cu
Hand dressed ore	4	16
Stamped and washed	3	34
1860 Regulus	4	30

The question must have been raised regarding the production of metallic copper, for Napier advised that this would require another two furnaces, presumably to oxidize the charge first to cuprous sulphide and then to the metal. Even the cost of upgrading the matte from 12% to 20% copper would be equivalent to that of transport to Swansea, which is what Napier recommended (4/8/26, 43).

Smelting continued satisfactorily during August; some ore appears to have been stockpiled earlier at Fir Bush pier, six miles up the loch towards Killin. But by 3 September Gribble reported that his workforce (which included some women) were preparing all the copper ore they could 'by hammer dressing to keep the smelter going as long as possible' (4/8/27, 28).

At this stage the Earl commissioned a financial assessment of the Tomnadashan operation. The value of the ore treated from December 1860 until August 1861, using corresponding Wheal Jane prices, was found to be £371 18s 11d. The cost of running the works for this period was £515 1s 0d. This meant a net loss of over £200 on an annual transaction of £746 *pa* (4/8/33x). An appraisal of the mining side by W J Henwood, manager at Tyndrum, led him to report that there was 'no great hope of success for further operations'. Exploration work had already ceased (4/8/34x).

During September a final 5¹/₄ tons of vitriol were made, while phosphate production lasted several more weeks. By the time the mill ceased, a total of 60 tons of fertilizer had been made at the site. The furnace ran throughout the month, using a blend of old regulus and an equal weight of ore, a mixture which caused some wear on the brickwork. Some time in October the smelter was shut down for lack of feed, and the operators were

compensated and laid off (4/8/44, 45).

In the face of heavy financial losses, Breadalbane decided to strip the installation. Napier found himself dismissed at short notice: '... to be thus dismissed whenever the works are completed without compensation is not what I expected from Lord Breadalbane' —James Napier, October 1861.

The Tomnadashan slag

Napier's reference to the beginning of furnace construction in late May 1861 shows that Thost's two-tier furnace, comprising roasting and smelting stages, must have been completely dismantled. His accounts of the operation of the smelter during the months July-October make no mention of a roasting stage, and therefore it may be assumed that a single stage smelting was carried out. In addition, the interior walls of the furnace seen today are sheer, showing no sign of the slight shelf in the masonry which appears in the diagram.

The two types of slag found on the shore of Loch Tay were analysed by courtesy of the British Geological Survey, Keyworth, Nottingham. The relevant assays are as follows:

	SiO ₂	Fe ₂ O ₃	CuO
Reflective Slag	51.21	8.51	0.07
Non-reflective slag	40.12	25.96	0.15

The dull non-reflective slag was found to be appreciably magnetic, the reflective slag not so. The distinctively high iron content of the non-reflective slag may be ascribed to the earlier 1860 smelting campaign under Thost, with the two-tier furnace. Thost went to great lengths to roast the pyrites to iron oxide in order to ensure a fluid slag, and it may be assumed that the dull slag has survived on the shore of the loch from that time. While obtaining good results, Napier smelted in a single stage and it is likely that the glassy high-silica reflective slag belongs to the 1861 campaign.

One may wonder why the copper content of Napier's slag is lower than that of Thost's slag, given that Napier obtained a matte of 10-11% Cu and that Thost's matte assayed 3-4%. The reason may be that roasting would convert a high proportion of the copper to oxide, making it liable to dissolve in the silicate phase. Another factor may be that a high proportion of the feed in Napier's 1861 campaign consisted of Thost's matte, in which the copper would report straight to the newly formed matte with little tendency to enter the slag.

