QUATERNARY HISTORY OF THE SOLENT SYSTEM

1. Introduction

This account explains the origin and development of the landforms of the Solent. It covers a period of several major alternations of cold and temperate climatic conditions with associated low (fluvial and sub-aerial conditions dominant) and high (marine inundation and erosion dominant) sea-level intervals (Table 1). It is important to understand this geomorphological history of the Solent for many of its present day features and controlling influences are inherited from earlier periods. Past behaviour therefore provides valuable insights into the types of change that might be anticipated in the future under the changing climatic conditions associated with global warming.

2. The 'Solent River': Overview of Evolution

The concept of a major unified river system draining a large catchment of central southern England throughout most of the Pleistocene has attracted geologists, geomorphologists and others for almost two centuries (Tomalin, 2000). The case for an ancestral Solent River flowing west to east approximately along the axial line of the strongly asymmetrical Hampshire Basin syncline was initially inspired by the apparent confluence of numerous former tributary rivers, their lower sections having been submerged by a rise of sea-level that eliminated the 'master' river and converted it to a double entrance estuarine strait. A major contribution to this dismemberment was the breaching of the former 17km Chalk monocline ridge connecting the present day Needles (Isle of Wight) with Handfast Point, north of Swanage. The timing of the destruction of this "Wight-Purbeck" ridge has generated much debate, and it is only recently that more definitive evidence has emerged to clarify the likely sequence of events that ultimately destroyed the Solent River and created the connection between the western Solent waterway and Christchurch Bay (Velegrakis, et al., 1999, 2000).

The most extensive and convincing evidence for the existence of a Solent River is the pattern of terraces, from +130m to –37mOD, that occupy much of the area of Eocene and Oligocene rocks that form the Hampshire Basin lowlands (Figure 1). They form a descending "staircase" of platform-like surfaces cut into bedrock but supporting up to 5 or 6 metre thick gravel-dominated aggradational deposits. These create near continuous sheets at low elevations, but are more fragmentary at higher elevations. This suggests that the highest terraces and their deposits are the oldest, having been subject longer to mass wasting and stream dissection. Most terrace surfaces have transverse and lateral gradients consistent with their creation by fluvial processes at, or close to, contemporary base-levels. Their spatial pattern is strikingly consistent with the alignments of the present day Solent and its major tributaries, including rivers now draining into Poole and Christchurch Harbours.

The terraces are mantled by a cover of aggradational deposits made up of angular and sub-angular gravel-sized flint clasts, whose ultimate origin is the wide Chalk outcrop that bounds the Hampshire Basin (Palmer and Cooke, 1923; Everard, 1954; Mottershead, 1976; Allen and Gibbard, 1993). They have a coarse sandy matrix but only occasionally exhibit any distinctive fabric or textural features. Cryptic stratification is sometimes evident, with more clearly developed interstratified and lens-like inclusions of sands and loams on the lower terraces. Collectively referred to as 'Plateau Gravel', they show little variation in composition, texture and structure throughout their entire height range (White, 1921). The Plateau Gravels grade into very similar valley gravels that mantle the surfaces of terraces within all of the major and minor valleys draining to the Solent, Poole and Christchurch Bays and Poole Harbour. Both types of deposits are devoid of fossils and organic materials and provide no opportunities for absolute dating of the time(s) of their formation. Deposits up to +25mOD, and also below modern sea level, do however contain cultural artefacts, allowing a degree of crude relative age distinction for the period approximately 15,000 to 2,500 years BP. It is widely accepted that the characteristic texture and fabric of the Plateau Gravels indicates their formation under a high river discharge regime capable of substantial bedload transport. This is most likely to have been a periglacial (tundra) floodplain environment promoting channel braiding (Keen, 1980). Internal ice wedge casts, involutions and other structures diagnostic of intensely cold conditions during and after their formation are known from several sites.

The most comprehensive analysis of the terraces of the Solent River by Allen (1990), summarised by Allen and Gibbard (1993) and Gibbard and Allen (1994) has confirmed and elaborated on previous work on their evolution (e.g. Everard, 1954). Allen and Gibbard (1993) suggest that the Solent River is at least early Pleistocene in origin and its history is a complex response to a succession of climate and sea-level changes, regional geological structure and rock lithology, and neotectonics. There are analogies with the evolution of the Thames, but with the major difference that the Solent developed as an extra-glacial river system throughout its history (Gibbard, 1988).

The succession of terraces and fluvial aggradations can be broadly divided into two geographical groupings as follows: (i) a western area drained by the Frome and its tributaries, where individual gravel units are identified on the basis of their stratigraphical relationships and clast populations and (ii) the Bournemouth-Southampton-Fareham area, where age equivalence is more readily based on relative altitude and height-range. Taking both areas together, there is a suite of 14 gravel units above present day sea-level that indicate that the Solent River catchment extended at least as far west as Dorchester and received, as tributaries, the Stour and the Avon. Its course was fixed during the Wolstonian and early Devensian cold (glacial) stages of low sea level when there was strong channel incision. A more southerly course was established during the middle and late Devensian, a development consistent with the river's long term southwards migration (Keen, 1975; Allen and Gibbard, 1993). This accounts for the comparatively fragmentary survival of right bank terraces, in Purbeck and the Isle of Wight; coastal recession has also removed much of the Solent River's former southern catchment area. Terraces, gravel deposits and buried channels also occur below present day sea-level (Everard, 1954, 1956; West, 1980; Hodson and West, 1972; Dyer, 1975), but have not been systematically mapped. West (1980) has published a provisional map of the main buried channel of the Solent River in the eastern and central Solent, with an extension into lower Southampton Water, beneath Calshot Spit, at –14mOD (Figure 2). Dyer (1975) identified a central buried channel at –40m at the Nab Tower, eastern Solent and at –46mOD further south-east. Offshore bathymetry suggests that this channel connects with an infilled palaeovalley that is tributary to the former westwards-flowing 'English Channel' river (Figures 1 and 2). These depths may have been increased by tidal scour during the early Holocene, but are consistent with maximum late

Devensian sea levels determined from surveys of other palaeochannels incised into the English Channel seabed. An example is the palaeovalley east of Owers Bank, 20km south of the Worthing, West Sussex, which is considered to be the seawards extension of the Arun Valley cut during the maximum low sea-level of the late Devensian (Bellamy, 1995). This was a tributary of the Northern Palaeovalley and has a rock head depth of –56mOD near its confluence. Valley depths vary between –20 and –40m closer inshore, where infill sediments record multiple cut and fill events. Each of these indicate a progressive change from fluviatile to estuarine and sub-littoral environmental conditions, with phases of sea-level transgression preceded by shoreface erosion. During low sea-level stages, gravel and sands were deposited and their texture and fabric indicate high discharge and channel braiding in a tundra climate. The comparison with terrace deposits in the Solent River catchment is therefore close, and they are considered co-eval.

