Acta Geologica Polonica, Vol. 71 (2021), No. 3, pp. 287–304
DOI: 10.24425/agp.2020.134555

The erratic rocks of the Upper Cretaceous Chalk of England: how did they get there, ice transport or other means?

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ABSTRACT

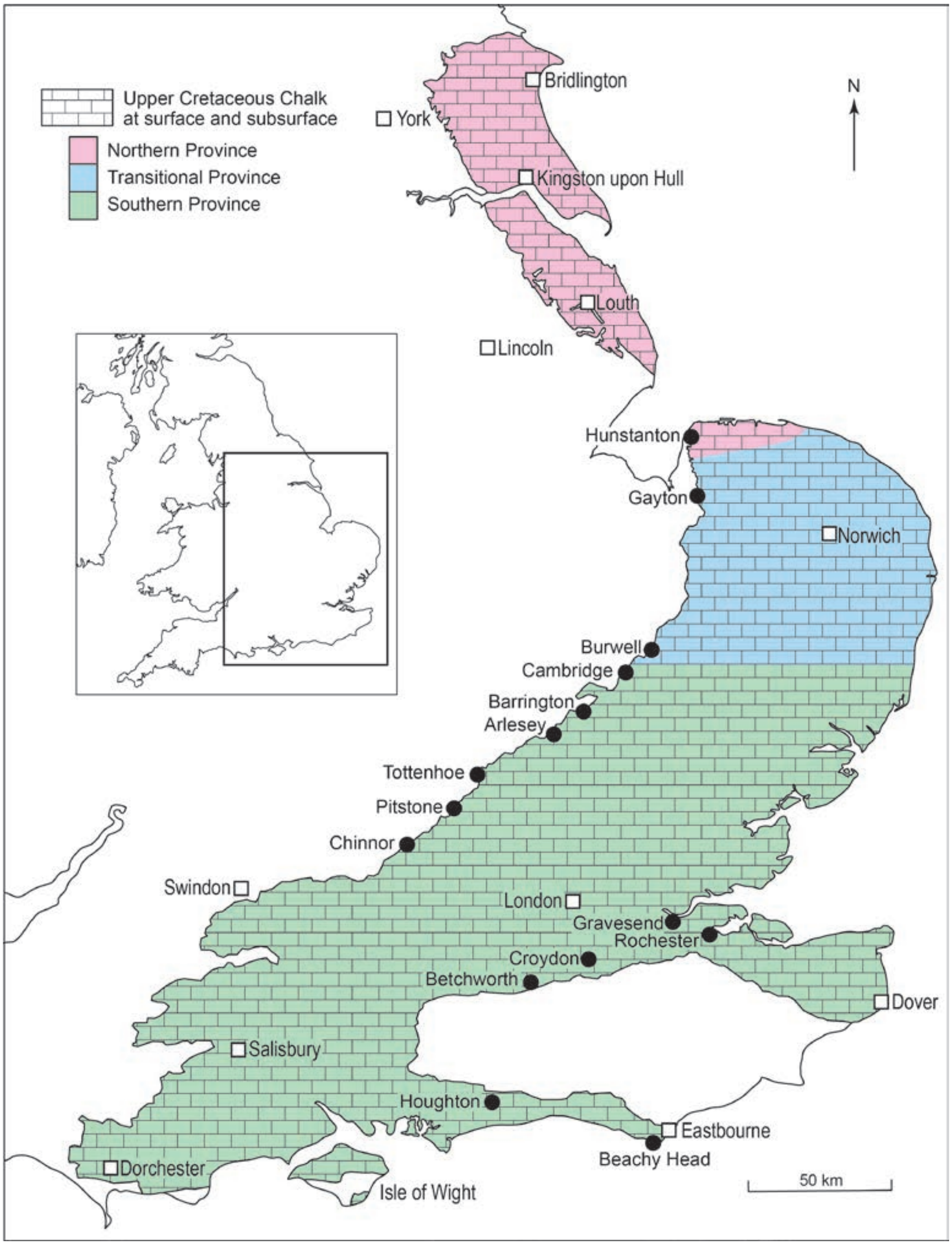
Jeans, C.V. and Platten, I.M. 2021. The erratic rocks of the Upper Cretaceous Chalk of England: how did they get there, ice transport or other means? *Acta Geologica Polonica*, **71** (3), 287–304. Warszawa.

Rare erratic clasts – extraneous rock types – occur in the Upper Cretaceous Chalk, including a local basal facies, the Cambridge Greensand. The underlying Upper Albian Gault Clay and the Hunstanton Red Chalk Formations have also yielded erratics. The discovery of these erratics, their description and the development of hypotheses to explain their origins and significance are reviewed. They became the subject of scientific interest with the interpretation of a particularly large example "The Purley Boulder" by Godwin-Austen (1858) as having been transported to its depositional site in the Chalk Sea by drifting coastal ice. Thin section petrography (1930–1951) extended knowledge of their diverse provenance. At the same time the Chalk Sea had become interpreted as warm, so drifting ice was considered out of context, and the preferred agents of transport were entanglement in the roots of drifting trees, as holdfasts of floating marine algae, or as stomach stones of marine reptiles or large fish. Reconsideration of their occurrence, variable nature and sedimentary setting suggests that there are three zones in the English Chalk where erratics may be less rare (1) near the base of the Cenomanian in the Cambridge area, (2) the Upper Cenomanian–Middle Turonian in Surrey, and (3) the Upper Coniacian and Lower Santonian of Kent. The assemblage from each level and their sedimentary setting is subtly different. Present evidence suggests that the erratics found in the Upper Albian–Lower Cenomanian and the Upper Cenomanian–Middle Turonian zones represent shallow water and shoreline rocks that were transported into the Chalk Sea by coastal ice (fast-ice) that enclosed coastal marine sediments as it froze. The Upper Coniacian and Lower Santonian erratics from Rochester and Gravesend in Kent are gastroliths.

Key words: Cretaceous; Chalk; Erratics; Gastroliths; Fast-ice; Palaeogeography; NW Europe.

INTRODUCTION

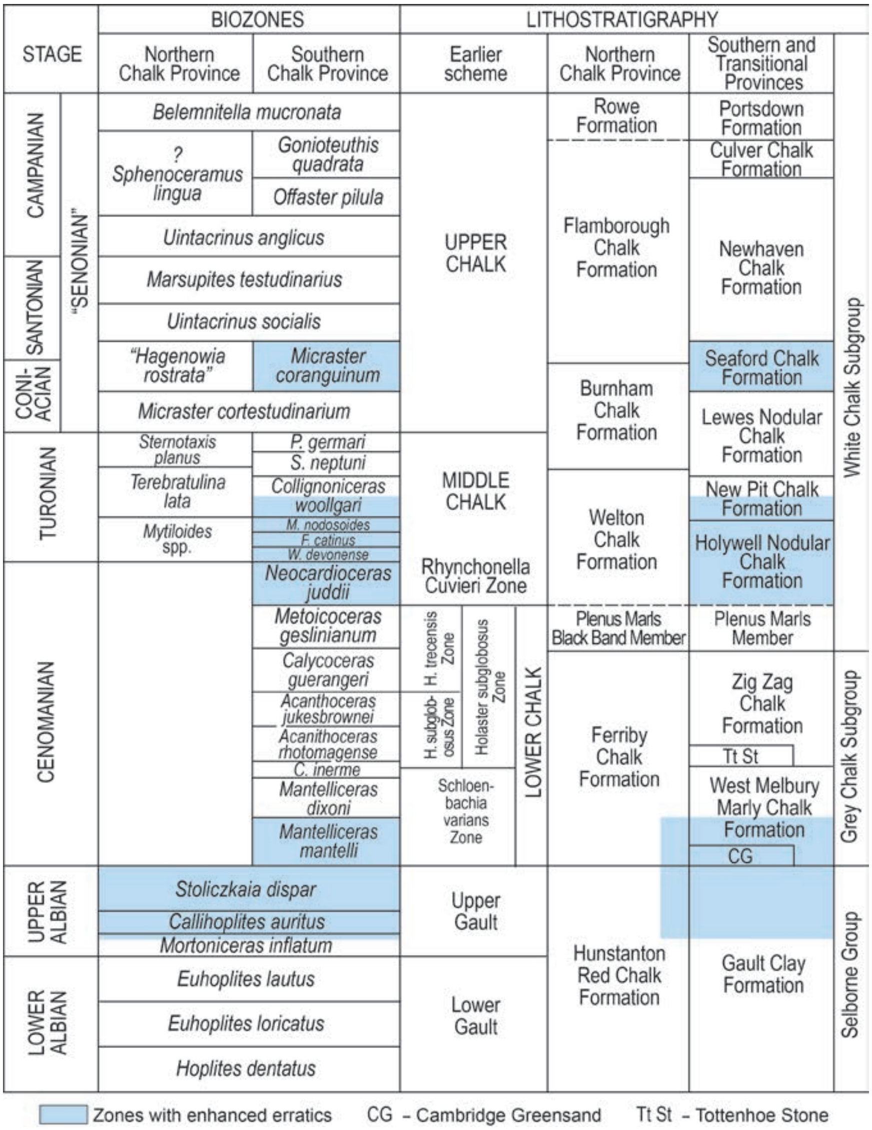
The presence of very occasional clasts of extraneous rock types in the Upper Cretaceous Chalk Formation of England was well known among collectors in the first half of the 19th Century. Many entered the collections of gentlemen scientists with geological interests. The rock types varied from sedimentary, through metamorphic and igneous to volcanic scoria and masses of coal (Godwin-Austen 1858, 1860). In size they ranged from small pebbles to boulders, in shape they varied from angular to well rounded, very occasionally having highly polished surfaces. They have been referred to by authors as stones, erratics, or dropstones. In this paper they will be referred to as erratics for reasons that will be discussed later. Extraneous clasts are also known from the Upper Cretaceous Chalk of Northern Ireland, northern France, Germany, Denmark and Sweden, however they seem to be absent from the Chalk of eastern Europe (Chumakov 1998).



