Spatial and temporal patterns of erosion along the Holderness coastline, North East Yorkshire, UK

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Abstract
There is an increasing problem of erosion in coastal environments, particularly in soft material cliffs which need to be protected; migration to these environments is increasing, up to 75% more of the total population is predicted to live in close proximity to the coast by 2020. The Holderness coast (located in North East Yorkshire, UK) is the fastest eroding coastline in Europe. It comprises of soft clay, glacial till deposits from the Devensian period (18-13Ka). Previous studies have calculated that many parameters such as till properties, cliff geomorphology, cliff topography, strength and reaction to varied water contents are varied throughout this environment, spatially and temporally, which would give rise to varied erosion rates. However, averaged retreats from the whole location are given in the literature, which lacks a combined study. This study aims to investigate the spatial and temporal erosional variations along the coast by investigating and correlating trending data from parameters that vary spatially and temporally across the study area, with standardised methodology. The use of sinuosity is a new approach in cliff erosion. The main findings were that the lowest erosion was located in the middle section, where the Withernsea and Skipsea till combination gave high shear strength and formed the highest cliffs. The highest erosion rate was in the south, Withernsea till area, which had low shear strength, the highest plasticity index and the lowest cliffs. Throughout, high erosion correlated with high sinuosity and low erosion with low sinuosity. Predictive models imply that the middle location has a dominant subaerial erosion process. The south location however has the same subaerial and marine erosional process intensities, but the erosion varies due to water content which is controlled by seasonal variation; this effect differs between each location due to varying plastic and liquid limits. A maximum loss of 208m in the next 100 years is predicted.

1. Introduction

1.1.   The wider perspective

Coastal areas are extensively used globally; there is an attraction to visiting or settling in these environments as they provide many human benefits, such as: food, trading, fertile alluvial soils, spectacular scenery, wildlife, income and recreational activities. Two thirds of the largest cities in the world occupy coastal regions (Masselink and Hughes, 2003). However, 70% of coastlines are eroding, endangering coastal users and the settlements. Up to 75% more of the total population could live in close proximity to the coast by 2020 (Masselink and Hughes, 2003), therefore it is important to understand the rates of recession and how and why cliff lines erode.

1.2.   How coastal cliffs erode

Bird (2000) identifies that wave action mainly generates cliff cut back, which is further intensified during storm activity. Different erosional processes are presented by the varied types of the material within coastal environments. Figure 1 shows the UK's distribution of diverse material types. North, West and South Westerly parts of the UK have hard rock coastal environments, compared to the North East, South and Eastern sections which contain softer rocks and quaternary soil deposits. The latter softer materials are most at risk from intensive erosional recession and subjected to highly episodic processes which generate spatial and temporal varied erosion rates (Masselink and Russell, 2010).
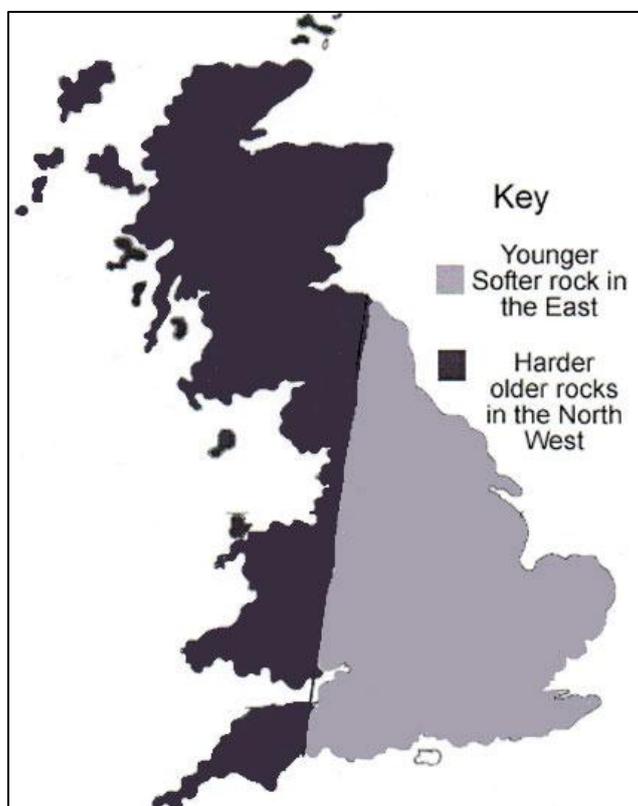

Figure 1: Distribution of soft and hard material (Roberts, 2008).

1.2.1. Varied processes

Bird (2000) expresses that rock falls triggered by heavy precipitation give rise to erosion, particularly in the winter season, when freeze thaw action expands and fractures the material. For example, in 1999, Beachy Head in Sussex (South eastern England) had a massive rock fall during cold weather. Freeze thawing can also generate slumping and toppling, distributing failed material at the base of the cliff, retreating the cliff top, but advancing the base by accretion of the slumped material, which is eventually broken and removed by wave action. This is typical in softer material, such as unconsolidated glacial deposits, in many locations such as Bournemouth and the Yorkshire coastline.

1.2.2. Spatial and temporal varied recessional erosion rates

Recession rates depend on many factors from the coastal environment such as: cliff geomorphology and the resistance of coastal material (figure 1), subaerial erosion, wave energy and tidal range. These factors are generally irregular along coastlines, giving rise to episodic erosional rates (Bird, 2000). It is mentioned by Bird (2000) that man-made structures and coastal use activities can generate varied recessional rates. Sea wall defences can stop the erosion in one location, but continuous factors of retreat occur adjacently, rapidly cutting back the cliff. For example, dredging at Hallsands (South Devon) accelerated cliff erosion, destroying a fishing village in the 1890s.

1.3. Study area

The UK is comprised of soft and hard rock material, which is subjected to varied erosional rates. In order to protect coastline, understanding erosion rates in softer rock and soil coastlines is needed, as they are prone to rapid erosion.

The Holderness coast, situated in North East Yorkshire, England (figure 2), is the area of interest, as it is highlighted as the fastest eroding coastline in the UK and Europe (Furlan, 2008; Quinn *et al.,* 2009). It extends for 60km, with undulating cliffs and a concave morphology (Quinn *et al.,* 2010). Pye and Blott (2010) identify average cliff heights of 15m, but these vary; they later express that the typical land use comprises of agriculture and tourism, with some energy resource stations. The EUROSION report (2007) indicates that the Holderness coastline is subjected to a maximum fetch which extends across the whole North Sea.
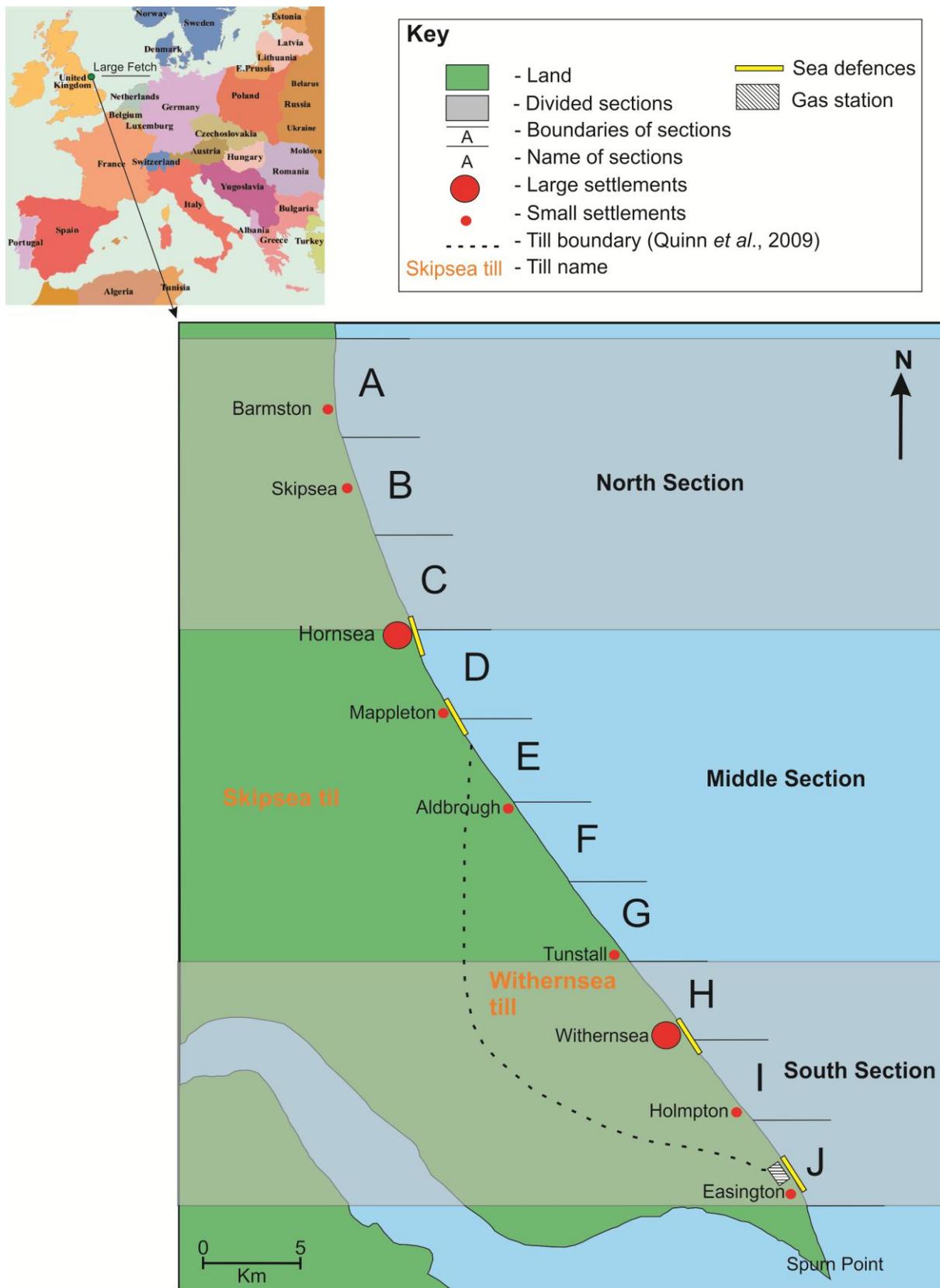
Figure 2: Study area location (Google Earth, 2012).

Many parameters, as discussed in section 1.2.2., imply varied erosional rates which are typical along the Holderness Coastline. For example the fetch across the North Sea as demonstrated in Dosser (1955) endorses destructive waves, intensifying erosional rates. Dosser (1955) further states that storm surges in this location have been recorded ranging from 1.8m up to 3.4m which intensified erosion and flooding. However these are rare episodic events, only occurring for one hour every two years.

Cliff morphology, such as the sinuosity, can identify locations of lower and higher erosion. For example, as expressed in Bird (2000), eroded material is deposited at the base of the cliff, acting as a temporary defence against wave action. However, continuous erosive activity still occurs, generating more cliff cut back in other locations, producing a dissimilarity of sinuosity along cliff sections.

The geomorphology of the beach can also provide a connection to varied erosional rates as suggested by NERC (2012b). They state that ord formations (which is a submerged barrier developed during storms as cited in Quinn *et al.,* 2009), can protect the cliff from erosion, but can also intensify erosion either side, due to exposure of cliffs to wave attack, which can also produce different cliff sinuosities.

Many other characteristics (parameters) such as the various till types and their geotechnical properties (shear strength) can contribute to this sinuosity morphology which are further detailed below.

1.3.1. Geology

The bedrock geology of this location is 30m below the surface and comprises of chalk originating between the Santonian and the Maastrichtian (85.5-65Ma) stages, within the Upper Cretaceous series (Quinn *et al.,* 2009; Quinn *et al.,* 2010). Figure 3 shows the geology of the study area, in relation to its surrounding geology in the North East England location. However, this material does not outcrop the surface as there are overlying Quaternary glacial till deposits; indicating that the soil bedrock lacks importance when considering the effects of varied erosional rates.
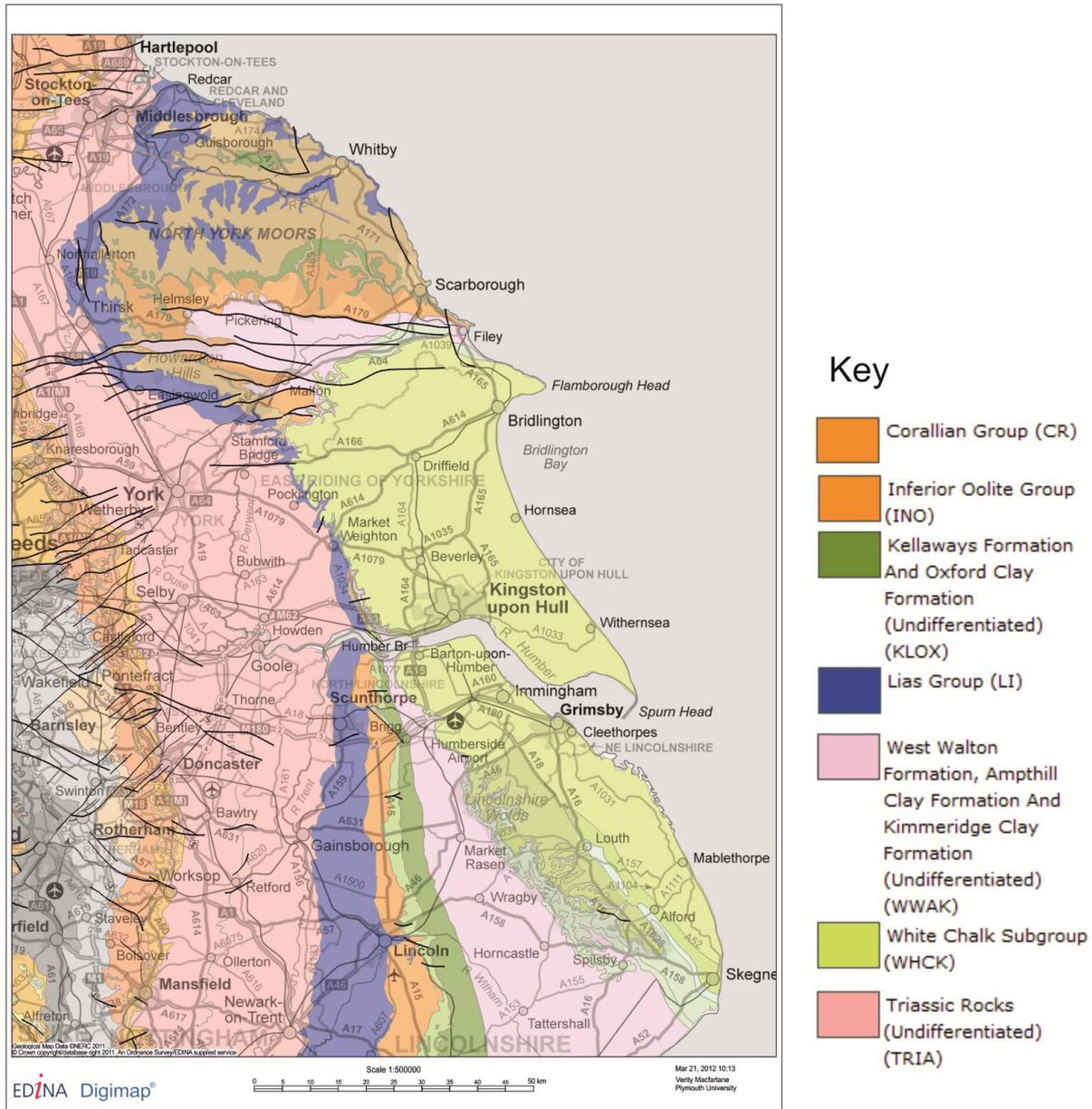
Figure 3: Geology of study area in relation to its surroundings.

1.3.2. Cliff geomorphology and relevant Quaternary history

The typical characteristics of the cliffs found in North East England are presented in Clarke *et al.,* (1998). Cliff layer one, Skipsea till, and two, Withernsea till, (Bell and Forster, 1991; Bell, 2002; HR Wallingford, 2002; Quinn *et al.*, 2009; Pye and Blott, 2010 and Quinn *et al.*, 2010) are the main materials investigated in this report, as the basal layer is rarely exposed at the surface within the Holderness coastline (Catt, 2007; Evans and Thomson, 2010; Quinn *et al.,* 2010), generating insufficient data for correlation.

HR Wallingford (2002) further expresses that Skipsea till extends along the base over the whole study area, with the Withernsea material overlaying the Skipsea only within a localised area ranging between Easington and Tunstall. Quinn *et al.*, (2009) and Quinn *et al.*, (2010) argue that there is an extension up to Mappleton.

Many literature sources state that both tills were transported and deposited during the last glaciation in the Devensian period (18-13Ka) (Bell and Forster, 1991; Bell, 2002; HR Wallingford, 2002; Quinn *et al.*, 2009; Pye and Blott, 2010 and Quinn *et al.*, 2010). Evidence further stated by Pye and Blott (2010) implies that the Skipsea till was deposited during 11,000-13,000 years ago and the Withernsea was deposited during 13,000-18,000 years ago; indicating two ice sheets, which is the idea presented by HR Wallingford (2002). Bell and Forster (1991) and Bell (2002) however oppose this notion by identifying that the time interval between both depositions is too short for two glacial advancements, and therefore propose both materials were deposited by a composite glacier containing two glaciers derived from different locations within Northern Britain.

1.3.3. Till properties

The distinctive colour difference between the till units is presented by NERC (2012b), (figure 4). The Skipsea till contains more chalk erratic clasts that the Withernsea material (HR Wallingford, 2002).
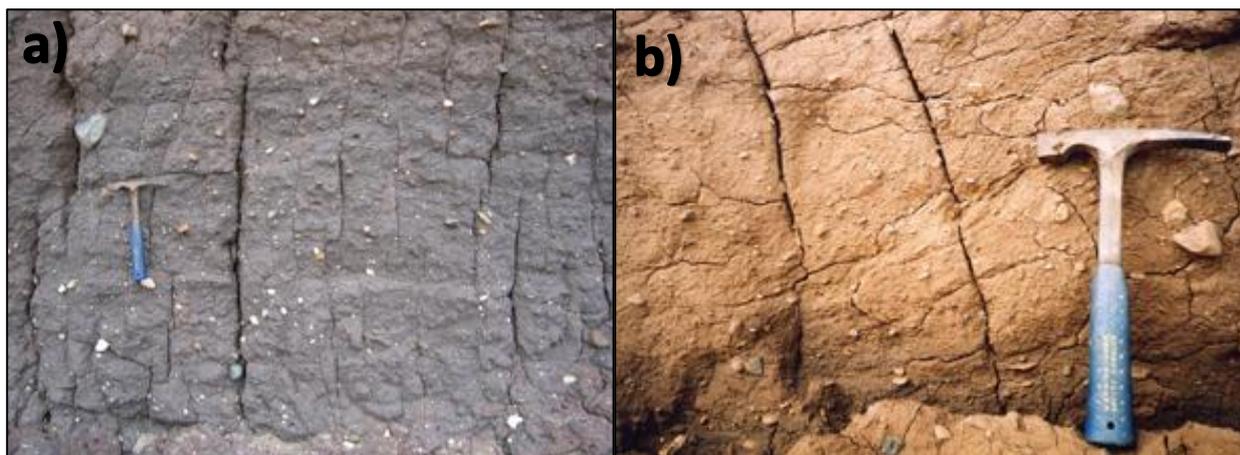

Figure 4: Colour variance of the tills found at Holderness a) Skipsea till b) Withernsea till (NERC, 2012b).

