R. A. Ixer & P. Turner

A detailed re-examination of the petrography of the Altar Stone and other non-sarsen sandstones from Stonehenge as a guide to their provenance

R. A. Ixer & P. Turner, (2006) "A detailed re-examination of the petrography of the Altar Stone and other non-sarsen sandstones from Stonehenge as a guide to their provenance" from Wiltshire archaeological and natural history society, *Wiltshire archaeological and natural history magazine* **99** pp.1-9, Devizes: Wiltshire Archaeological and Natural History Society ©

Staff and students of the University College London are reminded that copyright subsists in this extract and the work from which it was taken. This Digital Copy has been made under the terms of a CLA licence which allows you to:

* access and download a copy;
* print out a copy;

Please note that this material is for use ONLY by students registered on the course of study as stated in the section below. All other staff and students are only entitled to browse the material and should not download and/or print out a copy.

This Digital Copy and any digital or printed copy supplied to or made by you under the terms of this Licence are for use in connection with this Course of Study. You may retain such copies after the end of the course, but strictly for your own personal use.

All copies (including electronic copies) shall include this Copyright Notice and shall be destroyed and/or deleted if and when required by the University College London.

Except as provided for by copyright law, no further copying, storage or distribution (including by e-mail) is permitted without the consent of the copyright holder.

The author (which term includes artists and other visual creators) has moral rights in the work and neither staff nor students may cause, or permit, the distortion, mutilation or other modification of the work, or any other derogatory treatment of it, which would be prejudicial to the honour or reputation of the author.

This is a digital version of copyright material made under licence from the rightsholder, and its accuracy cannot be guaranteed. Please refer to the original published edition.

Licensed for use for the course: "ARCL3098 - ARCL3098: The Age of Stonehenge".

Digitisation authorised by June Hedges

02626608

WILTSHIRE ARCHAEOLOGICAL
AND NATURAL HISTORY SOCIETY

BOARD OF TRUSTEES (from 1 January 2006)

Chairman
W A Perry, MSc

Deputy Chairman
D L Roseaman, BSc(Eng), CEng, MIMechE

Other Elected Trustees
Miss A Arrowsmith, BSc (Hons) Microbiology (Lon)
Lt Col C Chamberlain
Ms C Conybeare, MA, FMA
J A Gunter, BA (Hons)
Mrs V Knowles
Mrs W P Lansdown (Hon. Treasurer/Company Secretary)
J S S Stewart, BSc (Oxon), MB, ChB (Glasgow), FRCS (Ed). FRCS (Glasgow), FRCS
Mrs J Triggs

Nominated Trustees
J N Fogg (Member, Kennet District Council)
A Molland (Member, Wiltshire County Council)
P R Saunders, BA, FSA, FMA, FRSA (Director, Salisbury & South Wiltshire Museum)
Mrs J Swabey (Member, Wiltshire County Council)
Mrs K J Walling, BA (Hons), PGCE (Member, Devizes Town Council)

In attendance:
T Craig BA, MA, AMA, DipMgmt (Wiltshire County Council Heritage Services Manager)

OFFICERS

Curator	P H Robinson, PhD, FSA, AMA
Assistant Curator	Miss L Webb, BA, MA
Sandell Librarian and Archivist	Mrs L Haycock, BA (Hons), PhD, FRHistS, Dip ELH, Cert. Ed.
Outreach Officer	Miss A Siviter, BA, MA
Volunteer Co-ordinator	Mrs H Ault, BA
Finds Liaison Officer (Wiltshire)	Miss C A Hinds, BA (Hons), MA
Documentation Project Manager	A Martin, BA (Hons), M.Phil, PhD
Documentation Officer	Ms P Luscombe, BA (Hons), DMS

Wiltshire Archaeological & Natural History Magazine, vol. 99 (2006), pp. 1-9

A detailed re-examination of the petrography of the Altar Stone and other non-sarsen sandstones from Stonehenge as a guide to their provenance

by Rob A. Ixer[1] and Peter Turner[2]

The Altar Stone at Stonehenge has a disputed origin and sandstones from both the Devonian (Old Red Sandstone) Cosheston Group and the Senni Beds in South Wales have been proposed as possible parent lithologies. A thin section of the Altar Stone together with those of four fragments of non-sarsen sandstone excavated at Stonehenge and attributed to the Cosheston Group sandstones have been re-examined. These detailed petrographical descriptions are compared/contrasted with earlier published accounts and with new descriptions of typical lithologies from the Senni Beds of South Wales.

The Altar Stone is petrographically very similar to fine- to medium-grained, calcareous sandstones found in the Senni Beds and this is consistent with the suggestion they are the best candidates for being the parent rock. The Altar Stone is, however, very different lithologically from the four fragments; comparing their petrography with that published confirms that that they are probably not Cosheston Group sediments and that their degree of deformation may indicate that they are older than the Devonian. As their origin remains unknown it is still not possible to provenance them. None of the five samples originated from the Old Red Sandstone rocks around Milford Haven.

