SPIT EXTENSION AND BARRIER ROLLOVER AT BLAKENEY POINT AND SALTHOUSE: HISTORIC MAPS AND FIELD OBSERVATIONS

Julian E. Andrews

School of Environmental Sciences, University of East Anglia,

Norwich, NR4 7TJ, UK

e-mail: J.Andrews@uea.ac.uk

ABSTRACT

In the late 1990s, Brian Funnell used historic maps (1586 and 1797) and aerial photos (1952-1989) of the Blakeney area to calculate the mean extension rate of Blakeney Spit. He also charted landward rates of barrier movement (rollover) in the Salthouse area using a 1649 map. The mean centennial rate of extension of Blakeney Spit was ~3.5 m a^{-1} *implying a likely age of the spit of 3000-4000 years. Change in barrier beach position between 1649 and the present day recorded a mean landward rollover rate of ~0.85 m* a^{-1}*. These rates concur with earlier estimates and are supported by offshore data published since 2000. This hitherto unpublished work is augmented by more recent field observations from storm surges in 2007 and 2013 that record the episodic nature of barrier rollover and breaching. The most important observations are that shingle-entraining washover events at Salthouse are probably in part conditioned by local topography, favouring topographic lows. In 2013, shingle washover was accompanied by two breach channels. These temporary breach channels were cut principally by seaward drainage of floodwater trapped in the back barrier area following storm overtopping of the barrier. Moreover, the channels were sited on former creek and channel locations visible in the 1649 map. The inherited hydrological topography of the back barrier area thus continues to influence recent coastal geomorphic change.*

Bull. geol Soc. Norfolk (2020), **69**, 35-63.

INTRODUCTION

In the late 1990s, before his untimely death in 2000, Brian Funnell was part of a UEA-led thematic programme grant funded by the NERC Land Ocean Interaction Study (LOIS). Specifically, the Land Ocean Evolution Perspective Study (LOEPS). Special Topic 32 was studying the 'Sedimentary Evolution of the Norfolk Barrier Coastline in the context of Holocene Sea Level Change'. A number of papers from this work were published between 1998 and 2000, but one aspect, left in unpublished manuscript form, was Brian's observations on historical rates of spit extension and landward barrier rollover in the Blakeney - Salthouse area (Fig. 1). I suspect these findings remained unpublished mainly because Brian felt they were hardly new in approach (cf. data and observations in Oliver & Carey 1918; Steers 1927; Hardy 1964; Barfoot & Tucker 1980) and largely speculative in outcome. However, the issues they focus on remain pertinent to coastal management today, and the precision of thought embodied in them, make them well worth airing. Moreover, the approach Brian took (and his confidence in it), inspired me to use it, both in teaching undergraduate students, and in researching the on-going effects of barrier beach movement, particularly in the context of recent storm surges.

In this paper I allow Brian's words to speak mainly for themselves inserting a few edits for clarity or updated usage and providing linking sentences (in square brackets) for context. The text began life as a draft BGSN paper in 1996, subsequently incorporated into (but then removed from) a 1998 version of what became Funnell *et al*. (2000). The methodology and terminology he used is self-explanatory, except perhaps his use of the word 'laterals'. Laterals are gravel-dominated bars that form at the end of a spit where wave refraction has curved the bars around the spit end to form hook-like features. Non-active laterals show up as recurved gravel ridges in aerial photos and mark the former end of a spit in historical times. The Blakeney Spit laterals have been of geomorphological interest for over 100 years, Oliver (1913) mapping 26 of them from the Marrams (see below) westward to the then active tip.

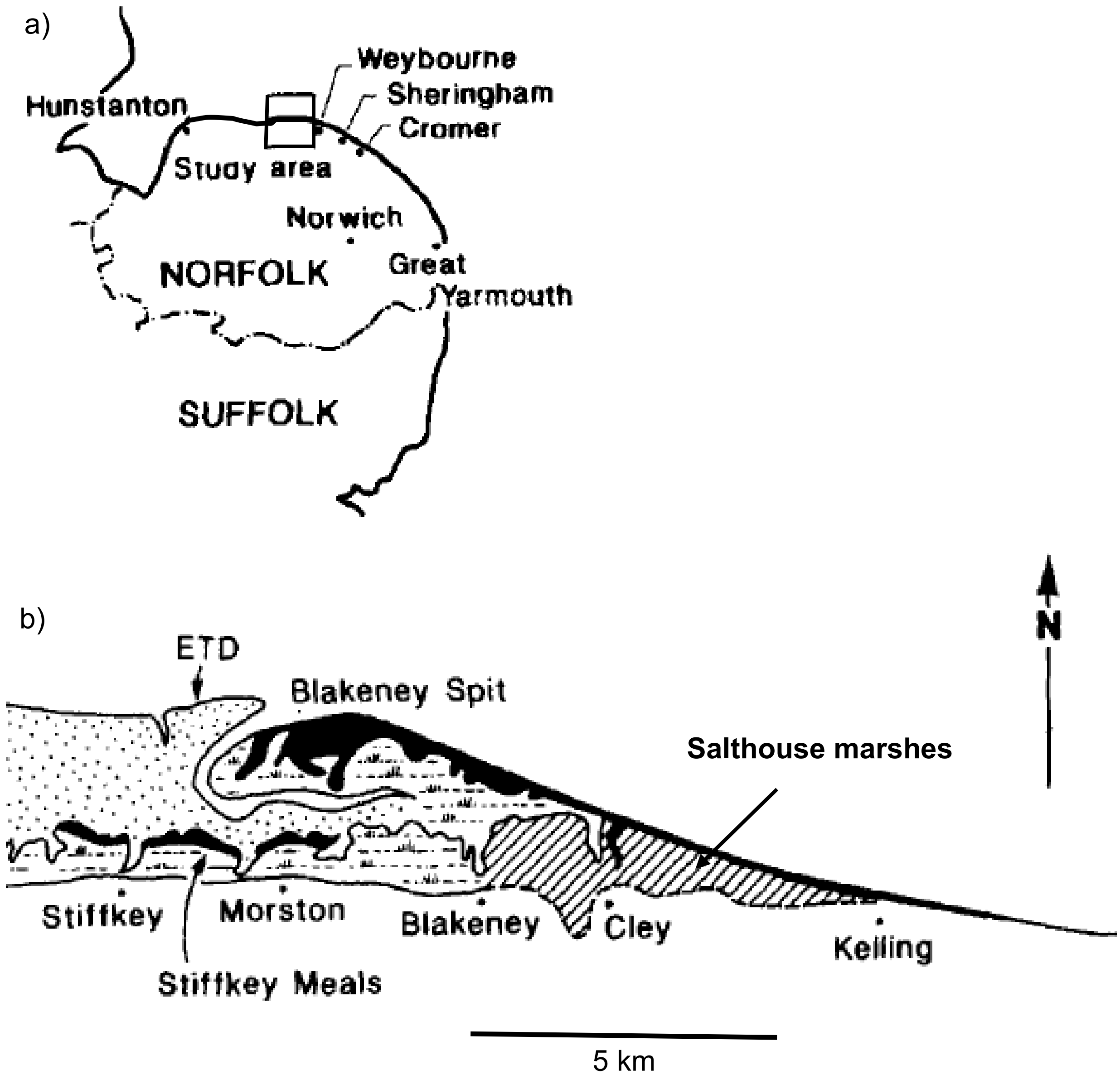

Fig. 1. a) Location of the study area (inset box) in Norfolk. b) Main elements of coastal geomorphology between Kelling and Stiffkey. Blakeney Spit (black) is a sand and shingle barrier not covered by normal tides. The hatched ornament shows reclaimed back barrier salt marsh while the stipple shows sandflat. Natural backbarrier saltmarsh is present between Blakeney and Morston. ETD = ebb tidal delta.