3. The Breaching of the Wight-Purbeck Ridge

Allen and Gibbard (1993) report that terrace gravel gradients in the Frome Valley are steeper than those east of Wareham; these, in turn, have higher NW/SE gradients than the main set of Solent terraces east of Bournemouth. The steepest gradients characterise the youngest terraces in the Frome Valley, with a tendency for higher (older) and lower (younger) terraces to converge close to the Chalk/Tertiary boundary. This relationship may therefore be a function of differences in the erodibility of these two bedrocks, but could also be a result of reduction of catchment area over time, discharge regime or subsequent tectonic uplift. Allen and Gibbard (1993) favour the last explanation, and note that terraces in the lower Avon show the same relationship. Other researchers have reported difficulties linking the Solent River terrace suite east and west of Poole Harbour. Nicholls (1987) notes that the youngest of the Frome terraces appear to correlate with the base level inferred by a buried channel at –15.5m beneath Poole Quay. He also identifies a buried channel passing beneath Hurst Spit and Pennington Marshes, at a mean depth of –7mOD. This is well above the –15mOD of the channel at Hamworthy, although it is possible that the former channel flowed westwards. Velegrakis, et al. (1999, 2000) have estimated the morphology and elevation of the upper bedrock erosional surface of Christchurch and Poole Bays from shallow seismic and echo sounder profiles. This has revealed seven partially sediment infilled palaeovalleys, three of which cut through the former Purbeck-Wight Chalk ridge (Figure 2). Headwards extrapolation of the thalwegs of the two most westerly palaeovalleys link closely with the longitudinal gradients of the younger Frome terraces. Their sediment infill reveals a gradual transition from fluvial to marine conditions, thus strongly suggesting that the Frome (upper Solent River of previous authors) had been diverted southwards before the most recent (Holocene) rise of sea-level (Velegrakis et al, 1999). This would indicate that the Wight-Purbeck monocline ridge was breached by at least three river gaps during the low sea-level stage of the mid to late Devensian, a conclusion anticipated by Nicholls (1987) (Figure 2).

The probable magnitude of long-term fluvial erosion and mass wasting of this 17km monoclinal ridge is discussed further by Nowell (2000) and Tyhurst and Hinton (2001). They argue that erosional breaching must have occurred during earlier glacial and interglacial stages and point to the substantial river gaps through the Chalk at Corfe Castle and on the Isle of Wight. These have been identified as very long established (pre mid-Tertiary) elements of the landscape by Jones (1980). Nowell (1995; 2000) has identified north to south trending faults between Arish Mell (Dorset) and Shide, Newport (Isle of Wight) that may have guided the development of structurally discordant rivers. Thus, the upper Solent river was routed through pre-existing valleys, possibly dating to the Ipswichian interglacial. Others are inferred from geological mapping of the submerged outcrop of the Chalk between the Needles and Handfast Point (Nowell, 2000). Although it is now apparent that the upper Solent River was diverted via one or more of the palaeovalleys, the details are not clear. The Corfe, Freshwater, Medina and Brading gaps continue to accommodate south to north flowing truncated right bank tributaries of the former Solent; and there is no direct evidence, for example, of palaeovalleys in Freshwater and Sandown Bays (Tomalin, 2000a). Brampton, et al. (1998) however, imply that there may be a case for the continuation of the palaeovalleys identified by Velegrakis, et al. (1999, 2000) up to 10-15km south of the former Wight-Purbeck ridge. They describe several southward-directed sub-parallel valleys, incised into bedrock and containing mostly sandy and sandy clay sediment infills. This study also reports a coarse grained sediment at the heads of the palaeovalleys that originate at the Wight end of the former ridge. These could be former pocket beach deposits.

Velegrakis, et al. (1999) also report four infilled palaeovalleys within, and south of, Christchurch Bay. Their sediment infills indicate abrupt transitions, with no transgressive facies. Two of the valleys head into, but fail to breach, the Chalk outcrop west of the Needles. It is thus apparent that Christchurch Bay was submerged later than Poole Bay, possibly very rapidly or commencing as a shallow estuarine embayment protected by a south-eastwards extension of Hengistbury Head. The complex seabed bathymetry created by Hengistbury Ledges may be a bevelled remnant of this former barrier (Tyhurst and Hinton, 2001). The Solent River east of Hengistbury continued to flow at least up to 10,000 to 9,000 years BP, when rapid sea-level rise successively breached the eastern remnant of the Wight-Purbeck ridge, created the outline of Christchurch Bay, reworked the gravel terrace deposits and finally began to open up the western entrance of the Solent estuarine.

4. Middle Pleistocene High Sea-Levels

The earliest evidence for relative sea-level change in the Solent region occurs in the West Sussex and South-East Hampshire Coastal Plain. This lowland narrows rapidly westwards of Chichester and eastwards of Worthing, and is composed of a succession of Pleistocene ("drift") sediments that almost completely conceal underlying Tertiary (Eogene) clays and sands. Collectively, these sediments record a sequence of profound climatic changes that caused alternations of temperate and tundra (arctic) conditions during middle and late Pleistocene times. Related movements of sea-level are preserved by the features of several now displaced shorelines, and associated marine sediments.

At the highest level is a sequence of beach and intertidal deposits occurring between 38 to 43mOD in association with a fossil cliff. They have been ascribed to the 'Goodwood-Slindon Raised Beach' by several researchers, most recently described in detail by Roberts (1986, 1998). The archaeological significance of these sediments are proving critical to understanding early Palaeolithic cultures in Europe. At Bembridge, Isle of Wight, Holyoak and Preece (1983), Preece and Scourse (1987) and

Preece, et al. (1990) have described an estuarine deposit (the Steyne Wood Clay) at a similar elevation. Based largely on the close correspondence of altitude above modern sea-level, of these sediments, Preece et al. (1990) interpret them as being contemporary in age. They suggest that they were deposited in a wide, shallow estuarine embayment during an interglacial period of high sea-level. The latter cannot be dated with certainty, but amino acid ratios obtained from molluscan shells in the Slindon Sands suggests either the late "Cromerian complex" or Holsteinian (Keen, 1995) of the middle Quaternary.