Introduction

A lithologically unremarkable, grey-green, micaceous sandstone is perhaps the most famous Welsh lithic export in the world. Stone 80 (numbering after Atkinson, 1979), namely the fallen 'Altar Stone' from Stonehenge, at nearly 5m long, is the largest bluestone (following the convention that uses the term to denote all non-sarsen lithologies) at the site, weighs over six tonnes and is the only sedimentary rock to be visible amongst the otherwise igneous bluestones (Figure 1).

The geographical, as opposed to mythical, origin of this sandstone (alongside all the other stones at Stonehenge) has been a matter of speculation since the mid-18th century and is succinctly reviewed in Thorpe *et.al.* (1991, 119-124). William Stukeley (1740) thought the Altar Stone to be a Derbyshire marble, Phillips in Maskelyne (1878, 151) noted it was 'a grey sandstone composed of quartz sand, silvery mica and dark grains (possibly hornblende)' and suggested it was Devonian (Old Red Sandstone) or Cambrian in age and Davies on the same page in Maskelyne noted the nearest similar looking sandstones cropped out at Frome in Somerset. H. H. Thomas (1923, 244-245) too, believed the Altar Stone to be Devonian in age and his is the most complete, published, macroscopic and microscopic description of the Altar Stone to date. He suggested that the Altar Stone compared well with certain green, micaceous and calcareous Old Red Sandstones in South Wales, namely the Senni Beds that crop out in a band between Kidwelly and Abergavenny or the Cosheston Beds of Pembrokeshire close to Milford Haven. Thomas highlighted the difficulty of deciding between the two formations either in the field or in the laboratory.

Thomas's work has been the basis for subsequent

[1]Dept. of Geology, University of Leicester, University Road, Leicester, LE1 7RH [2]School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT

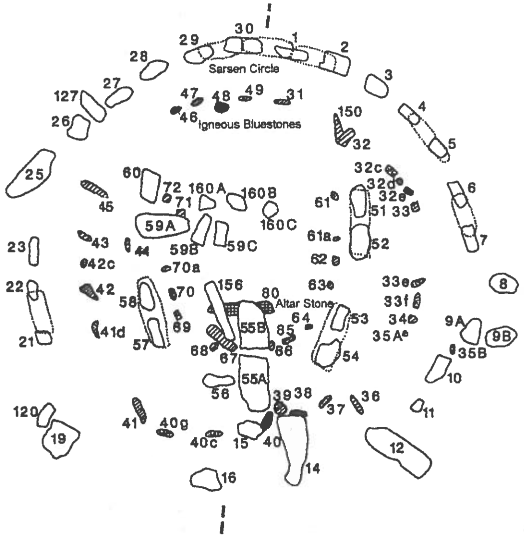

Fig. 1. Plan of the central stone settings after Atkinson (1979) and modified from Thorpe et al. (1991). Sarsens are plain and the bluestones have a textured infill. The Altar Stone close to the centre is number 80.

attempts to provide a provenance for the stone with most workers favouring the Senni Beds over the Cosheston Group.

Later, R.G. Thomas in Thorpe *et al.* (1991, 152-153) macroscopically described the Altar Stone as highly micaceous and without a pervasive spaced cleavage and, based on his extensive knowledge of the Cosheston Beds (Thomas 1978), noted that the Senni Beds were 'the most likely parent unit for the Altar Stone'. He cautioned, however, that a thin section description was needed before any provenance could be given.

Most recently, Kellaway (2002, 59) has opined that the Altar Stone derives from the Lower Old Red Sandstone (Senni Beds) but probably where the outcrop pattern widens, namely to the east, in the Brecon Beacons. Kellaway's Brecon origin is informed by his views that an inferred Pliocene ice-sheet transported the Altar Stone to Wiltshire.

A more cautious approach to the origin of the Altar Stone is given by Clough and Cummins (1988, 156, thin section 277). Here, the Altar Stone is left unprovenanced and described as a 'micaceous sandstone' distinguished from four other non-sarsen sandstone fragments found in the Stonehenge area, namely 'Stonehenge Cursus' (thin section 275), at 'Stonehenge' (276) and from Aubrey Holes 1 and 5 (thin sections 444 and 450 respectively). These latter four are described as 'sandstone (Cosheston Beds)' by Clough and Cummins (1988, 157). Table 1 tabulates the five sections.

'Total petrography' using polished thin sections combined with high quality geochemistry has proved to be effective in describing and assigning fine-scale provenancing to lithics (Ixer 1996; Ixer *et al.*, 2004), including other bluestones from Stonehenge (Ixer 1996; 1997a). Total petrography alone has also proved other 'bluestones' not to be associated with the site (Ixer 1997b, 279; 1997c, 1-2). Sadly these techniques (combined transmitted and reflected light microscopy and XRF chemical analysis) were not possible for the present samples as all the sections have a glass cover slip over them, are too valuable to reprepare and can only be investigated in transmitted light. In transmitted light it is only possible to identify transparent or translucent minerals hence much of the potential mineralogy of a rock, most especially that of the abundant, opaque iron and/or titanium oxides, cannot be determined. These oxides display a wide range of mineralogical and petrographical complexity and are used alongside other 'heavy minerals', in the routine, geological provenancing of sediments and metasediments.

