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PRediction Of The Erosion of Cliffed Terrains: "PROTECT" Technical Report

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PRediction Of The Erosion of Cliffed Terrains: "PROTECT": Technical Report

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Instrumenting the cliff at Mensil-Val, France. December 2001.

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Foreword

This report is a detailed technical account of the data collected over a period of three years in order to investigate and better understand the mechanisms involved in cliff slope stability issues in fractured rock. If successful, the methodology might be adaptable as techniques for providing an early warning of impending cliff failure. The investigations formed part of the co-funded project 'PROTECT' (PRediction Of The Erosion of Cliffed Terrains) that was supported by the EU 5th Framework research and development programme.

Acknowledgements

The data in this report were collected at five research sites, distributed between the East Sussex coast of the UK, the Normandy coast of France and the Baltic coast of Denmark. Generous help was provided by colleagues in the PROTECT consortium in establishing the sites and in collecting the subsequent field data. PROTECT consortium members also provided other data sets that have contributed to the interpretation of the data presented here. The authors would like to thank in particular:

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Executive summary

PROTECT (Prediction Of The Erosion of Cliffed Terrains), is a European 5th Framework part funded research programme undertaken by the national geological surveys of Denmark and Greenland (GEUS), France (BRGM) and the U.K. (BGS) and the University of Brighton, supported by the French Geotechnical Laboratories at Nancy (INERIS). BGS are the co-ordinating partner.

Rocky, coastal cliffs of North West Europe are continually subjected to changes in stress caused by marine erosion and climatic factors. This leads to fresh geological features and materials becoming an active part of the cliff instability regime. To investigate the possibility of providing better ways of predicting ***when***, ***where*** and ***how*** cliff instability would occur, chalk cliffs were chosen by the PROTECT team. Chalk cliffs form extensive coastlines on the Baltic coast of Denmark and along the English Channel coasts of northern France and southern and eastern England. These are in areas where, either communities are built on the cliffs (Mensil-Val, Criel, northern France) or the cliffs are open to public use (Beachy Head, U.K. with >200,000 visitors a year; Møns Klint, Denmark with similar number of visitors) under and on top of the cliffs. A further advantage of choosing chalk cliffs is the level of previous research carried out under other European funded programmes such as ROCC (Risk Of Cliff Collapse) which made selection of the PROTECT sites easier. The PROTECT programme set out to investigate new ways of (i) determining the temporal aspects of movements in the cliffs leading to collapse (ii) identifying the failure mechanisms. This required integrating the detailed engineering geology with the results from the geophysical techniques and the rock mechanics testing.

The PROTECT results indicate that each geophysical technique is suited to a particular type of geology, but not to all the geological situations investigated. Hence, the detailed engineering geology is an essential prerequisite to the interpretation of results and the application of the techniques.

1 Introduction

The 'PROTECT' (Prediction Of the Erosion of Cliffed Terrains) project started in April 2001 to research methods to predict and develop models of cliff collapse and involved nine partners from five different countries (Busby *et al*., 2002). The PROTECT project is co-ordinated by the British Geological Survey and other partners comprise the University of Brighton (UoB), the Bureau de Recherche Géologiques et Minières (BRGM), the Geological Survey of Denmark and Greenland (GEUS), the Institut National de l'environement Industriel et des Risques (INERIS), the Isle of Wight Centre for the Coastal Environment (IWCCE), the Direction Departementale de L'equipement de la Seine Maritime (DDE76), Urzad Morski w Gdyni (PMA) and Consorzio Ferrara Ricerche (CFR).

A large proportion of the European cliffed coastline is subject to erosion and recession. This dynamic process continually exposes fresh geological features and materials to changes in the hydrogeological and mechanical stress regimes. The assessment of cliff-line recession is an important factor in land-use planning. Hard rock cliffs generally recede through catastrophic collapse on many scales creating hazards to local communities. Pre-existing discontinuities in the rock mass are a controlling factor in slope failures and these may be either ancient faults or joints, orientated at a variety of angles to the cliff face, or relatively new tension fractures formed during cycles of cliff recession, sub parallel to the cliff face.

In Northwest Europe glacial and periglacial activity and weathering processes, have disturbed the bedrock and mantled the top of the cliffs with a variety of sediments. This weathering, combined with the inaccessibility of many cliff sections, makes it difficult to map discontinuities in the topmost bedrock along the summits of the cliffs. Hence it was hoped that geophysical techniques might 'see-through' the mantling sediments and disturbed zones into the underlying fracture network. The initiation of tensional discontinuities that ultimately lead to cliff failures may predate the final cliff collapse by months or even years. Knowledge of the orientation of these and other discontinuities, and the rate at which they open, is necessary in order to predict the mode, extent, and rate of cliff failure, and to determine the stress field(s) causing cliff failure. It is likely that increased tension within the fracture network generated by progressive fracture opening, will eventually lead to rock failure, although the final failure may be triggered by an extreme climatic event. Knowledge of the tensional and shear stresses acting in the rock mass will help to identify vulnerable sections of coastline.