The relative height of sea-level at the time of their deposition is also difficult to determine. Scourse and Austin (1995) have analysed the assemblage of calcareous nannofossils in both the Slindon Sands and Steyne Wood Clay and have concluded that it indicates a well-stratified water mass with a strong themocline. This may imply that, at the time of deposition, the English Channel was a closed embayment, pre-dating the creation of the Strait of Dover. If this is a valid conclusion, palaeoceanographic modelling would suggest that the tidal range at this time was substantially higher than it is now. Tyhurst and Hinton (2001), although referring to a later interglacial stage, hypothesise a mean tidal range of between 10 and 20m. It is thus difficult to accept the argument of Preece, et al. (1990) that middle Pleistocene deposits have been tectonically uplifted some 35 to 40m since their formation, at approximately 500-550,000 years BP. This is reinforced by their isolation from the progressive downwarping of the southern North Sea basin. Taking account of probable palaeotidal conditions, a more plausible estimate of net uplift is approximately 25m (Gibbard and Allen, 1994). The absence of evidence for differential warping or tilting in this area suggests episodic 'platform-like' uplift due to reactivation of the Portsdown anticline and Isle of Wight monocline. This would give a rate of tectonic elevation of 0.05-0.07m per 1,000 years (Roberts, 1998). However, multiple glacial-interglacial cycles will have introduced the growth and collapse of glacio-isostatically induced forebulges in the range of 25-35m. There may also have been hydroisostatic effects resulting from loading effects once the eastern English Channel was connected to the southern North Sea Basin. The latter, involving the creation or substantial enlargement of the Strait of Dover, probably during the Anglian glacial stage, may have been a catastrophic event (Smith, 1985). It is difficult to model the relationships between these various events, not least because their magnitudes and timescales of operation are not known. It may, however, be significant that Allen and Gibbard (1993) note that there are no progressive or sudden changes in the longitudinal gradients of Solent system terraces nor any fluvial aggradations that are presumed to be younger than middle Pleistocene. This would tend to support the concept of slow, progressive (though probably non-uniform) uplift.

Sea-level rise in the Hoxnian interglacial is likely to have detached the British Isles from the European continent for the first time. Bates, et al. (1998) suggest that the marine sands and gravels of the West Sussex Coastal Plain (Hodgson, 1964) below approximately 30mOD can be differentiated into distinct sequences of raised beaches of this age. The highest, between 20 and 28mOD, is termed the 'Aldingbourne' Raised Beach and rests against a discernible break of slope marking a former cliff line; sediment facies indicate a high energy beach deposit. A chronological equivalent may be the raised beach fragment at Cams Hall, western Portsdown, between 15 to 18mOD, where gravels overlie sands (Mottershead, 1977; Apsimon and Shackley, 1976). The lower – 'Pagham' – sequence occurs between 5 and 13.5mOD and extends from east of Chichester to near Havant. It also rests against a now degraded cliffline and consists predominantly of marine sands and silts overlying a planation surface. Bates, et al. (2000) have proposed a further subdivision, identifying the Norton Farm Formation, between 5.3 and 9.1mOD as the more extensive in this sequence of sediments. On sedimentological and palaeontological evidence, these sediments are likely to have been deposited during the transition from temperate to cold climate conditions (i.e. during the regressive phase of the Hoxnian interglacial). This is supported by amino acid ratios from shells and may therefore be the same age as estuarine deposits outcropping at +1mOD on the Earnley (West Wittering) foreshore (West, et al., 1984). This interpretation may link with the presence of numerous non-local (erratic) clasts – many of them large boulders - which occur at a range of elevations between Pagham and Portsmouth. It tends to support the long held hypothesis that they were rafted by icebergs. However, the majority of erratics of known provenance match with original outcrops in South-West England, the Channel Islands and North-West France. A few can be matched with rock exposures marginal to the North Sea, suggesting the possibility that an ancestral Strait of Dover was potentially available for long distance transport. Many of the erratics that now occur in younger (Ipswichian interglacial) deposits, as well as on the modern foreshore, have presumably been subject to the erosional re-working of this earlier deposit.

Detailed field mapping and sediment boreholes subject to litho-, bio- and chronostratigraphical analytical approaches, reveal five distinct high Middle Pleistocene sea-levels. They represent what is probably the best evidence anywhere in north-west Europe for coastal change during this long period of time. This is primarily due to their subsequent preservation due to tectonic uplift. There remain some very significant questions, the main one in the present context being the relationship between these sea-levels and the terrace sequence of the Solent River. Presumably the older and higher, terraces (Everard, 1954; Allen and Gibbard, 1993) were graded to base-levels controlled by higher sea-levels. Whilst exact correlation using gradient and altitudinal criteria would not be expected, an approximate spatially-integrated chronosequence might be anticipated. This cannot be achieved, at present, because: (i) the fluvial aggradational deposits overlying most terrace surfaces offer few opportunities for absolute or relative dating; and (ii) there are no co-adjacent contacts between marine and fluvial surfaces. Indeed, higher level terraces are absent in the critical area between Fareham and Chichester. Perhaps because this is it was a long-established open estuary head that experienced periodic storm surge erosion along a fluctuating shoreline with a large tidal range. Erosion may have removed the potential evidence for establishing the links between the ancestral Solent River and sea level transgression/regression further east during the Middle Pleistocene.