Geotechnical properties have been investigated by Bell and Forster (1991) and Bell (2002) who state that till shear strength can be obtained from Atterberg limits. These "define the boundaries between brittle, plastic and liquid behaviour" of material (Fookes *et al.,* 2007). The shear strength is varied in each state, and is measured by the moisture content within the material, as varying water generates expansion and shrinkage of soil and clay material, generally producing varied erosional rates, (giving rise to the importance of water within the cliff material) (Seed *et al.,* 1967). Seed *et al.,* (1967) further imply laboratory testing is needed to identify the moisture content within the materials to generate the plastic limit, liquid limit and plasticity index which are defined in figure 5.

Plastic Limit (PL)	"The minimum water content at which a soil can be rolled into a 3mm diameter cylinder", without disarticulating. This signifies the limit between a brittle and plastic material.
Liquid Limit (LL)	The moisture content at which a material changes from plastic to a liquid and flows as a result overall, reducing its shear strength
Plasticity Index (PI)	"A measure of plasticity" which is the difference between the LL and PL.

Figure 5: Definitions of Atterberg limit testing (Fookes *et al.,* 2007).

1.3.4. Varied erosion on the Holderness coast

The average erosional retreat rate has been calculated for this study area by many studies, which convey varied results. For example, Valentin (1954, cited in Lee *et al.,* 2001); Lee *et al.,* (2001) and the EUROSION report (2007) state that the average erosion rate is 2m per year compared to Valentin (1971, cited in Quinn *et al.,* 2009) and Pye and Blott (2010) determining a vague annual retreat rate of 1.2-1.8m per year and an even more ambiguous rate cited in Cambers (1976); RH Wallingford (2002) and Quinn *et al.,* (1010) of 1-2m per year for the whole coastline. These calculations are for the whole coastline; however as mentioned above, parameters of this coastline vary temporally and spatially, thus indicating varied erosional rates along the coastal section, further indicating these calculations to be vague and inaccurate.

Combining spatial and temporal differences would help provide a better understanding of the varied recessional rates; which is the idea presented by Quinn *et al.,* (2010) who state that the Holderness coastline has variable topography which gives rise to dissimilarities in stability. Details of combined parameters such as cliff heights, failure characteristics and material type are limited within the literature.

 It seems likely that an investigation that brings all proxies together could provide a reliable and more accurate understanding of how and why varied erosion rates occur. A review by Quinn *et al.* (2009), showed the importance of combining parameters, but the datasets were not standardised in respect to data collection and methodology, resulting in the inability to make accurate correlations between each parameter. This report seeks to achieve this aim by studying all parameters simultaneously from one dataset.

1.4.   Aim and objectives

The main aim of this study is to investigate the spatial and temporal erosional variations along the Holderness coast. This will be achieved by investigating many parameters and correlated findings.

A preliminary desktop study will indicate areas of interest, which will be assessed by cliff sinuosity, determining areas of lower and higher erosion. This method will be adapted from the original mountain front sinuosity method which determines the cause of mountain morphology. This will either be tectonic forces generating straighter mountain fronts, or curved fronts generated by erosional forces, such as

river incisions (Keller and Pinter, 1996). This definition will be applied to the varied sinuosity along the Holderness cliff line, which has not previously been used within the literature as a method to detect spatial variable erosional rates. Increased (high) sinuosity would imply higher erosional rates than those seen in straighter cliffs.

Data collection will be taken in the field, investigating areas of interest previously identified. Erosion rates will be investigated spatially across the location area, and also calculated temporally, comparing against older photographic imagery. Mapping of the two till types, their sedimentology, and cliff morphology, will determine the extent of their spatial distribution and the variance across it. Geotechnical properties of the soil material will be investigated, determining the shear strength of in situ material, and the moisture content, defining plastic, liquid limits and plasticity index of soils; tests will be undertaken within the laboratory from a collection of soil samples.

Data will be correlated to produce the spatial differences, identifying the characteristics of the highest and lowest erosion locations, providing a more concise understanding of why erosion rates vary along this location. With this information, predictive models will be produced to explain how various locations erode. Then generalised future scenarios will be developed, calculating the amount of retreat within the next 20, 50 and 100 years (with relation to global warming) and estimating how this will affect the coastline's future.

2. Methodology

2.1. Planning and desktop study

Planning production entailed construction of a written proposal including logistics and an extensive risk assessment form for preparation of data collection whilst 'in the field'. Background research was further analysed to understand the nature of the environment in terms of the geology and geomorphology of the landscape.

Cliff erosion was also investigated to apprehend its significance to this report. Preliminary data collection was assembled using Google Earth as a reconnaissance tool, surveying the whole location for areas of interest to investigate 'in the field'. The whole location was divided into 10 areas (section A-J) approximately 5km long, totalling to a 50km study area. This desktop study initiated the idea of cliff sinuosity which could pose a possible link to varying erosion rates along the Holderness Coastline. This method has been adapted from the original mountain-front sinuosity technique demonstrated in Keller and Pinter (1996). To determine the cliff sinuosity, each section was calculated by dividing the straight line distance (approximately 5km) by the length of the actual cliff line within each section (which was measured using the path tool in Google Earth). The 50km study area was divided into ten 5km sections because this was a suitable distance to map during daily field work collection, considering tidal restrictions.

This technique produced preliminary quantitative data, which enabled a classification system to be devised for determining low, medium and high sinuosity locations. Classification scales were creating considering the minimum and maximum giving a full range of values; categories were then selected, sectioning the data that represented the spread of results. Thus this study determined specific locations for further investigation whilst 'in the field'.

2.2. Primary data collection

Areas of interest from the desktop study were further analysed with different techniques in the field. GPS waypoints were logged at each measured location using a Garmin GPS. These waypoints furthermore were measured differently due to different settings; either at the cliff base or along the top of the cliffs to acquire various data sets.

2.2.1. Cliff top data collection

Along the cliff top, distances were measured along sections of the coastline by attaining the distance from the logged waypoint to the edge of the cliff, using a Trupulse 200 (perpendicular to the cliff line). Also specific markers within the landscape, called objects on Google Earth data, such as military pillboxes built in the Second World War and houses, acted as a static point to calculate the erosion rate upon re-measuring the same distance on Google Earth, which comprises of 2007 imagery. These methods were constructed to calculate an average erosion rate in various locations on the Holderness coast (see section 2.3 below for further details). Classifications were created, which defined locations of low, medium and high erosion. These ranges were different to the classifications produced for the desktop study, due to a dissimilar type of values. This erosional method was implemented from Fookes *et al.,* (2007) which displays a similar approach to investigating erosion rates. Static posts were used as markers to measure the distance to the cliff edge on a temporal scale, generating an average erosion rate.

2.2.2. Cliff base data collection

The cliff base measurements consisted of stratigraphic logging, along with visual aids of field sketches and photographs. Various parameters were also investigated along the cliff base. Using the Trupulse 200, the cliff height and thickness of till units were recorded, as well as the overall inclination of slopes (particularly of slumped material). Soil samples were collected randomly throughout the study area, for further laboratory analysis. Geoengineering designed equipment was used at random waypoint locations. This equipment included a Geovane Soil Shear Strength Tester and a Proctor Penetrometer.

The Geovane contained a series of cross-hare rods of varying size, only the small and large rods were used (20x40mm and 16x32mm). These were attached to the Geovane dial to begin. The rod was inserted into the in situ material until the whole of the cross hare was submerged, making sure no twisting motion occurred. The dial was set to 0 and then clockwise rotated at a steady slow rate. The maximum shear strength is determined when the material begins to shear (Humboldt, 2009a). Hartley, R states that 19mm dial is used to take a reading for the small rod and 33mm dial is used for the larger rod, furthermore the readings are expressed in Kilopascals (kPa), (personal communication, June 28, 2011).

The Proctor Penetrometer comprises of a range of penetrative needles which are inserted into the in situ material. Needle sizes used were: 3/4 square inch (4.84cm^2), 1/3 square inch (1.29cm^2) and 1/10 square inch (0.65cm^2). Only one needle is required, this is determined through trial and error of actually being able to penetrate the material, making sure the dial is set to 0 prior to this. The surface moisture penetration resistance is determined when the needle has penetrated up to the first

centimetre (only) marked on the rod (Humboldt, 2009b). The readings are expressed in pounds per square inch (Psi) thus a calculation is required to convert them to Kilopascals (kPa). Hartley, R indicates that the penetrometer reading is divided by the needle size which converts the values correctly, (personal communication, June 28, 2011).

Three or more readings were taken from both Geovane and Proctor Penetrometer which were then averaged; only surface strength was measured using the Geovane and Proctor Penetrometer, measurements at depth did not occur.

2.2.3. Laboratory data collection

Additional laboratory based data was collected after the field visit using the collected soil samples. Atterberg limit testing was conducted on the samples, identifying varied strengths between the till types, along the Holderness coast. Initial set up was required where the soils were dried for 24hours in a 40°c oven and grinded down to <500 microns, extracting clasts and adding distilled water, depleting any aridity. The plastic limit of the samples was tested first, this is where a walnut sized sub sample was flattened to 6mm thick, and then rolled with equal pressure 10 times making sure it does not crumble apart and is 3mm thick. The plastic limit is reached when surface cracks appear on the sub sample and it is still intact. This is then added to a previously weighed phial and re-weighed immediately and stored. This procedure is repeated a further 2 times, totalling in 3 sub samples per soil sample. The sub samples are dried for 24 hours in a 40°c oven and then reweighed. Basic calculations determine the moisture content at the plastic limit of the samples, (Hartley, R, personal communication, June 28, 2011).

The liquid limit was finally tested, which required the samples to start off wetter than the previous plastic limit. A cone penetration testing (CPT) method was conducted; a sub sample was placed in a cup, ensuring no air holes, and the surface scraped smooth. The sample was put under the CPT apparatus so the cone just lightly touched the sample. The start button was pushed allowing the cone to drop into the sample for five seconds. After this time the dial was turned to reach the top of the cone rod, and the reading from the dial was recorded. This overall process was repeated three times enabling an average reading. A pea sized piece of the sub sample was then put into a previously weighed phial and re-weighed. A new sub sample was generated using the same method but adding more distilled water to the sample each time. The samples were dried for 24 hours in a 40°c oven and reweighed. The process was repeated four or five times. Calculations were generated to obtain the moisture contents. The results were plotted on a graph, ideally making sure that at least two readings were below 20mm (liquid limit) and two were above. A line of best fit was applied onto the graph to determine the moisture content at the liquid limit (20mm). The Plasticity Index was calculated by subtracting the liquid limit from the plastic limit (Hartley, R, personal communication, June 28, 2011). Only a small amount of samples were collected and used for this further analysis thus indicating a minor role towards final results.

2.3. Data processing

Initially GPS waypoints were uploaded onto Google Earth (2007 imagery), zonation of the Holderness coast sections were divided into North, Middle and South locations and databases were generated from all the collected data. All cliff top data

represented current up to date values (2011). These waypoints were re-measured estimating a new distance to the cliff edge from the 2007 Google Earth imagery using the path tool. The two values were then subtracted from each other to calculate the amount of erosion which occurred at the specific locations over 4 years, and then were further calculated to produce an average annual rate of erosion at various locations of the Holderness coast. Each variable was plotted onto graphs stacked below each other and annotated with relevant sketches, photographs and logging to show variation over the Holderness coastline. Lastly all the parameters were divided up into zones (low, medium and high) to show changes spatially, to allow easy correlation between them (see chapter 3 for the final results).

2.4.   Data analysis

Results were correlated (figure 23) illustrating the spatial trends of the parameters along the Holderness coast, to enable identification of higher and lower erosion locations. Predictive models were created (figure 23) showing the possible processes that could produce the erosion, judging by the cliff geomorphology and till types. Results were compared to the literature and applied to generalised future scenarios, illustrating the cliff retreat in the next 20, 50, and 100 years, with relation to climatic instabilities (figure 30).

Results

3.1.   Desktop study results

The sinuosity measurements generated by the preliminary desktop study give an indication of whether erosion is occurring at different rates along the Holderness coastline; with high sinuosity implying higher erosional rates than those seen in straighter cliffs. Figure 6 depicts the sinuosity values of each divided section of the area as well as giving an overall general value and averages. Overall, the Holderness coastline has a mean sinuosity value of 1.21 which falls into the medium classification. The minimum sinuosity reading was 1.08 located in section D, and a maximum value of 1.35 was recorded with the H.1 section.

3.1.1. North section sinuosity results

The north, section A shares this same value of medium sinuosity, but further down the coast in sections B and C the values range from 1.12 (C) to 1.15 (B) showing a low sinuosity, giving a low average for the northern section (1.16).

3.1.2. Middle section sinuosity results

Section D, E, F and G convey the middle of the Holderness coast, which seems to also convey low sinuosity, with a value of 1.18. However some variation is apparent within the individual sections. The lowest value of 1.08 is located in section D which increases overall through the middle section of the Holderness coast; for example, low sinuosity of 1.08 in section D increases to 1.08 to 1.20 in sections E and F, which further increases to 1.23 in section G further down the coastline. Section D contains the lowest sinuosity therefore the straightest cliff section within the Holderness coast. 1. This may indicate that this location is the least active in terms of erosion, further implying that this location could contain less erosion as sinuosity may be a function of erosion.

3.1.3. South section sinuosity results

Within the southern locations (sections H, I and J) the overall trend of sinuosity is 1.23 (medium). In sections H and J, two seawalls dominate the coastline which would represent an incorrect sinuosity reading for the locations, and so smaller locations (sections H.1, J.1 and J.2) have been produced to only measure the exposed cliffs within the sections. Section H conveys a medium sinuosity (1.22) involving the seawall, however the value increases dramatically to 1.35 in the concentrated location (section H.1) thus demonstrating that the seawall (approximately 2.1km long) would skew the results. Section H.1 is demonstrated to have the highest sinuosity of the Holderness coastline, which may indicate more erosive activity in this highly active location. To follow, section I also seems to demonstrate this high sinuosity, measuring 1.31. At the end of the study area in section J, the overall sinuosity is low, generating a value of 1.17; however as mentioned above, this area contains a fairly large seawall, which is approximately 1km long to protect the gas station at Easington. Concentrated areas show an increase in sinuosity, with the greatest value south of the seawall (section J.2) rather than before the seawall (in section J.1), but both are within the medium frequency of sinuosity. Section J.1 is valued at 1.20 which increases by 0.5, giving a total of 1.25 sinuosity in the south (section J.2).

3.1.4. Overall sinuosity trend

On the whole, the cliff line tends to become more sinuous down the coastline towards the south. The straightest cliffs are located within the Northern sectors (sections B, C and D), with section D as the straightest throughout the Holderness coastline. The highest sinuous cliffs however are found within a smaller concentrated area in the south (sections H.1 and I). These findings may indicate an increased erosion rate generally tending southwards, but further analysis is needed. However, it is clear that this data has indicated that there is a variance of erosion occurring within the Holderness coastline due to general increased activity towards the south. These findings can be further analysed from the generated erosion rates mentioned below (figure 7), and summarized spatially in figure 8.

Desktop study - Remote Sensing Database (2007)

Whole Cliff Data **Km**

Straight line	50
Cliff Line	60.51
Sinuosity reading	1.21

Sinuosity Classification

Reading	Rate
0.0-1.19	Low
1.20-1.29	Medium
1.30-1.40	High

Sections	Cliff Divisions	Straight Line Length (km)	Cliff Length (km)	Sinuosity Reading	Sinuosity classification	Additional Description
A	North	5.1	6.19	1.21	Medium	
B	North	5.15	5.91	1.15	Low	
C	North	5.15	5.79	1.12	Low	
D	Middle	5.1	5.53	1.08	Low	Lowest, straightest inactive section
E	Middle	5.12	6.12	1.20	Medium	
F	Middle	4.92	5.92	1.20	Medium	
G	Middle	5	6.16	1.23	Medium	
H	South	5	6.11	1.22	Medium	Lower due to sea wall
H.1 (above sea wall only)	South	3.1	4.17	1.35	High	Concentrated area
I	South	5.17	6.78	1.31	High	Highest, most active section
J	South	5.14	6	1.17	Low	Lower due to sea wall
J.1 (above sea wall only)	South	3.52	4.21	1.20	Medium	Concentrated area
J.2 (below sea wall only)	South	0.64	1.89	1.25	Medium	Concentrated area

Summary Averages

Reading	Average Sinuosity	Classification rate
Whole cliff	1.21	Medium
North	1.16	Low
Middle	1.18	Low
South	1.23	Medium

Figure 6: Remote sensing desktop study measuring the sinuosity of the Holderness Coastline.

3.2. Erosion rate results

To test the significance of the pilot desktop study erosional rates were calculated implying that high and low areas of sinuosity can correlate showing varied erosions along the coastline.

Figure 7 depicts these findings as well as displaying them as a spatial component in figure 8. Figure 7 suggests that the majority of the coastline has a relatively low annual erosive rate. On average the northern sections of the Holderness coastline have a low erosive rate of 1.72m/y; this decreases slightly to 1.58m/y located at section G in the middle section of the study area. Towards the south, the erosion activity increases rapidly over a small distance from sections G to H (approximately <5km). This generates a medium erosion frequency of 2.08 meters per year.

In detail, each section has a wide variation of values producing a diverse range of erosion rates per year. This may be due to the types of methods used to collect this data, which spatially generate varying erosion rates in a small localised area or spread across a larger zone. Reliance on method type is further discussed in Chapter 4. The track data (day 1 and 2 tracks) are spread over a wider area indicating an average rate. However, the static object data conveys an erosion rate specific to that location. Thus, explaining why the two types of methods produce dissimilar results; for example, the day 1 track (approximately 3.20km long) located in section H produced a medium average erosion rate of 2.39 meters per year. However, in comparison, object number 11 found in the same location as the track only conveyed a low erosion rate of just 1 meter per year. This trend occurs also with day 2 track data (approximately 0.3km long) with a highest erosion rate of 3.33m/y, compared to object number 12 which shows at a value of 1.58m/y, these are both located in section I. Due to the dynamic nature of the coastline, the localised readings may not provide sufficient results to demonstrate an overall average for each section within the study area.

3.2.1. Combining sinuosity and erosion rate data

Linking with the sinuosity data, it is apparent that the high sinuosity recorded mostly in the southern locations (mostly concentrating in sections H.1 and I) strengthens the idea of highly curved cliff lines being more erosive than straighter cliffs. This evidence is further supported by the opposite measurements. For examples in the northern locations the average annual erosion rate is low and the sinuosity is classed as low, indicating that those straight cliffs are less actively erosive.

