Diamicton from the Vale of Pickering and Tabular Hills, north-east Yorkshire: evidence for a Middle Pleistocene (MIS8) glaciation?

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ABSTRACT

Diamicton deposits (up to 6.90 m thick) in the Vale of Pickering and the Tabular Hills (North York Moors) have been confirmed by cored boreholes. The diamicton is interpreted as glacial till with a matrix consisting predominantly of grey-brown, yellow-brown and dark grey, stiff to very stiff clay and sandy clay with occasional thin beds of laminated sand and clay. Sub-rounded to sub-angular erratic clasts were sourced predominantly from local Upper Jurassic Corallian Group bedrock exposed in the southern part of the North York Moors. Clasts include well-rounded, pebbles of Jurassic sandstone, mudstone and sparse Jurassic coal derived from outcrops on the North York Moors. Fragments of underlying Upper Jurassic mudstone bedrock form the predominant clasts in the lower part of the till. The paucity of exotic clasts and a local derivation suggests a relatively small glacier - perhaps a temperate-plateau ice-field, was established on the Tabular Hills. The glacier subsequently advanced southwards to the Vale of Pickering depositing locally derived subglacial traction till at the base, passing up to lodgement till. Local preservation of the degraded till outcrops in the Vale of Pickering, the overconsolidated nature of the clay till matrix, striated pebbles and the presence of sub-rounded pebbles suggests deposition during a glacial cold stage post-MIS 12 (Anglian) and pre-MIS 2 (Devensian). A tentative Middle Pleistocene MIS8 age is proposed, possibly coeval, but not coincident, with the Basement Till (Bridlington Member) of the Holderness coast and the Wragby Till of central and eastern England.

Keywords: Middle Pleistocene, till, Last Glacial Maximum, Vale of Pickering, MIS 8, Late Devensian

1. Introduction

Evidence for glacial deposits of pre-Ipswichian age (i.e. Middle Pleistocene) in north-east Yorkshire is sparse, probably as a result of removal of earlier deposits by glacial and periglacial erosion or concealment beneath younger deposits related to subsequent cold stages so that evidence for earlier glaciations before the Last Glacial Maximum (Dimlington Stadial; Late Devensian; dated at between 18.5 ka and 13 ka calendar years BP (Clark et al., 2012) is generally absent (Catt, 2007). Pre-Ipswichian glacial tills, Ipswichian interglacial deposits and Late Devensian tills have been described from Holderness coast and east Yorkshire by early workers (Lamplugh, 1879) and their stratigraphical relationships, provenance and mineralogical composition determined by more recent workers (Catt and Penny, 1966; Madgett and Catt, 1978; Berridge and Pattison,1994; Bateman and Catt, 1996; Edwards, 1978). In a recent review, Catt (2007) summarised the Holderness sequence, in upward sequence as the Basement Till (pre-Ipswichian in age), Skipsea Till and Withernsea Till (both of Late Devensian age). However, Catt noted that correlation of this sequence to the north and south of the type Holderness area is problematic and, furthermore, that correlation on a purely lithostratigraphical basis with deposits resulting from other ice streams is not yet possible (see Boston et al., 2010; Evans and Thompson, 2010).

It is generally assumed that the Anglian (MIS 12) glaciation was present throughout most of the British Isles with its glacial limit extending approximately east-west from Suffolk through north London to South Wales (Bowen et al., 1986; Clark et al., 2004 a,b; Lee et al., 2011, 2012). However, evidence for lowland glaciation in the British Isles between the Anglian and Late Devensian (MIS 2) cold stages is sparse and somewhat controversial. Evidence for the proposed 'Wolstonian' glaciation (Mitchell et al., 1973; Straw, 1979, 2011; Catt, 1981) included the Oadby Till, but some authors regard this as deposited by the Anglian ice-sheet (Perrin et al., 1979; Sumbler 1983, Rose 1987) although this has now been revised (Rose, 2009). More recently, dating of Middle Pleistocene deposits of the Trent Valley demonstrated evidence for a post-Anglian, pre-Devensian glaciation (MIS 8; Wragby Glaciation) that affected much of central and eastern England (Bridgland et al., 2014, 2015; White et al., 2016). It has been suggested (White et al., 2016) that the late Middle Pleistocene Wragby Glaciation (MIS 8) deposited till in the upper Trent Valley and that this is a correlative of the Wragby Till in the lower Trent and Witham basins of Lincolnshire and, possibly with the Basement Till (Bridlington Member) of Holderness, thus supporting the age designation of Catt (1981). Consequently, there is an increasing body of evidence for additional Middle Pleistocene glaciations in east and central England

There is abundant information for the Late Devensian glaciation (British and Irish Ice Sheet) in north Yorkshire (Fox-Strangways et al., 1885, 1886; Fox-Strangways and Barrow, 1915; Kendall, 1893,1902; Gaunt, 1976, 1981; Powell et al., 1992; Frost, 1998; Thomas, 1999; Evans et al. 1995; Boston et al., 2010; Evans and Thompson, 2010; Roberts et al., 2013; Busfield et al., 2015; Bateman et al., 2015; Evans et al, 2016). In the late 19th century the primary geological survey mapped till (or 'boulder clay' as it was then described) in the Vale of York and along the Yorkshire coast (Fox-Strangways et al., 1885, 1886; Fox-Strangways and Barrow, 1915). They recognised the 'terminal' moraines at York and Escrick, and marginal moraines at Ampleforth and Wykeham (Fig.1). The Ampleforth Moraine marks the eastern limit of the Late Devensian ice-sheet where it advanced into the western end of the Vale of Pickering along the topographically low ground of the Coxwold-Gilling Gap (Fig. 1). The Wykeham Moraine is generally taken to mark the maximum western advance of the North Sea arm of this ice-sheet, at the eastern end of the Vale of Pickering (Penny and Rawson, 1969; Evans et al., 2016), although others have suggested a more westerly maximum ice limit to the east of Pickering (Foster, 1985). However, the deposits of the Wykeham Moraine are not tills (diamicton), but consist of glaciofluvial sand and gravel, probably deposited at the frontal lobe of the ice-sheet (Penny and Rawson, 1969; Edwards, 1978).