Cunnington (1884) identified five fragments of the Altar Stone, that he assumed resulted from dressing of the stone, amongst his loose finds, although they are now missing. Obtaining geochemical data using a non-destructive, portable XRF machine placed on the Altar Stone is possible but removing *in situ* material for petrographical and detailed geochemical characterisation is unlikely to be permitted. Therefore, the thin section labelled '277 Altar Stone Stonehenge' in the Salisbury Museum Collection is likely to remain, for the foreseeable future, the only piece of the monolith available for investigation. It is imperative then that it should be described as fully as possible and that this description becomes widely available.

Table 1 List of thin sections as given in *Stone Axe Studies 2*

Number and find spot	Type of sample	Rock type
TS 275 Stonehenge cursus	Loose Sandstone fragment	Fine metasandstone
TS 276 Stonehenge	Loose Sandstone fragment	Fine metasandstone
TS277 Altar Stone	Samples collected in situ?	Calcareous sandstone
TS444* Aubrey Hole 1	Loose Sandstone fragment	Fine metasandstone
TS450 Aubrey Hole 5	Loose Sandstone fragment	Fine metasandstone

*Thin section 444 is designated as OU9 in (Thomas 1991)

Table 2 Modal analyses of the Altar Stone based on 750 counts

Column 1 is the modal analysis, column 2 is the analysis recalculated without the calcite matrix and showing the rock to be a subarkose/sublitharenite based on the classification of Folk (1974).

Quartz	48.48	75.15
Potassium feldspar	3.44	5.33
Calcite	35.50	-
Plagioclase	1.32	2.05
Opaques	1.59	2.46
Clays	0.93	1.44
White mica	0.93	1.44
Rock clasts	4.50	6.98
Chlorite	0.79	1.23
Accessory minerals	2.51	3.90

To this end a large number of standard (3" x 1") thin sections of lithics collected from Stonehenge were loaned out by Dr Vin Davis on behalf of the Southwest Group of Museums and Art Galleries Implement Petrology Committee and included the five non-sarsen siliciclastics 275, 276, 277, 444 and 450. The first three thin sections were described in detail by the present authors and the last two briefly. All five were compared with representative samples of Old Red Sandstone siliciclastics from the Senni Beds near Kidwelly loaned by Dr G. Owen. Both authors independently described the Altar Stone thin section and later its mineralogical composition was determined by point counting (750 points) (Table 2).

Thin section mineralogical identifications were made following Kerr (1959) and Deer, Howie and Zussman (1992) and petrographical and lithological descriptions with reference to Folk (1974) and Adams *et al.* (1984).

The Altar Stone

Macroscopically Thomas (1923, 244-245) described the Altar Stone as 'a fine-grained, pale sage-green, micaceous sandstone with a partly calcareous and partly siliceous cement and with prominent mica along its divisional planes' (bedding/laminae). Microscopically he identified angular quartz, mica flakes, abundant chlorite and 'a greenish mineral that might be glauconite in a fine textured calcareo-siliceous matrix'. A heavy mineral 'residue' from the Altar Stone was 'exceedingly rich in angular, pink or colourless garnet' some grains being idiomorphic; other heavy mineral grains were less abundant but included zircon, tourmaline, rutile and anatase. This account can be compared with the present description.

Detailed petrography of thin section 277

Macroscopically the thin section shows the Altar Stone to be a fine-grained, buff-pale grey sandstone. Microscopically the rock is a very fine- to fine-grained, well-sorted sandstone with a mean grain size of 0.13mm and a maximum grain size of approximately 0.32mm. The clastic grains are angular to subrounded and the modal group is subangular. The grains predominantly show a high sphericity but a number of prolate grains with a width/length ration of <0.5 are also present.

The rock has a homogeneous fabric but bedding is observed by thin, less than 0.5mm wide, opaque mineral-dominated, heavy mineral laminae (Figure 2) and by the orientation of thin phyllosilicate laths, mainly white mica and chlorite, lying parallel to those laminae.

There is very little detrital, interstitial material. Authigenic kaolinite is locally present but the main matrix is a pervasive carbonate cement. A number of detrital grains float in the cement and show both pristine and corroded grain boundaries. The sandstone is only moderately compacted and the carbonate cement is probably pre- or syn-compaction.