Various geophysical and geological techniques were employed on the PROTECT programme to determine the stresses operating in the rockmass (a combination of the discontinuities and material properties). These techniques were specifically targeted at determining time dependant opening (tension) of fractures in the top of the cliff (e.g. azimuth resistivity, land survey) and other failure mechanisms within the cliff face (e.g. acoustic emission). Geological data was collected at all sites to develop conceptual engineering geology models of the cliffs on which the geophysical interpretations were dependent.

This report brings together the wide range of scientific results from all the working partners in the PROTECT Project:

- University of Brighton: the engineering geology of the sites including rock mass characteristics, strength testing and external influences on the chalk cliffs.
- The British Geological Survey: the application of azimuthal apparent resistivity (AZR).
- The Bureau de Recherche Géologiques et Minières and the Institut National de l'environement Industriel et des Risques: the mechanical behaviour and acoustic emission characteristics.
- The Geological Survey of Denmark and Greenland: the control field survey.

2 Scientific objective and method

The principal objective of the PROTECT project was to provide long and short term alerts of impending coastal cliff instability including measurement of alterations within the rock mass prior to a collapse.

For longer term monitoring a non-invasive geophysical technique, ***azimuthal apparent resistivity*** (AZR), was developed to measure temporal changes in anisotropy of the rock mass near the cliff edge. Increased tension (dilatency) within the fracture network would increase the anisotropy. The technique identifies the change in apparent resistivity with orientation of the measurement within a volume of the rock mass determined by the extent of the measuring array. It was considered that these variations would be controlled by the fracture network within the rock mass and changes with time would indicate changes of tension within the fractures. Increased tension would indicate a weakening of the rock mass. The time scales of such changes and the extent of the affected zone near the cliff-edge could then be determined. The AZR technique should also measure the orientation of faults and fractures near the cliff-edge and determine the zone by the cliff-top affected by temporal anisotropic variations. Hence a relative measure of the increased anisotropy should indicate sections of cliff where the fracture tension was increasing.

For short-term alerts, a vulnerable section of coastline was investigated with ***microseismic monitoring*** to measure ***acoustic emissions*** and was especially developed for the PROTECT programme. These methods required the emplacement of instrumentation in the cliffs to detect cracking of the rock mass. It was hoped that the microseismic method would detect the ***acoustic emissions*** generated by cracking and enable the location of the source of the cracking to be determined. The relationship between the onset of cracking and the onset of failure was also to be investigated. It was thought that these techniques would be applicable to cliff sections that were in a state of collapse.

To assist in understanding the cliff failure process, behaviour of the total rock mass and the interpretation of the results, ***geological and land surveys*** were also undertaken.

At the beginning of the PROTECT programme it was uncertain whether any or all of the above techniques and methods would successfully identify sections of cliffed coastline that were approaching a state of imminent collapse and thus allow accurate predictions to be made of the timing of the collapse.

It was also hoped that the outcomes of the research would:

- Contribute to the wider goal of understanding the physical properties and mechanical behaviour of the rock masses, which lead to unstable cliffs.
- Determine the causal mechanisms of any major change in anisotropy by recording all other influences on the rock mass and how these results relate to any movement of the cliff edge and the effect of collapse.

It was also the intention of the PROTECT team to work with and be guided by the user community. This involved ensuring development was adapted to the users requirements identified at regular meetings with end users. The outcomes of the research would then enable the user community to:

I. Issue informed hazard warnings in areas of cliffs.
II. Make more informed land-use planning decisions in the coastal zone.
III. Maximise the use of the cliffed coastline as an amenity.
IV. Develop informed conservation plans.

The outcomes of the research were also to be used to determine the most efficient methodologies to advance the technology sufficiently so that guidelines for implementation by coastal managers and/or development into an industrial prototype could be made. This would ensure that the outcomes of the project were utilised in the future.

In order to meet the objectives of the project a broad range of investigations were carried out. These can be summarised as follows.

At all research sites:

1. Determine if azimuthal apparent resistivity (AZR) can be used to indicate cliff instability in the long term.
2. Determine if fracture orientations on the cliff top can be obtained from azimuthal apparent resistivity measurements.
3. Collect and collate information on the three-dimensional nature of the rock mass as well as external influences at each site.
4. Perform a topographic ground survey for calculation of incremental displacements on the ground.

In addition to the above surveys, the French research site at Mesnil-Val was also instrumented to:

1. Determine the suitability of the microseismic monitoring as an early warning tool of imminent cliff collapse.
2. Identify the location of cracks in the cliff.
3. Measure temperature, humidity and extension within the cliff.
4. Explain crack mechanisms and estimate when the final collapse could happen.

To verify the field data, a series of laboratory tests were undertaken on samples from the cliffs to support the fieldwork and to investigate other problems and issues that arose as a result of the field investigations. These comprised:

1. Porosity and Intact Dry Density (IDD) measurements.
2. Natural Moisture Content (NMC) measurements.
3. Unconfined Compressive Strength (UCS) tests with or without measurements of deformation.
4. Drained and undrained triaxial compression tests.
5. Shear strength of natural fractures.
6. Sonic triaxial tests (speeds of compressive (p) and shear (s) waves).
7. Laboratory induced acoustic crack emissions.