I follow up with some comments and observations on Brian’s text and then present my own research on coastal geomorphic and sedimentological changes caused principally by storm surges in 2007 and 2013.

It is worth noting that in June 2001, Google Earth images became freely available and, for Blakeney Spit, they begin in 1999, a year after Brian wrote his text, linking up the present day with the aerial photographic records he utilised up to 1989. Another ‘new’ public resource is the Historic-Maps Norfolk website (www.historic-maps.norfolk.gov.uk/mapexplorer) where, among other resources 1988 and 1946 aerial photos are available, although the former only has coverage of Blakeney Spit as far west as the Long Hills (Fig. 2) while the latter has almost no coverage of the Spit.

BLAKENEY SPIT: LATEST HOLOCENE (HISTORICAL) CHANGES (written by B.M. Funnell c. 1996-1998)

At the present day Blakeney Spit, from the point at which it leaves the cliffed coastline at Weybourne to the New Far Point, is approximately 12 km long (Fig. 2). This is almost exactly the same length as the original East coast Yarmouth Spit (TG 530040) was at the time that it reached Lowestoft, and before it was truncated by the action of engineers to create the present Yarmouth harbour entrance between Yarmouth and Gorleston. It is also approximately the same overall length as the spit forming Orford Ness (TM450490) further south on the East coast. Neither Yarmouth spit, nor Orford Spit, are at all similar in any other way to the Blakeney Spit, but the similarity in their overall natural lengths is interesting.

It has so far proved difficult to obtain full evidence of historical period changes along the Blakeney coastline, at least not as far back as Roman times. However, with the introduction of detailed, and increasingly precise maps, from the late 16th century onwards, a clearer picture quickly emerges. There are three principal “mapped” sources of information about the rate of westward extension of Blakeney Spit in the last few centuries and decades, and one “map” providing clear evidence of the rate of the Spit’s landward roll-over. [Figure 3 is a 2017 Google

Fig. 2. Blakeney Spit study area from its point of landward attachment at Weybourne Hope to its western tip. Google Earth image 24th September 2017. Data SIO, NOAA, U.S. Navy, NGA GEBCO, image © 2018 TerraMetrics.

Fig. 3. Blakeney Spit from Cley Eye to its western tip with principal geomorphic features labelled. Google Earth image 24th September 2017. Data SIO, NOAA, U.S. Navy, NGA GEBCO, image © 2018 TerraMetrics.

Earth image of the Spit from Cley Eye in the east, to New Far Point in the west, as a reference figure for the discussion that follows].

For a 1586 map, several slightly different copies exist. Two of the best copies were referred to by Godfrey Sayers of the Wellston Galleries, Blakeney, when he was preparing an edition of 250 prints of it in 1992 (Hooton, 1998). Part of its image appears as a coloured dust-cover on the "The Glaven Ports" book (Hooton, 1996), but the whole is reproduced here as Figure 4 at a much reduced scale. The 1586 map has previously been published as an 1856 Tidal Harbours Commission version, as a photographic image of another version of the original in Cozens-Hardy (1927), and as a simplified, but clear figure of the map in both Hooton (1996) and Hooton (1998).

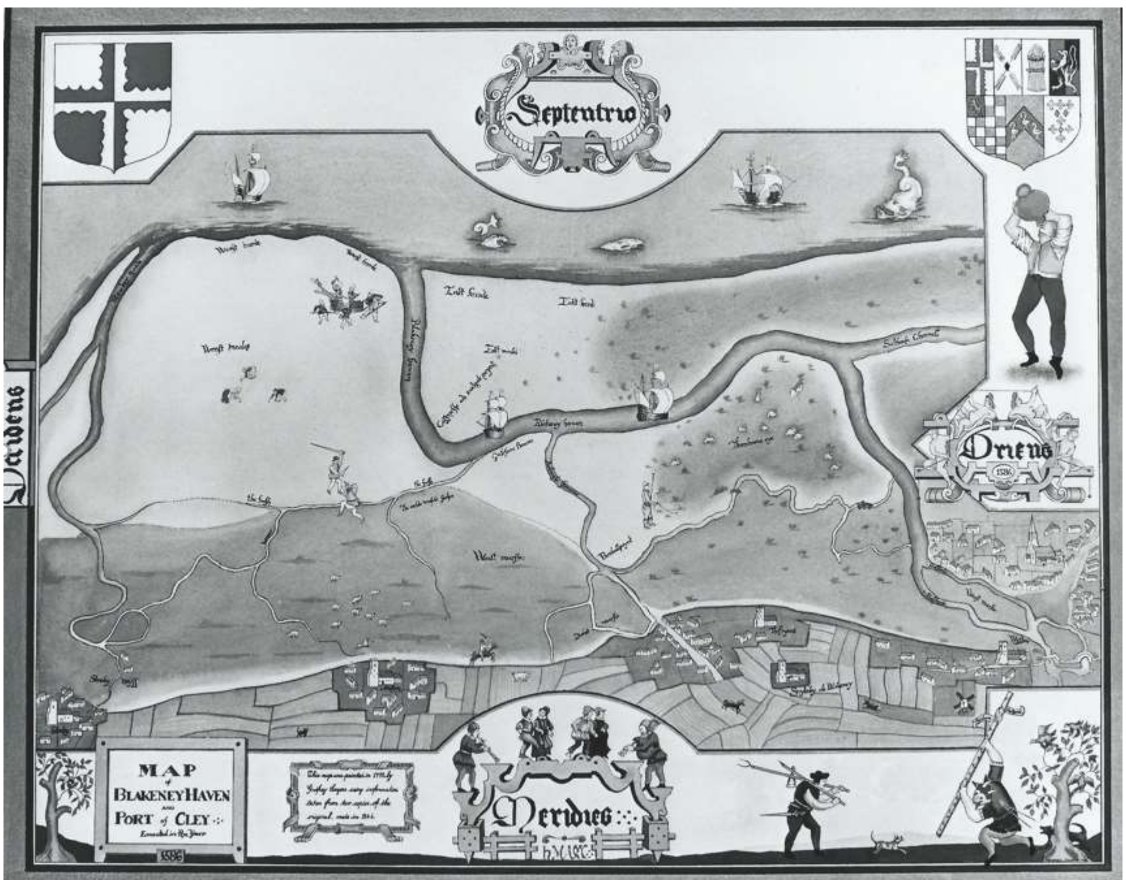

Fig. 4. 1586 map of Blakeney Haven. Note that the N-S part of Blakeney Channel is mapped to the east (right) of Morston Church fixing the position of the end of the spit at that time. Map reproduced with the permission of Godfrey Sayers.

