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A unique, far-travelled graptolite-bearing erratic pebble from the Lowestoft Till (Quaternary: Anglian Stage) of North Lopham, Norfolk

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Abstract: An erratic chert pebble discovered on an exposure of the Lowestoft Till (Anglian Stage, Pleistocene) of North Lopham, Norfolk, UK, contains graptolites preserved three-dimensionally in silica in a mode not known in the UK. The graptolites are *Monograptus parapriodon*, *Monograptus priodon*, *Monoclimacis linnarssoni* and an undetermined retiolitid that indicate an *Oktavites spiralis* Biozone (mid-late Telychian, Late Llandovery, Silurian) age. The graptolites are associated with organic-walled microfossils, some containing internal bodies. The combination of lithology, preservation and low thermal maturity seem to exclude a British origin. The closest comparison is with Silurian chert pebbles in Miocene and Pleistocene gravels in central Germany, thought to be derived from bedrock in the Frankenwald region of Thuringia. A conjectured natural transport vector for this pebble involves drainage along the proto-Rhine system flowing into early/mid Pleistocene North Sea deltaic/marine deposits, with subsequent glacial transport to Norfolk. The possibility of an anthropogenic vector is also considered, but dismissed.

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The provenance of erratics in tills can be useful in reconstructing ice-flow pathways and the former extent of ice sheets (Phemister 1926; Harmer 1928). However, they may also be emplaced by reworking from older glacial and non-glacial deposits or by ice-rafting as glacial dropstones rather than being transported from their source by an ice sheet. Thus, their use in determining glacial history needs consideration of both specific erratic lithology and geological context.

East Anglia contains some of the best-preserved glacial deposits in NW Europe, but their provenance and exact age have been widely debated, including the extent of the influence of Scandinavian ice sheets upon them. Were East Anglian tills deposited in the Mid Pleistocene in part from Fennoscandian ice sheets or solely from British ice sheets? East Anglian tills such as the Happisburgh Till and Corton Till (Bowen *et al.* 1986; Lunkka 1994 and references therein), both members of the Happisburgh Glacigenic Formation (HGF) (Fig. 1), were once thought to include a Scandinavian source (owing to the reported presence of Scandinavian-derived erratics – mainly distinctive igneous rocks including rhomb porphyry and larvikite). However, as early as the 1960s John Catt noted a ‘tradition … that any unrecognisable igneous or metamorphic [erratic] … is Norwegian’ (Catt 1963, p. 127). Subsequent careful observation and quantitative work suggested a dominantly British source for this erratic material, as the numbers of Scandinavian erratics are minuscule in proportion to British-derived material. The main source is now thought to be in northern Britain, with ice transporting material southwards from central and southern Scotland, and then incorporating material from eastern England and the western margins of the North Sea Basin (Lee *et al.* 2002, 2004).

Where did the (now, seemingly extremely rare) Scandinavian material come from? Potential sources include ice-rafted glacial debris or outwash from a Scandinavian ice sheet (Moorlock *et al.* 2000; Larkin *et al.* 2011) or reworked Scandinavian lithologies from the North Sea seabed (Pawley *et al.* 2005). While most of the classic Scandinavian indicator pebbles reported are igneous, we describe here a remarkable sedimentary rock pebble – so far unique to eastern England – that includes finely preserved fossil graptolites of non-British aspect. We tentatively suggest this may indicate yet another potential source region, adding a further dimension to the narrative of Britain’s far-travelled indicator erratics.

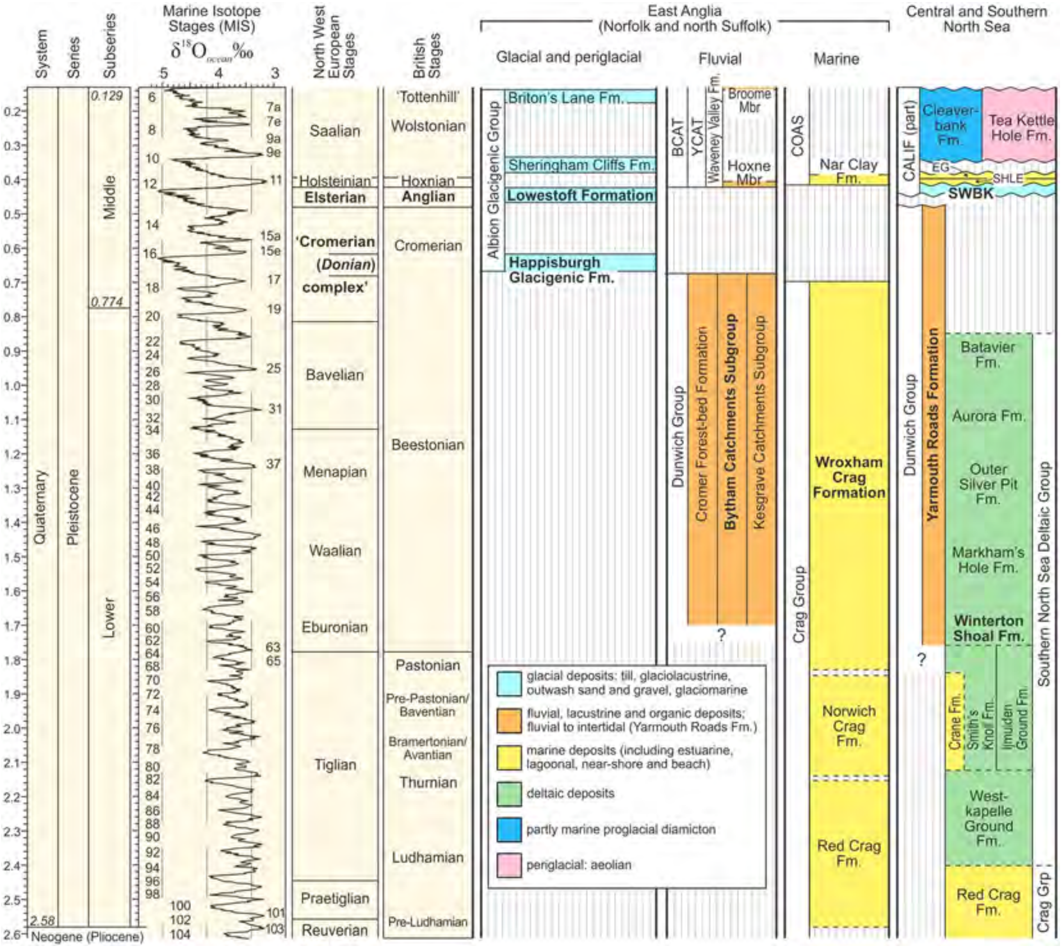

Fig. 1. Lower and Middle Pleistocene successions in East Anglia (Norfolk and north Suffolk) and the Central and Southern North Sea correlated with British and NW European stages and with Marine Isotope Stages. Correlations are based on McMillan *et al.* (2011, table 15, columns for NW Norfolk, NE Norfolk and southern Norfolk and north Suffolk) and Lee *et al.* (2015) for East Anglia, and Cameron *et al.* (1992), Gatliff *et al.* (1994) and Stoker *et al.* (2011) for the North Sea. Lithostratigraphical units and chronostratigraphical divisions mentioned in the text are in bold type. The Hill House Formation (not shown) succeeds the Norwich Crag Formation and is overlain by the Happisburgh Glacigenic and Lowestoft formations at Happisburgh on the north Norfolk coast; it is correlated with MIS 21 or 25 (Parfitt *et al.* 2010, including their supplementary information table 1). Members in the Happisburgh Glacigenic Formation (Banham, Corton Till, Happisburgh Till and Starston Till members) and Lowestoft Formation (Lowestoft Till Member) are not differentiated. Abbreviations: BCAT, Britannia Catchments Group; YCAT, Yare Catchments Subgroup; COAS, British Coastal Deposits Group; CALIF, California Glacigenic Group; EG, Egmond Ground Formation; SHLE, Sand Hole Formation; SWBK, Swarte Bank Formation. Left-hand columns (chronostratigraphical divisions including MIS) are from the global chronostratigraphical correlation chart (Cohen and Gibbard 2019, 2022).