Mineralogically, both visual inspection and

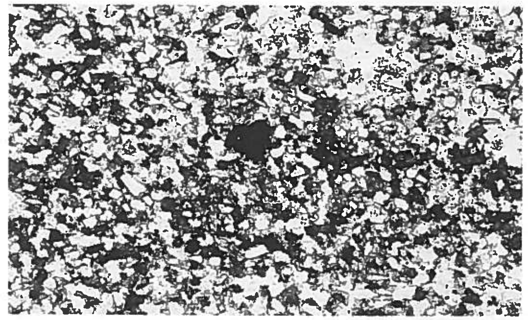

Fig. 2 Thin, heavy mineral laminae (east-west concentrations of black grains) alternate with quartz-rich bands. Angular to subangular quartz grains (white) are enclosed within carbonate (grey and speckled). An east-west orientated prismatic zircon lies above one of the heavy mineral bands (middle right hand edge). The average grain size of the quartz grains is 0.1 –0.15mm. Plane polarised transmitted light.

determination of the modal composition of the Altar Stone by point counting show quartz to be the most abundant detrital clast accompanied by lesser amounts of (in order of decreasing abundance) fine-grained rock clasts, alkali and plagioclase feldspars and phyllosilicates including white mica and a number of optically different chlorite minerals. Accessory minerals are dominated by equant, opaque mineral grains accompanied by zircon, tourmaline and rutile with lesser amounts of apatite and trace amounts of possible amphibole and garnet. Glauconite was not recognised. Modal analysis (table 2, column 2) shows the rock is a subarkose/sublitharenite.

Rounded to subangular, single quartz grains showing uniform extinction are present within the carbonate matrix (figure 3). Polycrystalline quartz clasts are rare but include some with strained extinction suggesting a metamorphic origin.

Untwinned or simply twinned, tabular alkali feldspar shows slight alteration; this is seen as pale brown/orange, turbid cores or as replacement by fine-grained white mica. Microcline, if present, is rare. Lath-shaped, multiple twinned, sodic plagioclase (albite?) is fresh to slightly altered. Neither of the feldspar groups, nor quartz, show authigenic overgrowths.

Muscovite laths lie parallel to the bedding but many show fine-scale kinking about quartz or feldspar grains, whilst others have splayed ends. Pale to dark green or brown-green chlorite laths showing a range of interference colours are widespread, lie parallel to bedding and show fine-scale kinking. Other chlorite patches are fine-grained mosaics. Although very minor amounts of biotite altering to chlorite occur, interlayered muscovite-chlorite grains are absent.

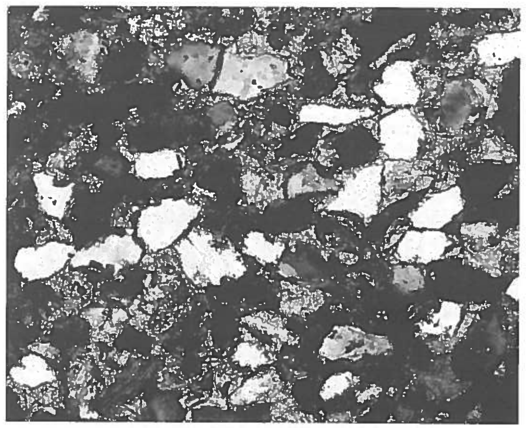

Fig. 3 Typical quartz-rich area at higher magnification. Angular to subrounded, exclusively monocrystalline quartz grains (white, uniform grey and black) float in a carbonate cement (grey and speckled). The concentric bands around many quartz grains are an optical effect. The average grain size of the quartz grains is 0.1 –0.15mm. Crossed polarised transmitted light.

Accessory minerals are concentrated in heavy mineral bands dominated by opaque iron titanium oxide minerals and by TiO_2 minerals including orange-brown rutile. Lesser amounts of euhedral to rounded zircon, green-brown tourmaline, apatite laths and rare, blue-green and brown amphibole and colourless ?garnet accompany the opaque minerals.

Rock clasts are the same size as the mineral clasts. Most are fine-grained, siliceous "cherts" that probably include acid volcanic lavas; minor amounts of quartz-chlorite or quartz-white mica phyllite are also present.

There is no primary matrix. Although fine-grained kaolinite locally infills void spaces between clasts, the main matrix/cement is an untwinned carbonate, optically identified as calcite.

The absence of mixed chlorite-muscovite grains may indicate that the sandstone is sub-greenschist in facies; it is essentially unmetamorphosed and has no tectonic fabric. This in turn suggests that rock is post Caledonian Orogeny in age and hence Devonian to Carboniferous (or younger) in age. Rock clasts and sparse garnet may indicate that the source area comprised first generation acidic rocks rather than high-grade metamorphics. The absence of authigenic overgrowths on quartz and feldspar is typical of many of the finer grained rocks from the Old Red Sandstone. However, the corroded grain margins indicate that early overgrowths might have been dissolved during calcite cementation.