Further analysis is needed to understand why the south is more erosive than the northern locations. Investigations of the physical properties within the coast will could determine this.

Comparing the findings generated in the southern location, using objects and using tracks, using the tracks data suggested much higher retreat rates. For example, day two track calculated 3.33m retreat rate, compared to only 1.58m retreat calculated from object 12; both lye within section I.

Annual Erosion Rate Classification (m)

1.00-1.99	Low
2.00-2.99	Medium
3$^+$	High

Locations	Sections	Cliff Divisions	Amount of cliff eroded in 4 years (m)	Annual erosion rate (m)	Classification rate (m)
Average for Objects 1,2,3 and 4	A	North	6.88	1.72	Low
Object no. 10	G	Middle	6.10	1.53	Low
Day 1 track	H	South	9.57	2.39	Medium
Object no. 11	H	South	4.00	1.00	Low
Object no. 12	I	South	6.30	1.58	Low
Day 2 track	I	South	13.34	3.33	High

Summary Averages

Locations	Average annual erosion rate	Classification rate
North	1.72	Low
Middle	1.53	Low
South	2.08	Medium

Figure 7: Calculated erosion Rates from the Holderness Coastline.
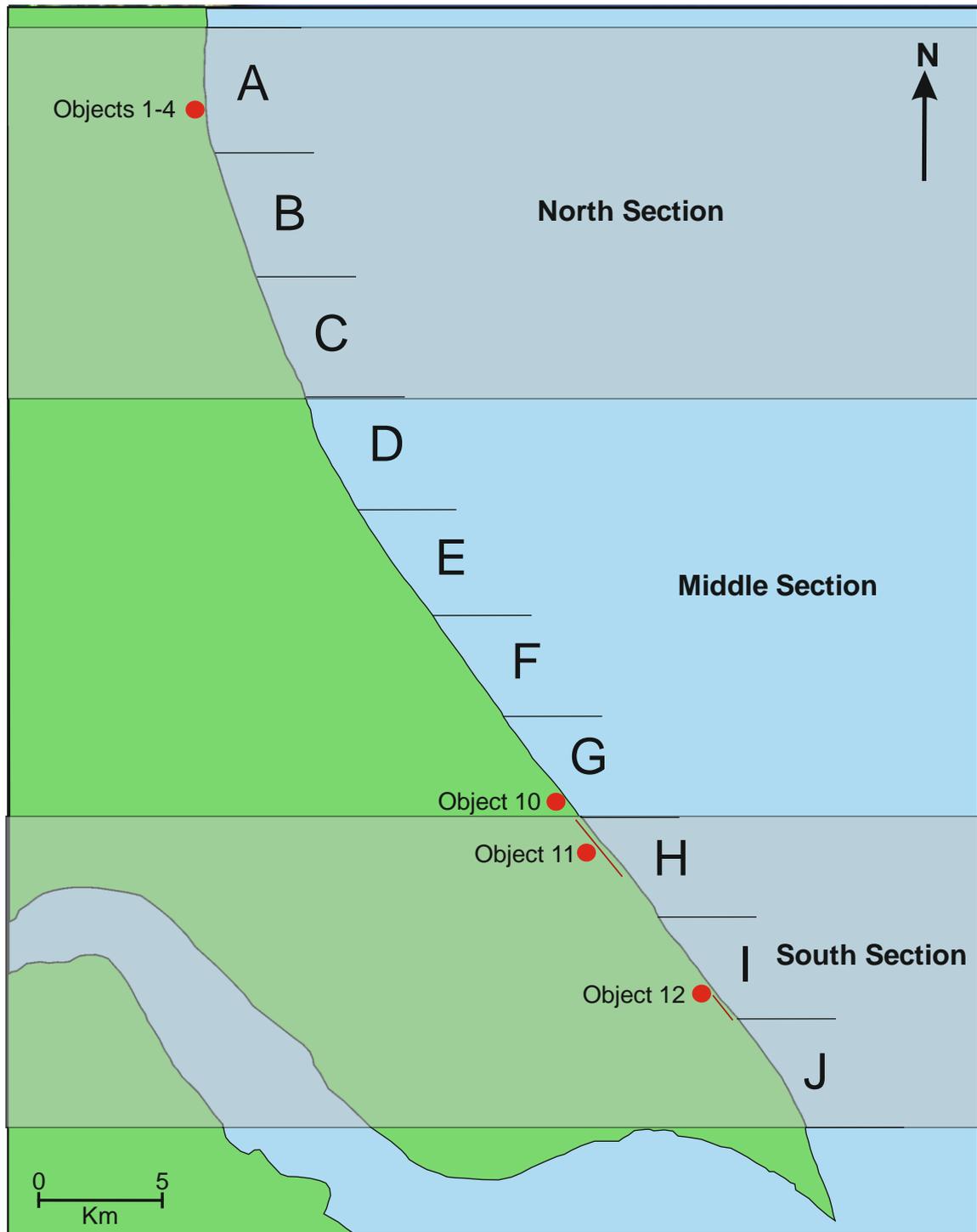
[345]

Figure 8: Summarising the spatial distribution of collected annual erosion rates along the Holderness coastline

3.3. Cliff characteristic results

The general stratigraphy and lithology of the Holderness coastline is displayed using three visual mediums which are: stratigraphic logs, photographs and field sketches. These all represent the general findings of the material found at the north, middle and south locations of the Holderness coastline.

3.3.1. Stratigraphy and lithology of the North section

The northern location was investigated only in section A. Figure 9 indicates a Skipsea till platform is present (see figure 10 for further details on the Skipsea till) along with a laminated sand layer which dominates the cliff. Sand layers have been located over the majority of section A (waypoints 001-012) which vary in thickness (approximately from 1 to 5m) eventually graduating away, leaving just the Skipsea till unit (waypoints 013, 20 and 25).

Figure 9: Photograph taken in the field within the northern location of the Holderness at waypoint 001 showing a platform, comprised of Skipsea till and laminated sand cliff stratigraphy.

Figure 10 presents a stratigraphic log which conveys the soil strata found at waypoint 003. It indicates that the whole unit is facies 1 (Skipsea till) with a top soil horizon located in the top 0.4m of the cliff. The Skipsea till is dominated by clay but contains a small amount of sub-rounded gravel clasts (1cm). A sharp boundary at 4.3m introduces the laminated sand layer which is 1.1m thick. It then changes to a minor conglomerate layer, 0.5m thick, housing more small clasts than the basal layer (approximately 1-2cm sized).

Figure 11 depicts the stratigraphy and lithology information at waypoint 011 locates the Skipsea unit colour which has changed to a darker brown layer including thin

laminations; also the sand layer is again present towards the top of the section. Around this area rock armour sea defences have been put in place fronting the cliff, protecting it from marine erosion; which may indicate that this location is a weaker zone. Other evidence supports this; for example the basal Skipsea till unit contains a series of indent cave like features which look like they have been undercut by wave action; also the thin laminations found are very easy to crumble in your hands. A soil sample was taken at this location to undergo lab analysis, to determine whether it is susceptible to erosion (see section 3.5 for more information).

FACIES	SCALE (m)	LITHOLOGY	MUD SAND GRAVEL	NOTES
1			clay silt vf f m c vc gran pebb cobb boul	

Top Soil

Small, 2 cm pebble sized clasts

Brown, yellowish colour

Light Brown colour contains flat platform approx 1.5m from base. D/DD - 08/084 Rubble texture Contains some very small clasts (1cm), sub rounded
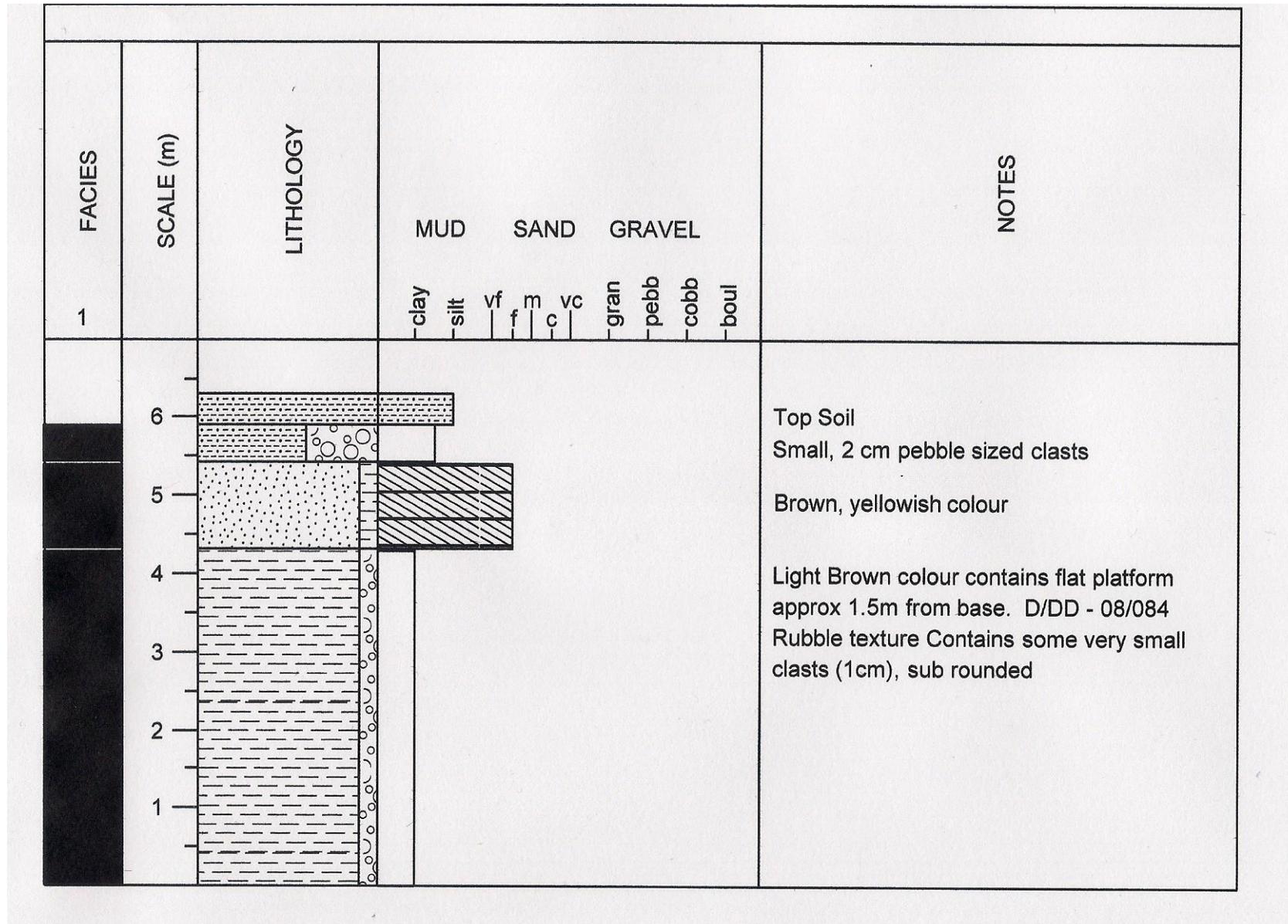
Figure 10: Stratigraphic log from the north location at waypoint 003 (section A) (scale 1:100).
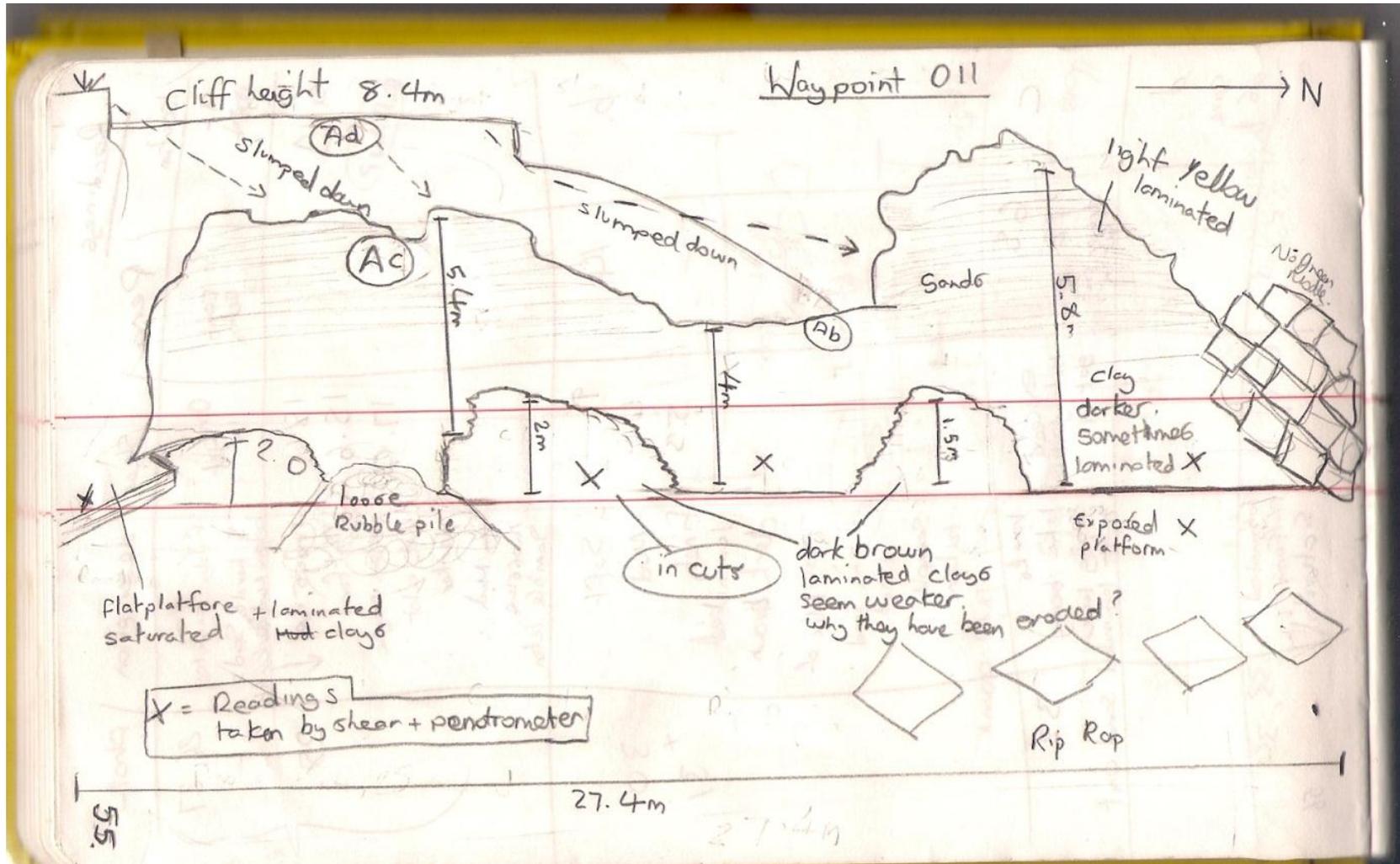
Figure 11: Annotated sketch developed in the field showing the stratigraphy within the northern location Holderness at waypoint 011.

3.3.2. Middle location cliff characteristics

The larger middle location was investigated over the sections D, E, F and G. Figures 17 to 20 visually display the general patterns occurring in this area.

3.3.2a. Stratigraphic log description

The stratigraphic log (figure 12) shows that the middle location is vastly different from the north area. At section D (waypoint 076) the Skipsea till (facies 1) is still present at the base (3.3m thick) however the unit colour is a darker brown than the northern sections. It also contains more conglomerate/clastic material consisting of sub-rounded clasts which vary in size (1-5cm). The majority of the clasts are bright white in colour and very soft which could possibly be chalk material. This unit has many vertical cracks and fissures which are probably due to overconsolidation of the soils during glaciation (also see figure 15); this could be important when considering erosion retreat rate, however whether it increases erosion will be shown by the shear strength results.

Still contained within facies 1, a new layer is found (facies 3) which is 0.5m thick. This layer is dominantly clay material like the rest of facies 1, but contains more fine to medium sized sand grains, generating a moderately sorted band of reddish brown material, which is very distinctive. Facies 3 is found irregularly along the middle section of the Holderness coastline which is more concentrated in section E at waypoints 122 to 130 (further presented in figure 13). The thickness varies towards the south from 0.5m up to approximately 0.8m within section E (waypoint 130). This band of discolouration may be simply to do with iron oxide located within the material, or it could possibly be a weaker zone which is more prone to erosive activity (also see figure 13). A soil sample was taken close to this location (waypoint 077) within the Skipsea till, to allow further analysis of the material, in order to establish why there is varied erosive activity over the Holderness coastline.

The final top layer which is 10m thick is the Withernsea till unit (facies 2). This is lighter coloured compared to the basal Skipsea till, which gives an easily definable distinction between the two. The material is dominantly clay and contains a smaller amount of clastic material compared to the Skipsea till; the clasts are generally smaller sized (1-4cm). The material consisted of loose broken up clay with a weathered profile, which may indicate this unit to be weaker. A further indication of this unit being weaker than the Skipsea unit is demonstrated by the photograph (figure 14).

Figure 12: Stratigraphic log from the middle location at waypoint 076 (section E), (scale 1:200).

Figure 13: Photograph taken in the field within the middle location of the Holderness coast at waypoint 123 (Section E), illustrating facies 3.

