Iron Ore from the Magor Boat

Abstract

The cargo of iron ore recovered by the excavators from the Magor Boat comprised 171 kg of ore, which they divided into 49 kg of lump ore (average weight 0.43 kg) and 122 kg of "powder" ore. The "powder" ore is a very poorly sorted material dominated by clay-grade material (ochre), but with clasts ranging up to 70 mm. The lump ore material includes pieces hand-picked from, or washed out from the "powder" ore, as well as large (>64 mm, >150 g) blocks which probably formed a separately-extracted component of the cargo. The lump grade material can be subdivided into four facies of ore (stalactitic, layered, botryoidal and replacement), of which more than one facies may occur within an individual ore lump. The ores are dominantly formed of the hydrated iron oxide goethite (α–FeO.OH), but small quantities of the anhydrous oxide haematite (α–Fe_2O_3) are also present in most samples of the lump ore. The range of textures and compositions present is typical of the iron ores found around the Bristol Channel area, but detailed considerations on the origin of the ore are still ambiguous. The provenance of the cargo is at least constrained by several strands of evidence, even if not yet positively identified. The current evidence favours a source either (1) in an area of the Forest of Dean in an area where quartz is more abundant than typical or (2) in a now worked-out superficial part of one of the Glamorgan ore-bodies, possibly near the Taff Valley. The material forms a broad cross-section of the ore types likely to be encountered in a source in these areas. The dominance of the powder ore may represent the relative ease of extracting this material relative to the lump ore, and the much higher degree of effort required to prepare the extremely hard lump ore to a grainsize suitable for smelting.

Contents

i. Introduction

The determination of the provenance of the Magor cargo is made extremely difficult by the almost complete absence of any published petrographic or analytical studies of the iron ores of the Bristol Channel Orefield. This report therefore includes a summary of the authors' ongoing unpublished research into the origin of the Bristol Channel Orefield, which will be published in full elsewhere in due course.

In the Forest of Dean particularly, modern studies are hampered by the working-out of the principal ore horizons (Crease Limestone, Drybrook Sandstone) from crop workings. Comparative material collected from the old workings or from modern quarries (dominantly in the Lower Dolomite) may not be representative of the ore worked in antiquity. As understanding of the geology of the orefield improves, then so will the provenancing of the Magor cargo. This report is preliminary, for the study of the orefield will have progressed significantly before the final compilation of the publication on the Magor boat. A subsequent report will update the conclusions reached here.

ii. Geological Background

The Bristol Channel area hosts a significant orefield (Figure 1) of haematite (α– Fe_2O_3) and goethite (α– FeO.OH) ores. The best-known areas of mineralization are in the Vale of Glamorgan, where the Llanharry haematite mine operated until 1978, and the Forest of Dean which provided a major component of the British iron industry in Roman and Medieval times. The orefield is, however, much more widely spread than this. In the west, iron ores have been worked in Gower (Oxwich, Mumbles) and they occur widely in the Vale of Glamorgan (South Cornelly, Barry, Wenvoe) and the South Crop of the South Wales Coal Basin (Llanharry, Miskin, Lesser Garth, Fforest Fawr). Ores are hosted within the Carboniferous limestone on both sides of the Forest of Dean Coal Basin, and locally within Upper Carboniferous sandstones within the coalfield. Iron ores occur at localities near the fault system forming the western boundary of the Worcester Graben, including Newent (hosted in Silurian sandstones), and areas in the Coalpit Heath Coal Basin (Iron Acton, Frampton Cotterell, Downend). Ores also occur associated with the Carboniferous limestone south and west of Bristol (Long Ashton, Yatton) and in the Mendips (Axbridge, Banwell, Hutton, Harptree, Priddy) and within the Upper Carboniferous sandstones of the Radstock Coalfield (Temple Cloud). At many localities, particularly in the Bristol and Mendip areas, the mineralization is dominantly hosted within the Dolomitic Conglomerate, of Triassic age, which lies unconformably on the Carboniferous succession around the margins of the Permo-Triassic basins. The published literature on most of these occurrences is now rather old (Cantrill *et al.* 1919, Sibly 1919), but a relatively recent account of the Llanharry deposit has been given by Gayer and Criddle (1970). A discussion of the Bristol Channel orefield is made in passing, during a description of the similar Cumbrian orefield by Shepherd and Goldring (1993).

The iron ores of this region are all closely associated with the post-Variscan unconformity. Most of the ores below the unconformity are hosted in cavernous porosity (caves, joints and faults). In most cases the ores occur within cavernous porosity within the Carboniferous limestone succession and particularly occur at horizons where there is such porosity immediately below an impermeable caprock. The most important of these horizons is the Gully Oolite Formation (and its lateral equivalent, the Crease Limestone) which is mineralised throughout its outcrop in the Forest of Dean and also in the Taff Valley area of the south crop in Glamorgan; areas where it is capped by an impermeable palaeosol. The major ore bodies farther west in the Vale of Glamorgan occur at a variety of horizons higher in the Carboniferous limestone succession, capped by the base of the impermeable Namurian mudrocks. In South Wales the relationship between the orebodies and the post-Variscan unconformity can frequently be seen, or inferred. In the Forest of Dean the Permo-Trias cover is lacking, but the unconformity probably lay at a horizon only slightly above the modern level of erosion. At many localities where the Permo-Trias cover is seen, the mineralization has been found to continue up into the overlying beds, particularly the Dolomitic Conglomerate.

Three phases can be determined in the development of the ores. The first phase is associated with the initial iron emplacement, and may be accompanied locally by silicification of the host rock and, more generally, by the intimate association of bipyramidal quartz with the haematite. The second phase is interpreted as reworking of the primary ores and is typically of goethite with botryoidal or stalactitic form. The third phase is the disruption of the ore deposits by karstic processes, leading to the development of ferruginous cave sediments and other derived deposits (the yellow ochres of the old literature).

The origin of the ores has been controversial. A source of the iron within the Permo-Triassic "redbed" sediments was favoured by most early workers (Etheridge 1870; Sibly 1919), but more recently a deep origin for the iron within the Carboniferous succession has been proposed (Shepherd & Goldring 1993). It is also important to note that recent

interpretations of the lead-zinc mineralization occurring in the same region have stressed the importance of fluids derived from the surrounding subsiding Mesozoic Basins (Haggerty *et al.* 1996). Discussion of the origin of the ores is not appropriate here, but it is sufficient to say that interaction between rising reduced iron-bearing basinal fluids and the oxic porewaters of the Permo-Triassic sediments is likely to have produced precipitation of the primary iron deposits. Crampton (1960) provided evidence that the primary iron mineralization predated the latest Triassic. The later phases of ore development are associated with near-surface processes and might be indicative of processes operating in the Triassic to early Jurassic, or after regional unroofing (Oligocene or younger).

iii. Historical Background

The iron ores of the Bristol Channel orefield have been worked from early times. Much of the archaeological emphasis has been placed on the Forest of Dean area, where iron-making certainly started before the Roman conquest. Pre-Roman iron-making slags consistent with ore sourced in the Forest of Dean have been identified at Ariconium and Frocester Court (authors' unpublished data). Pre-Roman working of South Crop ores has been suggested on the basis of a small amount of material from Mynydd Bychan (Savory 1955). During the Roman period the Forest of Dean was a major source of iron ore, which was smelted both within the Forest and in neighbouring areas (e.g. map in Fulford & Allen 1993). Outside the Forest and its immediate environs ore from the forest was apparently smelted at Usk (20 km W of the Forest of Dean), many localities in the Gloucester and Stroud areas (20 km to the E and SE of the Forest) and probably at Caerleon (30 km SW of the Forest) and possibly at Worcester (35 km NE of the Forest).