Four Sandstone Fragments from Stonehenge and the Aubrey Holes

Thin sections 275 labelled 'rock, Stonehenge Cursus', 276 'rock, Stonehenge', 444 'rock, Aubrey hole 1' and 450 'rock, Aubrey hole 5' in the Salisbury Museum Collection have been identified as sandstones from the Cosheston Beds (Clough and Cummins, 1988). Detailed petrography of thin sections 275 and 276 shows them both to be clast-supported, metasandstones and very similar to each other. Briefer examination of sections 444 and 450 show them to be sufficiently similar to each other and to 275 and 276 that they require no further description.

Thin Section 276 was initially described by Judd (in Gowland 1902) as 'an argillaceous flagstone' with 'a mass of angular quartz grains of two sizes cemented with micaceous material. Small amounts of muscovite, chlorite and feldspar are present. Scattered fragments of volcanic material also occur'. K.C. Dunham in a letter (17/10/1947) to Dr Stone stated that it is 'an impure sandstone, colouration due to chlorite. Also muscovite, hydrobiotite and clay mica are present. Fresh oligoclase is a conspicuous minor constituent.' These descriptions can be compared with the present account that combines the results from sections 275 and 276.

Detailed petrography of thin sections 275 and 276

Microscopically rounded to elongated, monocrystalline quartz grains have syntaxial overgrowths about them; elsewhere touching quartz grains display serrated edges due to pressure solution effects. Some quartz grains have patchy extinction suggesting a metamorphic origin. Simply twinned, alkali feldspar including perthite is more abundant than polysynthetically twinned microcline; plagioclase has clean, syntaxial overgrowths on dusty cores and is partly replaced by calcite (in 276). All feldspars alter to fine-grained, white mica. Large, detrital chlorite, muscovite and rare biotite (altering to chlorite) laths are present. However, much phyllosilicate is authigenic and includes rounded, interlayered, muscovite-chlorite grains and fine-grained, white mica. This mica lies along the main planar fabric of the sandstones or forms cross-cutting veinlets lying at a high angle to bedding, suggesting a syn- or post-tectonic age; elsewhere, much fine-grained white mica occurs as selvages/fringes about quartz grains.

Angular, zoned zircon, orange-brown and green tourmaline, euhedral apatite, euhedral TiO_2 minerals and epidote plus opaque minerals including altered pyrite (in 275) are accessory minerals.

Rock clasts include polycrystalline quartz, shale and metashale, 'chert'/acid volcanics, chlorite-rich clasts and a little graphic granite. Rhombic carbonate forms a very minor, local cement or replaces plagioclase.

Petrography of Rock 444 and OU9

Section 444, was not studied in detail in the present study as preliminary investigations showed it to be very similar to 275 and 276. However, another thin section of the same rock sample has been described by R.G. Thomas (1991) and later by J. Huggett (1993) as sample OU9; their detailed petrographical descriptions are very like the present one for sections 275 and 276. They too noted that most rock fragments are 'chert' but include low grade metamorphics namely slates/phyllites, that garnet is almost missing from the heavy mineral suite, that abundant white mica shows preferred orientations and that there is a pervasive spaced pressure solution cleavage. Huggett classified the sample as a micaceous sublitharenite and suggested that the minor amounts of carbonate were siderite whereas Thomas (1991, figure 16.153) plots the rock in the middle of the subarkose field.

All the rocks have a marked tectonic fabric and are low-grade metasediments suggesting they suffered deformation during the Caledonian (or possibly Variscan) Orogeny. Although this does not eliminate Devonian/Carboniferous rocks, it also allows that either the sandstones are older Palaeozoic sediments or that they originated from outcrops present in the more tectonically deformed very west of Wales. Authigenic overgrowths on quartz and feldspars and the growth of neomorphic phyllosilicates are important characteristic of these sandstones and indicate a complex diagenetic and post-diagenetic history.

Sediments from the Senni Beds

The Lower Old Red Sandstone Senni Beds dominated by grey-green sandstones with lesser amounts of siltstones, conglomerates and calcretes are up to 380m thick and lie beneath the red-brown, unfossiliferous Brownstone Group. They crop out in South Wales from west of Kidwelly to the Welsh Marches and include widespread outcrops in the Black Mountains of Powys, Gwent and Hereford and Worcester. They are the lateral equivalent of the Cosheston Beds that are found to the west in southwest Dyfed. The Senni Beds notably carry plant remains and potentially this is an important macroscopic aid to identifying them and any artefact manufactured from them. Published petrographical descriptions of the rocks are rare and the first detailed sedimentological analysis of the Senni Beds is given by Owen (1995).

Thin sections of typical sandstone, siltstone and cornstone lithologies present within outcrops of the Senni Beds from a coastal exposure on the estuary of the River Taf at Craig Ddu were investigated in order to compare them with the Stonehenge samples. The outcrops are at the western end of the Senni Beds outcrop, closest to Milford Haven. The lithologies range from micritic limestones with minor amounts of muscovite and quartz (cornstones) to carbonate-poor, matrix-supported siltstones and carbonate-poor, clast-supported, very fine-grained sandstones and to fine- to medium-grained carbonate-cemented sandstones. Characteristically, all of the lithologies lack any significant signs of a tectonic fabric.

