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Puddingstones and related silcretes of the Anglo-Paris Basin – an overview

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ABSTRACT

Anglo-Paris Basin silcretes are rarely observed in situ, particularly in the UK, do not form continuous layers, are mostly under a metre thick and are readily displaced in the surrounding soft sediments, moved by periglacial and/or subsequent human agencies (e.g. Stonehenge). Hertfordshire Puddingstone (HPS) was widely used in quern manufacture, mainly during the Romano-British period. New stratigraphic interpretations, and isotopic data presented here, are consistent with the HPS having formed at the Palaeocene–Eocene Thermal Maximum. The existing evidence is in favour of the HPS being a groundwater deposit, though other Tertiary silcretes in the Anglo-Paris Basin may be pedogenic.

1. Introduction

On 16 May 2014 a Conference on *Puddingstones and related Silcretes of the Anglo-Paris Basin* was held at the Geological Society of London, organised by the Geologists' Association, the Geological Society of London, and the Society of Antiquaries to review research on the subject and bring the findings to a wider audience. This overview summarises the principal findings that were presented at the conference. An excellent outcome of the meeting was that the speakers took away the ideas that were new to them and have incorporated them into their final papers. Whilst the evidence in favour of a sub-surface origin is favoured by many, there is evidence, particularly from France, that a single origin cannot be applied to all Tertiary silcretes. Evidence from diverse sources does however point to *the conclusion that* acid leaching of soils/clays in an exceptionally warm climate generated the silica cement.

There has long been widespread public recognition of the Tertiary silcretes, in both the UK and in northern France. As a result of this interest these rocks have been given many vernacular names such as puddingstone, breeding stone, sarsens, and grey-wethers, but their origin was not widely debated in geological circles before the 1970s. The Geologists' Association has a long tradition of field trips to view these rocks, including that led by Robinson (1994) and the field trip associated with the 2014 conference. These recent trips followed many earlier excursions (Green, 1890; Hopkinson and Whitaker, 1892; Woodward and Herries, 1905; Evans, 1953; Potter, 2013). Recent collaboration between archaeologists and geologists, on both sides of the English Channel, has brought previously separate lines of inquiry within the two communities together. The first discovery by geologists Bryan Lovell and Jane Tubb of a Roman quarry for Hertfordshire Puddingstone (Lovell and Tubb, 2006) was followed by archaeological work led by Chris Green (Green, 2016) of the Society of Antiquaries. This combined research helped a fusion of interests between the disciplines, leading to the joint 2014 conference. Following the 2014 conference, a second Roman quarry was discovered at Great Gaddesden in Hertfordshire, England. We include here an account of this latest development in archaeological–geological collaboration (Green et al., 2016). The area of the quarry has now been surveyed by LIDAR and joint studies are underway.

2. Geology

The origin of the Hertfordshire Puddingstone (HPS) has been much discussed over the years, with Hopkinson (1884) being the earliest study. This paper is a report of a the Geologists' Association excursion to Radlett, Hertfordshire, on 12th July 1884 in which the 'Hertfordshire conglomerate' is described as a

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'shore-deposit. . .the shingle-bed of flint-pebbles consolidated by the infiltration of silica' (Hopkinson, 1884, p. 453)", a description that is still accepted (Lovell and Tubb, 2006; Lovell, 2015; Lovell, 2016).

Although these silcretes are both geologically and culturally important rocks, in England at least, research into their origins is at something of a disadvantage. They are very rarely observed in situ; they do not form continuous layers, are mostly under a metre thick and the discontinuous concretions/rafts/lenses/boulders are readily displaced in the surrounding soft sediments, or are moved by periglacial and/or subsequent human agencies. A consequence of this is that the HPS features in Geological Survey reports rather than on maps, yet may be obvious features where found at the ground surface. Typically they are included in a periglacial slope deposit (gelifluctate), shown as 'head' on the British Geological Survey maps. A similar situation pertains in the Paris Basin, where pedogenic silcrete has been reworked into Pleistocene fluvial deposits.