Pebble location and local geological context

The pebble was found in ploughed soil by one of us (TH-W) in 2010 in a field at Park Farm Cottages, North Lopham, Norfolk [TM 0450 8370] (Fig. 2), and is curated in the collections of the British Geological Survey, Keyworth, its three sections post-slicing being numbered Zx 21049–51. The site is located at approximately +42 m Ordnance Datum (OD), part of a predominantly glacial till plateau. It is mapped as Lowestoft Till, with Starston Till recorded nearby (British Geological Survey 1989). These two units have been attributed to separate phases of the Anglian Stage of the early Middle Pleistocene, and they are now given member status as parts of the Lowestoft and Happisburgh Glacigenic formations, respectively (Lee *et al.* 2017).

The characteristics of both tills were summarized by Mathers *et al.* (1993; see also Lee *et al.* 2015). The Lowestoft Till is a grey diamicton rich in glacially reworked Jurassic Kimmeridge Clay and Cretaceous Chalk and flint, with minor amounts of other Mesozoic lithologies. It was deposited by British ice of western to northwestern provenance and now forms the thick plateau layer that underlies central East Anglia. In this area it typically also includes quartz and quartzite pebbles derived from pre-Anglian fluvial deposits, which are proved by borehole to be patchily present in the North Lopham area. These fluvial deposits include clasts introduced to the region by the Bytham River from as far away as the Welsh Borderland (Rose *et al.* 2002).

The brown sandy Starston Till contains abundant flint, together with a small proportion of exotic igneous and metamorphic clasts, almost all of Scottish origin. It also incorporates North Sea marine material derived from the Crag formations. It does not have ready surface expression, but is found cropping out in localized patches beneath the Lowestoft Till and resting on either pre-Anglian Bytham River deposits or Crag bedrock (Lee *et al.* 2015, p. 149). It was deposited earlier than the Lowestoft Till by an ice sheet of northeastern provenance centred on the North Sea (Lee *et al.* 2015, fig. 65).

The ploughsoil at North Lopham in which the pebble was found is clearly developed on a weathered surface of Lowestoft Till, which includes clasts derived from many source areas.

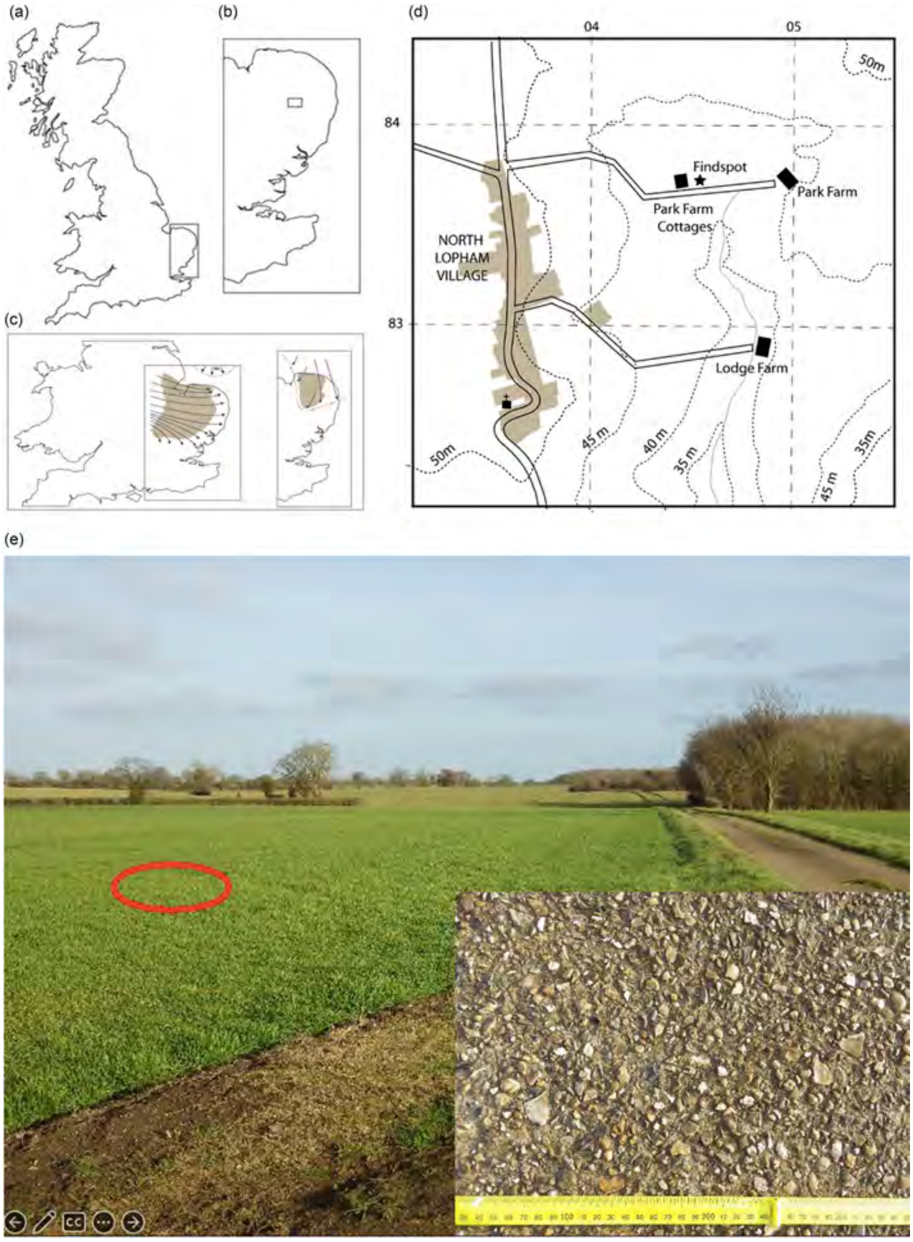

Fig. 2. Location of pebble find. (**a**, **b**) General location in Great Britain and East Anglia. (**c**) Inferred extents of deposition of the Lowestoft Till (left) and earlier Starston (Corton) Till (right) (following Lee *et al.* 2017, fig. 14, maps (e) and (b)). (**d**) The findspot immediately to the west of Park Farm Cottages. (**e**) The findspot (circled), with the lithological appearance of the track-forming gravel in the insert.

Methods

This study involved: fieldwork, during which this pebble was located and put into geological context; graptolite palaeontology, including using a Wild stereomicroscope equipped with camera lucida, and by photography; micropalaeontological study from thin sections (maceration was attempted, but unsuccessfully); and petrography by light microscopy and back-scattered scanning electron microscopy (BSEM).

Fig. 3. Photo of the pebble, following sectioning, showing the dark tones, striations and one graptolite.