Although the overall mineralogy including the heavy minerals suite is similar, there are significant differences between the petrography of the siltstones and sandstones from Craig Ddu. Only the coarser grained sandstones have significant carbonate (>10% by volume) and long muscovite laths lying along bedding planes, whereas only the fine-grained lithologies carry significant interlayered chlorite-muscovite grains.

The fine- to medium-grained carbonate-cemented sandstones, as typified by thin section 86.31, resemble the Altar Stone and so are described in detail.

Macroscopically the rocks are grey, micaceous, fine- to medium-grained lithic arenites with a calcareous cement (Owen 1995, 223), but are pale grey-green in thin section.

Detailed petrographical description of Senni Beds sandstone 86.31

Microscopically the rock is a fine-grained, well-sorted sandstone with a mean grain size of 0.15mm and a maximum grain size of approximately 0.30mm. The clastic grains are angular to subrounded and the modal group is subangular. The grains are predominantly equant in shape, but a number of prolate grains are also present.

The rock has a homogeneous fabric but thin, planar bedding is observed by less than 0.5mm wide, phyllosilicate-rich laminae that are muscovite- and green and brown chlorite-rich. There is very little detrital, fine-grained, interstitial material/clay and the main matrix is a carbonate cement. Quartz and feldspar grains float in this cement and show both pristine and corroded grain boundaries.

Mineralogically, visual inspection shows quartz to be the most abundant detrital mineral accompanied by lesser amounts (in order of decreasing abundance) of fine-grained rock clasts, alkali and plagioclase feldspars and phyllosilicates including white mica and a number of optically different chlorites. Accessory minerals are dominated by equant, opaque mineral grains accompanied by zircon, tourmaline and rutile plus very rare amounts of garnet, sphene and anatase.

Angular to subangular, single quartz grains showing uniform extinction and no authigenic overgrowths are present within the carbonate matrix. Polycrystalline quartz clasts include quartzite and stretched quartz suggesting a metamorphic origin for them.

Untwinned or simply twinned, tabular, alkali feldspar, including some perthite, shows slight alteration; this is seen as pale brown/orange, turbid cores. Microcline, if present, is rare. Lath-shaped, multiple twinned, sodic plagioclase is predominately fresh and shows very rare, thin, authigenic overgrowths.

Long muscovite laths lie parallel to the bedding and many show fine-scale kinking about quartz or feldspar grains. Pale to dark green or brown-green chlorite laths show a range of interference colours and are widespread. They too lie parallel to bedding and show fine-scale kinking. Biotite, if present, is very rare. A single interlayered muscovite-chlorite intergrowth was identified.

Accessory minerals are concentrated in poorly defined heavy mineral bands. These bands are dominated by opaque iron-titanium oxides and TiO_2 minerals including orange-brown rutile. Lesser amounts of rounded, zoned zircon, dark green-brown tourmaline, sphene and subhedral garnet accompany the opaque minerals. A little authigenic anatase associated with carbonate infills void spaces.

Rock clasts are the same size as the mineral clasts. Many are fine-grained siliceous 'cherts' that include acid volcanic lavas but minor amounts of quartz-white mica phyllite, graphic granite and foliated feldspathic lava ('trachyte') are also present. The matrix/cement is untwinned carbonate, probably calcite.

The sandstone is unmetamorphosed and lacks any tectonic fabric. It lacks significant, authigenic overgrowths on its detrital quartz and feldspar clasts or any interlayered chlorite-muscovite grains. Its rock fragments and heavy mineral suite suggest that its source area comprised eroding acid igneous rocks rather than high-grade metamorphics.

Lithologically, it is clear that this rock shares many characteristics with the Altar Stone and since carbonate-cemented sandstones are common in the Senni Beds, one of them may well be the source of the Altar Stone.

In addition, although the fine-grained Senni Beds lithologies (very fine sandstones and siltstones) share certain mineralogical characteristics with the four Stonehenge rock fragments, the lack of a strong tectonic fabric in any of the rocks from the Senni Beds precludes them from being the source of those fragments.

Discussion

This paper represents the first detailed description of the Altar Stone for over eighty years and is in broad agreement with H.H. Thomas, other than his identification of abundant garnet and glauconite. Glauconite is a green, chlorite-like mineral and so, if present, has been subsumed under chlorite in the present description. The disparity over the amount of garnet is more significant and puzzling. Thomas noted significant amounts of garnet in his 'heavy residues' (Thomas, 1923, 244) but did not report garnet in his thin section description of the Altar Stone. Although trace amounts of garnet can be overlooked/underestimated in thin section the present study could not confirm significant amounts of garnet microscopically. The presence and amount of garnet is important as Thomas was struck by the coincidence between the garnet-rich nature of his Altar Stone 'heavy residues' and the unusually garnetiferous nature of the Cosheston Beds and it was the presence of these unusual amounts of garnet in both that led him to suggest the Cosheston Group might have been the origin of the Altar Stone. Without further sampling (this would require many grammes of Altar Stone to crush before separating the heavy minerals) the garnet problem must remain unresolved.