Pebbles in the HPS are predominantly flint with very rare quartz and quartzite. They are typically well rounded, brown, or light to dark grey, variably stained red to brown. Occasional examples of HPS have a high proportion of fractured pebbles (Huggett and Longstaffe, 2016). Questions remain as to which lithostratigraphic units were silicified to form the HPS, and when the silicification took place. Catt and Doyle (2010) suggest three potential episodes of silicification: (1) after deposition of the Upnor Formation but before deposition of the Reading Formation, (2) soon after deposition of the Reading Formation basal pebble bed and (3) during breaks in deposition of the Reading Formation. All of these propositions would place the period of silcrete formation in the Lambeth Group of the Palaeocene Epoch. We may note that these timings could apply both if the HPS is a groundwater silcrete, or if silcrete formation was a surface phenomenon.

The papers in this volume discuss the mainly detached boulders of HPS in a range of ways, both geological and archaeological, beginning with the stratigraphy. The importance of correctly interpreting the stratigraphic position of the HPS is essential for understanding its possible relationship to the Palaeocene–Eocene Thermal Maximum [PETM]. It is reasonable to propose that the PETM warming event may have provided the environmental conditions conducive to silcrete formation, either as a tropical soil at the surface, or diagenetically within the host rock. Lovell (2016) and Tubb (2016) seek to constrain the date of deposition of the pebble bed host rock, and the date of silicification, focussing on evidence from the Palaeogene outlier at Colliers End, near Hertford and Ware in the northern part of the London Basin. The Colliers End Pebble Bed (CEPB, Lovell, 2016) has recently been exposed in situ through road building, and drilling of the Dowsett's Farm borehole also in Hertfordshire. The regional extent of the CEPB remains to be determined, although it is known to be at least 10 km from East to West (Hopson personal communication, quoted in Lovell, 2016). Tubb (2016) describes the stratigraphy and sediments of the Colliers End outlier using data from the Dowsett's Farm borehole, the A10 bypass and associated survey pits, plus historic data from the A120 road widening. From her observations she concludes that the HPS is of early Eocene age. The sequence of events she proposes are:

(1) Early Palaeocene regression led to exposure of flints.
(2) Marine transgression resulted in rounding of angular flints to rounded pebbles.
(3) Continued transgression led to deposition of the Upnor Formation, with both pebbles and fresh flints incorporated into the basal bed.
(4) Reading Formation: regression revealed a beach-line of rounded flint pebbles. The pebbles were partially reddened (by formation of a thin coating of haematite) on exposure to air.

Tubb (2016) goes on to propose that the sandy matrix then became cemented as a result of evaporation of groundwater, drawn upwards during the PETM. An early Eocene timing for silicification is broadly consistent with the scenarios proposed previously by Catt and Doyle (2010), Lovell and Tubb (2006) and here by Lovell (2016). Taking a sequence stratigraphic approach to understanding the timing of the CEPB, Lovell (2016) interprets the CEPB as a part of the Lambeth-2 depositional sequence of Knox (1996) that includes deposits assigned to both the Upnor Formation and the lower part of the Reading Formation. Lovell (2016) suggests that silicification occurred beneath the Mid-Lambeth Group land surface (the Mid-Lambeth hiatus), at the time of the PETM.

Ullyott and Nash (2016) looked at silcretes not just in the Anglo-Paris Basin but also across the world and show how their structure, both at a macro scale and in thin section, may indicate formation both through pedogenesis at the land surface or by groundwater in the sub-surface. They discuss in detail the four main forms of silcrete: (1) pedogenic, (2) groundwater, (3) drainage-line, and (4) pan/lacustrine. Unfortunately identification of silcrete type is complicated because seemingly diagnostic features result from more than one mode of origin. Indeed, the mode of origin of features is not everywhere clear, for example hollow tubes may be pedogenic root casts or sub-surface dissolution features. Pedogenic silcretes are typically laterally continuous (Thiry and Milnes, 1991), unlike the HPS that has a discontinuous distribution, although continuity is an imperfect guide to origin. Further complication results when composite profiles are formed as a result of more than one period of silicification: most commonly groundwater silcretes form at the base of older pedogenic silcrete.