Pebble lithology

The pebble measures 40 × 25 × 20 mm, is subrounded and has a glacially striated surface. It is a medium–dark-grey, indistinctly banded chert with fine, pale quartz-filled fractures and orange graptolite fragments (Fig. 3).

In thin section, the rock is a cryptocrystalline silica aggregate containing abundant pale, three-dimensional, silica-filled organic-walled microfossils ranging in size from ~50 to ~100 μm (Figs 4a, 5e, f and 8a–n). These have been infilled with diagenetic silica and so have resisted sedimentary compaction. The graptolite fragments appear as translucent yellow-orange periderm locally showing growth-banding (Figs 5b, d and 7a). The rock also contains abundant, variously orientated quartz veins (Fig. 4d). The graptolites have a silica infill, in which crystallization appears to have occurred in at least two phases, with a

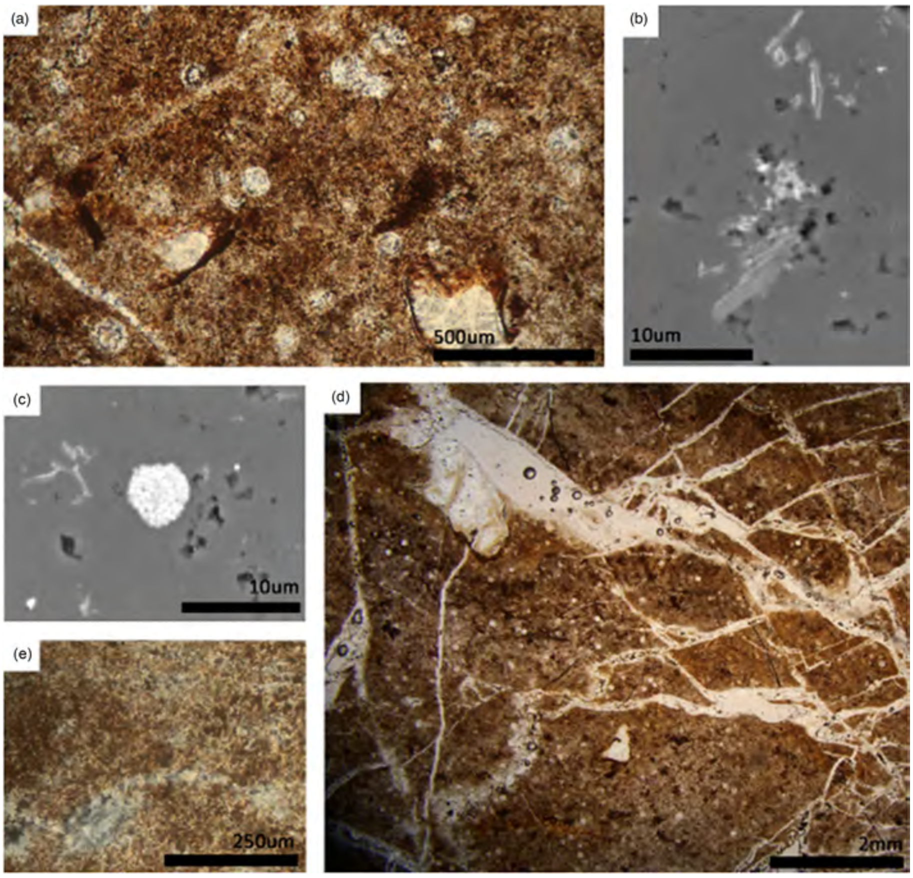

Fig. 4. (**a**) General rock texture in thin section (plane polarized light), showing mottled coloration and sections through spherical microfossils. (**b**) SEM photo showing phyllosilicate minerals, with significant levels of Al, Fe, Mg and K and with ?pyritized halos. (**c**) Pyrite framboid in the groundmass; small phyllosilicate minerals are also visible, enriched in Fe and Al. (**d**) General lithology, showing complex quartz veining and indistinct colour-banding within groundmass. (**e**) Groundmass under higher magnification.

finely crystalline outer layer and a more coarsely crystalline interior (Fig. 5c).

Faint crystal outlines can be observed by BSEM imaging, with the groundmass of the rock made up of quartz crystals ranging in size from 3 to 10 µm. The darker-toned microcrystalline quartz groundmass contains flecks of brighter material, which can be seen distributed randomly or as rounded outlines. These brighter areas contain elevated levels of iron, and possibly represent pyrite or its weathering product, the rounded shapes seeming to represent pyrite replacement of/or crystallization on microfossil walls (Fig. 5f), being comparable in size to the microfossils seen in optical thin section (~50–100 µm). Graptolite fragments are sporadically visible under BSEM (Fig. 5a, d). There are rare laths of Al-enriched phyllosilicate (Fig. 4b), usually with white, Fe-enriched halos.

Palaeontology

Graptolites

The sample (British Geological Survey Zx 21049-51) contains several very well preserved graptolites and graptolite fragments, which have been assigned to three species (Fig. 6): *Monograptus parapriodon* Bouček, 1931, *Monograptus priodon* (Bronn, 1835) and *Monoclimacis linnarssoni* (Tullberg, 1883), together with one indeterminate retiolitid graptolite. *Monograptus parapriodon* (Fig. 6b, c and h–j) is distinctive through its parallel-sided prothecae, compared with those of the long-ranging *M. priodon* (Fig. 6e, k) while *Mcl. linnarssoni* has distinctively convex supragenical walls (Fig. 6a, g). A fragmentary proximal end of a monoclimacid (Fig. 6d) seems too narrow for *Mcl. linnarssoni* and so is assigned to *Monoclimacis*? sp.; a similarly narrow monoclimacid proximal end from the *Oktavites spiralis* Biozone of central Wales was questionably assigned to *Monoclimacis griestoniensis nicoli* (Rickards 1965) by Zalasiewicz (1994), although it was noted (Zalasiewicz 1994, p. 381) that closer study might show that it lies within the range of variability of *Mcl. linnarssoni*. This assemblage indicates the material is from the *Oktavites spiralis* Biozone of mid-late Telychian age (Silurian: Late Llandovery; cf. Zalasiewicz *et al.* 2009).

Graptolite preservation

The graptolites are preserved completely three-dimensionally, as orange/yellow periderm with a silica infill that, especially in optical thin section, shows two phases of silica growth: a finely crystalline silica layer that appears milky/opaque on the rock surface and finely crystalline in thin section that coats the interior of the periderm; and a clear central infill of coarsely crystalline quartz (Fig. 5c) on the rock surface and in plane polarized light that appears coarsely crystalline in cross-polarized light.

In thin section, the periderm is translucent with a yellow/orange hue, and commonly shows fine preservation of the fusellar (growth band) structure (Fig. 7a). The orange colour suggests low thermal maturity and contrasts markedly with the black, carbonized appearance of typical British graptolites. In detail, the periderm commonly appears to show a 'corroded' appearance that may be evidence of decay or early diagenetic alteration (Fig. 7b, c).