Text-fig. 1. Distribution of (1) the surface and subsurface of the Upper Cretaceous Chalk Formation in England, (2) the southern, transitional and northern provinces for latest Albian and early Cenomanian times, and (3) locations.

HISTORICAL RECORD OF DISCOVERY AND INTERPETATION

In England, Chalk erratics became a topic of particular scientific interest through Godwin-Austen's masterly description and interpretation of the 'Purley Boulder' presented at the meeting of the Geological Society of London on 16th December 1857 (published 1858). The 'Purley Boulder' was excavated from a chalk pit near Croydon (Text-fig. 1). It was a large, rounded but now broken (Text-fig. 7G), granitic boulder ~90 cm in length and at least 30 cm in diameter (Godwin-Austen 1858; Woolnough and David 1926). It had been excavated by the quarrymen but



Text-fig. 2. Stratigraphic scheme (based on Jeans 2006) showing the zones of relative abundances of erratics in the Gault, Red Chalk and Chalk of England.

the rounded mould was still visible when Godwin-Austen visited the site. The host chalk horizon is thus known to be Upper Chalk of the *Micraster coranguinum* Zone (Text-fig. 2). Intimately associated with the boulder were substantial blocks of gabbroic rocks (each up to 9–12 kg) and well-sorted quartzose sand and gravel. Godwin-Austen (1858) considered all possibilities about their origin and emplacement and he drew the conclusion that the only reasonable means of transport of such a large associated mass of different rocks and sand, typical of a rocky coastal region, into the low energy environment of the Chalk Sea was by the drifting of coastal ice that had picked up its load from a distant shore. Such an explanation for the presence of smaller Chalk erratics, but still of considerable size, seems to have been accepted as the most likely means of transport during the late 19th and the beginning of 20th century.

Collections of erratic clasts from the Cambridge Greensand were also growing during the second half of the 19th Century and the first two decades of the 20th Century, as this horizon was being commercially worked for its phosphatic nodules as a source of superphosphate as a fertilizer and for munitions. Sollas and Jukes-Browne (1873, pp. 13–16) and Bonney (1872) recognised that the assemblages included rocks only known to occur in Wales, northern England, Scotland and possibly Norway, requiring long distant transport. Sollas and Jukes-Browne (1873, pp. 13–16) described scratched surfaces on a clast of silicified limestone that were overgrown by Cretaceous epifauna. They concluded that such scratches had to be formed by natural processes before deposition of the clast and suggested that they were ice scratches although other scratches were of uncertain origin. Only one other striated clast was found. All the erratic clasts were inferred to have been transported by floating ice.

Stebbing (1897), in his discussion of two granitic boulders from the upper part of the Upper Cenomanian–Upper Turonian Chalk at Betchworth, Surrey (Text-fig. 1), noted that shore ice had occurred on the east coast of England and it had carried away the shingle frozen into it. Drifting shore ice remained the main explanation for the transport of erratic rocks in the Chalk in the late 19th and the beginning of the 20th Century. However authors (e.g. Godwin-Austen 1858; Stebbing 1897; Double 1931) did not overlook the possibility that other means of transport of erratics were possible, such as entanglement in tree roots, as holdfasts to buoyant marine algae (cf. kelp), or as gastroliths (stomach stones, Wings 2007) of marine reptiles.

Scientific interest in the English erratics went largely into abeyance during the first decades of the 20th Century. Recorded finds were absent, reflecting the closing down of the phosphate industry in the Cambridge area and possibly the mechanisation of quarry working and the reduced chances of the quarrymen finding erratics to pass on to collectors. Systematic petrological investigation of the erratics started with Double's (1931) account of nineteen examples from the Butler Collection housed at the British Geological Survey that had been "*found all near together in the chalk at Betchworth*". These were dominated by quartzites with lesser number of sandstones and metamorphosed granites. Double considered they came from a very distant source but there was little or no positive evidence for the means of transport.

Petrological interest continued with Hawkes's study (1943) on the petrology of the erratics from the Cambridge Greensand (Text-fig. 4) in the Sedgwick Museum, Cambridge, then his later study (Hawkes 1951) of the Chalk erratics in the Wiltshire collection (Sedgwick Museum) and the Dibley collection (The Geological Survey and Museum: Text-figs 6, 7). Hawkes (1951) recognised within the Wiltshire Collection numerous small, well-rounded chert pebbles with polished surfaces (Text-fig. 8), which he considered to be gastroliths, possibly of marine reptiles – an interpretation that has so far stood the test of time. Glacial transport was considered most unlikely, particularly as the Chalk Sea and climate were now considered to be warm.

In 1996 Nicolay Chumakov, a specialist in glaciogenic strata, from the Russian Academy of Sciences in Moscow, spent much of the year forensically examining erratics from the Cambridge Greensand and the Chalk collections of the Sedgwick Museum, Cambridge (Chumakov 1998). He was particularly concerned with the origin of striations on a small number of erratics from the Cambridge Greensand that had been reported earlier (Sollas and Jukes-Browne 1873; Stebbing 1897). Could they be of glacial origin? However, evidence suggested their biogenic origins or, in some instances, attrition during their mining. Overall he favoured biological transporting agents, suggesting roots of drifting trees, floating algae with the stones attached as holdfasts, or marine reptiles for the highly polished stones recognised by Hawkes (1951).

The idea of glacial transport was revived by Jeans *et al.* (1991) when putting forward the glacioeustacy hypothesis for the Cenomanian–Turonian Oceanic Anoxic Event (CTOAE; OAE2 of many authors). However this suggestion applied only to the erratics from the Upper Cenomanian and Middle Turonian Chalk at Betchworth, Surrey. They were considered to reflect deposition from drifting coastal ice developed during a very brief cold snap within the CTOAE. Since then the stratigraphy of the CTOAE in Europe has been refined (see Jeans *et al.* 2021) and this occurrence of erratics is no longer considered a feature of the CTOAE, but of the CTOAER – the Cenomanian Turonian Oceanic Anoxic Event Recovery. This revival of transport by floating ice led to an extensive discussion on Chalk erratics and their climatic significance (Bennett *et al.* 1996; Bennett and Doyle 1996; Marwick and Rowley 1998; Price 1999). None of these authors dealt specifically with, or provided any new observations on, or gave a critical assessment of the Chalk erratics under discussion. They pointed out that alternative transport mechanisms to ice – such as holdfasts attached to kelp, stomach stones in large marine reptiles, or as entanglement in tree roots – all possibilities that had been discussed previously, even in Godwin-Austen's original paper published in 1858.