In addition to the fieldwork and laboratory testing, desk studies were also conducted including:

1. Generation of a geoelectric model for the research sites so that results could be corrected for the influence of the cliff face (across which there is no electric current flow).
2. To establish the most suitable method of processing and presenting the data.
3. Analysis of micro-seismic activity in relation to geotechnical, hydrogeological and meteorological measurements.
4. Calculation of rock volumes lost in rock falls.

   Rock modelling of chalk coastal cliffs using RESOBLOK and UDEC modeling schemes.

3 Site selection

The selection of the sites was one of the most important factors in the PROTECT project. The project team felt that a number of research sites, representing a range of geological settings in the cliffs of Europe were required to fully test out the aims of the project. The chalk cliff coasts of the U.K., France and Denmark met these criteria most closely.

Preliminary studies indicated that each geophysical technique required particular geological conditions for successful implementation. The ideal site for the AZR would be cliff tops in regularly fractured chalk with consistent joint orientations and a simple lithological profile. The Seaford Chalk Formation, exposed in the cliffs at Birling Gap and Beachy Head, potentially offered these ideal conditions.

For the microseismic monitoring and the acoustic emission techniques, the ideal site would contain a few well constrained discontinuities whose location behind the cliff could be predicted so that the monitoring instruments could be placed adjacent to a fracture. Chalk with many fracture sets such as the Seaford Chalk Formation would not be ideal. From the INTERRG II ROCC investigations it was known that there were a number of potential sites along the French coast in Chalk formations which contained a few well constrained master joints. The Lewes Nodular Chalk Formation at Criel and Mesnil-Val was potentially suitable. Additional requirements for the instrumented site in France, were an electricity supply near the cliff edge and a secure building for the instrument monitoring controls. Following several site visits the following sites were selected.

3.1 THE RESEARCH SITES

Based on the site selection criteria, five research sites were established at three localities, (i) Beachy Head and Birling Gap on the East Sussex coast of the UK; (ii) Mesnil-Val on the Normandy coast of France and; (iii) Jættebrink and Dronningestolen located at Møns Klint, Denmark on the island of Møns facing the Baltic Sea.

3.1.1 Beachy Head research site, U.K. National Grid (km) co-ordinates [558.11E, 95.29N]

The cliff at the Beachy Head site is composed of the Seaford Chalk Formation in the upper part of the cliff, underlain by Lewes Nodular Chalk Formation. The Seaford Chalk Formation is characterised by sub-vertical fractures with dominant fracture azimuths of 70^{o} and 150^{o} (Figure 3.1). The site is on a westerly facing slope that has undergone moderate periglacial weathering that may have created randomly orientated fractures near surface and a variety of dissolution features. The site is on the northerly limb of the Beachy Head Anticline and dips at 15^{o} to 20^{o} to the north-west. Tourist use at the site is heavy and as a result the grass is short and there is excellent access at all times (Figure 3.2). No cliff falls were observed during the two years of measurements.

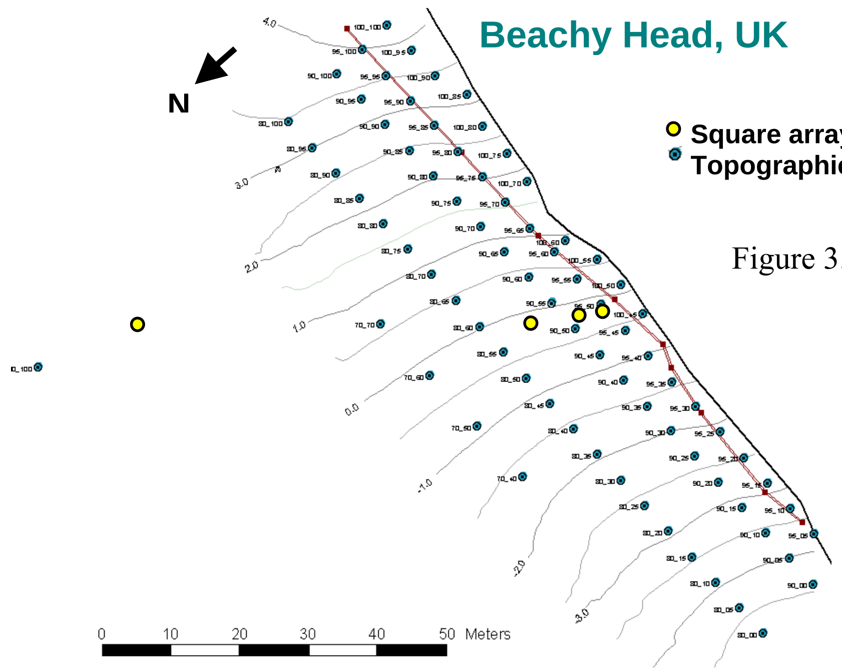


Figure 3.1. Beachy Head research site, UK. Base map courtesy of GEUS.