3.3.2b. Cliff geomorphology

Figure 14 shows that in a cross section, the Withernsea till is set further back than the Skipsea till. This may be an indication that marine erosion to the base layer of Skipsea till is not the main cause of retreat, and perhaps sub-aerial erosion of the Withernsea till is the dominant element.
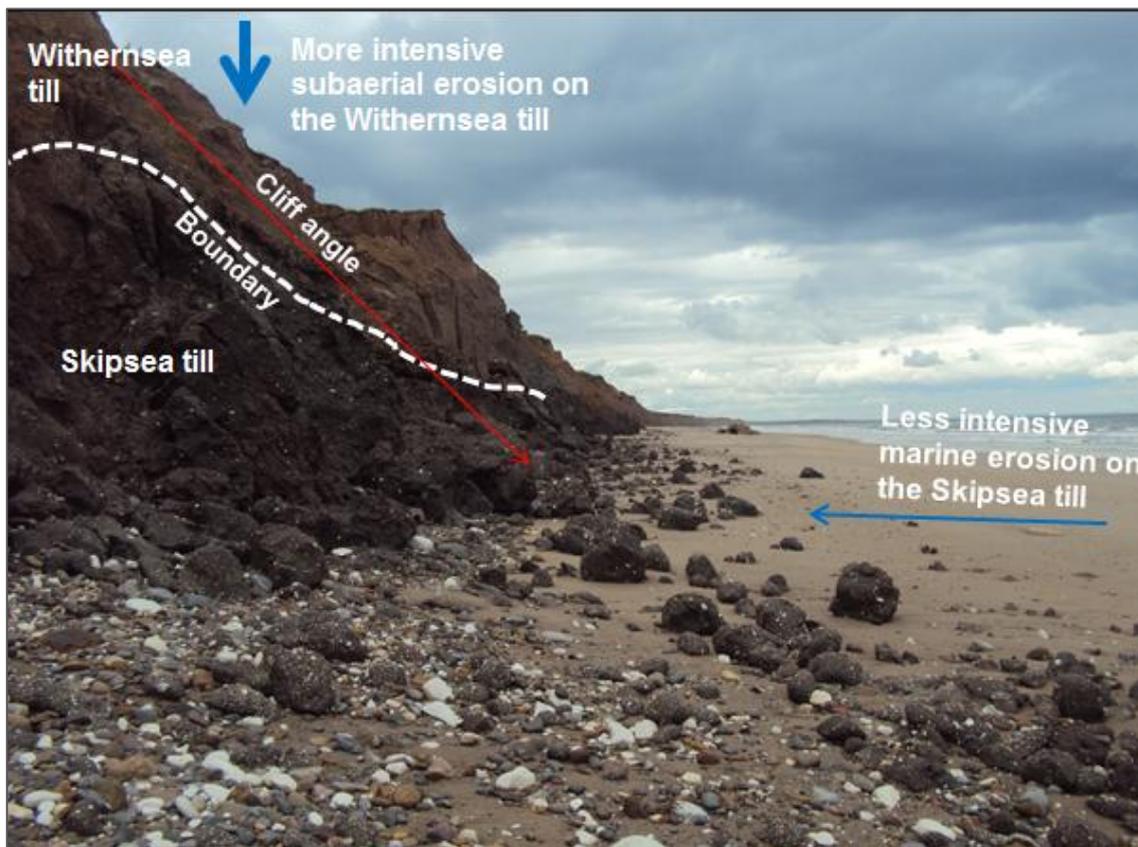
Figure 14: Photograph taken in the field showing a cross section of the typical geomorphology within the middle location of the Holderness coast at waypoint 127 (Section F).

It can be questioned whether the main cause of erosion could be due to the cliffs' physical properties, the geomorphology or a combination of the two; as in the northern section the Skipsea till cliffs tend to be very straight and vertical, which is the same as the Skipsea till in the middle section. Further investigation addresses this query in chapter 4.

Figure 15 depicts a dominant facet of the coastline in this middle location concentrated over sections D and E. It expresses various parts of the basal Skipsea till unit which have detached from the in-situ cliff, and were found on the beach, as well-rounded congealed pieces containing white clastic material; also see Figure 13 and 14. This finding may suggest that the Skipsea till unit is easily erodible due to wave action entering the cliff through the vertical cracks, which eventually generates more stress, leading to shearing along the weakened fracture. But the rate of this erosion is unclear; investigating the strength of both till units can allow an understanding of which unit is more susceptible to erosion.
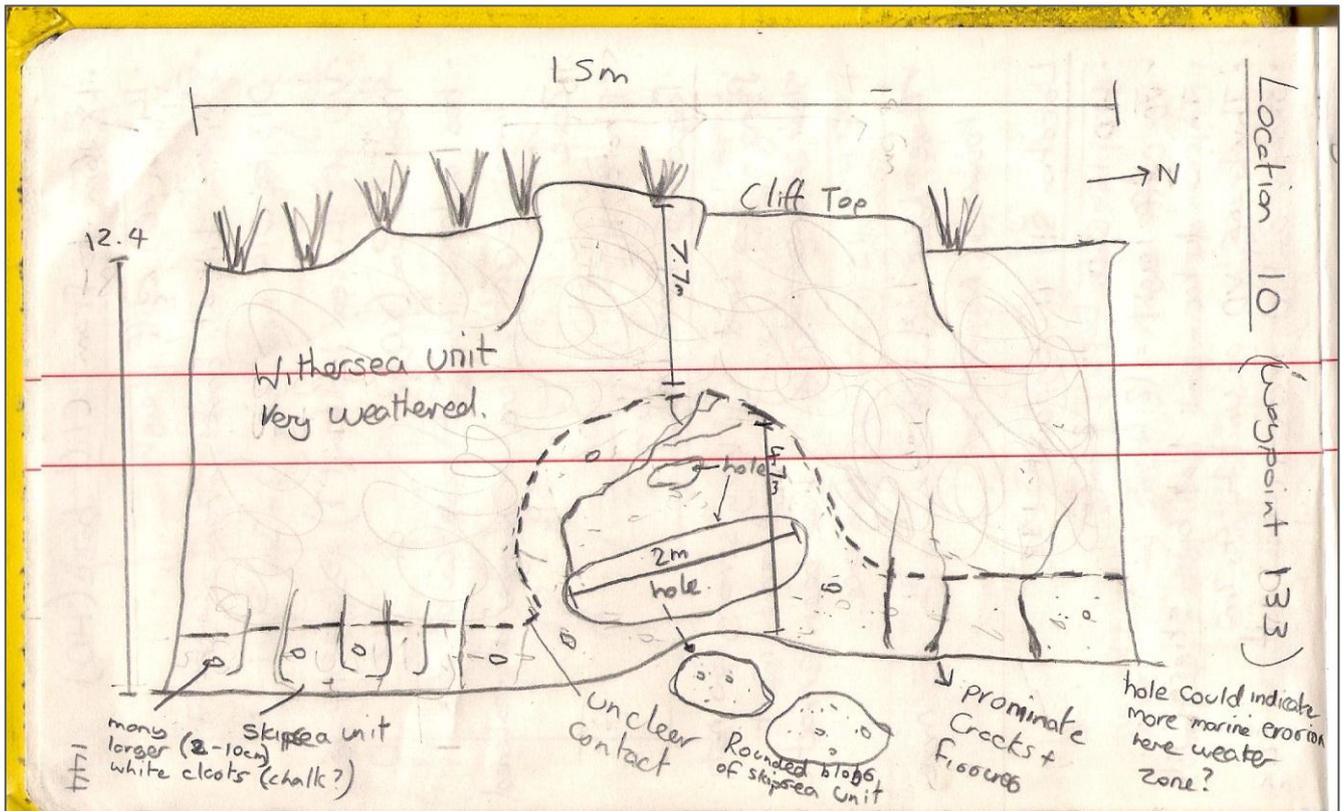
Figure 15: Annotated sketch showing detached sections of the Skipsea till material which was developed in the field within the middle section of the Holderness coastline at waypoint 133 (section E).

Section G (waypoint 195-199) is located towards the end of the middle part of this coastline. There is a differential change to this area which is that the cliffs only contain Withernsea material and no Skipsea units. At waypoint 199 a sand layer has been detected running along the base (approximately 0.6m thick) which has more orange and yellow tinge compared to any previous sand layers found before. This medium sized sand layer contains Withernsea clay, and is poorly sorted with a clast supported breccia appearance containing sub-rounded to sub-angular clasts, roughly 2cm in length, with no white (chalk material), indicating this layer is not part of the Skipsea till. This further indicates that within both tills sand layers can be found; however the Withernsea till tends to show a more clast supported band compared to the Skipsea till, which is matrix supported. To summarise, the difference between these properties could generate varying strengths, thus indicating different erosion rates within the material.

3.3.3. South location cliff characteristics

The south location is depicted in figures 16, 17 and 18.

3.3.3a. Stratigraphic log description

Figure 16 is a stratigraphic log conveying a distinctive difference from the rest of the study are (section H, waypoint 201) all within the Withernsea till. Along the base of the cliff a 0.5m thick and sharp band of clast supported conglomerate was found set in a clay matrix. The clasts were sub-rounded to well-rounded, varying in size (approximately 1-5cm). Above this layer the clay matrix becomes more apparent and

only contains a small amount of clasts (<10%) which have dramatically reduced in size (approximately 1-2cm). This band is 0.3m thick with a massive structure and sharp contacts. The top layer is again very different defined by a sharp contact; it still houses the clay matrix with a small amount of clasts (5%) like the previous layer, but the material is looser and heavily cracked, displaying a weathered profile. The clasts are hard to find, but they seem to be smaller and less frequent than the layer below. It could be possible that the middle and top layer used to be one whole unit within the Withernsea till, however over time the top unit has been subjected to sub-aerial erosion, weakening the soil and generating this weathered profile. This may be the onset of erosion before subsidence, thus depicting the onset of a weaker zone. This further implies the importance of water degrading the strength of the soil, making it more susceptible to erosion. This will be considered when producing predicted erosion process models (see figure 23).
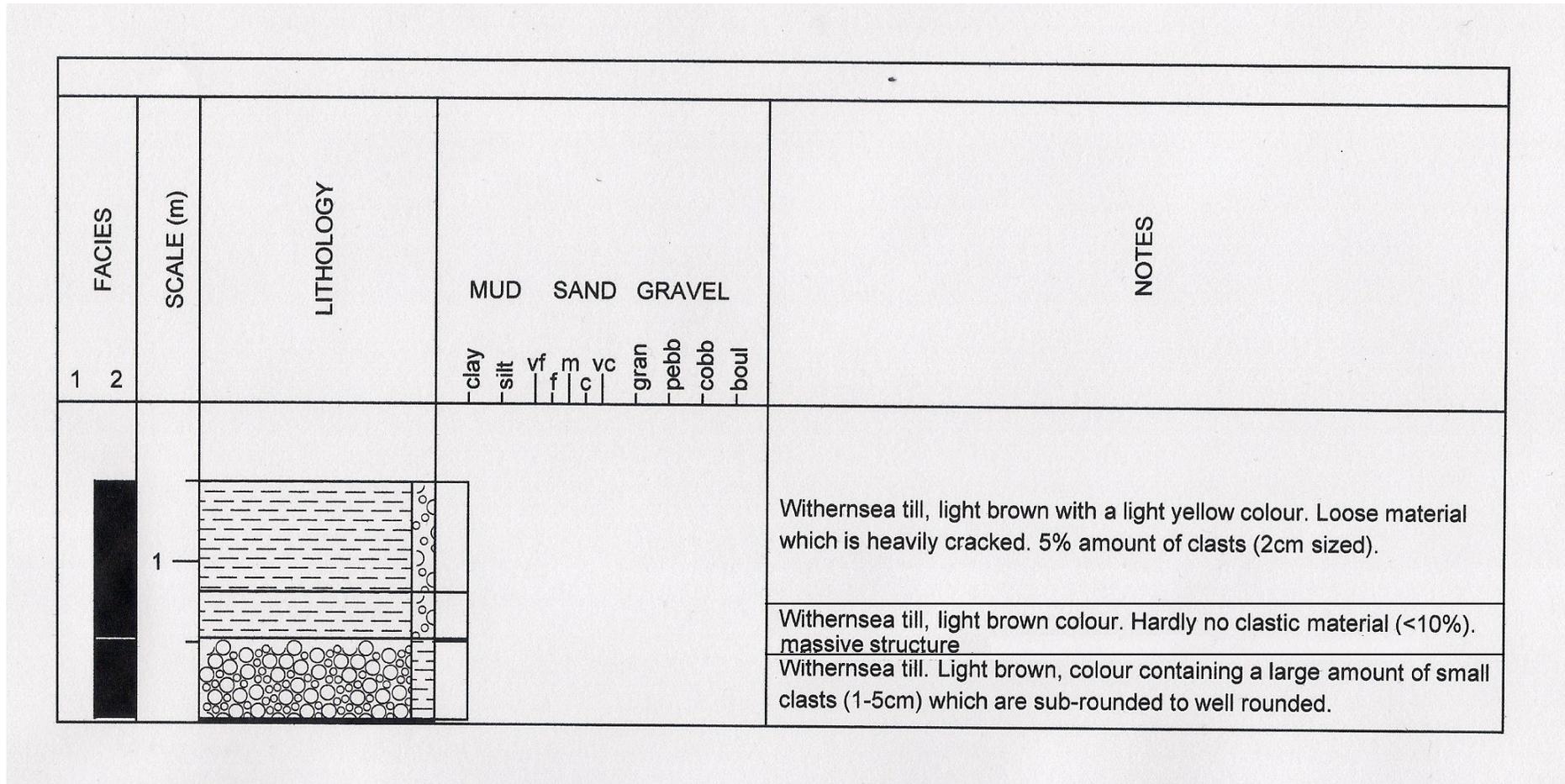
Figure 16: Stratigraphic log form the south location at waypoint 201 (section H), (scale 1:50).

3.3.3b. Cliff geomorphology

Figure 17 shows a photo taken from section H (waypoint 259) depicting a 1.4m thick block of Withernsea till attached to the Withernsea till platform layer. This block is separate from the overall cliff, thus indicating the cliff line has retreated. It seems apparent that marine undercutting occurs, weakening and breaking the material, causing the cliff top to subside and slump down. The reasoning for this block staying attached to the platform could be due to a localised area of high strength within the materials and therefore a localised section of less erosive activity (see the shear and penetrometer readings for more information).

Figure 17: Photograph taken in the field within the southern section of the Holderness coast at waypoint 259 (section H) which depicts evidence of cliff retreat.

3.3.3c. combined geomorphology and stratigraphy

Figure 18 demonstrates the general stratigraphy and lithology located in section J where only Withernsea till is found within the cliff section. At waypoint 329, the Withernsea clay is heavily cracked and fragmented indicating a weakening weathered profile. Within this a 3m thick medium sand lens was recorded which contained fine laminations and a conglomerate feature. The clasts dominated the lens (90%) which was sub-rounded to rounded and approximately 1-2cm sized. Above the Withernsea layer, the top layer was 1.2m thick, containing clay with a dark mud (80%) top soil and clastic material (2-3cm sized).

Other parameters such as the cliff height and till unit thickness could be used to further investigate patterns of erosive locations (see section 3.4).
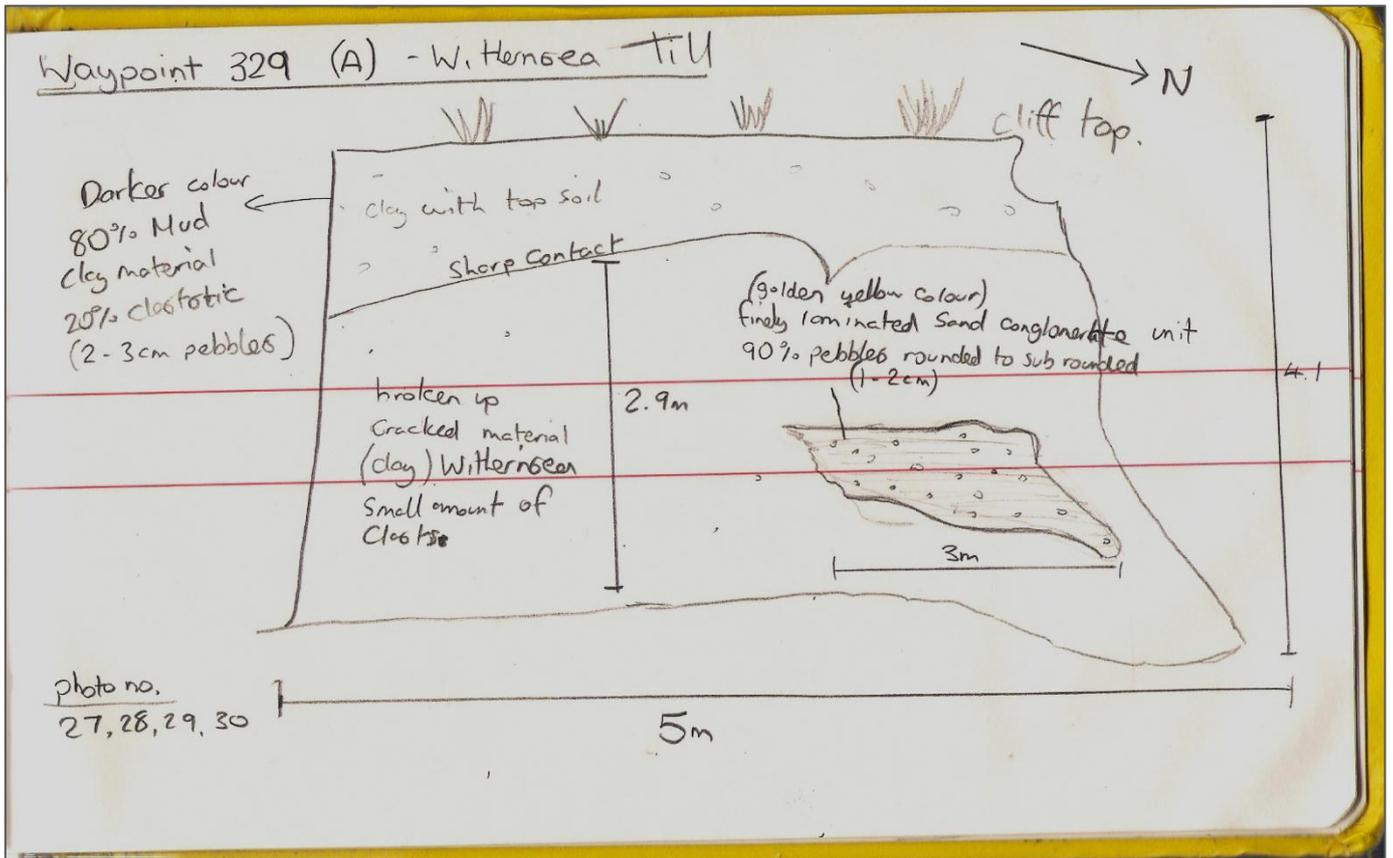
Figure 18: Annotated sketch developed in the field showing the typical stratigraphy and lithology of waypoint 329 (section J) within the southern location of the Holderness coastline.

3.4. Variance of cliff height and till thickness

Figure 19 expresses the variance of cliff heights and the distribution of the till types along the Holderness coastline.

Within the northern locations only Skipsea till is present which gradually increases from 2m cliffs up to 10m which then decreases down to approximately 6m. Comparing this to the middle location which is drastically different, the Skipsea material roughly remains the same height, but increases to 12 and 16m in some locations. The Skipsea till is topped by a thicker Withernsea layer reaching maximum heights of approximately 20m. The Withernsea tills are roughly 10m thick with some variance. Towards the end of this section (particularly in section G), only Withernsea is located, which again generates the idea of Withernsea generally being thicker units as it increases (approximately by 2-3m).

Within the southern location only Withernsea till is found, of roughly the same thickness as previously in the middle location (approximately 10m). However, towards the end of the location (section J) the Withernsea till thickness sharply increases to 14m, and then rapidly diminishes to 4m.