Bateman et al., 2011 revised the chronology of the Dimlington Late Glacial Maximum type site (Rose, 1985), showing that the Yale of York and North Sea ice lobes advanced between 21 – 19 ka, thereby blocking the western and eastern ends of Glacial Lake Pickering (Evans, et al., 2016). These authors suggested that the Vale of York ice lobe extended briefly at about 18.7 ka to the south of the River Humber to reach Lindholme before retreating northwards to form the recessional Escrick and York moraines. Late Devensian ice was, therefore, assumed to be absent from the Vale of Pickering, which was occupied by a lake (Glacial Lake Pickering) from ca. 21 – 15 ka (Clark et al., 2004 a,b; Bateman et al., 2015, fig. 10; Evans et al., 2016). Glacial meltwater emanating from the ice-sheet margins and from snow/ice fields on the upland areas of the North York Moors discharged southwards via deeply incised valleys such as Ryedale and the deeply incised Newtondale glacial meltwater Channel (Kendall, 1902). Lake water ponded-up between the Ampleforth and Wykeham marginal moraines (Fig.1), and eventually found an outlet to the south via deeply incised Kirkham Gorge (Kendall, 1902; Evans et al., 2016). Glacial Lake Pickering subsequently drained to leave a vestige of Lake Flixton (near Star Carr) at its eastern margin by about 15 ka (Palmer et al., 2015).

The primary geological survey recognised and mapped isolated outcrops of 'till' *within* the confines of the former Glacial Lake Pickering and on the southern margins of the Tabular Hills (Upper Jurassic, Corallian Group). In addition, they reported relict patches and scattered erratic pebbles of quartz, quartzite and chert along with sparse pebbles of probable Lake District origin on the tops of the North York Moors (Penny, 1974; Gaunt in Kent, 1980). At the time of the primary survey mono-glacial theories were current and, consequently, the Geological Survey maps and publications did not separate these 'tills' from the more widespread Late Devensian tills known from the coastal exposures and the Vale of York, although in later publications (e.g. Kendall, 1902; Fox-Strangways and Barrow, 1915, Bisat, 1939) the presence of 'Older and Newer Drifts' was recognised. These early workers, and subsequent re-surveys in the Vale of York (BGS, 1992; BGS 1994; Powell et al. 1992; Frost 1998; Ford et al., 2008), recognised that the Late Devensian ice-sheet bifurcated around the North York Moors uplands to form the Vale of York ice-sheet lobe to the west, and the North Sea ice-sheet lobe to the east. The geographical distribution of the Late Devensian till deposits indicates that the Late Devensian ice–sheet was absent from the high ground above approximately 230 m elevation in the Hambleton Hills (Powell et al. 1992) and 250 m in the Eskdale area (Gregory, 1962). The 'older' glacial deposits have been described as 'pre-Ipswichian' (Penny, 1974 and Gaunt in Kent, 1980, figure 27) who recognised the enigma of 'till' deposits within the Vale of Pickering. Outcrops of the 'pre-Ipswichian' glacial deposits are shown on the Pickering (Sheet 53) and Scarborough (Sheet 54) Geological Survey maps, and further incorporated in the Provisional 1:50 000 scale sheets (BGS, 2000; 1998, respectively).

Recent uranium series (U-Th) isotope studies (thermal ionization mass spectrometry, TIMS) of carbonate flow-stone from 'windy-pit' caves (Cooper et al., 1976; Murphy and Lundberg, 2009) in the North York Moors at elevations ranging from around 100 m to 275 m asl support this earlier assumption that the upland moor-tops were not glaciated during, at least, the last 208 ka, (i.e. since MIS 7).

In this paper we describe the results of field and laboratory investigations of these 'pre-Ipswichian' diamictons including the drilling of five shallow, cored boreholes, four of which were located in the Vale of Pickering, and one on the southern flanks of the Tabular Hills (Figs. 1, 2a). The aims were to investigate the distribution, geomorphology, sedimentology and fabric of the diamictons and their clast provenance with a view to determine the origin and possible age of the deposits.

2. Material and methods

2.1 Field Surveys

A number of localities were selected (Fig. 2a) to encompass a range of geomorphological, sedimentological and stratigraphical features of the known outcrops of diamictons in the southern Tabular Hills and Vale of Pickering. These comprise:

a) The area near Westfield Grange (SE 75204 87858) which represents 'till' (boulder clay) mapped by the Geological Survey in 1892 (BGS, 2000) overlying Corallian Group limestone bedrock at the southern margin of the Tabular Hills (North York Moors). This area lies at approximately 120 m above sea level (asl) and lies outside the known limits of the Late Devensian Ice Sheet advance from the east (Ampleforth) or west (Wykeham) along the axis of the Vale of Pickering. The outcrop also lies to the southof the margin of the Late Devensian Ice Sheet that is known to have terminated in Eskdale (Kendall, 1902; Gregory,1962) located about 25 km to the north of the Vale of Pickering (Fig. 1).

b) The low ground (approximately 50 m asl) adjacent to the River Rye near Rye House Farm (SE 63326 82736), Harome, located at the western margin of the Vale of Pickering, also representing 'till' mapped by the Geological Survey in 1882 (BGS, 2000). The bedrock in the vicinity is the lower part of the Upper Jurassic Ampthill Clay Formation, which is not distinguished from the overlying Kimmeridge Clay Formation on the 1: 50 000 scale geological map in this area (BGS, 2000).

c) The outlier at near Habton Grange Farm, Great Barugh (SE 75045 78840) which represents one of the centrally located small hills that rises above the general level of the Vale of Pickering (Fig. 3). , where 'till' is shown on the geological map overlying Jurassic Kimmeridge Clay Formation bedrock. The top of Great Barugh hill is 41 m asl, rising above the flat-lying, clay and sand deposits of the former Glacial Lake Pickering, with a surface level at approximately 20 m asl.

d) The outliers in the Howardian Hills near Crambe (SE 720 640), above Kirkham Gorge, lying at about 70 m asl and at Huttons Ambo (SE 74 69). This deposit was not proved by boreholes, but geological field surveys carried out by BGS in the York district during 2004 provided information on the diamicton and its erratic clast suite, at surface.

Field surveys comprised identification of diamicton matrix and glacial erratics, at surface, and further identification of the diamicton matrix using an Edelman soil auger, generally to a depth of 1.2 m. Auger samples were taken at approximately 0.25 m intervals; the diamicton matrix was logged with reference to the Munsell colour chart. Boundaries with the underlying bedrock and or Vale of Pickering glacial lake deposits were noted on field maps.

