Early Holocene geomorphology of the Great Yarmouth area, Norfolk, UK.

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Abstract

A 1: 15 000 scale map of the early Holocene geomorphology of the Great Yarmouth area, covering 33 km^2 between National Grid Reference (NGR) 651022, 312244 (northwest corner) and NGR 654523, 303498 (southeast corner) is presented. This was interpolated from elevations for early Holocene deposits derived from 467 borehole records and 539 constraining points extracted from British Geological Survey mapping. The depth to the base of the Holocene sequence ranges from -30.46 mOD to +7.61 mOD. Key morphological features identified include: a 5 km wide trough trending west-east throughout the area; isolated peaks of pre-Holocene sediment reaching to -3 mOD within the centre of this trough and; a series of steep topographical lows. As well as providing a means of assessing palaeomorphology, reconstruction of the region's early Holocene topography can be used to inform research investigating the available sediment prism, palaeocoastline positions and possible responses to future climate change.

Keywords: palaeomorphology; early Holocene; coastal geomorphology; Great Yarmouth

1. Introduction

Coastal areas are amongst the most sensitive regions to climate change and are likely to be affected by future changes in sea level, storminess and wave climate. This is especially pertinent in areas such as the Great Yarmouth region of Norfolk, UK where the current coastal geomorphology protects extensive tracts of low-lying land from coastal flooding and the integrity of this protection may be threatened under altered climatic conditions. Despite the important defensive role played by the Great Yarmouth coastal morphology, relatively little is known of the features buried beneath the current topography or the sediment volume contained within the coastal prism.

This paper describes the reconstruction of the area's early Holocene geomorphology from borehole records and 1:50 000 scale digital geological maps (DiGMapGB50) published by the British Geological Survey (BGS). The resulting map, presented here at a scale of 1:15 000, reveals the major morphological features existing in the Great Yarmouth area during the early Holocene and updates a lower resolution contour plot of the area by Arthurton, Booth, Morigi, Abbott & Wood (1994). This data could provide a baseline for reconstruction of palaeocoastlines, calculation of Holocene sediment volumes (e.g. Jordan, Hamilton, Lawley & Price, 2014) and investigation of potential responses to future climate change.

2. Geomorphological and geological setting

The area under examination covers a total of 33 km^2 around the town of Great Yarmouth, Norfolk on the east coast of England, UK, extending in a broadly rectangular area from (NGR) 651022, 312244 (northwest corner) to NGR 654523, 303498 (southeast corner). The present coastline in the region is characterised by the Great Yarmouth spit, a coastal promontory attached to the mainland at Caister-on-Sea [NGR 652813, 312146] and projecting southwards towards Gorleston-on-Sea [NGR 653296, 303763]. To the west the spit is bounded by the River Yare and to the east by the North Sea.

Topographical highs provided by coastal cliffs (which reach a maximum of 27 mOD at Corton, NGR 654560 296974) and the Great Yarmouth spit (which achieves 7 mOD at Fuller's Hill, 652306 307994) protect the adjacent inland areas (the Norfolk Broads) from coastal flooding. Indeed, approximately 7 % of the Norfolk Broads area lies at or below the current sea-level and 14 % lies below 1 mOD (Figure 1).

A coastal barrier is reported to have existed in the location of the Great Yarmouth spit since approximately 2000 yBP (Arthurton et al., 1994). The barrier has taken numerous forms throughout its existence, from an offshore sandbank to a coastal spit. Protection afforded by the development of these features is believed to be responsible for the reestablishment of terrestrial conditions between repeated Holocene marine inundations of a now-buried valley system in the area (Ashwin & Davison, 2005; Chatwin, 1961; George, 1992). Engineering works for the cutting of the current river mouth undertaken between 1559 and 1567 truncated the current spit, which originally extended as far south as Lowestoft [NGR 655578 293724] (Manship, 1845). Arthurton et al. (1994) presented a small-scale contour plot of the buried valley system existing within the Great Yarmouth and larger Broadland area but provided little detailed morphological information.