Fig. 5. Blakeney spit as shown on the 1797 Faden map of the County of Norfolk. Map scale of c.1:63360 (1 in to 1 mile). Note the tip of the spit is by this time W of Morston village.

The 1797 Faden map of the County of Norfolk (Fig. 5; but see also a navigable version at www.historic-maps.norfolk.gov.uk) was surveyed in 1790-1794, and published in 1797 on a scale of c.1:63360 (1 in to 1 mile; 1.6 mm to 1 km).

From 1952 to 1989 maps and aerial photographs of Blakeney Point were presented in the National Trust booklets on Blakeney Point and Scolt Head Island (Steers, 1952; 1964; 1971; 1976; 1989).

The chief features (laterals) recognisable on these maps and aerial photographs (Figs. 3-5) are: (a) The Marrams (extending east to west, over 1150 m); (b) The Hood (700 m west of the westernmost Marrams lateral); (c) the Long Hills (1150 m west of The Hood); (d) the Beacon Hill (the first, easternmost component of this complex can be identified on the Faden 1797 map; 300 m west of the distinctive bifurcating Long Hills lateral); (e) Far Point (as shown on the 1961 map in Steers (1964), is 600 m west of the easternmost component of the Beacon Hills); (f) New Far Point (seen on 1986 aerial photographs, 500 m west of Far Point).

From these reference points we can attempt to calculate rates of westward extension, assuming that in 1586 Blakeney Point extended no further west than Long Hills. [This is inferred from the 1586 map where the main north-south part of the 'Blakeney Haven' channel is mapped east of Morston Church (Fig. 4) thus fixing the terminus of the spit, the Long Hills lateral, on the east bank of the channel].

1961-1986	25 years	500 m	=	20 m per year
1794-1961	167 years	600 m	=	3.6 m per year
1794-1986	192 years	1100 m	=	5.7 m per year
1586-1794	208 years	300 m	=	1.4 m per year
1586-1961	375 years	900 m	=	2.4 m per year
1586-1986	400 years	1400 m	=	3.5 m per year

Using the rate of 3.5 metres per year ($m\ a^{-1}$) the date of formation of the easternmost Marrams lateral can be estimated at 729 CE, of the westernmost Marrams lateral at 1057 CE, and The Hood at 1257 CE.

The *length* of the laterals has been:

	1986	1961	1797
New Far Point	1700 m		
Far Point	1000 m	1400 m	
Long Hills	900 m	1000 m	1125 m
The Hood	250 m	300/800 m	
The Marrams	135-270 m	300 m	c.325 m

If the length of all the laterals was originally between 1000 and 1500 m, similar to Far Point and New Far Point recently, and if the main spit rollover rate is c. 1 $m\ a^{-1}$ (see later), then reducing The Marrams to c.200 m in length would have taken c.800 to 1300 years, i.e. since 686/1186 CE, and reducing The Hood to 250 m would have taken 750 to 1250 years, i.e. since 736/1236 CE. The dates estimated above for The

Marrams and The Hood from a westward extension rate of 3.5 m a^{-1} are: 729 to 1057 CE and 1257 CE respectively. There is a considerable degree of coherence in these estimates, which doesn't necessarily mean they are correct, but does suggest rapid rates of change in the spit's configuration.

It is really almost impossible to estimate the time that Blakeney Spit would take to grow from its proximal end abutting the cliffed coastline at Weybourne to its present western limit. If an average rate of westward extension of 3.5 m/year were assumed, (in spite of the very high variability of the rate over the shorter term, but based on the average value of extension that can be calculated from maps and aerial photographs over the last 400 years), an estimate can be made. A westward extension of the spit at that rate over 12 km would take only 3430 years. (At 3 m a^{-1} it would be 4000 years, and at 4 m a^{-1} it would be 3000 years).

During the period of time since 3500 years BP, if the current rates of coastal erosion and barrier rollover of c. 1 m a^{-1} were sustained, the spit, (and cliffed), coastline could simultaneously have retreated by about 3.5 km. We have evidence from Holocene estuarine deposits, off the Norfolk and Suffolk East coasts (Arthurton *et al*., 1994; Brew, 1990; Brew, Funnell *et al*., 1992) that such a rate of retreat has been sustained there during the Holocene. Although this remains more speculative without comparable evidence from off the North Norfolk coast, such a sustained rate of retreat has been considered quite possible (Clayton, 1989).

In practice, a single 1649 map clearly gives that evidence regarding the roll-over rate. It was first published as an illustration in Cozens-Hardy (1927), but recently Hooton (1996) has renewed interest in it, and Mary Ferroussat of Blakeney Area Historical Society has made a very careful reproduction copy of the best original copy, which was produced on a 1:400 scale (25 cm to 1 km). [Figure 6 is a modern coloured version of the map, although Brian Funnell's measurements were all made from a copy of the original.] From the present point of view, we only wish to point out that it must have been very accurately surveyed. It can be directly compared by overlaying a transparent copy of it over a modern Ordnance Survey 1:10,000 sheet. [Here it can be compared with the 2017 Google Earth image (Fig. 7)].

The comparison shows that the 1649 widening of what was then the Salthouse Channel towards the west is now the site of Arnold's Marsh (Fig. 7). Rough Brough Hill (near Cley Eye), Flatt Eye and, at the present time almost completely, Great Eye, have been lost to the sea, and that Little Eye and Gramborough (Green Burrough) Hill are now in contention. A yellow pecked line on Figure 6 indicates the position of the barrier beach crest in 2018. It shows c. 300 m of landward displacement over a period of 350 years, i.e. 0.85 m a^{-1} (~1 m a^{-1}).