The Holderness coast generally shows a high variance of cliff heights with some localised trends. For example, the low cliffs found in section J containing just Withernsea till. Linking this with previous data, it is apparent that the sinuosity is higher within this material compared to straighter higher cliffs in the middle and south. This would generate a high erosion rate by looking at the results produced so far but no erosive data was collected here.
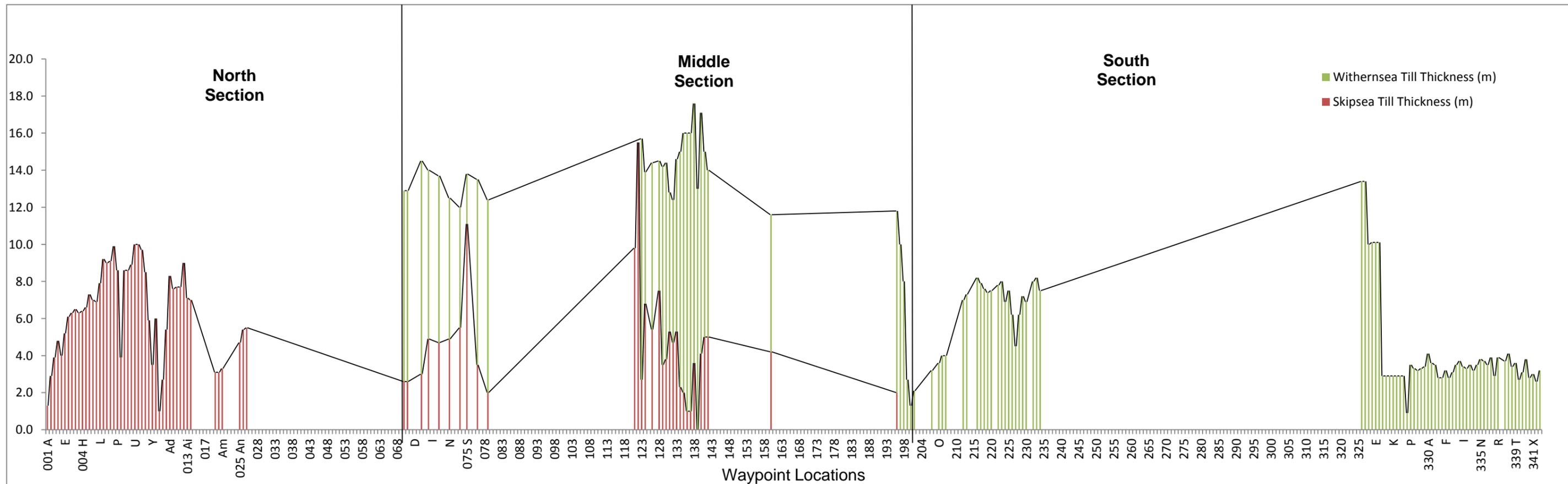
Figure 19: Graph conveying the cliff height of the Holderness coastline including till unit thicknesses.

3.5.   Atterberg limit testing results

Figure 20 conveys Atterberg limit results from this study and the locations of collected soil samples. The general trend generated from the Atterberg limits suggest that the Plastic limit, Liquid limit and the Plasticity index increase from north to south.

The plastic limit within the North section (where the samples only represented section A), is valued at 15.38% which increases to 17.38% in the middle of the Holderness coast in section D. Towards the south however, the plastic limit only slightly decreases to 16.30%; this could suggest anomalous results, as the rest of the data (Liquid limit and Plasticity index) follows the overall increasing trend from north to south.

The liquid limit of the collected soil samples convey a steady increase from 29% in the north, to 30.4% in the middle and an increase of 5.4% within the southern location with a value of 35.8%. This increasing trend (mostly between the middle and southern sections) demonstrates that the higher percentage of moisture content within the soils implies that the pore pressure is larger and can take more water into the soil before it becomes saturated and fails. Thus indicating that the southern locations could be less prone to fail compared to the northern section.

The results of the plasticity index also concur with this trend. The results imply that 13.62% is calculated in the north, 13.02% in the middle, and 19.5% in the south. This implies that larger water content could increase the swelling of the clay generating failures with higher plasticity values. This further indicates that materials with higher plasticity index values are subjected to more erosive activity. Linking this to previous data, the till type investigated showing the highest plasticity index was recorded in the south within the Withernsea till, and the lower values were recorded within the Skipsea till, suggesting that the Withernsea material is more susceptible to erosion. This also correlates with the collected erosion rate database, as the high erosion occurs within the southern locations.

However this data could present many errors, for example; a limited number of soil samples were collected, which could be too small to represent the whole zonation of the coast. In addition the values generally are very close to each other (approximately only a maximum difference of 6%) thus indicating limited relevance.

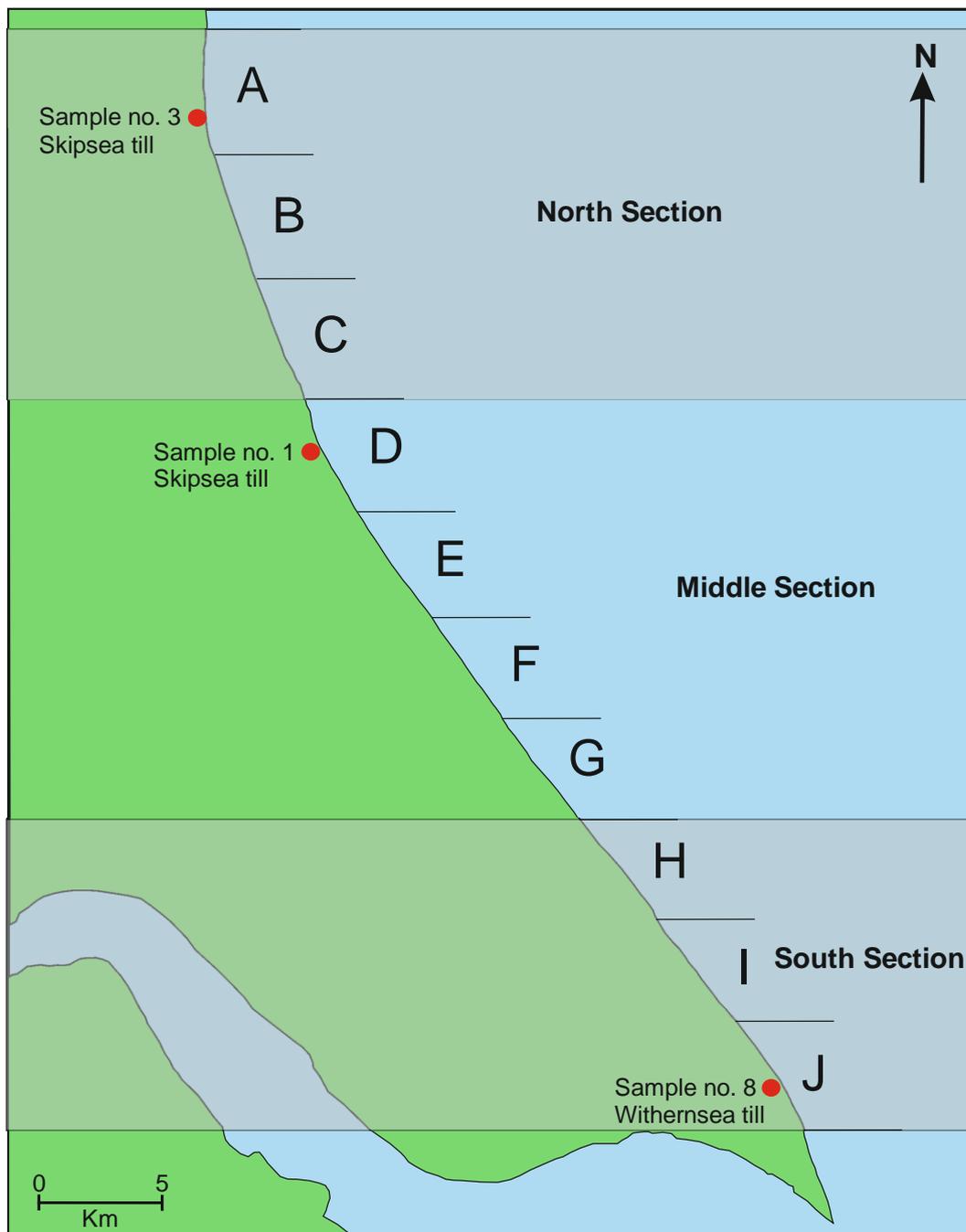| Location sections	Cliff Divisions	Sample no.	Plastic Limit (PL %)	Liquid Limit (LL %)	Plasticity Index (PI %)
A	North	3	15.38	29	13.6
D	Middle	1	17.38	30.4	13.02
J	South	8	16.30	35.8	19.5

Figure 20: Results for laboratory testing and distribution of the soil samples collected in the field.

3.6.   Proctor Penetrometer results

The appendix conveys the moisture penetration resistance values. However their standard deviation was considerably high (reaching up to 165.28) so were seen as not valid enough to give conclusive results, and were discounted and put into the appendix.

3.7.   Geovane soil shear tester results

Figure 21 depicts the undrained shear strength between the Skipsea and Withernsea tills. In general the standard deviations of the values were low, thus implying clear and conclusive results.

Within the northern location (all within the Skipsea till unit) the lowest value was 7.47kPa and the highest was 17.10kPa. In comparison, the south location only investigating the Withernsea till the highest value was 15.70kPa and the lowest was 4.50kPa. This implies that the Skipsea till generally is stronger than the Withernsea unit because the shear strength is higher and so further implies that the south location is weaker than the north indicating more susceptibility to erosion. Correlating this data to all previous data it seems concise that the southern location is subjected to more erosion than the north.

There is some variation within the middle section this could be however due to the influence of both till types found in the location but generally the values indicate that the Withernsea material is the strongest and the weakest within this location. The standard deviation is fairly high and so these results maybe anomalous a further indication to this idea is that the highest Withernsea value of 37.50kPa is not typical to the rest of the Withernsea data which is generally around 10-13kPa and so random high value could possibly be anomalous. The values for the Skipsea till within the middle location tend to be significantly higher compared to the northern location; the maximum values increase from 17.10kPa to 28kPa generating the idea that the Skipsea till become stronger from north to south.
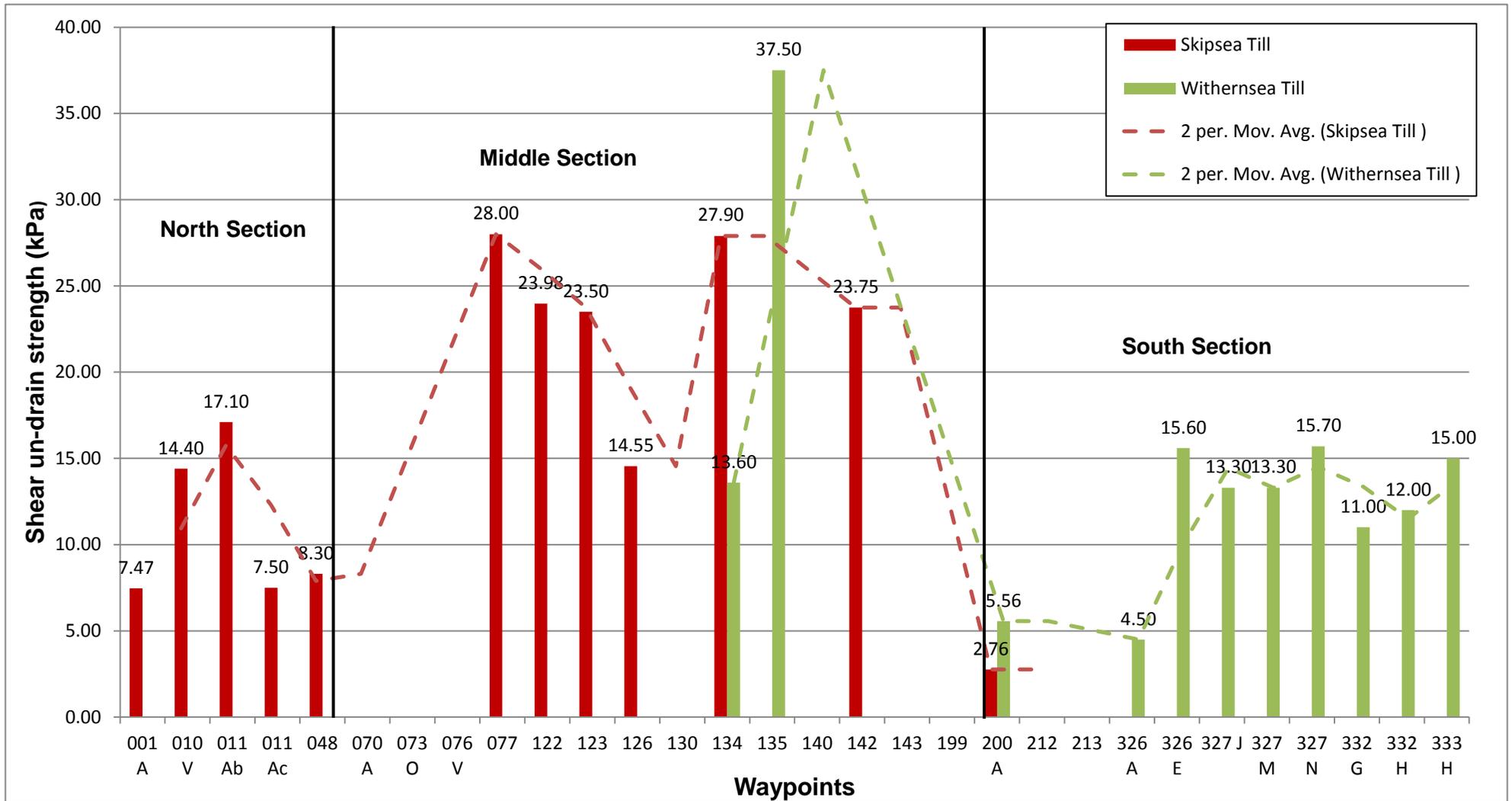
Figure 21: Comparing the un-drained shear strength values along the Holderness coastline.

3.8.   Result summary

The table below expresses all the findings produced from this investigation. It is apparent that collectively the data can further identify varied erosion rates along the Holderness coast and give some reasoning behind the trends which is later discussed in chapter 4.

Location	Sinuosity	Annual Erosion Rate	Plasticity Index	Undrained shear strength	Cliff height	Till Type
North	Low	Low	Lowest	Low	Low	Skipsea
Middle	Low	Low	Low	Highest	Highest	Both
South	Medium	Medium	Highest	Lowest	Lowest	Withernsea

Figure 22: summary of collected results.

The table conveys that this coastline has varied erosion due to many combined characteristics.

The highest erosion occurs within the south section; in particular section I which is located south of the Withernsea sea wall with the highest erosion rate of 3.33m of retreat a year. This is further supported by the sinuosity results, which identify that the southern location has the most sinuous cliffs, with the highest value of 1.35 in section H.1 (north of the Withernsea sea wall), and 1.31 in section I located south of the Withernsea sea wall. The cliff characteristics imply that only Withernsea till is present, which tends to be looser, weathered, weaker material; identified from the undrained shear strength readings ranging from 4.50kPa to 15.70kPa. These cliffs are also more prone to swelling, indicated by the Atterberg limits which show the highest plasticity index of 19.5%. These highly eroding cliffs have the smallest heights in the study area ranging from 1.3m to 8.3m.

In comparison, the middle location has the slowest erosion rate within the whole study area; the lowest erosion rate occurred in section G with a value of 1.53m. The sinuosity readings also imply that the middle location has low erosion, which is mostly concentrated in section D, with the lowest value of 1.08; conveying the straightest cliffs throughout. The till material characteristics contain both Skipsea and Withernsea material. The Skipsea is overconsolidated because it is overlaid by the thicker Withernsea layer. These cliffs are the highest throughout the area, reaching up to maximum of 17.1m high. Strength results reveal that the basal Skipsea material is the strongest thought the Holderness coast, which is due to this overconsolidation. Atterberg limits show the lowest plasticity index of 13.02% implying less chance of swelling with increased water content, and the high value of 28kPa is identified from the Skipsea material in the middle location from the undrained shear strength results.

Chapter 4 will analyse these findings, and predictive models will be constructed to help determine possible explanations of why and how these varied erosion rates occur spatially and temporally.

4.0 Discussion

4.1. Combined data

It is apparent that this investigation has focused mostly on spatial variance of erosion rates in conjunction with the lithology, stratigraphy, geomorphology and strength of the material. As shown in the results chapter, individually the separate results give an incomplete picture of the Holderness coastline, incapable of producing sufficient information to predict the varied erosion rates along the study area. For example, Pethick, 1996 (cited in Quinn *et al.,* 2009) criticised the recession rate method used by the East Riding of Yorkshire Council in 2004, which fails to "provide any information regarding process" (cited in Quinn *et al.,* 2009). The processes that generate varied erosion rates need to be understood. The data collected by this study not only has average annual erosional data, but it also contains descriptive geomorphology, along with the erosional rates, till descriptions and strength, figure 23 conveys these spatial trends.

Together, these trends have enabled construction of predictive models showing erosion process intensities; thus providing an idea of erosional causes generating the varied erosion rates along the coastline; these process intensity models are illustrated in figure 23 and mentioned below in section 4.4.