The geology of the Great Yarmouth coast comprises Holocene sand and subordinate gravel of the North Denes Formation (Table 1) resting unconformably upon estuarine clays, silts, peats and sands of the Breydon

Formation (Arthurton et al., 1994). The Holocene deposits are variably underlain by Late Pleistocene gravels and sand of the Yare Valley Formation or River Terrace Deposits which, in turn, rest upon late Pliocene to early Pleistocene shallow marine sediments of the Crag Group. Coastal cliffs to the north and south of the spit area are formed of tills and sand of the Happisburgh Glacigenic Formation and tills of the Lowestoft Formation, dating to the Middle Pleistocene. The sequence is capped locally by alluvium and wind-blown sand.

3. Methodology

The early Holocene in the Great Yarmouth area is characterised by deposits of the Breydon Formation (Table 1) and elevations derived from the base surface of this unit provide a useful indicator of surface morphology during this time. Borehole records held within the BGS's Single Onshore Borehole Index were interrogated between NGR 649839, 312737 (northwest corner) and NGR 654341, 303093 (southeast corner) (Figure 2). This larger study area reflects the Great Yarmouth study area plus a buffer zone of an additional 1 km to the east and west and 0.5 km to the north and south. This was designed to minimise edge effects in the resulting interpolated grid by utilising boreholes and constraining points (see below) in the area immediately adjacent to the Great Yarmouth study area. The final interpolated grid was then clipped to the smaller study area resulting in a surface that was less affected by low data densities at the study area's extremities. 1 496 boreholes were investigated, of which 467 contained sediments interpreted as Breydon Formation. The latter were divided into those proving the base of the

Breydon Formation (310 boreholes) and those with Breydon Formation material at borehole termination depth (157 boreholes).

Deposits shown on BGS 1:50 000 scale geological maps posses a thickness of at least 1 m. The position of the edge of the Breydon Formation on BGS 1:50 000 Geological Map Sheet 162 (British Geological Survey, 1994), therefore, provides additional data points at which the thickness of the Breydon Formation is at least 1 m (Figure 2). Maximum elevations for the base surface of the Breydon Formation were calculated by extracting a thickness of 1 m from NEXTMap Digital Surface Model (DSM) elevation data at these points. These constraining points were digitised at a scale of 1: 2 000 within ESRI ArcMap 10.0.

Additional information was added to the offshore portion of the interpolated grid by digitising the boundary between the Crag Group and Breydon Formation deposits from BGS 1:50 000 Geological Map Sheet 162 (British Geological Survey, 1994). Breydon Formation thickness at these points is at least 1 m and maximum elevations for the base of the Breydon Formation were derived by subtracting this thickness from bathymetric data (United Kingdom Hydrographic Office, 2009). The Crag Group was used to represent pre-Holocene deposits in these areas, rather than the Yare Valley Formation as no direct evidence for the age of this formation has been established (Arthurton et al., 1994; Wessex Archaeology, 2008). Areas where the mapped Breydon Formation abut stratigraphically younger units were not used as the younger deposits could mask a continuation of the Breydon

Formation at depth. The onshore and offshore constraint data were added to the interpolated grid as an additional 539 base proven data points.

The incorporation of offshore data is designed to extend the reconstruction of early Holocene geomorphology beyond the area of the modern coastline. A previous contour plot by Arthurton et al. (1994) terminated at the coast so precluding examination of the buried valley system which is believed to extend offshore (Tizzard, Baggaley & Firth, 2011; Tizzard, Bicket, Benjamin & De Loecker, 2014; Ward, 2014; Wessex Archaeology, 2008). The inclusion of offshore data also helps to reduce edge effects in the coast-proximal portions of the model which would be caused by otherwise clipping to the current coastline. Data density is inevitably lower in the offshore areas and is formed of constraining points derived from BGS mapping (interpolated from cores and surface grabs) rather than direct borehole evidence as is the case for the onshore portions. These differences in data density and resolution should be taken into account when viewing the interpolated grid.