5. Last (Ipswichian) Interglacial Sea-Level

Unfossiliferous raised beach deposits between 2 to 3m in thickness occur on the Selsey peninsula between +3 and +7mOD. These were dated as Ipswichian by Sparks and West (1960) on the basis of the palynology and biostratigraphy of underlying freshwater muds. They consist of indurated, rounded to sub-rounded flint clasts in a sandy loam matrix, with evidence of textural and fabric changes due to subsequent cold climate (periglacial) conditions. Some 5km distant is the Foreland, (Bembridge), raised beach, north-east Isle of Wight, where there is a fining up sequence of intertidal sands and high energy beach gravels overlying organic muds (Preece, et al., 1990). The latter have yielded an Ipswichian pollen assemblage, whilst a thermoluminesence date of 115ka has been obtained from a sand lens. Although they occupy a height-range of 5 to 18mOD, thickening westwards and resting against a cliffline cut into the local substrate, they are considered to have the age equivalent of the Selsey deposit. Contemporary sea-level was therefore approximately 5-8mOD, if allowance is made for tidal range and high energy (storm) waves creating the higher level deposits at Bembridge. Preece, et al. (1990) consider the latter to be a remnant of a larger barrier spit or cuspate foreland probably contiguous with, or incorporating, the Selsey material. This poses the question as to why the entrance to the eastern Solent was, at this time, occupied by a large accretion structure resulting from exposure to a high energy wave regime. However, the contemporary coast to the west would have been several kilometers southward and may not have indented the Purbeck-Wight ridge at this time. This would create greater focusing of waves from the south and west, although whether or not offshore bathymetry included any equivalence to the present day Bembridge Ledges is not known. If that were not the case, wave refraction would be significantly less than it is now. A long distance longshore transport pathway perhaps operating over several of the Pleistocene high sea-level phases is supported by the presence of clasts derived from metamorphic rocks that outcrop on the modern South Devon coast.

Other Ipswichian interglacial deposits in the Solent area have been identified from boreholes and trial pits at two sites in the Western Solent, viz: Pennington (Allen, et al., 1996) and Stone (Brown, et al., 1975; Green and Keen, 1987). At both sites, fossiliferous organic sediments are interstratified with fluvial gravels deposited by the ancestral Solent River. The Pennington Organic Bed occurs between –3.9 and –5.3mOD and its molluscan and ostracod assemblages are typical of a shallow freshwater stream (or, possibly, an abandoned channel). The Stone deposits are estuarine in character, occur at +2mOD, and are overlain by a palaeosol. Given this difference in elevation, it is possible that the two deposits belong to different stages of the Ipswichian, or that the Stone organogenic sediments are older. If the first hypothesis is correct, the Stone deposit would have accumulated once rising sea-level promoted aggradation to the level of the higher terrace. This time-lag concept can also be applied to a correlation of both of these floodplain/inner estuary deposits with the outer estuary barrier beach/foreland sediments. Presumably the latter post date the former if their accumulation excluded estuarine conditions. These are very tentative interpretations that assume an approximately constant sea-level during their formation. (Keen (1995) has suggested the possibility of post-Ipswichian tectonic depression of the Pennington-Stone area, but admits that this is not an attractive hypothesis given the apparent evidence of contemporary uplift in the north-east Wight and south-west Sussex Plain areas.

Kellaway, et al. (1975) have attempted an explanation of the Pleistocene deposits of the West Sussex coastal plain by invoking the invasion of the western and central English Channel by a large (Anglian?) ice sheet. This, it is argued, may have become stagnant in the vicinity of the modern position of the south or east coasts of the Isle of Wight. Meltwater was discharged eastwards, but was confined by the rising ground surface of the South Downs. This created a proglacial Lake Solent, with associated overflow channels and glaciogenic sediments. Apart from providing a possible mechanism for the transport of erratics, there is little reliable evidence in favour of this hypothesis. It is not, therefore, considered further in this account.

6. Holocene Sea-Level Rise and Coastal Change

Much of the evidence of relative sea-level change during the past 5-12,000 years derives from the interpretation of sediment sequences recovered from shallow boreholes. In a limited number of localities, it has been possible to use cultural artefacts as a means of reconstructing coastal environmental change and obtaining relative dating of the sediments in which they occur. However, a more precise chronology has come from radiocarbon 14 (^{14}C) dating of buried organic deposits, together with palynological analysis of biogenic sediments. Although this has provided a valuable means of correlating the relatively few securely dated horizons within the Solent, there remain considerable uncertainties over inferred rates of relative sea-level change. The following account attempts a synthesis of the most reliable data, identifying a sequence of stages of Holocene sea-level transgressions and intervening regression. Site-specific detail is excluded in the interests of generalisation. This is available from the major references sources used, viz: Ackeroyd (1972); Allen and Gardiner (2000); Churchill (1966); Devoy (1987a, 1987b); Everard (1956); Godwin (1945); Godwin and Godwin (1940); Hack (1998, 1999); Hodson and West (1972); Long (1995); Long and Tooley (1995); Long and Scaife (2000, 2001); Long, et al. (2000); Mottershead (1976); Munt and Burke (1986); Nicholls and Clarke (1986); Tomalin (2000b and c); Velegrakis (2000); Wallace (1967, 1968, 1990) and West (1980). Earlier attempts at integration include Bray, et al. (1994); Carter, et al. (1999); Gale (1991); Tubbs (1999) and West (1980).

In terms of the more general context of changes during the Holocene, Anthony (2002) has discussed why there is dominantly sand accumulation on the French coast of the eastern English Channel and dominantly gravel barrier beaches on the English coast. He attributes this segregation to the inherited coastal morphology and lithology, to the orientation of the coastlines in relation to the Coriolis effect and in relation to westerly wind forcing.

Figure 2 attempts a reconstruction of the River Solent near the beginning of the Holocene, when sea-level was –35mOD. Table 2, based on Tubbs (1999) but including additional data, provides a diagrammatic summary that places the principal stages of relative sea-level change in the framework of Holocene environmental change and cultural development. It also gives an approximate timescale.

From evidence of the depth of the main buried channel of the River Solent (Dyer, 1975) sea-level has risen at least 46m since approximately 16000-14000 years Before the Present (yBP). All but 7m of this rapid recovery occurred before 6300 to 6400 yBP, with some 4.5m of sea-level rise taking place since 3700 to 3500 yBP. Thus, in the intervening period of 3,000 years sea-level rise rapidly decelerated, from an earlier maximum of 5-6mma^{-1} to less than 1mma^{-1}. In the most recent three millennia it has steadily increased from 1.5mma^{-1} to contemporary rates that may be close to those experienced in the early Holocene. Projected sea-level rise for the next century may achieve rates higher than any that have prevailed since the last interglacial. These figures should, however, be treated with considerable caution, as they are mean values that simplify the probable complex behaviour of Holocene sea-level. It is likely that recovery was not progressive, but was a sequence of relatively short transgressions (advances) and intervening, probably longer, regressions (retreats). Existing chronology is heavily dependent on litho- and bio-stratigraphy of Holocene sediments (up to 20m in thickness in optimum locations for accretion) which carry several interpretational problems. Amongst these are the possible removal of unknown thicknesses and sequences of sediments by erosion during regression phases, and that organogenic sediments are notoriously subject to post-formation dewatering, compaction and consolidation. Thus, assumptions of the contemporaneity of spatially separated sediment sequences or horizons based on relative elevation are unjustified. Temporal correlation of buried freshwater and brackish peats on the basis of their fossil pollen (palynological) "signatures" is also a hazardous approach. This is due to major differences in the dispersal potential of different tree, shrub and plant pollen, so that the pollen profile for any one location may be unique to that site.