Figure 23: Summary trends of collected data along the Holderness coastline and predictive erosional process models.
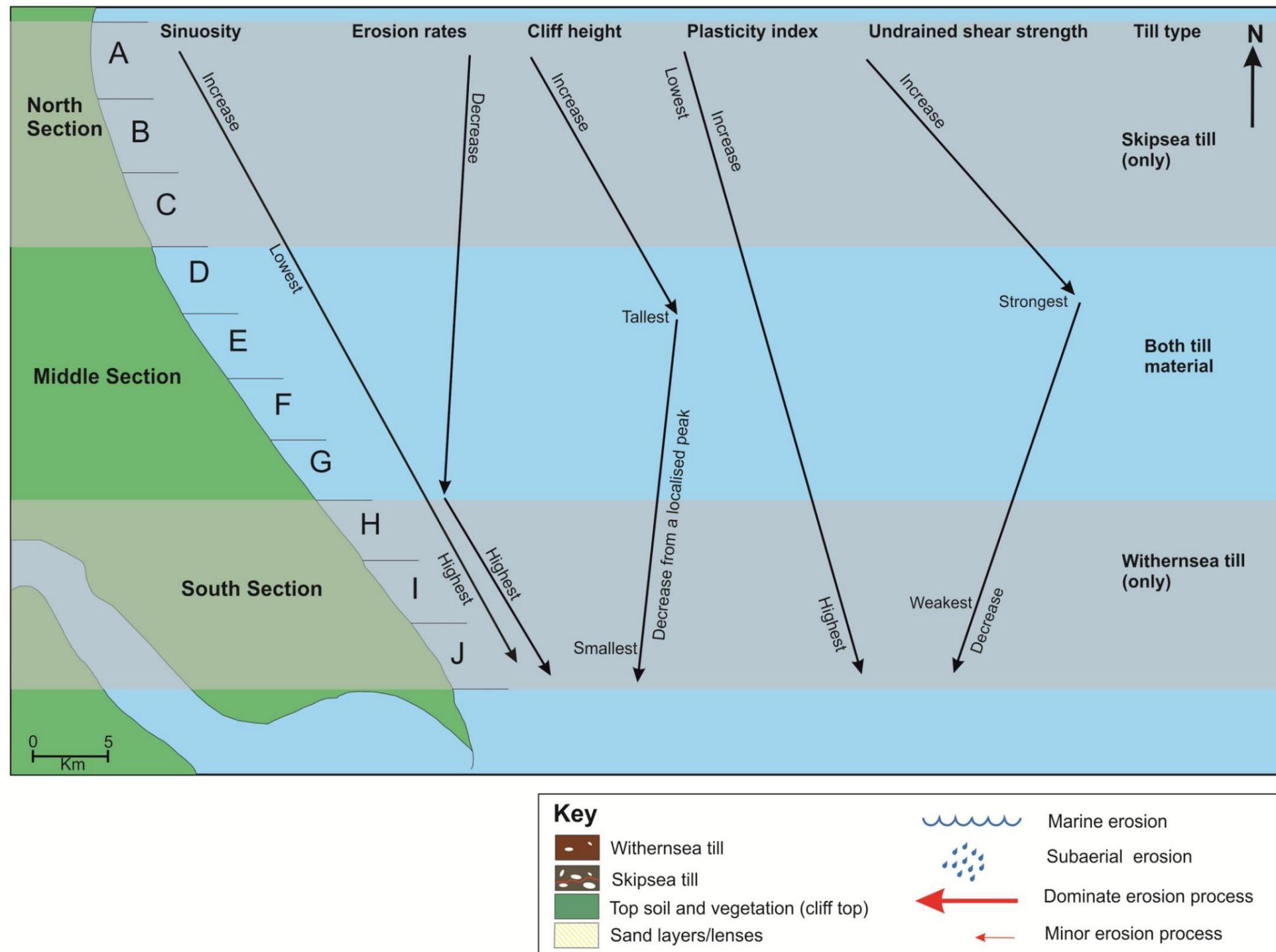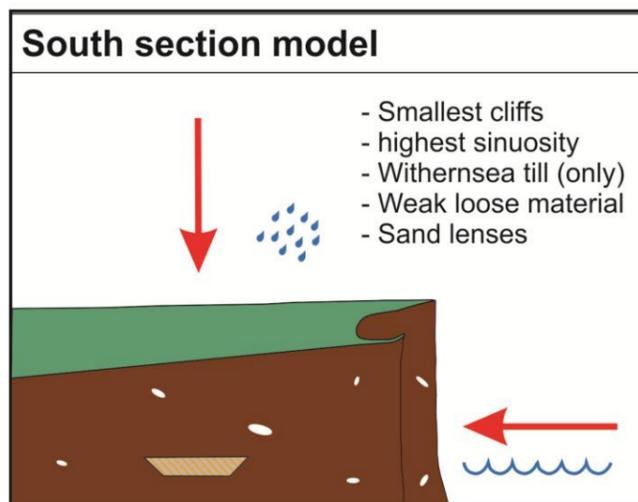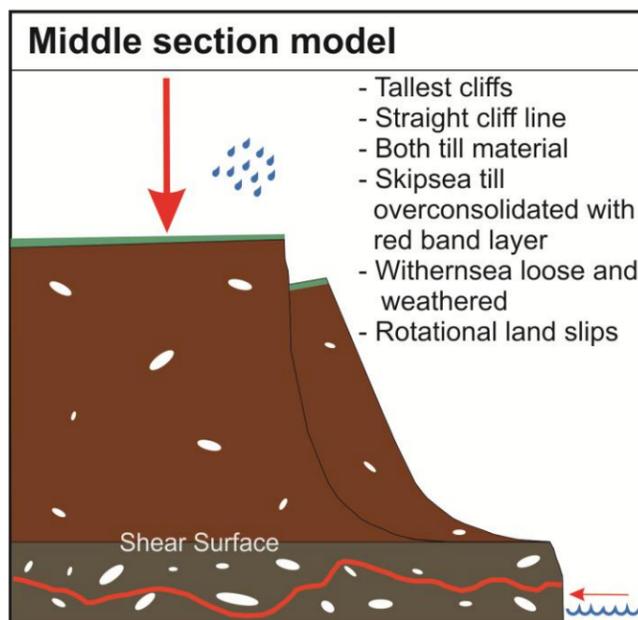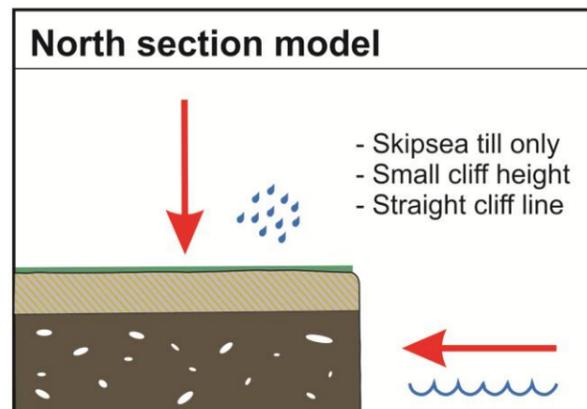
4.2.   Spatial and temporal variation analysis

4.2.1. Sinuosity analysis and method evaluation

The sinuosity data gives an indication that coastal erosion rates are varied spatially along the Holderness coastline. The method (called the mountain front sinuosity) was adapted from Keller and Pinter (1996); originally it was used to investigate the balance between tectonic and erosional forces along a mountain front. Adaption of this method enabled a focus on patterns of coastal erosion rates in this investigation. The results signify that increased sinuosity indicates increase erosive activity when comparing collected datasets. This suggests that the southern location (particular section H.1 and I) has the highest annual erosion rate in the study area, compared to sections A and G in the North and Middle, which contain straighter cliffs and decreased erosion rates.

The adaption of the mountain front sinuosity method seems to be unique in the study of coastal erosion, as no previous literature has demonstrated its use before; implying an undetermined significance to the report, however it holds high value within this investigation. It assumes that the greater the sinuosity, the higher the erosion rate is, due to rotational slumping of the top material which leaves curved back scars; also failed material can act as a temporary defence to a localised section. The rotational slumping only occurs within the top material (mostly Withernsea till) as it is looser than the overconsolidated lower layer (Skipsea till) which tends to form a straighter basal cliff line. However, the lower layer may still be eroding, suggesting that the sinuosity method may only apply to the top material. This study aims to address erosion throughout the coastline, including both layers of the cliff, so the method may not prove a good approach to spatial erosion variance for the whole study area. However, the method has identified that there is a difference between the properties and erosion rates of the two till types.

4.2.2. Erosion rate analysis

The annual erosion rate found from collected data implies a declining trend of low erosion in the north, to lowest in the middle location (particularly in section G). The highest erosion rates are found in the south location (sections H and I). Quinn *et al.* (2009) specifies that recessional rates have been documented by the East Riding of Yorkshire Council in 2004. Their findings indicated that the highest erosion rate of 2.74ma^{-1} is located between Hornsea and Mappleton. Comparing to the collected results, this location is within the middle of the study area in location D. Overall the middle location (sections D-G) has an average annual erosion rate of low erosion (1.53m). Section D was not individually investigated for erosion rates and only object data from section G was used to represent the average erosional findings in this middle location, indicating an imprecise reading between Hornsea and Mappleton. It seems that the lack of erosional data could prove a problem when comparing previous studies to the collected readings. According to Quinn *et al* (2009) there is a danger in using an average value taken from a 'large area', due to spatial variability and the erosion rates being dynamic and episodic. Thus, taking an average can produce imprecise results when considering a smaller scale.

However, the desktop sinuosity results could be used to estimate erosion rates on a more local scale. Section D conveys a low sinuosity of 1.08 which is the lowest found along the Holderness coastline, implying the straightest cliffs are found here. Thus,

indicating that the low erosion results may be accurate between Hornsea and Mappleton. This differs from the East Riding of Yorkshire Council findings dramatically, as the collected data conveys this location to possibly have the lowest erosion rate throughout the Holderness coastline, and the council imply it has the highest erosion rate. Quinn *et al.* (2009) also suggest that the council identified the lowest erosion rate occurring between Bridlington and Barmston (0.43ma^{-1}). The collected data suggests that this location roughly lies in section A of the study area. Low erosional rates were also calculated in this location, implying a comparable trend of low erosion in the northern section. The values however do not specify that this location is the lowest throughout. These comparisons, along with other various annual erosion rates taken from previous literature, are displayed spatially in figure 24.

The south section, illustrated in figure 24, reveals that the highest erosion rate occurs here, supported by literature dating from the 1920s (Valentin, 1971 from Quinn *et al* 2009; Yet King and Doornkamp, 1971, from Cambers 1976; and Thompson, 1923). They further imply a decreasing erosional trend within the middle of the Holderness coastline. These findings are consistent with the trend pattern of undrained shear strength (see figure 23), as the weakest material is located within the south, and the strongest in the middle, thus indicating less erosional occurrence. The measured Atterberg limits also correlate with the pattern. For example figure 23 depicts the trend of increasing plasticity index from north to south; implying an increasing possibility of the clay material swelling and failing, resulting in high erosion of the weakened material within the southern location.
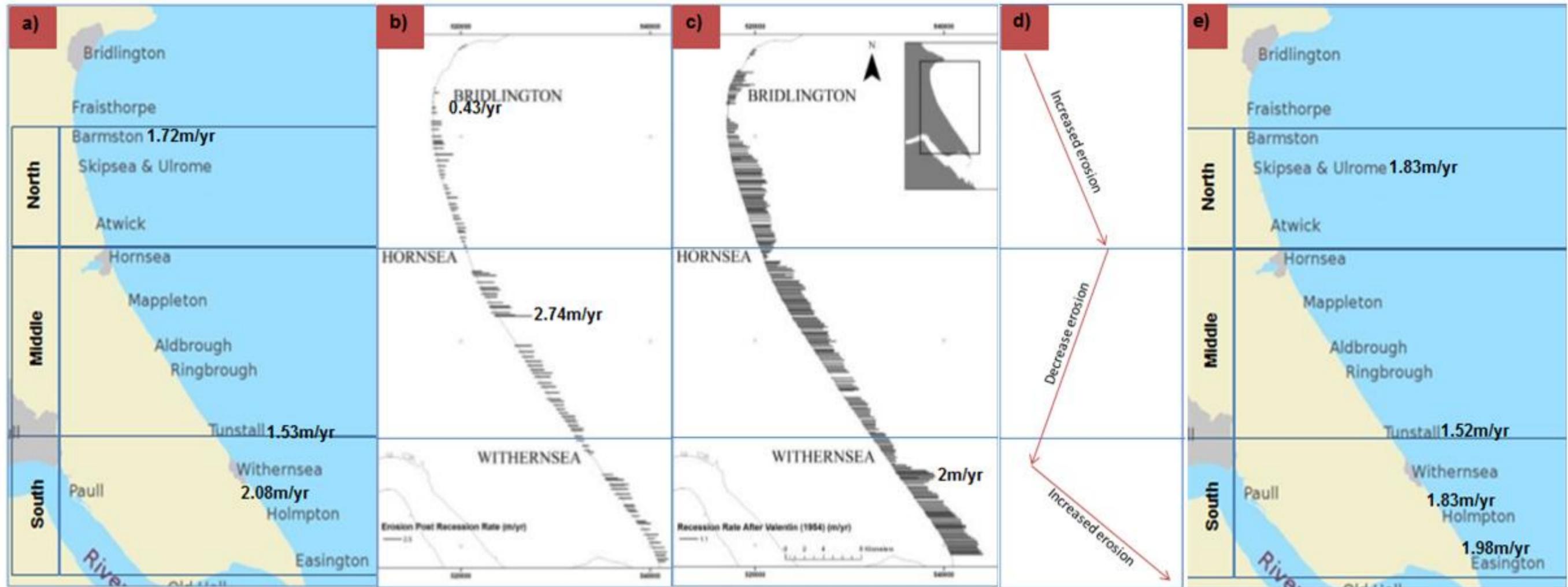
Figure 24: Summary of erosion rates. a) This study's results (2007-2011), b) East Riding of Yorkshire, 2004 (taken from Quinn *et al.*, 2009), c) Valentin 1971 results taken from Quinn *et al* (2009), d) Yet King and Doornkamp, 1971 results taken from Cambers (1976) and e) Review taken from Thompson (1923).

4.2.3. Analysis of till material

4.2.3a. Atterberg limit variance

Generally, geotechnical properties (such as Atterberg limits) have not been extensively investigated along the east coast of England throughout the literature, but these investigations are essential to understanding the materials' engineering performance (Bell, 2002). Glacial tills in particular have varying properties such as strength, which has been investigated by Bell (2002) along the Holderness coast. Figure 25 depicts these Atterberg limits, which are compared to the collected moisture contents from this investigation.
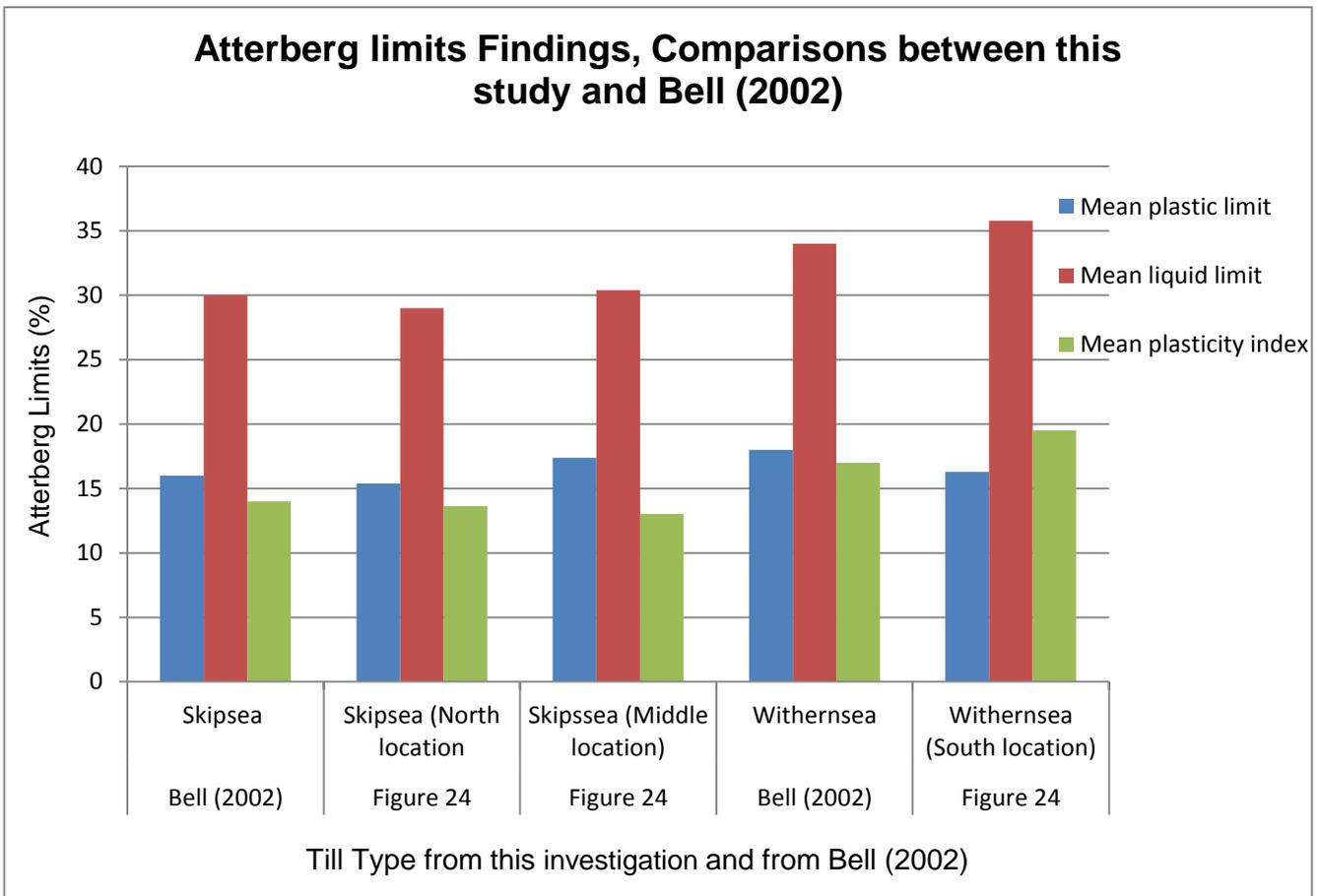

Figure 25: Comparing the collected Atterberg limits from this study with those presented in Bell (2002).

Compared results imply a correlative trend between this study and Bell (2002). Bell (2002) specifies that both Skipsea and Withernsea till members have low plasticity. Additional outcomes from Bell (2002) imply that the measured consistency index can identify whether tills are soft, firm, stiff, very stiff or hard. Results convey that the Skipsea till is stiffer than the Withernsea unit. According to Bell (2002), "this presumably reflects the differences in composition and degree of overconsolidation"; indicating that the general lithology composition of the till is an important factor when assessing strength. These findings imply that the Skipsea till layer may be subjected to less erosion, and the Withernsea could pose as the weakest material out of the two, generating the highest erosion rates at Withernsea till locations. These trends

were considered when developing the predictive erosional process models (see section 4.4).

However, methodological problems are presented here by the fact that averaged data is used. Quinn *et al.*, (2009) indicates that this type of collective data may pose inaccurate results. Another problem occurring is that the tested tills are collected from different locations to Bell's (2002) investigation. However, this may imply that the limits remain the same; but values may change seasonally, which was taken into account in the predictive models. As previously stated; the difference between the Skipsea and Withernsea till must be understood to identify varied strengths and erosion rates along the Holderness coast; although Quinn *et al.,* (2009) indicates that both tills do not have a significant impact on the variation in failure mechanism, as they both lack great strength variability. The EUROSION case study (2007) also implies that "there is no relationship between rates of erosion and type of till".

Atterberg limits from this study conflict with these concepts; figure 23 conveys that the plasticity index increases from north to south, implying an increasing swelling rate and high likeliness of failure occurring within the south, which only contains Withernsea till. The undrained shear strength values (from this investigation) also oppose Quinn *et al's.,* (2009) remarks, as findings produced define that there must be some strength variation between the two till types (see figure 25). Nevertheless, this distinction is not obvious, especially when comparing Skipsea till (only) in the north to Withernsea till (only) in the south. The distinct difference occurs within the middle, containing the strongest tills (Skipsea), which could give rise to spatial variation being the important factor when understanding varied erosion rates, as Quinn et al., (2009) suggests. Further inconsistencies are suggested by Boston *et al.,* (2010) whose geochemistry findings reveal that there is a difference between both tills, but these refer to variation of till sediments within a till deposit and not between till deposits (more intra-till than inter-till).

4.2.3b. Clay content

Clay mineralogy testing produced by Bell and Forster (1991) implies a difference in the till composition. They established that Illite is the most common clay mineral within the Skipsea till, compared to the Withernsea till in which Kaolinite was the dominant mineral. Waltham (2009) suggests that these minerals have different plasticity indexes. For example, Illite has a higher plasticity index of 70%, compared to Kaolinite with 30%. These findings, produced by Bell and Forster (1991), conflict with findings from this investigation, which determined the Skipsea till to have a lower plasticity index than the Withernsea till; thus further implying that Bell and Forster's (1991) study could indicate that Skipsea till is more prone to swelling and failing than this current study's proposed weaker Withernsea layer.