Figure 3.2. Beachy Head Site A, view looking east.

3.1.2 Birling Gap research site, U.K. National Grid (km) co-ordinates [555.65E, 95.73N], approximately 2.5 km west from the Beachy Head site

Due to the north-westerly dip, the Seaford Chalk Formation that is exposed at the top of Beachy Head is found at approximately 20 m below the top of the cliff at Birling Gap. The entire cliff is composed of Seaford Chalk Formation and is characterised by sub-vertical fracturing. A north-west-trending fault is clearly visible in the wave-cut platform that intersects the cliff at the research site. The strata at Birling Gap are approximately horizontal. Periglacial weathering is less intense than at Beachy Head and there are less dissolution features. The area is owned by the National Trust and is again favoured by short grass and easy access (Figure 3.3 and 3.4). Two small cliff falls occurred during the project, one between March and May 2002 and the other on 9th January 2003.

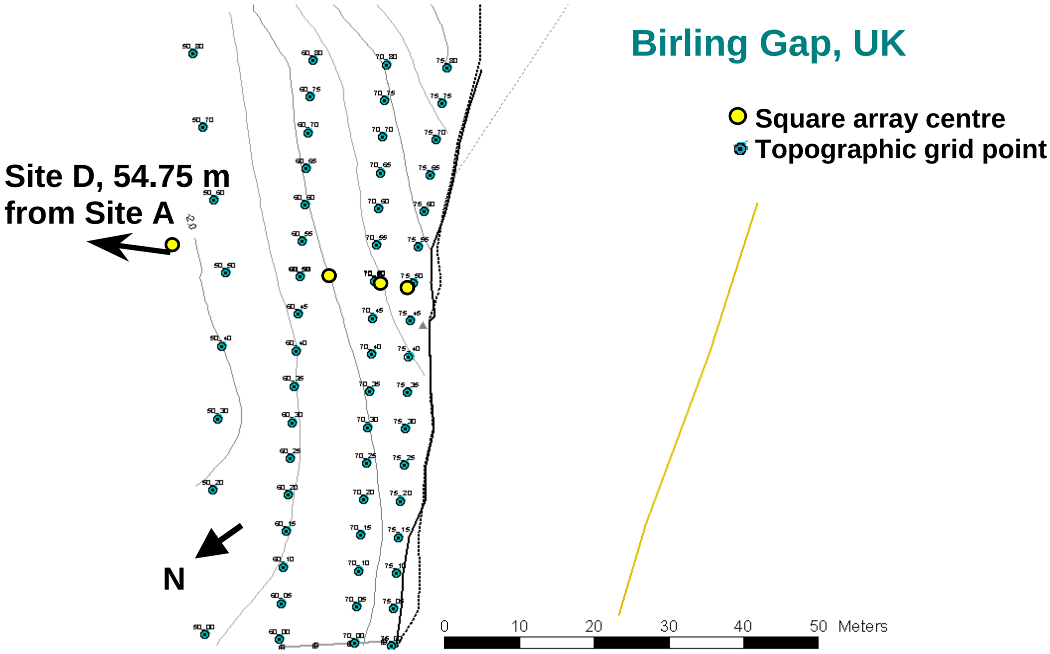


Figure 3.3. Birling Gap research site, UK. Base map courtesy of GEUS.

Figure 3.4. Birling Gap research site, view looking west-north-west.

3.1.3 Mesnil-Val research site, France IGN km co-ordinates of [528.2E, 1261.35N]

The Mesnil-Val site is different to Beachy Head and Birling Gap, as the land surface behind the cliff edge is comprised of farm fields, which slope inland into a dry valley running obliquely to the cliff-line. The south-facing slope of this dry valley forms the research site and this has been subjected to deep periglacial weathering, which thickens downslope behind the cliff-line. Within this periglacially weathered ground profile are a number of linear cryoturbated lobes filled with silty material that have a strike direction of 20° (Figure 3.5). The field at Mesnil-Val was not farmed for the duration of the project and as a result the grass grew very long during the summer, making it difficult to find the exact location of the survey points (Figure 3.6). The cliff is composed of the Lewes Nodular Chalk Formation. The fracturing is sub-vertical and two conjugate fracture sets (master joints) have been mapped with strike directions of 40° and 138°. A medium sized cliff fall occurred during the research period on June 23rd 2002.