Other areas of the orefield were also utilised during the same period: large quantities of iron-making slags have been recovered at Cowbridge (Parkhouse 1982; GGAT 1983), a furnace at Llantwit Major (Nash-Williams 1955), ore and slag from Whitton and slags of supposed Roman date are recorded from near Miskin (Wilkins 1903) suggesting utilisation of the South Crop ores. The major iron production recorded by the large quantity of slags used in road surfacing in the 3rd Century fort in Cardiff may represent the working of ores from the Taff Gorge area, but might equally represent the working of ores brought in by sea. Utilisation of ores east of Bristol has been suggested by a smelting site associated with the outcrop of a haematite vein at Hansham Abbots (Russett 1992).

Post-Roman iron-making is much less well known, but the 7th century site at Dinas Powys included iron making residues and pieces of iron ore suggested to be from the South Crop (Alcock 1963; Tylecote 1986; Campbell 1988). The Domesday Book records, besides locations in the Forest of Dean and Gloucester, a very high tax in iron for Pucklechurch (*6 men pay 100 lumps of iron, less ten*), suggesting working of the Coalpit Heath ores, and the AD 950 Charter of Pucklechurch includes a reference to *Sinder Ford* (Cinder Ford) on the boundary with Iron Acton. A large volume of iron-making slags at Iron Acton probably represents the product of Medieval activity (authors' unpublished data).

In Medieval times Forest of Dean ores were certainly moved outside the Forest for smelting, for the Medieval quays at Woolaston on the west (Fulford *et al.* 1992) and Hills Flats on the east (Allen & Fulford, 1996) bank of the Severn yield fragments of iron ore. Indeed, the royal status of the Forest of Dean in Medieval times promoted the development of iron making sites outside the bounds of the forest itself, including Monmouth and Goodrich. The origin of the ores smelted at the Medieval iron making centre at Trellech to the west of the Wye has not yet been determined, but is generally assumed to be the Forest of Dean.

Margam Abbey is recorded (Rees 1968) as gaining rights for iron mining at South Cornelly in 1253. The Annals of Tewkesbury record finds of iron ore in the Lordship of Glamorgan in 1228 and 1282. Rees (1968) claims evidence for mining of ore at Llantrisant in 1262 and that in 1316 the lord's toll of iron from the commotes of Miscin and Glynrhondda was 4 loads of smelted iron. Rees also states that in 1319 Hugh le Despenser requested the transfer of workers from iron mines in Gloucestershire and Somerset to Glamorgan. It is possible, however, that this working was of Coal Measures claystone ironstones, for there are also records quoted by Rees of iron working of the Carboniferous ores at Neath, Blaenavon, Ebbw Vale and Glyntawe by the 14th century. Jocelin, Bishop of Bath was accorded mining rights for iron in Mendip in 1235 (Gough 1967), which follows earlier charters allowing the Bishops of Bath lead mining rights in the same area close to port facilities they were developing at Compton Bishop.

During the 16th Century the exploitation of the South Crop ores near Llantrisant was resumed, with the opening of a new mine in 1531 (Rees 1968). Late Medieval activity in this area was suggested on the basis of smelting slags and a bloom from Hendy (GGAT 1992). However, changes rapidly overtook the iron industry, with the introduction of blast furnaces at Tongwynlais and Pentyrch by 1565 (Riden 1992) probably working the Lesser Garth and Fforest Fawr ores respectively, but shortly after at Coity, Dyffryn, Blaencannaid, Cwmaman and Pontyryrn in Glamorgan and Abercarn,

Pontypool and Monkswood in Gwent, marking the start of large scale iron production from the claystone ironstones of the South Wales Coalfield.

It is clear that the Bristol Channel iron ores were commonly smelted away from the site of mining from early times. The sites of smelting include centres of a dominantly industrial nature (e.g. Roman Ariconium or 13th Century St Briavels), but also large numbers of sites of small scale production, presumably for domestic consumption (e.g. pre-Roman/ Roman Frocester Court or early medieval Dinas Powys). Much of the movement of iron must have been by river. The quays of Woolaston and Oldbury are direct witness to this, as are, indirectly, the large numbers of smaller iron-making sites recorded by Allen and others along the banks of the River Severn.

iv. Techniques

All specimens of lump ore were examined macroscopically and 17 representative specimens were the subject of further detailed study. 3 samples of the powder ore were studied in detail. The detailed investigation of the lump ore samples included examination of polished blocks using reflected light optical microscopy, back-scattered electron scanning electron microscopy (BSEM), geochemical analysis using X-ray Fluorescence (XRF) of fused beads (major elements) and powder pellets (minor and trace elements) and geochemical analysis using Induction Coupled Plasma - Mass Spectrometry (ICP-MS) of solutions (minor and trace elements). The specimens of the powder ore were examined using secondary electron scanning electron microscopy (SEM) and were subjected to the same range of geochemical investigation as the lump ore specimens.

Analytical Scanning Electron Microscopy (ASEM): The Scanning Electron microscope is a Cambridge Instruments (LEO) S360 with a secondary electron detector for surface imaging, a 4 quadrant back scatter electron detector for density imaging, and a cathodoluminescence detector. The analytical instrumentation comprises a Link Analytical Ltd. (now Oxford Instruments) AN10000 energy dispersive x-ray analysis system and a Microspec WDX-2A wavelength dispersive x-ray spectrometer, (now also Oxford Instruments). Image recording is either by standard 35 mm film via a high resolution CRT, by PCIT (personal computer image transfer) or to an optical disc for image archiving.

X-Ray Fluorescence Analysis (XRF): The XRF is a Philips PW 1400 sequential spectrometer incorporating a rhodium side window x-ray tube, a 6 position pre-aligned crystal changer, a scintillation detector, a gas flow detector and a 72 position automatic sample changer. The system is controlled by a Digital PDP 11/34 computer running X-14 software. The principal application is the whole analysis of rocks, whereby the major elements (Na, Mg, Al, Si, P, K, Ca, Ti, Mn, and Fe) are determined using a fused bead in order to overcome grain size effects and 34 minor/trace elements are determined using compressed powder briquettes. Loss on ignition is determined prior to preparing the fused beads and is incorporated in the results. The machine is calibrated against > 30 international rock standards.