Most graptolite fragments are not visible under a scanning electron microscope (SEM), perhaps because of the tenuity of the periderm. However, the periderm of one robust specimen of *M. priodon* can be seen under the SEM preserved as fine,

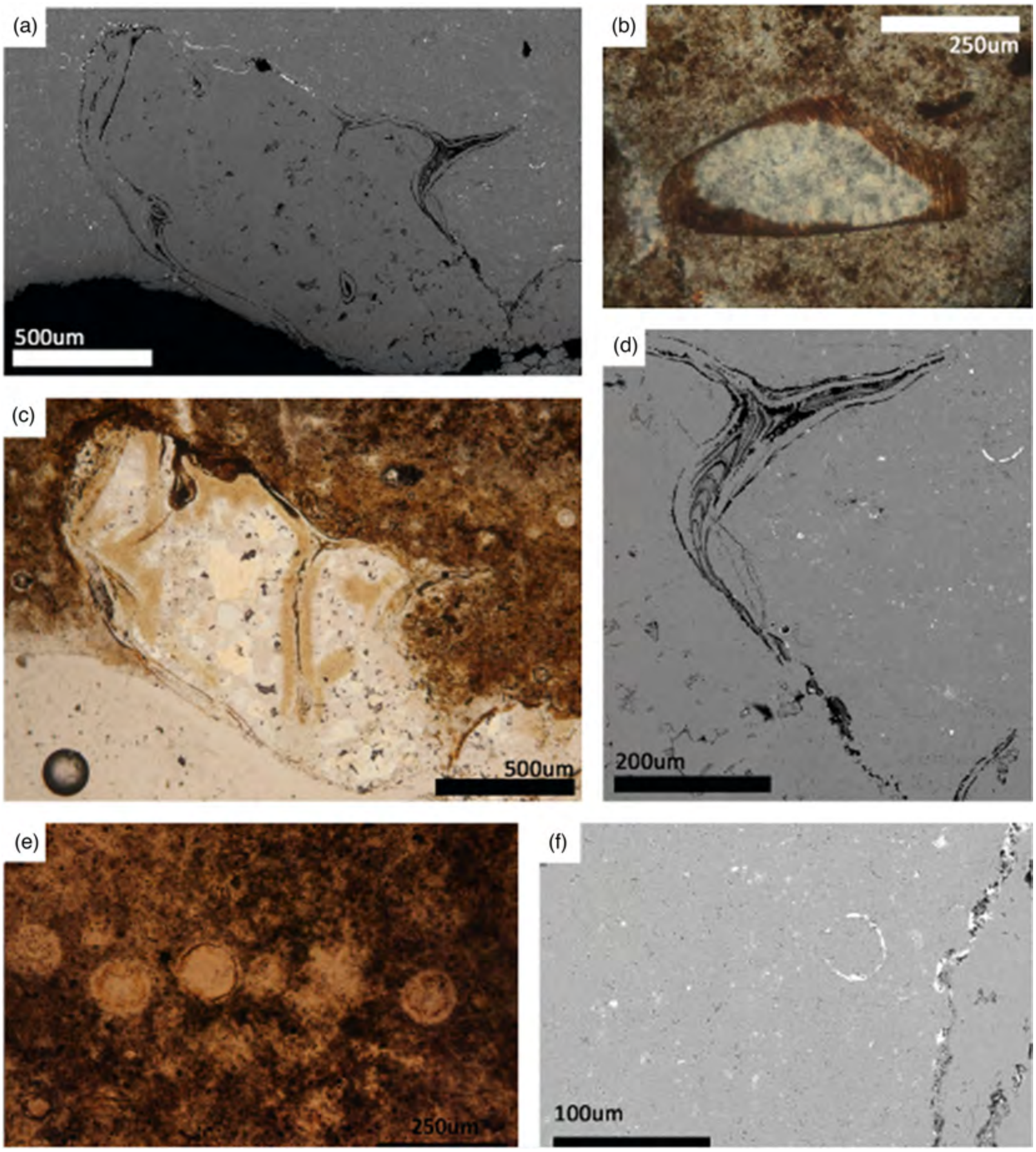

Fig. 5. (**a**, **c**, **d**) Section through *Monograptus priodon* specimen, imaged respectively by BSEM (a, d) and light microscope (c); BSEM images show infill of graptolite fragments to differ in texture from the surrounding groundmass, lacking the white flecks and other debris seen in the groundmass. (**b**) Cross-section of graptolite fragment showing internal fusellar structure. (a, d) Internal structure of apertural spine seen under BSEM. (**e**, **f**) Sections through spherical organic-walled microfossils seen under light microscope and BSEM, respectively; one of the latter shows a bright coating of or replacement by pyrite.

dark carbon laminae with a silica infill (Fig. 5a, d). Banded structures can be seen within the preserved spine, representing the periderm microstructure in cross-section.

Microfossils

Scattered through the matrix, there are distinctive spherical organic-walled microfossils typically 50–100 µm in diameter (Figs 4a, 5e, f and 8a–n). Some may be identified as radiolarians (Fig. 8a): one specimen showed spiny-rayed surfaces that may correspond to *Secuicollacta*, the internal part of this specimen being filled with microcrystalline quartz, while a few other specimens display a multi-shell test recalling members of the family Inaniguttidae.

There are also more enigmatic organic-walled microfossils, with the organic wall being complete in some and tenuous and incomplete in others, while in some aspects it can appear to take the form of an irregular two-dimensional mesh (e.g. Fig. 8d, e). Nevertheless, the organic wall apparently acted as a barrier during silicification, as the interior of the microfossils is typically composed of optically clear silica, lacking the orange-brown, presumably organic detritus present within the matrix external to the microfossils. Some of the microfossils, though, contain one or more large (~5–10 µm) opaque to slightly translucent objects (dark brown to black in transmitted light) that are sub-circular to elongated in outline (Fig. 8l–n).

Discussion

Comparison with British graptolite material

This material is remarkable in several respects. To our knowledge, these are the only graptolites ever found at the surface in East Anglia or within the Pliocene and Pleistocene deposits that cover the area. Moreover, while mid-Telychian graptolites including the taxa recognized occur in Wales (e.g. Davies *et al*. 1997), the English Lake District (Hutt 1974, 1975) and in southern Scotland (Bull and Loydell 1995), we

