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Facies analysis and diagenesis of late Pleistocene shoreline sands, Saunton, North Devon

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Abstract

The succession at Saunton is composed of all the major elements of Pleistocene coastal stratigraphy from across north Devon. The aim of this study is to analyse and interpret the depositional environment of the laterally variable late Pleistocene sedimentary succession at Saunton, using facies analysis. This knowledge is used to infer local relative sea level changes from patterns of transgressions, normal, and forced regressions and an attempt is made, using sequence stratigraphy, to constrain the relative ages of the deposits based on marine oxygen isotope stages. Petrographic observations of the different facies and grain types are used to evidence the palaeo-environmental interpretations and to describe the diagenetic alteration of the rocks. Previous literature presents a hypothesis for the palaeoclimate during the time of deposition of the rock units. This thesis therefore endeavours to test whether deposition occurred within a temperate climate during an interglacial period of geologic time using palaeontological evidence. Field observations of sedimentary structures, grain size and type indicate 5 separate sandstone facies which indicate deposition within a near shore shallow marine environment from sub-tidal shoreface to backshore/aeolian dune sub-environments. The arrangement of these suggest a pattern of transgression, normal regression, forced regression before another period of transgression. This, combined with previous models for sequence stratigraphic base level curves, suggest deposition of the raised shoreline deposits either side of the palaeosol horizon to be marine oxygen isotope stage (MIS) 7 and 5 in age. With this knowledge and the use of a final stratigraphic model which accounts for lateral variations in facies, the age of the palaeosol, solifluction and glacial head deposits are tentatively constrained to MIS 6 and 4 respectively. Unfortunately the degree of diagenetic alteration of the rock, makes bioclast species identification complex and palaeo-climate reconstructions difficult. However the inferred MIS ages of the units present evidence for deposition under interglacial conditions.

Introduction

This chapter aims to introduce the project by highlighting the study area in relation to the UK. An examination of previous literature on the raised shorelines of Saunton, North Devon and south-west of England highlights work that can be developed and possible areas for further study, and places the thesis into context of these previously studied raised shorelines. This chapter is also utilised to explain how the field and laboratory work was undertaken.

Aims

The aim of this study is to interpret and reconstruct relative changes in sea level from facies analysis on a sedimentary succession at Saunton, north Devon. This thesis also endeavours to test the palaeo-climate hypothesis that the rocks were deposited within a temperate climate during an interglacial period of geologic time.

Objectives

The objectives of this work were to,

- 1) Use field and petrographic observations to determine the depositional palaeoenvironments of the rock units.
- 2) To identify patterns of relative sea level changes since the beginning of the formation of the sequence. Studying the petrography of the rock units acts as further evidence for the environmental conditions and the sea level story interpreted from fieldwork, using diagenesis and micropalaeontology to indicate water table levels and changing temperatures respectively.

Background

Location

This study was undertaken on an approximate 500m long outcrop along the cliff face at Saunton. Figure 1 highlights the location of Saunton relative to the UK; it is located in north Devon, England. The black rectangle within the inset illustrates the exact section of the cliff under analysis. Figure 2 shows this section closer and draws attention to the headlands used as marker points within field observations, which are referred to in subsequent chapters.

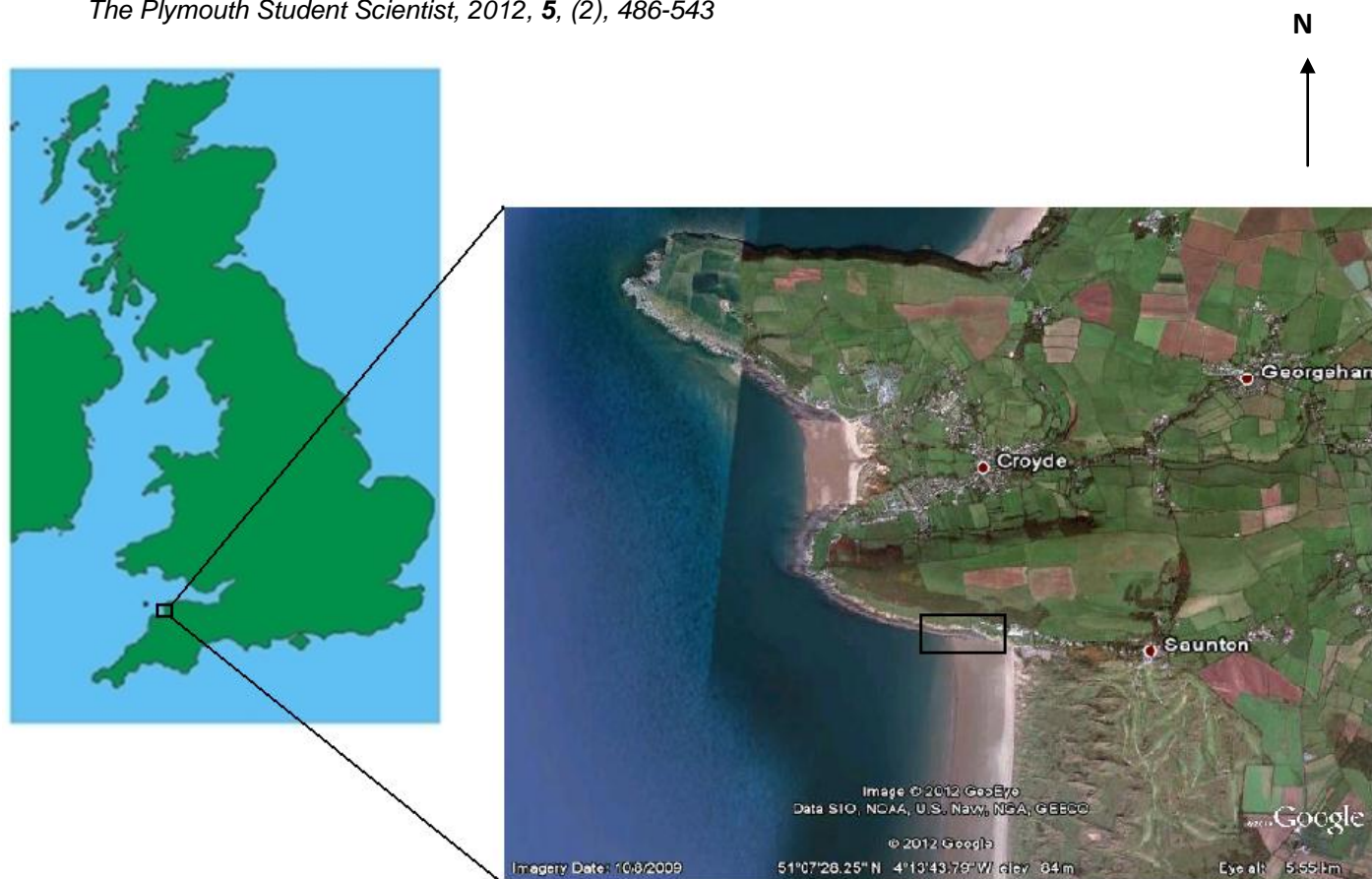


Figure 1: Location map highlighting the location of Saunton relative to the UK See figure 2 for inset. Grid ref: SS 44021 37858 – SS44496 37728 (Google maps, accessed 20/01/12).



Figure 2: Aerial photograph of cliff section at Saunton highlighting the headlands used as marker points.

Stratigraphy of units

The outcrop at Saunton is comprised of all the major elements of Pleistocene coastal stratigraphy seen in north Devon (Durrance *et al.*, 1982).

The exposed geology at Saunton is underlain by bedrock of steeply dipping Devonian sandstones and shales which are cut across by a shore platform. Above this, to the west of the study section, rests a large erratic boulder of pink gneissose granite (4.5-5m OD), seen in figure 3. The origin of this boulder is widely debated within the literature (Bates *et al.*, 2003; van Vliet-Lanoë *et al.*, 2000).



Figure 3: Image showing the pink gneissose granite erratic bolder (taken facing east).

The boulder is overlain by raised shoreline material consisting of sand with some pebbles and shell fragments (consisting of much erratic material). The raised shoreline deposit reaches up to 2m thick in places, and fossils present in the unit (marine mollusca) are thought to be indicative of a temperate (interglacial) climate (Durrance *et al.*, 1982; Gilbert, 1996). Moving upward through the stratigraphical sequence the rock type changes into a “sandrock” thought to be cemented aeolian sands. However, in more recent literature, it has been interpreted as being deposited within a shallow marine environment during rapid emergence (Scourse *et al.*, 2001.) Above this sits a thick section of “head” (approximately 20m) taken to be the result of a solifluction in a periglacial regime (Harris, 1987 in Boardman, 1987). This research indicates that the stratigraphic sequence at Saunton include Quaternary age rocks which lie on top of Devonian bedrock, separated by an angular unconformity.

Much of the work carried out at Saunton is over a century old now. Sedgwick and Murchison first recognised the raised beach deposits within the stratigraphic sequence at Saunton in 1836. Their stratigraphic research lead to the conclusion that most of the beds were wave lain in origin. Since 1836 the section has been re-examined a number of times. A few years later, De la Beche (1839) completed

further stratigraphic studies concluding the rocks to be mostly marine in origin. The first disagreements with these findings were discussed by Hughes (1887) who considered the upper part of the section to be terrestrial, a fossil aeolian dune to be exact. Prestwich (1892) furthered this work with palaeontological investigation on the beds, finding marine bivalves in the lower sands and terrestrial gastropods in the upper sand units, ruling them as marine and fossil dunes respectively. Stephens (1966) agreed with this work suggesting the changing depositional environments through the sequence were attributed to transgressive and regressive phases of an interglacial sea level. Greenwood (1972) used modern aeolian and wave-laid sand classifications and size frequency statistics as a model for identifying the depositional environments of the Pleistocene sands within the sequence. His work concluded (tentatively) that the preserved sands of Saunton were most likely to be aeolian in origin forming the backshore of a larger scale backshore-foreshore environment running further along the ancient north Devon coast. Gilbert (1996) completed further facies analysis here, his interpretations mirrored the earlier work (Williams, 1837; De la Beche, 1839; Prestwich, 1892) suggesting the sequence to be divided into marine and terrestrial facies. Figure 4 synthesises Gilberts (1996) model and his suggested environmental origins. Gilbert (1996) and Campbell (1998) both suggest the presence of a basal conglomerate above the Devonian shore platform.

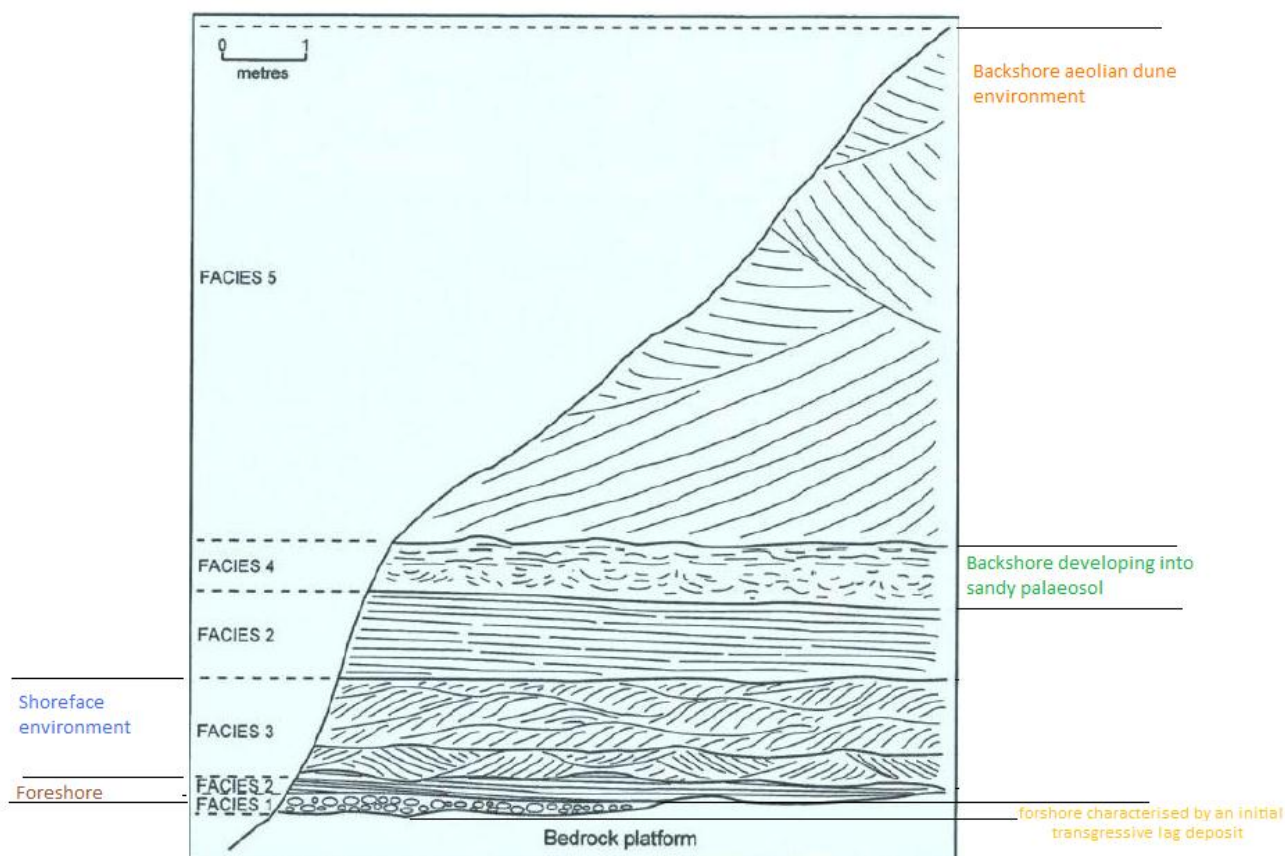


Figure 4: Gilberts proposed stratigraphic sequence of Saunton. (edited from Gilbert, 1996).

Age of units

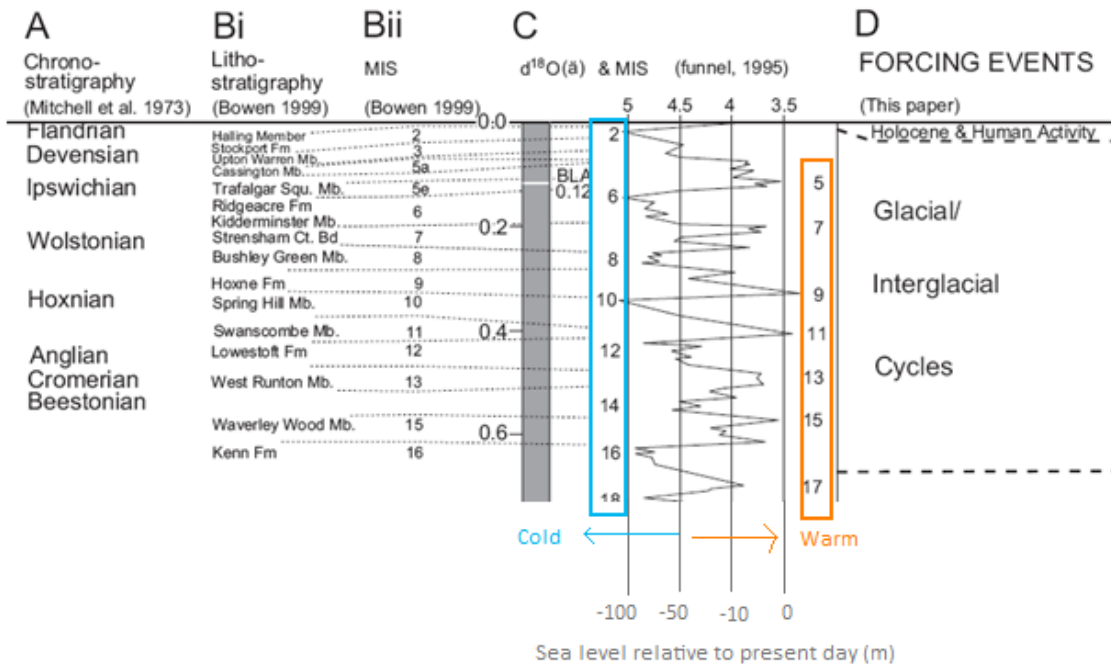


Figure 5 – Diagram showing stages of the Pleistocene with their corresponding marine oxygen isotope stage and sea level fluctuations (Edited from Rose, 2010). MIS = Marine oxygen isotope stage.

Figure 5 shows how odd marine oxygen isotope stages (MIS) represent warmer (interglacial) periods of geologic time, low delta $\delta^{18}\text{O} / \delta^{16}\text{O}$ ratios (in the ocean) provide a proxy for these and are linked to higher sea levels due to lack of land ice cover. This is because the lighter $\delta^{16}\text{O}$ isotope is preferentially evaporated to the $\delta^{18}\text{O}$ isotope. During even MIS stages the climate is relatively colder and the evaporated $\delta^{16}\text{O}$ isotope is precipitated from the atmosphere as ice. This explains the high $\delta^{18}\text{O} / \delta^{16}\text{O}$ ratios of the ocean and lower sea levels when land ice is dominant during glacials (Campbell *et al.*, 1998).

The climate of the north Devon coast during the deposition of these rocks is conflicted by various evidence in the literature; some authors suggest an interglacial origin and others a glacial one. Campbell *et al.*, (1985) explain how studies are increasingly correlating the deep-sea oxygen isotope framework (seen in figure 5) with sedimentological evidence for changing climate and environments using geochronology and other dating techniques.

Andrews *et al.*, (1979) carried out some of the earliest studies on raised beaches of the British Isles using amino acid geochronology, specifically, D/L ratios (alloisoleucine/isoleucine) on marine mollusc shells of the palaeo-beach units. His studies included Saunton and they concluded that the raised beaches formed over two or three higher sea level events but were unable to establish whether they were a whole or part of MIS 5 or maybe in part from an earlier interglacial. Bowen *et al.*, (1985) furthered this work using the same dating techniques but more specifically on fossil beaches in the south-west. They concluded the main raised beach deposit of Saunton and Croyde to be dated back to marine oxygen isotope stage (MIS) 7. More advanced dating techniques were used by Scourse (1996) who utilised

thermoluminescence dating on the littoral sands and AAR (amino acid racemisation) on molluscs contained in the units, also deduced that the raised beach was formed in

an interglacial (warm) climate, akin to the studies mentioned previously. These conclusions were further evidenced by the ecological requirements of the *Talitrus saltator* (Montagu) sandhopper found within the succession. Scourse and Furze's (2001) study of raised beach sequences on the shores of the Celtic Sea and English Channel also concluded that deposition occurred at or during a regression, after interglacial eustatic highstands (that are characteristic of temperate stages of geological time.) Bates *et al.*, (2003) used a variety of dating methods that included U-series dating, amino-acid geochronology and biostratigraphy on terrestrial formations of Pleistocene marine and periglacial deposits along the English channel, their conclusions mirrored that of Bowen *et al.*, (1985), Durrance *et al* (1982) and Scourse and Furze (2001) suggesting the rock units here can be identified as

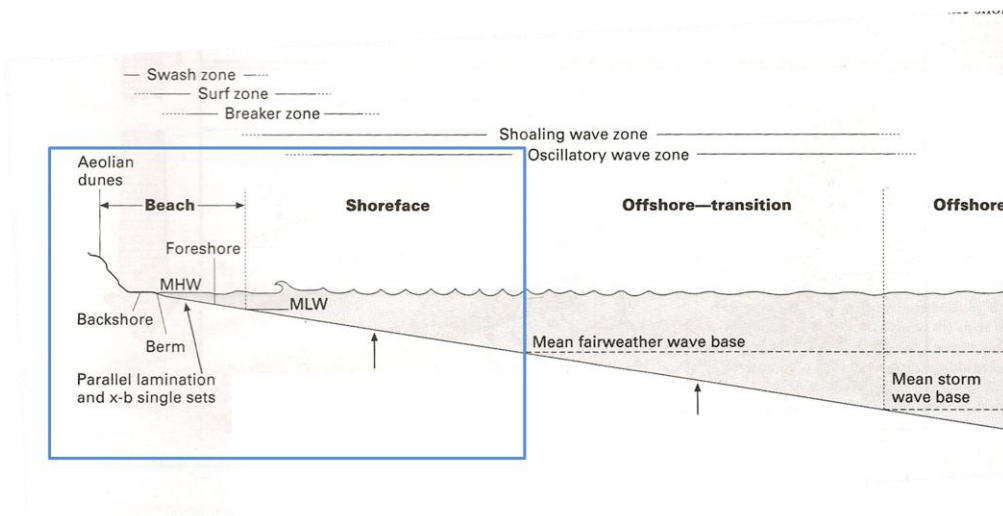


Figure 6: The depositional environmental model suggested by Scourse and Furze, 2001; Gilbert 1996 (edited from Reading, 1996).

deposits of the last three pre-Holocene temperate marine oxygen isotope stages (stages 9, 7 and substage 5e) forming over several interglacial highstands. Gilberts (1996) work agrees with this, he used luminescence dating on quartz grains from both the marine and aeolian sediments, dating the deposition to be interglacial, between MIS 5e (~120Ka yrs BP, Ipswichian) and 4 (~70ka) respectively. His data suggests the units to be slightly younger than that obtained from Scourse and Furze's (2001) work but never the less to have been formed during or just after an interglacial. The main authors who oppose this are Eyles and McCabe (1991) who suggest the raised beach sequences are representative of arctic shore face facies related to glacio-isostatic depression when in a glacial low stand.

Scourse and Furze's (2001) sedimentological investigation concluded that the quaternary stratigraphy of Saunton is consistent with the palaeoenvironmental model deduced from the stratigraphic sequence at The Berry Head cave complex, South Devon; interpreted to represent foreshore -backshore-dune sequence environments, highlighted in figure 6. Fitting with Gilbert (1996) whose facie interpretations at Saunton show evolution through a shallow marine environment. van Vliet-Lanoë *et al's.*, (2000) paper re-examined the stratigraphy and age of middle and upper Pleistocene palaeo-shorelines of the English channel. Figure 7 highlights the stratigraphic sequence they interpreted for Saunton. The dating technique used on the section at Saunton was that of ESR (electron spin resonance dating) on infratidal sands. The paper correlates successions from across Barnstaple Bay including; Baggy point, Croyde, Saunton, Fremington and Westward Ho!