In order to interpolate the early Holocene palaeomorphology, natural neighbour analysis (cell size 25 m, aggradation distance 50 m) was performed on the data (using Vertical Mapper 3.1 in MapInfo 8.0) where the base of the Breydon Formation was proven. This technique geometrically estimates unknown values around each data point using natural neighbourhood regions and, through its use of area-weighting, is particularly effective in cases with a clustered or sparse data distribution (MapInfo, 2010; Watson, 1992) so reducing inaccuracies caused by edge effects and hotspots. Natural neighbour analysis also honours the local minima and maxima of the data used, ensuring a good fit of the final surface to the input data.

The resulting interpolated grid was refined by ensuring that minimum Breydon Formation depths identified in borehole records with Breydon Formation at termination depth were correctly represented. At a few locations the early Holocene surface appeared shallower than seabed level; an unviable situation in locations with mapped Middle to Late Holocene seabed sediments which is likely to result from a relatively low offshore borehole density. In these cases the early Holocene surface was corrected to seabed level.

The exact date of onset of deposition of the Breydon Formation is likely to vary throughout the study area and as such a precise age cannot be assigned to the palaeomorphology being mapped. The Breydon Formation can be divided into five peat or clay units which are not found uniformly throughout the wider Broadland region (Arthurton et al., 1994). The inland extent of the oldest of these units, the Lower Clay is demonstrated to be limited in comparison to the other units (Coles & Funnell, 1981), whilst the north-south extents of these units vary less dramatically (Coles & Funnell, 1981; Arthurton et al., 1994). In order to minimise the effects of this coast-perpendicular variation in age of the Breydon Formation deposits the study area is limited to the more directly coast-proximal regions.

The potential for erosion and reworking of pre-Holocene deposits prior to and/or during deposition of the Breydon Formation and erosion and reworking of younger Breydon Formation units at later stages cannot be discounted. Relatively rapid sea-level rise modelled during the early Holocene (Shennan, Bradley, Milne, Brooks, Bassett & Hamilton, 2006) reduces the likelihood of erosion and/or reworking by wave action and shallower tidal currents as water depths over the older deposits increased rapidly. The potential for rapid burial of sediments in line with the rate of sea level rise may also have helped to reduce the effects of post-depositional erosion and reworking. There is no borehole evidence for interdigitation of deposits of the Breydon Formation and pre-Holocene deposits. As a result, the onshore portions of the interpolated grid were clipped to the mapped limit of the Breydon Formation as the areas beyond these limits are characterised by stratigraphically older units. In offshore areas of the interpolated grid, however, a paucity of boreholes meant that the constraining points were used to provide elevation information but were not used to determine the interpolated grid extent.

Changes in land level as a result of glacial isostatic readjustment are likely to have affected the area since the Early Holocene (Shennan et al., 2006). As a result the accompanying map shows the relative elevation of the Early Holocene surface, distinguished by the depths at which Early Holocene deposits can be found today rather than the absolute depth at which they formed.

4. Early Holocene geomorphology of the Great Yarmouth area

Examination of borehole records and geological data has allowed detailed mapping of the early Holocene geomorphology of the Great Yarmouth area, Norfolk, UK. This provides higher resolution information for the current coast-proximal zone than the reconstruction of the area's Holocene topography published in Arthurton et al. (1994) and allows identification of finer-scale features than previously possible. Surface elevations present in the area during the early Holocene are shown to range from -30.46 to 7.61 mOD and gradients between 0.00 and 25.10 degrees. The major morphological features identified in the area are discussed in detail below.

The 'variance from input' grid (Figure 3), which maps the difference in elevation between the input data (boreholes and constraining points) and the value of the natural neighbour interpolated grid, can be used to assess confidence in the interpolated grid. Larger variances reveal a greater difference between the input data and the interpolated Early Holocene elevation. These differences may derive from data density issues, where clustered boreholes displaying different elevations are being averaged by the natural neighbour interpolation method. This variance of borehole data may, in turn, result from natural, sudden variations in the Holocene topography or data quality issues such as a poorly-levelled borehole.