With these difficulties in mind, the following principal stages of relative sea-level movement can be identified with a reasonable degree of confidence.

Stage 1, 10-6000 yBP

Sea-level invaded the eastern Solent, which was gradually widened by coastal erosion and landward migration of barrier benches. Invasion of the proto-Test Valley (lower Southampton Water) had occurred by approximately 7000 yBP. This is evidenced by the accumulation of alluvium, tufa and freshwater peat on the waterlogged valley floor between 9000 and 8300 yBP; the presence of beach deposits at –23mOD beneath Calshot Spit, and saltmarsh and mudflat accumulation resting on up to 4m of riverine deposits below the present day location of Fawley, dated to approximately 7000 yBP.

Between 8600 and 6800 yBP the land isthmus connecting the present day north-west Isle of Wight and Hampshire mainland was breached, creating a connection with the shallow but rapidly expanding Christchurch Bay. Sea-level at this time would have been –16 to –18mOD. Subsequently, tidal currents and wave action widened and deepened Hurst Narrows, introducing large quantities of gravel into the West Solent. The latter was rapidly widened, and the former channel of the Solent River deepened, in less than 2,000 years. Evidence of interbedded peat deposits at the base of a drowned cliffline at –11.3mO.D offshore Bouldnor, Isle of Wight, together with evidence of Mesolithic occupation, dating back to approximately 8000 yBP goes some way to confirm this critical event in the history of the Solent (Momber, 2000; 2002).

Evidence from Fawley gives a radiocarbon date of 6366 yBP for saltmarsh, and may indicate a short pause (stillstand) in sea-level rise.

Stage 2, 6-3600 yBP

Sea-level rise was interrupted by an apparent regression phase, with freshwater replacing saltmarsh at Hythe (Southampton Water) at circa 5500 yBP. Terrestrial peat also accumulated at Stansore Point (Western Solent) between 5320 (+/-200) and 3750 (+/-105) yBP, possibly in a lagoon site. Several other Sub-Boreal organic sediment horizons have been described from the Solent. These include (i) peats at –2 to –3.6mOD below Pennington Marshes, which may have accumulated below a seepage line at the base of a Solent River gravel terrace; (ii) buried peats in front of

Hurst Spit, which must have originally formed behind it, thus demonstrating that it has migrated at least 400m during the past four to four and a half millennia; (iii) peats, with frequent sub-fossil tree remains, ("submerged forests") on the contemporary inter-tidal shorefaces of Stokes Bay (Gosport), Hill Head, Southsea and several locations on the Isle of Wight; and (iv) freshwater peat at –2.8m at Dibden Bay (Southampton Water), dated at 5040 ∀60 yBP. Peats representing several regressive stages, punctuated by stillstands, are intercalated between minerogenic sediments infilling channels in the western Yar estuary, Isle of Wight, at –10.5m; -8.5m and between –5.4 and –2.8mOD.

Neolithic intertidal trackways, radiocarbon dated to 4920-4600 yBP are known from Yarmouth and Newtown Harbours and Wootton Creek, Isle of Wight, to depths between –2.9 and -1.60mOD. Peat which accumulated just above the tidal limit at Fawley occurs at –2.5mOD and has been approximately dated at 3600 yBP.

Although much of the above evidence points towards a Sub-boreal regression, it is possible that sea-level was stationery or slowly rising during this period. The buried peats detailed above may reflect the ability of estuarine sedimentation to keep pace with submergence. The evidence from cores below Dibden Bay reveal a thin layer of broken shells, silt and clay, overlain by a grey, silty clay, above an abrupt contact with the upper peat surface. This could indicate a short-lived phase of marine inundation, representing up to 1.7m of sea-level rise. Foraminfera from the upper clay reveals a low marsh to mudflat range of environments. A similar stratigraphy is also known from the lower Hamble. More detailed, integrated litho-, bio- and chronostrati-graphical research is required for more definitive evidence of sea-level oscillation during the Sub-Boreal.

Stage 3, 3600-3300 yBP

Although the evidence is not secure, there is a possibility of sea-level stillstand or major reduction in rate of rise during this stage. Intercalated lenses of shell debris, sand and gravel within grey silty clays may, however, represent sedimentation behind beach formations (or barrier washovers) during slow sea-level rise transgression. Submerged remnants of gravel barrier beaches at between –3.5 to –4.5mOD in the eastern Solent have been identified, thus suggesting that significant protection was afforded against the penetration of waves from Spithead and the English Channel during this period. A late Neolithic trackway built across saltmarsh at Wootton Creek, Isle of Wight, and possibly extending over Mother Bank, may belong to this period. Precise depths are of relatively little value in reconstructing the contemporary position of sea-level as the height-range of barrier structures would be a partial function of palaeotidal range and sediment availability.

Stage 4, 3300 yBP to Present

Commencing at approximately 3500 to 3300 yBP in the eastern and western Solent, and 3000 BP in lower Southampton Water, minerogenic mudflat and saltmarsh sediments overlying late Sub-Boreal buried peats indicate a period of relative sea-level rise. This has continued to the present, involving approximately 4.5m of marginal submergence and the progressive expansion of estuarine environment. There was probably some acceleration of sediment input associated with human deforestation of catchments drained by river systems tributary to the Solent. This may have commenced in the early Sub-Boreal, but pollen analysis suggests that it became a sustained factor in the Bronze Age at most locations. This influence may have contributed to estuary sedimentation keeping pace with sea-level rise and thus promoting saltmarsh development. Local variations in sediment stratigraphy post dating 3000 yBP have suggested the possibility that sea-level transgression was pulsed, but some of the erosional contact surfaces may reflect the interplay between high energy storm wave action occasioned by the increasing width of the major estuaries and the formation and occasional breakdown of protective barrier beaches and spits. Gravel barrier beaches would have initially migrated landwards with rising sea-level, but might have been segmented and eventually submerged during one or more excursions of accelerated sea-level rise. This may account for one or more banks, such as Horse Tail, in the eastern Solent, now between –4 to –3mOD below modern sea-level. Variations in sediment supply may also have contributed to episodes of barrier building and breakdown. The complex pattern of submerged banks in the eastern and central Solent, many of them consisting of closely fitting large cobbles and other clast types often cemented together naturally, may provide further details of shoreline change between approximately 3000 and 2000 yBP. Some occur at depths of nearly –20mOD, and several would appear to have come to rest on submerged eroded platforms between –10 and –5mOD (e.g. Pullar Bank, south of Selsey, and the foundation substrate of Horse Sand Fort). These either represent ancestral abandoned multiple barriers of earlier Holocene age or involve modern redistribution of Solent River terrace deposits.