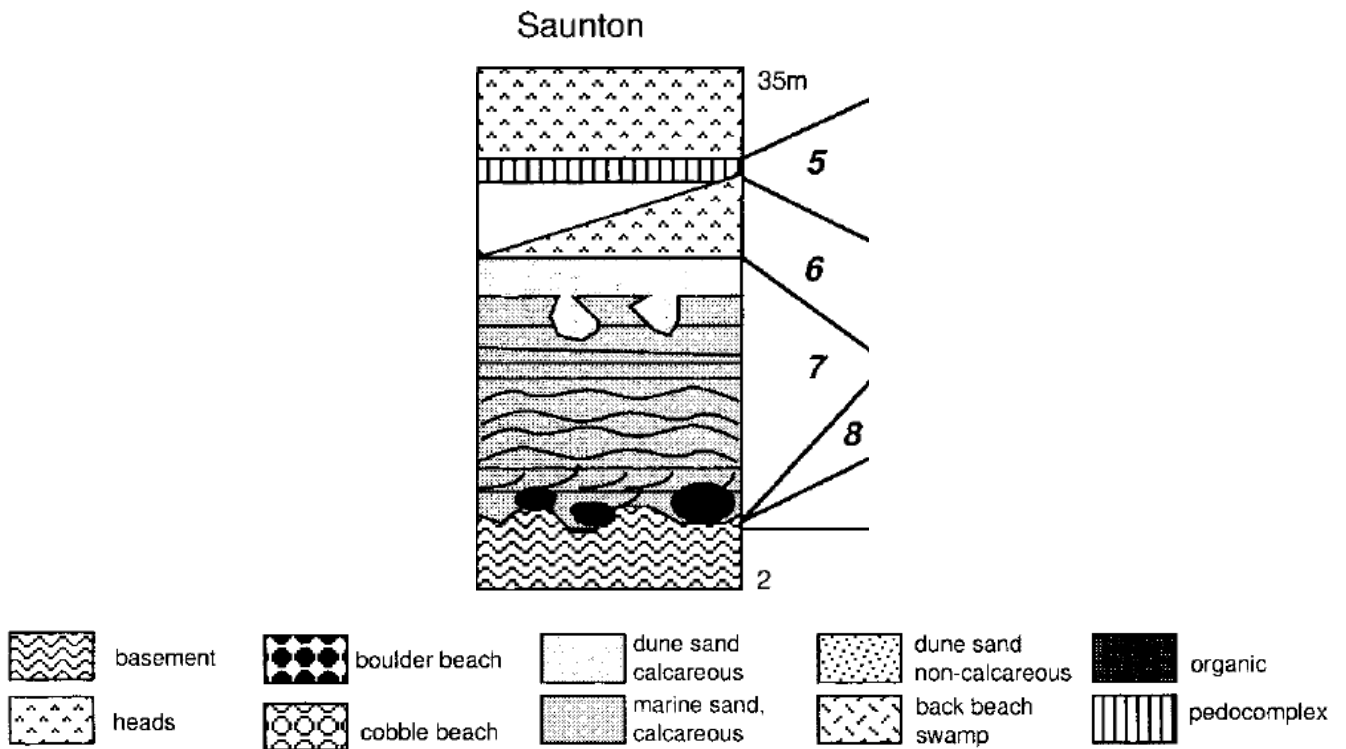


Figure 7: Stratigraphic log and corresponding oxygen isotope stages (MIS) (edited from van Vliet-Lanoë *et al.*, 2000)

The log illustrates lateral variations in the facies within the sequence. Like much of the earlier work (Williams, 1937; De la Beche, 1839; Prestwich, 1892; Gilbert 1996) the sequence depicts a vertical change from marine to terrestrial sediments. It is also suggested the raised marine terrace corresponds to the interglacial (OIS 7) concurring with other work (Bowen *et al.*, 1985; Scourse and Furze, 2001). The head is correlated to represent formation during the glacial period of OIS 6 with the pedocomplex forming during the next interglacial in OIS 5.

The sequence interpreted by van Vliet-Lanoë *et al.*, (2000) differs slightly from that of Gilbert (1996) with the inclusion of recent dissolution pits in the marine sands and the interpretation of the pedocomplex above the dune/head facies association instead of below.

There appears to be a lack of literature surrounding the diagenesis of the Saunton outcrop. However there have been studies upon similar carbonate concretions (to

those seen within the palaeosol horizon at Saunton) at other localities across the globe (Cavazza *et al.*, 2009). This thesis therefore aims to begin analysis of diagenesis upon the rock succession as well as to examine stratigraphic, petrologic and micropalaeontological evidence from the sedimentary succession outcropping at Saunton, north Devon to test the hypothesis that they formed in a temperate environment during an interglacial period of geologic time rather than forming in a colder climate relative to that of the modern day during glacial cycles.

Methods

Facies analysis was undertaken at the study site of Saunton, North Devon. Field descriptions containing information regarding sedimentary structures, palaeontology, grain type and size were made for the individual units within the section. This information was used for the interpretation of the separate facies in terms of process and depositional sub-environments. This information combined, painted a wider picture of the complete depositional setting and how it has changed through geological history. This data collection created an opportunity to create five sedimentary logs from across the section, allowing for the identification of changes in facies and therefore depositional environments through space and time. Further allowing for the interpretation of changing relative sea level in terms of regressions and transgressions. The relative location of each can be seen in figure 8.

To evaluate palaeoshoreline and palaeoflow directions a compass clinometer was used to measure thirty dip directions of bedding planes of the beach facies (planar horizontally laminated sandstones) and thirty dip and dip directions of parting lineations on the same facies respectively. The number of measurements recorded in the field (thirty) were decided upon as sufficient enough to give an accurate vector mean (Tucker, 2003). This data was collected to investigate whether flow patterns correlated to the regressive and transgressive phases at the time of deposition as well as being a helpful indicator in facies interpretation.

The maximum height of individual sets of the trough cross beds of the subtidal shoreface facies were measured, drawn up and correlated in the hope of finding a trend in flow depth and velocity across the rock sequence at this period in geologic time. This information provides an idea of the conditions in which the sediment was deposited and where the maximum flooding surface lies within the unit.

To investigate the internal structure and components of the rock, samples (no smaller than the size of a fist) were taken from each facies at the location where each sedimentary log was recorded; using a chisel and hammer. The rock was labelled with a unique code, an arrow indicating the "way up" and placed in a labelled bag to keep them separate from one another. The way up arrow being important during petrographic interpretation; as noticeable changes in cements or grains may be able to be explained by changing conditions moving up or down the sequence. Samples were also taken to examine the cements and level of diagenesis of the rock. Thin sections were cut perpendicular to the bedding planes and were impregnated with resin to increase their grain stability before one side was stained with Dickson's stain to highlight any evidence for early diagenesis e.g. cementation, dissolution and replacement. In total 17 samples were taken from 4 locations across the section, see figures 9 and 10.

Sample and Log locations



Figure 8: Map locating sample sites for petrographic analysis.

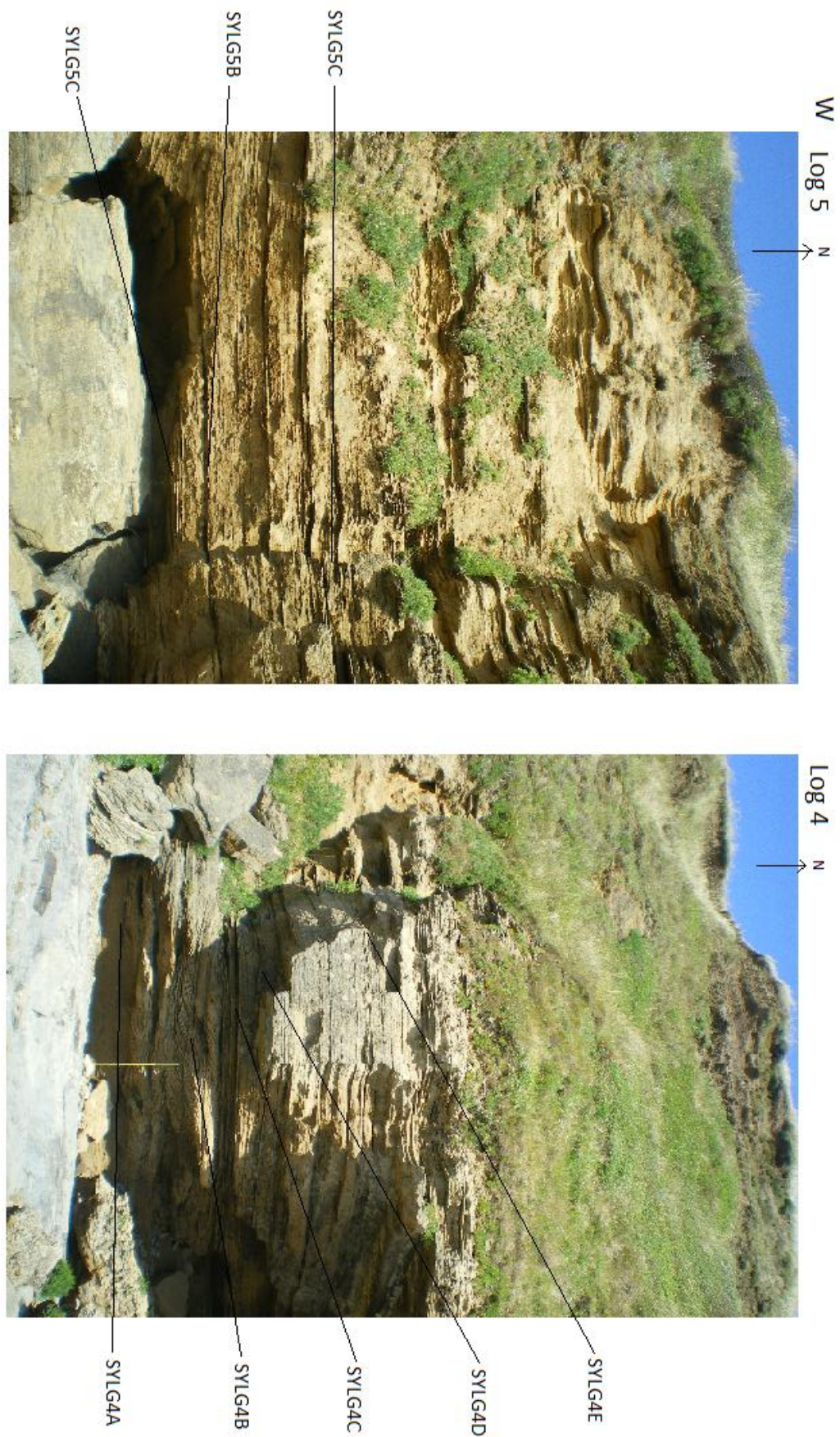


Figure 9: Sample locations in relation to the vertical section from logs 4 and 5

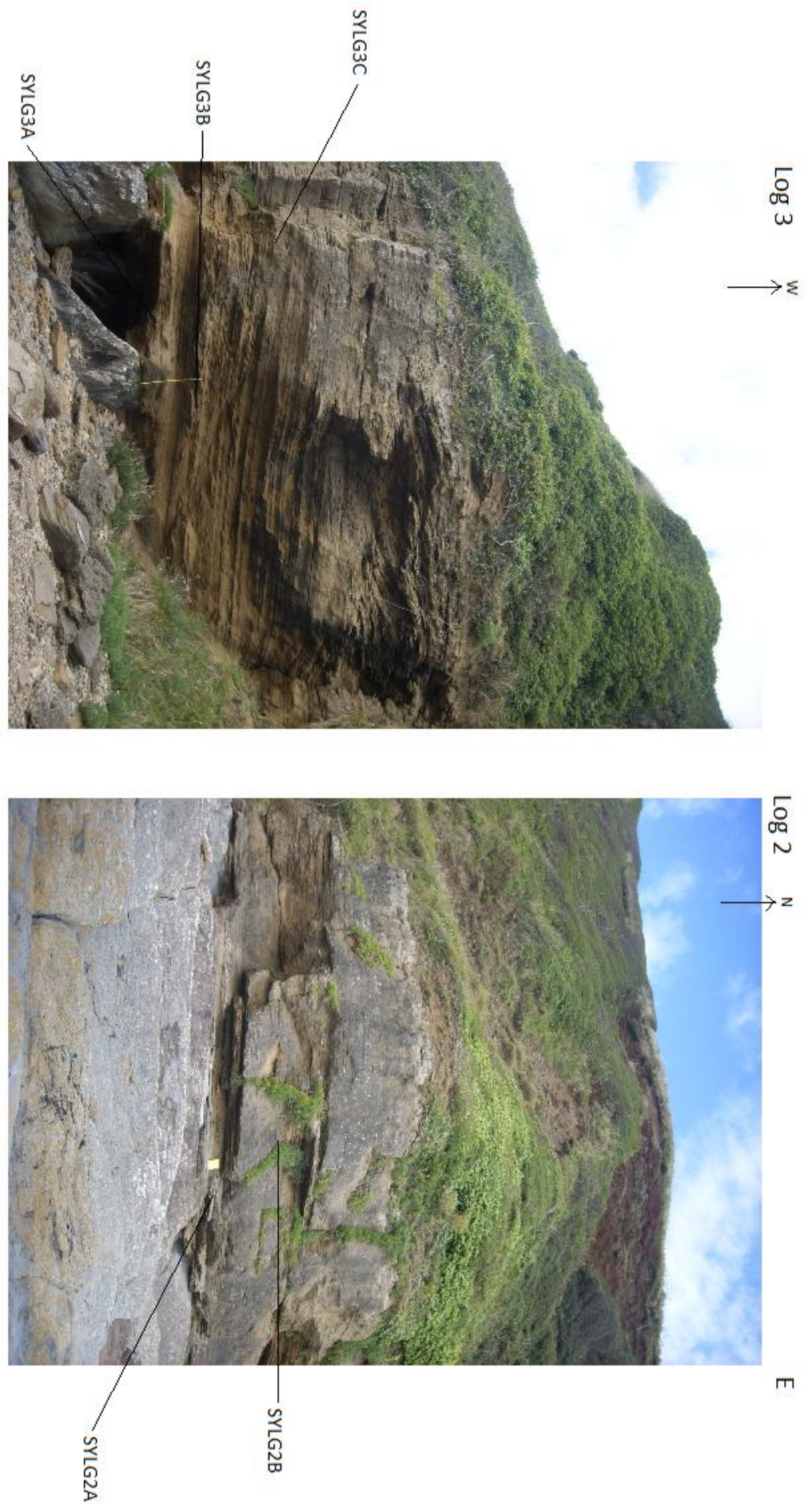


Figure 10: Sample locations in relation to the vertical section from logs 2 and 3

Facies

This chapter presents the results for the facies analysis undertaken in the field. These are further interpreted in terms of depositional environments and developed into sedimentary associations, successions and facies models. Furthermore local sea level patterns during deposition were established and described in terms of regression and transgressions.

Facies Description

Table 1 – Description of facies identified in the stratigraphic sequence at Saunton

Facies #	Lithology & Textures	Composition	Colour	Sedimentary Structures	Fossil Content	Facies name.
1	Medium – coarse sand grains. Very well - well sorted	Within the field quartz appears to be very dominant. Feldspars are very scarce. The first unit is overlain with a thin layer of pebbly sandstone.	Orange / Brown	Horizontally planar laminated beds Parting lineations.	Fossilised barnacles between the bottom of the unit and the dipping Devonian shale bedrock	Planar Horizontally laminated medium - coarse sandstone
2	Medium – Coarse sand Well sorted	Dominated by quartz grains, unable to identify any feldspars with a hand lens.	Orange / Brown	Medium scale trough cross bedding.	None visible within the field	Medium scale trough cross bedded sandstone
3	Medium – coarse sand Well sorted (in thin section) siliclastic grains are well sorted, presence of bioclasts make for a moderately sorted rock.	As described above.	Orange / brown	Low angle planar cross bedding with localised scours containing trough cross beds.	None visible within the field	Low angle planar cross bedded sandstone
4	Palaeosol	N/A	Grey	Tubular concretions known as rhizocretions, calcium carbonate precipitates out around vegetation roots continual accretion has resulted in them fusing together abundant presence of carbonised rootlets	Fossilised rootlets	Calcrete soil palaeosol rhizocretion horizon
5	Grainsize – Located at inaccessible height to measure exact grainsize.	N/A	Orange / Brown	Large scale trough cross bedding	N/A	Large scale trough cross bedded aeolian sands

Interpretation

Table 2 – Interpretation of the facies described in table 1.

Facies #	Name	Description	Interpretation	Depositional Environment
1	Planar horizontally laminated medium to coarse sandstone	<p>The base of this well sorted medium to coarse sand unit contains in situ fossilised barnacles which lie on top of the Devonian bedrock. Seen in figure 10. Sedimentary structures include distinct horizontal laminations and parting lineations. In places facies overlain by a pebbly sandstone which thickens to the west of the section. Pebbles composed of a wide range of lithologies. Between 0.5 – 5cm in length. Image 1 shows evidence for marine fossils within this facies.</p>	<p>The in situ fossilised barnacles can be interpreted to be the establishment of a rocky coast. The planar laminations are a result of variations in grain size caused by changing depositional conditions within beach environments. Boggs (2011) writes that these arise from sand transported by traction in water. Swash and backwash, along with this causes the formation of heavy- and light-mineral laminae. The laminae show parting lineation structures (also known as primary current lineation.) This suggests deposition in a subaqueous environment at high-flow velocities in the upper flow regime (Collinson <i>et al.</i>, 2006). The lineations which form parallel to the trend of the current, are produced by turbulent cork screw eddies that are close to the sediment surface (Tucker, 2003). The well-articulated burrowing bivalve fossil seen in figure 12 was found in situ in the sand and is evidence for a depositional environment such as a shoreline, beach and shoreface (shallow marine). The fact it was burrowing explains its quality of preservation. Pebbly layer between this intertidal foreshore/backshore beach facies and the subtidal facies described below can be interpreted as a ravinement surface.</p>	Intertidal (upper) foreshore/backshore beach.
2	Medium scale trough cross-bedded sandstone	<p>Facies 2 and facies 1 is separated by a subhorizontal planar erosive surface with a local pebbly layer (ravinement surface) in places. The sedimentary structure in this unit is of medium scale trough cross beds. From field observations, there are no evident fossils. Individual sets of cross beds range from 5cm to 39cm.</p>	<p>The cross bedding here indicates a migration of medium scale lunate and sinuous dunes down current (Collinson <i>et al.</i>, 2006). Reading (1996) suggests that cross bedding is the product of large flow-transverse bedforms. Forming one of the best known ancient subtidal sandstone facies. At various locations along the section foresets were full and had not been eroded subsequent to the dune formation. Suggesting a subtidal rather than</p>	Sub-tidal shoreface

MLWM

			intertidal environment.	
3	Low angle planar cross-bedded sandstone	Structures within this rock consist of low angle planar cross bedding with random local scours containing trough cross bedding. As before no evidence of fossilised plant or animal remains. It lies above a low angle erosional boundary above facies 2 with the presence of some local pebbles.	Planar bedding indicates deposition of bedload sediment in the upper flow regime. (Blatt <i>et al.</i> , 1980)	Lower Foreshore
4	Palaeosol rhizocretion horizon	This facie is abundant in rhizocretions (cemented roots); composed of carbonate which has cemented from the precipitation of calcium carbonate around the roots of vegetation. Through geologic time, continual accretion of carbonate has resulted in fusing together of individual rhizocretions into large calcareous nodules.	These fossilised rootlets indicate a time of subaerial exposure. They are moulds of former plant roots and highlight their former orientation (Beckner and Mozley, 1998). Collinson <i>et al.</i> , (2006) write that they would have been formed from the precipitation of calcium carbonate from pore waters. The calcium carbonate sourced from either outside shell fragments or calcitic bioclasts within the sediment. These concretions within clastic sediments are representative of early diagenetic processes.	Sub-aerial exposure (backshore)
5	Large scale trough cross-bedded sandstone	The large scale trough cross beds in this unit are largely hidden beneath vegetation as seen in figure 14. With only 2 parts of the section clear enough to reveal the structures. The unit appears to be poorly cemented in comparison to the previous facies. The unit is capped with a well developed, thick, head deposit.	Formed by the migration of aeolian sand dunes, sand grains moved as bedload. Cross bedding developed through repeated and continuing lee-slope sedimentation (Tucker, 2003).	Backshore aeolian dune environment

MLWM = Mean low water mark



Figure 11: *In situ fossilised barnacles between the Devonian bedrock and Facies 1.*



Figure 12: *Image showing the in situ burrowing bivalve fossil found in fallen rock belonging to facies 1 (distinguishable from the parting lineations which are running parallel with the black lines).*

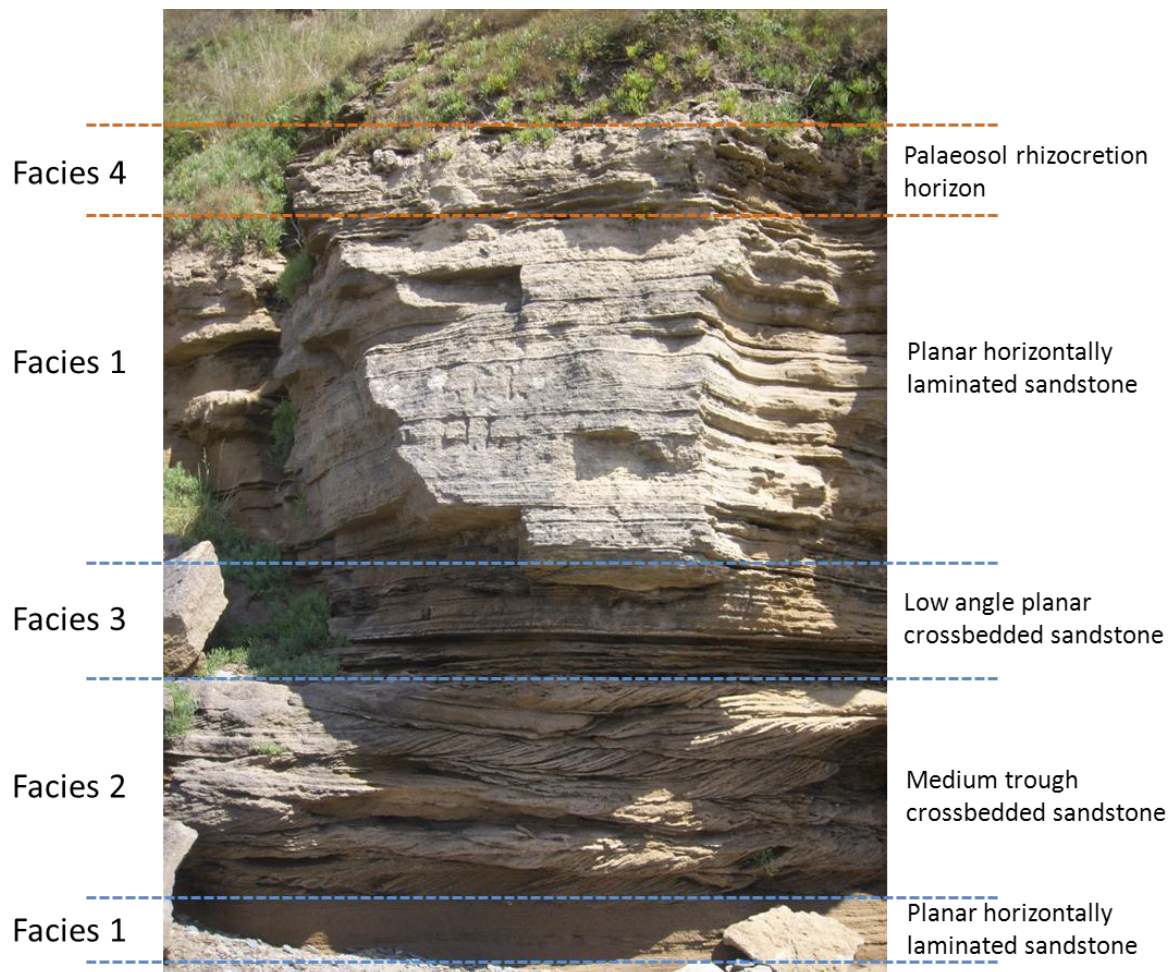


Figure 13: The first 4 facies identified across the section scale = 1.8m.