4.1 East-west orientated trough

The early Holocene geomorphology of the Great Yarmouth area is dominated by a broad, east-west orientated trough-like feature which cuts the modern coastline between Caister-on-Sea [NGR 652813, 312146] in the North and Gorleston-on-Sea in the South [NGR 653296, 303763]. This feature extends across the study area, narrowing westwards from 5.5 km at the eastern limit of the study area (the current offshore zone) towards 2.5 km in the region of Breydon Water [NGR 650971 308231].

Whilst the narrowing may be due, at least in part, to the lower offshore data density and resolution (Figure 2; 3), evidence for a palaeovalley in the region extending both inland (Arthurton et al.,1994; British Geological Survey, 1994) and offshore (Tizzard et al., 2011; Tizzard et al., 2014; Ward, 2014; Wessex Archaeology, 2008) beyond the limits of the current study area has been demonstrated and so the feature is regarded as a trough or palaeovalley rather than an embayment or basin.

The northern and southern boundaries of the trough are sharply-defined and steeply sloping, with gradients lying between 3.64 and 5.41 degrees. The northern boundary of the trough is especially smooth with slight benches evident only in Profile 1. The southern boundary is more complex, with benches, spurs and hollows present.

The trough reaches a maximum depth of -27.95 mOD in the vicinity of NGR 652449 309945. In general the trough floor lies between -18.00 to -22.00 mOD although a slight shallowing eastwards is evident (-15.00 to -18.00 mOD). As borehole density is lower in the eastern portion of the study area (the current offshore zone) than other portions this may reflect the modelling process rather than actual conditions (Figure 2; 3). The floor of the trough is relatively flat with gradients for the majority of the area ranging between 0.00 and 2.26 degrees. The location of this feature corresponds well with that of the proposed ‘Great Estuary’ (Arthurton et al., 1994; George, 1992; Manship, 1845) and the Holocene sediments infilling the trough record a series of marine inundations, interrupted by the reestablishment of terrestrial conditions.

4.2 High ground

Areas of high ground evident to the north and south of the trough in the early Holocene geomorphology coincide broadly with areas of current high ground. Elevations of 6.00 mOD sloping eastwards (at between 0.00 and 1.18 degrees) to -0.40 mOD are achieved along the northern boundary of the study area. Slightly higher elevations (maximum 6.60 mOD) are reached to the south of the trough but here the ground slopes eastward at a higher angle than in the north (3.64 to 7.68 degrees) resulting in the high ground to the south extending for a shorter distance to the east than its northern equivalent. Current elevations in the area of this high ground reach 12.75 mOD in the north and 15.45 mOD in the south. These features may originally have extended further eastwards but could have been truncated by erosion during Holocene marine transgressions

4.3 Isolated mounds

Within the trough, five distinct topographic highs have been identified (Figure 4). These are clustered towards the centre of the trough [NGR 652130 308373] in a north-south alignment. They are largely circular in shape, forming individual mounds rising sharply from the trough floor. The western sides of these features are particularly steep with gradients of 10.63 to 25.10

degrees. Mounds 1 to 3 are slightly elongated in a north-south direction. Maximum axis lengths of all the topographic highs vary from 0.75 km to 0.11 km. A maximum elevation of -2.99 mOD or approximately 18.00 m above the trough floor is achieved by Mound 2 [NGR 652115 308387].

Mound 1 is constrained by relatively few boreholes (Figure 4) and in none of these is the Breydon Formation base proven. However, as the other mounds are defined by a larger number of boreholes, and in more than 40% of these are the deposits interpreted as Breydon Formation base proven, there is no evidence to suggest that the highs are relicts of the interpolation process.

The western margin of the current Great Yarmouth spit crosses these mounds raising the possibility that the spit is grounded against them. Marine transgression during the Holocene has been demonstrated for the area (Cameron et al., 1992; Brew, Holt, Pye & Newsham, 2000) and retreat of coastal barriers, including barrier islands and spits is well known in the face of such transgression (Andrews et al., 2000; Hails, 1975; Massey & Taylor, 2007). As such, it is possible that the Great Yarmouth spit migrated westwards to its current position throughout the Holocene.