2.2 Cored boreholes

Five shallow cored boreholes were drilled at localities a, b and c noted in Section 2.1 (Fig. 2a). Three boreholes were drilled near Rye House Farm, but one of these, Borehole No. 1b, was abandoned at 2.0 m depth due to an obstruction. The succession in this area was characterised in Borehole No.1 located approximately 5 m to the north. The BGS mobile Dando drill rig was deployed using percussion technique with a 102 mm barrel and 2 m or 3 m casing lengths. Penetration rates were recorded; the core was logged briefly on-site, and then transferred to plastic tubes with a plastic film liner to preserve moisture.

2.3 Core logging, sampling and clast identification

In the laboratory, the core was cut lengthwise using a circular saw, and the cut halves photographed using a high-resolution, large-format digital camera (80MP large format scanning back in a 5 inch X 4 inch camera).

The cores were logged in detail using a Munsell colour chart, preserving one half of the core as a permanent record. Cores and samples ae curated at the National Geological Repository, British Geological Survey, Keyworth, Nottingham. The other half of the core was sampled at intervals and subjected to a number of standard laboratory tests including particle size analysis; erratic clasts were sampled and identified, visually, by reference to known outcrops in the region. Measurements of the stiffness of the clay matrix were taken at regular intervals down the core using a Schmidt hammer. Larger clasts, above granule grade were sampled directly from the core. Other representative till samples were washed in water and sodium hexametaphosphate to disaggregate the clay matrix; small grains and granule-size clasts were then picked from split, washed residues and identified using a binocular microscope. A number of small black coaly and organic mudstone clasts were identified at a number of levels in the Westfield Grange core; these were analysed for spores and pollen by JBR to determine their age and provenance.

2.4 Geomorphological analysis

In order to test if there is any evidence of sub-glacial or post-glacial sculpting of the diamicton outcrops that might indicate direction of travel of an ice-sheet/glacier or post-glacial fluvial incision, twenty-five mapped outliers of suspected pre-Ipswichian ‘till’ shown on the BGS 1: 50 000 scale maps of the area (Pickering (BGS, 2000), Scarborough (BGS, 1998) and York sheets) were measured to record the relative length of their long and short axes so as to provide a measure of their elongation from 1 (round) to 4 (elongate); the azimuths of the long axes of these till outliers were recorded and plotted as a rose diagram (Figure 2b).

3. Results

3.1 Field Surveys

3.1.1 Westfield Grange, Cropton [SE 57 87]

The Westfield Grange area represents two isolated outliers of 'till' (SE 75 87) mapped during the primary survey (see BGS, 2000) to the east and west of the Wrelton-Cropton road. The area is inclined gently to the south following the regional dip-slope of the Upper Jurassic Coralline Oolite Formation (Corallian Group) bedrock. The diamicton occupies a generally flat lying area east of Cropton Banks Wood. Degraded sections in the dimicton are exposed in a sunken track (SE 7531 8803) where well-rounded cobbles of hard quartzite are present in a grey–brown clay matrix. Additional well-rounded cobbles and boulders of yellow-grey, hard quartzite are also present, adjacent to the track; these may have been transported from the adjacent fields by farmers. The area of diamicton was under pasture at the time of survey, but auger holes to 1.2 m depth recorded stiff, grey-brown clay matrix with small ooidal limestone granules, the latter derived from the local bedrock.

3.1.2 Great Barugh Hill (SE75 89) and adjacent hills

Located in the central part of the Vale of Pickering the hills at Great Barugh (SE 75 79), and Salton Holme (SE 71 79) to the west and Little Barugh (SE 76 79) to the east, represent upstanding hills capped by 'till' deposits as mapped by the primary survey (see BGS, 2000) (Fig. 2a). In English 'barugh' means a barrow-like hill feature, as illustrated in Fig.3. Patches of Upper Jurassic Kimmeridge Clay bedrock on the lower slopes of Great Barugh and Little Barugh hills suggest that the diamicton is relatively thin (< 1 m) in these marginal areas, and this was confirmed by augering and exposures in adjacent field ditches during this study. Deposits of Glacial Lake Pickering, consisting of brown laminated clay with thin sand laminae, onlap onto both the Kimmeridge Clay bedrock and the diamicton deposits at Great Barugh and Little Barugh. The Kimmeridge Clay Formation bedrock was proved in the Kirby Misperton No. 1 Borehole (SE 7710 7893) on the southwestern flank of Little Barugh hill (BGS, 2000). Walkover surveys and auger holes to 1.2 m depth at Great Barugh hill revealed yellow-brown and grey, stiff clay matrix with erratic granules and pebbles of Corallian Group ooidal limestone and calcareous sandstone. The fields are strewn with well-rounded erratic pebbles and cobbles of similar lithologies together with well-rounded pebbles and cobbles of yellow-grey, hard quartzite; the latter similar to those seen at Westfield Grange.

3.1.3 Rye House Farm, Harome (SE 63 82)

This locality represents an elongate lobe-shaped outlier of diamicton adjacent to the Harome to Helmsley road to the east of the River Rye. It is gently undulating, dipping gently to the south-east. The underlying bedrock, exposed in a dissused quarry (SE 6321 8229) adjacent to the River Rye, comprises the Upper Calcareous Grit Formation (Upper Jurassic) overlain by grey-brown mudstone, representing the lower part of the Ampthill Clay, capped by grey-brown, pebbly clay diamicton. The succession in the quarry suggests that the diamicton is relatively thin in this area, as confirmed by subsequent boreholes. Walkover surveys of the ploughed fields east of Rye Hill Farm and shallow exposures in a sunken track nearby (SE 6322 8269) revealed a yellow-brown diamicton matrix with abundant well-rounded pebbles and cobbles, mostly comprising yellowish-grey and grey quartzite and spiculitic, decalcified sandstone ('calcareous grit' of the Corallian Group) and less common pale grey ooidal limestone (Corallian Group).

4.2 Borehole Cores

The cores from the boreholes at Westfield Grange, Rye, and Habton Grange Farm (Great Barugh No.1) are illustrated in Figs.4 to 11. The most significant features are commented on here for each of the boreholes.