Most of the erratic material currently available was collected during the second half of the 19th and the beginning of the 20th Centuries and is held in the national collections of the Geological Survey of Great Britain and the Sedgwick Museum, Cambridge. For example, the Wiltshire Chalk collection – studied petrographically by Hawkes (1951) – was donated to the Sedgwick Museum at the very end of the 19th Century by the Reverend Thomas Wiltshire (1826–1902), a former fellow of Trinity College, Cambridge, and professor of mineralogy and geology at King's College, London.

NOMENCLATURE

Hawkes (1951) discusses the nomenclature of boulders in the Chalk: *"These boulders and pebbles have been called 'foreign stones', 'extraneous stones' and 'erratics'. The last-named term is preferred with the warning that it carries no implication of transport by ice. (An erratic is a stone which has been transported by some agent other than those which have laid down the fine sediment in which it occurs.)*" Judging from museum collections *chalk erratic* has been applied to non-chalk clasts of ~2 cm or more in diameter found in any of the different chalky and marly lithofacies that constitute the Chalk Formation. Hawkes had previously (1943) also used *erratic* for the boulders and pebbles collected from the Cambridge Greensand Formation. The descriptive term *erratic* is thus used in preference to (1) *dropstone* (Bennett *et al.* 1996) because there is no implication to its origin, means of transport or deposition, or (2) *stone* of Chumakov (1998) so as to differentiate them from reworked diagenetic nodules developed within the local setting of Cambridge Greensand or Chalk. However our use of erratic or erratic clast differs from Hawkes (1951) in that it is not applied to intraclasts that cannot be clearly differentiated by lithology from the Chalk strata. For example the bored limestone pebbles associated with the sandstone erratic (Text-fig. 5B) are considered to be lithified chalk although more detailed examination may show them to be otherwise.

STRATIGRAPHICAL OCCURRENCE OF ERRATICS

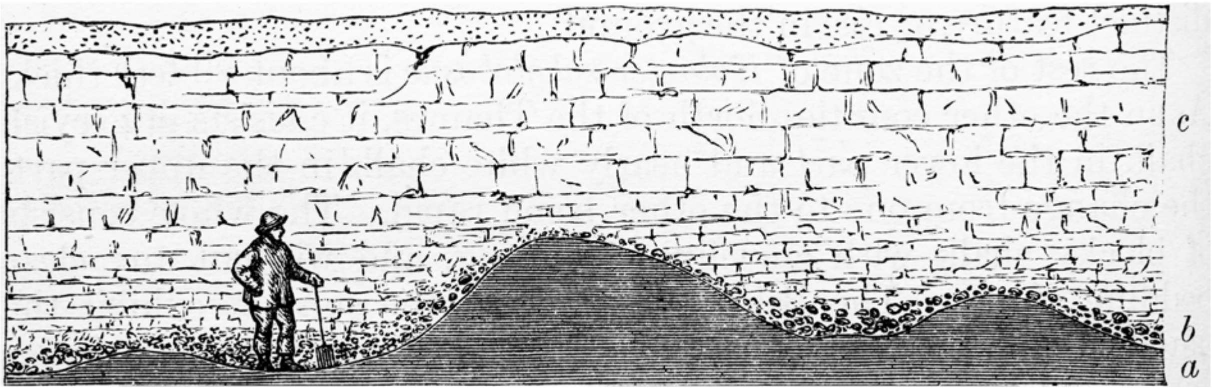
Much has been written about the infrequency of erratics particularly by those without the advantage of being familiar with the working quarries and pits in England from which considerable collections have been made since the first half of the 19th Century. To give some idea of this apparent rarity, four experienced investigators (Terry Fletcher (Fletcher 1977), Ramues Gallois, Rory Mortimore and Christopher Jeans) with a collective total of many years of working on the Chalk of England and Ireland – but without making a special search – have each come across only one erratic. In the past Jukes-Browne was well aware of Cretaceous erratics from the Cambridge Greensand, having described them with Sollas (Sollas and Jukes-Browne 1873), yet he does not record additional sites in his exhaustive account of chalk exposures in England (Jukes Brown and Hill 1903, 1904).

Does that mean that they are equally rare throughout the Chalk as suggested by Cayeux (1897) and Hawkes (1951), and their apparent abundance at certain horizons and locations just reflect the huge volumes of chalk at certain pits that had been excavated, observed and picked over by the quarrymen? Or they are rare, but less rare at certain horizons? Does this apparent absence above the Seaford Chalk Formation (Text-fig. 2) reflect the fact that it is particularly difficult to recognize erratics in flint-rich chalk sequences exposed in high cliffs? The partial answer to this question is found in Dibley's (1918) report on the Chalk of southeast England at a time when there was no shortage of working Chalk pits. He makes no mention of finding any erratics in either the *Schloenbachia varians* or *Holaster subglobosus* zones of the Lower Chalk – that is the Cenomanian succession up to the top of the *Calycoceras guerangeri* Zone – whereas between the base of the Upper Cenomanian *Metoicoceras geslinianum* Zone and the Coniacian/ Santonian *Micraster coranguinum* Zone he had made a collection of 200 erratics.

The suggestion (Text-fig. 2) is put forward that there are three stratigraphical zones in the English Chalk where erratics are less rare: (1) the Upper Albian–Lower Cenomanian interval consisting of the Upper Gault–Cambridge Greensand–Hunstanton Red Chalk Formation that extends at least 120 km along the outcrop from Arlesey to Hunstanton (Text-figs 1, 2), (2) the Upper Cenomanian–Middle Turonian Chalk at Betchworth, Surrey, which is tentatively linked to the records of erratics in the Middle Chalk at Houghton, Sussex (Stebbing 1897, p. 214), and to the tonalitic boulder observed by Rory Mortimore at Beachy Head ,Eastbourne (Text-figs 1, 2), and (3) the Coniacian–Santonian Seaford Chalk (*Micraster coranguinum* Zone) of Gravesend and Rochester, Kent (Text-figs 1, 2).

Upper Albian–Lower Cenomanian zone of erratics

These are mainly from the Cambridge Greensand, the glauconitic and marly basement bed of the Chalk in the Cambridge region**.** The erratics, consisting of sedimentary, metamorphic and igneous rocks, are



Text-fig. 3. View of a coprolite pit near Horningsea, Cambridge (Jukes-Browne and Hill 1903, fig. 46, p. 194) showing the uneven surface of the Gault on which the Cambridge Greensand rests. The field sketch does show pebble size objects in the Cambridge Greensand but it should be noted that these are very likely to be all phosphatic nodules. *a*. Gault Clay (Upper Albian). *b*. Cambridge Greensand with the coprolite bed and its concentration of phosphatic nodules (Lower Cenomanian). *c*. Chalk Marl (Lower Cenomanian).

not locally derived. This is a condensed bioturbated deposit lacking laminations overlying a regional erosion surface truncating and channeling into the upper part of the underlying unlaminated Gault Clay Formation of Late Albian age (Text-fig. 3). It is of Cenomanian age belonging to the *Neostlingoceras carcitanense* Subzone of the *Mantelliceras mantelli* Zone (Mortimore *et al.* 2001). The lithofacies is rich in non-carbonate clay and silt (~<50%) and phosphatic nodules that include an extensive remainié assemblage of fossils and phosphatic nodules derived from the underlying Gault Clay. It is referred to as the coprolite bed. Volcanoclastic grains make up ~60 percent of the glauconite grains (Jeans *et al.* 1982). It is not a near-shore lithofacies comparable to the neritic greensand facies such as the Turonian Soest Grünsand in northern Germany – where erratics have been reported by Schmidt and Schreyer (1973) – or the Lower Greensand (Aptian) and Upper Greensand (Upper Albian) in southern England.