Inductively Coupled Plasma - Mass Spectrometer (ICP-MS): The instrument is a Perkin-Elmer Elan 5000A ICP-MS. the sample is introduced into an inductively coupled argon plasma where it is ionised. Sample ions are drawn through an orifice, focused by a series of electrostatic lenses, filtered by a quadropole mass analyser and finally detected by an electron multiplier. For undiluted freshwater solutions detection limits are <10 ppb for REE, Y, Th, U, Cs, Be, Bi, 10-50 ppb for Ag, Cd, Ga, Rb, Sn, Sb, Ta, Nb, Tl, 50-100 ppb for Ba, Pb, Sc, Sr, Co, Ge, W, Mo and 100-200 ppb for V. Cr and Cu. Other elements are being added to list, and the machine can now be used, in addition, for Ca, Ti, Mn, Fe and Al. Typically 100-200 mg solid samples are dissolved using a variety of acids to a dilution of 2000, but higher dilutions (up to 10,000) are required for iron rich materials because of clogging of the orifices, giving typical detection limits for the REE of 20 ppb in these materials.

v. Physical State of the Ore

The iron ore was divided by the excavators into 122 kg of “powder” ore and 49.4 kg of lump ore. This division was at least partially arbitrary, with some larger clasts being hand-picked from the “powder” during its recovery and no evidence for segregation of the cargo was recorded by the excavators. The relatively fresh appearance of most of the larger blocks is in contrast to the more rubbly, weathered appearance of many clasts within the “powder” ore, suggesting that the two materials may have been mined separately, even if then mixed together for transport.

a. Lump Ore

The lump ore comprised 114 recovered pieces, with a total weight of 49.4 kg. The mean weight was 433 g, with a standard deviation of 690 g, and the range of recovered material was 2.6 g to 4270 g. 75% of fragments weighed less than 500 g, but these constituted only 24% of the weight of the lump ore. Petrographic examination of the lump ore and comparison with the grainsize distribution of the "powder" ore suggests that much of the less than 64 mm fraction of the lump ore has been derived from the "powder" ore component . Thus it would appear that the surviving cargo comprised approximately 129 kg of bulk "powder" ore and 43 kg of picked lump ore. The lump ore can be divided on the basis of the dominant ore facies into 25.0 kg of material dominated by stalactitic ore, 12.5 kg dominated by the layered facies and 5.1 kg of replacement facies.

b. Powder Ore

As described above, approximately 6.8 kg of the material isolated as lump ore can be added to the 122 kg of "powder" ore bagged by the excavators, providing a total of 129 kg of this ore. The powder ore is a poorly sorted aggregate material, dominated by orange/brown coloured clay-grade material (ochre), but containing a wide variety of clast sizes ranging up to 80 mm. The powder ore has a dry bulk density of 1.62 $t.m^{-3}$.

A subsample of the bagged "powder" ore was disaggregated in de-ionised water and sieved. 37% of the sample was <100 μm (and is described below as ochre); a cumulative frequency curve for the coarser material is presented (Figure 2). The sieved sample contained some material that was clearly intrusive (e.g. modern gastropods, fish and bird bones, and organic material including grasses and mosses). In the light of this contamination, interpretation of the small amount of non-iron ore material in the sample is difficult. Such material included flat pebbles of grey bioclastic limestone, together with sand- and granule-grade grains of various materials, including vein quartz. In this analysis, all such material has been regarded as probably being contamination and derived from the palaeochannel gravels, but small amounts of siliciclastic material do occur in the infills of karstic features, both in South Wales and in the Forest of Dean.

The powder ore is dominated by material derived from the lump ore, and much of it probably represents disaggregated stalactitic or replacement ore. There is little admixed material, with chemical analysis showing the bulk "powder" ore as comprising approximately 75% Fe_2O_3 (corresponding to approximately 83% goethite). A significant minor component of the >16 mm fraction of the powder ore is provided by thinly layered yellow-brown silicified ochreous dolomite.

vi. Petrography

The ores are subdivided here into 5 categories: layered ores, stalactitic (brush) ores, botryoidal ores, replacement ores and ochre. The four facies of lump ores occur intimately associated, and only a very small number of specimens contain ore of a single facies. The powder ore comprises small fragments of lump ore, together with other clasts in an ochreous matrix.

The ores are dominantly formed of the hydrated iron oxide goethite (αFeO.OH), but small quantities of the anhydrous oxide haematite are also present in most samples of the lump ore, particularly layered facies ore.

Some specimens of ore (generally the more calcareous lithologies) show indications of alteration during burial in the estuarine silts. In extreme cases this is seen as the tendency of the normally grey/brown ores to take on a slightly greenish tinge. This alteration affects only a very small proportion of the ore and specimens affected were avoided for detailed study. During the detailed study of selected specimens the only effect associated with estuarine diagenesis is the appearance of pyrite framboids within the larger pore spaces of the lump ores. There appears to have been little involvement of the solid ore in the diagenetic reactions and the bulk chemical composition of the ores can confidently be taken to be largely unaltered, but slightly elevated S and Cl contents indicate minor modification.

a. Layered ores

(with detailed examination of M14, M47, M48, M71, M90, M91, M113)

This ore facies comprises dense, hard layers alternating with porous low density layers and open cracks (Plate 1). The dense layers range from 0.6 to 6 mm in thickness, the porous layers up to2 mm and they grade upwards into open cracks up to 2 cm wide. No specimens from Magor are solely of this facies, but many specimens dominantly comprising stalactitic ore contain a proportion of layered facies, upon which the stalactitic facies has grown. The maximum thickness of layered facies observed was approximately 5 cm.

The high density layers are dominated by goethite, but haematite may often comprise 10-20%. This relatively elevated haematite composition is higher than recorded in the other facies. Overall porosity is low, reaching a maximum of 6% in

the specimens studied in detail, but individual porous layers commonly have 25% porosity. Haematite concentrations are generally lower than in the dense bands. The porous structure of these bands is generally seen to be combination of large open pores and smaller porosity within pseudomorphs of carbonate crystals (Plates 2, 3 & 4). These carbonate crystal pseudomorphs range up to 1 mm in size. The iron oxide crusts marking the surface of the former carbonate mineral are often rich in haematite (Plates 2 & 3).

Both dense and porous layers are often rich in quartz crystals up to 200µm. These quartz crystals are well formed and variously predate (Plate 4), post-date (Plate 5) or are intergrown with (Plate 6) acicular goethite crystals.

Specimens with larger open pore spaces may demonstrate a botryoidal goethite overgrowth (Plate 2), but this is usually only weakly developed. Some cavities show the development of a minute stalactitic facies (M14). Stalactitic material associated with the layered facies gives an indication of the orientation of the layers (assuming that the stalactites are vertical) and show that the layers form on surfaces of all orientations from steeply dipping to horizontal with a predominance of surfaces between 40 and 65° (see below).