Notes on Funnell's barrier extension and rollover rates

Brian Funnell's calculations of barrier extension rates agree with earlier calculations by Steers (1927) who recorded a mean rate of extension of 3.4 m a^{-1} between 1886 (first Norfolk 6 inch to mile OS map) and 1925. Funnell's figure was 3.6 m a^{-1} between 1794 and 1961. Funnell's fastest rate of tip extension of 500 m in the 25 years between 1961 and 1986 is a short-term rate, and much of the 'extension' is probably recording the most westerly position of the terminal spit, which can be driven eastward by >500 m in a single westerly gale, as first noted by Oliver (1913). If growth of New Far Point actually initiated in 1966 (Barfoot and Tucker 1980) then the extension rate was more like 25 m a^{-1}. Google Earth images show no significant extension over the 18 years between 1999 and 2017. The modern spit tip (New Far Point) probably reached a quasi-equilibrium length by the early 1980s, possibly by 1979 based on figure 1F in Barfoot & Tucker (1980).

Brian Funnell considered the 1649 map to be very accurate, a view shared by Hooton (2003) who calculated that the 1649 map under-recorded distances by an average of just 0.94% when compared to the 1:10,000 Ordnance Survey map. Funnell was careful to say in 1998 (see above), that his Blakeney Spit rollover rates were speculative in the absence of clear evidence from offshore north Norfolk. It is worth noting that such evidence was soon available when Shennan *et al*. (2000) reported discovery of an *in situ* 8360 cal. year old saltmarsh peat and intertidal clay

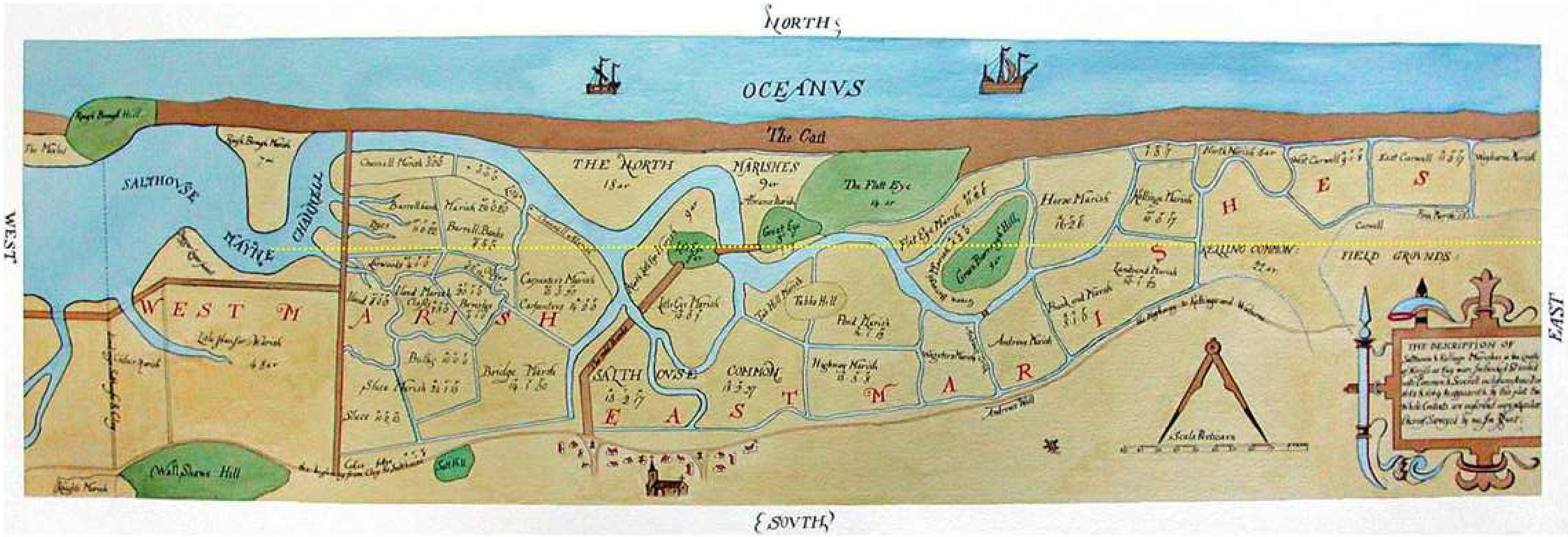

Fig. 6. Coloured version of the 1649 ‘John Hunt’ map made by Val Fiddian from an original belonging to Paul Long. This colour version is in the public domain from Wikimedia Commons. The yellow pecked line indicates the position of the barrier beach crest in 2018.

Fig. 7. Salthouse marshes between the Cley East Bank and Gramborough Hill showing location of geomorphic features associated with the 2007 and 2013 storm surges. Google Earth image 24th September 2017. Data SIO, NOAA, U.S. Navy, NGA GEBCO, image © 2018 TerraMetrics.

in core 52/+01/2699 about 5 km offshore of the present north Norfolk coastline. This information implies an average rate of coastline landward movement around 0.6 m a^{-1}, a rate identical to that calculated by Pollard *et al*. (2019) for Blakeney Spit, and consistent with Funnell's rate of 0.85 m a^{-1} over the last 350 years. Shorter-term rates of mean landward shoreline movement, over 22 years between 1992 and 2014, at Brancaster Bay and Scolt Head Island are similarly between 0.75 and 0.85 m a^{-1} (Brooks *et al*., 2017). This said, mean shoreline movement over the same 22 years at Holkham Bay is negligible (Brooks *et al*., 2017) because storm erosion here is offset by strong sediment supply and progradation at other times.

SEDIMENTOLOGICAL EFFECTS OF THE 2013 STORM SURGE ON THE NORTH NORFOLK COAST

On 5th December 2013 the north Norfolk coast experienced a strong storm surge with water levels in places higher than those recorded in the well-documented 1953 event (Spencer *et al*., 2015). The impacts of the 2013 surge on the shoreline were considerable; barrier crests retreated in places by over 10 m (Brooks *et al*., 2017), sea walls were breached and the marshes behind them were flooded.

Specifically, at Brancaster Bay, Scolt Head Island and Holkham Bay, mean landward shoreline movements during this storm were 4.29 (± 0.22), 4.81 (± 0.24) and 7.36 (± 0.97) m, respectively (Brooks *et al*., 2017). The degree to which such shoreline retreat is 'permanent' very much depends on sediment supply to the local shoreface during intervening fair weather conditions (Brooks *et al*., 2017).

This documented shoreline retreat is thus mainly visible on positive topographic features, either natural ones – foredunes (JEA estimated 10 m retreat at Holkham Bay), gravel barriers, or artificial ones – typically clay-embankments. The morphological effects of storm surges on Norfolk saltmarshes has typically been negligible (Steers 1953; Steers *et al*., 1979; Spencer *et al*., 2015) and so it proved in 2013. For example, on Stiffkey Marsh in January 2014 the only physical signs of the surge were the debris strewn stand line at about +5 m OD (maximum 5.34 m; mean 5.06 m; Spencer *et al*., 2015) and the 'floatation' of buoyant structures like wooden pilings of 'creek bridges' out of the marsh muds.