Erratics have also been recorded from the Upper Albian Gault Clay in Bedfordshire and Cambridgeshire (Jukes-Browne and Hill 1903, p. 190), the Upper Albian part of the Hunstanton Red Chalk Formation (Text-fig. 5A), the lower part of the Cenomanian Chalk Marl at Burwell and Gayton (Jukes-Browne and Hill 1903, p. 347), and in Lower Cenomanian (*Mantelliceras mantelli* Zone) at Hunstanton (Text-fig. 5B). Jukes-Browne and Hill (1903) were of the opinion that those in the Cambridge Greensand were derived partly by erosion from the underlying Gault but the majority was deposited during early Cenomanian times.

Erratics are rare in the Cambridge Greensand. For example, the senior author visited the Cambridge Greensand exposure at the Barrington Rugby Portland Cement quarry (Text-fig. 1) at a number of times between 1961 and 1982, however no erratics were recovered. The extensive museum collections of erratics and derived Gault fossils from the Cambridge Greensand were largely obtained during the period when this phosphatic-rich coprolite bed was being mined in shallow workings (Text-fig. 3). The raw material was processed through horse-powered washing mills to concentrate the phosphatic nodules and to remove clay and sand prior to their transport to the processing factory. The nodules were then ground and mixed with sulphuric acid to produce a soluble superphosphate (Grove 1976). The great majority of interesting finds were probably recovered by the local work force during the washing phase and these were purchased by collectors, providing the miners with an additional source of income. The first curator of the Sedgwick Museum, A.G. Brighton (1900–1984: personal communication) related how care had to be taken when purchasing erratics to ensure that there was evidence of encrustations by phosphatic nodules or Cretaceous bivalves, serpulids or bryozoa – otherwise there was no way they could be differentiated from erratics from the local Pleistocene Boulder Clay.

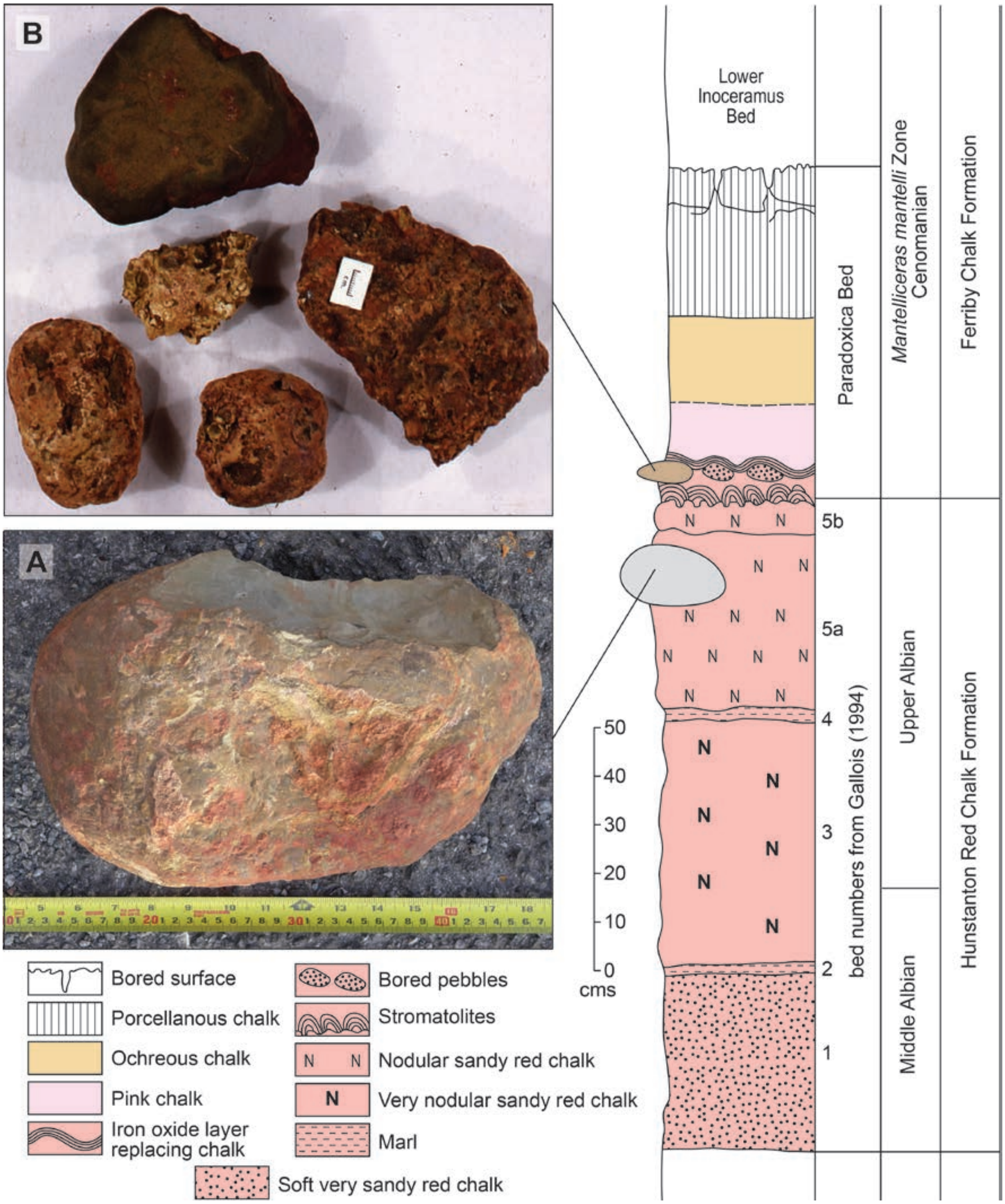
Erratics, now preserved in the collections of the Sedgwick Museum, number more than three hundred. Some are heavily encrusted with sedentary bivalves, others are not (Text-fig. 4). It is questionable to what extent they are representative of the erratic's population. The purchase of only those encrusted with Cretaceous epifauna might have biased the assemblage against penecontemporaneous clasts as these

Text-fig. 4. Part of the collection of erratics from the Cambridge Greensand in the Sedgwick Museum, Cambridge. Those marked with an asterisk are very heavily encrusted, others are much less colonized. Ruler for scale ~20 cm.

would be less likely to be encrusted. Hawkes (1943) carried this selectivity even further as he did not investigate the unencrusted erratics in the museum collection. Hawke's (1943) petrological study was based upon a selection of 163 erratics from a collection of ~200 examples. They ranged from 5 cm to 55 cms in maximum dimension, 26% were over 1 kg, 12% were over 2 kg with the largest weighing 60 kg. Most were subangular, 12% were well rounded, differing little from Jukes-Browne's (Jukes-Brown and Hill 1903, p. 196) physical description of the erratics he was familiar with…. "*Some of the softer rocks are water worn but the great majority are angular, some remarkably so...They vary in size from a mere pebble up to a block 14 × 12 × 6 inches* (~36 × 30 × 15 cm)".

The erratics were dominated by arenaceous sedimentary rocks (50%), biotite granitic gneiss and crushed granite (9%), vein quartz, rhyolite, schist and chert (26%), with the remaining 24% made of a wide range of mainly igneous rocks, with lesser amounts of different varieties of metamorphic and sedimentary rocks. Hawkes confirmed earlier researchers' recognition of the possibility of a Welsh and possibly Scottish origin for many of the erratics and also the presence of a few clasts that may be of Norwegian origin. He also identified clearly a small set, including some distinctive tourmaline bearing granites, that could have been derived from southwest England.

It is not surprising that little is known about the spatial arrangement of erratics within the Cambridge



Text-fig. 5. Recently discovered erratics in the Hunstanton Red Chalk and the Ferriby Formations at Hunstanton, Norfolk. **A**. Greywacke boulder (11.7 kg) from the upper part (*Callihoplites auritus* Subzone) of the Albian Hunstanton Red Chalk Formation. **B**. Sandstone cobble (upper left) from the base of the Paradoxica Bed (*Neostlingoceras carcinatense* Subzone) of the Cenomanian Ferriby Formation: it is associated with bored limestone cobbles, possibly chalk clasts or derived nodules from the underlying Hunstanton Red Chalk Formation.