Figure 14: Image showing the main large scale trough cross bedded sandstone exposure across the section. Scale = 1.8m (example of facies 5)

Figure 13 highlights facies 1 through 4 identified in the previous table illustrating how they appear in the field and how they relate to one another. Figure 15 combines these with a palaeoenvironmental model of deposition which is utilised in subsequent chapters to create a model for temporal and spatial changes in depositional environments.

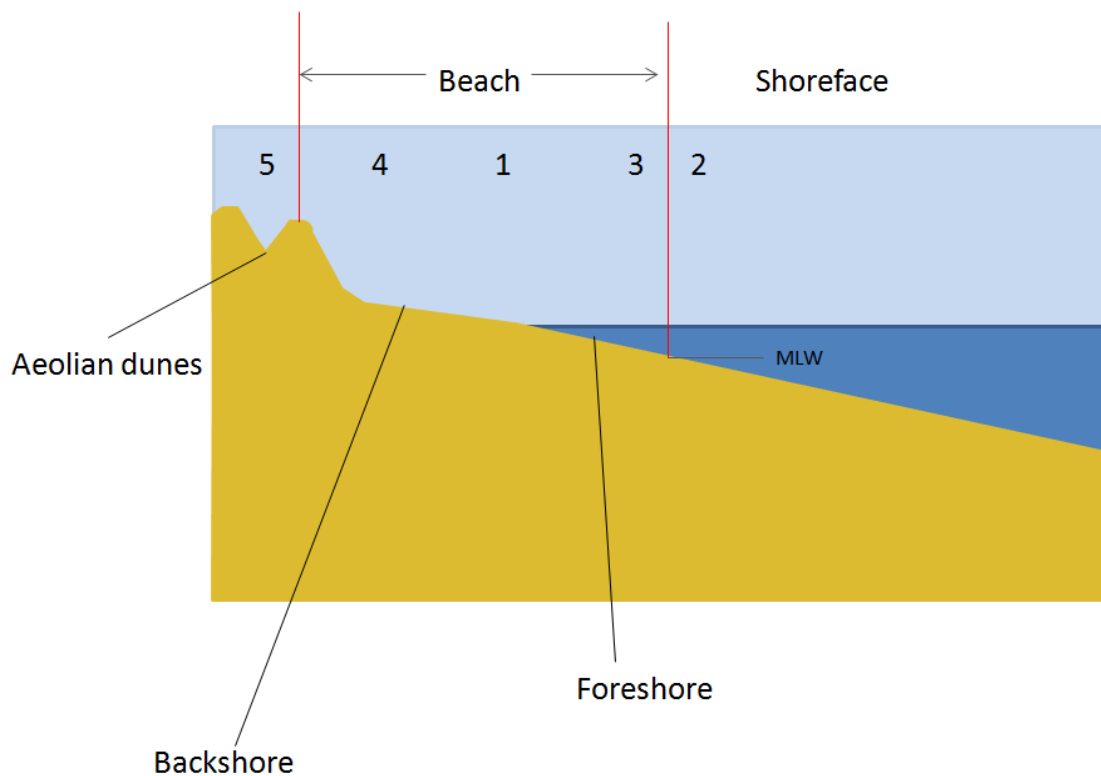


Figure 15: Illustration of the palaeoenvironments associated with each facies and their relation to one

Palaeoshoreline

Unit 1, Facies 1

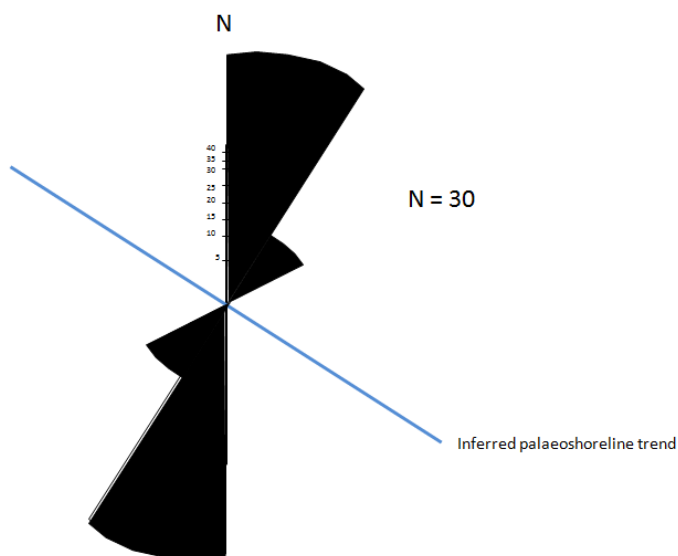


Figure 16: Rose diagram presenting palaeoflow data from the dip direction of parting lineations of facies 1, unit 1. Blue line = paleoshoreline orientation (WNW-ESE)

Unit 3, Facies 1

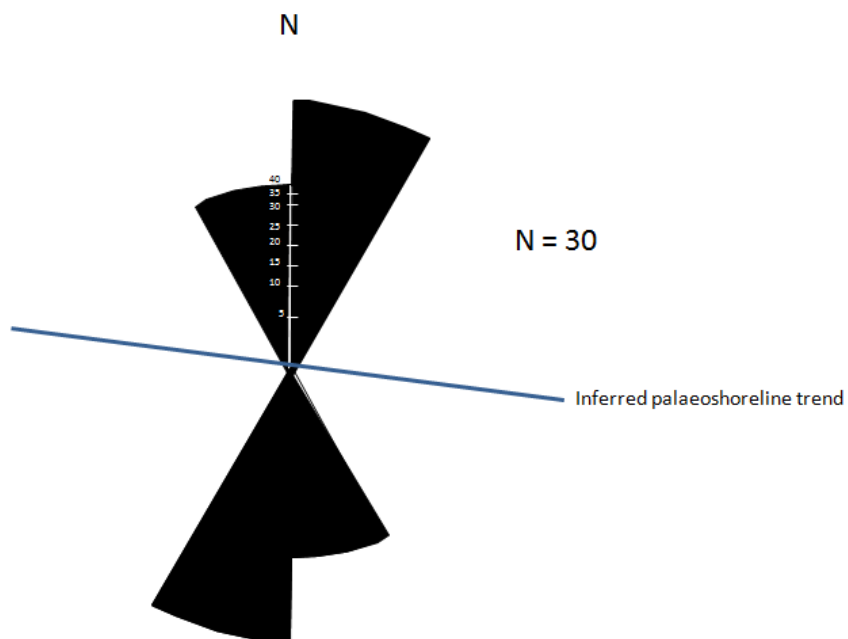


Figure 17: Rose Diagram presenting the palaeoflow data from the orientation of parting lineations on the 2nd unit of facies 1. Blue line = palaeoshoreline trending WNW-ESE

The rose diagram in figure 16 illustratively shows the orientations of parting lineations found on Unit 1, facies 1 (Planar horizontally laminated medium-coarse sandstone.) Parting lineations represent bidirectional current flow as they are formed during the process of swash and backwash on a beach. The figure shows that the direction of water trended 030-210°. From this information, the palaeoshoreline can be deduced because the sedimentary structures form perpendicular to it. These results indicate that the palaeoshoreline trended WNW-ESE during deposition of the rock unit. This differs greatly from the modern shoreline which trends N-S.

The rose diagram for the second unit of Facies 1, seen in figure 17, shows bidirectional currents trending approximately 000-180°. Similarly to the first unit of this facies the palaeoshoreline trends approximately WNW-ESE.

This palaeoshoreline reconstruction follows the same trend as the Pleistocene outcrop.

Associations

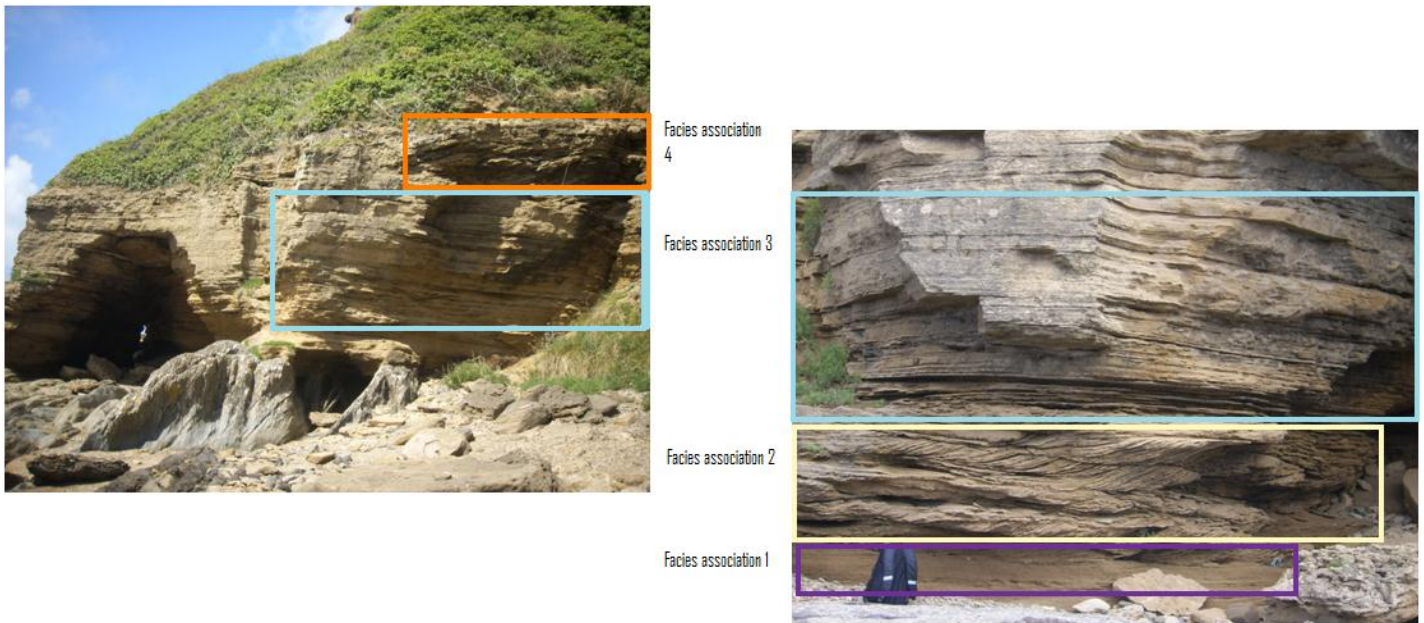


Figure 18: Shows the facies associations defined within the field

The 5 facies identified within the section can be grouped into 4 facies associations, shown diagrammatically in figure 18.

Facies associations 1 represents a time of transgression. The Devonian/Carboniferous sandstones and shales are the bedrock to the sedimentary sequence, in which an irregular shore platform has been cut. The presence of fossilised barnacles that overlie the shales and represent the base of the first unit of the planar bedded sandstone can be interpreted as the establishment of a rocky coast (refer to figure 11 in chapter 1). The sandstone alone indicates a near shore depositional environment with the low angle planar horizontal stratification reflecting a foreshore-backshore beach zone in particular (Masters, 1967). A sub horizontal, planar erosional surface separates this beach facies from the subtidal shoreface facies above it. This ravinement surface is overlain by a unit of pebbly sandstone in most places along the section however in some areas it is missing from the sequence. This facies association marks an initial transgression in the sequence.

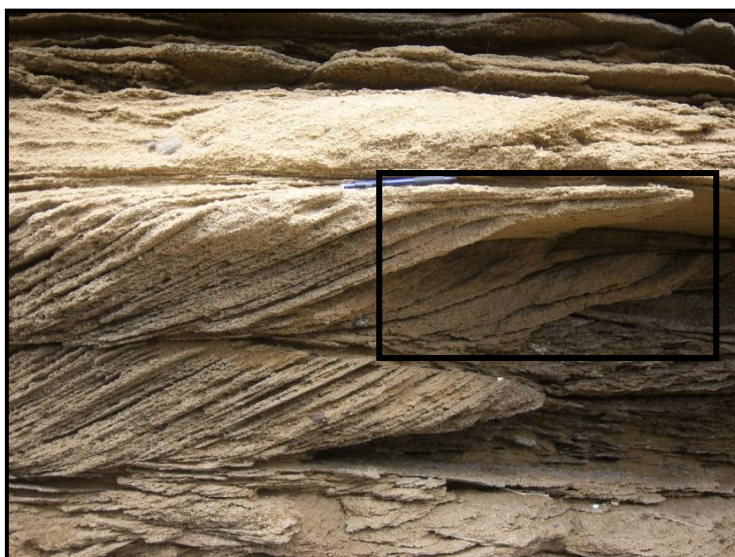


Figure 19: Image showing well preserved crests of paleodunes within trough cross bedded sandstone. Taken facing NNW.

Facies Association 2 is dominated by trough cross bedded sands. The fossilised Pleistocene dunes within this unit could suggest deposition within an intertidal environment; however observations of well preserved crests in certain sets (figure 19) suggest the dunes were not always eroded during swash/backwash indicating deposition of the sands in a subtidal shoreface setting rather than an intertidal one. This association marks the end of the transgressive period and maximum flooding.

Facies Association 3 sees the reappearance of Facies 1, diagnostic of an intertidal (upper) shoreface environment above the subtidal shoreface facies. This marks a period of regression, progradation of the shoreline due to sediment supply outpacing the rate of sea level rise.

In some but not all places this association can be split into 2 sub environments:

3a) A unit composed of planar cross bedded coarse sandstones with scours (Facies 3)

3b) Planar horizontally laminated sandstones (Facies 1)

This is only seen on the western part of the section and in some cases this facies association can consist of 3 units 3a, 3b and another unit of 3a overlying them.

The top of this association is marked by a palaeosol horizon consisting of tubular carbonate Rhizcretions, calcite has cemented itself around plant roots, the continual accretion of this has resulted in singular cemented roots fusing together to create an extensive cemented unit. The presence of rhizcretions is evidence for plant colonisation of the sands and a period of exposure due to the continued progradation of the shoreline. This exposure is more noticeable on the western side of the section and seems to thin and die out to the east.

Facies Association 4 can be interpreted to represent transgression or continual regression and aggradation. This arises from lateral variations in the section from east to west. The west of the section is dominated by horizontally stratified sandstones with localised trough cross beds (Facies 1.) Moving easterly along the section large scale trough cross beds are evident. On the far eastern side of this unit,

the beds have been cut by a younger solifluction (a mud matrix supported conglomerate) deposit. The boundaries between these lateral variations are difficult to locate and can only be inferred due to the localised landslides and high abundance of vegetation which dominate the sedimentary sequence above the soil rhizocretion horizon.

Successions

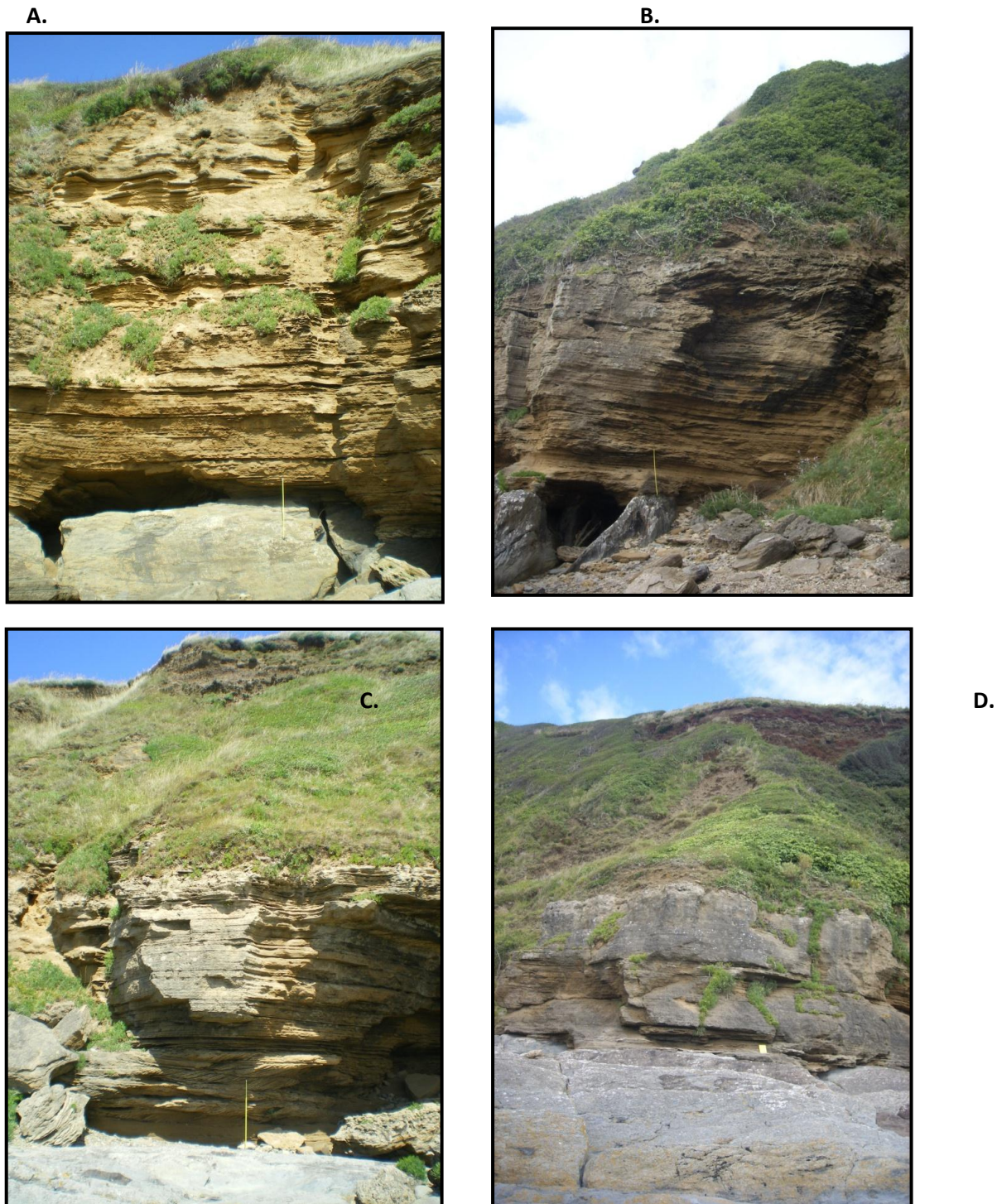


Figure 20: 4 locations in section logs were drawn from a) the most westerly point and d) being the most easterly. A) log 5 facing north scale =1m. B) log 4 facing north scale =1m. C) Log 3 facing west scale =1m. D) log 2 facing north scale =20cm.