Evidence from Langstone Harbour reveals late Neolithic (mid Sub-Boreal) terrestrial peats at between –1 to –0.5mOD. Contemporary organic sediments from the Quarr-Wootton (Isle of Wight) foreshore and lower Southampton Water are between –2.5 and –3mOD, thus suggesting that brackish conditions did not occupy much of the Langstone shallow tidal basin until approximately 2000 yBP. [This excludes the main incised channels in Langstone Harbour, where buried freshwater peats at –11 to –14mOD have been dated to between 8000 and 6800 yBP]. Perhaps barrier breakdown had to occur before Langstone Harbour could be invaded by late Holocene sea-level rise; and this observation may also apply to other harbours in the eastern Solent, notably Portsmouth, Chichester and Pagham. However, a series of incised channels within the main Langstone Channel, cut to a maximum depth of –8.75mOD, suggests the possibility of one, or several, earlier events of barrier breaching and reformation at the basin entrance. Bronze Age artefacts are known from elevations between +0.75 and +1.75mOD from occupation sites on islands in Langstone Harbour, thus confirming the above timescale but also suggesting the possibility of subsequent local tectonic or isostatic elevation. The latter is a factor that might explain non-systematic or local displacements of Holocene sediments throughout the Solent region.

Several authors have suggested that there was a sea-level transgression in the mid to late Romano-British period. This is based, in part, on the presence of earlier Roman artefacts occurring below estuarine deposits at Southampton Docks and probable Roman occupation of the Mixon, Malt Owers and The Dries, south of Selsey. All three of these latter features are now submerged reefs and rock outcrops. However, Roman artefacts on Middle Ryde Bank may result from vessel shoaling and cargo offloading. Apparent evidence of up to 3m of sea-level rise since the building of Fishbourne Palace, Chichester, in the second century AD may be misleading, as it was built adjacent to an artificially dammed lagoon-like inlet at the head of Chichester Harbour. A brief sea-level stillstand may have occurred between the fifth and tenth centuries, but accompanied by rapid coastal recession at exposed sites such as the apex of the Selsey peninsula. Extensive flooding of the lowland margins of the eastern and western Solent is well documented for the tenth and fourteenth centuries AD, as a result of barrier destruction. However, these relatively catastrophic coastline changes may have been the product of a series of very high magnitude storms superimposed on a background rate of sea-level rise of approximately 1-1.5mma^{-1}. This rate has prevailed for much of the last 3,000 years, until the acceleration of recent decades.

7. Historical Development of Barrier Beaches and other Accretion Structures

Parts of the open coastline of the Solent are defined by substantial accumulations of gravel and mixed gravel and sand. Some extend several hundreds of metres inland from the backshores of modern shingle beaches and are composed of various sets of parallel or sub-parallel low ridges and intervening swales. The largest examples, such as Browndown (Gosport) and Sinah Warren (Hayling Island) have a planform similar to cuspate forelands. The other major accretion structures are sand and shingle spits that have developed across the entrances of the majority of estuarine inlets. Most of the latter occur as pairs, and appear to have grown in opposite directions to effect narrowing and deflection of estuary mouths.

The most substantial spits are Hurst, at the entrance of the western Solent, and Calshot, at the western mouth of Southampton Water. Both are known to have developed in response to coastal erosion during the early to mid-Holocene sea-level rise, and to have been relatively stable in their size, position and planform in subsequent millennia. (Some features have become increasingly mobile in recent decades.) Most, if not all, of the smaller examples are likely to be much more recent in their origins. Historical evidence shows that there have been fluctuations in their shape, volume and stability in recent centuries (Tubbs, 1999). Examples include (i) East Head, at the mouth of Chichester Harbour, which may have experienced cyclical growth, decay and even temporary extinction [the present spit dates from the mid-eighteenth century]; and (ii) Warren Farm Spit and Needs Oar Point, at the western entrance to the Beaulieu River, characterised by significant episodes of growth over the past 500 years. However, some have shown very little change over the past four hundred years of cartographical record, such as Calshot Spit and Hook Spit, to the south-east of the mouth of the Hamble.

All of these spits are the product of the storage of sediments supplied from littoral drift pathways, although several authors have postulated that some inputs from offshore to onshore movement may also occur. More problematic in origin are the several examples of 'double' or paired spits at estuary mouths. In some cases there are significant contrasts in size, morphology and sediment composition between each spit, as at Bembridge and Chichester Harbours. In others, they are comparable, e.g. the spits confining the entrance to Newtown Harbour, and King's Quay (Isle of Wight). In most examples convergent and – usually – apposition spit growth has been interpreted as evidence of convergent littoral transport pathways. This involves short distance reversal of the net direction of longshore transport on one side of the estuary inlet. This may occur along a morphologically uniform length of beach, where there is no landform evidence for drift divergence other than a zone of erosion. Good examples are the apparently quasi-stationary drift divergence boundaries some 600 metres westwards of the entrances to Langstone and Chichester Harbours. Eastwards movement away from these points feeds Eastney and Black Point spits, respectively. The strongly recurved form of both spits, together with evidence of progressive curvature of East Head, indicates the role of wave refraction and complex interaction of waves and tidal currents with large partially submerged sandbanks adjacent to each channel, created by a combination of sustained longshore and onshore sediment transport.