Fig. 8. Flooded back barrier marshes at Salthouse (December 2013) looking N. The emergent islands in the floodwater are Little Eye (left) and the remains of Great Eye (right). The area W of Little Eye with the row of posts is the site of the 'Little Eye breach channel'. Image courtesy of Mr David North.

Washover fans and breach channels at Salthouse

At Salthouse the flooding was spectacular (Fig. 8) but the marsh morphology was largely undisturbed once the floodwater had drained away. The shingle barrier, by contrast, suffered extensive morphological change with large washover fans driven landward from the barrier beach onto the adjacent saltmarsh surface (Fig. 9). Long sections of the shoreline, particularly in the 1 km section between Gramborough Hill and west of Little Eye were overtopped, with shingle shunted landward in excess of 100 m, locally building washover fans in excess of 1 m thickness in their proximal parts (e.g. in the area of Beach Road carpark; Fig. 9), but thinning landward. This event largely destroyed sections of the artificially steepened beach profile inherited from bulldozing in the 1990s that had already been subdued by previous storms, in particular by the November 2007 surge (Brooks *et al*., 2016).

Fig. 9. Landward edge of 5th December 2013 shingle washover fans spilling onto reclaimed saltmarsh at Beach Road**.** The 'islands' of brown sediment top left are remnants of Great Eye also visible in Figure 8. Photograph taken 2nd January 2014.

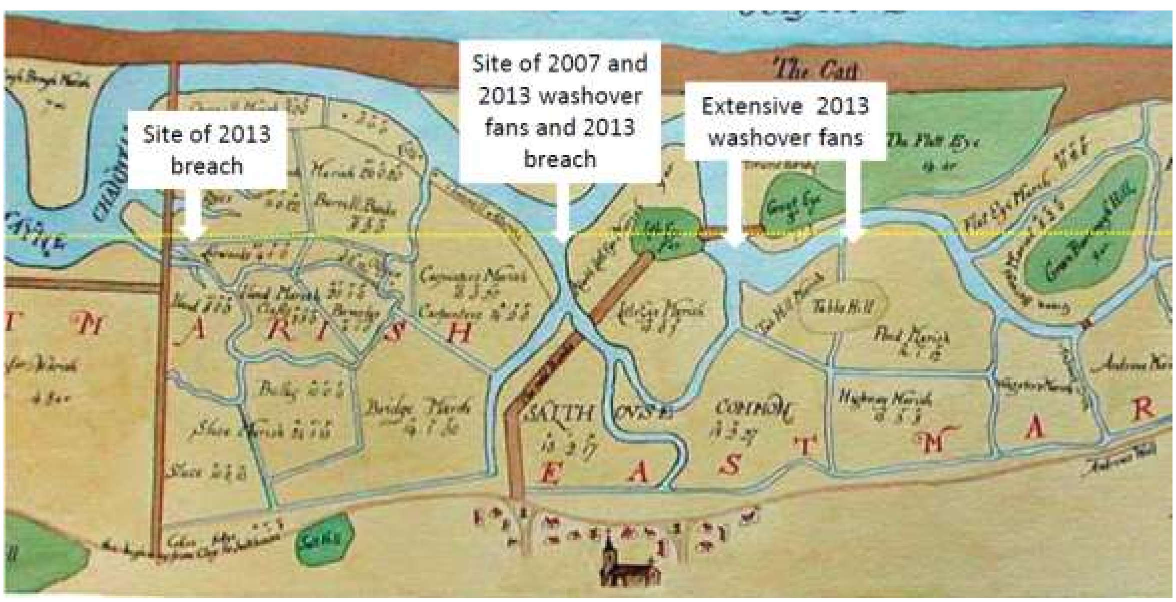

Fig. 10. Part of the 1649 'John Hunt' map in Figure 6 showing the position of large washover fans formed in the November 2007 and December 2013, and the site of the breach channels following the December 2013 surge (cf. Fig. 7). The yellow pecked line is the position of the present day beach crest.

This said, the barrier-beach crest did not migrate landward significantly, rather it broadened and lost elevation as its natural profile was regained (Andrews 2009).

The geomorphological changes effected by the 2013 and 2007 surges at Salthouse are particularly interesting in the context of the 1649 map. In Figure 10 the present day position of the barrier-beach crest is marked on the relevant part of the 1649 map using Gramborough Hill and Little Eye as local reference points. These low but prominent hills are 'outliers' of glacial diamicton, sands and gravels likely of Devensian age (Andrews *et al*., 2002) that crop out through the Holocene coastal sediment prism. Also marked on Figure 10 is the position of the largest washover fans formed in the 2007 and 2013 surges. The age assignation of the washovers is possible by comparison of aerial photos taken after November 2007 and then again after December 2013 (Fig. 11). The latter were taken by Dr Tony Dolphin using a Cefas owned Remotely Piloted Aircraft System (RPAS); similar image comparisons can also be made using the Google Earth 'history function'.

One of the most striking of these images is that taken to the W of Little Eye in 2014, which can be compared directly with the pre-2013 image. The older image shows a large washover fan that formed in November 2007, lapping against the glacial hillock of Little Eye. In the 2014 image, taken after the 2013 surge, the 2007 washover shape is largely unchanged, with even some of the subsidiary lobes on the S margin preserved almost unchanged. The most obvious difference is the arrival of the elongate shingle lobe to the W, separated from the 2007 fan by a prominent re-entrant floored by the pre-existing saltmarsh. The NW corner of the 2007 lobe where it joins the beach is also clearly moulded into a series of recurved large bar forms, and bars of similar magnitude are also clear on the southern tip of the 2013 lobe.

The juxtaposition of these lobes is at first glance peculiar, there being no obvious reason why the smaller 2013 washover fan did not weld itself to the W margin of the pre-existing 2007 fan. The explanation is, however, simple: the shingle-free re-entrant between the fans [TG 07675 44428] marks the position of a drainage channel that breached the barrier (Spencer *et al*., 2015) as floodwater