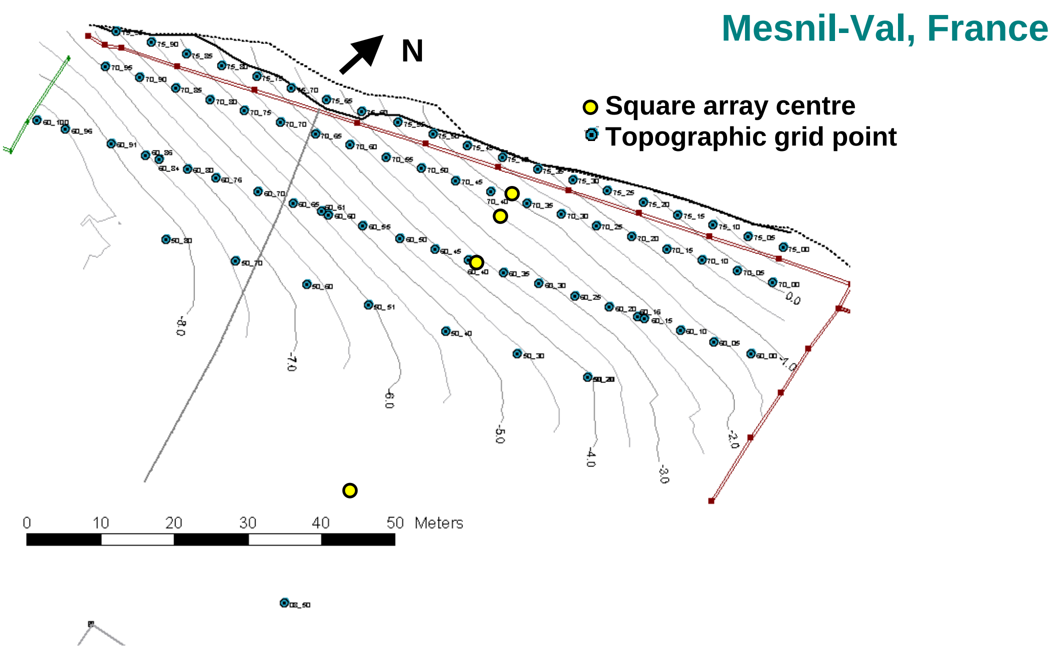


Figure 3.5. Mesnil-Val research site, France. Base map courtesy of GEUS.

Figure 3.6. The Mesnil-Val research site, view looking south, downslope from the cliff edge across the farm field and into the dry valley.

3.1.4 Jættebrink research site, Denmark. UTM Zone 33 km co-ordinates of [342.86E, 6092.3N]

The chalk of Møns Klint has been highly deformed by glaciotectonics. As a result, thrust sheets of chalk lie over and are intermingled with slabs of glacial till. The Jættebrink cliff is 25 to 30 m high and contains no till, but a sub-horizontal thrust divides the cliff into an upper and lower section. The glaciotectonics and associated periglacial weathering has generated a highly fractured chalk with many fracture sets, but with low persistence and high frequency (Figure 3.7). No cliff falls occurred during the two years of measurements (Figure 3.8).

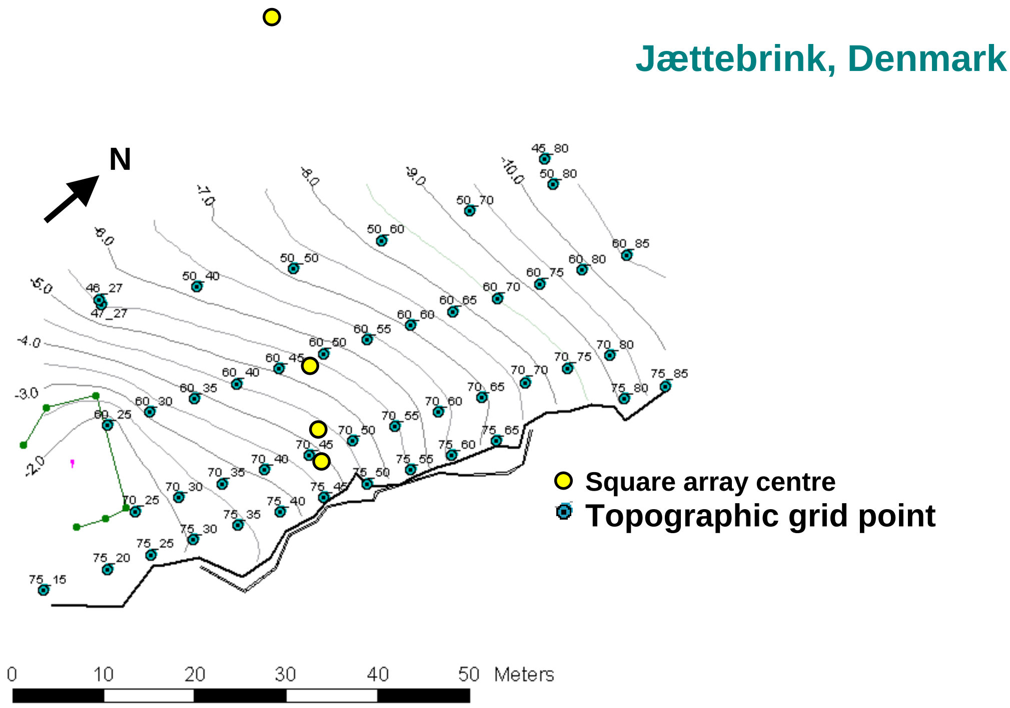


Figure 3.7. Jættebrink research site, Møns Klint, Denmark. Base map courtesy of GEUS.

Figure 3.8. Jættebrink Site B, view looking north-north-east.