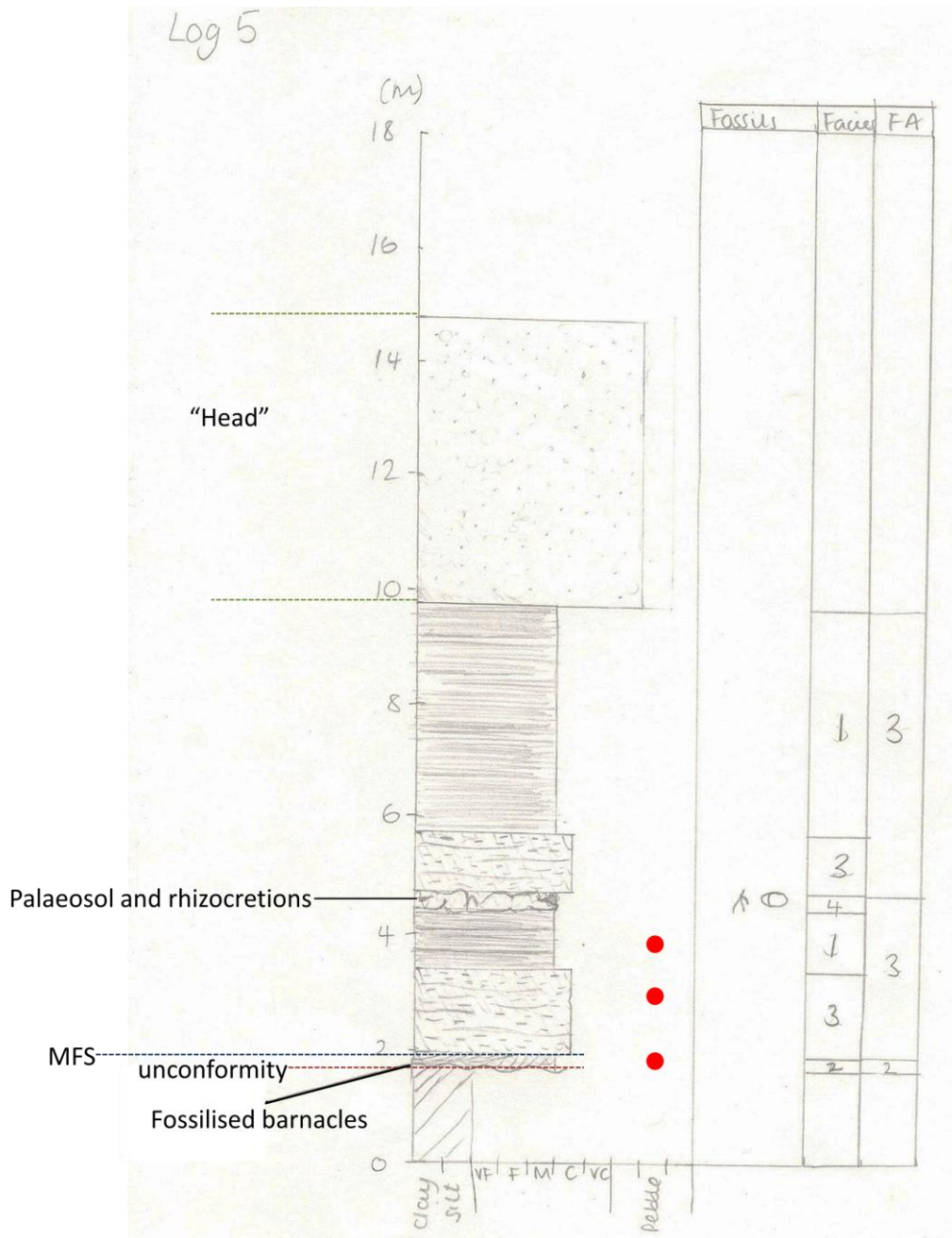
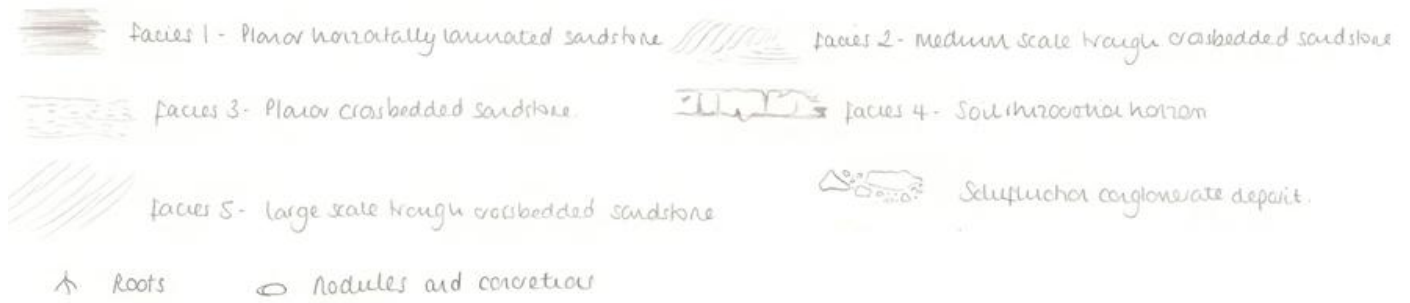


Figure 21: Key and sedimentary log 5 where F = Facies and FA= Facies Association red circles indicate sample locations

Figure 20 shows, photographically, the sections logged in the field.

Figure 21 represents the section at the most westerly point of the outcrop. The sequence has the very first unit of facies 1 missing, instead, the section starts at the erosive surface between the dipping Devonian Shales and a unit of trough cross bedded sandstone. This represents the establishment of a rocky coast and subsequent flooding during a period of transgression where the rate of sea level rise outpaced the rate of sedimentation. The top of unit 1, facies 2 represents the time of maximum flooding where the sequence was at its deepest point of deposition. From here the sequence shallows upward from a lower foreshore to a subaerial sub environment. This represents a period of regression where the rate of sedimentation is outpacing the rate of sea level change resulting in the progradation of the shoreline. The end of the transgression is marked by a unit of tubular concretions, interpreted to represent vegetation roots indicating sediment deposition at this point in time, was in an exposed environment. Above the soil rhizcretion horizon is the second unit of the lower foreshore facies. This change in facies represents another period of drowning (transgression) at this location. It also highlights the absence of a backshore/upper foreshore facies between the two. This could possibly be a result of differential or rapid erosion during shoreline retrogradation. The lower foreshore facies gradually shallows up into the upper foreshore/backshore facies, another period of normal regression. This top unit contains localised trough cross bedded scours.

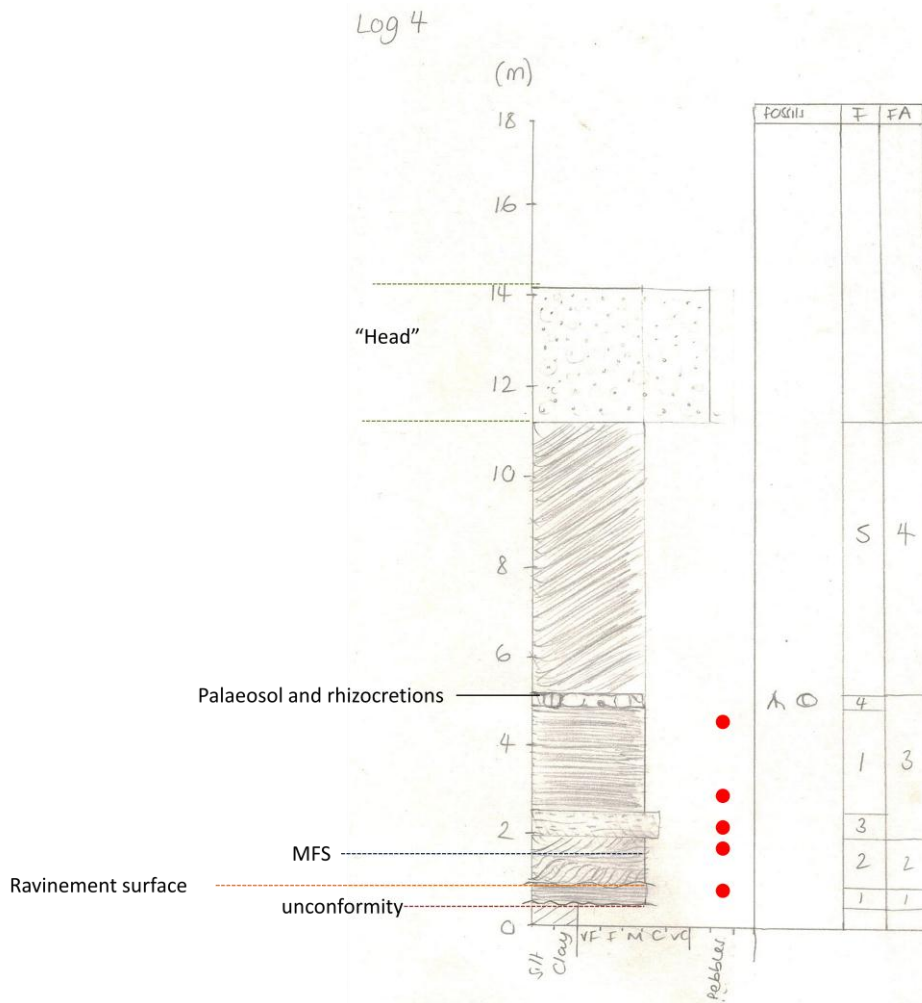


Figure 22: Sedimentary log 4 .Red circles = location of samples.

The sedimentary succession in log 4, seen in figure 22 shows an initial deepening up sequence, a period of transgression. The 2 units change from upper foreshore into subtidal shoreface facies, with a missing unit of lower foreshore planar bedded sandstone. The bounding erosive surface between the first unit of facies 1 and unit of facies 2, is a ravinement surface. The localised pebbles above are representative of a transgressive lag deposit (a depositional product from a rise in sea level). The maximum flooding surface (MFS) lies within the unit of trough crossbedded sands (facies 2) later work in this study tentatively locates this MFS.

The next 4 units show a shallowing up trend from lower foreshore to backshore, exposure and aeolian dunes with no missing facies. This is a great example of a parasequence indicating a state of normal regression where the rate of sedimentation has outpaced the rate of relative sea level, resulting in shoreline progradation.

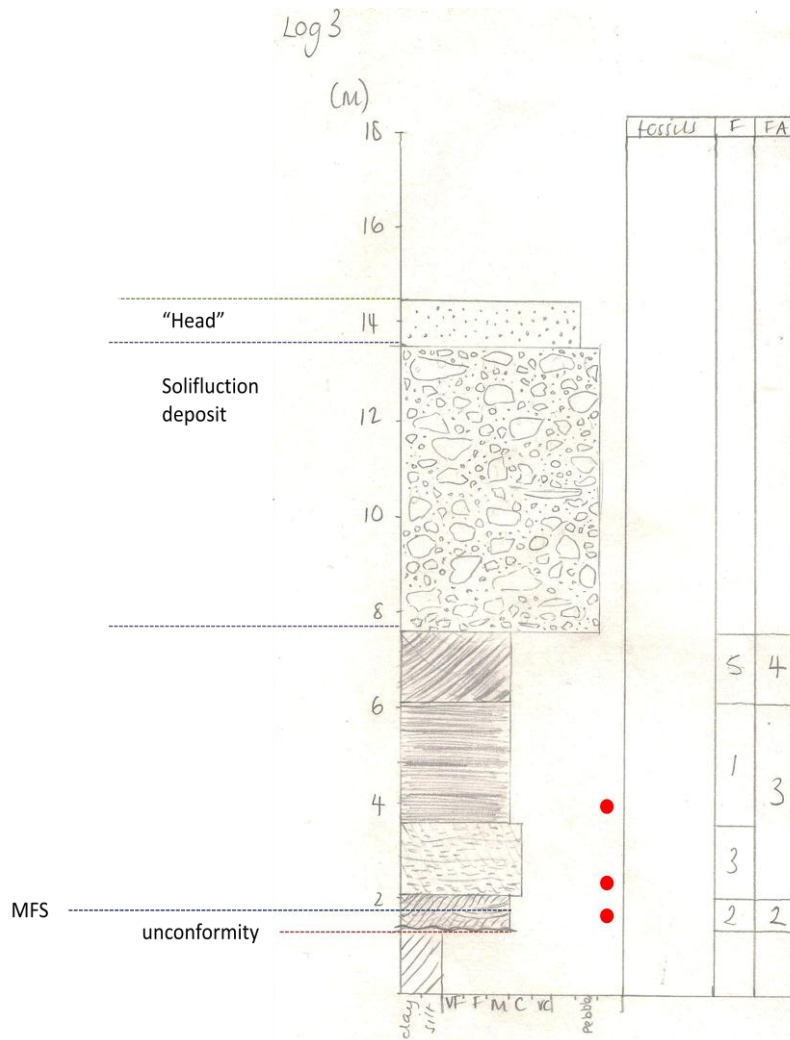


Figure 23: Sedimentary log 3 red circles = sample locations

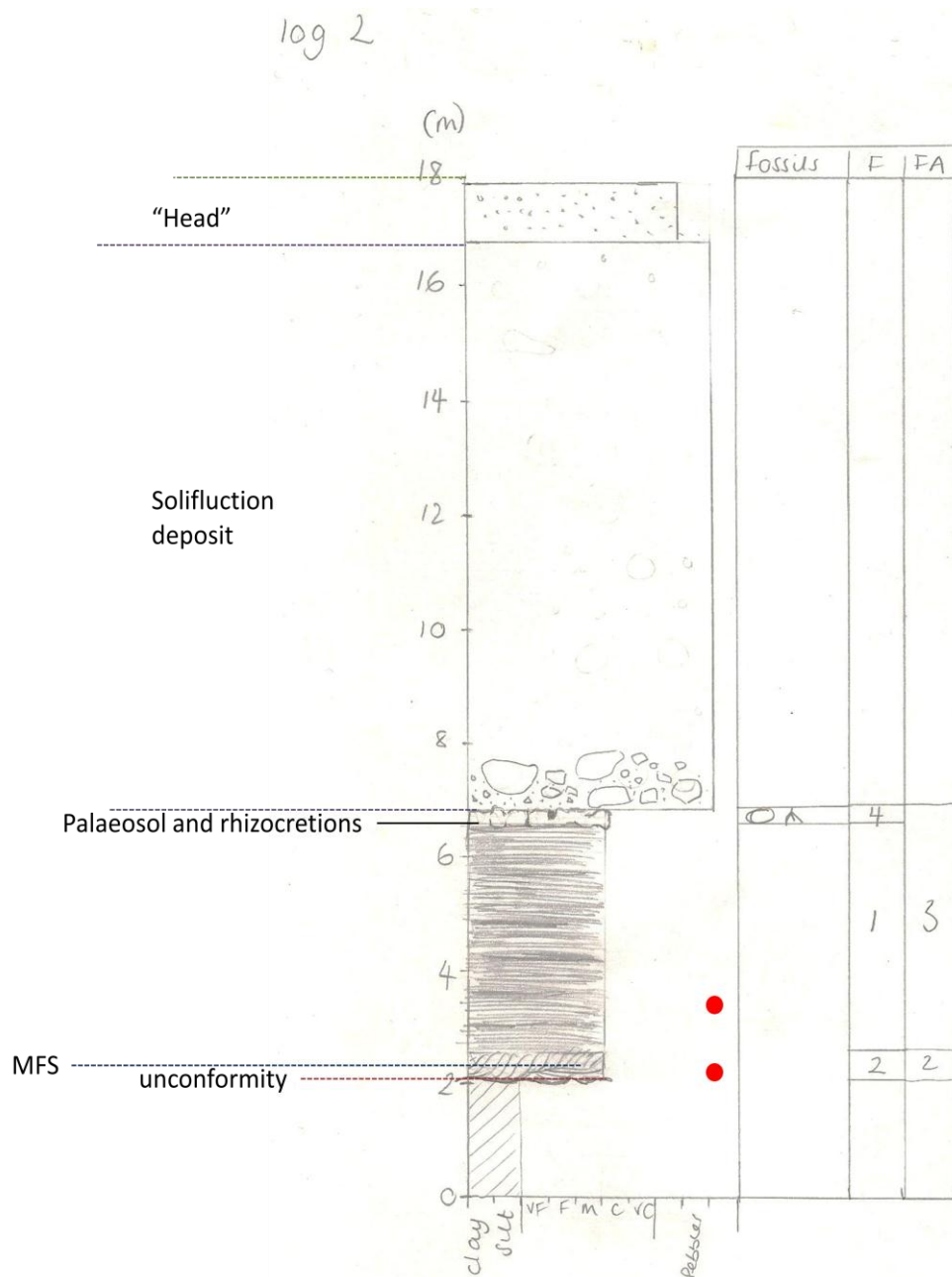


Figure 24: Sedimentary log2, red circles indicate locations of samples.

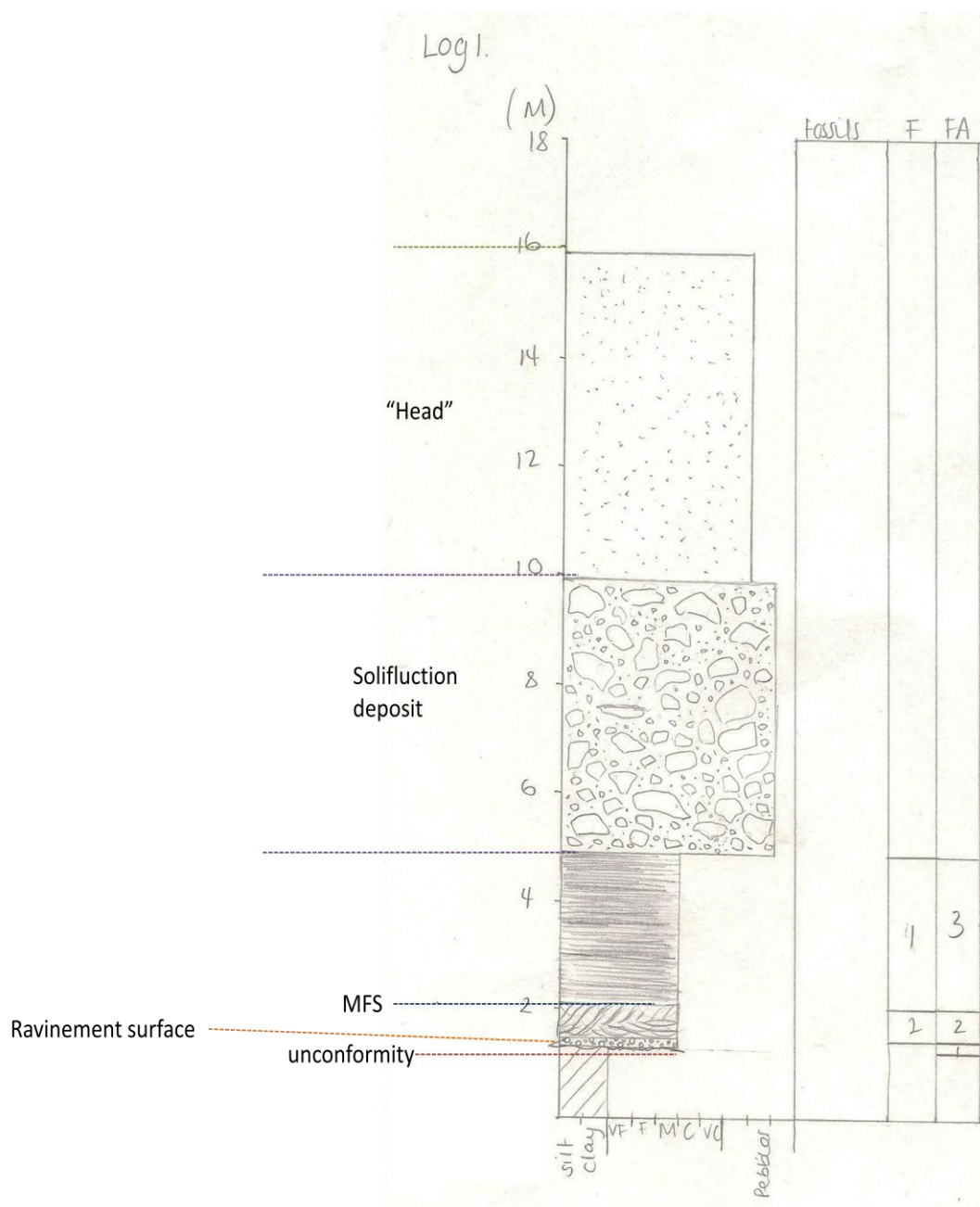


Figure 25: Sedimentary log 1.

Figures, 23, 24 and 25 are the graphic interpretations of logs 1 through 3 respectively. All three logs have a continual shallowing up pattern representing the regressive pattern previously identified in the upper section of logs 4 and 5.

Comparison of the 5 logs, show how, many of the facies thin out and disappear towards the east, with just the subtidal shoreface and upper foreshore/backshore facies remaining. The initial phase of transgression is lost. All 5 logs highlight a regressive phase of sea level but it is obviously necessary to study laterally across the section to develop the full picture of changing sea levels recorded in the rock record. The basal sandstone unit of planar bedded sandstones disappears for two reasons; firstly because the modern beach overlies the Devonian dipping shales, concealing a small area at the base of the section and secondly because the dipping shales onto which the sand was deposited did not provide an even surface for the preservation of flat beds resulting in the sandstone being distorted, owing to why some of the sandstone appears in between the Devonian shale beds.

Further fieldwork undertaken on facies 2 tentatively shows the initial transgression to extend higher up into the sequence.

The individual sets of trough cross beds of facies 2 were measured in terms of thickness, orientation and dip in the hope of identifying patterns in depositional conditions across the section. Coset thickness and palaeo-dune size being a function of water depth and flow velocity during sediment deposition (Tucker, 2003). Each set was plotted against thickness, seen in figure 26.

From the 6 sections studied a tentative trend can be observed:

- There is an initial thickening of cosets representing an increase in water depth and flow velocities which corresponds to the continuation of the transgressive period of sea-level change identified with in sedimentary logs (4 and 5) and successions previously.
- Following this there appears to be a thinner coset where water velocity must have decreased and become shallower representative of a short period of regression.
- Above this, sets thicken once more, before ultimately thinning out and moving into the regressive period seen to carry on throughout the vertical succession.
- The thickest coset seen to be D in sets 1,2,4 and co-set C in 5 and 6 can be interpreted to represent a period of time where deposition was occurring at its deepest suggesting that it is the top of these cosets which represent the true maximum flooding surface.

However, admittedly, these conclusions are drawn from a very limited dataset and further work would be needed to be undertaken laterally across the whole section to provide stronger evidence.