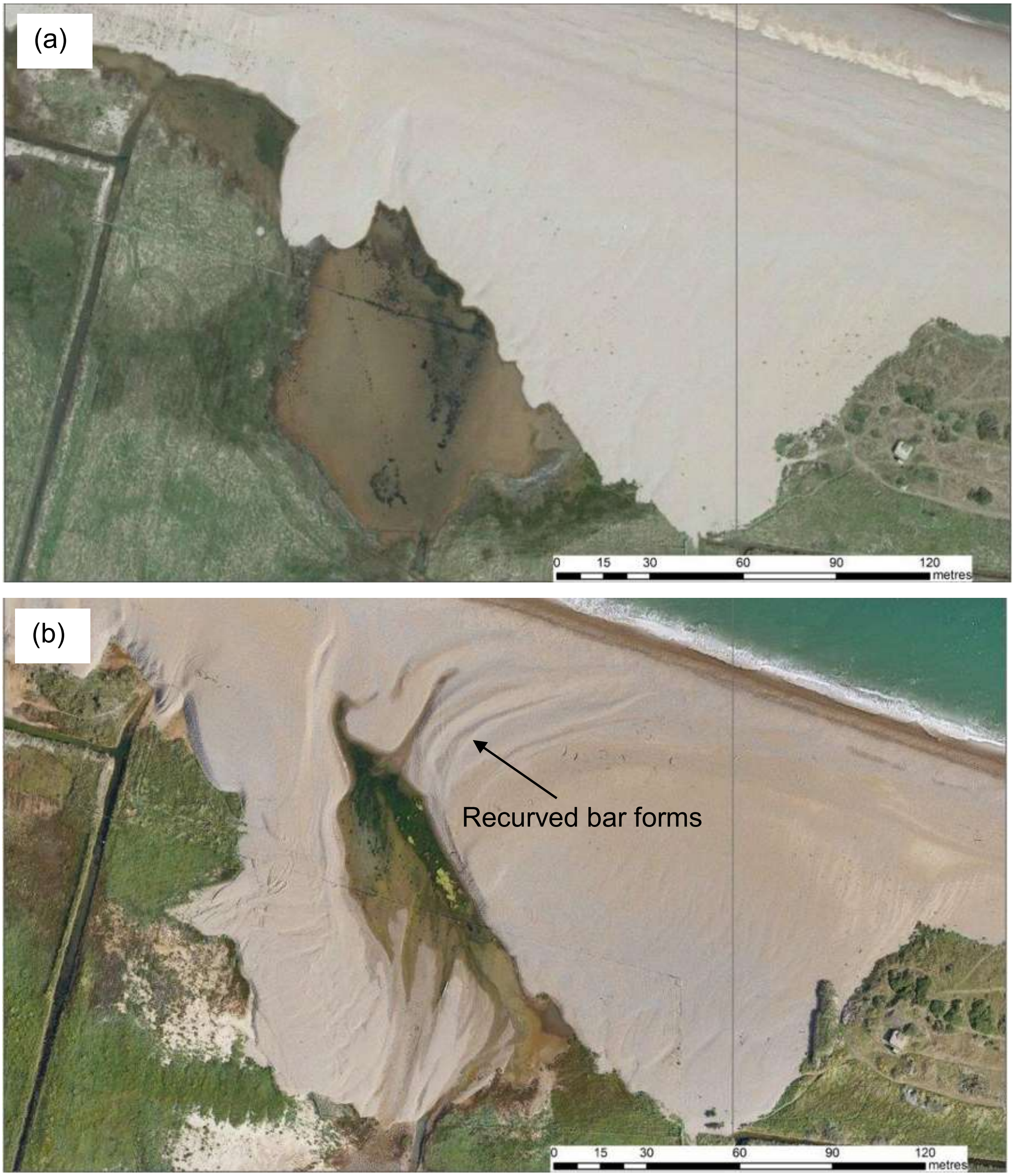

Fig. 11. Comparison of washover fans W of Little Eye in aerial photos (a) taken in June 2008 after the November 2007 surge and (b) taken in September 2014 after the December 2013 surge. The shingle-free re-entrant between the fans in (b) is centred on TG 07675 44428. Cley Eye pillbox is clear in the bottom right of both images. Image (a) is from the EA website (https://data.gov.uk/dataset/4921f8a1-d47e-458b-873b-2a489b1c8165/vertical-aerial-photography) under Open Government Licence v3.0; image (b) taken by Dr Tony Dolphin using a Cefas-owned RPAS as part of a NERC funded urgency grant.

Fig. 12. 'Little Eye breach channel' (a) looking seaward (N) and (b) looking landward (S). Note the pale grey Holocene muds exposed by channel bed erosion. The elevation of these muds, just above mean sea level can be used to infer an age of around 2000 years BP based on the data in Funnell & Boomer (1998, p.55). Images courtesy of Mr David North taken on 12th December 2013.

Fig. 13. Transient ebb tidal delta formed at the seaward end of the 'Little Eye breach channel'. Image courtesy of Mr David North taken on 12th December 2013.

escaped seaward from the lagoon ponded on the landward side of the barrier following the 2013 surge. This drainage was photographed Mr David North of Norfolk Wildlife Trust on 12th December 2013 (Fig. 12). David North observed that at low tide, drainage flowed seaward "like a white water rapid" eroding the sides of the breach and deepening the channel (see also Changing Coastlines, 2014a). At high tide the flow reversed, but seawater in-flow was very gentle. There was also evidence of a transient ebb tidal delta at the seaward end of the channel (Fig. 13) which confirms the channel was cut mainly by strong drainage seaward, isolating the 2013 washover lobe as a distinct geomorphic feature. Channel bed erosion also exposed pale grey Holocene muds that underlie the shingle, particularly at the seaward end of the channel (Fig. 12b & 13).

The recurving of the bar forms on the NW corner of the 2007 washover (Fig. 11b), was caused largely by wave action. The channel began to 'heal' on its seaward side by east to west long-shore shingle movement between the 18th and 22nd January 2014 with further infilling on 20th February 2014 (Spencer *et al.*, 2015; see also Changing Coastlines, 2014b & c).

Fig. 14. 'Arnold's (Pope's) Marsh breach channel' (TG 06874 44675) viewed, a) from the backbarrier looking E. The artificially steepened bank east of the channel was overtopped in 2013 but retained some topography. b) viewed SE along the barrier crest. Images courtesy of Mr David North taken on 2nd January 2014.

The location of the 'Little Eye' drainage channel was not a chance event. Examination of the 1649 map shows that the channel is sited directly on a former saltmarsh channel, a landward branch of the 'Mayne Channel' shown on the 1649 map (Fig. 10). The implication is that modern flood drainage was conditioned by former hydrological topography, presumably because this part of the marsh, being a former channel bed – albeit infilled by reclamation practices – was topographically lower than its surroundings, a conclusion also reached independently by Hooton (2003).

Fig. 15. Site of the former 'Arnold's (Pope's) Marsh breach channel' in November 2018 looking SE. The field of view is similar to that in Fig. 14a. The prominent line of 'barrier stabilising posts' has been exposed as the barrier profile has been flattened. Only the first three posts at the left end are visible in Fig. 14a.

A second drainage channel formed 800 m west of the 'Little Eye' channel, photographed by David North on 2nd January 2014 (Fig 13). The channel was associated with a large washover (as at Little Eye) and located just east of Arnold's Marsh (Pope's Marsh) at TG 06874 44675 (see also Changing Coastlines 2014d). Comparison between Google Earth images for 24thSeptember 2017, 1st January 1999 and a 29th March 2016 EA LIDAR image (https://data.gov.uk/.../lidar-composite-dsm-1m) again shows that this channel was located in a topographic depression. While this area has been 'scraped' for bird conservation, remnants of saltmarsh creeks, clear in the 1 January 1999 Google Earth image, can tentatively be matched to a SW orientated creek branching off the 'Mayne Channel' (Fig. 10) on the 1649 map. It is thus likely that the siting of modern flood drainage was, as at Little Eye channel, inherited from former hydrological topography. The channel was also 'healed' on its seaward side by long-shore shingle movement by 22nd January 2014 (Changing Coastlines 2014e).