4.2.3c. Colour variance

Catt (2007) identifies a colour variance between the Skipsea and Withersea tills. The Skipsea till has a "dark greyish brown" colour compared to the Withersea till which is "reddish brown", (Catt, 2007). Catt (2007) further states that unweathered Withernsea material is also located within the Holderness coast, with a dark brown appearance which lacks reddish colour. This signifies that red coloured material could represent a weathered state, thus implying a weakened zone, which is more prone to erosion. The undrained shear strength values and plasticity index produced

from this investigation also support this notion, that Withernsea till is weaker than the Skipsea till.

4.2.3d. Evaluation of till age

Investigating the age of the till materials can help identify a difference between both till units. Both Bell (2002), and Bell and Forster (1991), state that Skipsea till contains clasts of Carboniferous age (359-299Ma) and Withernsea contains Triassic aged clasts (251-201Ma). Both studies further imply that the till units would have deposited within a time interval of 5,000Ka. In comparison, a 5,500Ka interval time was presented by Catt (2007) from the Dimlington stadial radiocarbon dates (see figure 26). Additionally, according to Catt (2007) there is a contradiction, in that radiocarbon dates produced from the Dimlington interstadial produce "no evidence for an age difference between the two tills". This introduces a vague time gap for the deposition to occur.
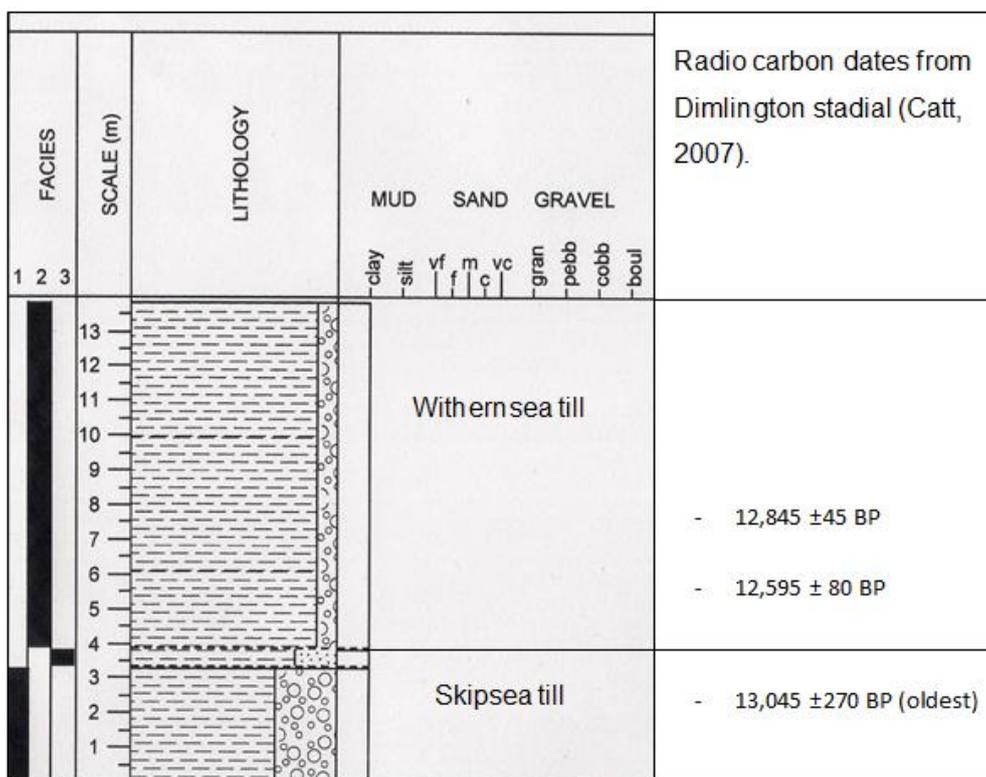

Figure 26: Stratigraphic log showing the different ages of till material (log taken from figure 12, additional information acquired from Catt, 2007).

Madgett and Catt (1978) imply that this interval is too short for separate glacial advances to deposit the two till members. Thus Bell (2002), and Bell and Forster (1991) suggest the likelihood of a composite glacier (composing of two glaciers from various parts of Northern Britain) having deposited both Skipsea and Withernsea tills. This would indicate that there is no (or a small) difference between the tills, further demonstrating the insignificance of the study of erosion rate variation, which is the idea presented by Quinn *et al.*, (2009). Furthermore, Catt (2007) signifies that if Skipsea and Withernsea till were deposited by separate ice sheets, disturbance of

the lower Skipsea material would be apparent due to the later advance of the overlying Withernsea till, but this is not present within the Holderness coast. The North Sea glacier also contained a large mass, preventing other glacial advance (Catt, 2007). However, according to Madgett and Catt (1978), glaciers may have over-ridden the North Sea glacier, forming a two-tiered surge ice sheet; this is also proposed by Boston *et al.*, (2010). Kamb, 1987 (cited in Catt, 2007) supports this theory, suggesting that gravel deposits could be an indication of surging. Results from this investigation show that gravel sized clasts have been found within conglomerate layers, which are located mostly within the Withernsea till, further supporting this surge theory. Further research is needed to understand this complexity in order to know if varied till types could pose indications towards the varied erosion rates.

4.2.4. Geomorphology analysis

Other investigated parameters within this investigation, such as the cliff geomorphology could give an understanding of varied erosion rates. Quinn *et al.*, (2009) proposes varied geomorphology cliff models subjected to erosion, identifying that erosional behaviour can change the cliff geomorphology, implying the importance of geomorphology in understanding varied erosional rates. Quinn *et al.*, (2009) illustrate that initial destabilising of the cliff caused by moderate erosion then triggers larger failures, changing cliff top morphology, weakening and generating accelerated erosions rates. Quinn *et al.,* (2009) further state that one particular model, which contains a similar morphology to the middle location categorised within this investigation, may be due to low marine erosion.

Furthermore, this middle location also depicts the highest cliffs found within the Holderness coast, along with low erosion rates (as shown in figure 23), implying that cliff height may pose as another parameter, generating varied erosion rates. This is supported further by figure 23, illustrating that the highest cliffs generate low erosion compared to lower cliffs, with the south section in particular having high erosion rates. However, the EUROSION case study (2007) implies that cliff height does not correlate to erosion rates. Nevertheless, Quinn *et al.,* (2010) indicate that high retreat from storm activity can happen to low cliffs over a long temporal scale, demonstrating the importance of temporal scales within this investigation. However, they later express the conflicting views that high cliffs have the greatest erosion rates, and landslide activity is less probable at low relief cliffs, as the angle is too long to generate stresses and mass failures, contradictory to this investigation's findings (expressed in figure 23). These models, depicted in Quinn *et al.,* (2009) and Quinn *et al.*, (2010), were considered when producing predictive models of the process intensities, generating varied erosion.

4.3.   What is the evidence for varied erosion rates along the coast?

The reasoning used in the literature to explain the varied erosion rates is incomplete, however many studies have mentioned that human land use over time may be of importance when considering the recessional rates along the Holderness coast.

4.3.1. Human influence and land use

Data used by Valentin (1971), (cited in Quinn *et al.,* 2009), covers a period of regular extraction of beach material for constructional purposes (Dosser, 1955).This may

have exposed the cliff (due to beach level reduction) implying increased vulnerability to the cliff base from marine erosion. This could give rise to inaccurate readings being depicted in Valentin (1971), (cited in Quinn *et al.,* 2009). If these extraction processes were taking place around the time of this investigation, this may skew the results.

Other land use factors such as sea defence construction have been shown to cause a dynamic change in erosion rates (Quinn *et al.*, 2009; EUROSION, 2007). The study by Duclos and Jean-Pierre (1998) presents this idea. The findings show that change in volumetric erosion rates particularly occurred during winter periods in which stormy conditions prevail. This seasonal variation was considered when producing predictive models (see section 4.4), bearing in mind that the erosional data was collected over 4 years (2007-2011), implying an imprecise correlation for seasonal variation. However, other data produced in this investigation was collected within the summer season, and so may provide an understanding of how erosion rates change between winter and summer months, which is summarised in figure 35. These results are: geomorphology, topography, stratigraphy, till strength and plastic and liquid limits, detailed in the results chapter.

The notion of seawalls changing the erosion rate (presented by Duclos and Jean-Pierre, 1998) is also illustrated in figure 27 showing detailed recessional rates, (produced from Valentin, 1971 (cited in Quinn *et al.*, 2009)), with annotations of sea defence locations along the Holderness coastline. The figure implies that generally, erosion rates tend to increase (fairly rapidly), south of sea defences. For example, south of the Withernsea seawall, the erosion rate rises by 1.2-1.4m/yr, from 0.6-0.8m/yr, north of the seawall, to 2m/yr south of the seawall, further implying the significance of coastal defences in localised areas of increasing retreat rates. Although there are local areas of reduced erosion due to the seawalls, the benefits may be outweighed.
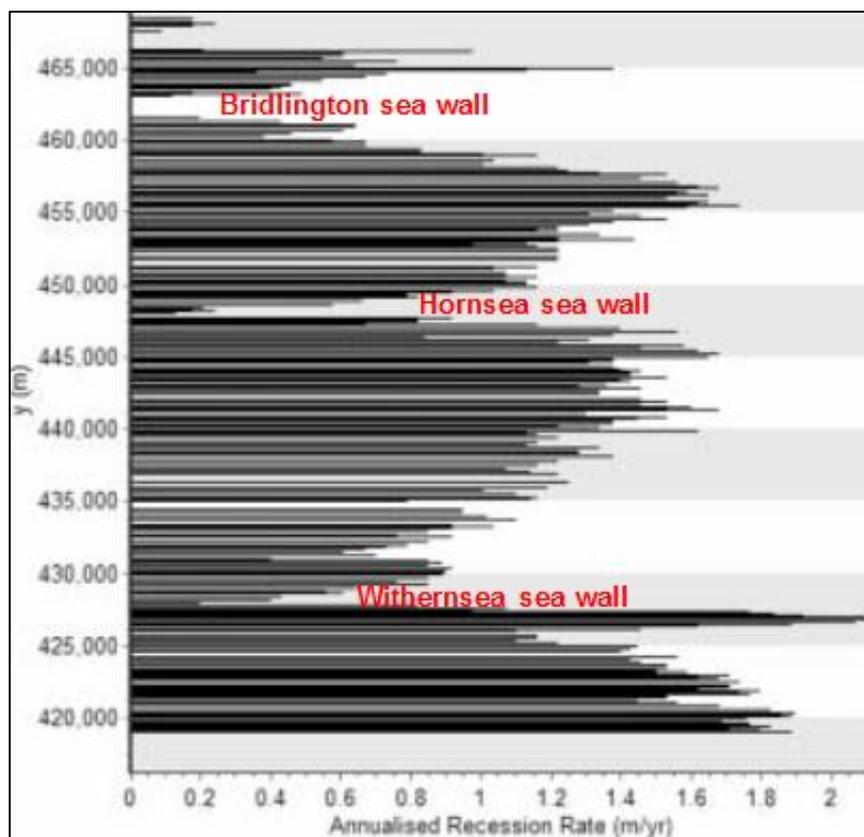
Figure 27: Erosion rate variations along the Holderness coastline measured by Valentin, 1971 (cited from Quinn *et al, 2009*.) annotated with sea defence locations.

4.3.2. Natural occurrences

As mentioned in section 4.2.4., where a link between geomorphology and erosion rates is made apparent, it has been demonstrated that 'ord' features accelerate coastal erosion by leaving the cliff exposed to the sea (figure 28) (NERC, 2012a; Richards, 1997; Pethick, 1996 (cited in Quinn *et al.,* 2009); and Quinn *et al.,* 2009).Quinn *et al.,* (2009) specify that these are sandbars formed in intertidal zones during stormy conditions. Moore *et al.,* (2003), NERC (2012a) and Pethick (1996), (cited in Quinn *et al.,* 2009) all express that these 'ords' migrate due to season variation, further implying that monitoring of this could explain episodic varied erosion rates along the Holderness coastline. Within this study, high erosional areas (section I and H.1) could be due to an 'ord' present between the two locations, intensifying the erosion alongside the 'ord'. These findings were considered when producing predictive erosional process models.

'Ord' formation can generate local episodic protection from erosion; however the rest of the Holderness coastline is unprotected. This generates a long fetch across the North Sea, increasing wave process intensity (EUROSION, 2007).
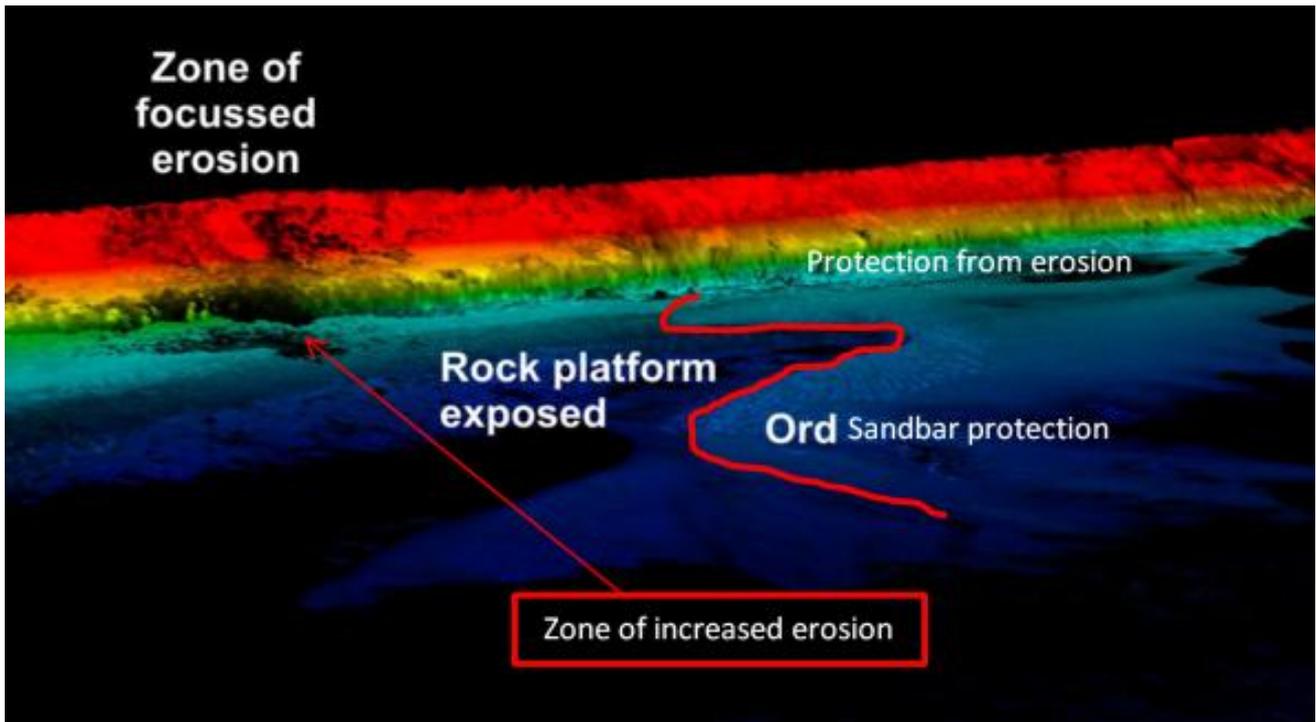
Figure 28: LiDAR data produced by the British Geological Society, adapted to convey the typical morphology found at the Holderness coast NERC (2012a).

4.4.   Predictive models of erosional process intensities

Figure 23 presents these models developed from the collective results and analysis.

4.4.1. North section model

The north location model identifies that both erosional processes from subaerial and marine sources could be the dominant causes of cliff erosion. This is recognised from the Atterberg limit results which convey low plastic and liquid limits, meaning that only a small amount of water entering the material would cause it to reach its plastic limit, stiffen, and strengthen the material, producing low erosion rates. However, in intensive erosional processes (storm environments), more water entering the till may cause the material to reach its liquid limit, and be more prone to fail, thus introducing higher erosional rates in this location. The undrained shear strength readings imply that the Skipsea till type material (at this location) has low strength, and is prone to erosion. However, according to the collected erosion rates, this location is subjected to low erosion, contradicting the results suggested by the material properties; this is because of the changing nature of erosional processes, and episodic erosion may be apparent in this location.

4.4.2. South section model

In the southern location, the cliff face is subjected to the same intensity of erosional processes. Conversely, the plastic and liquid limits are higher; indicating more water is required to reach the plastic limits, and even more to reach the liquid limit. This implies that increased erosional stormy activity could possibly not be enough to reach the liquid limit, and therefore would be likely to strengthen the material, which would stay within its plastic limit; further implying that the southern location would have a less erosive nature; however according to collected data, it has the highest

erosion rate. During less stormy periods, there is less water within the material; it seems apparent that the plastic limit may not be reached, thus indicating that the weak material (identified from the undrained shear strength) is highly prone to erosion.

If the southern location is eroding faster than the northern location, then this indicates that less erosional processes took place in the north at the time the investigation results were collected, which was summer. With these findings (see figure 23), if the data was collected in winter season you would expect to find the reverse of the investigational results.

 The increased storm erosional activity would introduce high erosion in the north and low erosion in the south, judging by the plastic and liquid limits, and undrained shear strength, assuming they stay the same. Figure 29 below summaries these seasonal characteristics.

Season	Location	Erosion rate	Erosional intensity	Strength	Plastic and Liquid limit
Summer (identified from the investigation)	North	Low	Poor	Low	Low
	South	High		Low	High
Winter (predicted)	North	High	Strong (storm activity)	Low	High
	South	Low		Low	Low

Figure 29: The theory of seasonal episodic variation.

4.4.3. Middle section model

Combining the series of collective datasets, the middle location presents a different predictive model of erosional occurrence compared to the north and south episodic erosional locations along the Holderness coastline. This middle location model presented in figure 23 indicates that subaerial erosion would hold a strong intensity compared to the marine erosion which would produce minimal effects to the coastline.

This notion has developed from the combined data for example; Geomorphology results suggest that both till types were found at this location, with a fairly thin Skipsea till base layer topped by a thicker Withernsea till material. The Withernsea may cause an overconsolidation on the Skipsea till generating a stronger layer which is supported from the high undrained shear strength values collected and the fairly low Atterberg limit readings (particularly the plastic and liquid limit) as the pore water spaces had decrease from compaction. Despite the vertical cracks produced from overconsolidation within the Skipsea material the shear strength and Atterberg limits (see figure 23) indicate that this is unlikely to make the material susceptible to marine erosion (as previously speculated in section 3.3.2a in the results chapter).