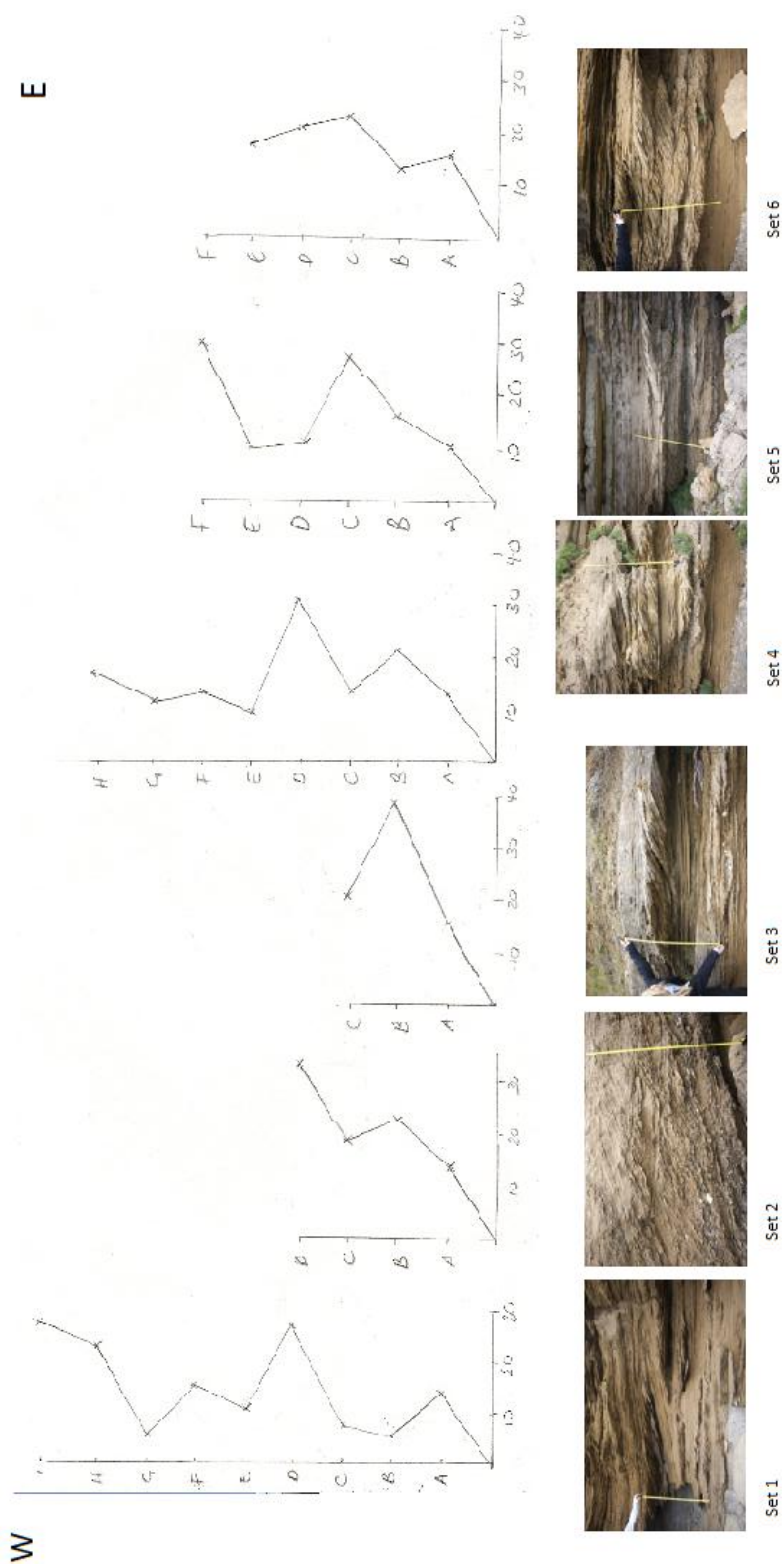


Figure 26: Sets of trough cross beds. Unit plotted against thickness in cm.

Lateral Variations

Unit 1 of facies 1 thins from west to east, eventually dying out and disappearing completely from the sequence at headland one. The deposition of the sands on top of the irregular cut shore platform of the resistant dipping Devonian shales, distorts the horizontally laminated sandstone at various locations along the section, this is highlighted in figure 27. The second unit of facies 1 is evident below the conglomerate in the east but disappears to the west, here facies 2 overlies the dipping Devonian shales.

Between the first 2 units of facies 1 and 2 lies a ravinement surface, a pebbly sandstone (seen in figure 28) which is more prominent to the west. Thinning so it becomes almost unnoticeable between headland 1 and cave headland and thickening again to the east of the section. This pebbly sandstone is representative of a transgressive lag.

Facies 2, the unit of trough cross bedded sands which lie above Facies 1, similarly thins towards the easterly side of the cliff section and in places where the dipping bedrock protrudes higher into the sequence. Part of this unit is hidden by the modern beach at the most easterly point at headland 1.

Facies 3 is only evident from cave headland westwards along the rock section and is overlain by a second unit of Facies 1. On the easterly side this second unit of Facies 1 lies directly above Facies 2.



Figure 27: Image showing the deformation of unit 1 due to the dipping bedrock.

The rhizcretion horizon is only visible from the cave headland westwards. To the east the fourth unit consists of large scale trough cross bedding. At one location on the east side of cave headland this unit overlies a part of the rhizcretion horizon. On the westerly side of cave headland the rhizcretion horizon is overlain by a third unit of Facies 1. However most of the rock unit above the rhizcretion horizon in the west and above the second unit of facies 1 in the east are obstructed by vegetation. Above unit 2 of facies 1 at headland one is a large conglomerate unit on the order of 10m.



Figure 28: Image showing pebbly sandstone layer (ravinement surface) between unit 1 of Facies 1 and Facies 2.

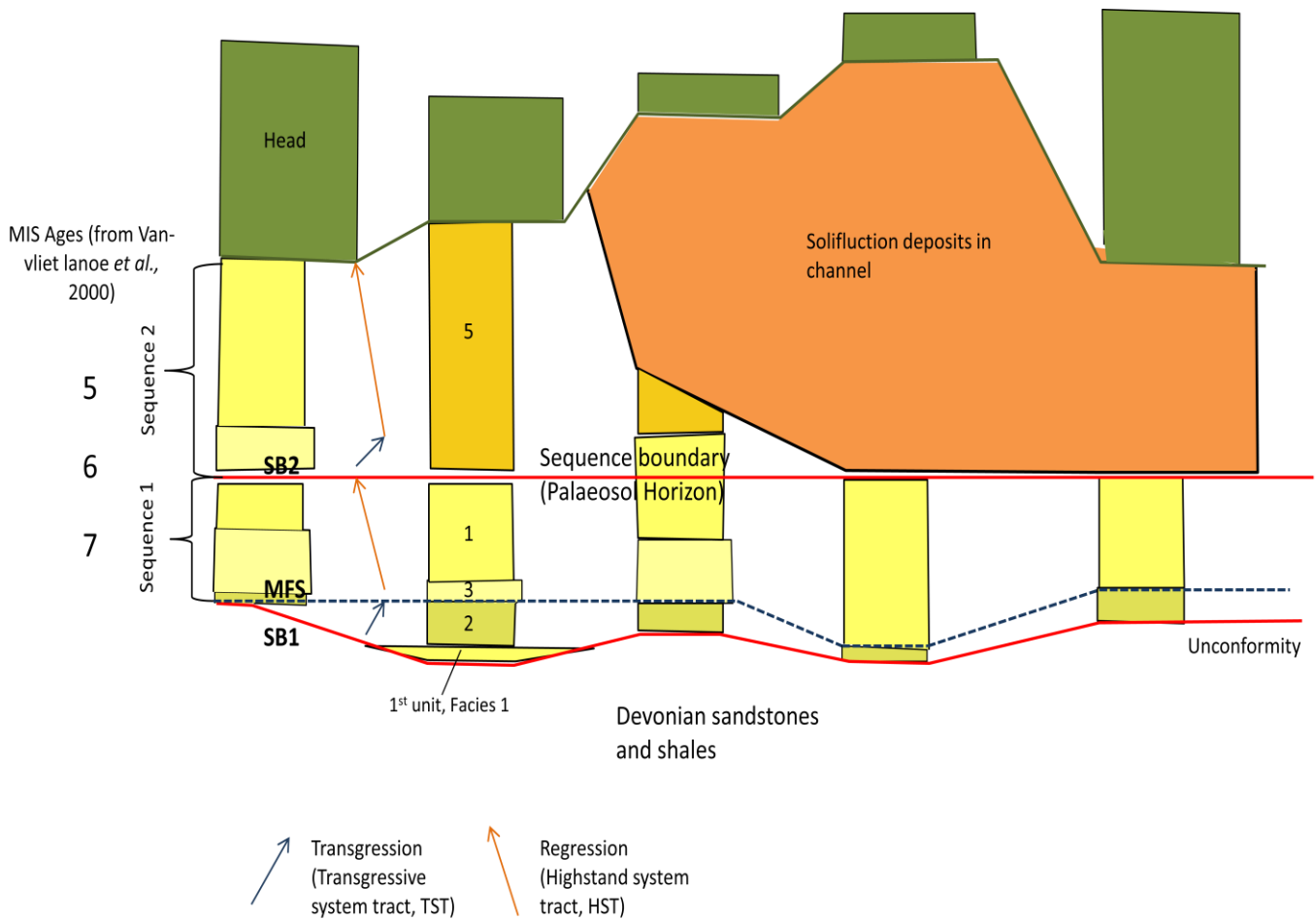


Figure 29: Correlation of logs. SB=Sequence boundary MFS=maximum flooding surface numbers correlate to Facies.

Figure 29 highlights the irregularity of the unconformity between the Devonian bedrock and the bottom of the sedimentary succession. It shows how the unconformity has caused the lateral variations in the first unit of Facies 1. It also shows how the solifluction deposit above the Pleistocene sands has been deposited within a channel before the deposition of the head on top. Sequence 1 fits with the transgressive interglacial of MIS 7, the forced regression and relative sea level fall during the glacial of MIS 6 fits with the regression, highstand system tract to sequence boundary 2. The overlying sands of sequence 2, deposited during another transgression fit with the van-Vliet laneo *et al's.*, (2000) work which dates them to be last interglacial in age (MIS 5).

Sequence Stratigraphy

The previously interpreted transgressions, forced and normal regressions from the stratigraphic sequence (seen in figure 29) combined with changing sedimentation rates of the shoreline are used to create a curve of rate of base level change. This is based on the model, seen in figure 31, constructed by Catuneanu *et al.*, (2009). This model further aids in the use of this “rate of base level change” curve to create a magnitude sea level curve during the time of sediment deposition.

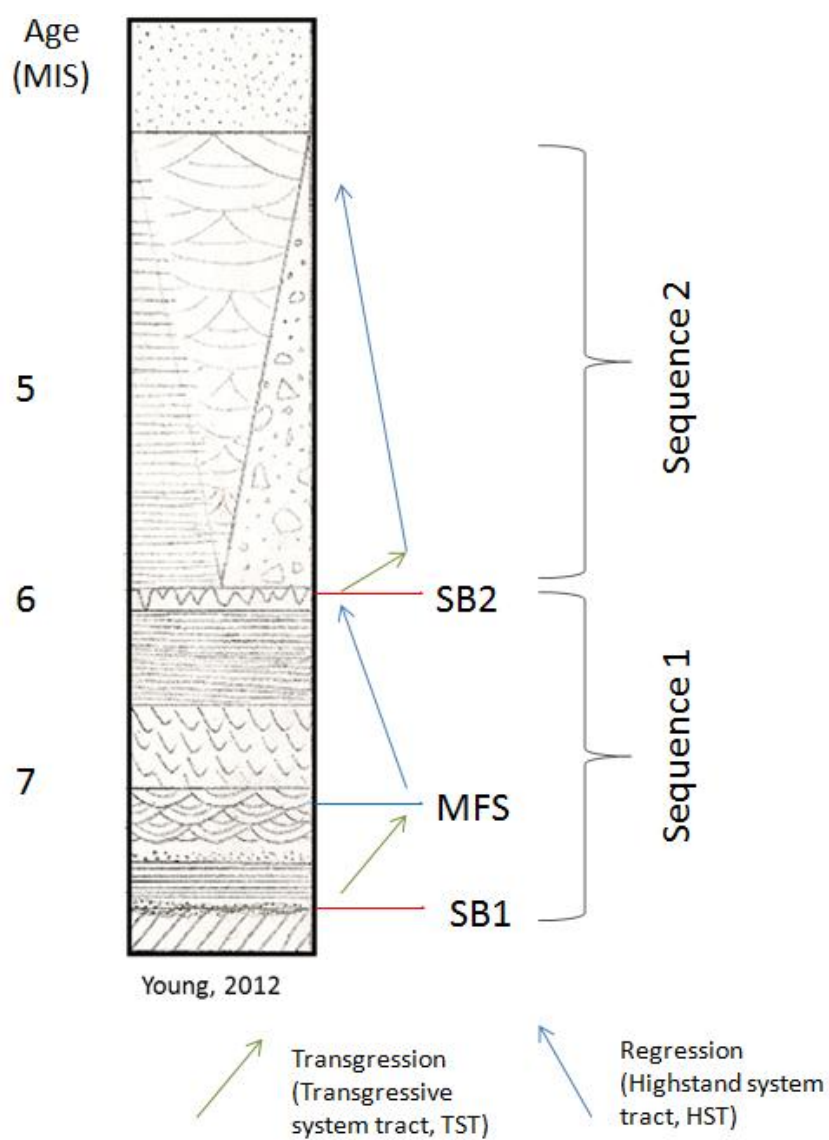


Figure 30: log with stratigraphic boundaries where SB= Stratigraphic boundary
MFS=maximum flooding surface

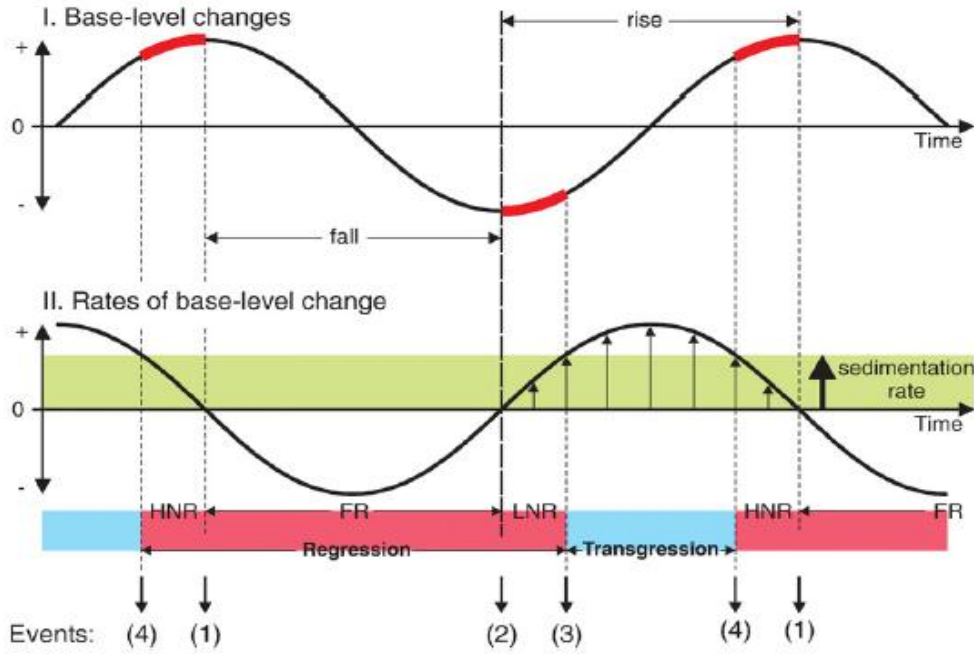


Figure 31: magnitude and rates of base-level change (Catuneanu et al., 2009) where 1= onset of forced regression 2= eng of forced regression 3= end of regression and 4= end of transgression. HNR= highstand normal regression and LNR=lowstand normal regression.

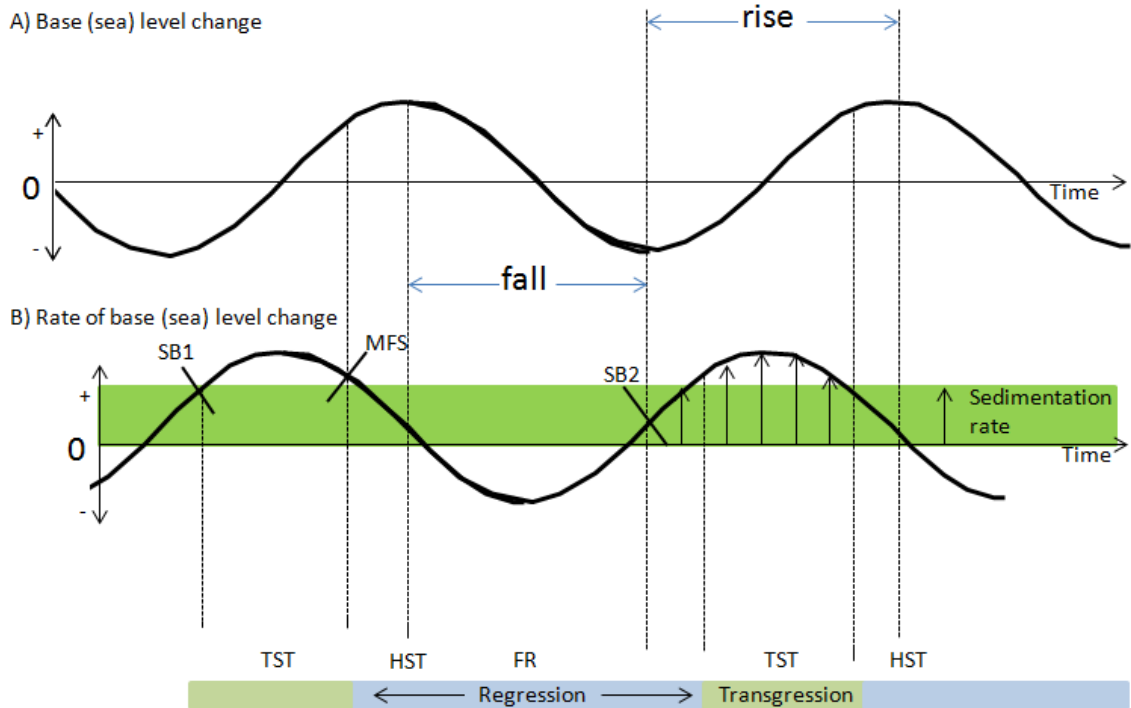


Figure 32: A)magnitude of base level change and B) the rate of base level change based on transgression, normal regressions, forced regressions and the sedimentation rate of the shoreline. TST= transgressive system tract, HST= highstand systems tract, SB=sequence boundary, MFS= maximum flooding surface, FR= forced regression

The stratigraphic surfaces interpreted from the sequence at Saunton seen in figure 30, are used in figure 32 to create a curve of rate and magnitude of base (sea) level change.

It is evident that high system tracts correspond to peaks in sea level and that lowstand sea levels correspond to the end of normal regression and the onset of forced regression. Figure 30a therefore suggests that the lowest sea level was during the deposition of the palaeosol horizon and that there were 2 peaks in sea level recorded within the rock succession at Saunton; during the deposition of Facies 3 and the second unit of Facies 1 in sequence 1 and again in sequence 2 during the formation of the aeolian dunes.

Detrital Composition

Siliclastic Grains

Quartz is the most dominant siliclastic grain within every facies. Monocrystalline quartz being more abundant than polycrystalline quartz. Lithic fragments within the sands include cherts, slates, granites, volcanic glass and clay minerals. Clay minerals such as glauconite and kaolinite are present in very small quantities in some samples. Feldspars are uncommon across all units. Multiple twinning, plagioclase is the most common of the feldspars, however the abundance is very low considering the rock is a sandstone. Other siliclastic grains include first order pinks, blues and yellow biotite mica based on petrographic observations. Figure 33 highlights some of these grains in thin section.

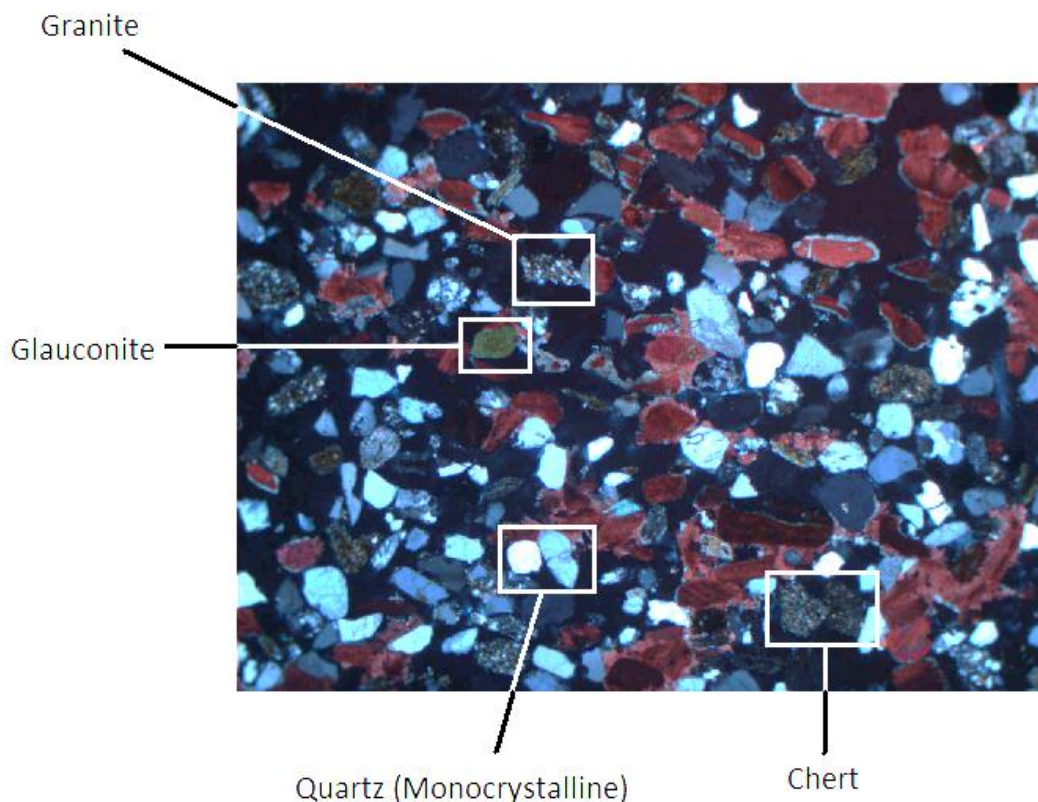


Figure 33: Photomicrograph of thin section, SYLG4C (facies 3) locating some of the siliclastic grains within the sandstones

Carbonate Grains

The main carbonate grains are bioclasts with some peloids present in Facies 1, 2 and 3. The most commonly occurring bioclast is bivalve found in every sample of each facies. Calcitic and porcelaineous foraminifera are also present in all facies samples except for the palaeosol rhizocretion sample. Echinoderms are also found in the sands, mostly within facies 2 and 3. Fragmented Bryozoans are also evident however there are no fully fossils. These are highlighted in figure 34.