4.4 Basins

Distinct basin areas are also evident within the early Holocene geomorphology of the Great Yarmouth area. Four main areas have been identified: north basin [NGR 652871 310049], central east basin [NGR 652292 307901], central west basin [NGR 651502 308043] and south basin [NGR

653189 305328]. The north basin is the largest and least regularly shaped of these features. Whilst the other areas of low ground resemble isolated hollows, this feature encompasses the northern topographic high described above, covers an area of 314.3×10^4 m^2 and extends for 2.64 km in a north-south direction and 1.90 km in an east-west direction. The main body of the depression reaches a maximum depth of -27.99 mOD (Figure 4), and similar depths are achieved by a deep spur which extends northwards from the main body.

The central east basin is small (5.7×10^4 m^2) and roughly circular, achieving a maximum depth of -27.1 m and gradients of 7.67 to 10.63 degrees on its western margin. The central west basin is broad and relatively shallow, reaching a maximum depth of -23.52 mOD and gradients of 0.39 to 1.18 degrees. The southern basin lies outside of the main trough area. This feature is deep (reaching a maximum of -30.46 mOD) and very steep-sided (Figure 5), particularly on its western margin where gradients of between 10.63 and 15.85 degrees are evident. A fifth, less pronounced basin is evident at NGR 653331 304196 in the vicinity of the current harbour mouth. However, this feature is constrained by only one borehole and so should be treated with caution.

The location of the northern and southern topographic basins within the early Holocene surface coincides with documented historical locations of mouths of the River Yare (known locally as Havens). That to the north reflects the location of Grubb's Haven whilst the southern low corresponds with recorded positions of Great Yarmouth's 2nd and 6th Havens, existing between 1392 and 1407 AD and 1548 and 1549 AD, respectively (Crisp, 1871; Press, 1956; Swinden, 1772; Ward, 1922). It is possible, therefore, that these lows were reflected in the surface expression of the Breydon and/or North Denes formations during the later Holocene and the River Yare merely reoccupied the location of pre-existing channels. A relatively low abundance of borehole records in the eastern (current offshore) portion of the interpolated grid (Figure 2) means that the seaward extent of the northern and southern topographic lows is relatively poorly constrained and they may in fact extend further offshore as channel-like features rather than enclosed basins.

5. Conclusions

Examination of the early Holocene geomorphology of the Great Yarmouth area, Norfolk, UK reveals the existence of a wide trough intersecting the present coastline between Caister-on-Sea and Gorleston-on-Sea. This trough corresponds with the location of the proposed 'Great Estuary' and the Holocene sediments infilling the feature record an alternating series of marine inundations and the reestablishment of terrestrial conditions. Within the trough, a number of isolated mounds and distinct basins have been identified. These may have played a part in determining the location of the current Great Yarmouth spit and previous mouths of the River Yare, respectively. In addition to allowing examination of palaeotopography, the 3D mapping of early Holocene geomorphology provides a baseline against which to determine Holocene sediment volumes and evaluate coastal geomorphological responses to Holocene and future sea-level changes.

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Software

Data for the location and elevation of Breydon Formation deposits were combined within ESRI ArcGIS 10.1. Vertical Mapper 3.1 in MapInfo 8.0 was used to create a gridded surface and 3D Analyst extension in ESRI ArcGIS 10.1 used to compute slope gradient and profile plots. The figures and map were created in ESRI ArcGIS 10.1, ESRI ArcScene 10.1, Adobe Illustrator CS6 and Adobe Photoshop CS6.

Map Design

- The main map is published at a scale of 1:15 000 and associated smaller maps cover the same geographic area in order to maintain clarity and allow comparison between the associated maps.
- The chosen colour range allows a sufficient number of categories to be distinguished as well as a suitable blend between the categories.
- Black lines are used on the main map to distinguish different category areas. Heavier line weights identify significant contour values.