The contact of the layered facies with the host rock is marked in several specimens by a red ochreous zone. In some specimens there is evidence for botryoidal facies subsequently developing in a crack between the layered facies and the host rock.

b. Stalactitic ores
(with detailed examination of M1, M6, M43, M48, M54, M71, M75, M82, M87, M90)

Stalactite facies comprises most of the lump ore present. The facies commonly overgrows layered ores, and is itself almost ubiquitously overgrown by botryoidal material. The stalactites are generally thin, ranging upwards to 3 mm diameter (Plates 7 & 8), but these thicker examples are generally the product of an original stalactitic ore, secondarily coated with botryoidal ore (Plate 9). The botryoidal material often overgrows the stalactitic facies to such an extent than the inter-stalactitic porosity is almost completely occluded, giving the ore a massive appearance. In some examples the botryoidal material only completely fills the porosity in the lower part of the stalactitic facies, leaving a more porous region near the root of the stalactites. The maximum demonstrable thickness of the stalactitic layer was 18 cm, but several specimens show no contact with a supporting substrate and the layer may originally have been much thicker.

In polished section the stalactites have a porous microstructure with goethite crystals radiating from small clumps to form an interlinked mesh (Plates 7, 8 & 9). The centres of the dense clumps are often seen to contain haematite in six-pointed star-shaped structures with 6 haematite crystals up to 6 µm in length and 0.5 µm wide radiating from a central point (Plate 9).

c. Botryoidal ores
(with detailed examination of overgrowths on stalactitic ore M1, M6, M43, M48, M75, M82, M87, M90, and on layered ore M71, M91)

Botryoidal material is dominantly of goethite. The botryoidal goethite comprises acicular crystals and has concentric banding (Plate 10). Some specimens show thin horizons of haematite (up to 40 µm) running through the goethite (Plate 11). The material is commonly recrystallised into more polygonal morphology. The botryoidal overgrowths are typically up to 500 µm thick, but locally much thicker botryoidal layers up to several mm thick may occur.

One interesting feature of these botryoidal overgrowths is that they, in turn may be overgrown (e.g. M82, Plate 12) by sheathes of radiating large acicular goethite crystals up to 150 µm in length and 5 µm in diameter. In sample M82 these overgrowths form on an altered surface layer of the botryoidal material consisting of equant grains of haematite. In sample M14 at least two generations of these acicular overgrowths approximately 100 µm in length have formed on a layered ore substrate.

d. Replacement ores
(with detailed examination of M7, M54, M110)

Only a very small proportion of the Magor material can be identified as a replacement of a pre-existing rock. This is keeping with most localities within the Bristol Channel orefield, where the iron ores are generally cavity-filling. However, these specimens may provide considerable insight into the host rock.

Specimen M7 is a massive red/brown rock, cut by a series of irregular fractures. At one end of the block the fractures are parallel and evenly spaced. In polished section the rock shows a microstructure of goethite plates. At one end of the specimen there is a crudely radiating structure of plates formed from clumps of small goethite crystals.

Specimen M54 (Plate 13) comprises a piece of replaced coarse dolomite, supporting a growth of stalactitic ore. The dolomite crystals (up to 1.5 mm) have been replaced by a geopetal infill of goethite and haematite showing a gradation in the frequency of goethite clots centred on haematite "stars" similar to those present in the brush ore. The outlines of the dolomite rhombs are marked by porosity.

Specimen M110 is badly weathered, but shows a poorly preserved texture of goethite-replaced dolomite, with extensive secondary porosity infilled with a sparry calcite cement.

e. Ochre
(with detailed examination of M115, M116, M117)

The ochres comprise material of clay grade. The material dominantly comprises iron oxide, presumably goethite, grains, but there is a minor component of quartz and clay minerals, together with rare grains of barite. The ferruginous grains include "six-pointed stars", which can be seen to be axially aligned (Plate 14), and also to be linked together laterally in some larger fragments of material (Plate 15). Other grain types include various tabular and platey forms, sometimes of rhombic or hexagonal shape. The tabular ferruginous grains are frequently arranged in crudely radial clumps. There is little variation in goethite grainsize with the largest clumps reaching approximately 15 μm, the largest six pointed star 5 μm, and the tabular grains typically between 0.5 and 3 μm. The "six-pointed stars" are also abundant in lump material, both of ore grade (e.g. M54; see above) and in ochreous dolomites (e.g. M52, M59, M60, M61, M63, M64, M65, M66, M100, M104, M106, M109; see below).

The most likely origin of the ochre is through dissolution of the ochreous dolomite material. Dissolution of this material would liberate large amounts of the microscopic goethite grains within them, and would also remove the wall rock to which pieces of lump ore were attached, supplying the coarser components of the "powder ore". Much of the intermediate grade material in the "powder ore" (100 μm - 5 mm) appears to be degraded brush ore, which would be particularly liable to fragmentation during this period of karstic activity.

f. Non-ore material within the "powder ore"

Specimen M114 is a large (1081.5 g) block of reddened, haematised, dolomite. The dolomite occurs as coarse rhombs, up to 1000 μm. The dolomite is cut by calcite veins, associated with small patches of yellow ochre. There are also small vugs, with calcite fill, around which the dolomite rhombs have a particularly marked iron oxide rim. Within the bulk of the rock the rhombs are marked by irregular oxide rims.

The powder ore contained many examples of layered yellow silicified ochreous dolomite. Several samples of this had been picked out by the excavators and appear in the lump ore collection (M52, M59, M60, M61, M63, M64, M65, M66, M100, M104, M106, M109). This material shows layering defined by degree of induration (goethite, quartz) of the weathered dolomite substrate. In some cases the hard layers become separated by gaps, and have surfaces covered on goethite replacements of dolomite rhombs. At this stage the rock is of relatively low iron content, but shows textures equivalent to those of the layered facies ore, into which it grades via porous, low density, layered goethite ore. In polished section (M59) these ochreous dolomites show abundant develop of particularly within grains as "6-pointed stars", which are often axially linked into elongate chains. This again demonstrates the continuity with ochre grade material.

g. Relationship of the lump ore facies

The ore specimens show a consistent relationship of facies (Figure 3). Stalactitic and laminated facies ores are overgrown by botryoidal facies. Stalactitic facies ore can be seen to overgrow laminated facies and to form within the larger cracks within laminated facies specimens. The replacement ores are seen in one specimen to be overgrown by stalactitic facies. These relationships suggest that the cavernous porosity within the altered dolomite may first develop a laminated lining. The orientation of stalactitic overgrowths on the laminated facies suggests that the laminated facies formed on surfaces of any orientation. The laminated facies was subsequently overgrown by the stalactitic facies, which provides the majority of the lump ore material and then the stalactitic facies was in turn overgrown by thin deposits of botryoidal facies ore.