Within the medium trough crossbedded sands (Facies 2) the larger bioclasts (e.g. bivalves and bryozoans) are fragmented. This reflects the high energy subtidal environment the sediment has been interpreted to have been deposited in. The microfossils evident within the Intertidal (upper) foreshore/backshore beach facies (1) are much better preserved and are mostly well articulated. The planar cross bedded sands contain bioclasts preserved to a similar degree to those seen in Facies 2. Most are fragments of their former composition.

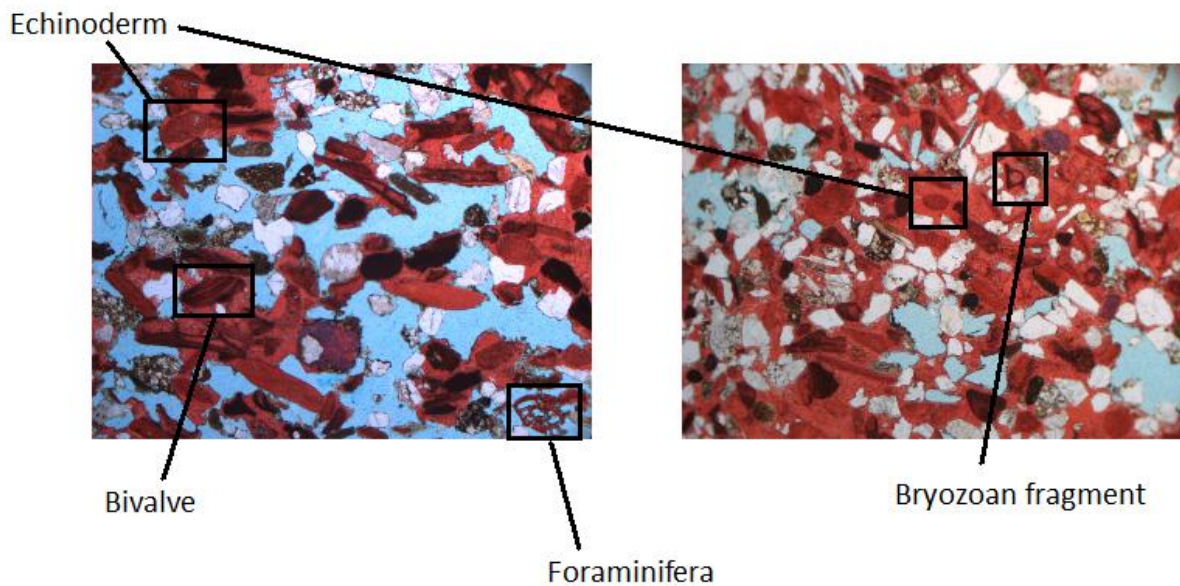


Figure 34: Photomicrograph showing bioclasts in thin section in samples SYLG4B and SYLG2A (facies 2) respectively

Classification

Classification of the rock (Table 3) is difficult to establish for some units due to the degree of dissolution of siliclastic grains. The lack of feldspars and high abundances of quartz and lithic grains place all facies as sublitharenite or lithic arenite bioclastic sandstones based upon petrographic analysis of the current composition, not at the time of deposition and upon Pettijohn's (1975) classification scheme.

Table 3 – Classification of facies based on petrographic observations

Facies #	Sample #	% of quartz	% of lithic grains	% of feldspar	Classification
1	SYLG4E SYCF1	80	20	~1	Sublitharenite bioclastic sandstone
	SYLG2B, 3C, 4A, 4D, 5C	60-70	30-40	0	Lithic arenite bioclastic sandstone
2	SYLG2A	75	25	0	Sublitharenite bioclastic sandstone
	SYLG3A, 4B, 5A SYCF2	30-70	30-70	~1	Lithic arenite bioclastic sandstone
3	SYLG4C	85	15	~1	Sublitharenite bioclastic sandstone
	SYLG3B, 5B SYCF3	60-70	30-40	0	Lithic arenite bioclastic sandstone

Texture

The grains in the planar horizontally laminated sandstones (Facies 1) were typically subrounded to rounded with moderate sphericity. Facies 2, the medium trough cross bedded sands containing grains, subangular to subrounded in shape with mostly moderate to low sphericity. The low angle planar cross bedded sands (Facies 3) contain grains mostly subrounded and of low sphericity. All samples show the grains to be well sorted. The modal grain size was similar across all sandstone facies at approximately 2mm.

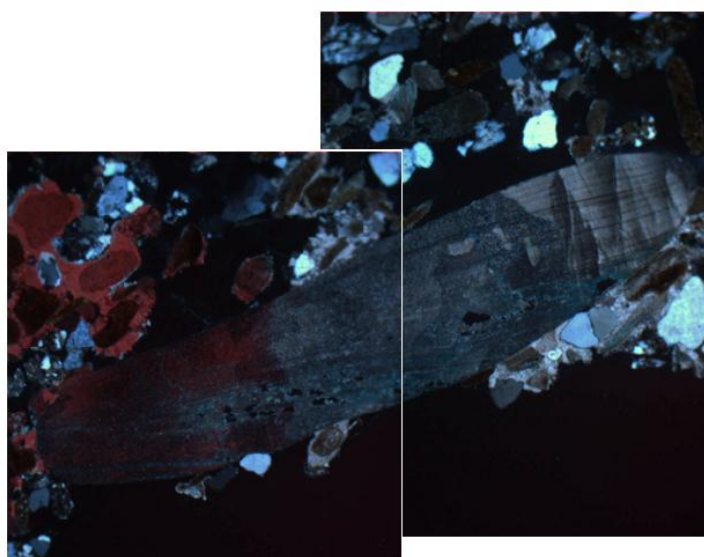


Figure 35: Photomicrograph of a Bivalve from sample SYLG3B (facies 3)

The largest grains found in the thin sections were usually large bioclasts such as bivalves and the smallest grain sizes were in the region of 0.5mm most commonly quartz grains. The largest bivalve found is seen in figure 35 this disarticulated fossil spans approximately 21mm.

The rocks lack any matrix. Instead the intergranular material is composed of pore space and calcitic cements. The cement geometry is that of equant spar drusy mosaic in all sandstone samples. In the thin sections for Facies 1 the cements become better developed moving up through the sample. Facies 3, the planar crossbedded sands, lack large proportions of cements, approximately 10-25% of the sample is cement. The cements are poorly developed, but resemble large equant spar crystals. The cements of the medium trough crossbedded sands consist of well-developed equant spar drusy mosaic.

The samples taken from lower down in the section had much less pore space than that of samples taken from further up. Noticeably the highest located samples had the most pore space ranging from 30 -60% of the slide.

Diagenesis

This chapter examines the presence of diagenetic features within the rock units. Diagenesis is the term used to define a number of processes which alter sediment or sedimentary rock subsequent to deposition (Berner, 1980). It can be either, physical, chemical or biological in nature. Diagenesis differs from weathering and metamorphism due to the lack of uplift and exposure to higher temperatures of the sedimentary particles, respectively. The 3 main diagenetic processes evident at Saunton are cementation, Dissolution and Replacement. The process of compaction is not apparent within the section studied. The poorly cemented sands above the well cemented palaeosol rhizocretion horizon suggest the main phase of diagenesis occurred before the deposition of Facies Association 4. The diagenetic features here can be divided by macro and microscopic scales. The main macroscopic features include solution cavities, orientated linear concretions and rhizocretions. On a microscopic scale diagenesis is evident from calcite cementation and replacement, and calcitic bioclast dissolution.

Cementation

Field observations

The cementation of Facies 1 appears layered, the horizontal laminations within the beds result from grain size variations. Parting lineation's are a feature of this cement, a product of cork screw, turbulent eddies near to the sediment surface and form parallel to flow direction. The orientation of which, can aid in the reconstruction of palaeo-flow directions (Tucker, 2003). These structures are highlighted in figure 36. This characteristic of the facies cement indicates formation in a subaqueous environment in the upper flow regime in shallow depth, high velocity flow conditions by the action of swash and backwash. (Collinson *et al.*, 2006 and Tucker, 2003). In Facies 2, cementation is apparent along the palaeo-dune foresets. In Facies 3 the sands appear to be cemented along planar cross beds and within troughs of local scours. In Facies 4 (palaeosol rhizocretion horizon) it is visible that cement has formed around rootlets resulting in tubular concretions. Continual accretion of the carbonate cement has resulted in the fusing of these nodules. The tubular carbonate concretions are orientated perpendicular to the shoreline and sub-parallel to the

direction of maximum topographic gradient. Facies 5 is poorly cemented but similarly to Facies 2, it follows and defines the foreset structures.

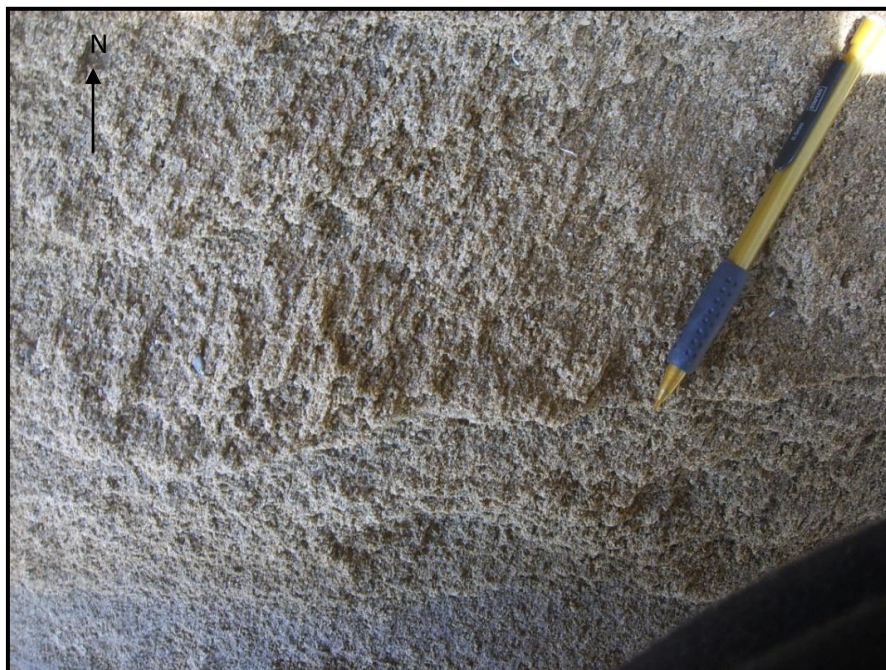


Figure 36: Image of parting lineations on unit 1, facies 1..

Petrographic observations

All the cement present in the units are calcitic. The main cement geometry of the medium trough crossbedded sandstone is that of a calcitic equant spar drusy mosaic. The rhizocretion horizon shows absolutely no pore space with a very distinct equant spar drusy mosaic. The calcitic cements seen within the planar horizontal laminated sands appear to be poorly developed at the bottom, moving up the unit the cement crystals become smaller and develop into equant spar drusy mosaics. Within the planar crossbedded sands there isn't a great deal of cements and is dominated by pore space. The calcitic cement that is present shows equant spar drusy mosaic geometry as seen in all other facies.

Syntaxial overgrowth of the cement is evident from the extinction of echinoderm bioclasts and calcite crystals as single entities when in crossed polars, figure 37.

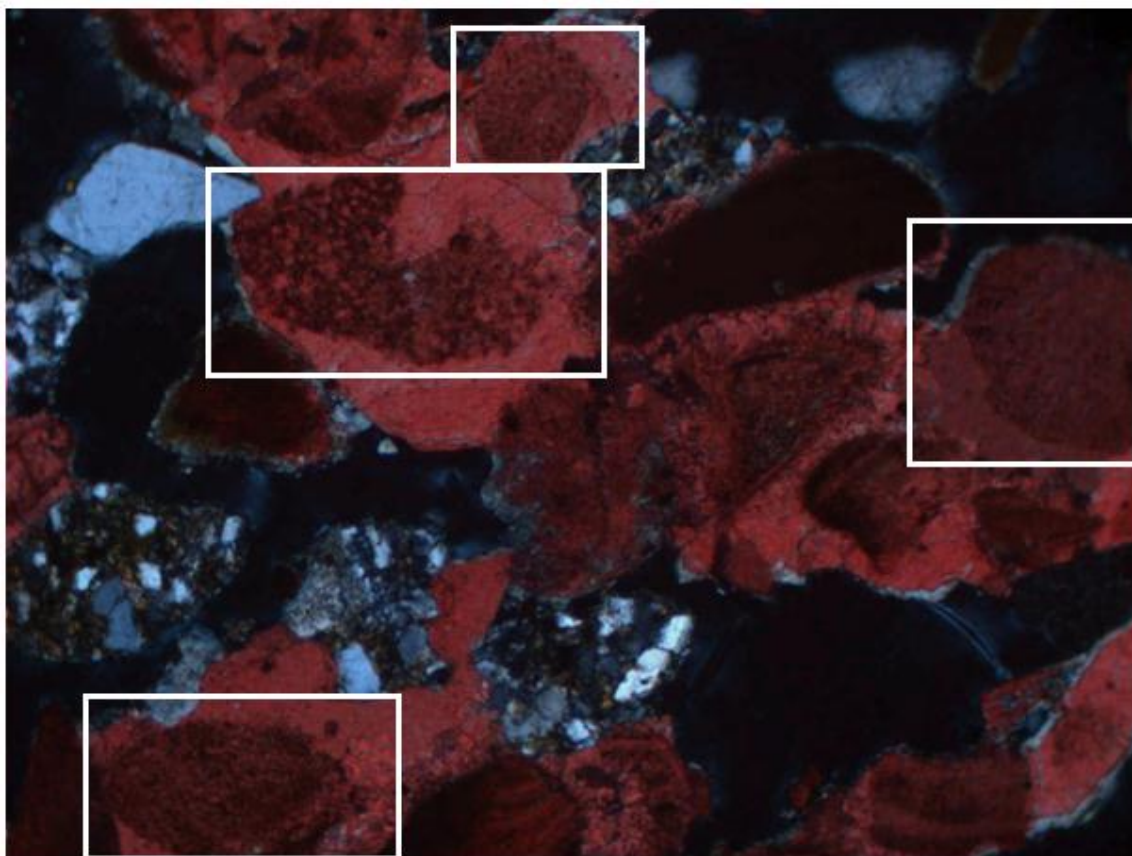


Figure 37: Photomicrograph showing syntaxial overgrowth of echinoderm spines from sample SYLG4B (facies 2, medium trough crossbedding).

Dissolution

Field observations

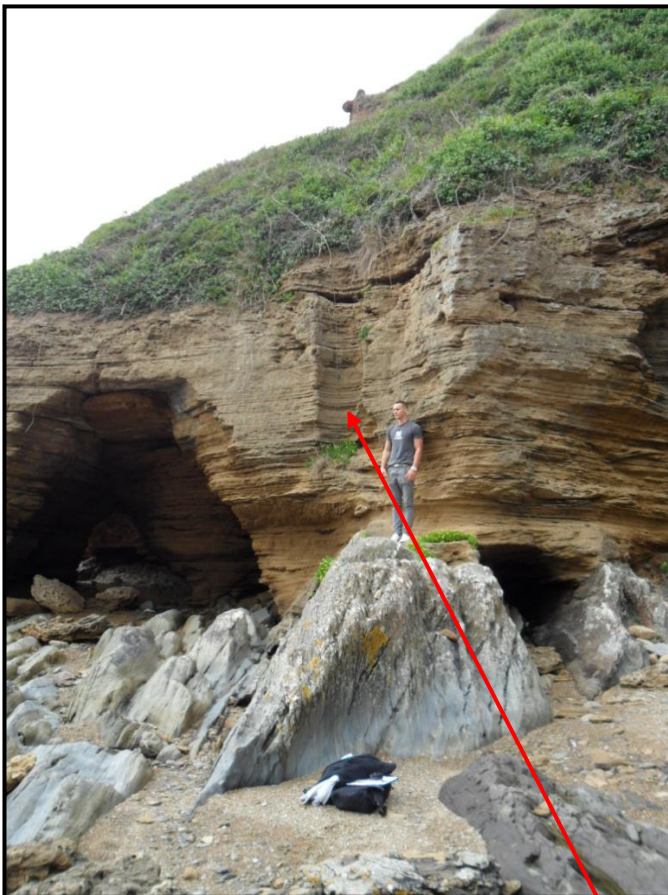
The main dissolution feature observed at Saunton were solution cavities seen in figure 38a-d. The tubular features formed from the weathering of rocks by percolating water under karstic processes (Pazdur *et al.*, 1995) and are evident across the entirety of the section studied. The cavities range from 50-75cm in diameter. It was also observed that these tunnel structures tended to die out as they hit the top of the medium trough crossbedded sands, they never stretch the length of the entire vertical section.



A.



B.



C.



D.

Figure 38: Solution cavities in the section A) scale 1m facing NE in unit 3 facies 1. B) scale 1.8m, facing NW, solution cavity extends vertically through the whole of sedimentary sequence at this location. C) This solution cavity (taken facing east) only extends through from the rhizocretion horizon into the second unit of facies 1. It does not penetrate through the planar cross bedded sandstone. D.) This image was taken from above located at headland 1 (refer to map.) It shows a series of solution cavities which have joined to form one large erosional feature.

Petrographic observations

Grain shaped pore spaces, could suggest feldspars have been dissolved away due to their instability.

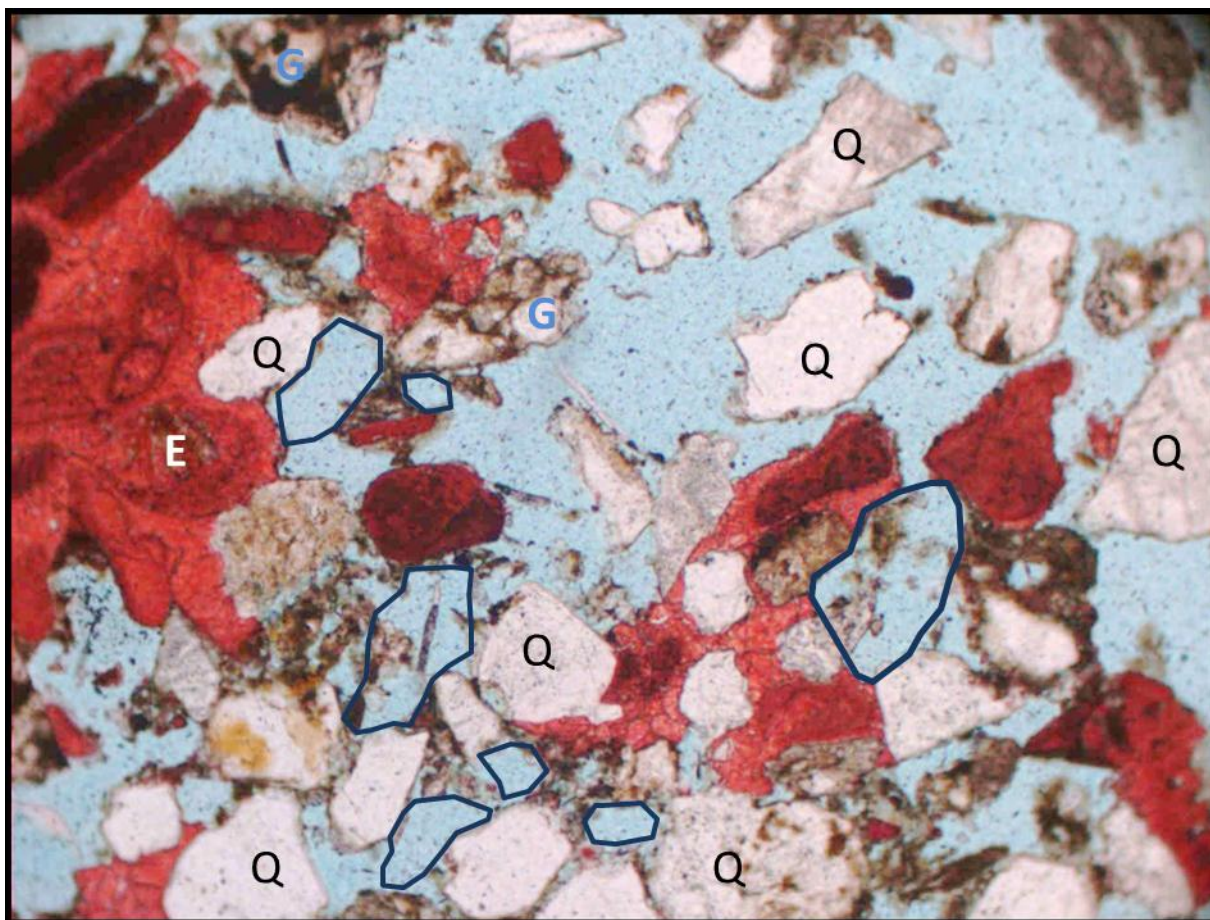


Figure 39: Photomicrograph of thin section, SYLG4D (Facies 1 unit 2). Blue outline = areas of dissolved grains. E= echinoderm Q=Quartz G=granite.

Figure 39 taken from a thin section from the second unit of Facies 1 appears to show evidence for dissolution of lithic grains, particular areas highlighted within boxes.

Within SYLG3C (facies 3) grains were seen to be “floating” within pore space (figure 38), this could suggest either dissolution of the former matrix/cement before the formation of the calcitic cement seen in all of the samples or it could imply that there has been dissolution of calcitic cement that has already formed.

Bioclasts are only evident and preserved around cements. Within pore space, bioclasts cannot be found this could suggest their removal by dissolution. Furthermore suggesting that the pore space is not solely attributed to the sandstones being characteristically porous in nature and that some pore space, especially in the facies (particularly 1 and 3) where pore space is dominant in thin section, can be ascribed to the dissolution of grains.

Petrographic observations of Facies 1 highlight a correlation between the samples from the second unit, the location near to macroscopic solution cavities and a greater amount of pore space. Whereas the samples taken from the first unit, have a far greater amount of cement and low percentages of intergranular voids. Figure 40 shows how parts of shells of some bioclasts have been dissolved away. It is one example of many across the 3 facies examined petrographically.