Ullyott and Nash (2016) emphasise that all features, both macroscopic and microscopic should be taken into account when attempting to determine the origin of a silcrete. Non-pedogenic silcrete generally, but not in all cases, lacks the complex macroscopic structure of pedogenic silcrete, while the micromorphological features, principally caps above pebbles, geopetal structures below pebbles, and colloform structures, that were once thought to occur only in pedogenic silcrete are now known to form in sub-surface silcretes (e.g. Thiry and Milnes, 1991; Milnes et al., 1991; Callender, 1978; Ullyott et al., 2015). To aid correct identification of silcrete, Ullyott and Nash (2016) provide a checklist of criteria (their Table 1). Effective use of the checklist requires, ideally, an understanding of the wider context, especially the palaeolandscape, as well as observation of the silcrete features. As emphasised by Ullyott et al. (2015), it is not simply the presence or absence of features that should be taken into account when attempting to determine the forces of silcrete formation, but the combination, abundance and degree of development of features that make-up the rock.

At the conference in 2014, Christian Dupuis presented the findings of a study of a rare in situ example of silcrete that will be published at a later date. He discussed the so-called "Grès landéniens", from the terrestrial-lagoonal "Sparnacian" beds between the Late Paleocene (Thanetian sand units) and the earliest Eocene, that occur from the northern part of the Paris Basin to the southern part of Belgium. Both near-surface and sub-surface features are observed in the Grès landéniens, implying that silicification either has either occurred over a wide depth range, or surface silcrete features (e.g. roots), have developed on an older silcrete formed at depth and subsequently become exposed through erosion.

Huggett and Longstaffe (2016), and Baele et al. (2016), report novel petrographic studies that shed light on the environment of silcretisation. Both papers use cathodoluminescence (CL) to study cement structure. Huggett and Longstaffe (2016) combined CL petrography with oxygen stable isotope analysis, while Baele et al.

combined CL with trace element electron probe micro-analysis (EPMA). Baele et al. investigate quartz cement in silcretes and puddingstones from the uppermost Palaeocene to the lowermost Eocene in north France and Belgium. These deposits include terrestrial, coastal and shallow marine sediments. They found that syntaxial cement overgrowing quartz grains exhibits mostly dark to dark-blue and yellow-brown CL in Ti-rich silcretes, while the fine-grained cement that is found capping flint pebbles has a typical milky-white to yellow CL, characteristic of illuviated material in intergranular pores.

Whilst investigating the origin of silcretes using CL Baele et al. also found substitution of typically 1000–5000 ppm Al and K for Si in dark-blue CL quartz, which contrasted with $<$100 ppm Al values in detrital quartz grains and syntaxial overgrowth quartz with yellow-brown CL. The zoned Al-rich syntaxial cement is interpreted by Baele et al. as indicative of silicification under acidic conditions, and a fluctuating water table. Sub-aerial exposure of sediments containing both acid-liberating (pyrite) and Al-rich (feldspar and clays) minerals would provide a favourable, but not exclusive mechanism for the formation of silcretes. This corroborates the field-based interpretations of Ullyott and Nash (2006) for Sussex silcretes. Elemental mapping was also used to illustrate the distribution of Ti-oxides, which are clearly deposited as coatings on the quartz grains and predate syntaxial overgrowth. Up to 8% Ti is concentrated along with subordinate Fe and Al in a heterogeneous, microcrystalline cement, which typically forms illuviated structures. This Ti-rich cement predates syntaxial quartz overgrowth and indicates vadose processes, pre-dating sub-surface cementation.