The exact relationship of the ochreous dolomite to the layered ores is less clear, but it seems likely that at least some of the layered material may have been produced through replacement and progressive enrichment of a dolomitic precursor. Specimens of the ochreous dolomite show surfaces covered in goethite pseudomorphs of the terminations of carbonate crystal, similar to those seen more strongly mineralised in the layered facies ore.

vii. Geochemistry

The lump ore represents a very high grade material with Fe_2O_3 of the non-replacement ores ranging from 87.2 - 89.9% (corresponding to a range of haematite + goethite from 97% to over 99%. Major element geochemistry of the ores is therefore rather limited in its variation, with a maximum SiO_2 content of only 2.9%. The minor element chemistry of the ores is marked by very low concentrations of Mn, Ca, Ti, Na, K and P. SiO_2 is in the range of 1-2% for most ore specimens, with Al2O3 typically only present at values of up to 0.4%. There is therefore little detrital material present in these highly pure ores. An elevated SiO_2 : Al_2O_3 ratio in some specimens reflects the presence of quartz as a gangue phase (particularly in the layered facies).

Only the ochres show significant impurities, but with haematite + goethite of approximately 85% these are still high grade ores. The ochres show SiO_2 and Al_2O_3 totalling approximately 12%, with clays, quartz and feldspar grains all identified under the SEM. The SiO_2:Al_2O_3 ratio is 5-6, much lower than for the more siliceous lump ores. CaO+MgO total approximately 2% in the ochres, suggesting the presence of some relict carbonate material. The P content of all the ores is very low reaching 0.044% in only a single specimen and typically less than half that value.

The ores are all typically very low in all trace elements. The Magor cargo has extremely low uranium contents. The ΣREE of < 16 ppm and generally < 10 ppm is low even in comparison with other Bristol Channel ores. The Upper Crust-normalised (Taylor & McLennan 1981) REE profile (Figure 4) shows a marked depletion in the light REE (LREE) and a slighter depletion of the heavy REE (HREE), giving a "humped" appearance to the profile centred on Gd. Superimposed on this profile is typically a small negative Ce anomaly. Comparison of curve shape by eye is not easy, so the Magor ores have been plotted on a diagram (Figure 5) of Gd_N/Lu_N (a measure of HREE depletion) v. Gd_N/La_N (a measure of LREE depletion). Indicated on the diagram are the fields occupied by analyses of ores from the western and eastern sides of the Forest of Dean. Analyses of the Glamorgan ores plot coincident with the western Forest of Dean samples. Further research is required to establish the origin of the REE patterns observed, before firm conclusions about geographical control can be established.

viii. Evidence for Provenance

Provenancing the Magor cargo involves consideration of several facets of the material: ore texture, ore mineralogy, ore geochemistry and the petrology of the associated non-ore rocks. No single indicator is an unambiguous pointer to a particular source, but taken together these features do provide a clue to the source area and further work on geological resources should clarify the situation further.

Ore texture:
There is a predominance of stalactitic ore. No pieces show more than one host rock contact, indicating that the ore bodies were emplaced in large cavernous porosity, rather than on narrow joints. The dominance of stalactitic ores distinguishes these ores from the recently-worked major deposits of the South Crop of the South Wales coalfield, where massive and layered ores generally fill the caverns, and from the ores of the north Somerset area, which are dominantly relatively narrow vein fills. Only a single passing reference has been found to ore as a cave fill in Somerset (Knight 1915; referring to a large pocket of goethite found in a cave at Dolebury in the mid nineteenth century), although

accounts of the ochre digging in western Mendip imply that the ochre deposits were linked to, or cut by, cave systems (Gough 1967). Despite the dominance of stalactitic ores, the layered facies shows a remarkable similarity to the layered goethite ores from Llanharry.

A further textural clue is provided by the occurrence of layered facies and/or a contact with host rock in 24 specimens which also contained stalactitic ore. The dip of the layered facies and contacts has a mean value of 49°, with 16 of the values between 40° and 65°. In many of the ore containing cavities observed in the field, the orientation of the cavity roof is controlled by the bedding. This is particularly clearly seen in the ore bodies of the Crease Limestone (e.g. in Clearwell Mine) where the roof is provided by the base of the overlying Whitehead Limestone. A dip of 49° is too steep to represent the dip of bedding on the western margin of the Forest of Dean (where bedding typically dips eastwards at 10-20°), but does correspond to the dip of bedding in parts of the east limb of the coalfield. Outside the Forest of Dean typical dip values are: Fforest Fawr 30°, Lesser Garth 44°, Mwyndy 30°, Llanharry 22°, Long Ashton 20°, Yatton 12°, Dolebury/Hutton 70°, Blagdon 45°, Harptree 20°, Axbridge 20°, Priddy 40°. A bedding dip average of 49° would therefore restrict the possible source area to the region on the east of the Forest of Dean north from Cinderford to the eastern side of Wigpool Common, two small areas on the west of the Forest of Dean (SW of Lydney, near Noxon Park), the Lesser Garth, the Blagdon area on the north of the Blackdown Pericline, and a region on the south of Mendip south of Priddy.

It has been suggested to the authors (J. Wright, personal communication 1996) that the dominance of stalactitic ore would suggest the western, rather than the eastern side of the Forest of Dean; the steeper dip on the east side leads to steeply inclined ore bodies which typically have a more granular texture. It has not yet been possible to investigate this suggestion in the field, but the data from stalactite orientation would support the dip values more common to the east of the Forest of Dean (see above).

Ore mineralogy: The key mineralogical feature of the Magor cargo is the presence of quartz in the layered facies. This feature apparently distinguishes the ores from those of the Forest of Dean, but Sibly (1919) does record quartz in bedding-parallel orebodies hosted by the Lower Dolomite at Red Hill Quarry, Lydney (a locality with dips of 35-60°). Our analyses of red ochre from Clearwell Caves Iron Mine shows an SiO_2 content of 9.70% and Al_2O_3 of 0.22%; values clearly indicative of silica enrichment. Thus quartz does occur, although not frequently, in Forest of Dean ores. The quartz in the layered facies ores is dispersed and has a crystal size only up to approximately 200 μm, but frequently smaller. This is in marked contrast to the quartz-bearing vugs, which occur in addition to the dispersed quartz in the S Wales and Somerset siliceous haematites, and form a prominent macroscopic feature of the ores. In these vugs the quartz crystals are typically up to 1.5 mm and may attain several centimetres.

Ore geochemistry:
The low uranium content of the Magor lump ores (m = 2.00 ppm, s = 1.03, n = 17) differs from the slightly higher levels recorded from both the eastern outcrop of the Forest of Dean (Shakemantle, Edgehills, Drybrook; m = 4.20 ppm, s = 1.58, n = 12)and the western outcrop (Clearwell, Scowles Quarry, Blakes Wood; m = 4.85 ppm, s = 2.93, n = 12), but is similar to ores from Upper Carboniferous sandstones in the central Forest of Dean (Minetrain Quarry; m = 2.01 ppm, s = 1.36, n = 5). The red and purple ochres from Clearwell on the western margin of the Forest have elevated uranium contents (25.9 and 20.5 ppm respectively) and even the yellow ochre from Clearwell is markedly richer (7.29 ppm, n = 1) in uranium than the Magor yellow ochres (m = 3.79 ppm, s = 0.27, n =3). The fault-hosted ores of the western margin of the Worcester Graben (e.g. Iron Acton and Newent) have a much lower uranium content (m = 0.85 ppm, s = 0.47, n = 4) than the Magor ores, whereas the Glamorgan ores are very variable, but most outcrops have yielded some very high uranium material (Figure 7). The exception in Glamorgan is Llanharry, which has uranium values comparable to Magor (m = 2.73 ppm, s = 1.04, n = 4).