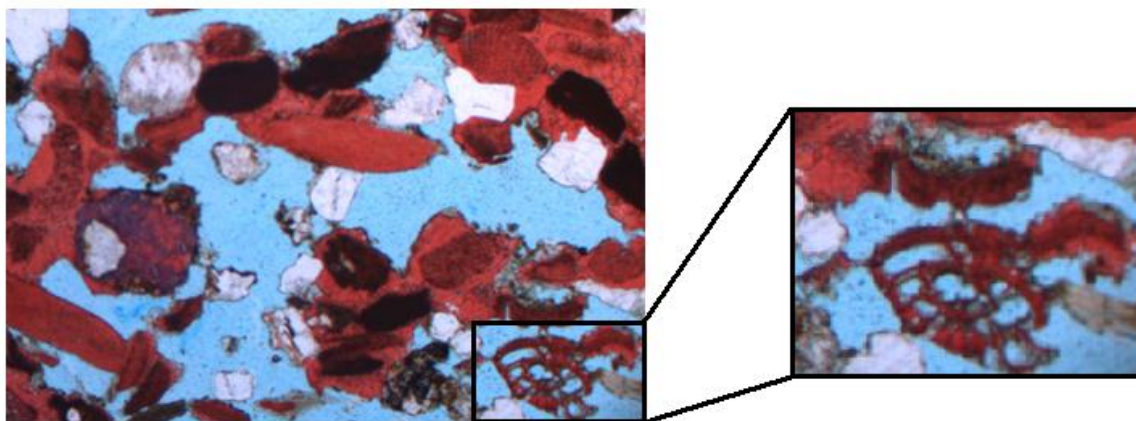


Figure 40: Foraminifera whose chambers have been effected by dissolution. SYLG4B (facies 2).

Replacement

Petrographic observations

Replacement of unstable aragonitic shells of bioclasts (e.g. Bivalves, foraminifera) with calcite are evident in almost every thin section across all facies. Figure 41 draws attention to one particular foraminifera whose chambers have been dissolved and subsequently filled with calcitic cements. Replacement of shells by calcite is evident across all samples, figures 42 through 43, show some of these examples within the black and white boxes.

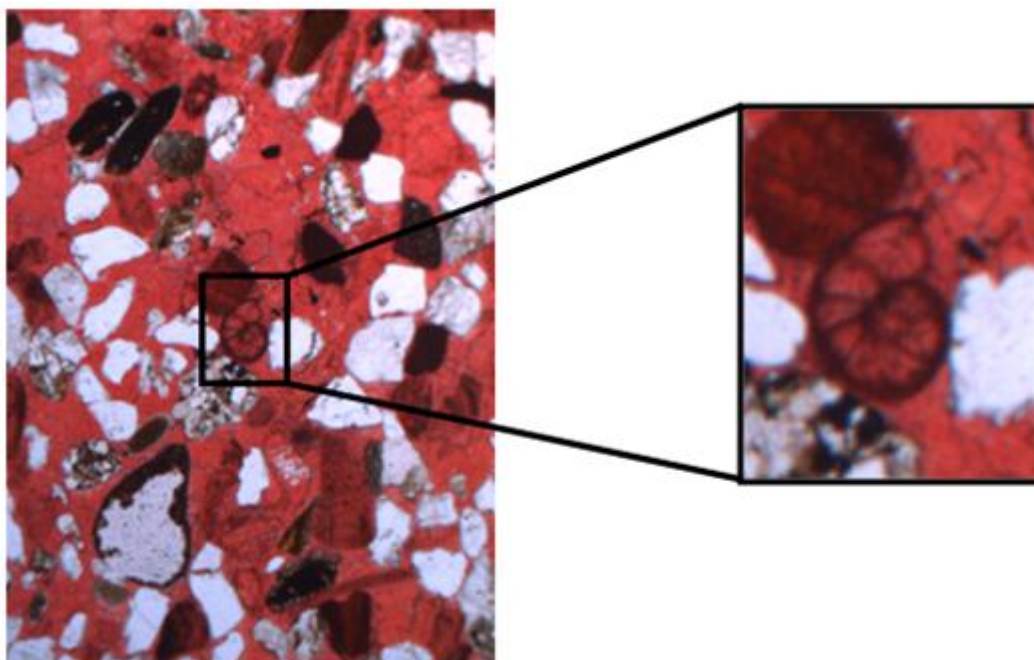


Figure 41: Perfectly intact calcitic Foraminifera found in SYLG2A (facies 1).

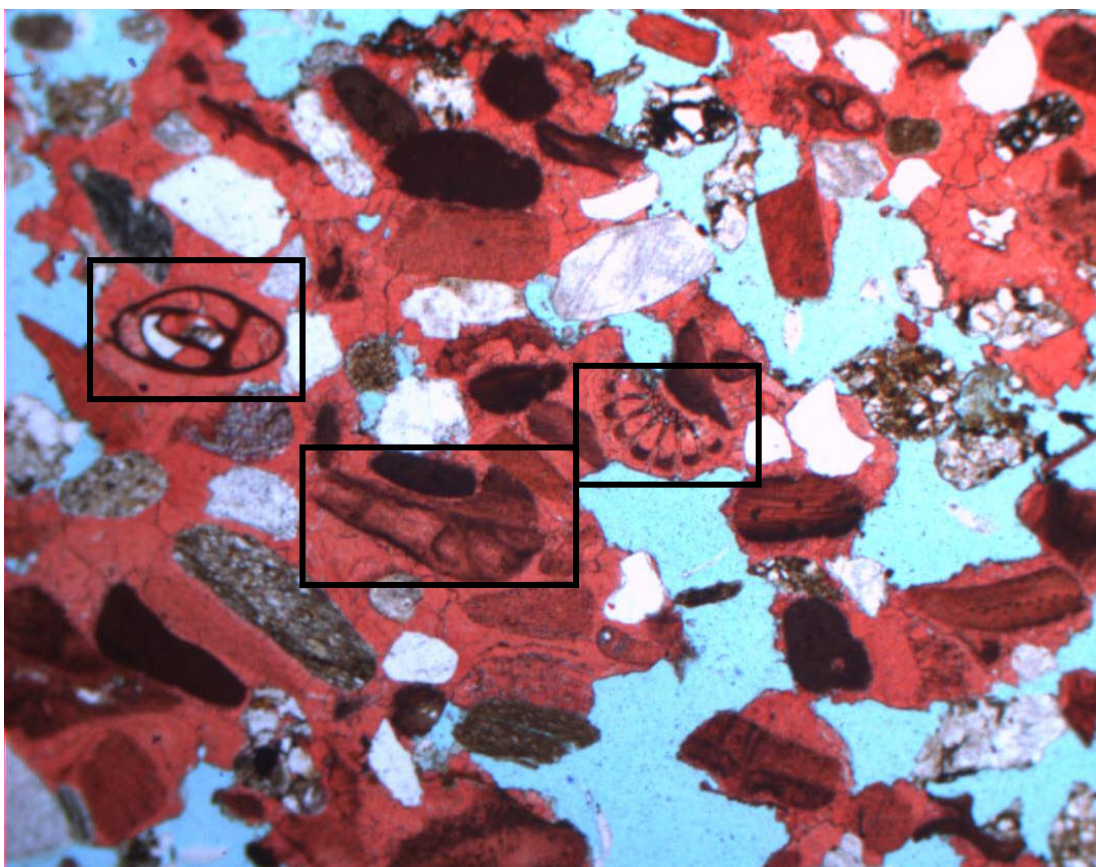


Figure 42: Photomicrograph of SYLG4B (facies 2) highlighting replacement by calcitic cements of an echinoderm, a porcelaneous foraminifera and barnacles.

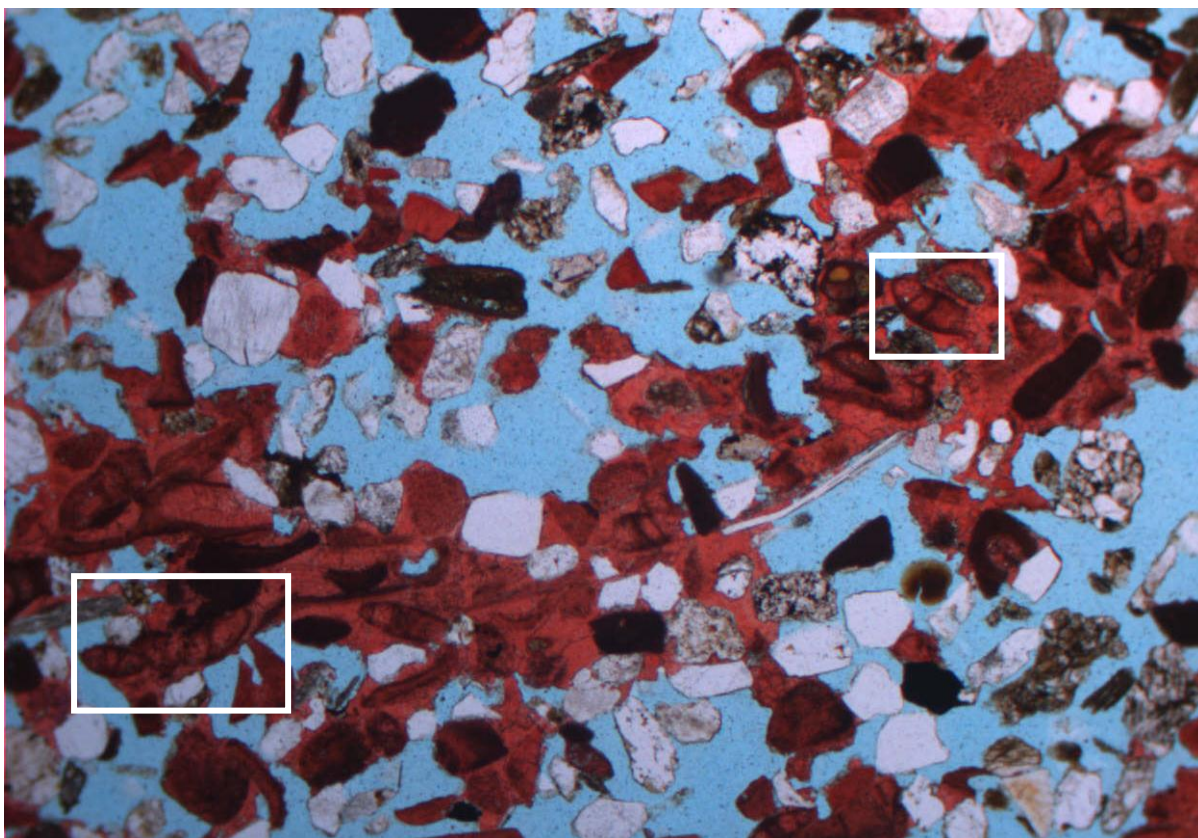


Figure 43: Replacement of original foraminifera test with calcite, photomicrograph of Sample SYLG5B (facies 3).

This chapter highlights that all the Pleistocene rock units at Saunton have undergone early diagenetic processes. The evidence suggesting that only dissolution, cementation and replacement have occurred, there is no field or petrographic evidence to suggest that the sediments under-went compaction during formation.

Discussion

This chapter looks to discuss and interpret the evidence proposed in subsequent chapters within the context of itself and other literature on a local and global scale.

Stratigraphic Model

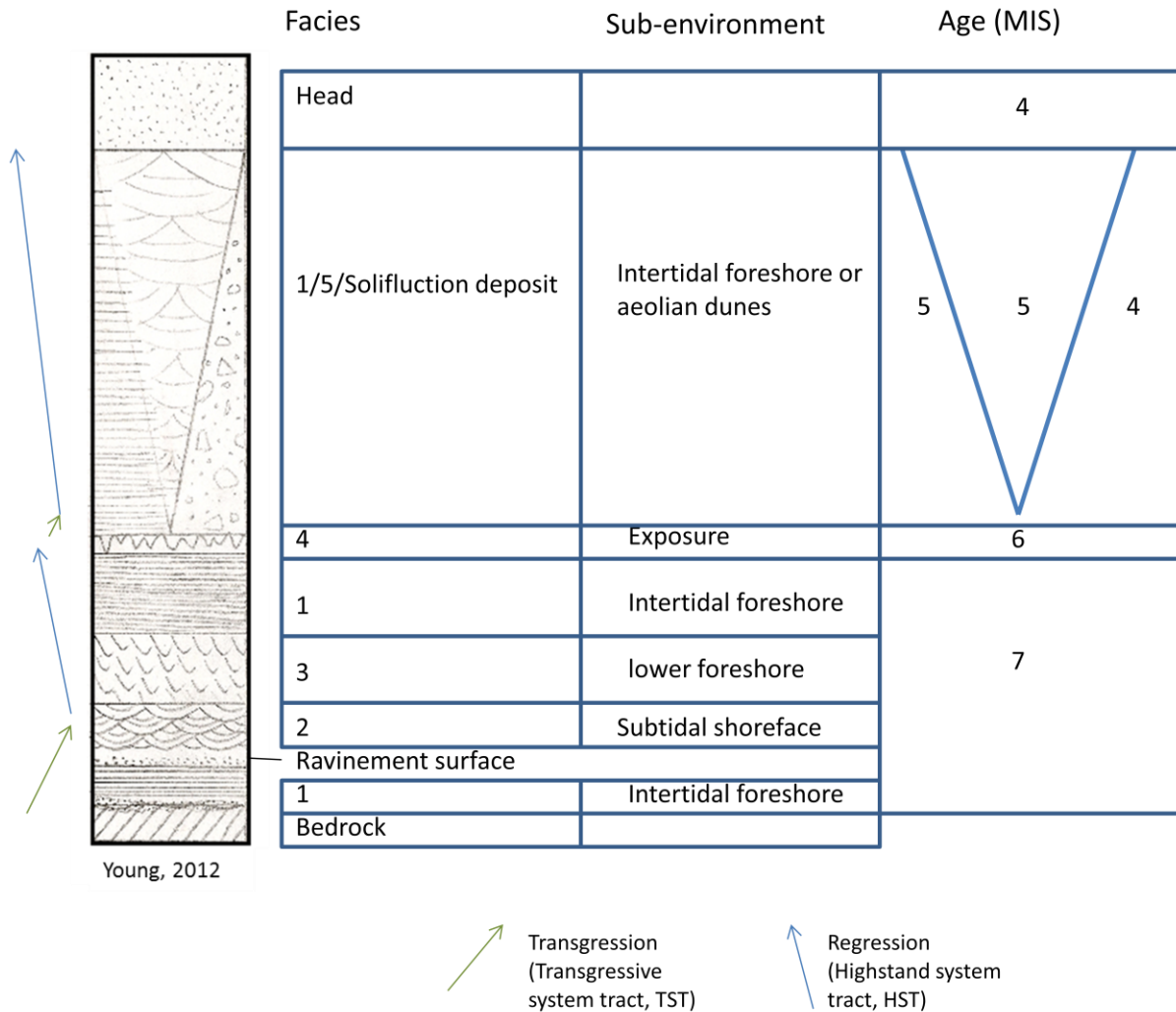


Figure 44: Final stratigraphic and environmental model.

The final stratigraphic interpretations, formed through the combination of facies interpretation and lateral variation observations, confirm the depositional model to be that of a shallow marine/beach environment. The presence of marine fossils, echinoderms, bivalves, foraminifera etc. in Facies 1,2 and 3 further evidence the interpretation that the environmental origin of the lower units in the succession is that of a marine one. These, along with the palaeosol and aeolian dune exposure facie interpretations combine to form a vertical succession model which contains both marine and terrestrial depositional environments. This fits with the earlier work by Williams (1937); De la Beche (1839); Prestwich (1892) and Gilbert (1996) who also split the succession into marine and terrestrial deposits.

The final model in figure 44, shows an initial phase of transgression whereby the rate of sea level rise has outpaced that of the sediment supply rate (Masselink and Hughes, 2003) causing the depositional environment to alter, from an intertidal foreshore/beach to a subtidal shoreface environment. Coset analysis has tentatively disproved the original thought that the maximum flooding surface (MFS) is represented by the top of trough cross bedded unit instead suggesting that the MFS lies within the unit (approximately half way up). At this point in the rock succession it was submerged the deepest. The pebbly sandstone layer located between unit 1 of facies 1 and facies 2 represents a ravinement surface and erosive surface caused by continued transgression. Following this point of maximum flooding, sediment supply must have began outpacing the rate of sea level rise, resulting in coastal progradation, a period of normal regression (Masselink and Hughes, 2003). Here the depositional environments migrated through the foreshore and backshore beach until reaching a point of exposure. The easterly part of Saunton continued this progradation becoming an aeolian dune environment however the model suggests the westerly part of the section underwent another phase of transgression, where the exposure surface was overlain with beach deposits. It could be suggested that the whole section continued aggrading during the last phase of normal regression and a second phase of transgression resulted in the partial erosion of the aeolian dune sediments, depositing beach sands in their place. Gilbert (1996) suggests the pinching out and disappearance of units laterally can be attributed to differential erosion across the section.

Campbell (1998) and Gilbert's (1996) facies models are proved incorrect with the inaptly named basal conglomerate facies being present in between Facies 1 and 2 instead of the suggested location of it above the shore platform and below Facies 1. It appears to be at the base of the succession on the most easterly point of the section as the first unit of Facies 1 is missing however moving westward it becomes apparent that this thin layer of pebbly sandstone lies between unit 1 of Facies 1 and Facies 2.

Figure 45 helps to highlight how Gilbert's (1996) stratigraphic log is missing the planar cross bedded sandstone facies identified within this study, instead he suggests the second unit of planar horizontally laminated sands lies directly above the trough cross beds. Unlike van Vliet-Lanoe *et al* (2000) and this study, where it is suggested that the units mentioned are separated by a unit of planar cross bedded sands.

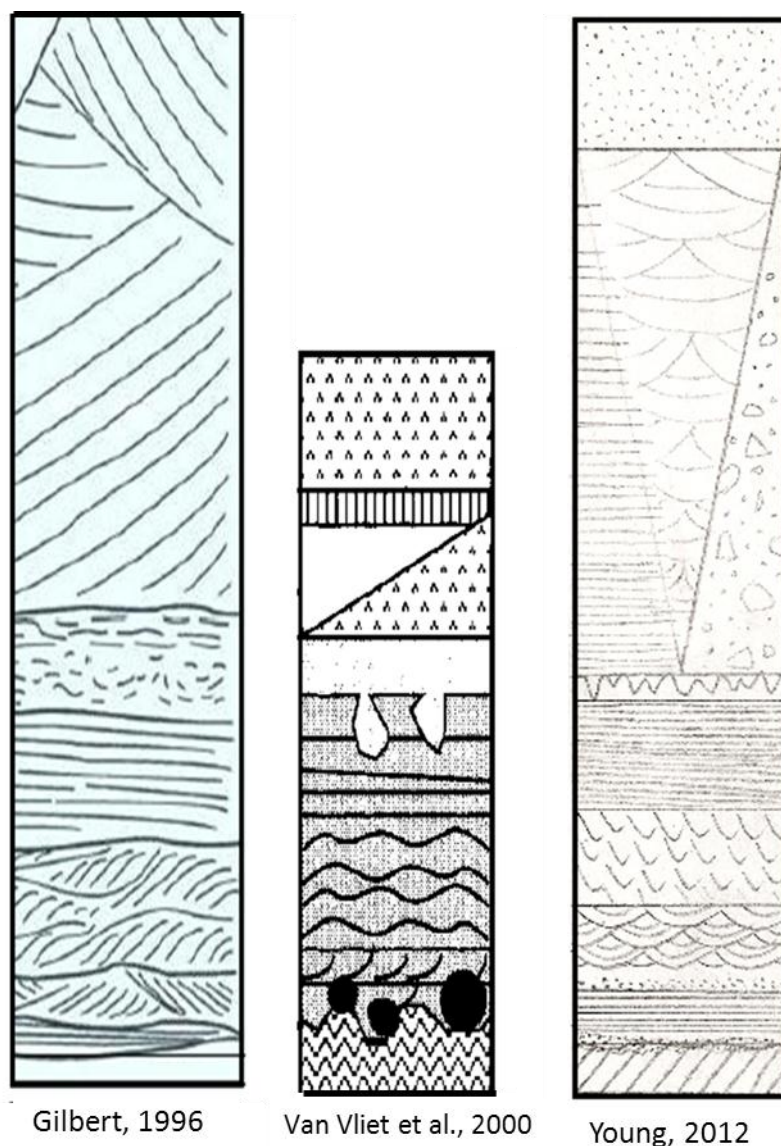


Figure 45: Stratigraphic logs of Saunton from 2 studies, Gilbert (1996), van Vliet-Lanoe et al (2000) and this paper.

Gilbert's model agrees in some way, with this revised model as it places the palaeosol (rhizocretion horizon) above this second unit of planar horizontally laminated sand. Unlike van Vliet-Lanoe *et al* (2000) who suggest that it lies between the dune/beach facies and the head deposit. This very well cemented rhizocretion horizon must lie under the large scale trough cross bedded unit solely because this facies is so poorly cemented. If the palaeosol had formed above the palaeo-aeolian dunes it would be expected that they would have under gone the same diagenetic processes which produced such well formed cements in both units.

The appearance of clay minerals within the sandstones acts as further evidence for the interpretation of the depositional environment, Tucker (2003) explains that glauconite (found in facies 2 and 3) forms in marine shelf environments that have been starved of sediment. Tucker (2003) also suggests that clay minerals form a part of the matrix of sandstones. Therefore the few grains could be remnants of a previous matrix which must have undergone precipitation during early diagenesis of the rocks to leave the few clay grains.

The textural maturity of the sandstones is hard to conclude. There are many characteristics of Facies 1,2 and 3 which could categorise them as super mature and others which would make them immature. The lack of matrix, very high abundances of quartz, rounded grains, well sorting of most samples and lack of chemically and mechanically unstable minerals (e.g. feldspars) suggest the sandstones to be very mature, however the presence of lithic fragments in moderate abundances relative to other grains in some thin sections present an argument that they are texturally immature. These interpretations are based on present composition and due to the extent of diagenetic alteration described in previous chapters, the original composition is somewhat misrepresented. Therefore it is difficult to summarise their original textural maturity. The lack of unstable minerals and intergranular matrix is evidently a result of dissolution and precipitation (Tucker, 2003). The characteristics of supermature sandstones e.g. well rounded and well sorted grains seen in Facies 2 and 3 can result from either long distance transport or from a lot of reworking of the sediment in high energy environments; this lends itself as further evidence for their subtidal shoreface and lower foreshore depositional interpretations.