Greensand considering the majority of specimens were probably not collected in situ. The only observation is that of Sollas and Jukes-Browne (1873, p. 14) that "*6 large stones of various constitution, were found huddled together*". Recently two new erratics have been collected from this zone of relative abundance, both from the Hunstanton Cliffs – a large well-rounded greywacke boulder (11.7 kg) from the

Callihoplites auritus Subzone of the Hunstanton Red Chalk Formation (Text-fig. 5A), and a sandstone cobble associated with bored chalky limestone pebbles at the base of the Cenomanian chalk (*Mantelliceras mantelli* Zone; Text-fig. 5B).

Upper Cenomanian–Middle Turonian zone of erratics

These were collected from the Melbourn Rock and overlying Chalk at the huge quarries (now disused) in the North Downs at Betchworth, Surrey (Text-figs 1, 2), where the chalk was being burnt for lime. Tentatively assigned to this zone are the erratics from the Middle Chalk at Houghton, Sussex (Stebbing 1897, p. 214), and the considerable tonalitic boulder (20 cm across) observed by Rory Mortimore at Beachy Head, Eastbourne (Text-fig. 1). The general lithofacies (Jukes-Browne and Hill 1903, p. 500) from which the erratics at Betchworth were collected contains very little non-carbonate material (<~2%). It is rich in calcispheres and shell debris and is assigned to the distal part of the middle shelf and the proximal part of the outer shelf as defined by Wilmsen *et al*. (2005). Any laminations, if present, have been destroyed by bioturbation. The erratics are always well rounded. There are no reports that they were found either at a particular horizon, or associated with a hardground or an erosion surface, or a change in chalk lithofacies – but this could just reflect the limited appreciation of Chalk lithofacies at the time when they were collected.

Dibley (1918) in his work on the Chalk of southeast England makes special mention of the relative abundance of erratics that occur in the Melbourn Rock and the overlying white chalk of the *Rhynchonella cuvieri* Zone (equivalent to the *Neocardioceras juddii* and *Watinoceras devonensis* zones) at Betchworth. "*From the R. cuvieri Zone I obtained a large number of erratics – the largest weighing about twelve pounds* (5.4 kilos) *– which are now in the Survey Collection at the Museum of Practical Geology, Jermyn Street* (Text-figs 6, 7A–E). *On each – with only one exception – Bryozoa or some other Cretaceous organism was attached"*. From this chalk quarry Stebbing (1897) described two boulders of granite (Text-fig. 7F) from the *Terebratulina lata* Zone. Gerard Weedon Butler made a considerable collection of erratics from this same location, but these seem to have been dispersed around a number of museums in England. The quartzite erratic in the Sedgwick Museum Collection (ref. no. B. 76697, G.W. Butler Collection) is one of 25 found in close proximity. Nineteen erratics, "*found all near together in the chalk at Betchworth*" from Butler's collection were passed onto I.S. Double at Liverpool for petrological investigation, the largest weighed nearly 5 lbs. (2.3 kg). Mr Double was informed that a collection of about 70 boulders, mainly from Betchworth, had been added since 1912 to the collections in the Museum of Practical Geology in London (Double 1931).

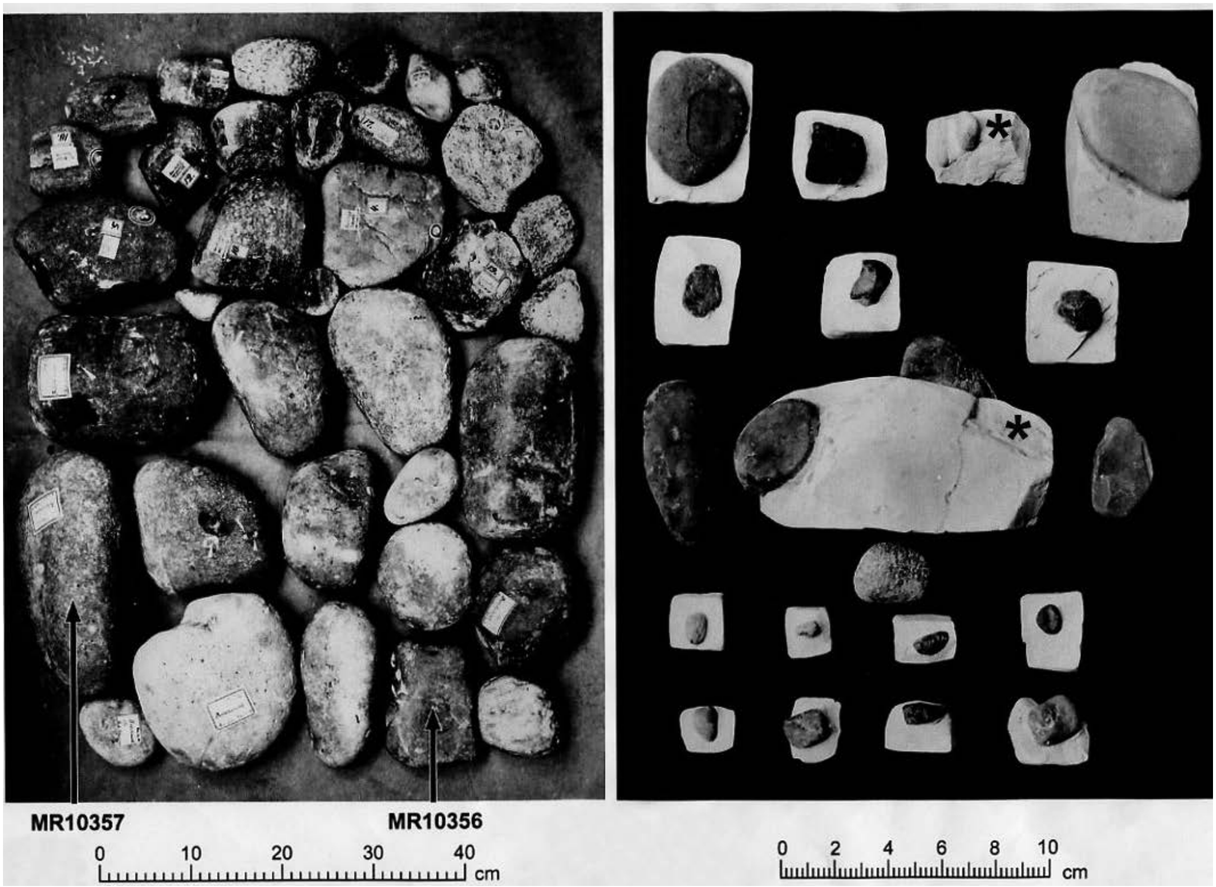
All the examples of these erratics that have been re-examined (Text-figs 6, 7), as well as those recorded in the literature, are worn and rounded pebbles, cobbles and boulders of igneous, metamorphic and sedimentary rocks. They may occur singly or in groups numbering up to twenty or thirty individuals in close proximity. Surface scratch marks or striations are absent. They lack the polishing, surface etching and high sphericity of gastroliths. The surfaces of the great majority of these erratics have traces of encrusting fossil serpulids, valves of sedentary bivalves, or other chalk fossils, however these fossils appear to have suffered attrition.

Upper Coniacian and Lower Santonian zone of erratics

This group is well represented in the Wiltshire Collection and forms the basis for part of Hawkes' (1951) study of Chalk erratics. The pebbles, averaging perhaps 15–20 mm in largest dimension, are often highly rounded, well polished, and may occur in groups within a fine-grained chalk matrix (Text-fig. 8). Hawkes suggested they were gastroliths, stomach stones released from dead and decaying carcasses of marine reptiles or large elasmobranchs. The majority (150) out of 212 stones making up the Wiltshire Collection is probably related to a single carcass of a marine reptile (Text-fig. 8). The other gastroliths in the collection come from chalk pits in the Rochester and Gravesend regions of Kent. A few are labelled from the *Micraster coranguinum* Zone, the majority are given no specific horizon, just *Chalk*. Rory Mortimore suggests they are all probably from the *Micraster coranguinum* Zone Seaford Chalk Formation of Late Coniacian and Early Santonian age (Text-fig. 2). The larger Purley boulders and associated material also come from the *Micraster coranguinum* Zone (Godwin-Austen 1858) showing that not all the erratics in this zone are gastroliths.