The REE profiles are comparable to analyses of material from localities in the Carboniferous limestone of the eastern margin of the Forest of Dean, but are distinct from localities hosted in Carboniferous sandstones of the central part of the Forest of Dean (which show a positive Ce anomaly), from those from the western margin of the Forest of Dean (which show a flat heavy REE profile) and in general from those of the South Crop of the South Wales Coalfield (which have flatter profiles, large positive Eu anomaly in some material and a large negative Ce anomaly in many samples), although some samples from Llanharry and Fforest Fawr do approach the profile of the Magor material.

Associated material:
Although there are very few pieces of replaced or altered host rock associated with this ore, those present are indicative of a coarse-grained dolomite; this demonstrates the ore was obtained from an ore body hosted by dolomitized limestone, and so excludes those deposits hosted by sandstones (Bristol Coalfield, central Forest of Dean) or those hosted by the Dolomitic Conglomerate (most of which are also of a dominantly haematitic rather than goethitic mineralogy).

The ore bodies of the Forest of Dean and Glamorgan are always associated with the development of iron-rich dolomites, typically red, but becoming yellow where altered immediately adjacent to veins and karstic fissures. In contrast, none of the ore bodies we have sampled in North Somerset, shows significant associated dolomitisation, although some may show a thin (few cm) dolomitized and/or silicified layer on the wall of the ore body.

ix. Discussion

Despite the fact that the ores fit within the general pattern of the Bristol Channel ores, they are without particularly close correspondence with any of the ores for which data is yet available. However, it should be remembered that the principal ore-bearing localities in the area have been so heavily worked that obtaining material from superficial positions equivalent to those likely to have been worked in Medieval times is difficult.

The evidence for provenance (as described above) is ambiguous and contradictory, and it is to be hoped that future work (see below) will help to clarify the issue. However, it is possible to make the following comments:

i. The coarse dolomitic host rock favours a Glamorgan or Forest of Dean origin
ii. The low quartz content and small size of the quartz crystals cannot be matched elsewhere at present being intermediate between typical Forest of Dean and Glamorgan/Somerset features
iii. REE data favour an E Forest of Dean origin (Somerset ores not yet sampled)
iv. U data are more like those from fault-related contexts than from the main limestone-hosted ores, although the Forest of Dean and Llanharry data are not very different
v. The morphology of the ore favours an origin in a relatively large cavern, a feature more likely to be encountered in Glamorgan or the Forest of Dean than in Somerset
vi. The orientation data suggest association with a cavern roof dipping at 45-60°, and if this reflects bedding it would restrict the source to a few areas of the Forest of Dean, Lesser Garth, NE of the Blackdown Pericline or S of Mendip
vii. Yellow ochre localities sampled to date in Somerset, have yielded only a “spongy” goethite lump ore facies and botryoidal facies material, making an origin at one of these deposits unlikely.
viii. The morphology and mineralogy of the layered facies ores closely resembles equivalent deposits from Llanharry.

These suggest that an origin of the cargo in South Wales or the Forest of Dean is likely, but further comparative data are still required to determine the exact source. There would appear to be two likely settings for the source of the Magor ore:

1. A superficial position within an orebody on the South Crop in Glamorgan. No deposits dominated by stalactitic facies have been recorded in this area to date, but locally there are examples of ores with similar trace element geochemistry. The possible high dip of the Magor source would be best satisfied by an origin in the Taff Gorge area, where analyses of trace element geochemistry are least compatible.

2. A location in the Forest of Dean where abnormally high quartz concentrations have been produced. Possible areas where this might occur would be near the major structural axes (and these same areas would satisfy the dip criteria). Such areas might be found west of Lydney and to the west of Mitcheldean.

The end use of the cargo would have been for iron smelting. The ochre component of the powder ores could have been used as pigment, but the large quantity present, its dull colour and the unsorted nature of the powder ores makes a metallurgical use far more likely. The use of powder grade material in smelting has often regarded as unlikely because of the rejection of fine grained material as charge for recent blast furnaces (due to problems with clogging). In contrast, however, experimental work with bloomery furnaces suggests that powder ores may be particularly suitable because of their ease of reduction; coarser grained charges are much more difficult to reduce thoroughly. In particular, the early exploitation of powder grade bog iron ores from Sweden is well documented.

In the Forest of Dean the use of powder grade material in Medieval times is suggested by the adoption of the standard measure “bellis”, which has been equated with the bushel (i.e. a volume measure). In 1282 a “regard” of the Forest used bushels as a measure for ore, and Nicholls commented (1866, p.23) “It would appear, too, that the ore was then measured by the bushel, as it has been ever since, owing, of course, to its loose powdery nature, which seems, therefore, to have been the sort preferred”. Nicholls described the use of the miners tools by saying “with the small mattock in his

right hand, he would loosen the fine mineral earth lodged in the cavity within which he worked, as occasion required, or else detach the metallic encrustations lining its sides". On discussing a claim that the ore had been washed before smelting he also states " were it to be applied to the mineral here, much would be washed away, because of its finely divided nature". Although Nicholls was writing in the mid nineteenth century, it is clear that traditional methods of mining the iron ores persisted at that time in many parts of the Forest, despite the advent of deep mining and his comments provide an insight into the nature of the material worked.

The total weight of recovered cargo (171 kg) might be expected to yield around 40% of this weight as raw iron blooms (68 kg) during smelting in bloomery furnace. There is little information available for the production from bloomeries of the period of the Magor boat. The only blooms known from the Forest of Dean have been assumed to be Romano-British, but are undated, and are approximately 2 kg in weight. A bloomery would probably only produce a single bloom per day -so the surviving cargo would have kept a single bloomery furnace producing blooms of this size in operation for over a month. It provides a perspective on the volume of ore being shipped, to note that this potential iron product corresponds approximately to the weight of the iron nails used to build the Magor boat.

x. Further research

On a short-term timescale, additional analyses of Glamorgan and Somerset ores currently being produced and will be available shortly. Additional fieldwork and analytical studies during the early part of the summer will be focused on the areas of the Forest of Dean to the SW of Lydney and on the E side of the Wigpool Syncline. We will also examine areas around the Mwyndy and Lesser Garth deposits for any evidence that their now worked-out upper zones contained more "phase 2" ores than the more recently worked parts of the orebodies.

On a slightly longer timescale a project examining the role of uranium in these deposits will take place during the later summer, which should help to clarify the mechanism of uranium concentration and therefore assist with interpretation.

Research completed by mid-summer will be consolidated with a revised version of this report and submitted to GGAT.