The cements seen within Facies 1-3, representing the marine facies from the bottom half of the succession are described as equant in shape, suggesting it is composed of a HIGH Mg calcite cement (Tucker and Wright, 1990). The cement geometry is mosaic in nature, summarising the type of calcite cement present across all samples as equant spar drusy mosaic (Tucker and Wright, 1990). The cementation observed within the sandstones at Saunton, can be compared to that of model D in figure 46. This diagenetic model is based on the appearance of rock affected by a zone of CaCO₃ saturated meteoric water. The key diagenetic features in rock being that of cementation and grain replacement; which have been evidenced in chapter 3. Tucker and Wright (1990) explain how meteoric diagenesis operates on shelf margins and platforms of islands and not just on continental shelves, this fits with the depositional environmental model determined for the Saunton rock succession. Furthermore Tucker and Wright (1990) describe how meteoric diagenesis occurs soon after deposition where sediments rise above sea level either due to shoreline progradation/slight fall in sea level. The final stratigraphic model (figure 44) proposes a period of normal transgression where the bottom half of the sequence would have been exposed above sea level providing an opportunity for diagenetic processes to take place via these freshwater (meteoric) sources.

The solution cavities, cement geometries and rhizocretions all provide evidence for percolation of water through the succession, suggesting diagenesis occurred in the vadose (above the water tables) environment. Furthermore Beckner and Mozley (1998) state that rhizocretions are intimately linked to vadose cementation. It can be concluded that the diagenetic alteration across the first 4 facies represents formation in the meteoric vadose environment.

The presence of calcitic bioclasts within the sands suggests that they produced the concentration of calcium carbonate within pore waters, from their shells, which

precipitated out to form the carbonate concretions seen in the palaeosol horizon. This concurs with earlier work (West, 1973) where it was concluded that carbonate sources were internal for the cementation at Saunton and that they originated from redistribution of skeletal carbonate.

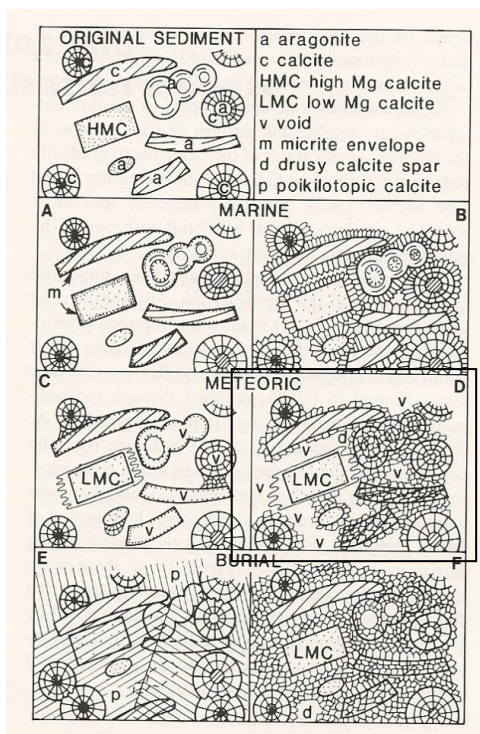


Figure 46: Diagenetic models for marine, meteoric and burial environments (adjusted from Tucker and Wright, 1990)

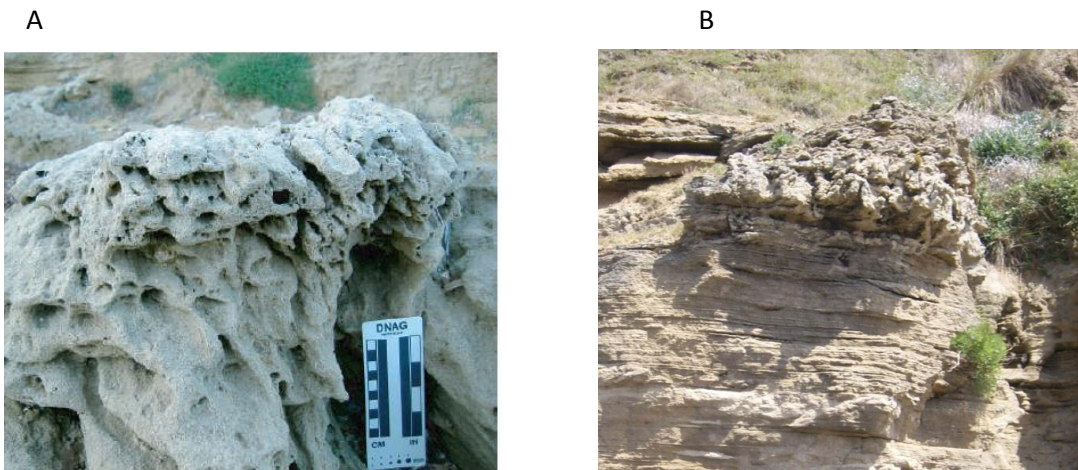


Figure 47: a) the carbonate concretions in Corsica from Cavazza et al., (2009) and b) the carbonate concretions in Saunton.

Cavazza *et al.*, (2009) undertook a study, specifically analysing carbonate concretions, very similar to the ones in abundance in the palaeosol horizon (seen in figure 47). Similarly to Saunton the marine terrace studied in Sian-Florent, Corsica was underlain by a well-cemented, low permeable Miocene andesite much the same as the Devonian sandstones and shales here and overlain by Holocene coastal sediments (e.g. low angle cross bedded beach and trough cross bedded shoreface deposits). They concluded, from cement chemistry, morphology and stable carbon and oxygen isotopic signatures that the concretions were formed by the precipitation of meteoric phreatic water flowing toward the coast. Furthermore they also found that elongate concretions (like the ones seen at Saunton) can be used as interstitial palaeo-flow indicators. A parallel can be drawn between both sets of results. The arrangement of concretions at both localities (perpendicular to the shoreline and sub-parallel to the direction of the maximum topographic gradient) suggests they are the result of cement precipitation of meteoric waters flowing toward the sea through porous rock.

The figure below (figure 48) taken from Cavazza *et al.*, (2009) can also be adapted for the succession at Saunton and the formation of the concretions there. Where QS1 is representative of sequence 1 during a period of transgression where relative sea level is rising and QS2 is the forced regression, linked to the formation of the palaeosol horizon shown here to have been formed by the percolation of meteoric water through the succession and towards the sea.

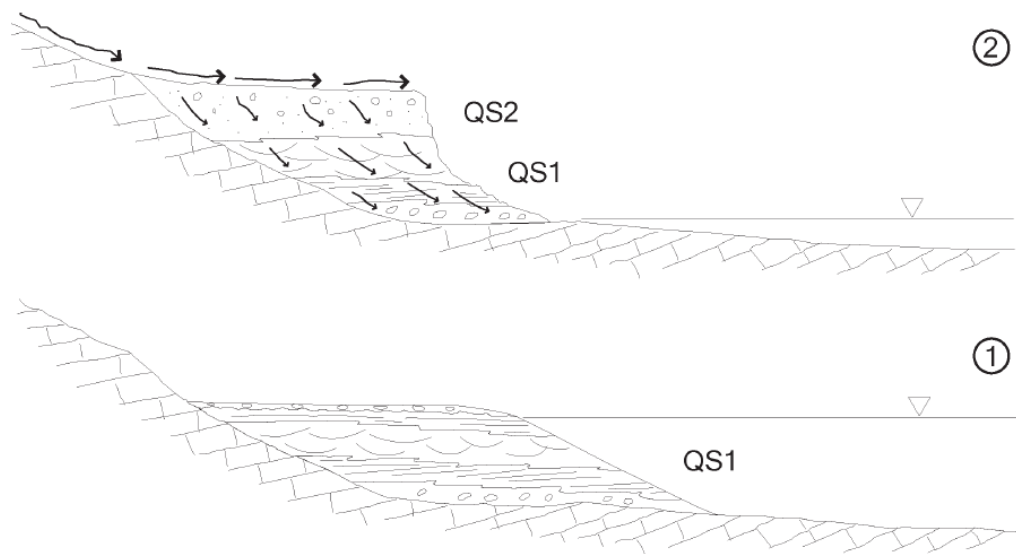


Figure 48: Diagram showing the direction of meteoric water through coastal sediments which results in the precipitation of cement and formation of carbonate concretions (rhizocretions) in Corsica (Cavazza *et al.*, 2009).

The syntaxial overgrowth cements seen across the echinoderm grains in many samples provide further evidence for precipitation in near surface, meteoric or mixing zone diagenetic environments (Tucker and Wright, 1990). Evamy and Shearman (1965) describe two limestones both with echinoderm fragments surrounded by calcite which go in and out of extinction together. The first of which mirrors the description of the sands seen at Saunton; whereby skeletal fragments, sand and interstitial fine-grained material which have been cemented by a coarsely-crystalline mosaic of calcite. They interpret these echinoderm overgrowths to have grown freely into open pore space and can be described as a true cement.

Relation to literature on South-west raised beaches

The second unit of stratified beach deposits and overlying head can be closely compared to the stratigraphy seen near Prawle point south Devon known to be last interglacial in age (MIS 5 - ~125Ka yrs) (Scourse, 1996).

Van vliet-lanoë *et al.*, (2000) suggest the marine sands above the shore platform (Facies 1-3) and overlying dune sands are representative of the OIS 7 interglacial (based on ESR dating) these units can be traced across from Baggy Point and Croyde Bay in north Devon owing to the same age. These units are missing from the sections at Fremington and Westward Ho! They also correlated the combined stratigraphy of Barnstaple Bay which includes Saunton across Dorset, Devon and Cornwall. The units related to OIS 5e appear to be shore face facies overlain with soil horizons (Fistral Bay, Prah Sands, Portland and Torbay) much the same as seen in the top of the westerly section at Saunton.

The magnitude sea level curve created from sequence stratigraphic analysis (figure 49), suggests that the succession at Saunton was in fact formed over 2 interglacial highstands of sea level. This fits with the conclusions of van-Vliet lanoë *et al.*, (2000), Bates *et al.*, (2003), Bowen *et al.*, (1985) and Scourse and Furze (2001).

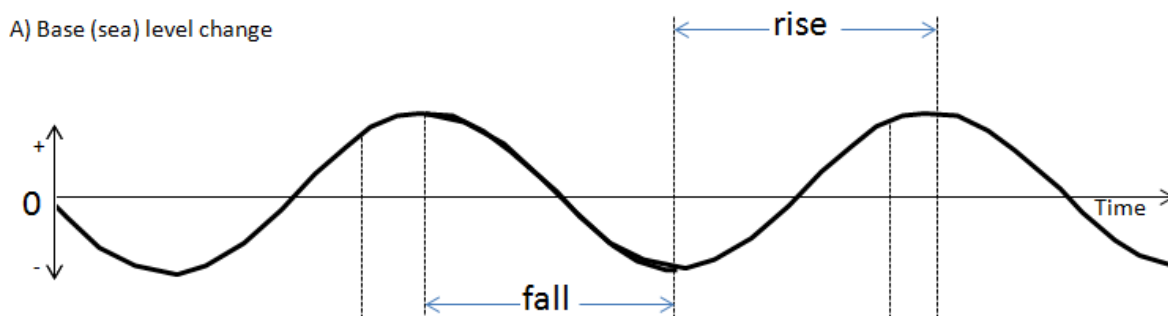


Figure 49: Magnitude sea level curve

These 2 sea level; highstands must be from the last 2 interglacials, MIS 5 and 7. With this knowledge it can be inferred that the palaeosol was deposited during a forced regression during MIS 6 and that the glacial solifluction and head deposits where formed during the subsequent glacial phase in MIS 4. This is summarised in figure 50.

Allen 2002 identified and studied 44 raised beach deposits from across the Bristol Channel and Severn estuary that date to the Ipswichian (OIS 5e) including those at Saunton. From these he concluded that sea levels were between 5-10m OD with during the last interglacial but this synthesis is based on the assumption that the tidal regime was not greater than today's macrotidal regime. This sea level reconstruction from MIS 5 concurs with the present location of the raised shoreline unit above the palaeosol horizon, which sits around 6m OD. Due to the glacio-isostatic adjustment of the south west of England after the disappearance of the British Ice Sheet after the last glacial maximum (Gehrels, 2010; Gehrels *et al.*, 2011; Shennan and Horton, 2002) it can be assumed that the units are more or less representative of former sea level heights with a slight alteration, taking into account subsidence of the southwest over the last 21Ka years. This provides further evidence for deposition of the sequence (2) during MIS 5.

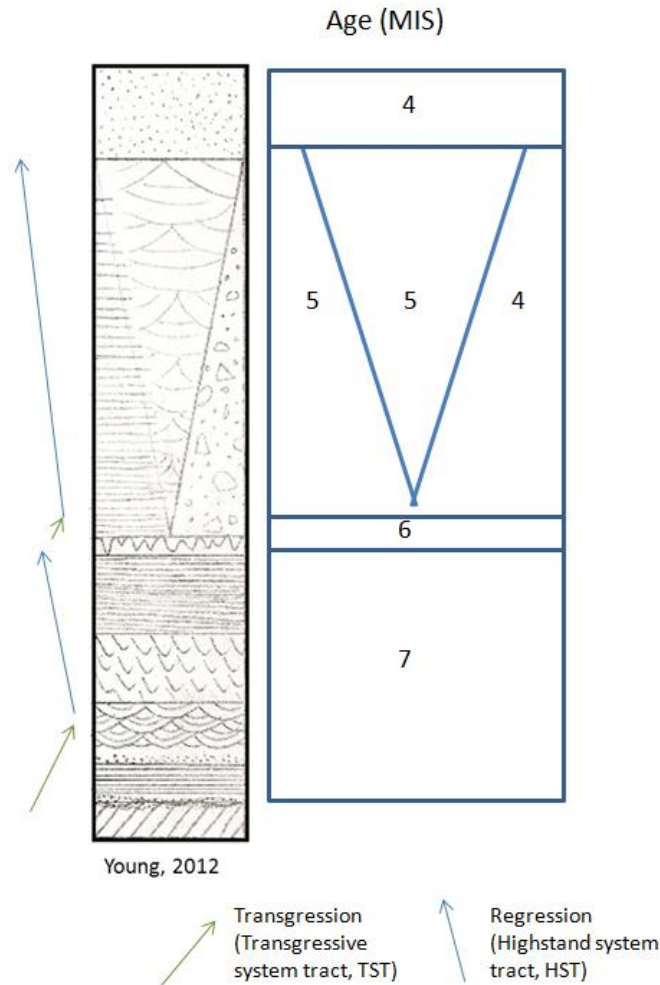


Figure 50: Stratigraphic sequence and inferred marine oxygen isotope (MIS) ages.

Kopp *et al.*, (2009) present further evidence for the interpreted ages of the sands above the palaeosol horizon. They used a combination of local sea level indicators and a statistical approach for global and local sea levels and ice sheet volumes taking into account any limitations for the last interglacial. Summarising that there was a 95% probability that global sea level peaked at ~6.6mOD corresponding to field observations of shoreline deposit heights.

Relation to wider literature

The solution cavities seen across the section help to constrain the palaeo-environmental sequence of events. Pazdur *et al.*, (1995) dated these “tubular pipe” walls and their host rocks across several localities in Southwest England (including those evident at Saunton) and South Wales. Using ¹⁴C and thermoluminescence dating. Their conclusion stated that the cavities post-dated cementation of the host rock. Furthermore a palaeoenvironmental timeline was reconstructed from their results which suggested initial formation of the raised shoreline which subsequently underwent cementation followed by the karstic formation of the pipes within the stratigraphic sequence. This can be applied to the sequence of events which occurred at Saunton to form said tubular dissolution features.

This, combined with the diagenetic observations in thin sections, suggest the sequence of diagenesis to be dissolution, of carbonate grains, cementation of precipitated calcite from the calcium carbonate saturated pore waters, replacement

of the bioclast shells with calcitic cements and possibly another period of dissolution which produced the solution cavities and continued dissolution of some cements and grains within the host-rock (sandstones).

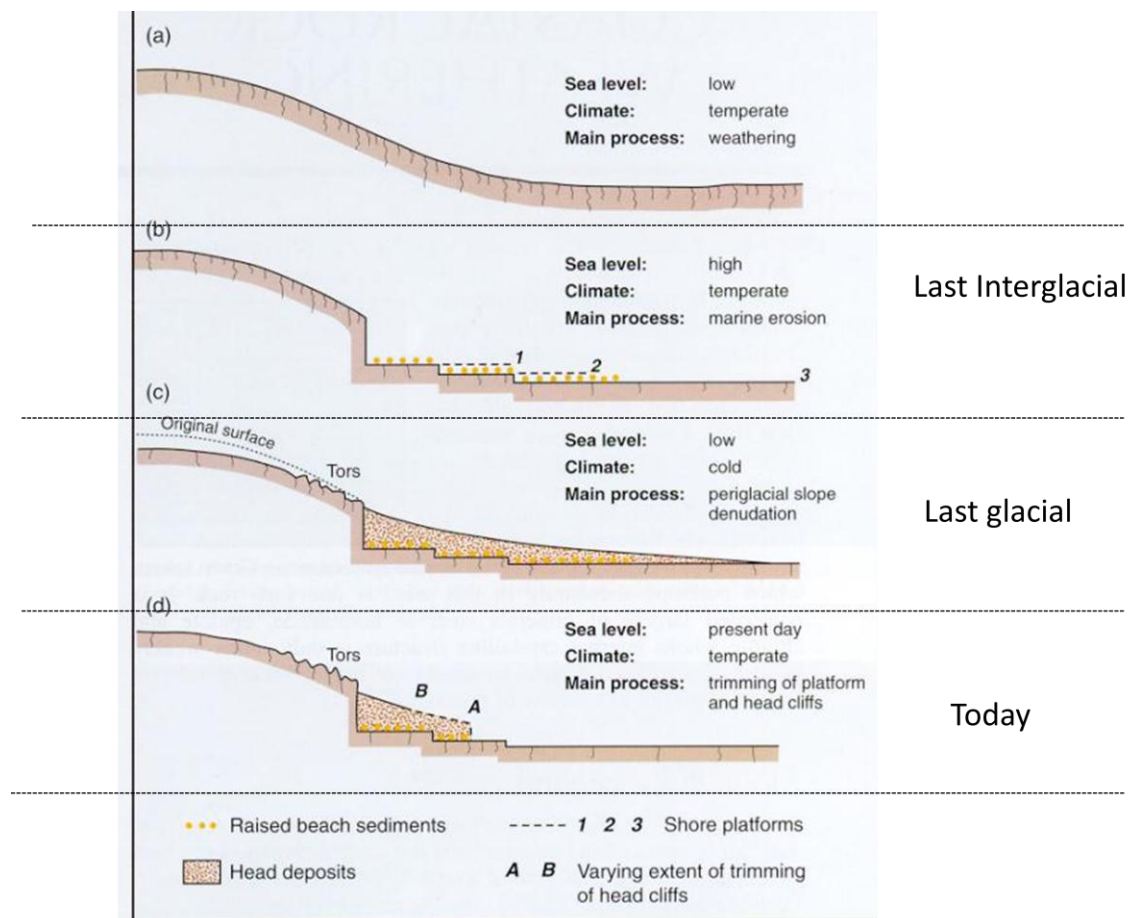


Figure 51: Diagram showing processes related to the formation of solifluction head deposits like those seen in the eastern section at Saunton and their relation to climatic conditions (edited from Mottershead 1997)

Figure 51, above, edited from Mottershead (1997), shows the stages of beach deposition at higher sea levels during the last interglacial and the processes under which they become overlain with periglacial solifluction and head deposits in subsequent glacial periods. The stratigraphy shown in figure 50d corresponds to the top of the succession at Saunton, suggesting the head to be of glacial origin and the underlying beach deposit to the west to have developed in during the higher sea level of the last interglacial. From this it can be further interpreted that the first unit of raised beach deposits could represent the previous sea level highstand before that of OIS 5e. This would link it to the interglacial linked to OIS 7 which would concur with the conclusions from the sea level curve.

Mauz and Hassler (2000) used luminescence dating on littoral sediments of marine terraces in southern Italy. The interpreted nearshore sediments dated back to MIS 5e. Other work on Pleistocene raised shorelines in Spain and Italy (Zazo et al., 2003 and Belloumini et al., 2002) also date them as last interglacial in age. These raised shorelines are evidently traceable across Europe which suggests the changing sea level responsible for the deposition of the raised shorelines at Saunton were a result of eustatic sea-level rise during the Pleistocene.

Conclusion

It can be summarised that the sedimentological and micropalaeontological evidence presented here indicate deposition of the raised beach deposits and overlying shallow marine sandstones under a temperate climate. Furthermore the stratigraphic sequence at Saunton appears to record two former sea level high stands. It is tentatively concluded that these relate to the last two interglacial marine isotope stages, MIS 5 and 7. To further constrain these interpretations for the relative dating of the raised beach deposits radiometric dating should be applied laterally and vertically across the section.

Similar Pleistocene geology to that of Saunton, dated to MIS 5e can be traced along both sides of the English Channel as well as in other countries e.g. Spain and Italy, strong evidence that the second unit of raised shoreline deposits here are a result of a eustatic sea level high stand during the last interglacial, 125,000 years ago.

The aim of the study, to use palaeontological evidence from bioclasts as palaeoclimate indicators was not fulfilled. The bioclasts found (e.g. bivalves, echinoderms and bryozoans) are not useful in constraining climates as they live across a range of temperatures. However, the foraminifera, could provide possible climatic evidence as different species inhabit specific temperature ranges. The extent of diagenesis upon them, within the samples used, made identification difficult therefore making palaeoclimate reconstructions near on impossible. However the MIS ages constrained from the sequence stratigraphy indicate deposition of the raised shoreline deposits under interglacial conditions and the palaeosol, solifluction and head deposits in a glacial setting.

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