4.2.1 Westfield Grange No.1, Cropton (SE 75204 87858)

At this locality diamicton overlies Corallian Group bedrock at ca 120 m asl. The diamicton matrix is a yellow-brown, stiff to very stiff, sandy clay (Figs. 4,5). Clasts are matrix supported, and randomly orientated. They are dominated by sub-rounded and sub-angular pebbles of Coralline Oolite Formation (Corallian Group), especially the Birdsall Calcareous Grit Member (calcareous spicular sandstone) and Hambleton Oolite Member (ooidal limestone) to 2 m depth. Below this depth, the clast component is similar, but occasional small, rounded pebbles of Lower and Middle Jurassic sandstone and sparse Jurassic ironstone are also present. Occasional granule-size clasts of bright coal and organic-rich mudstone are present. Palynomorphs identified from the coal and organic-rich mudstone (Table 2) indicate a Middle Jurassic to Late Jurassic or Late Jurassic to Early Cretaceous age for these organic-rich clasts (Riding, 2012). The borehole terminated on a large boulder of Hambleton Oolite which is thought to represent bedrock at 6.91 m depth.

4.2.2 Habton Grange Farm (Great Barugh) (SE 75045 78840)

This borehole was sunk at ca 41 m asl at the top of Great Barugh hill where diamicton overlies Kimmeridge Clay Formation bedrock. The diamicton matrix is a yellow-grey, firm to stiff slightly calcareous clay with matrix-supported sub-angular to sub-rounded granules and pebbles. The clasts are dominated by Coralline Oolite Formation including Hambleton Oolite Member (ooidal limestone) and Lower Calcareous Grit/Birdsall Calcareous Grit (calcareous spicular sandstone) with occasional rounded pebbles of Lower/Middle Jurassic sandstone, some with bivalves. Clast composition is summarised in Table 1. From 1.30 m to 1.76 m depth the matrix is sandier and includes disturbed and folded laminae with a pocket of clayey fine-grained sand; pebbles clasts are predominately Lower/Middle Jurassic sandstone. From 1.76 m to 4.20 m the matrix is very stiff with only sparse pebbles of Coralline Oolite Formation and Middle Jurassic sandstone, but the proportion of local bedrock-derived sub-angular lithoclast fragments of Kimmeridge Clay Formation (organic-rich mudstone) increases down-hole.

Two beds of very stiff, fine-grained, ripple cross-laminated sand with grey clay laminae present from 4.20 to 4.34 m and from 5.07 to 5.12 m. In the upper bed, laminae are displaced by normal micro-faults in places; the bed passes down to very stiff clay with convoluted balls of yellow-brown silt (Figs.6,7); the latter are common in the lower bed. The lower diamicton (5.20 to 6.7 m) is a very stiff clay with some Coralline Oolite Formation and Middle Jurassic sandstone pebbles, and two pebbles of possible volcanic origin. However, the majority of clasts comprise sub-angular pebbles of dark grey mudstone derived locally from the Kimmeridge Clay Formation set in a finely ground matrix of this bedrock.

The borehole terminated at 6.70 m depth on an erratic boulder of calcareous sandstone, which is interpreted as the base of the diamicton because it coincides with the elevation of the mapped base of the diamicton in adjacent field and ditches.

4.2.3 Rye House Farm No.1a, Harome (SE 63488 82373)

The Rye House Farm boreholes (No.1a, 1b and 2) are located on a generally flat-lying spur trending south-southeast from Helmsley, south-eastwards to Rye House Farm (Fig.2). The bedrock comprises thin Ampthill Clay Formation overlying Corallian Upper Calcareous Grit Formation. The boundary between these units (see 3.1.3) is exposed nearby adjacent to the River Rye (SE 6321 8229). Ploughed fields adjacent to the borehole sites are rich in pebbles and cobbles consisting of pale yellow-grey, hard, well-rounded quartzitic sandstone.

In Rye House Farm No.1a borehole similar quartzite and quatzitic sandstone clasts are also common in the top 0.3 m soil and subsoil profile (Figs.8,9). From 0.30 m to 0.76 m depth, the sandy clay matrix is rich in Jurassic granules and pebbles mostly comprising spicular sandstone (Lower Calcareous Grit Formation or Birdsall Calcareous Grit Member) and ooidal limestone (Hambleton Oolite or Malton Oolite members) with occasional quartzite pebbles. A pebble of chert-rich, ooidal spiculitic sandstone may represent the Coral Rag Member. Weathered bedrock comprising brown mudstone and clay was present from 0.76 m to 2.00 m, passing down from 2.00 m to 3.00 m to yellow brown, slightly micaceous, laminated mudstone with small thin-shelled bivalves (Ampthill Clay Formation).

4.2.4 Rye House Farm No.1b, Harome (SE 63488 82374)

The succession penetrated in this borehole is similar to borehole No. 1a, located 5 m to the north. Clasts in the upper 0.4 m comprise both Birdsall Calcareous Grit/ Lower Calcareous Grit together with sparse well-rounded pebbles of grey-brown quartzitic sandstone.

4.2.5 Rye House Farm No.2, Harome (SE 63326 82736)]

This borehole (Figs.10,11) was drilled to the northwest of Rye House Farm No.1a and No.2, and was located adjacent to a sunken track that exposes brownish-grey clay with abundant well rounded pebbles and cobbles of quartzite and Coralline Oolite Formation. Similar clasts are common in the top 0.4 m of the borehole in the soil and sub-soil horizons. Below 0.45 m depth the diamicton matrix comprises clay or very sandy clay with abundant sub-rounded pebbles and cobbles composed predominantly of spicular calcareous sandstone (Lower Calcareous Grit/Birdsall Calcareous Grit) with occasional chert-rich pebbles probably derived from the Coral Rag Member. In places the diamicton is clast-supported and includes rounded pebbles of micaceous sandstone, ferruginous sandstone and green-grey siltstone, probably derived from the Middle Jurassic, Ravenscar Group. Importantly, some of the softer erratic pebbles have striated surfaces. Ampthill Clay Formation bedrock, weathered in the top 0.2 m, was penetrated from 3.0 m to 4.0 m.