Whilst drift convergence may be a viable explanation for several examples of paired spits within the Solent system, it cannot apply to all of them. The opposed growth of spits that have constricted the entrance to Portsmouth Harbour provide a particular problem. Under contemporary conditions of longshore sediment transport, inputs from updrift are very small and both spits were apparently stable prior to their use as the foundation for defence works in the fifteenth century. In the case of Pagham Harbour, West Sussex, cartographical evidence back to the late sixteenth century indicates that the southern spit has experienced significant dynamic change whilst its smaller northern counterpart has been comparatively stable. It is possible that the latter is fundamentally the relict of successive breaches of a barrier beach or spit that has grown north-eastwards. However, sediment supply in this case is from offshore, probably from abandoned former ebb-tidal deltas, as well as updrift, and the northern spit owes something of its form to localised counter-drift.

The Pagham spits point to the strong possibility of a significant contribution from barrier beach transgression in historical times. This is also apparent from the recent behaviour of Hurst Spit, and may be applicable to many other accretion structures in the Solent. Tubbs (1999) has made a provisional analysis of map and chart evidence for the initiation and growth of several depositional forms within the Solent. He notes that the gravel forelands of Gilkicker and Browndown (Gosport) do not appear until the late seventeenth centuries. They, rather like Sinah Warren (Hayling Island), then prograded rapidly during the succeeding 130-150 years through the addition of several sets of closely-spaced beach ridges. In the case of Browndown, growth commenced with a spit that deflected the mouth of the River Alver east of Gilkicker Point. Gilkicker foreland eventually became contiguous with the earlier Haslar spit. By contrast, sustained growth of the cuspate plain at Sinah Warren well into the twentieth century actually promoted a new recurved spit form at the mouth of Langstone Harbour.

There is no definitive evidence of the source of shingle that has built these foreland features. This is also true of a similar, but older, arcuate accretion plain to the immediate south-east of the mouth of the river Hamble. Shingle ridge topography is less well preserved here, but a link between this sediment store and the subsequent development of Hook spit might be conjectured. As feed from longshore drift is modest in some of the examples mentioned, it is tempting to explain their construction as a result of regular pulses of offshore to onshore shingle transport and, indeed, this provides the only viable explanation of the speed and magnitude of growth. Each ridge is likely to be the product of one or more events of storm sedimentation. In many cases, beach cannibalisation and coast erosion updrift can provide reasonable explanations.

Evidence for transgressive barrier beach development within recent centuries is available from numerous locations and cannibalisation of earlier barriers may have sustained the process of barrier creation and breakdown throughout the late Holocene (Section 5). However, it is becoming apparent that large quantities of shingle have been moved onshore very quickly as a result of one or more storms of exceptional magnitude (e.g. 1014, 1085, 1099, 1270, 1284, 1298, 1430). These events appear to have promoted barrier-like sedimentation, in some cases causing permanent blockage of pre-existing small estuarine inlets, such as the Mopley Stream and Dark Water, both on the north-western Solent shoreline. Stanswood, on the Mopley, is known to have been a port in early medieval times. In these, and other cases, shallow lagoons have been subsequently infilled, both naturally and as a result of land claim. There may be other similar, but as yet undocumented, examples such as Elmore Lake (Lee-on-the-Solent); Meon (Titchfield) Haven; the Stone Stream, near Beaulieu, and Seaview Duver, North-East Isle of Wight. Some inter-tidal shingle and sand foreshores are exceptionally wide and may be partially understood as the product of one or more periods of sustained (if pulsed) off- to onshore transport that nonetheless failed to generate true barrier structures. An alternative plausible explanation is that these features might be relict, but partially re-worked, ebb tidal deltas that accumulated at former small tidal inlets. Reworking has created onshore transport in the form of translational swash bars, a process that may still be in progress. Examples include most of the shoreline between Calshot and Stanswood and the Hill Head to Warsash foreshore.

The accretion and breakdown of the barrier beach at Medmerry, Selsey, has been documented in several sources. Although there is disagreement over details, it is accepted by most researchers that the former island of Selsey was linked to the mainland by a barrier structure from at least the eighth century AD. It is likely to have been breached and reformed on several occasions over the subsequent centuries. Several 'super' storms are recorded for Selsey (and Hayling Island) between 1014 and 1490, some of them accounting for significant erosion and permanent inundation. The earliest reliable maps of the Selsey peninsula indicate that the channel (rife) that connected Pagham Harbour with Bracklesham Bay had been closed at Medmerry by 1587, and was still in place in 1644. A number of partial breaches of the Medmerry shingle barrier have occurred since the early eighteenth century. This process of overtopping, crestal breaching and periodic reconstruction has been active up to the present, but with management input since the 1970s to offset shingle losses.

Wallace (1990) has argued from map and documentary evidence that the open coastlines of Hayling and Portsea Islands were set back several hundred metres, compared to their present positions, up to at least the mid fifteenth century. He proposes that an ancestral barrier beach, dating perhaps to approximately 3000 years BP and extending from Malt Owers to Southsea, was breached in stages between the eighth and fourteenth centuries. The existing barrier beach structure was therefore created between the mid-fifteenth and early eighteenth centuries. Southsea Castle was built in the early sixteenth century on the position of this migrating barrier, thus fixing its position and creating the modern coastline salient at this point. At approximately the same time, the Great and Little Morasses were created as lagoonal swamps behind this barrier structure, which must have reconnected with the pre-existing Old Portsmouth Spit. Borehole evidence from Wimbledon Park, Southsea, on the site of the Great Morass, suggests several alternating events of shingle overtopping and organosediment accumulation.

Both Wallace (1990) and Tubbs (1999) have inferred sea-level excursions from inferred barrier breakdown and landward migration over the past 1,200 years. Perhaps the most convincing is a rise of relative sea-level, of up to 1m above where it is at present, between the late eleventh and early fifteenth centuries. However, the evidence is not conclusive, and it is difficult to reconstruct subsequent regressions. It may be more realistic to suppose that barrier breakdown, inlet blockage and other apparently rapid changes affecting inshore sedimentation were the product of the well-documented series of major storm surges, previously mentioned. The fact that major changes during this period, creating both submergent and emergent features, are more pronounced in the eastern Solent reflects its exposure to higher wave energy; low hinterland relief, and substantially larger nearshore/offshore sediment stores that are available for redistribution.