The Altar Stone shares sufficient petrographical similarities with carbonate-cemented Senni Beds fine-grained sandstones to state that the microscopic description reinforces earlier, macroscopic identifications of the Altar Stone as probably originating from the Senni Beds.

The dimensions of the Altar Stone are known and it should be possible to compare them to bed thicknesses and joint spacings within suitable, Senni Beds, calcareous sandstones. Were the Altar Stone anthropogenically transported to Stonehenge then coastal exposures would be a sensible first place to search but were natural agencies the prime mover then the search area is considerably widened.

The exact geographical location of the source bed, whilst it would be very interesting to know, is perhaps not as significant as knowing that the source for the Altar Stone is far from either the Preseli Hills and its environs or Milford Haven and that the rock does not appear to have any innate macro- or microscopic characteristics that mark it as special.

Petrographically this study allied with previous descriptions clearly shows that the four rock samples from Stonehenge (275, 276, 444 and 450) are low-grade metasediments and have the same lithology and provenance; their common grouping in *Stone Axe Studies Two* is confirmed. They are quite unlike either the Altar Stone (this is again in agreement with *Stone Axe Studies Two* (Clough and Cummins 1988)), or any lithology from the Senni Beds at Craig Ddu. The four rocks fragments differ from the Altar Stone and carbonate-cemented, Senni Beds sandstones as the four carry significant amounts of shaly rock fragments and mixed-layered muscovite-chlorite grains; they have abundant fine-grained, white mica along spaced cleavage and lack any carbonate cement. This suggests that the four rock samples originated from a different source area (geological provenance) and have suffered divergent diagenetic and post-diagenetic histories from the Altar Stone/carbonate-cemented Senni Beds lithologies. Although the fine-grained siliciclastics at Craig Ddu share more petrographical features with the four Stonehenge rocks, notably a lack of carbonate cement and presence of mixed layered muscovite-chlorite grains, there are significant differences. In particular their detrital rock clasts and metamorphic/tectonic histories as evidenced by their phyllosilicates are quite disparate.

The origin of these fragments remains contentious. Thin section 275 has been matched to British Geological Survey Slide E8148 with a suggested source from the shore of Mill Bay, Milford Haven estuary some 0.75 miles from Cosheston (pers. com. V. Davis 1996). By contrast R. G. Thomas (1991, 152-3), an authority on the Cosheston Group, compared sample 444 with a 'typical' sandstone from the Mill Bay Formation (Cosheston Group), taken from the Mill Bay (west) section and listed a number of 'fundamental dissimilarities' in both mineralogy and fabric. In particular he noted the absence of pervasive pressure solution seams and stress-related authigenic white mica but the presence of high-grade metamorphic rock fragments and a wide-ranging heavy mineral suite dominated by abundant garnet in the Cosheston Group lithologies. Further, he stated that the Senni Beds were not the source of sandstone 444 either and concluded that 'the compositional differences between these potential source formations (Senni Beds or Cosheston Group) and OU9 (444) are obvious' and (OU9) 'definitely did not derive from the Cosheston Group or Senni Beds'. Rather he suggests that OU9 might be a more tectonically deformed Devonian sandstone from westernmost Pembrokeshire (southwest Dyfed) but more likely from a Welsh Silurian or older Lower Palaeozoic sandstone formation. Based on the degree of metamorphism/tectonism shown by the four sandstone fragments detailed, thin section petrography supports this view.

Modern, detailed petrography suggests that none of the five sandstone samples have an origin within the Old Red Sandstone lithologies around Milford Haven. Therefore they cannot be cited as evidence for Milford Haven being the exit port for the bluestones as suggested by Atkinson (1979, 57 and108) and repeated by Hawkins (1970, 82) in their popular and influential paperback books.

Conclusions

The Altar Stone is confirmed as an unmetamorphosed, carbonate-cemented sandstone most probably from the Devonian (Old Red Sandstone) Senni Beds of South Wales. The exact geographical origin for the artefact is far from the Preseli Hills and Milford Haven.

The four other non-sarsen sandstone fragments collected from Stonehenge are not from the Senni Beds and probably not from the Old Red Sandstone Cosheston Group as has been suggested. Their tectonic fabric and metamorphism suggest that they may be from an older, more deformed, Lower Palaeozoic sandstone-bearing sequence. Without a knowledge of either their geological age or formation it is not possible to provenance them further.

Acknowledgements

The authors are grateful to Drs Vin Davis, Geraint Owen, Jenny Huggett and Olwen Williams-Thorpe for lending material and/or allowing permission to quote from their unpublished works. Dr Vin Davis is further thanked for his many acts of kindness and academic generosity and including perspicacious comments on an earlier draft, that allowed this study to be started and finished. The Constantine Palaeologos Research Fund is acknowledged for its usual assistance.