Other occurrences of erratics

Erratics are rare in the Chalk between these three zones of relative abundance in spite of there being no



Text-fig. 6. The Dibley Collection of Chalk erratics in the National Geological Repository, British Geological Survey, consists of 176 specimens (Hawkes 1951, p. 19). **Left print**. Historical photograph (MN 151) of the larger erratic boulders, the majority or all of which are from chalk of the *Rhynchonella cuvieri* Zone, Betchworth, Surrey. Erratics MR10356 and MR 10357 are illustrated in Text-fig. 7A, B and C. **Right print**.Historical photograph (MN 70) of a selection of small erratic pebbles from the Dibley Collection. Most are preserved in their chalk matrix. Two examples (asterisk) show pebbles in close proximity.

shortage of chalk pits in which the intervening chalk was extracted. Between the Lower Cenomanian and the Upper Cenomanian–Middle Turonian zones there are very few records. These erratics are usually of small size with maximum dimensions between 4 and 30 mm, the majority between 10 and 15 mm. A pebble of an ‘arkosic’ sandstone (8 × 4 × 3 cm) from the Totternhoe Stone of Chinnor, Oxfordshire, is recorded in Mortimore *et al.* (2001, p. 337). The same horizon at Pitstone (Buckinghamshire) has provided granitic fragments as well as very angular, glassy looking, sand sized, fragments of flow banded rhyolite. Some small erratics from this same level in the Cambridge area are present in the Sedgwick Museum’s Chalk Pebble collection. Jukes-Browne and Hill (1903, p. 354) record two small quartz/quartzite pebbles from the Plenus Marls of Cambridgeshire and a single one from the same horizon in Lincolnshire.

The fist-sized quartz porphyry found by Fletcher (1977) in the Campanian Chalk of Antrim (Northern Ireland) was from an even higher horizon. It occurred, in association with chalk clasts, in the Bendoo Pebble Bed that separates the *Offaster pilula* and *Gonioteuthis quadrata* zones (Text-fig. 2).

INTERPRETATION

All researchers agree that the Chalk erratics are hydrodynamically out of context with the fine-grained silt- and clay-grade sediments in which they were deposited and are now preserved. It is assumed that they had been floated into the Chalk Sea using either a raft of tree roots or marine algae (Kelp), or inside a swimming marine reptile or fish, or frozen into floating ice. There is no evidence of their actual

Text-fig. 7. Erratics from the Chalk. **A**. Quartzite cobble (MR10356), *Rhynchonella cuvieri* Zone, Betchworth, Surrey. Dibley Collection. Weight 2 lbs. 14 oz. (~1.31 kg). **B**. Side view of MR 10356 showing encrusting *Ostrea* and *Plicatula*. **C**. Quartzite boulder (MR10357), *Rhynchonella cuvieri* Zone, Betchworth, Surrey. Dibley Collection. Weight 11 lbs. 4 oz. (~5.05 kg). **D**. Quartzite cobble (MR17290) containing feldspar and sericite, *Rhynchonella cuvieri* Zone, Betchworth, Surrey. Dibley Collection. **E**. Fractured surface of MR 17290 showing a thick outer zone of alteration. **F**. Fragment (MR 4084) of a decomposed granite boulder, *Terebratulina lata* Zone, Betchworth , Surrey. Described as "boulder A" in Stebbing (1897, p. 215), weight 7 lbs. 7 oz. (~3.40 kg). National Geological Repository, British Geological Survey. **G**. Fragment (MR 16358) of the huge decomposed granitic boulder – the Purley Boulder – estimated as ~3 feet in maximum dimension (Woolnough and David 1926, p. 342) reported by Godwin-Austen (1857), *Micraster coranguinum* Zone, Croydon, Surrey. The large tabular feldspars are clearly visible. National Geological Repository, British Geological Survey.

Text-fig. 8. The 700 ml chalk block (B.77073) discussed by Hawkes 1953, p. 264) contained 16 visible pebbles with the label attached *"All pebbles marked "R" came from a pit near Rochester. They were in number about 150 and were found within a radius of 3(? 6) feet"*. One hundred and seven of these pebbles were in the collection. The 14 pebbles sectioned comprised 4 radiolarian and 2 spicular cherts (probably Carboniferous), 4 unfossiliferous cherts, 3 quartzitic sandstones, and 1 strained vein-quartz. Reflections on the pebble surfaces indicate their polished nature. Moulds, from where two pebbles that have been lost, can be seen. The Wiltshire Collection, Sedgwick Museum, Cambridge.

deposition recorded in the fine-grained sediment in which they are found. Any laminations that could record the impact of a descending erratic on the bottom sediment had already been destroyed by bioturbation. This floor was either a soft chalk mud or the partially consolidated clay that made up the eroded surface of the Gault upon which the Cambridge Greensand developed. It is assumed that erratics were released from their floating marine transport and fell to the bottom of the sea.

Four possible means of transport have been considered by different authors. What type of evidence would favour one or more of these? Entanglement in floating tree roots would be supported by the association of erratics with fossil remains of tree roots. Soil and stones entangled in a root mass will rapidly loose their coherence with extended submergence in water as gravity and wave action exceeds the cohesive forces holding the soil particles together. Cycads – abundant in the Cretaceous – have fleshy roots and are unlikely to retain clasts even over a short distance. In contrast pines have a woody root system and could be a possible mode of transport for larger stones but not for sand or fine gravel as this would be lost after a very short period of submergence. Holdfasts of marine algae would be supported by the presence of the print of the holdfast area on the surface of an erratic, this area of attachment would be protected from colonisation by sedentary epifauna. Gastroliths from marine reptiles or large cartilaginous elasmobranch fish can be positively identified when associated with bones or teeth. Clusters of rounded and highly polished stones, some of which may show signs of etching (Whittle and Onorato 2000), are the best indicators of gastroliths. Floating ice itself can leave no direct trace as it melts. However much is now known about the characteristics of recent and Pleistocene glacial and sea ice transported rock debris and sediment (eg., Osterkamp and Gosink 1984; Gilbert 1990; Dowdeswell *et al.* 1998; Lisitzin 2002; Ben and Evans 2013; Hansom *et al.* 2014; Ballantyne 2018) and this provides a good basis for interpretation.

There are three different environmental settings for floating ice and rock debris, associated either with glaciated regions with permafrost, or riverine and coastal fast-ice associated with permafrost areas, or coastal fast-ice without permafrost. Surface striae may occur on stones as the result of grinding and can give indication of climatic conditions. They may occur in well-developed permafrost soil profiles where cryoturbation results in soil heave and movement, as well being associated with glaciers and ice sheets as the result of grinding of their embedded rock debris as it moves over rock surfaces and piles of moraine.