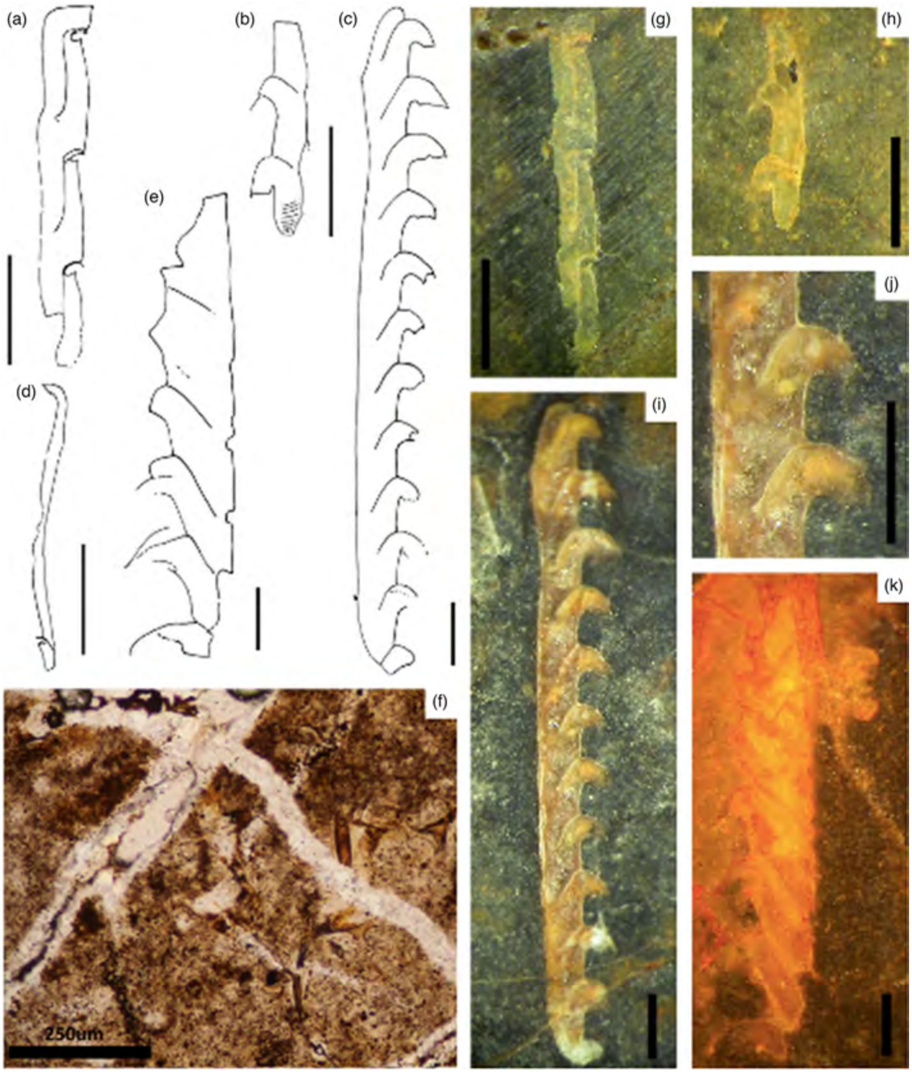

Fig. 6. Graptolite taxa found in specimen, as photographs and camera lucida drawings: (**a**, **d**, **g**) *Monoclimacis linnarssoni* (Tullberg, 1883); (**b**, **c**, **h**–**j**), *Monograptus parapriodon* Bouček, 1931; (**e**, **k**) *Monograptus priodon* (Bronn, 1835); (**f**) indeterminate retiolitid. All scale bars 1 mm with the exception of (f).

know of no British equivalent to the remarkable preservation of the fossils in this pebble.

British graptolite material is typically found either as flattened periderm or as rhabdosomes that are wholly or partly infilled either with sediment or with early diagenetic pyrite. At higher metamorphic grades than late diagenetic, pale phyllosilicate coatings can form on the periderm (Page *et al.* 2008). The periderm of British material is typically opaque (black in transmitted light) because of thermal maturation through deep burial.

The translucent and pale orange/yellow periderm of the graptolites in the North Lopham pebble, and the preservation of the organic-walled microfossils, suggest relatively shallow burial, with sustained burial temperatures not exceeding those of the oil window (~140°C: cf. Legall *et al.* 1981). Furthermore, the infill of early diagenetic silica, which has preserved the specimens three-dimensionally and is now seen as two generations of quartz, suggests very early mobilization and transport of silica in large amounts.

The early mobilization of large volumes of silica also differs from typical British Silurian deposits: the pebble is extremely clay-poor (with only occasional laths of phyllosilicate) and rich in very finely crystalline silica: the rock is a true chert. It is therefore quite unlike the clay-rich mudrocks of Wales and northern England, and is even more silica-rich than the variably cherty condensed deep-water mudrock successions of the Moffat Shales in the Southern Uplands of Scotland. In the latter, the graptolites are thermally mature and blackened, having been included in an accretionary prism (Stone 2012, 2014; Stone *et al.* 2012), and commonly have late diagenetic/low-grade metamorphic phyllosilicate coatings. The mid-late Telychian graptolites of the Midland Valley (Bull and Loydell 1995) seem to be of lower grade, judging from the associated acritarchs (Molyneux *et al.* 2008), but these rocks are rapidly deposited mudstones and sandstones, and no lithological equivalent of the East Anglian pebble has been recognized among the rocks of that region.

Possible provenance of graptolite material

The extremely fine-grained quartz mosaic that now makes up the pebble is of unknown origin, with little to constrain whether the original material was a chemical precipitate (e.g. from a volcanic spring) or of biogenic silica. All of the common spherical fossils seen in thin section seem to be organic-walled and thus more akin to acritarchs rather than to radiolarians. It is unlikely to have been derived from wind-blown dust (e.g. loess) not least because of the high early silica mobility needed to provide the large amounts of silica required to completely fill the graptolite rhabdosome interiors.

The affinities of the organic-walled fossils are obscure. Maceration of a small portion of this pebble yielded no

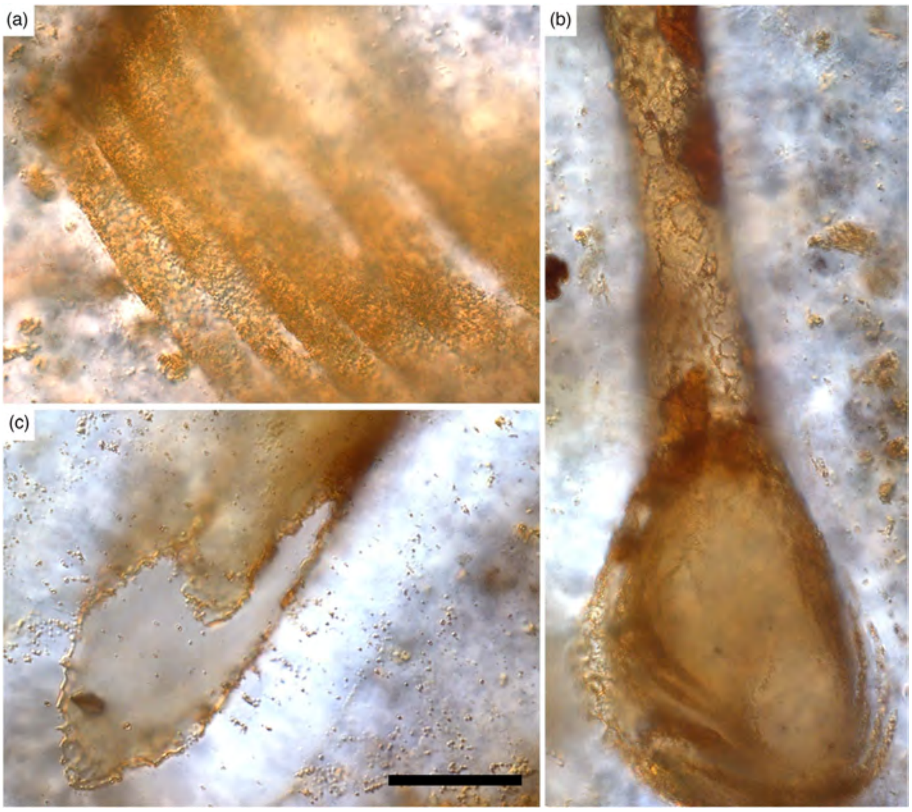

Fig. 7. High-magnification light microscope images of graptolite periderm wall showing (**a**) fusellar structure, and (**b**, **c**) spines showing irregular preservation of periderm structure. Scale bar represents 20 µm.

acritarchs, perhaps because degradation of the specimens, as seen in thin section, led to their disintegration during processing. Candidates for the source rock of the East Anglian pebble might be found among the Silurian cherts (locally termed 'lydites') recorded from the Świętokrzyskie (Holy Cross) Mountains of south-central Poland (Kremer 2005; Kremer and Kaźmierczak 2005) or within chert-hosted phosphatic nodules in the Bardzkie (Bardo) Mountains, part of the Sudetan Mountains of southern Poland (Porębska and Sawłowicz 1997). The former have yielded spherical microfossils identified as cyanobacteria, while the latter include diagenetically altered acritarchs and acritarch-like forms referred to mazuelloids, in which part of the organic matter (and earlier apatite diagenetic phases) is commonly replaced by silica. Some of the cyanobacteria recognized from the Holy Cross Mountains include putative baeocytes (internal reproductive bodies, formerly known as 'endospores'), and this is one possible explanation for the internal bodies seen in our material from East Anglia (Fig. 8l, m), although the East Anglian examples may be distinguished by their greater opacity and variety of shape. The silica replacement observed in the Bardo cherts may be an explanation for the 'corroded' appearance of the graptolite periderm in detail (Fig. 7), and for the observed tenuity and irregular meshwork appearance of the organic spheres; if so, then the silicification, while exquisitely preserving the overall morphology, may have degraded it at very small scale.