It is worth mentioning that the remnant topography of the artificially steepened bank east of the channel, still present after the 2013 surge (Fig. 14) and

Fig. 16. Last remnant of the artificially steepened shingle bank (left hand, seaward, side) and remains of the 1851-1855 seawall (right hand, landward, side) fronting Arnold's Marsh in November 2018. View is to SE. The gap between the two 'banks' will gradually fill with shingle as the beach profile flattens and rolls landward.

Fig. 17. Remains of a concrete seawall, built by the Cozens-Hardy family over 100 years ago to protect their wildfowling interests. The wall is now (January 2019) engulfed in mobile shingle. View is W at the seaward end of the East Bank at TG 0588 4490.

still intact in a 29th March 2016 EA LIDAR image (https://data.gov.uk/.../lidar-composite-dsm-1m) is today (November 2018) almost wholly flattened, probably by the storm of 13th January 2017. The area now has a largely natural beach morphology with broad washover fans on the landward side (Fig. 15). On the 8th January 2019 this section was again overtopped by a spring tide with onshore northerly winds; this caused minor gullying in the 2016 washover fans and in parts of the degraded shingle bank but there was no drainage breaching. Indeed the whole 4 km stretch of coastline between Cley Eye car park and Gramborough Hill now retains <17% of its 1990s artificial profile, mostly in the region where the Cley Reserve East Bank meets the coast around Arnold's Marsh. This section has a clay embankment behind the shingle ridge (Fig. 16), a remnant of the 1851-1855 seawall (Harris 2003). It is not clear, however, if this embankment is in any way affecting the seaward shingle ridge stability and it may simply be that this area is topographically the highest point along the 4 km stretch. Certainly the former concrete sea wall at the north end of the East Bank, that 100 years ago had temporarily slowed erosion in this area (Oliver & Carey 1918), is no longer impeding landward rollover (Fig. 17).

HISTORICAL EVIDENCE OF THE 1938 STORM AT SALTHOUSE

While overtopping of the Salthouse gravel barrier and back barrier flooding has been observed frequently over the last century (Brooks *et al*., 2016), channelized breaches in the Salthouse shingle bank are not so well documented. A breach channel was opened in the 1953 surge (Steers 1953) although no details were recorded. A 200 m wide 'breach' in February 1995 is mentioned by May (2003), although this was probably a 'breach' of the artificially steepened bank caused by the 1st January 1995 storm rather than a breach channel as described above.

It is still possible to reconstruct, at least partially, evidence of bank overtopping in the absence of field documentation and on-site photography, by the presence of washover fans that show up clearly on aerial photographs (Pollard *et al*., 2019) and now on resources such as Google Earth. For example, the 1946 aerial survey (www.historic-maps.norfolk.gov.uk/mapexplorer) has unbroken coverage of the coast between Cley Eye and Weybourne Hope, showing a prominent area of amalgamated washover fans ~600 m long (shore parallel) to the west of Little Eye, that had been driven in excess of 100 m landward (south). These washovers formed in the same area as the 2013 'Little Eye channel' described above, confirming that this topographic low point on the marsh is flood prone. It is likely that these washovers formed in the storm surge of 12th February 1938, when the coast road at Salthouse was flooded (Brooks *et al*., 2016; Steers *et al*., 1979). The change in landward barrier beach position in this area in the 71 years since 1938 is about 125 m suggesting a mean rollover rate of 1.8 m a^{-1}, which is between 2 and 3 times the longer-term rates given above.

Similar sized washover fans are prominent in the ~1 km stretch of coast where the East Bank joins the coast. The eastern 500 m of this section are more or less identical to those described above near Little Eye, while the 500 m fronting Arnold's Marsh had their landward run-out baulked by the remains of the 1851-1855 seawall (see above). The 'freshness' of the landward edge of these shingle washovers, photographed in 1946, 8 years after the storm, is consistent with the excellent integrity of washovers viewed in 2017 Google Earth imagery that had formed 10 years earlier in 2007.

ACKNOWLEDGEMENTS

Godfrey Sayers, Mary Ferroussat and John Wright of Blakeney, kindly allowed BMF to borrow, copy and publish figures based on their documents as part of the 1994-1997 NERC funded LOIS: LOEPS Special Topic allocation GST/021737 'Sedimentary Evolution of the Norfolk Barrier Coastline in the context of Holocene Sea Level Change'. The late Pat Funnell gladly gave permission for her husbands unpublished writing to be aired here. The more recent research by JEA started as part of a 2014 NERC funded Urgency Grant NE/M001261/1 'Environmental Impacts of the December Storm Surge on the North Norfolk Coast' but has grown as a result of both UEA undergraduate teaching and outreach events. JEA particularly thanks David North for sharing his field observations of the December

2013 surge at Salthouse, and for permission to use some of his photographs. Dr Tony Dolphin kindly gave permission to use his image as Fig. 11b. Tom Spencer and Jamie Pollard (both Cambridge University) gave valuable review comments and helpful discussion. The responsibility for all the interpretations offered in this contribution lie wholly with Julian Andrews.

REFERENCES

ANDREWS, J.E. 2009. Natural processes reshape the Cley Bank. *Newsletter of the Geological Society of Norfolk*, **74**, 6-8.

ANDREWS, J.E., CORBETT, W.M., FUNNELL, B. M., & BOOTH, S.J. 2002. Pilot study in differentiating north Norfolk glacial sediments using mineral magnetic data. *Bulletin of the Geological Society of Norfolk*, **52**, 73-87.

ARTHURTON, R.S., BOOTH, S.J. ABBOTT, M.A.W. & WOOD, C.J. 1994. *Geology of the Country around Great Yarmouth*. Memoir for the 1:50,000 geological sheet 162 (England and Wales). British Geological Survey, HMSO, London.

BARFOOT, P.J. & TUCKER, J.J. 1980. Geomorphological changes at Blakeney Point. Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **25**, 49-60.

BREW, D.S., FUNNELL, B. M., & KREISER, A. 1992. Sedimentary environments and Holocene evolution of the lower Blyth estuary, Suffolk (England), and a comparison with other East Anglian coastal sequences. *Proceedings of the Geologists' Association*, **103**, 57-74.