 The topography also links with this model as Withernsea till has retreated back further than the Skipsea till which is fronted at the base, developing a concave topography. This implies that the Skipsea till must be of stronger material at this location. The Withernsea till however judging from the topography seems weaker but limited undrained shear strength data was recorded failing to produce sufficient correlations. Linking to the erosional rates which are low in this location, this also supports this predictive model.

The geomorphology of the middle location is very distinct compared to the north and south locations; this can be explained from till property analysis. As previously mentioned (section 4.2.3.) it is apparent that there is a strength variation between the till types, which would give rise to a proposed shear surface between the two layers. The weaker and loose Withernsea material will be percolated by subaerial erosion. The water will percolate down fast, and then slow down at the shear surface due to overconsolidation, which could lead to a drainage system of water flowing along the shear surface, producing a line of weakness, and leading to slump failures in the top layer.

4.4.4. Importance of combing results

Overall the predictive models mentioned above are incomplete ideas, but show the importance of combining datasets, which provide sufficient modelling of varied erosional causes. Further analysis is needed, which is expressed by Quinn *et al.,* (2009) who state that spatial variability alone is still not enough to develop a precise picture. More temporal type data is needed, which is lacking in this investigation.

4.5.   The future of the Holderness coastline

Furlan (2008) and Quinn *et al.*, (2009) express that predictions of coastal erosion are fundamental to future coastal planning and shoreline management, which shows the importance of this study.

Figure 30 shows future prediction scenarios of cliff retreat in the next 20, 50 and 100 years. Average calculations are also given of possible retreat rates within the north, middle and south locations. In the next 20 years, only minor loss of holiday homes will occur. However, in the next 50 to 100 years, retreat will increase rapidly, particularly within the southern section, losing a maximum of 208m of coastline. This will affect transportation from south regions to the north, as the major road, B1362 which links the regions together (highlighted in section H, number 3) will be partly eroded. The gas station at Easington will also be affected in the next 50-100 years.

These are generalised models, in order to raise awareness of possible future problems and how to overcome them. IPCC (2007) and Masselink and Russell (2010) suggest that these erosion rates are likely to increase due to sea level rises and increased storminess in the future.
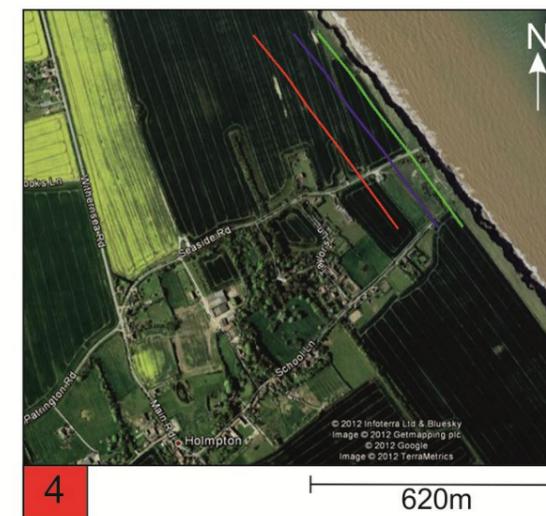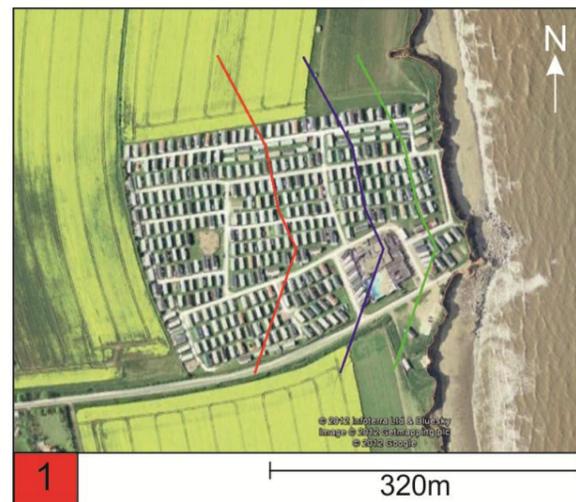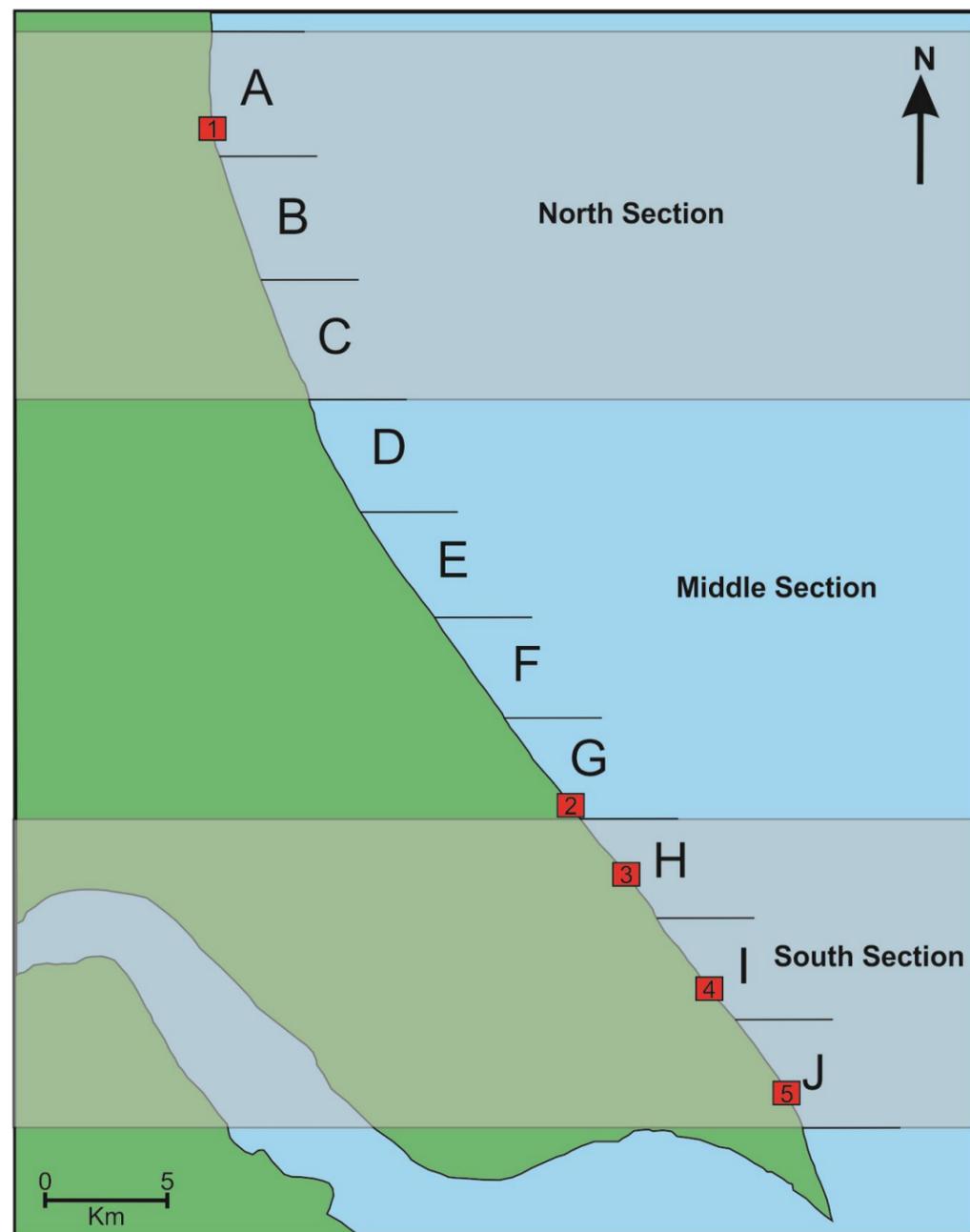
Key

— Cliff line retreat in 20 years

— Cliff line retreat in 50 years

— Cliff line retreat in 100 years

	Year			
	Within 1 year	Next 20 years	Next 50 years	Next 100 years
	Erosion rate (m)			
North location	1.72	34.4	86	172
Middle location	1.53	30.6	76.5	153
South location	2.08	41.6	104	208

Figure 30: Future scenarios of cliff retreat along areas of the Holderness coastline in the next 20, 50 and 100 years, presenting cliff retreat variance in the north, middle and south locations and identifying locations at risk.

4.6.   Future work and limitations

For further advancement towards understanding varied erosional rates within the Holderness coastline, it would be beneficial to incorporate more data through further study. Locations not investigated due to poor access or time constraints could be studied, increasing the spatial variance data from along the coastline. Temporal data collection could also be conducted, especially throughout seasonal changes, which will further support understanding.

Examples of increasing the data spatially and temporally would include: more soil sampling, within both Skipsea and Withernsea material in every divided section throughout the Holderness coast; to conduct a more extensive Atterberg limit testing; and for more readings to be measured using the Proctor Penetrometer and Geovane soil shear tester. The erosional rate dataset could also be increased, generating localised erosional rates throughout the whole study area. New parameters could be introduced, especially marine based data which is lacking in this report; such as tide ranges, wave height, storm history, and ord migrations. Lastly there should be further consideration of climatic instabilities which will occur in the future.

A possible limitation of this study occurred when considering retreat data. When comparing the erosional data based on findings generated using objects and using tracks, using the tracks data suggested much higher retreat rates. This might suggest inaccuracies with the GPS location recordings, and another reason could be the use of averaged data on track results which was not used on object data.

This might suggest that although the highest retreat rate occurs within the south due to this area having the highest sinuosity, the extent of this erosion may be exaggerated due to the reliance on track data in the southern location only. It is recommended that only one method, either objects or tracks, should be used in future studies.

These proposals for future studies will introduce this combined research method, furthering understanding of why and how coastal erosion variation occurs. This method could also raise awareness of other similar coastlines, and help management plans to enable a safe and sustainable environment for future growing coastal populations.

Conclusion
This study has investigated the spatial and temporal erosional variations along the Holderness coastline, located in North East Yorkshire (UK) which as previously stated is the fastest eroding coastline in Europe (Furlan, 2008; Quinn *et al.,* 2009). The cliff stratigraphy is comprised of soft glacial clay tills deposited from the Devensian period (18-13ka), (Bell and Forster, 1991; Bell, 2002; HR Wallingford, 2002; Quinn *et al.*, 2009; Pye and Blott, 2010 and Quinn *et al.*, 2010).
This aim was achieved by carrying out detailed investigations into many parameters that vary spatially and temporally across the study area. The current literature has separately investigated many similar characteristics which are also included in this investigation; however, these datasets have been standardised with respect to data collection and methodology which is lacking in the literature.

An initial desktop study was carried out before field data collection locating areas of high and low erosion. This was calculated by using the sinuosity of the cliff identified from Google Earth, along 10 divided sections of the study, further subdivided into north, middle and south locations. This method was adapted from the mountain front sinuosity method which is a unique reconnaissance tool within the literature for identifying varied erosion rates. It is assumed that the curvier the cliff line, the higher the erosion. More data was obtained from the field, to investigate erosional rates, by measuring distance from a waypoint to the cliff edge using a Trupulse 200, and subtracting the same distance from 2007 Google Earth imagery. Sinuosity has not previously been used in cliff erosion studies.

Other field data included cliff stratigraphic descriptions, cliff heights, geomorphology, as well as strength of the material using a Geovane Soil Shear Strength Tester and a Proctor Penetrometer. Additional soil samples were collected for Atterberg limit testing. The results were analysed together, identifying the spatial trends of parameters. Predictive models were produced showing erosion process intensities, to understand how and why erosion rates vary spatially and temporally. Finally, generalised future scenarios were produced illustrating cliff retreat in the next 20, 50 and 100 years with relation to global warming. This signified the reasoning for report construction, as predicted future increases in coastal populations make it important to understand erosional rates.

Results suggest that the highest erosion rate of 3.3m per year is located within the south location (section I). The sinuosity results support this notion, showing that the south location has the curviest cliff line, implying the highest erosion rates. In comparison, the middle location has the straightest cliffs and the lowest erosion rate of 1.53m per year.

Other results indicate that these locations contain varied cliff characteristics which give rise to these varied erosional rates. The middle location has two till members; Withernsea till is located on top of the lower Skipsea till unit which is overconsolidated. The North section only has Skipsea till and the south contains Withernsea till only. The Skipsea till is darker in colour than the Withernsea unit. Shear strength results reveal that Withernsea till is the weakest material (ranging from 4.50kPa to 15.70kPa) especially in the south location, and the Skipsea material increases in strength from an average of 10.95kPa in the North location to 23.61kPa in the middle location (identifying the middle location as a strongest basal layer, which is probably due to over consolidation). Atterberg limits indicate that the south location (Withernsea till) is more prone to swelling and failing than the middle location (Skipsea till), which is identified from the highest plasticity index value of 19.5% in the south and the lowest value of 13.02% in the middle location.

The highest erosion rate location (south) contains the lowest cliffs found within the study area ranging from 1.3m to 8.3m high. This is compared to the lowest erosion rate location (middle section) which has the highest cliff heights reaching a maximum of 17.1m high. The cliff geomorphology is distinctly different in the middle location due to both till members being located there. The Withernsea till is set further back than the Skipsea till, comparing this to the north and south locations where the cliff is fairly vertical.

The predictive models produced from combining the data identify that the north and south locations have the same erosional process intensities but erosion rates vary due to water content (identified from the Atterberg limits), which will change during the seasons (winter will bring increased storminess). This introduces a seasonal variation of erosion rates within the north and south locations.

Low plastic and liquid limits calculated in the north section imply high erosion within the winter and low in the summer season, which contrasts with high erosion in the summer and low in the winter in the south section indicated by higher plastic and liquid limits.

The middle section has a dominant subaerial erosional process and a minor marine process which are identified from the shear strength and geomorphology results. The results indicate that subaerial water erosion will percolate through the weaker Withernsea layer and stop at the boundary between the two till units, because the lower Skipsea till layer is overconsolidated, leading to the water flowing along the boundary, producing a line of weakness (shear surface) generating slumping failures.

Future scenarios of cliff retreat identify a maximum loss of 208m of cliff in 100 years in the south location. This will affect many holiday homes, farm land and main road links within the study area, implying that erosion rates are important in protecting the coastline in the future.

Limitations of this study included GPS inaccuracies, and the use of varied methods to produce the erosion rates. In further studies, more data could be collected from all sections of the study area, and also new parameters could be introduced such as temporal data, especially identifying seasonal variation and marine type data like wave heights and Ord migrations, in order to help protect the coastline's future.

Acknowledgement

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Appendix

Minimum, Maximum and Standard Deviation of the Proctor Penetrometer Results

All readings		Skipsea Till	Withernsea
	Minimum	21.21	374.44
	Maximum	700.08	926.02
	Standard Deviation	213.63	165.28

North Section only

North	Minimum	21.21	0.00
North	Maximum	657.65	0.00
North	Standard Deviation	279.60	0.00

Middle Section only

Middle	Minimum	265.18	374.44
Middle	Maximum	700.08	678.87
Middle	Standard Deviation	144.83	155.39

South Section only

South	Minimum	0.00	604.62
South	Maximum	0.00	926.02
South	Standard Deviation	0.00	144.66
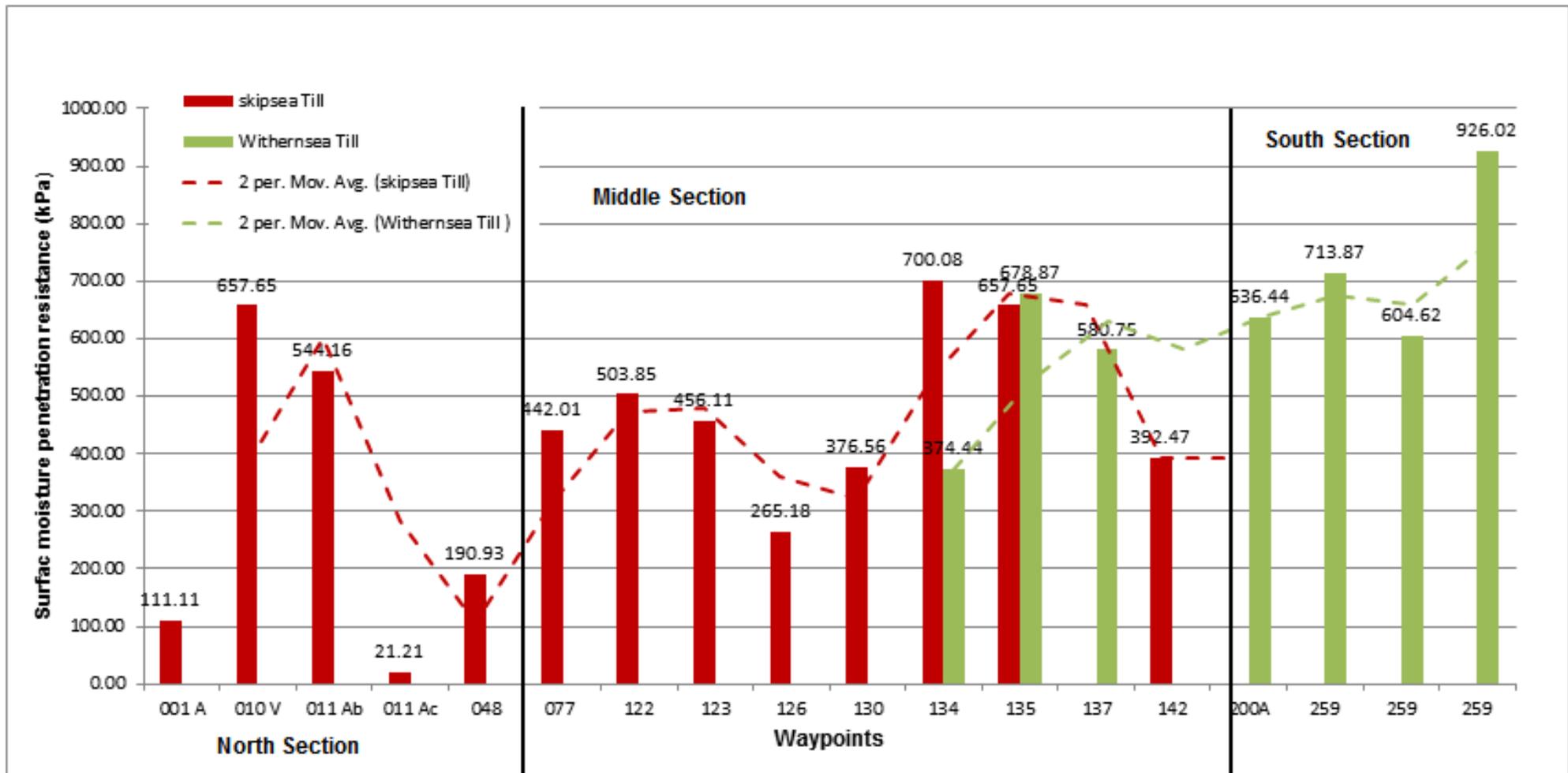
Appendix: Graph and table comparing the surface moisture penetration resistance (Proctor Penetrometer readings) between Skipsea till and Withernsea till (kPa).