The closest possibility for a specific source for the pebble seems to lie among a suite of reworked early Silurian graptolitic cherts sporadically reported from southern Germany, including in the region around Erlangen, Donauworth, Aschaffenberg and Frankfurt am Main (Hundt 1957; Berger 2011). These contain silicified graptolite species of broadly similar age, with at least one species in common, the widespread and long-ranging *M. priodon*, with the illustration of a pebble in Berger (2011, figs 3 and 4) and the descriptions suggesting a strikingly similar lithology to the pebble we describe. Berger (2011, p. 107) emphasized the pale, three-dimensional graptolites encased in diagenetic quartz, and the networks of silica-filled fractures in the specimens, as in the pebble described here (Figs. 7b, c, 8c and 6f, respectively). A source area for these reworked German pebbles was suggested to include the 'Thuringian' Silurian rocks of the Frankenwald to the north in Germany, which include a lower Silurian succession that includes 'lydites' (cherts) with silicified graptolites. Graptolites of this age and assemblage type have been recorded from Scandinavia and the Baltic Region, but they are typically present in shales, which locally may include limestones (Bjerreskov 1975), with cherts in this region being present in older (Ordovician) levels (Schallreuter and Hinz-Schallreuter 2011). Thus, an origin from central European, probably German, terrain seems considerably more likely than a Scandinavian source.

Methods and directions of transport

The presence of a far-travelled pebble of this kind in East Anglia raises questions about possible transport routes and vectors. These questions revolve around a consideration of possible (1) anthropogenic and (2) natural agency.

(1) Anthropogenic agency: The possibility that the pebble was introduced by human agency into the ploughsoil at North Lopham cannot, *a priori*, be discounted. For instance, the presence of German prisoners of war carrying out agricultural work in Norfolk during World War Two is a matter of public record (Hansard 1944), and two Prisoner of War camps (Diss and Redgrave) were located within 9 km of the site

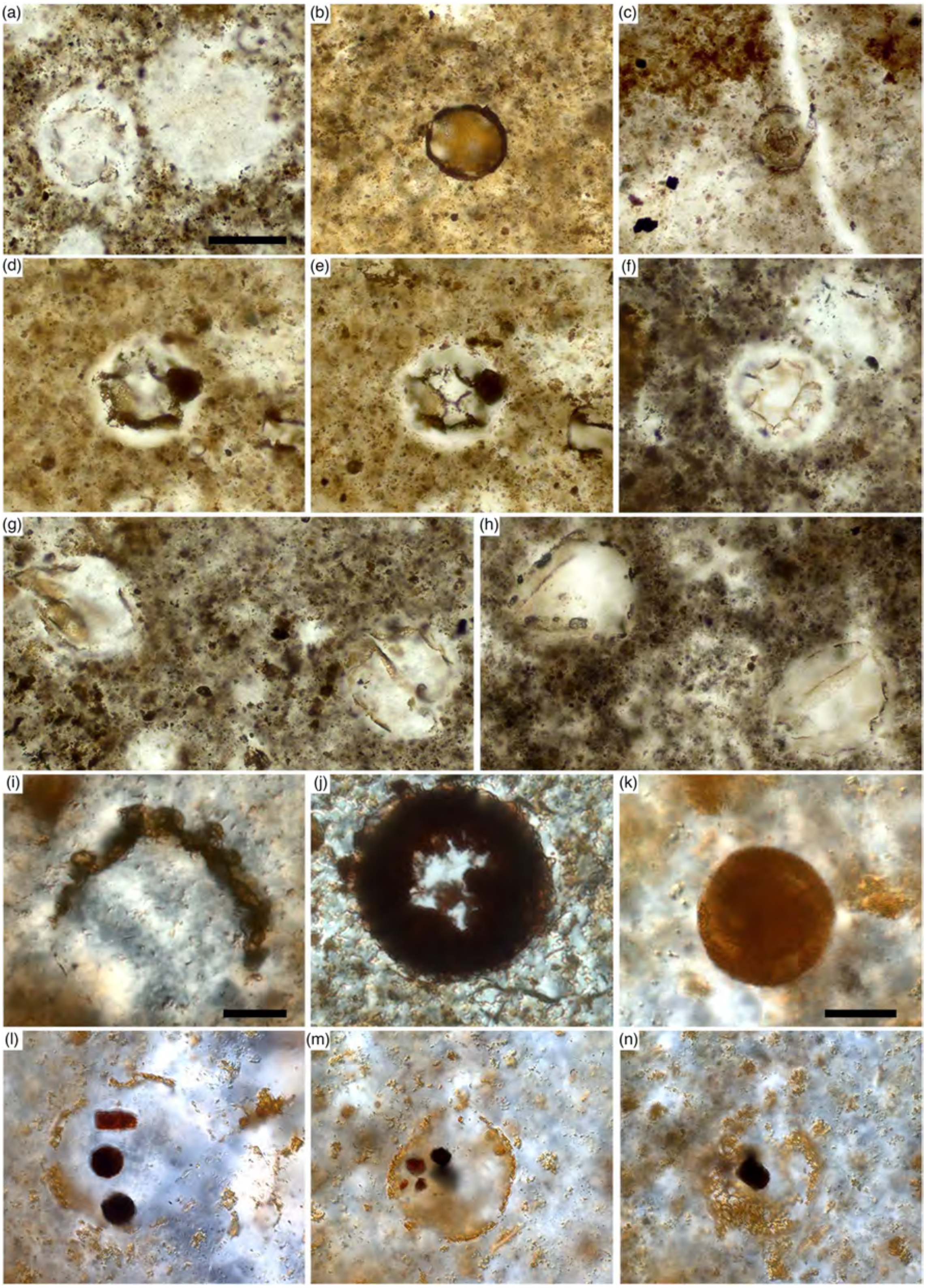

Fig. 8. High-magnification light microscope images of (**a**, right-hand side) possible recrystallized radiolarians and organic-walled microfossils, including (**b**) simple thick-walled sphaeromorphs, (**c**) double-walled forms, (**d**–**f**) forms with reticulate or polygonal walls, (**g**, **h**) thin-walled sphaeromorphs with apparent dehiscence splitting, (**i**, **j**) forms with pustulose walls, (**k**) thick-walled sphaeromorphs, and (**l**–**n**) thin-walled forms with multiple internal bodies. Scale bar in (a) represents 50 μm and applies to (a–h); scale bar in (i) represents 20 μm and applies to (i) and (j); scale bar in (k) represents 20 μm and applies to (k–n). Images (d) and (e), and (l–m), represent successive focal planes of each field of view.