5. Discussion

5.1 Diamicton Genesis

The diamicton successions penetrated in the boreholes described above and from observations derived from field surveys and auger holes are interpreted as glacial till. A glacial till origin is supported by the following characteristics. Clasts derived from the Corallian rocks of the Tabular Hills are generally rounded to sub-rounded, and include striated clasts (Rye House N0.2 Borehole); both evidence of glacial abrasion and transport. Well-rounded, hard quartzite pebbles in the upper parts of the diamictons are also far-travelled erratics, but may be the products of earlier geomorphological processes. Furthermore, the clay matrix of the diamicton is, in engineering geology terminology (BSI 5390, 2015), stiff to very stiff, indicating considerable overburden pressure. Consolidation of the clay matrix is also interpreted as subglacial traction till (Evans et al., 2006). Furthermore, the angular to sub-angular shape of the clasts in the lowermost diamicton overlying soft Kimmeridge Clay Formation (e.g. Habton Grange Farm Borehole) indicates sub-glacial traction with erosion of bedrock clasts at the base of a glacier.

An origin as a periglacial gelifluctate ('head' deposit as mapped by the British Geological Survey) is discounted based on the above characteristics and the absence of a significant geomorphological gradient between the foot of the scarp of the Tabular Hills and the isolated diamicton outcrops in the Vale of Pickering. Rounded and sub-rounded Corallian clasts and the presence of sparse Middle Jurassic coal-rich clasts also preclude an origin as gelifluctate'.

We confirm the presence of till deposits in the Vale of Pickering and on the southern slope of the Tabular Hills, as mapped by the Fox-Strangways during the primary survey (BGS, 2000). At the time of the primary '6-inch to the mile' survey (Fox-Strangways and Barrow, 1915) the till deposits mapped in the Vale of Pickering were not distinguished from the more continuous spreads of till and associated glacial deposits now known to have been deposited during the Late Devensian (LGM) by the Vale of York and North Sea ice-lobes that advanced, respectively, southwards along the Vale of York and eastern coastal margins of the North York Moors (Catt, 2007; Clark et al., 2012; Bateman et al., 2015 and references therein). Recognition that the Vale of Pickering tills were not deposited during the Late Devensian ice-sheet advance was first made by Kendall (1902) and further noted by Bisat (1940) and Gaunt (figure 27 in Kent, 1980). These scattered till outcrops were referred to as 'pre-Ipswichian glacial deposits' or 'older drift' and, furthermore, it was recognised that there is little evidence, except at Speeton, Kirmington and Welton-le-Wold (Catt and Penny 1966; Boylan, 1981; Madgett and Catt, 1978), to determine their age. Characteristics, such as the isolated position of the Vale of Pickering glacial deposits outside of the limits of the Late Devensian marginal moraines at Ampleforth (to the west) and at Wykeham (to the east) (Fig.

1), the onlapping nature of glaciolacustrine silt, clay and sand deposited on the floor of Glacial Lake Pickering (Fig. 2a) (Kendall, 1902) and the patchy, geomorphologically degraded nature of the outcrops, preclude a surge of the Late Devensian (MIS 2) ice-sheet, laterally, from the east (North Sea lobe) or west (Vale of York lobe) along the low-lying, east-west axis of the Vale of Pickering. Furthermore, definitive Late Devensian glacial deposits have not been identified in the central upland areas of the North York Moors south of Eskdale, indicating that this upland area was ice free during the Last Glacial Maximum and, therefore, that the Vale of Pickering till could not have been deposited as a result of a surge of the Late Devensian ice-sheet southwards, from Eskdale, over the top Tabular Hills.

Relict patches and scattered glacial erratics including vein quartz pebbles have long been identified on the moor tops (Fox-Strangways, et al., 1885,1886; Fox-Strangways and Barrow, 1915, Bisat, 1940; J. Rose pers. comm. July 2016) indicating that the area must have been overridden and glaciated during at least one of the pre-Ipswichian (pre-MIS 5) cold stages, or perhaps during the Early Devensian. The erratics in the patchy 'older' glacial deposits on the North York Moors described by previous authors (Fox-Strangways, et al., 1885,1886) are of indeterminate provenance, being mostly composed of quartz, quartzite and chert, but a few clasts are recognisably from the Lake District, north Pennines or north-eastern England (Bisat,1940; Gaunt in Kent, 1980) indicating, in part, a distant provenance: they are interpreted as being deposited during the MIS 12 (Anglian) glaciation that is thought to have covered the upland areas of the British Isles (Clark et al., 2004)

The better known and more continuous pre-Ipswichian glacial deposits, mostly till, are exposed on the Holderness Coast (Lamplugh, 1879; Catt and Penny, 1966; Catt, 2007; Evans and Thompson, 2010). The oldest unit, the Basement Till (Bridlington Member) in this area has a grey (locally greenish grey) clay matrix, containing erratics derived mainly from north-eastern England (Cretaceous chalk and flint, Jurassic sandstones and shales, Permian 'Magnesian Limestone', Carboniferous limestone and shale, Whin Sill dolerite, and Scotland (granites, basalts and gneisses), but including a few pebbles of larvikite and rhomb porphyry from Scandinavia. The latter exotic erratics were probably picked up in the North Sea from older glacial deposits or by a contemporaneous ice-sheet originating in Scandinavia that approached the Holderness coast from the north-east (Penny and Catt 1967; Catt 2007). However, others have suggested that the Basement Till is of Devensian age and that there is no evidence to indicate that it was deposited by a Middle Pleistocene ice-sheet on the east coast of the UK (Boston, et al., 2010; Evans and Thompson, 2010) and, furthermore, that the exotic clast component represents reworking of earlier glacial deposits (Catt, 2007).

However, these interpretations ignore the observed stratigraphical position of the Basement Till beneath Ipswichian beach deposits at Sewerby (Catt and Penny, 1966).

5.2 Provenance of Vale of Pickering erratic clasts

The erratic clasts in the Vale of Pickering tills provide evidence of the provenance and geographical extent of the ice-sheet that transported and deposited these sediments. Furthermore, a comparison with erratics described from better known tills in north-east England and Holderness provides some evidence on the likely extent and direction of movement of the ice-sheet. In contrast to the erratic clasts of the oldest Basement Till of Holderness (regarded as Wolstonian, MIS 6-10 by Penny and Catt 1967; Catt 2007) the Vale of Pickering tills are remarkable for their near absence of far-travelled rock types. No erratics of Scandinavian origin or clasts derived from the Lake District (e.g. 'Shap Granite') or Permian and Carboniferous rocks of north-east England were found during this study. Furthermore, the erratics in the Vale of Pickering tills are predominantly derived from bedrock locally outcropping in the Tabular Hills, comprising the Upper Jurassic Corallian Group, and principal among this group, spicular calcareous and decalcified sandstone (Lower Calcareous Grit and Birdsall Calcareous Grit) and ooidal limestone (Hambleton Oolite and/or Malton Oolite) (Wright, 1972; Powell, 2010). These clasts are mostly sub-rounded to sub-angular in roundness, indicating that they are not far-travelled. The provenance of these erratics is likely to be the Corallian Group outcrop of the Tabular Hills and southern Hambleton Hills located, respectively, to the north and north east of the Vale of Pickering.