Bibliography

ADAMS, A.E., MACKENZIE, W.S. and GUILFORD, C., 1984, *Atlas of Sedimentary Rocks under the Microscope.* Harlow, Essex: Longman Scientific and Technical

ATKINSON, R.J.C. 1979, *Stonehenge.* Harmondsworth: Pelican Books

CLOUGH, T.H.McK and CUMMINS, W.A. (eds), 1988, *Stone Axe Studies, Volume 2,* CBA Research Report No. 67. London: Council for British Archaeology

CUNNINGTON, W. 1884. Stonehenge notes: the fragments. *WANHM* 21, 141-49

DEER, W.A., HOWIE, R.A. and ZUSSMAN, J., 1992, *An Introduction to the Rock-Forming Minerals, Second Edition.* Harlow, Essex: Longman Scientific and Technical

FOLK, R.L., 1974, *Petrology of Sedimentary Rocks.* Austin, Texas: Hemphills

GOWLAND, W. 1902. Recent excavations at Stonehenge. *Archaeologia* 58, 37 –118

HAWKINS, G.S., 1970, *Stonehenge Decoded.* Glasgow: Fontana Books

HUGGETT, J. 1993. *Stonehenge Project. Petrology of sandstones.* Unpublished consultancy report to Open University Earth Science Department. 9th November 1993 6pp

IXER, R.A. 1994, 'Does ore petrography have a practical role in the finger-printing of rocks?' in N. Ashton and A. David (eds), *Stories in Stone. Proceedings 10th Anniversary Conference. Oxford 1993.* Lithic Studies Occasional Paper 4. 10-23. London: Lithic Studies Society.

IXER, R.A. 1996. Ore petrography and archaeological provenance. *Mineralogical Society Bulletin,* 113, 17-19

IXER, R.A. 1997a, 'Detailed provenancing of the Stonehenge Dolerites using reflected light petrography: a return to the light'. in *A.* Sinclair, E. Slater, and J. Gowlett, (eds). *Archaeological Sciences 1995.* Oxbow Monograph 64, 11-17

IXER, R. 1997b. Steep Holm "Bluestones". *Current Archaeology* 151, 279

IXER, R. 1997c. Steep Holm "Bluestones". *Steep Holm Newsletter,* New Year 1997, 1-2

IXER, R.A., WILLIAMS-THORPE, O., BEVINS, R.E. and CHAMBERS A.C. 2004. 'A comparison between 'total petrography' and geochemistry using portable X-ray fluorescence as provenancing tools for some Midlands axeheads.' in E.A.Walker, F.Wenban-Smith and F.Healy (eds). *Lithics in Action.* Lithics Studies Society Occasional Paper 8. 105-115. Oxford: Oxbow Books

JUDD, J.W. 1902. 'Note on the nature and origin of the rock-fragments found in the excavations made at Stonehenge by Mr Gowland in 1901' in W Gowland. (ed) Recent excavations at Stonehenge. *Archaeologia* 58, 106 –118

KELLAWAY, G.A. 2002. Glacial and tectonic factors in the emplacement of the Bluestones of Salisbury Plain. *The Survey of Bath and District.* 17. 57-71

KERR, P.F., 1959, *Optical Mineralogy. Third Edition.* New York, London: Mcgraw-Hill

MASKELYNE, N.S. 1878. Stonehenge: the petrology of its stones. *WANHM* 17, 147-61

OWEN, G. 1994. Senni Beds of the Devonian Old Red Sandstone, Dyfed, Wales: anatomy of a semi-arid flood plain. *Sedimentary Geology,* 95, 221-35

STUKELEY, W., 1740, *Stonehenge a Temple restored to the British Druids.* London

THOMAS, H.H. 1923. The source of the stones of Stonehenge. *The Antiquaries Journal* 3, 239 – 60

THOMAS, R.G. 1991, 'Petrography and possible provenance of sandstone sample OU9 (Aubrey Hole 1) and a comment on the Altar Stone' Appendix 2 in R.S.Thorpe, O. Williams-Thorpe D.G.Jenkins and J.S.Watson (eds) The Geological Sources and Transport of the Bluestones of Stonehenge, Wiltshire, UK. *Proceedings of the Prehistoric Society,* 57, 152-3

THOMAS, R.G. 1978 *The Stratigraphy, Palynology and Sedimentology of the Lower Old Red Sandstone Cosheston Group, South-West Dyfed Wales.* Unpublished Ph.D thesis University of Bristol

THORPE, R.S., WILLIAMS-THORPE, O., JENKINS, D.G. and WATSON, J.S. with contributions by R.A. IXER and R.G. THOMAS. 1991. The Geological Sources and Transport of the Bluestones of Stonehenge, Wiltshire, UK. *Proceedings of the Prehistoric Society,* 57, 103-157