8. Summary

- The ancestral Solent River drained a large catchment throughout the Pleistocene stage of the Quaternary Period, to which all of the modern rivers discharging into the Solent, Christchurch and Poole Bays were tributary. Its principal legacy is a descending sequence of gravel covered terraces, which record the complex adjustment of the Solent River to changing climate and fluctuating sea (base) level. It appears that it was a major tributary of the "English Channel" River, which it joined south and east of the present day Isle of Wight.
- High sea-levels during Middle and Late Pleistocene interglacial stages cut extensive shore platforms extending to the toes of the South Downs and Portsdown Hill. Mantled by subsequent periglacial deposits these platforms now form the SE Hants and West Sussex Coastal Plain. Several fringing raised beaches developed at different levels provide evidence of the marine origin of the plain. However, it is not yet possible to correlate these with any of the Solent terraces, as the latter have not provided opportunities for dating so far. Nowhere are fluvial and marine surfaces co-adjacent.
- The Upper Solent River was diverted to a south-eastwards course via one or more breaches through the formerly continuous Wight-Purbeck Chalk ridge. This is likely to have occurred during the last (Devensian) glacial stage of low sea-level, but may be older. The lower Solent River continued to flow eastwards across the present site of Christchurch Bay and along the main axes of the West and East Solent.
- Final dislocation took place in the early Holocene (post-glacial) period, when rapidly rising sea-level flooded the East Solent and created the West Solent waterway by inundating Christchurch Bay and removing the 'land bridge' connecting the present- day north-west Isle of Wight and the opposing Hampshire shoreline. This is likely to have been achieved between 8600 and 6800 yBP. Before 6000 yBP estuarine conditions occupied the East and West Solent and lower Southampton Water. Between 6000 and 3500 yBP sea-level rise decelerated and may have withdrawn from higher and marginal parts of the estuary. The re-advance of sea-level commenced between 3500 and 3000 yBP,

and has achieved some 4.5m of submergence up to the present. The detailed record of relative sea-level rise is preserved in sequences of submerged sediments. These include several coastal and terrestrial peat deposits, a few of which have been radiocarbon dated. Ambiguous evidence of submerged barrier beaches or barrier islands and foreland/spit growth in the eastern Solent provides additional evidence of mid to late Holocene sea-level rise. Archaeological and documentary evidence suggests one or more periods of rapid submergence during the past 2,000 years.

- Because of the complexity of the environments coupled with a paucity of data and several difficulties associated with the interpretation of all types of evidence used in the reconstruction of the Solent River, it is not yet possible to provide a definitive detailed history.

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	STAGE NAMES	GLACIAL EPISODES	INTER GLACIALS INTER STADIALS	0^{18} STAGES	APPROXIMATE DATES 10^3 YRS BP
LATE QUATERNARY	FLANDRIAN			1	10
	DEVENSIAN LATE	LOCH LOMOND GLAC.			
			WINDERMERE I.S.		14
	DEVENSIAN	DIMLINGTON GLAC.		2, 3, 4,	
	MIDDLE		UPTON WARREN I.S.	5a, b, c, d.	
	EARLY		CHELFORD I.S.		
	IPSWICHIAN		IPSWICHIAN I.G.	5e	122; 128-132
MIDDLE QUATERNARY	WOLSTONIAN COMPLEX		MARSWORTH I.G.?	7? 6, 7, 8	
	HOXNIAN		HOXNIAN I.G.	9, 10, 11	297-302; 440-428
	ANGLIAN	LOWESTOFT GLAC.			
			CORTON I.S.?	12, 13, 14	
		NORTH SEA DRIFT GLAC.			
	CROMERIAN		CROMERIAN I.G.	15	542-562
EARLY QUATERNARY	BEESTONIAN	GLACIATION IN WEST MIDLANDS & N. WALES		16	592-630
	PASTONIAN		PASTONIAN	17	627-687; 647-718
	PRE-PASTONIAN	GLACIATION "			
			?		
		GLACIATION "			
			?		
		GLACIATION "			
			?		
	BAVENTIAN	GLACIATION IN NORTH SEA REGION			
	BRAMERTONIAN				
	ANTIAN				
	THURNIAN				
	LUDHAMIAN				
	PRE-LUDHAMIAN				

I.G. = Interglacial
I.S. = Interstadial

Table 1: Classical Stages of the Quaternary (note Flandrian = Holocene) (Mannion, 1991)

Years BP	Stages Before Present	Events	Cultural Periods
		Sea-level rise accelerates (4-5mma^{-1}) in late	Modern
		C20th.	Medieval
1000 –	Sub-Atlantic	} Medieval transgression (sequence of major	
		} storms, and erosional losses)	
		Regression(?) Stillstand of sea-level(?)	**Anglo-**
2000 –		} Possible sea-level transgression (1-2m?)	**Saxon**
		} Langstone, Chichester and Pagham Harbours	Romano-
		} inundated; barriers breached and some	British
		inundated	
		] Sea-level rise at 1-2mma^{-1}	
3000 –		] Proto-Barrier formation	Iron Age
	Sub-Boreal	Sea-level at approximately –4.5mOD	
		} Probable sea-level stillstand or regression (peat	
4000 -		} horizons and "Submerged Forests" of modern	
		} foreshores). Enhanced sedimentation due to	
		} catchment deforestation	Bronze Age
		] } Sea-level continues to rise, but at rate of no	
5000 –		] } more than 1-1.5mma^{-1}. Adjusted mudflat	
		] and saltmarsh sedimentation in Southampton	
		] Water and West Solent. Brief episodes of	Neolithic
		] replacement of salt marsh by freshwater	
6000 -	Atlantic	] conditions	
		Upper Southampton Water created by continuing	
		sea-level rise	
		} Rapid rise of sea level, interrupted by brief	
		} stillstands. Sea-level at –7.0mOD at	Mesolithic
7000 –		} approximately 6,300 BP	
		East and West Solent from contiguous channel	
		Invasion of Western Solent and final separation of	
8000 –		Isle of Wight from mainland	
	Boreal	Possible brief regression of sea-level	
		Marine penetration of lower proto-Test	
		(Southampton Water) Sea-level at approximately	
9000 -		–25mOD	
		Inundation of lower reaches of Solent River	
		tributaries in east Solent	Upper Palaeo-
10000 -	Pre-Boreal	Invasion of eastern Solent approaches. Sea-level	lithic
	Late	between –28 and –30mOD	
11000 -	Devensian	Incised palaeochannels of Solent River and major	
		tributaries	

Table 2: Holocene Sea-level Chronology, Solent Area (mostly adapted from Tubbs, 1999)