Legacy

Lord Breadalbane died the following year, and there can be no doubt that the trustees must have tried to sell off everything that could be salvaged from the site—matte, ore, equipment; iron, timber and brick. Practically the only thing that was left was in natural stone, apart from the large lumps of slag resting on or near the shore. The mine site has already been described. Descending through the forest to the shore of Loch Tay, two rows of stumps of the former pier are visible (Fig 7). To the E of the small burn, which, just as in Napier's day, often runs dry, can be seen three tiers of walling approximately 0.5, 0.9 and 2.0m high. These sections of walling are marked on the plan (Fig 8) as *lower walling*, *middle walling* and *upper walling* respectively. To the NE of the lower and middle walling sections stand the remains of the furnace (Fig 9), the W wall of which is built on to a heavy projecting buttress sloping at an angle of 45°. This buttress is thought to be part of the charging system.

In line with the E wall of the furnace, 6m inland, is an opening in the hillside about 0.7m wide with a stone lintel (Fig 10). Inside a flooded passage of good quality masonry can be seen, with mud on the floor of the tunnel. This structure is referred to as the *horizontal flue on Figure 8* and appears to go into the hillside for approx 3m.

5.3m E of the opening of the horizontal flue, is a stonework arch 1.4m wide, and 6.5m SE of this stonework arch is a section of masonry walling 2.8m in length. This latter is believed to be part of the furnace stack, and is marked on the plan as the *stack wall*. To the E of the stack wall stands another stone wall, approx 1.25m high and supporting the soil behind, which



Figure 7: Remains of pier in Loch Tay, (see Fig 4).

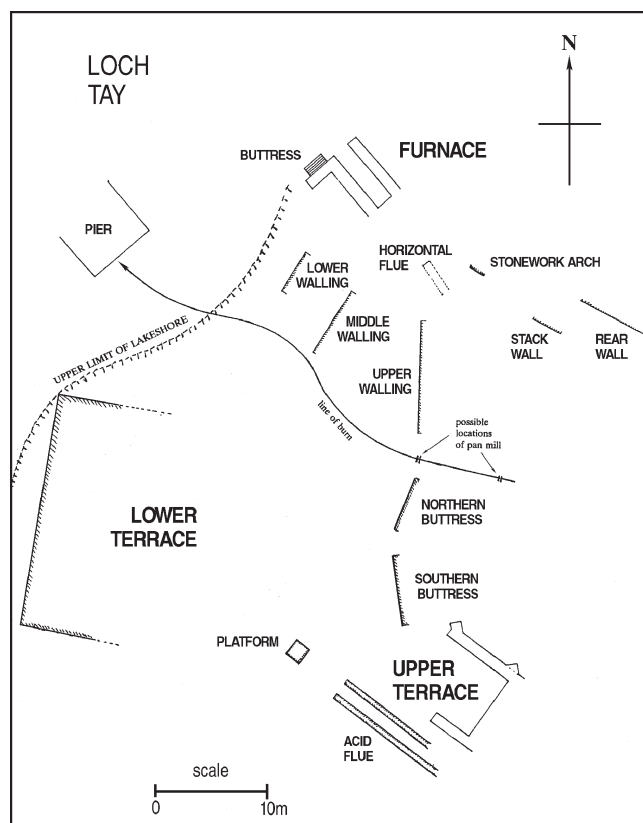


Figure 8: Lochtayside site plan, Tomnadashan.

extends for at least 7m. It is possible that this wall, referred to as the *rear wall* and the section of stack wall described above, are part of the same structure. Taken together, the exposed sections demonstrate the construction of the flue in horizontal and vertical sections as originally recommended by Weil.

It is believed that the cuttings which were used for the water wheel are visible at two points in the burn which



Figure 9: View of the furnace looking SE. The buttress on the right side of the photograph is believed to have carried rails as part of the charging system.



Figure 10: The horizontal flue

separates the smelting from the acid-making parts of the site. At these locations a fall of water of about 1.7m is observed, together with surviving blocks of masonry built into the SW bank of the burn.