3.1.5 Dronningestolen research site, Denmark, UTM Zone 33 km co-ordinates of [343.22E, 6094.14N]

Dronningestolen is situated on the highest chalk peak of the glaciotectonic-stacked thrust pile at Møns Klint, 130 m above sea level. As at Jættebrink there is no till within the cliff. Unlike all the other research sites, the area is wooded and is managed by the Danish Agency of Natural Preservation and Forestry. The trees roots will alter the moisture distribution within the ground and it was expected that this might have an influence on the azimuthal resistivity measurements. No cliff falls occurred during the two years of measurements (Figure 3.9 and 3.10).

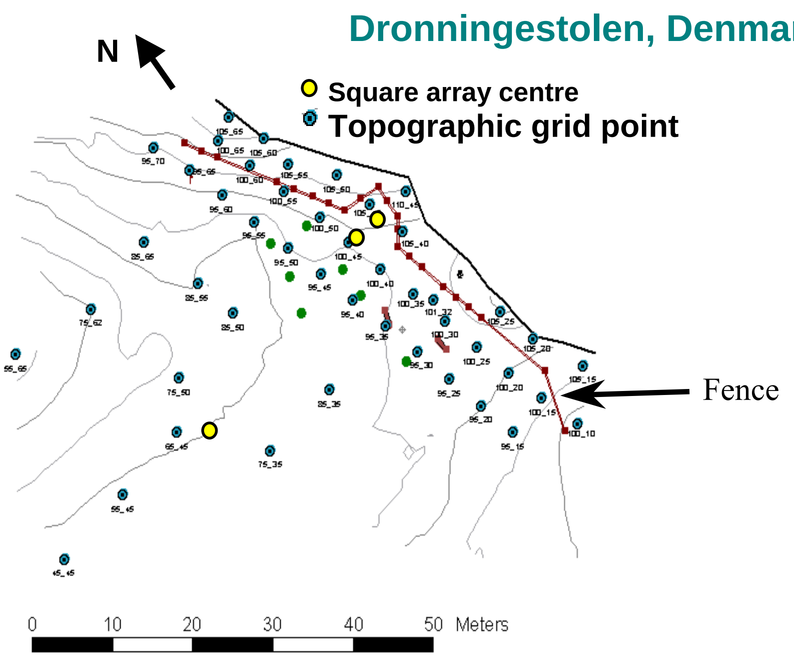


Figure 3.9. Dronningestolen research site, Møns Klint, Denmark. Note that due to space limitations there is no Site C, only A and B, near the cliff, and a Control. Base map courtesy of GEUS.

Figure 3.10. Dronningestolen, view looking from the cliff towards the west. The equipment is located at Site B and the yellow marker of Site A can be seen in the foreground.

4 Geological setting: site characterisation

Selection of the Upper Cretaceous Chalk cliffs of north west Europe (Figure 4.1) as the rock type within which to carry out the PROTECT project experiments, was based on the apparently fracture-controlled nature of cliff failure mechanisms. Part of the criteria for site selection was to the see if differences in geology affected the experiments. Hence each site required detailed geological characterisation so that the geophysics could be reliably carried out and interpreted. The aspects of the geology most critical to the site characterisation included lithology (types of chalk present), fracture (discontinuity) distribution, and the weathered profile. Geological processes causing differences in these characters included the original sedimentary history, tectonic evolution of the area and weathering processes including past glacial and periglacial conditions. Correct geological characterisation of the sites would allow extrapolation of results to similar geologies elsewhere along the coastlines.

The sites selected in the UK, France and Denmark fall into two distinct regional areas of European Chalk deposition. The UK and French sites are in the same broad Anglo-Paris Basin within which the preserved Chalk stratigraphy generally ends in the Campanian (Figure 4.1) with only local inland areas of Masstrichtian. The U.K sites at Beachy Head and Birling Gap are in the Upper Turonian to Lower Santonian. The Mesnil-Val site on the Normandy coast is in Upper Turonian to Middle Coniacian Chalk. In contrast, the Danish sites are entirely in the youngest Maastrichtian chalk located over the Ringkøbing-Fyn High (Figure 4.1).

4.1 THE ANGLO-PARIS BASIN

More than 120 km of chalk cliffs are present on the French coast of Upper Normandy from the Pays de Caux in the South to Ault in the Department of Somme in the north. Mesnil-Val represents Lewes Nodular Chalk Formation that formed in the main part of the Anglo-Paris Basin. This formation on its own represents some 15% of the French coastline and in combination with the Seaford Chalk Formation represents a further 40% of the coast, by far the largest and most representative unit of Chalk in the region (Duperret *et al*., 2004). Hence the choice of Mesnil-Val as a site for the PROTECT experiments has the advantage that the results can be directly applied to large parts of the coast.

Beachy Head and Birling Gap on the shorter U.K. Chalk coast also form part of the main axis of chalk sedimentation in the Anglo-Paris Basin. The Seaford Chalk formation is the predominant stratigraphical unit at the PROTECT experimental sites. At Beachy Head older formations underlie and form the basal part of the cliff involved in any instability but these are beneath the penetration levels of the geophysical techniques employed.