Upper Albian–Lower Cenomanian zone of erratics

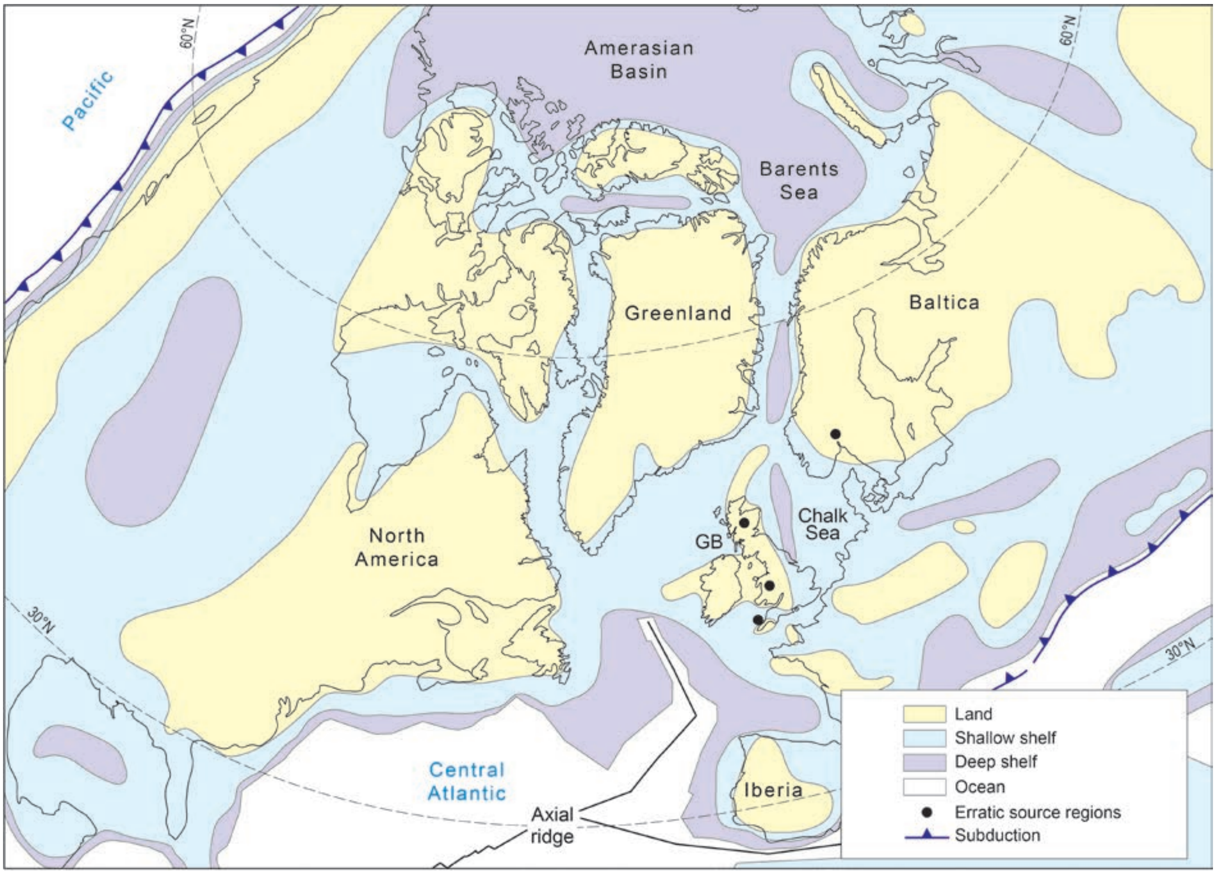
There is a general consensus (Sollas and Jukes-Browne 1873, Hawkes 1943) that many of the Cambridge Greensand erratics are comparable to rocks known from Wales, northern England and Scotland, which during the Early Cenomanian were parts of a western landmass (Text-fig. 9) that may have extended over Ireland, northeast and northern England, all of Scotland up to the Shetland Platform (Cope *et al*. 1992, p. 139). The Cambridge Greensand area of deposition lies at a minimum of ~130–140 km from the margin of the Welsh part of this landmass. A smaller group of erratics were linked to the granites ~250 km distant in southwest England (Cornubian massif) and another one to a Norwegian source, perhaps 1000 km away. The overall angular to subangular form of the majority of the erratics suggest a hard rock source terrain and limited transport prior to rafting. This would be consistent with the inferred provenance from Cornwall, Wales and Norway. It is also possible that frost shattering and mild permafrost activity was also involved (see below), as evidence points to a shoreline and a coast that experienced the development of fast-ice and frost shattering.

The absence of glacial striations on the clasts (see earlier) shows lack of evidence for glacial transport or permafrost activity. Similarly the lack of holdfast imprints on the surfaces of the clasts gives no support to their transport by floating kelp. There is no evidence that any of the 300 and more erratics now preserved from the Cambridge Greensand in the Sedgwick Museum were gastroliths. Similarly there is a great lack of any associated fossil wood or root systems. Hawkes (1943), who considered that tree root systems were a likely means of transport, admitted he knew of no fossil wood from this horizon, let alone an abundance! The only remaining mechanism is by floating ice but of non-glacial origin. The obvious contender is shore or fast-ice developed along the shore during cold phases that froze into its base both rock and pebble debris. This was carried out to sea during warm periods or seasonal melting where currents and wind dispersed it widely. For example, such wind driven ice has transported, during a Late Pleistocene low stand, blocks of basalt over 1000 kilometres from the shores of Iceland to the French coast (Lefort *et al.* 2019). It is unfortunate there are practically no observations on the spatial relationship between erratics in the Cambridge Greensand, the only one "*6 large stones of various constitution, were found huddled together*"(Sollas and Jukes-Browne 1873) suggests a dump structure, a feature of deposition of ice-rafted rock debris in glacial-lacustrine and glacio-marine settings (Thomas and Connell 1985; Benn and Evans 2013; P.L. Gibbard, personal communication).

The extent and preservation of the encrusting epifauna on individual erratics is very variable (Text-fig. 4). Some surfaces are completely colonized, others hardly at all. The preservation ranges from poor to good suggesting that some of the epifaunal fossils were already in place and worn before they were transported to the Cambridge Greensand area. Others with perfect preservation reflect colonisation in their new setting. The relationship between rock type and the nature of their fossil encrustations could benefit from further investigation.

Upper Cenomanian–Middle Turonian zone of erratics

Included here are not only the erratics from the Betchworth Chalk pits but also the "Purley Boulder" described by Godwin-Austen (1858) from a chalk pit near Croydon. These erratics are markedly different to those from the Cambridge Greensand. They are well rounded (compare Text-figs 6, 7 with Text-fig. 4) suggesting much greater maturity and an origin from a well-graded shoreline. Their sparse epifaunal encrustation and its worn condition suggests its shore-line development prior to transport, but not to epifauna activity on the Chalk seafloor prior to burial in the sediment. The absence of well preserved encrusting epifauna on these erratics is evidence that they fell directly into soft chalk sediment and were not left exposed as local hard surfaces. Such surfaces were in short supply in this soft bottom setting and would have rapidly colonised by epifauna. The surfaces of the erratics bear no evidence of having been the site of holdfasts of kelp. The form and surface textures of the erratic clasts excluded them being



Text-fig. 9. Palaeogeographical setting of Great Britain (GB) and the Chalk Sea in the Cenomanian (95 Ma). Modified from fig. 13.10 in Torsvik and Cocks (2017).

gastroliths of marine reptiles or large elasmobranch fish. They are not associated with fossil wood or tree roots. It would have been impossible for tree roots to have transported the complex mixture of blocks of rock, gravel and sand associated with the Purley Boulder – this assemblage, particularly sand and small pebbles, could not have survived within a root mass, even for a few hours, once suspended in water. Ice transport is the only possibility.

The absence of glacial striations on the clasts suggests that an origin in a glaciated area, or one in which there was extended permafrost activity, was unlikely. The setting is the development, during cold phases, of fast-ice associated with seabed and shoreline freezing in shallow water along the coast. Warm phases or seasonal meltng caused break-up and the subsequent floatation of the fast-ice with its embedded debris: This was carried out to sea where it was widely dispersed by currents and wind. As the floating ice melted in the relatively warm Chalk Sea it dropped its load of rock debris. The close association of mixed assemblages of erratics found *'all together'* (Godwin-Austen 1858; Double 1931; Butler Collection (Sedgwick Museum)) are comparable to the dump structures typical of deposition from ice-rafted rock debris in glacio-marine settings. (Thomas and Connell 1984; Benn and Evans 2013; P.L. Gibbard, personal communication).

CONCLUDING DISCUSSION

Geological setting of the erratics

There are few records of the detailed geological setting of most of the erratics now preserved in Museum collections. What type of matrix enclosed them, and how were they related to other detrital components and to erosion surfaces? What was the pattern of epifaunal encrustation and how was this related to the bedding. Such observations might allow an important part of their depositional history to be unravelled.