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Plate 15. Ochre. Lattice of “6-pointed stars” of goethite, together with other goethite grains. Secondary electron image of strew mounted ochre. Sample M115.

Sample	Texture	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
M14	layered	1.54	0.28	87.56	0.02	0.27	0.08	<	0.02	0.01	0.05	10.18
M47	layered	2.94	0.04	86.94	0.02	0.21	0.04	<	<	<	0.02	9.80
M71	layered	1.51	0.35	87.78	0.02	0.30	0.11	<	0.05	0.03	0.04	9.82
M75	layered	1.42	0.33	88.58	0.02	0.25	0.06	<	0.03	0.01	0.06	9.25
M91	layered	1.22	0.19	88.27	0.02	0.22	0.09	<	0.02	0.01	0.03	9.94
M113	layered	1.02	0.16	89.92	0.01	0.20	0.05	<	<	0.01	0.04	8.57
M48	brush on layered ore	0.87	0.10	88.68	0.03	0.20	0.04	<	<	0.01	0.02	10.05
M43	brush	1.15	0.12	88.06	0.02	0.25	0.04	<	<	<	0.03	10.34
M54b	brush	1.07	0.29	88.18	0.03	0.26	0.04	<	0.03	0.01	0.02	10.09
M90	brush	1.28	0.13	87.75	0.02	0.26	0.17	<	<	<	0.05	10.32
M1	spongy brush	1.54	0.48	87.19	0.02	0.30	0.03	<	0.05	0.02	0.04	10.34
M6	spongy brush	1.11	0.20	88.13	0.02	0.27	0.04	<	<	<	0.05	10.16
M82	brush with botryoidal, massive	1.53	0.26	87.43	0.02	0.30	0.04	<	0.03	0.02	0.05	10.33
M87	brush with botryoidal	1.72	0.10	87.36	0.02	0.31	0.05	<	<	<	0.10	10.33
M7	massive replacement ore	0.25	<	89.30	0.01	0.13	0.01	<	<	<	0.03	10.27
M54m	replaced dolomite	0.40	0.10	86.84	0.02	0.30	0.03	<	<	<	0.03	12.29
M110	calcite cemented replacement	3.92	0.28	53.28	0.05	0.31	20.81	<	0.01	0.01	0.02	21.30
M117	ochre	10.45	1.68	74.79	0.05	0.73	1.58	<	0.33	0.10	0.09	10.21
M115	ochre(aggregated)	10.28	1.75	75.81	0.05	0.56	1.23	<	0.35	0.11	0.08	9.78
M116	ochre(aggregated)	9.15	1.70	76.74	0.05	0.55	1.34	<	0.32	0.10	0.08	9.97

Table 1. Major element analysis of selected specimens by XRF as weight% oxide. All iron quoted as Fe_2O_3. < = value below detection limits. LOI = Loss on ignition

element	Be	Sc	V	Cr	Co	Cu	Ga	Rb	Sr	Y	Zr	Nb	Mo	Cd	Cs	Ba	Ta	Tl	Pb	Bi	Th	U
atomic number	4	21	23	24	27	29	31	37	38	39	40	41	42	48	55	56	73	81	82	83	90	92
M14	13.23	<	7.588	3.432	20.47	12.91	0.541	0.768	7.368	3.484	2.499	0.31	13.709	<	<	6.8937	0.1961	<	8.2533	<	0.1850	1.4210
M47	7.062	<	<	5.134	31.11	5.261	0.314	<	4.360	1.214	2.296	0.243	8.3614	<	<	1.9732	0.2809	<	2.1623	<	<	1.6082
M71	9.671	<	6.738	5.658	16.45	6.557	0.649	0.759	12.96	3.892	8.572	0.604	2.348	<	<	9.5926	0.1534	<	6.1978	<	0.5413	2.4954
M75	46.39	<	11.40	5.743	34.39	4.729	1.326	<	12.27	5.644	2.911	0.421	11.846	<	<	12.416	0.1946	<	9.7757	<	0.2501	3.2491
M91	3.752	<	14.60	9.384	23.12	9.707	0.556	<	7.103	1.346	3.249	0.300	2.8893	<	<	6.2708	0.1365	<	4.6508	<	0.1515	2.3803
M113	6.035	<	9.552	6.188	21.81	5.847	0.663	<	8.958	2.968	3.314	0.311	4.7128	<	<	5.1942	0.1677	<	15.019	<	0.0960	5.1044
M48	7.093	<	4.030	2.363	36.41	16.87	0.465	<	3.330	2.064	2.975	0.344	4.5838	<	<	6.0405	0.3752	<	2.0085	<	0.1462	1.0412
M43	14.06	<	5.489	1.761	20.34	5.404	0.402	<	4.831	2.911	1.659	0.199	12.396	<	<	2.4925	0.1627	<	2.7584	<	<	1.3492
M54b	4.966	<	<	2.273	29.43	16.79	0.944	0.861	5.397	3.092	2.626	0.287	6.2242	<	<	5.361	0.2378	<	3.6134	<	0.1265	1.6626
M90	20.04	<	8.299	2.551	18.14	3.934	0.715	<	8.578	4.063	1.655	0.190	23.569	<	<	4.5199	0.1682	<	4.9802	<	0.1589	2.5770
M1	12.24	<	10.51	<	31.68	20.28	1.457	1.886	12.82	3.837	3.026	0.383	12.348	<	0.0542	9.7017	0.2585	<	4.2340	<	0.2239	2.2584
M6	8.38	<	6.774	1.925	37.09	10.45	1.265	<	3.635	2.058	1.64	0.282	9.9102	<	<	2.0581	0.5953	<	2.7724	<	0.1060	1.6616
M82	19.23	<	8.114	4.261	30.33	7.631	0.613	<	6.772	4.240	3.908	0.412	24.227	<	<	5.0657	0.2302	<	6.4706	<	0.1954	1.9298
M87	25.40	<	2.277	<	16.55	4.229	0.399	<	6.498	4.449	1.578	0.160	32.486	<	<	2.3002	0.1185	<	4.1995	<	<	1.0687
M7	3.367	<	4.753	<	31.14	3.894	0.587	<	1.401	0.522	1.329	0.153	10.297	<	<	0.8858	0.2162	<	1.2047	<	<	0.6077
M54m	6.521	<	4.963	<	40.23	4.896	1.199	<	3.598	2.979	2.448	0.135	11.439	<	<	1.195	0.172	<	2.7596	<	<	1.6861
M110	7.639	<	8.431	3.383	43.85	6.406	0.841	0.418	48.43	6.327	2.299	0.282	3.8684	<	<	4.2824	0.1512	<	5.5300	<	0.1345	1.8765
M115	8.479	1.069	49.39	14.32	26.30	18.42	3.518	13.48	32.14	6.399	16.20	1.659	10.436	<	0.8462	43.779	0.2147	<	13.759	<	1.1407	3.4753
M117	8.727	0.972	44.05	13.37	16.92	5.701	3.507	11.96	30.92	6.629	16.24	1.471	10.903	<	0.7440	41.092	0.181	<	10.009	<	1.1517	3.9297
M116	9.136	1.051	46.46	15.38	21.52	35.40	3.575	12.19	32.28	6.289	16.94	1.561	11.47	<	0.7304	45.575	0.1583	<	9.8109	<	1.0540	3.9681