The Anglo-Paris Basin chalk did not simply blanket one large basin. It was deposited on a complex sea-bed with many undulations created by tectonic movements causing faults and folds to grow throughout the Upper Cretaceous. As sea-levels changed the impact of these changes was different in different places depending on the nature of the sea bed so that in some places hardgrounds coalesced into rock bands on the axes and flanks of fold axes and irregular surfaces of thickening and thinning occurred, as at Mesnil-Val and the nearby cliffs at Le Treport. The physical properties and the fracturing of the Chalk reflect these differences in sedimentation leading to some weaker beds (e.g. above the Lewes Marl at Mesnil-Val). Some fracturing took place while the sediments were forming (synsedimentary or penecontemporaneous fracturing events) and these have generated formation or strata-bound suites of fractures.

Each of the PROTECT sites contains similarities in the geology related to the more basin-wide sedimentary and tectonic events. Local effects have also been recorded.

4.1.1 Beachy Head – Birling Gap

Within the Anglo-Paris Basin, the U.K. coast section from Beachy Head to Birling Gap (UK) is one of the most important global sections for the Cenomanian, Turonian, Coniacian and base Santonian stages of the Upper Cretaceous due to the stratigraphical completeness of the sections. These cliffs need, therefore, to remain open and accessible to international scientific study. It is unlikely that any coastal protection engineering would be used on this coast section as the current policy is for managed retreat. Early warnings of impending failure would, therefore, greatly enhance the local authority management of this coastline which receives >200,000 visitors a year.

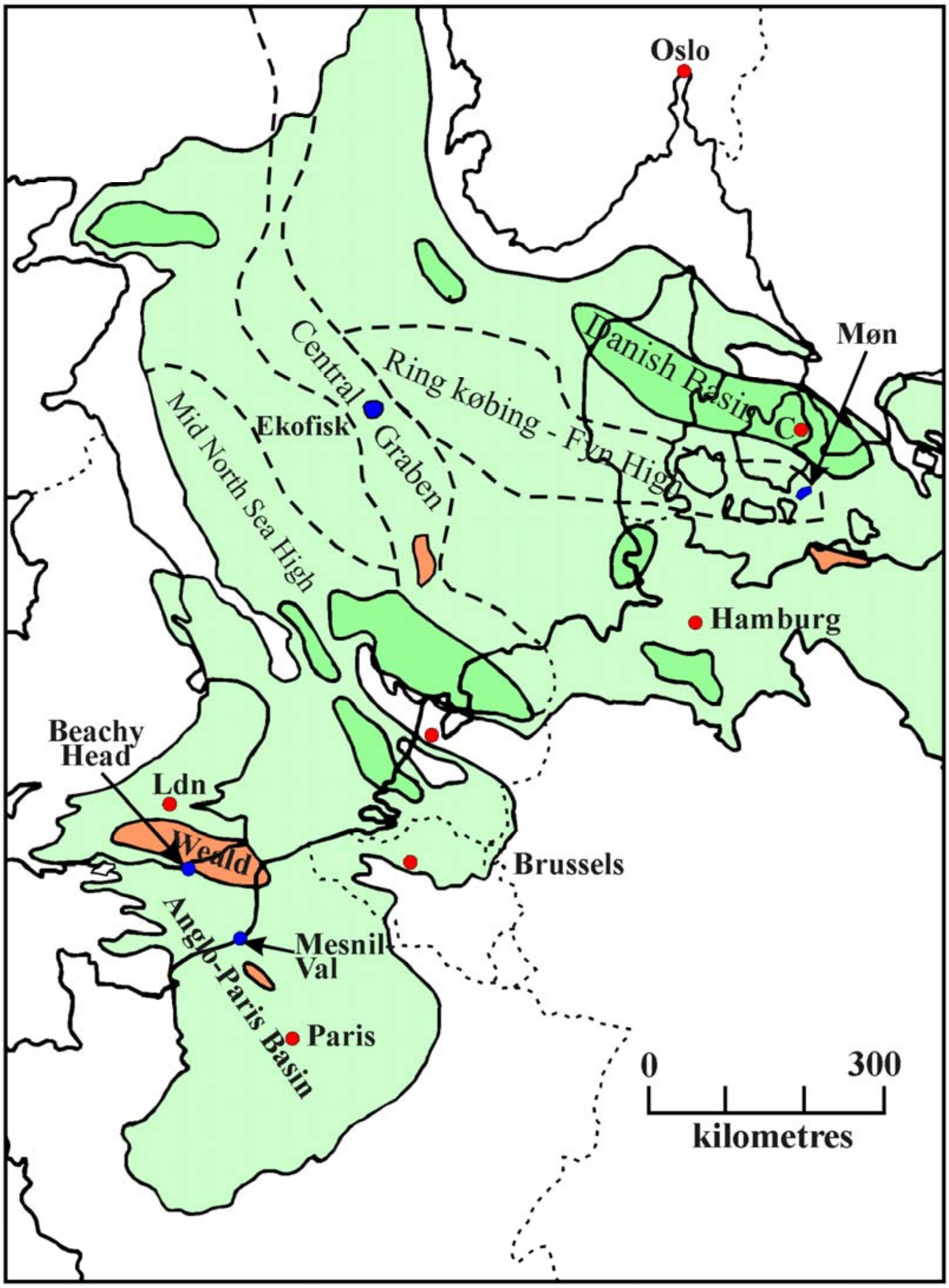


Figure 4.1. The main geological structural elements and the location of the PROTECT sites in the Chalk of north-west Europe.