In addition, well-rounded, generally smaller, pebbles of sandstone, ironstone and mudstone may have been derived from Middle Jurassic outcrops (Ravenscar Group) on the flanks of currently incised valleys such as Ryedale, Bilsdale and Farndale or, further north, from the northern part of the North York Moors between Guisborough and Eskdale. Small organic-rich mudstone and coal clasts from the Westfield Grange Borehole yielded terrestrially-derived spores and pollen ranging in age from Mid Jurassic to Early Cretaceous and probably derived from outcrops of Middle Jurassic paralic rocks (Ravenscar Group) or the Late Jurassic Kimmeridge Clay. The absence of Carboniferous palynomorphs, common constituents of North Sea derived tills (Lee et al., 2002; Riding et al., 2003; Davies et al., 2011, 2012; Busfield et al., 2015), precludes derivation from Carboniferous rocks in the Northumberland and Durham coalfields, located to the north of the moors, but suggests a provenance from the Middle Jurassic coal-bearing lithofacies of the Ravenscar Group exposed in the Middle Jurassic inliers such as Farndale, Ryedale and Rosedale (Powell, 2010).

The lower part of the till in the Habton Grange (Great Barugh) borehole (Figs. 6b,7b) is composed of very locally derived sub-angular and angular fragments of mudstone bedrock (Kimmeridge Clay Formation) that have been incorporated into a silt to clay grade matrix. We interpret this resulting from the basal shearing and plucking of the relatively soft mudstone at the base of the glacier and subsequent deposition as a subglacial traction deformation till (Evans et al., 2006). Similarly, in the Rye House boreholes, the underlying Ampthill Clay bedrock is incorporated into the basal till, but in these examples the depth of erosion and thickness of incorporated bedrock mudstone is less. Overlying tills (Figs. 4, 6 to 11) are paler, generally brown in colour (more oxidised) with a greater variety of clasts, but lacking deformed local bedrock clasts; these are interpreted as lodgement till.

The notable exception to the locally derived erratics of Corallian Group or Kimmeridge/Ampthill Clay bedrock and occasional Middle Jurassic sandstone is the presence of grey and grey-brown, well rounded, hard quartzite and quartzitic sandstone, and small pebbles of vein quartz in the upper part of the till. Similar quartzite pebbles and cobbles are common in the weathered soils in ploughed fields (at Rye House, Great Barugh and Huttons Ambo) and in piles of pebbles moved by farmers to the edge of the fields at Westfield Grange. The provenance of these quartzite pebbles, which are only present in the upper part of the tills, is uncertain. These erratics resemble the basal quartzite pebbles (so-called 'liver-coloured quartzite') found in the lower part of the Triassic Kidderminster Formation (Sherwood Sandstone Group), but are distinct from the harder sandstone beds of the Jurassic succession, such as the white-weathering and coarse grained Moor Grit (Middle Jurassic Ravenscar Group). The absence in these tills of other clasts typical of the Triassic and Permian succession in northern England suggests that the quartzite pebbles were not derived directly from Lower Triassic bedrock. They may, however, have been derived from a remanié deposit of such pebbles similar to the well-rounded orthoquartzite pebbles found at the base of the Upper Miocene Brassington Formation (Kenslow Member) of the Derbyshire Peak District (Walsh et al. 1972, 1980; Aitkenhead et al. 1985; Pound and Riding, 2016). In that region these hard, highly resistant quartzite pebbles are thought to be derived from a pre-existing Triassic cover succession, and later incorporated into Upper Miocene deposits that were preferentially preserved in dolines. It is not inconceivable that similar Triassic-derived remanié pebbles were incorporated into Upper Miocene deposits on the North York Moors during a period of Tertiary erosion, and subsequently re-incorporated into the Middle Pleistocene ice-sheet that deposited the Vale of Pickering till.

The sandy matrix with disturbed and folded laminae with a pocket of clayey fine-grained sand from 1.30 m to 1.76 m depth in the matrix in the Habton Grange Borehole and convolute laminae and micro-faults in fine-grained laminated sand with thin clay laminae (from 4.20 to 4.34 m and 5.07 to 5.12 m) are interpreted as soft-sediment dewatering resulting from changes in pore-water pressure in a sub-glacial or perhaps intra-glacial lacustrine environment.

5.3 Ice movement

The local provenance and sub-angular to sub-rounded shape of the majority of the erratics derived from the local Corallian Group outcrop (Westfield Grange) or local area (Vale of Pickering) indicates that a small ice-field or glacier was established on the high ground of the Tabular Hills above 150 m asl (Figs. 1, 2a, 12). The paucity of exotic clasts from farther afield (in contrast to the Late Devensian Vale of York/North Sea ice-sheet lobes and the pre-Ipswichian (pre-MIS5e) Basement Till/ Bridlington Member of Holderness) suggests the presence of a local ice-field. We envisage that a relatively small ice-field was established on the high ground of the Tabular Hills and the North York Moors (Middle Jurassic and Upper Jurassic bedrock), perhaps initially as cold-based ice (Fig. 13a). Subsequently, localised wet-based glaciers advanced southwards to the lower topographical area of the Vale of Pickering (ca 20-40 m asl) depositing till with locally derived clasts on the southern flanks of the Tabular Hills and farther south over much of the Vale of Pickering (Fig. 13b); the glacial advance extended southwards to the higher ground of the Howardian Hills (Huttons Ambo outcrop (SE74 69)). Kimmeridge Clay Formation bedrock (soft claystone) outcropping over much of the Vale of Pickering may have facilitated enhanced basal sliding of the glacier across the Vale of Pickering, eventually terminating against the higher ground of the Howardian Hills to the south. Similar enhanced basal sliding across underlying Late Jurassic mudstone has been postulated for the LGM North Sea ice-lobe (Bateman et al., 2011; Busfield et al., 2015). Plateau ice-fields and glacier lobes of similar size and altitudinal difference above surrounding topographical lowlands are currently present in Iceland; these include the Mýrdalsjökull; Eyjafjallajökull; Hofsjökull, Porisjökull and Langjökull glaciers (Evans and Twigg, 2002; Evans, 2005). These may provide modern-day analogues for the localised plateau ice-field that we envisage in the Tabular Hills and North York Moors, and which advanced southwards into the Vale of Pickering. Advancing glaciers scoured out the softer Kimmeridge/Ampthill Clay formation bedrock, thereby lowering the topographical level of the Vale through redistribution of the transported material within the Vale. The high percentage of sub-angular bedrock mudstone clasts within a comminuted matrix of the same lithology in the subglacial traction till (Figs. 5,7) also indicates comminution processes at the base of the glacier (Evans et al., 2006).