(Thomas 2003). Perhaps more pertinently, it is reported that large quantities of aggregate were imported to the UK from East Germany and Poland during the 1960s and 1970s, because it was cheaper to import than to extract the aggregate in the UK (J.R. Lee, pers. comm.). Could some of this have been used to construct the concrete farm track next to Park Farm Cottages? Investigation by one of us (TH-W) showed that the trackway material (Fig. 2e) comprises flint-rich chippings with occasional quartzose clasts, typical of locally sourced glaciofluvial and valley gravels. Pebbles and cobbles ($n = 395$) collected at random from ploughsoil in a 10 m wide by 20 m long corridor either side of the trackway identified a clast population characteristic of the Lowestoft Till plateau, comprising flint 74.43%, quartzose lithologies (vein quartz, quartzite, chert (including *Rhaxella*), 'schorl' breccia) 12.15%, sandstone 2.78%, chalk 2.53%, other sedimentary (Jurassic mudstone) 0.25% and igneous (dolerite) 0.25%; archaeological materials (principally prehistoric heat-crackled flint) composed a further 7.59%. No further examples of graptolitic chert or other exotic lithologies were found. On this evidence it seems reasonable to dismiss the idea that German or Polish aggregate was used to construct the road and that some may have become accidentally scattered on the fields either side of it.

(2) Natural agency: Fluvial, glacial and marine processes may variously have been involved in the natural transport of the North Lopham pebble from its source area in the Frankenwald. There are two plausible routes for the first stage of its journey. One is via rivers draining northwards towards the Baltic and into the Eridanos River, a major fluvial system draining the Baltic region from Miocene to early Mid Pleistocene times, and which received input from tributaries on the North European Plain (Overeem *et al.* 2001). The other route is via the palaeo-Rhine system including the River Main and its tributaries, which currently drain the western side of the Frankenwald. Both systems were major contributors of sediment to the North Sea basin (Gibbard and Lewin 2016; Lamb *et al.* 2017). Their deposits include detrital zircon spectra consistent with a Baltic or mid-German Crystalline Rise origin (Krippner and Bahlburg 2013).

A third possible transport route can be rejected on sedimentological and geomorphological grounds. Detrital mica grains of Saxothuringian Variscide origin have been recognized in Carboniferous sandstone from the Forest of Dean near the southern end of the border between England and Wales (Sherlock *et al.* 2000). Its transport from central Germany to the Forest of Dean is explained by a large-scale fluvial system in the late Carboniferous. From there we might hypothesize transport of a clast to East Anglia via the Palaeo-Thames system in the early Pleistocene (Rose 2009). However, the Forest of Dean is very distal to the German source area, and while detrital mica could have been transported there fluvially, the same is highly unlikely for pebbles. This part of the Anglo-Welsh border was close to the Equator in late Carboniferous times (Waters and Davies 2006, p. 174), so pebble transport by Carboniferous ice-rafting is not plausible either.

A sequence of upper Pliocene to Middle Pleistocene formations in the southern North Sea basin comprise deposits of predominantly continental (Eridanos and palaeo-Rhine) origin deposited on prograding delta fronts (Cameron *et al.* 1992; Overeem *et al.* 2001; Rose 2009, fig. 12A; Lee *et al.* 2012; Lamb *et al.* 2017: Fig. 9 herein). The Winterton Shoal Formation (Fig. 1) represents the first of the prograding deltas to enter the UK sector of the North Sea and

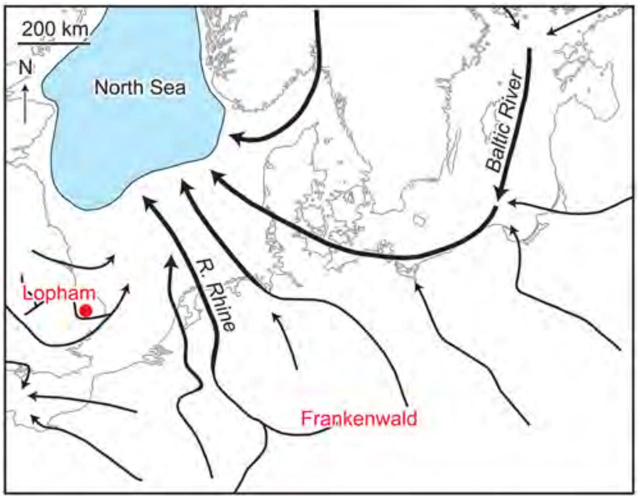

Fig. 9. Suggested Quaternary transport route of the pebble, by fluvial transport from the Frankenwald region into the North Sea, with subsequent transport (by iceberg rafting?) to northern East Anglia. Palaeogeographical map for the early Pleistocene based on Overeem *et al.* (2001), Rose (2009) and Gibbard and Lewin (2016).

is dated to *c.* 1.75–1.7 Ma. Later formations, such as the Winterton Shoal Formation in the Southern North Sea Deltaic Group (Fig. 1), represent continued northwestwards advance of this deltaic sedimentation. The upper part of the correlative Yarmouth Roads Formation, which comprises fluvial and intertidal deposits, has been dated to the 'Cromerian Complex' (*c.* 0.8 to 0.5 Ma; Fig. 1) and includes sandy and pebbly layers. By that time, the basin had become a wetland complex of delta-top sediments, which has been called Ur-Frisia, with a shoreline as far north as *c.* 55° N (i.e. the latitude of Newcastle upon Tyne). Glacial deposits of Cromerian age containing Scandinavian-derived clasts have been recovered from boreholes drilled on the Dogger Bank at a roughly similar latitude (Lee *et al.* 2012).

The influence of the Eridanos system lessened from *c.* 1 Ma, owing to reduced sediment supply to and accommodation space within the delta system. Additionally, its headwaters were truncated by the formation of the Baltic basin by ice-sheet erosion (Gibbard and Lewin 2016, pp. 209–210). This reduction in the Balto-Scandinavian elements in the southern North Sea basin was compensated by enhanced sediment influx from the Rhine, which transported ever more and coarser sand and gravel liberated from central Europe during increasingly severe glaciations (Cohen *et al.* 2014, p. 20). The southern North Sea Bight was dominated by the palaeo-Rhine delta, which by this time had filled the whole of the central and southern North Sea (Gibbard and Cohen 2015, p. 67). The delta complex received inputs on its western side from the British landmass (Overeem *et al.* 2001, p. 302; Rose 2009, fig. 10; Gibbard and Lewin 2016, fig. 8).

Thus, at the onset of the Mid Pleistocene glaciations the southern North Sea basin was a low-relief plain that comprised substantial deposits of continental and British origin (Hijma and Westerhoff 2012, fig. 13). It was subject to fluctuating sea-levels (Funnell 1995, p. 10) and provided a low-relief surface for the spread of Scandinavian and British ice sheets during the Mid Pleistocene (Cameron *et al.* 1992, p. 108), both of which would have involved reworking and transport of sediments.