To the W of the burn is a prominent masonry platform 21.5m wide, which stretches inland from the shore of the loch. This is shown in Figure 11 and labelled *lower terrace* on Figure 8. The upper boundary of this terrace is marked by two sections of walling, offset at an angle of 30°, with a gap in between, the *northern buttress* and *southern buttress*. Together, these support a smaller terrace, the *upper terrace*, some 3.5m above the level of the large lower terrace. The lower terrace would therefore be the base for Napier's acid plant, although its length at 98ft/30m precludes the 100ft chamber to which Napier referred in his design.

The upper terrace, which Napier referred to as the 'second terrace', was used for manufacturing fertilizer. It is bounded by three stone walls, each 6m long when complete, although part of the W wall is no longer



Figure 11: Front wall of Napier's lower terrace.

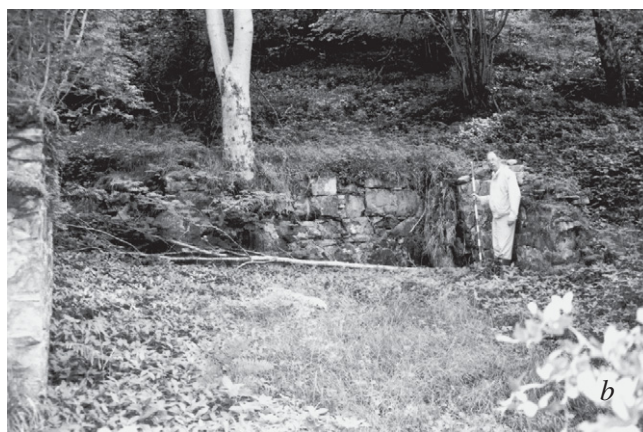


Figure 12: The upper (second) terrace, (a) as seen from the SW, (b) as seen from the NW.

standing (Fig 12 a,b). The purpose of the projections at each end of the NE wall is unknown.

At the SE side of the lower terrace two heavy stone walls 2m apart rise up the hill (Fig 13). These would appear to be the remnants of a large flue, the *acid flue*, which was used to conduct the sulphur and nitrogen



Figure 13: The main acid flue.



Figure 14: Earthenware pipe at junction of flue from second terrace with main acid flue.

oxide fumes away from the burners. At the level of the upper terrace the flue becomes smaller, but is easily traceable a further 15m up the slope to a large bifurcated ash tree, then less certainly upwards until thick vegetation is reached.

On the lower terrace, and approximately 5m NW of the acid flue, is an overgrown raised platform. This appears to consist of a fused mixture of brick and clinker, and probably there were other similar structures on this terrace, providing a base on which to support the acid chamber.

While examining the area just to the SE of the upper terrace, the author found a short alignment, lying across the slope, of pieces of brick and earthenware piping. Projecting the direction of the alignment toward the stone flue, there was found embedded in the side of the latter a piece of earthenware piping approximately 330mm in diameter (Fig 14). It is highly probable that this piece of earthenware represents the remains of a flue leading from the fertilizer plant to the main acid plant, and thus indicates the survival of three distinct flue systems from the 19th-century operation, viz copper smelter, fertilizer plant and acid plant.

Conclusion

One of the main themes of this project has been reconciliation of the history of the Tomnadashan enterprise, as shown through the Breadalbane archives, with the physical remains which have remained in particular by Loch Tayside and further inland.

Contrary to what has previously been believed, the archaeological remains of the enterprise, particularly from the copper-smelting circuit and the later 1860-61 acid and fertilizer plants, are substantial, while the

location of the ore-crushing apparatus and that of Jefferis' 1857-58 acid plant have been conjectured.

In addition, the availability of the indexed Breadalbane Muniments has enabled a coherent narrative account of the enterprise to be reconstructed with a high level of confidence. It is to be hoped that more detailed fieldwork and a more precise definition of the surviving installation may be possible in the future.

Acknowledgement

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The Breadalbane Muniments: These archives are held in the National Archives of Scotland, Princes St, Edinburgh, under the general heading GD 112. Documents relating to mining are classified under Section 18. Each document is then categorized under subsection, bundle and document number. Since all references used have the common initial designation GD112/18, this has been omitted from the reference citations.

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