The two recent finds of erratics in the cliffs at Hunstanton demonstrate their different depositional settings. The large greywacke boulder (Text-fig. 5A) from the Hunstanton Red Chalk Formation is not associated with any clasts approaching its dimensions. It is the only one that has been reported in these much visited, well-exposed and accessible cliffs. The sedimentary setting may represent its original placement on the seafloor – possibly as the result of ice transport – and could have preserved important evidence of its transport and subsequent history. In contrast, the sandstone erratic in the base of the Chalk (Text-fig. 5B) is associated with bored limestone pebbles of similar size. They rest on an erosion surface and are embedded in a fine chalk matrix, perhaps ranging in grade from fine silty clay to very fine sand. This association suggests that, at times, the Chalk Sea currents were capable of transporting rip-up clasts of chalk and hardened chalk pebbles up to 14 cm in maximum dimension such as occur at this level (Jeans 1967, fig. 31). This is not surprising as the bulk density of a hardened chalk pebble with low porosity is little different to that of a quartzite pebble as the specific gravities of calcite (2.71) and quartz (2.65) are fairly similar. Such horizons of clasts were probably concentrated during an exceptional storm whereas the much finer grained matrix represents a later phases of low-energy deposition. The question is whether the sandstone erratic was a clast, dropped into the chalk from its ice raft, then concentrated by storm action with rip-up clasts of cemented chalk? Or was it a near-shore, reworked Albian erratic, swept out from a remote shoreline in an exceptional storm?

Ice transported erratics and glacio-eustatic cycles

Is there a common controlling factor between the occurrences of ice transported erratics and the widespread transgressive-regressive cycles, possibly of glacio-eustatic origin, that defined the sequence boundary stratigraphy of the Cenomanian–Turonian strata in northern Europe (Janetschke *et al.* 2015; Jeans *et al.* 2021, text-fig. 2)? Or are they independent of each other, the well-defined cycles representing the global fluctuations of glacial conditions, whereas the development of coastal fast-ice and its transport of shelf sediments having being effected independently by local climatic variation? Correlation between the cycles, sequence boundaries of Janetschke *et al.* (2015), and the occurrences of ice-floated erratics is not good (see below) but this could reflect the lack of detailed stratigraphical information.

The Cambridge Greensand and its erratics represent the latest Albian–earliest Cenomanian regression-transgession cycle and can be matched with sequence boundary SB A11 (Jeans *et al.* 2021, text-fig. 2). No erratics have been reported from the two overlying cycles of mid-early and latest early Cenomanian age representing sequence boundaries SB Ce1 and SB Ce2. Exceptionally rare examples of erratics from the Totternhoe Stone can be related to the latest early Cenomanian sequence boundary SB Ce3. None are known from the late middle Cenomanian sequence boundary SB Ce4; a few small quartz pebbles are known from the mid-late Cenomanian sequence boundary SB Ce5, which represents the regression-transgression associated with the initiation of the CTOAE. Erratics from the Late Cenomanian–Middle Turonian Zone span an interval including SB Tu 1 and ending at SB Tu 2. This interval is difficult to interpret as some authors (e.g. Haq 2014 in Janetschke *et al.* 2015, fig. 6) show additional or different system boundaries and some of the erratics are poorly located. The younger gastrolith erratics are not relevant in this context. Correlation between the erratic zones and the cycles is at its best in the Cenomanian but overall is weak.

The relationship between the occurrence of erratics and the stratal cyclicity could be investigated by the combination of two approaches. First by determining more precise stratigraphical data on the occurrences of the erratics from the higher horizons in the Chalk – using either traces of chalk matrix still attached to the clasts in museum collections – or, very much better, finding new erratics and determining their stratigraphical level as well as their detailed geological setting within the chalk matrix. The second approach avoids the difficulty of finding these rare erratics. This is to analyze systemically the variation in the nature and mineralogy of the granule and sand fractions of the acetic acid insoluble residues extracted from bulk chalk samples taken across zones suspected of having provided erratics in the past. It would be reasonable to postulate that these zones are associated with a relative abundance of rock fragments and sand assemblages reflecting the source or sources from which the larger erratics originated. Previous research on the Cambridge Greensand at Barrington and the equivalent horizon at Hunstanton – both studies unrelated to the Chalk erratics problem – have recognised special features in their sand fractions. At Barrington there is a high percent of glauconitized volcanic debris (Jeans *et al.* 1982) whereas at Hunstanton the heavy mineral assemblage is characterized by an abundance of colourless pyroxene and blue amphibole (Rastall 1930). More recently our own unpublished research on the granule and sand fractions from the Totternhoe Stone of Pitstone (Text-fig. 1) – a level at which Mortimore *et al*. (2001, p. 337) recorded a pebble of 'arkosic' sandstone from a nearby quarry at Chinnor (Text-fig. 1) – revealed the presence of a granite fragment as well as very angular glassy fragments of flow banded rhyolite.

Palaeogeographic setting of fast-ice in the Cenomanian Chalk

Sea-and fast-ice is widespread in modern arctic regions but fast-ice extends south of the areas covered with widespread sea ice. These southern areas represent the margins of ice formation and are intrinsically subject to fluctuation in their development. At the southern limit of formation during a relatively cold phase they would be very rare and irregularly developed but absent during warmer phases. This edge zone is likely to be influenced by both geography and short term meteorological conditions leading to an intermittent formation and loss of fast-ice.

The palaeogeographical setting of the Chalk Sea (Text-fig. 9) is now fairly well established (Torsvik and Cocks 2017, fig. 13.10). In the Cenomanian there is an extensive landmass along 60°N, traversed by only two narrow straits that link to the polar Amerasian Basin. Eastern North America extends this landmass down to 30°N. Large landmasses show temperature extremes and the large Asian landmass today has sub-zero winter temperatures extending south of Latitude 50°N. The strait between Greenland and Baltica linked the Chalk Sea to the Barents Sea and Amerasian Basin. The Chalk Sea lay on an extensive shelf south of Greenland and Baltica and is bounded to the south and west by a group of large islands, including the extensive island postulated as the main source for the erratics in the Cambridge Greensand (see *Interpretation* above). These partly isolate the Chalk Sea from the, then small, Central Atlantic Oceanic Basin. This extensive island stretching from Wales and Ireland in the south to the Shetland Platform in the north (Cope *et al*. 1992) lies between approx. 45°N to 55°N in this reconstruction compared with its present position 51°N to 61°N.

The Chalk Sea thus has a setting significantly different from the current position of the British Isles on the northwest side of a continental mass and open to a major oceanic basin. Instead it is on the cold south/east-south-east side of a major landmass, comparable to the modern east American and Canadian seaboard or the east Asian seaboard from Japan northwards. It is also a partly enclosed sea that may be compared with the more enclosed modern Gulf of St Lawrence (south of 50°N), and Sea of Okhotsk (south of 60°N), which have extensive sea-ice development today. The setting (Text-fig. 9) suggests that conditions could be cooler in the Chalk Sea than other regions at the latitudes seen on the reconstruction of Torsvik and Cocks (2017).

The modern distribution of sea-ice and shore fast-ice is influenced by the distribution of oceanic and continental domains and oceanic circulation. Ice regularly forms down to 45°N on the northwestern coasts of the Atlantic and Pacific Oceans in the present interglacial epoch (Hansom *et al* 2014, quoting Forbes and Taylor 1994). The adjacent coasts are sub-arctic and have sub-zero winter temperatures. By contrast the Norwegian Atlantic coastline remains largely free of ice as a result of the warm North Atlantic Drift. We cannot assume that this warm water flow actually operated across the shelf and island areas in the Cenomanian. Comparing modern conditions with Cenomanian palaeogeography raises the possibility that sea- and fast-ice could be generated if local conditions were similar to the modern Canadian southeast coast.

Winter weather patterns also influence sea- and fast-ice distribution. In the authors' life times shore- and sea-ice formed along the North Sea and some Channel coastlines as far south as 51°N in the winters of early 1947 and 1963. These were exceptional events controlled by the position of anticyclones in the north and east, bringing in exceptionally cold air over the North Sea and UK from the Arctic or from the continental interior of Russia. Although exceptional now, these events were familiar to Godwin-Austen and the other 19th century geologists.

Acknowledgements

We wish to thank the following: Hugh Ivimey Cook, Mike Howe, Simon Harris and Tracey Gallagher of the British Geological Survey for help in tracking down the Chalk erratics in the National Geological Repository at Keyworth; Matt Riley for help with the Chalk erratics in the Sedgwick Museum, Cambridge; Ramues Gallois. Rory Mortimore, and Terry Fletcher for providing information about Chalk erratics; Philip Stickler for drafting the figures; two referees for their helpful comments.

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Manuscript submitted: 30th March 2020
Revised version accepted: 31th August 2020