A feature common to most of the isolated till outcrops in the Vale of Pickering (Fig.1) is the presence of underlying relatively soft Upper Jurassic mudstone bedrock (the Corallian Group bedrock at Westfield Grange is an exception). This association is also seen in the Crambe outlier and at Huttons Ambo where similar till overlies, respectively, Lower Jurassic and Upper Jurassic mudstone bedrock (Figs.1, 12). We suggest these tills are preferentially preserved where the glacier ground into soft mudstone bedrock, which was deformed, sheared off and locally incorporated as a basal till with a comminuted matrix of similar composition. The cohesive nature of the basal bedrock mudstone-dominated till may have resisted erosion during subsequent erosional episodes. Conversely, till and associated glacial deposits deposited on the more resistant Corallian limestone/sandstone areas appear to have been more prone to subsequent erosion, resulting in poor preservation potential in areas of hard bedrock. In addition, the low topographical setting of the Vale of Pickering and the absence of an erosive Late Devensian ice-sheet in the Tabular Hills and in the area of Glacial Lake Pickering helped to preferentially preserve these earlier glacial deposits.

The twenty-five mapped outliers of tills show a general orientation to the south (ca 185 degrees north) (Figs.1,12). Till outliers have width-length ratio mean of 1.8 (where 1.0 is circular) (Fig. 2b). The general southerly orientation and elongation is interpreted as erosional sculpting of the relatively soft bedrock mudstones (Ampthill and Kimmeridge Clay formations), and the remnants of the overlying till as the ice moved southwards across the Vale of Pickering and up onto the Howardian Hills located to the south (Fig. 1). The north-south orientated, elongate ridges ('barughs') of Jurassic bedrock mudstone, locally capped by till, appear somewhat anomalous because the topographical and structural grain of the bedrock and faulting in the Vale of Pickering and Howardian Hills is generally east-west. This indicates powerful deformation and erosive sculpting of the bedrock and till as the ice moved southwards, as shown in Fig. 13. The marked, approximately north-south orientation of the till outcrops suggests the development of glacial lineaments (drumlins) that formed as the ice-sheet advanced to the south. Similar landforms have been described from low ground below plateau icefields in Iceland (fig. 16.15 in Rea and Evans, 2005). Alternatively, the shape of the outcrops could have been produced by fluvial erosion (incision) of an original, more uniform till outcrop during the post-glacial phase.

5.4 Age of the Vale of Pickering Till

The Vale of Pickering boreholes did not penetrate any dateable organic sediments or marine shells of Quaternary age. Consequently, it is not possible to determine a precise age for these tills.

A surge of the LGM ice sheet southwards across the high ground of the North York Moors or from the east and west along the axis of the Vale of Pickering has been discounted (see above), nor is there any evidence for an ice-sheet on the high moors and Tabular Hills during MIS 2 (Bisat, 1940; Murphy and Lundberg, 2009). The ca 120 ka age (MIS 5e) of the classic Ipswichian 'hippopotamous mammalian fauna' from Victoria Cave, Kirkdale (Boylan, 1981, Gascoyne et al., 1981) located east of Westfield Grange, has been revised to 112 +-2 ka (Gilmour et al., 2007).

If our proposed model of a local ice field glaciation of the Tabular Hills with a plateau-sourced ice-sheet advancing across the Vale of Pickering is correct, then the locally derived erratic suite could have formed in isolation from major regional ice-sheets such as the south-eastward directed ice-sheet that moved onto mainland Britain from the North Sea during the pre-Devensian glaciation (Basement Till of Catt, 2007). However, the latter has a distinctive erratic suite including pebbles derived from Scandinavia and north-east England as would be expected from major ice-streams merging with the locally sourced tills from a local plateau glacier in the southern North York Moors. In addition, on the assumption that the Anglian (MIS 12) ice sheet was very extensive in the British Isles (Gibbard and Clark, 2011) and would have over-ridden the high ground of the North York Moors, any tills deposited by this ice-sheet would be expected to contain far-travelled exotic clasts (e.g. Lake District and Scandanavian lithologies) in contrast to the tills described in this paper.

Following on from the above discussion, we suggest the till was deposited by a local ice-sheet during MIS 6-10. This tentative age is supported by recent work on the dating of River Trent river terrace deposits and their relationship to till (Wragby Till and equivalents) in central and eastern England. The Wragby Till has been attributed to a post-Anglian, pre-Devensian glaciation which occupied much of central and eastern England during MIS 8 (White et al., 2016). We propose that this glaciation would have supported a plateau ice-sheet on the Tabular Hills and adjacent uplands. Deposition of the Vale of Pickering tills during the MIS 2 glaciation is discounted on the grounds of provenance, overconsolidation of the clay matrix, and geomorphology, as discussed above.

Recent U-Th (TIMS) age dates derived from carbonate flow-stone from 'windy-pit' caves in the Corallian Group limestones of the North York Moors indicate that the upland area has been ice-free since at least 208 ka (MIS 7) (Murphy and Lundberg, 2009). These authors suggest that the Basement Till of the Holderness coast (Catt, 2007) pre-dates MIS 7 and may be Anglian in age (MIS12; 480-430 ka). If the U-Th flow-stone dates are correct then the local ice-sheet on the North York Moors that deposited the Vale of Pickering till must pre-date MIS 7, a time when these fissures opened up and flow stone was deposited during an ameliorating climate. In conclusion, we propose, tentatively, a MIS 8 or Wragby Glaciation, part of the event that reached much of the north Midlands of England, for the Vale of Pickering till. It is likely that formerly more extensive deposits of this cold stage were eroded by subsequent erosional episodes, leaving only patches of remanié quartzite-rich gravel on the high ground; the till outcrop at Westfield Grange is a rare example of the preservation of this till on the high ground.