Huggett and Longstaffe (2016) found a range of quartz sand luminescence colours indicative of a diverse provenance, while the flint pebbles show little variability, consistent with a single source. The oxygen isotope compositional range of the flint pebbles is consistent with chemical sedimentation at normal temperatures from Cretaceous seawater, and with the pebbles being derived from the Chalk Group (Upper Cretaceous). A small proportion of the pebbles have been fractured in situ; this fracturing post-dates deposition and pre-dates silicification. HPS quartz cementation style varies from prismatic overgrowths to cryptocrystalline matrix cement. CL images of the prismatic quartz cement obtained by Huggett and Longstaffe show luminescent/non-luminescent zonation, implying changes in water chemistry during precipitation. This feature is consistent with the fluctuating water table interpretation of Baele et al. (2016).

The oxygen isotopic results for HPS silica cement were used to estimate its temperature of formation. This calculation first requires an estimate of the oxygen isotopic composition of the water involved in cementation. Increased meteoric runoff, from the East Shetland Platform and Scottish Highlands (Collinson et al., 1985; Coward et al., 2003; Zacke et al., 2009) probably accompanied the upward spike in temperature associated with the PETM (Charles et al., 2011). Hence a precipitating water source was assumed, that is: marine with fresh water dilution, similar to that determined by Zacke et al. (2009) from sharks teeth. Calculated temperatures for silica cementation range from 16 to 36 °C. Temperatures towards the higher part of this range are more probable, due to the strong possibility of the cement silica being contaminated by flint silica, and increased marine evaporation due to elevated temperatures. The multiple generations of silica cementation almost certainly would have involved a range of temperature and $\delta^{18}O_{water}$. Notwithstanding this complexity, the oxygen isotopic compositions of the silica cement strongly support silcrete formation from meteoric ground waters similar to those likely to have been present during the PETM in the region of what is now the London-Paris Basin. This strengthens the case presented by Lovell (2015, 2016) for HPS formation during the PETM.

3. Archaeology

Parker-Pearson (2016) gives an account of the silcrete or 'sarsen' blocks erected at Stonehenge around 4500 years ago, during the Late Neolithic. The huge sarsen blocks erected at Stonehenge, up to 9 m long, were manoeuvred into position as uprights and lintels. Recent research has completely revised Stonehenge's chronology and sequence to reveal that it was built in five constructional stages (Darvill et al., 2012). Geological provenancing of Stonehenge's silcrete monoliths has so far been largely unsuccessful. For more than 300 years, researchers have suspected that the majority of Stonehenge's sarsens were taken from the Marlborough Downs, 30 km north of Stonehenge. Sarsen was used for building megalithic monuments in Kent, Dorset and Oxfordshire so it is quite possible that some of these regions might have provided stones for Stonehenge, though Marlborough Downs remain the most likely source, along with areas south of the Kennet such as Lockeridge.

In contrast to this lack of interest or success in sarsen provenancing, research into the geochemistry and petrography of Stonehenge's Welsh bluestones has made huge strides in recent years. Recent work has established chemical matches with outcrops on the north side of the Preseli Hills in southwest Wales at Carn Goedog and its environs, and not the south side as previously thought (Bevins et al., 2014). Similarly, the source of the sandstone Altar Stone is not the Cosheston Beds of Milford Haven in southwest Wales, as once suggested, but the Senni Beds (Devonian) of south central Wales, perhaps from the Brecon Beacons (Ixer and Turner, 2006). One of the types of rhyolite found at Stonehenge has also been traced not to the Preseli Mountains but to an outcrop known as Craig Rhosyfelin, within a valley 5 km from the base of their northern slope (Ixer and Bevins, 2011).

The exotic provenance of the bluestones reveals that the choice of material for the first Stonehenge was not based on local availability. The extent to which this was also the case for the sarsens remains to be resolved. The Cuckoo Stone and the Tor Stone at Bulford (also in Wiltshire) are proof that local sarsens could have been selected for Stonehenge if the desire was merely for stones, of whatever size or shape, to be erected during Stage 2. It may be that constructional requirements over-rode any significance of place in terms of where those large and tabular blocks might be found. Disappointingly, geochemical variation within individual sarsen stones has been found to be greater than the geological variation between different stones, though some stones have distinctive macroscopic features that may allow them to be correlated with in situ stones elsewhere. Future provenance work will also require a range of spectroscopic and electron beam techniques, such as those utilised by Baele et al. (2016).