Table 2. Trace element analysis of selected specimens by ICP-MS quoted as ppm. < = value below detection limits.

element	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	*Σ REE*
atomic number	57	58	59	60	62	63	64	65	66	67	68	69	70	71	
M14	1.1919	2.7765	0.3653	1.8122	0.5464	0.1454	0.7061	0.1139	0.6465	0.1094	0.2953	0.0431	0.2927	0.0425	*9.0872*
M47	0.4421	0.9407	0.1308	0.5804	0.1570	0.0617	0.2083	0.0298	0.2046	0.0486	0.1124	<	0.0727	<	*2.9891*
M71	2.2998	4.5882	0.7082	3.0960	0.7745	0.1997	0.8954	0.1419	0.8293	0.1350	0.4120	0.0638	0.3563	0.0458	*14.5459*
M75	2.0666	4.4003	0.7238	3.6772	1.2042	0.3002	1.4905	0.2299	1.1922	0.1828	0.5441	0.0653	0.3426	0.0391	*16.4588*
M91	0.7746	1.3625	0.2239	0.8749	0.2407	0.0527	0.2823	0.0566	<	0.0344	0.1161	<	<	<	*4.0187*
M113	1.8195	3.7926	0.5323	2.3632	0.6674	0.1969	0.734	0.1342	0.6624	0.1131	0.2949	0.0483	0.2428	0.0316	*11.6332*
M48	0.8357	1.5819	0.3205	1.5307	0.4664	0.1106	0.4302	0.0733	0.4297	0.0636	0.1921	<	0.1739	<	*6.2086*
M43	0.8520	1.9792	0.2921	1.3698	0.3993	0.1417	0.6475	0.0914	0.4959	0.0818	0.2589	0.0304	0.1878	0.0233	*6.8511*
M54b	1.1845	2.7227	0.4182	2.0135	0.5170	0.1712	0.7572	0.1192	0.6054	0.1096	0.2754	0.0348	0.1948	0.0247	*9.1482*
M90	1.1506	2.5711	0.4243	1.9894	0.6293	0.1782	0.8891	0.1504	0.6712	0.1246	0.3936	0.0427	0.3661	0.0401	*9.6207*
M1	1.508	3.4394	0.4621	1.8014	0.5416	0.1708	0.7872	0.1186	0.5736	0.1079	0.3467	0.0571	0.3202	0.0439	*10.2785*
M6	0.6732	1.4689	0.2265	1.0596	0.3303	0.1102	0.4714	0.0661	0.3736	0.0709	0.1835	0.0353	0.1924	0.0234	*5.2853*
M82	1.4342	3.0074	0.4855	2.2087	0.7127	0.1998	0.9788	0.1455	0.7442	0.1379	0.3699	0.0537	0.2861	0.0369	*10.8013*
M87	1.1048	2.5496	0.4064	1.8779	0.7043	0.1910	1.0290	0.1418	0.7372	0.1409	0.3787	0.0512	0.3801	0.0463	*9.7392*
M7	0.1553	0.3778	0.0605	0.2764	<	0.0229	<	<	0.0839	<	0.0679	<	0.0676	<	*1.1123*
M54m	0.9704	2.3456	0.3433	1.6981	0.4677	0.1575	0.7451	0.1125	0.5542	0.1001	0.2432	0.0278	0.1683	<	*7.9338*
M110	2.3141	3.203	0.6961	2.8458	0.7970	0.2282	1.0977	0.1615	0.8704	0.1808	0.4251	0.0584	0.3184	0.052	*13.2485*
M115	5.6823	11.345	1.5099	5.9587	1.3876	0.3167	1.3675	0.2275	1.2163	0.1978	0.5862	0.0738	0.5059	0.0582	*30.4333*
M117	5.2612	10.383	1.3994	5.6341	1.3436	0.3265	1.5075	0.2353	1.1795	0.2207	0.6527	0.0755	0.4960	0.0664	*28.7813*
M116	5.0098	9.8518	1.296	4.8543	1.1605	0.3328	1.2549	0.2209	1.0418	0.1940	0.5601	0.0828	0.4623	0.0674	*26.3894*

Table 3. Rare earth element analysis of selected specimens by ICP-MS quoted as ppm. < = value below detection limits.

element	S	Cl	Cr	Co	Ni	Cu	Zn	As	Se	Ag	Cd	Sn	Sb	Te	W	Pb	Bi
atomic number	16	17	24	27	28	29	30	33	34	47	48	50	51	52	74	82	83
detection limit	*13*	*17*	*3*	*4*	*2*	*3*	*3*	*5*	*2*	*2*	*3*	*11*	*2*	*5*	*30*	*7*	*5*
M14	25	860	12	<	12	<	<	27	4	<	7	<	3	15	<	<	<
M47	104	569	17	<	11	<	<	41	3	<	9	<	3	19	36	<	<
M71	4661	2185	18	<	9	<	5	34	4	<	7	<	<	19	<	<	<
M75	121	1916	19	<	7	<	<	40	5	<	12	<	3	15	38	<	<
M91	<	506	12	<	12	<	<	39	4	<	7	<	3	16	<	<	<
M113	1828	668	14	<	6	<	4	32	4	<	12	<	3	16	37	<	<
M48	372	605	12	<	14	<	<	30	4	<	7	<	3	14	<	<	<
M43	77	412	7	<	10	<	<	48	4	<	6	<	4	15	<	<	<
M54b	63	932	9	<	12	<	4	39	4	<	8	<	4	16	<	<	<
M90	2448	984	18	<	9	<	<	42	4	<	6	<	<	14	<	<	<
M1	312	808	18	<	18	<	5	76	4	<	5	<	3	14	33	<	<
M6	3948	832	10	<	14	<	4	39	4	<	9	<	3	16	<	<	<
M82	84	742	13	<	14	<	4	46	4	<	8	<	<	16	33	<	<
M87	1273	610	8	<	10	<	17	42	3	<	8	<	<	18	<	<	<
M7	221	447	10	<	16	<	<	21	3	<	10	<	3	15	<	<	<
M54m	36	673	8	<	20	<	<	64	4	<	8	<	6	14	31	<	<
M110	6866	847	<	<	13	<	4	40	4	<	8	<	3	15	<	<	<
M115	4010	2235	27	<	16	<	8	58	4	<	7	<	4	12	<	<	<
M117	5116	1780	30	<	15	<	8	55	4	<	11	<	4	13	<	<	<
M116	4368	2667	29	<	15	<	10	56	3	<	10	13	3	14	<	<	<

Table 4. Trace element analysis of selected specimens by XRF quoted as ppm. < = value below detection limits.