6. Conclusions

- Till deposits in the Vale of Pickering and on the flanks of the Tabular Hills (North York Moors) have been confirmed by 5 boreholes at elevation of between 25 m and 120 m asl. The tills were proved to be up to 6.90 m thick and comprise predominantly grey-brown and yellow-brown and dark grey, stiff to very stiff (overconsolidated) clay and sandy clay matrix with occasional thin beds of laminated/convoluted sand and clay.

- Sub-rounded to sub-angular erratic clasts in the till are predominantly derived from local Upper Jurassic Corallian Group bedrock exposed in the southern part of the North York Moors, specifically the Tabular and Hambleton Hills. Other clasts include well-rounded small pebbles of probable Lower and Middle Jurassic sandstone some of which exhibit glacial striae, mudstone and sparse Jurassic coal probably derived from the incised inliers or northern crop of the North York Moors. Where the till overlies relatively soft Upper Jurassic Ampthill Clay or Kimmeridge Clay bedrock, fragments of these fissile mudstones form the predominant clasts in the lower part of the till, indicating that they have been sheared and plucked from the local bedrock at the base of the advancing glacier (sub-glacial traction till). Well-rounded quartzite pebbles found in abundance, along with pebbles of vein quartz, in weathered soil horizons in the vicinity of the boreholes and in the upper part of the tills may have been derived from Lower Triassic quartzite pebbles that were reworked into Miocene deposits during Tertiary uplift and erosion of the North York Moors, and which were subsequently incorporated into the Vale of Pickering ice-sheet.

- The paucity of exotic clasts from farther afield (in contrast to the Late Devensian ice-sheet and Basement Till of the Holderness coast) suggests a local ice-sheet. We envisage a relatively small, temperate plateau ice-field, similar to present-day examples in upland areas of southern Iceland, was established on the high ground of the Tabular Hills. Outlet glaciers from this ice-field subsequently extended southwards into the lower topographical area of the Vale of Pickering (ca 20-40 m asl) depositing locally derived sub-glacial traction till at the glacier base, passing up to lodgement till on the southern flanks of the Tabular Hills and over much of the Vale of Pickering, extending southwards to the higher ground of the Howardian Hills.

- Outliers of Middle Pleistocene tills in the Vale of Pickering show a general orientation to the south (ca 185 degrees north), with width-length ratio mean of 1.8. The general north-south orientation and elongation of these elongate ridges ('barughs') is interpreted as erosional sculpting of the relatively soft Upper Jurassic bedrock mudstones and the basal till to form degraded drumlins as the ice advanced southwards across the Vale of Pickering.

- Recent U-Th (TIMS) age dates derived from carbonate flow-stone from 'windy-pit' caves in the Corallian Group limestones of the North York Moors indicate that the upland area has been ice-free since at least 209 ka (MIS 7). This suggests that the Basement Till of the Holderness coast pre-dates MIS 7. If the U-Th flow-stone dates are correct then the local ice-sheet on the North York Moors that deposited the Vale of Pickering till must pre-date MIS 7, a time when these fissures opened up and flow stone was deposited during an ameliorating climate. In conclusion, we propose, tentatively, a MIS 8 or Wragby Glaciation, part of the glacial event that reached much of the north Midlands of England, for the Vale of Pickering till. It is likely that formerly more extensive deposits of this cold stage were eroded by subsequent erosional episodes, leaving only patches of remanié quartzite-rich gravel on the high ground.

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TABLES

Sample	Depth start (m)	Depth end (m)	Fraction size	Proportions (%) approx.																									
				Kimmeridge Clay	Bivalves from Kimmeridge Clay	Belemnites from Kimmeridge Clay	Chalcopyrite	Kimmeridge Clay with gypsum	Serpulids from Kimmeridge Clay	Jurassic sandstone	Grey sandstone	Ferruginous sandsotne	Shale	Coal and organic mudstone	Corallian Group	Various gypsum and calcite fragments	Tuff	Igneous granite	Rhyolite	Calcite	Quartz	Quartzite	Gypsum	Calcarious siltstone	Coarse grained sandstone	Fine-grained sandstone	Corallian Group chert	Wood fragment and pottery fragment	Unknown
1	0	0.24	>4mm							40	25			15	25						5								
2	0.24	1	>4mm							35		10		4	10				4			7				30	2	5	
3	1.36	1.44	>4mm							25		40			15						5				7	10			
4	1.84	2	4mm-425µm	25			5			15		10		8							40								10
5	2	2.49																											
6	2.49	2.82	>4mm	60						40																			
7	3	3.31	>4mm	35						20					20		8					10		10					
8	3.31	4	>4mm	70						25					7														
9	4	4.18	>4mm	60			7			15					15														
10	4.18	4.51																											
11	4.51	4.79	>4mm	35						35					20								2						10
12	4.79	5.37	>2mm	60					<1	15		2			15		2	<1	4	3									<1
12	4.79	5.37	4mm-425µm	70						8		2	2	<1	10						3								
13	5.37	6.45	>2mm	50	1	<1	1	6	1	15	<1	<1	2	<1	25	3													

Table 1. Percentage of clasts against depth for the Habton Grange Farm No.1 (Great Barugh) Borehole; sample depth intervals and fraction size are shown.

Westfield Grange Borehole No. 1				
Sample No.	**MPA No.**	**Depth (m)**	**Lithology**	**Age**
1	62013	3.25	Coal/highly carbonaceous lithotype	Probably Cretaceous
2	62014	3.95	Coal/highly carbonaceous lithotype	Probably Jurassic/Cretaceous
3	62015	4.85	Dark grey mudstone	Late Jurassic - Early Cretaceous
4	62016	4.85	Small mudstone clasts	Mid - Late Jurassic
5	62017	6.58	Small mudstone clasts	Probably Middle Jurassic

Table 2. Palynological age determinations from organic-rich mudstone clasts sampled from the Westfield Grange Borehole No.1.