Green (2016) provides a detailed account of quern history, manufacture and distribution. The uses of silcrete have mainly been (a) the manufacture, usually, from puddingstone, of querns (hand mills for grinding flour), and occasionally millstones, in the Late Iron Age and Roman periods (largely first century BC to first century AD); (b) kerbstones, paving blocks, and gate posts in the nineteenth and twentieth centuries; and (c) the local use of sarsen as a building stone, chiefly from mediaeval times (Green, 2016). Although massive and extremely hard, sarsen was never favoured for querns and millstones, as it is difficult and dangerous to work. HPS was very little used before Roman times as it was too hard a rock to work, and perhaps required the impetus of the Gallo-Roman industry in Normandy and Worms Heath in Surrey, to show how it could be exploited. Exploitation had ceased by (at the latest) AD 150 (Major, 2004), when cheap vesicular basalt lava querns from NW Germany were being imported in bulk. Extraction or working of the rock may therefore be constrained to the Romano-British period, from about AD 50 to 150 (Green, 2016). Sarsen querns and millstones are not abundant even in areas where sarsen abounds, or where there is no hard rock at all, as in Bedfordshire, to the north of the source rock localities. Saddle querns, where the top stone was rubbed to-and-fro by hand (Peacock, 2013, chapter 2) were relatively easily made; rotary querns, an invention of the European Middle Iron Age, were however much more difficult to make, requiring the first imperfect steel tools, considerable persistence, and very frequent re-sharpening. The geologically contemporary or near-contemporary silcrete-conglomerate 'puddingstones' of Normandy and the Chilterns held a great advantage over sarsen in grinding flour: the Tertiary flint pebbles embedded in the sarsen matrix could be roughened by light hammering to form a surface with many sharp cutting edges. The great hardness of these stones and the potential for roughening the surface of embedded flint pebbles means that they would have been excellent for milling: fast cutting, but slow wear (and hence much less silica in the flour than a sandstone might produce).

HPS querns are distributed in great numbers across East Anglia in eastern England, an area which lacks its own hard rocks, and even further afield. Collation of recorded HPS boulders shows that the rock is found over a much more restricted area than are the HPS querns. The great bulk of the available rock lay on the Chiltern dip slope and its valleys, and is associated with periglacial disturbance of the Palaeogene deposits to form Plateau Drift (Catt and Doyle, 2010, 106–108). An absence of convincing instances to the north and west of the chalk escarpment of the Chiltern Hills usefully defines an area in which it can be assumed that any boulders have been humanly transported. In Hertfordshire most puddingstone concretions will have been derived from the Plateau Drift and have been taken from the surface, or dug out if partially exposed. In Roman and later times, concretions were divided by cutting wedge-shaped slots and driving wedges into the rock to make 'slices'. Trimming the 'slices' to size involved successively finer work with hammer or pick, the shape being formed with a technique similar to flint-knapping. The querns were bored from both sides, hourglass-fashion. As the Romans possessed no drill nearly as hard as silica, it is thought that broken Puddingstone waste was used for boring. The finished stones were fitted out with (usually) four iron elements: a spindle to act as pivot, a ring about 25 mm in diameter to run round it, a driving band around the periphery of the top stone, and an eye to receive the ceiling pole by which such querns were turned.

Well over 700 HPS querns have been catalogued, excluding any possible double records. Each pair of stones will have consumed 80 kg, perhaps more, of this rather scarce rock, and it seems improbable that the 700+ now known represents even 10% of the original 'population. On the basis of that conservative estimate, the Romano-British quern industry would have consumed >560 tonnes of rock in the space of 50–100 years. This demonstrates most clearly that the former extent of the HPS was far greater than that of today and that the Chiltern Hills have been largely denuded of these boulders. The discovery of two Roman puddingstone quarries (Lovell and Tubb, 2006; Green et al., 2016) will help us to understand better the extent and nature of this vital Roman industry.

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