- The underlying topographic base map is coloured mainly in light grey so as to allow easy orientation of the map viewer without overcrowding the map. Multiply transparency in Adobe Illustrator CS6 was used to give the most effective appearance.
- Ordnance Survey Vectormap (OpenData) is used for consistency across the main and associated maps and has been styled according to the information that each contains. The larger-scale location map uses Ordnance Survey Miniscale data to give a clear indication of the study area's location in the UK.
- Identical colouring has been used for the lines denoting slope profile locations of different orientations on the main map and on the associated graphs to allow ease of identification.
- The early Holocene slope map uses 'Natural Jenks' to divide the scale into appropriate categories. Only 6 categories have been used on these to avoid cluttering the map at this scale.
- The 3D view map is styled in a similar fashion to the main map to allow the user to easily visualise the data in 3D and orientate themselves.

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Tables

Age			Lithostratigraphy	Characteristics
Period	**Epoch**	**Stage**		
Quaternary	Holocene	Flandrian	Blown Sand	Aeolian Sand
			Alluvium	Sand and silt

			(Undifferentiated)	
			North Denes Formation	Beach sand and subordinate gravel
			Breydon Formation	Estuarine clays, silts, peats and subordinate sands
	Pleistocene	Devensian	River Terrace Deposits (Undifferentiated)	Sand and gravel
		?Devensian	Yare Valley Formation	Gravel and subordinate sand
		Anglian	Lowestoft Till Formation	Chalky sandy till
			Happisburgh Glacigenic Formation	Sand, sandy till
Quaternary / Tertiary	Pleistocene/ Pliocene		Crag Group	Shallow marine sands, partly shelly, some silty clay

Table 1. The Quaternary sequence within the Great Yarmouth area, adapted from Arthurton et al. (1994).

Figure Captions

Figure 1. Topography of the Norfolk Broads. Inset: Square denotes location of study area in Eastern England. Contains Ordnance Survey data © Crown

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Figure 2. Boreholes containing sediments interpreted as the Breydon Formation and constraining points within the Great Yarmouth study area and buffer zone. Inset: Square denotes location of study area in Eastern England. Contains Ordnance Survey data © Crown Copyright and database rights 2016.

Figure 3. Variance from input: the difference in elevation between the input data (boreholes and constraining points) and the value of the interpolation grid across the Great Yarmouth study area. Inset: Square denotes location of study area in Eastern England. Contains Ordnance Survey data © Crown Copyright and database rights 2016.

Figure 4. 3D view from south east of isolated mounds and north, central-east and central-west basins in the Great Yarmouth area, Norfolk, UK. Vertical exaggeration 20x. Inset A: Early Holocene elevations in relation to current major places and borehole locations. Inset B: Point denotes location of study area in Eastern England. Contains Ordnance Survey data © Crown Copyright and database rights 2016.

Figure 5. 3D view from south east of the southern basin in the Great Yarmouth area, Norfolk, UK. Vertical exaggeration 20x. Inset A: Early Holocene elevations in relation to current major places and borehole

locations. Inset B: Point denotes location of study area in Eastern England. Contains Ordnance Survey data © Crown Copyright and database rights 2016.

Map. A 1:15 000 scale map of the early Holocene geomorphology of the Great Yarmouth area, covering 33 km^2 between National Grid Reference (NGR) 651022, 312244 (northwest corner) and NGR 654523, 303498 (southeast corner). This was interpolated from elevations for early Holocene deposits derived from 467 borehole records and 539 constraining points extracted from British Geological Survey mapping. The depth to the base of the Holocene sequence ranges from -30.46 mOD to +7.61 mOD. Key morphological features identified include: a 5 km wide trough trending west east throughout the area; isolated peaks of pre-Holocene sediment reaching to -3 mOD within the centre of this trough and; a series of steep topographical lows. As well as providing a means of assessing palaeomorphology, reconstruction of the region’s early Holocene topography can be used to inform research investigating the available sediment prism, palaeocoastline positions and possible responses to future climate change.