BROOKS, S.M., SPENCER, T. & CHRISTIE, E.K. 2017. Storm impacts and shoreline recovery: Mechanisms and controls in the southern North Sea, *Geomorphology*, doi:10.1016/j.geomorph.2017.01.007

BROOKS, S.M., SPENCER, T., McIVOR, A, & MÖLLER, I. 2016. Reconstructing and understanding the impacts of storms and surges, southern North Sea. *Earth Surface Processes and Landforms*, **41**, 855-864.

CHANGING COASTLINES, 2014a. Salthouse — the breach in the shingle ridge 18 January 2013. https://www.youtube.com/watch?v=8XZuATG8gQ0.

CHANGING COASTLINES, 2014b. Salthouse — breach now closed by longshore drift 22 January 2014. https://www.youtube.com/watch?v=dfvGlJ-LbLc.

CHANGING COASTLINES, 2014c. Salthouse, Norfolk — further infilling of the breach in the beach ridge 20th Feb 2014. https://www.youtube.com/watch?v=A6El6y-Ubgo.

CHANGING COASTLINES, 2014d. Cley — the breach in the beach ridge at Pope's Marsh 18 January 2014. https://www.youtube.com/watch?v=pRMEFMecoTs.

CHANGING COASTLINES, 2014e. Pope's Marsh — breach closed by longshore drift 22 January 2014. https://www.youtube.com/watch?v=UutHDi9co4U.

CLAYTON, K M. 1989. Sediment input from the Norfolk cliffs, eastern England - a century of coast protection and its effects. *Journal of Coastal Research*, **5**, 433-422.

COZENS-HARDY, B. 1927. Cley-next-the-Sea and its marshes. *Transactions of the Norfolk and Norwich Naturalists' Society*, **12**, 354-373.

FUNNELL, B.M & BOOMER, I. 1998. Microbiofacies tidal-level and age deduction in Holocene Saltmarsh deposits of the north Norfolk coast. *Bulletin of the Geological Society of Norfolk*, **46**, 31-55.

FUNNELL, B.M., BOOMER, I. & JONES, R. 2000. Holocene evolution of the Blakeney Spit area of the North Norfolk coastline. *Proceedings of the Geologists Association*, **111**, 205-217.

HARRIS, S. 2003. The landscape history and birdlife of the marshes. In: Fiddian, V. (ed.), *Salthouse, the Story of a Norfolk Village*, 66-69, The Salthouse History Group, Anthony Rowe Ltd., Chippenham.

HOOTON, J. 1996. *The Glaven Ports: a Maritime History of Blakeney, Cley and Wiveton in North Norfolk*. Blakeney History Group. Blakeney:

HOOTON, J. 1998. 1586 Map of the Blakeney Haven and Port of Cley: Part I. *The Glaven Historian (The Journal of the Blakeney Area Historical Society*), **1**, 3-7.

HOOTON, J. 2003. The marshes and Salthouse the trading port. In: Fiddian, V. (ed.), *Salthouse, the Story of a Norfolk Village*, 60-65, The Salthouse History Group, Anthony Rowe Ltd., Chippenham.

MAY, V. J. 2003. North Norfolk Coast. In: May V. J. & Hansom J.D. (eds) *Coastal Geomorphology of Great Britain*, Geological Conservation Review **28**: Chapter 11, Coastal Assemblage GCR sites (GCR ID: 2038), 1-19. Joint Nature Conservation Committee, Peterborough. ISBN 1-86107-484-0.

OLIVER, F.W. 1913. Some remarks on Blakeney Point, Norfolk. *Journal of Ecology*, **1**, 4-15.

OLIVER, F.W. & CAREY, A. E. 1918. Blakeney Point; from the point to Cley and Salthouse, 41pp. Reprinted by The History Centre, Blakeney 2012, with additional explanatory notes.

POLLARD, J.A., BROOKS, S.M., SPENCER, T., CHRISTIE, E.K., & MÖLLER, I. Will nature work with us? Erosion and flooding impacts on a UK barrier. Coastal Sediments 2019, Proceedings of the 9th International Conference, Tampa, FL, 114-127, September 2019.

SHENNAN, I., LAMBECK, K., FLATHER, R., HORTON, B., MCARTHUR, J., INNES, J., LLOYD, J., RUTHERFORD, M. & WINGFIELD, R. 2000. Modelling western North Sea palaeogeographies and tidal changes during the Holocene. In: Shennan. I. & Andrews, J.E. (eds) *Holocene Land–Ocean Interaction and Environmental Change around the North Sea*, 299-319, Geological Society of London Special Publication **166**. Geological Society, London.

SPENCER, T., BROOKS, S.M., MÖLLER, I., & EVANS, B.R., 2014. Where local matters: impacts of a major North Sea storm surge. EOS, Transactions of the American Geophysical Union 95, 269–270.

SPENCER, T., BROOKS, S.M., TEMPEST, J.A. & MÖLLER, I. 2015. Southern North Sea storm surge event of 5 December 2013: water levels, waves and coastal impacts. *Earth-Science Reviews*, **146**, 120–145.

STEERS, J.A. 1927. The East Anglian coast. Geographical Journal, **69**, 24–48.

STEERS, J.A. 1952. The Physical Features of Scolt Head and Blakeney Point, In: Steers, J.A. (ed.), Blakeney Point and Scolt Head Island (1st ed.), 9-21, The National Trust, Norfolk.

STEERS, J.A. 1953. The east coast floods, January 31-February 1 1953. *Geographical Journal*, **119**, 280-298.

STEERS, J.A. 1964. The Physical Features of Scolt Head and Blakeney Point, In: Steers, J.A. (ed.), Blakeney Point and Scolt Head Island (2nd ed.), 9-21, The National Trust, Norfolk.

STEERS, J.A. 1971. The Physical Features of Scolt Head and Blakeney Point, In: Steers, J.A. (ed.), Blakeney Point and Scolt Head Island (3rd ed.), 13-25, The National Trust, Norfolk.

STEERS, J.A. 1976. The Physical Features of Scolt Head and Blakeney Point, In: Steers, J.A. (ed.), Blakeney Point and Scolt Head Island (4th ed.), 13-25, The National Trust, Norfolk.

STEERS, J.A. 1989. The Physical Features of Scolt Head and Blakeney Point, In: Allison, H. and Morley, J. (eds), Blakeney Point and Scolt Head Island (5th ed.), 14-27, The National Trust, Norfolk.

STEERS, J.A., STODDART, D. R., BAYLISS-SMITH, T. P., SPENCER, T. & DURBIDGE, P. M. 1979. The storm surge of 11 January 1978 on the east coast of England. *Geographical Journal*, **145,** 192-205.

[Manuscript received 10 September 2019; revision accepted 3 October 2019]

GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk (GSN) website can be found at:

http://www.norfolkgeology.co.uk

The contents and abstracts of the Bulletins, starting in 1953, are all available for download on the website. Many back issues are available in print form from the editor.

The society also has a Facebook page and an Earth Science Database containing over a thousand articles relevant to the geology of Norfolk.