Until recently it was thought that the earliest evidence for ice sheets entering the North Sea basin was dated to *c.* 0.7 Ma. There is new evidence for ice-sheet incursions into the North Sea as far back as Marine Isotope Stage (MIS) 100 (*c.* 2.52 Ma), with coalescence of the British and Scandinavian ice sheets by *c.* 1.78 Ma (MIS 64) (Rea *et al.* 2018). Iceberg ploughmarks preserved in deposits in the Dutch sector of the North Sea provide evidence for ice sheets, presumably Scandinavian, with tidewater termini dating from as early as *c.* 2 Ma (Kuhlmann and Wong 2008, pp. 185–186; figs 11 and 18). Major glaciations occurred in MIS 16 (Donian) and MIS 12 (Elsterian, which correlates with the Anglian Stage in the UK): two pre-Elsterian formations are present in the Netherlands in which Scandinavian glacial erratics are mixed with material of eastern provenance (Zagwijn 1985, p. 21), indicating cold glacial conditions within the North Sea Province, although there is no evidence for glaciation reaching so far south (Laban and Van der Meer 2011). Donian deposits have been recognized in the British sector of the central North Sea (Bendixen *et al.* 2017), but not yet in the southern area. Elsterian deposits are represented by the Swarte Bank Formation (Cameron *et al.* 1992, pp. 108–109). Microfossils and heavy mineral analyses indicate that its sediments were deposited by ice of north British origin, with no evidence for a Scandinavian ice sheet in the western part of the North Sea basin at this time (Davies *et al.* 2011). Nor is there compelling evidence to support the former, long-held, belief that Scandinavian ice reached East Anglia during the Pleistocene (Lee *et al.* 2002, 2017; Evans *et al.* 2018). Fennoscandian clasts found in Early Pleistocene contexts in East Anglia, in sediments that predate the oldest undisputed signs of glaciation, are thought to have been introduced indirectly as ice-rafted materials from Scandinavian ice sheets that advanced towards but did not enter the region (Lee *et al.* 2012, p. 217). These may also, presumably, have entrained clasts, such as the pebble we describe, resulting, eventually, in them being transported to more distal regions by ice-rafting during periods of high sea-level.

At two sites in NE Norfolk, pre-Elsterian deposits contain clasts whose ultimate source is unmistakably Scandinavian. Deposits ascribed to Lee's (2009) Unit A–B of the Wroxham Crag Formation (Fig. 1) at Sidestrand [TG 2613 4005], 'an outer estuarine gravel bar', contain rhomb porphyry and other exotic material thought to have been emplaced by ice-rafting in the late Early–early Mid Pleistocene (MIS 34–16; *c.* 1.1–0.6 Ma) during 'Cromerian Complex' times (Larkin *et al.* 2011, p. 451). A rhomb porphyry clast was also recorded from the Lower or lower Middle Pleistocene Hill House Formation (HHF) at Happisburgh [TG 380313] (Hoare 2012, p. 345) (see Fig. 1 caption). The HHF was deposited in the upper part of the estuary of an eastward-flowing river (Parfitt *et al.* 2010). Reworking of local marine deposits such as the Wroxham Crag by local rivers is implied (Westaway 2011, p. 393).

Landwards migrating coastlines caused by marine transgression in the southern North Sea Bight during Early and early Mid Pleistocene 'interglacial' periods (Thurston 2017, p. 742) is another plausible route whereby palaeo-Rhine delta clasts could have been reworked into a British context, such as the Wroxham Crag. Such reworking and 'combing up' (during periods of high sea-level) of sediments deposited on the continental shelf (during cold periods) has been invoked to explain the exotic clast composition of Holocene shingle landforms, as at Chesil Beach, Dungeness and Orford Ness (Goudie 1990, p. 284; cf. May 2003, p. 263).

Once introduced into an area, robust exotic lithologies, such as the chert clast discussed here, may survive a number of geological cycles and be reworked into progressively younger sediments. There may have been fresh introductions of Scandinavian material to Norfolk in Mid Pleistocene times. The Happisburgh Till Member of the HGF overlies the HHF at Happisburgh and is widely regarded as the oldest glacial deposit identified in East Anglia. It has variously been dated to MIS 12 or MIS 16 (Lee *et al.* 2004), with the balance of evidence falling on the side of the latter (Lee *et al.* 2015, pp. 161–162, but see discussions in Rose *et al.* 2015 and Hodkin *et al.* 2016). The till was deposited by a north British ice sheet scouring the western side of the North Sea basin (Lee *et al.* 2002, p. 79, 2015, fig. 65) and reworking pre-existing Pleistocene deposits, principally those of the Wroxham Crag Formation.

The Lowestoft Formation at North Lopham is associated with ice-flow from the west (Lee *et al.* 2017, fig. 14c) and is composed of material reworked from older deposits, including the HGF. The latter is represented locally by the Starston Till Member and the Banham Member, which underlie the Lowestoft Till in the North Lopham area (Lawson 1982; Mathers 1988; Mathers *et al.* 1993). The Starston Till is typically a sandy to silty clay – most likely of Crag derivation – containing sporadic small pebbles, including exotic igneous and metamorphic types, but it does not have surface expression in the area (Mathers *et al.* 1993, p. 20). The Banham Member crops out patchily at the surface in the East Harling–Kenninghall–Banham area, some 2 km to the north and NW of the pebble's findspot. It consists of a sequence of glacial lake deposits containing seams of quartzose-rich gravels. Although an absence of igneous and metamorphic ('Scandinavian indicator') pebbles is noted (Mathers *et al.* 1993, p. 23), the deposit is assigned to the HGF (Lee *et al.* 2017, p. 151). The high quartzose component ratio suggests derivation from pre-Anglian river deposits or Wroxham Crag, and the heavy minerals indicate a mixture of Bytham River and glacial material derived from the North Sea (J.R. Lee, pers. comm.).

This far-travelled pebble is evidently a great rarity in the landscape of East Anglia. If a natural origin is accepted for the transport of this pebble from Germany, we may plausibly characterize its history as follows. It originated by rivers of the palaeo-Rhine system from Silurian bedrock in central Europe, most likely Franconia, which transported it to the North Sea region. Since the Early Pleistocene, the North Sea Province is likely to have undergone several cycles of erosion and deposition by marine processes at periods of high sea-level and by the Eridanos and Rhine palaeo-rivers when the sea-level was lower. These processes would have operated during the early or early Mid Pleistocene represented by the Wroxham Crag of the British Pleistocene. Mid Pleistocene glacial transport associated with emplacement of the HGF and later the Lowestoft Formation (Fig. 9) finally transported the clast to its present location at North Lopham in central East Anglia. A possible Welsh or north British origin can be discounted on lithological and graptolite preservational grounds.

Conclusions

- A unique chert pebble found in the Lowestoft Till at Lopham, Norfolk, contains exquisitely preserved Silurian graptolites of the *Oktavites spiralis* Biozone (Llandovery: Telychian), associated with abundant, three-dimensionally preserved organic-walled microfossils, some identified as radiolarians and probably acritarchs, while others remain more enigmatic.
- The palaeontology, lithology and the low metamorphic grade excludes a British origin for the pebble.
- The pebble resembles Silurian chert deposits described both as *in situ* bedrock and as derived clasts from the Frankenwald region of central Germany.
- A polyphase transport process is envisaged in the early Pleistocene from this region via the Eridanos River or Rhine River system and their associated North Sea delta, followed by a likely succession of glacial, glaciofluvial and marine agents spanning the Early and Mid Pleistocene.
- An anthropogenic transport route, via importation of industrial aggregate from northern Europe during the 1960s and 1970s, is discussed and discounted on the basis of the evidence presented above.

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