Detailed stratigraphical measurements have been made of these cliffs to determine the different types of chalk present. The Beachy Head site contains three Chalk formations and each formation has its own impact on the cliff-line profile and instability (Figure 4.2 & 4.3). The Seaford Chalk sections tend to be nearly vertical with a kink outwards in the basal Belle Tout Beds where steeply inclined fractures enter the section. The Lewes Nodular Chalk Formation has a more irregular profile and the combination of the underlying New Pit and Holywell Chalk formations produces a markedly inclined cliff profile (e.g. Mortimore *et al*., 2004).

The formations occur at different levels and places in these cliffs as a result of tectonic folding. At Beachy Head the older chalks are brought to the surface progressively eastwards as a result of uplift on the Beachy Head anticline. In contrast, the youngest beds in the upper units of the Seaford Chalk Formation are present at Birling gap in the Birling Gap Syncline. (Figure 4.4).

Scan-line surveys of the fracturing in the Chalk at Beachy Head and Birling Gap show a number of trends in the fracture orientation, frequency, persistence, aperture and control on location and depth of weathering.

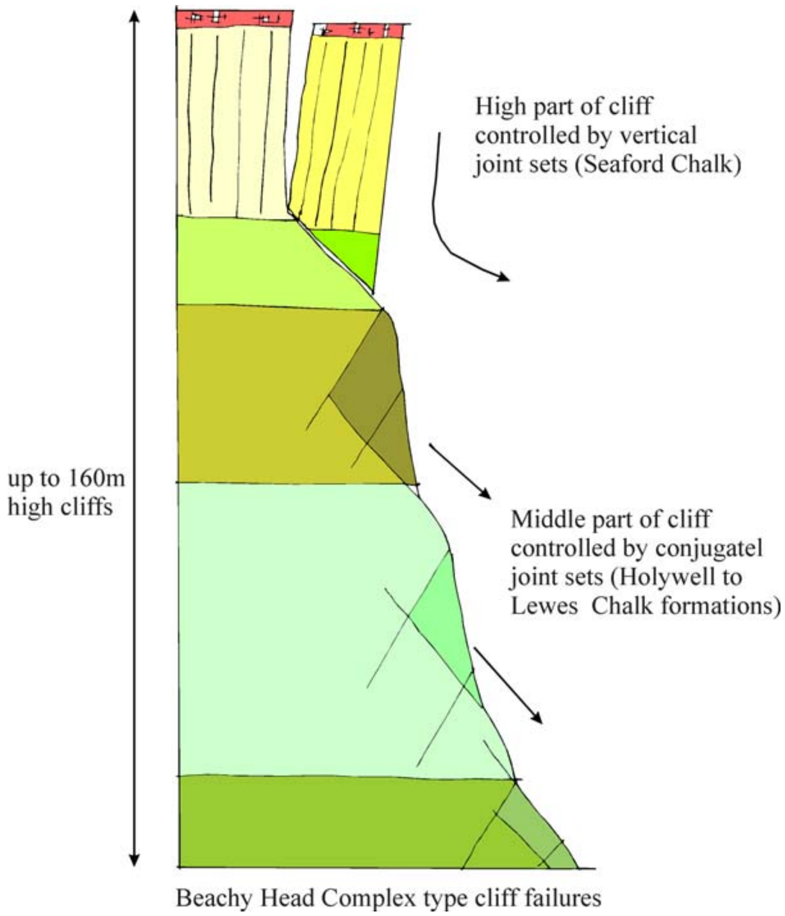


Figure.4.2 Beachy Head style complex failure in Holywell, Lewes and Seaford Chalk.

It is the Seaford Chalk Formation that is immediately beneath the surface geophysical survey sites at both Beachy Head and Birling Gap. The Seaford Chalk is characterised by two closely spaced orthogonal, sub-vertical to vertical fracture sets (Figure 4.5 & 4.6). There is a transition between the Lewes Nodular Chalk and the Seaford Chalk. The lowest division of the Seaford Chalk, the Belle Tout Beds, contain large inclined fractures cutting through the Shoreham Marls from the underlying Lewes Nodular Chalk. Most of the inclined fractures stop at the Seven

Sisters Flint Band which divides the underlying Belle Tout Beds and the overlying Cuckmere Beds. The upper two divisions of the Seaford Chalk, which make up the entirety of the cliff at the Birling Gap research site, are composed of sub-vertical fractures, with the occasional large fault running through the formation. An example of this is the fault at Birling Gap research site which contains an extensive fault breccia, dissolution and calcite cementation (Mortimore *et al.,* 1990)

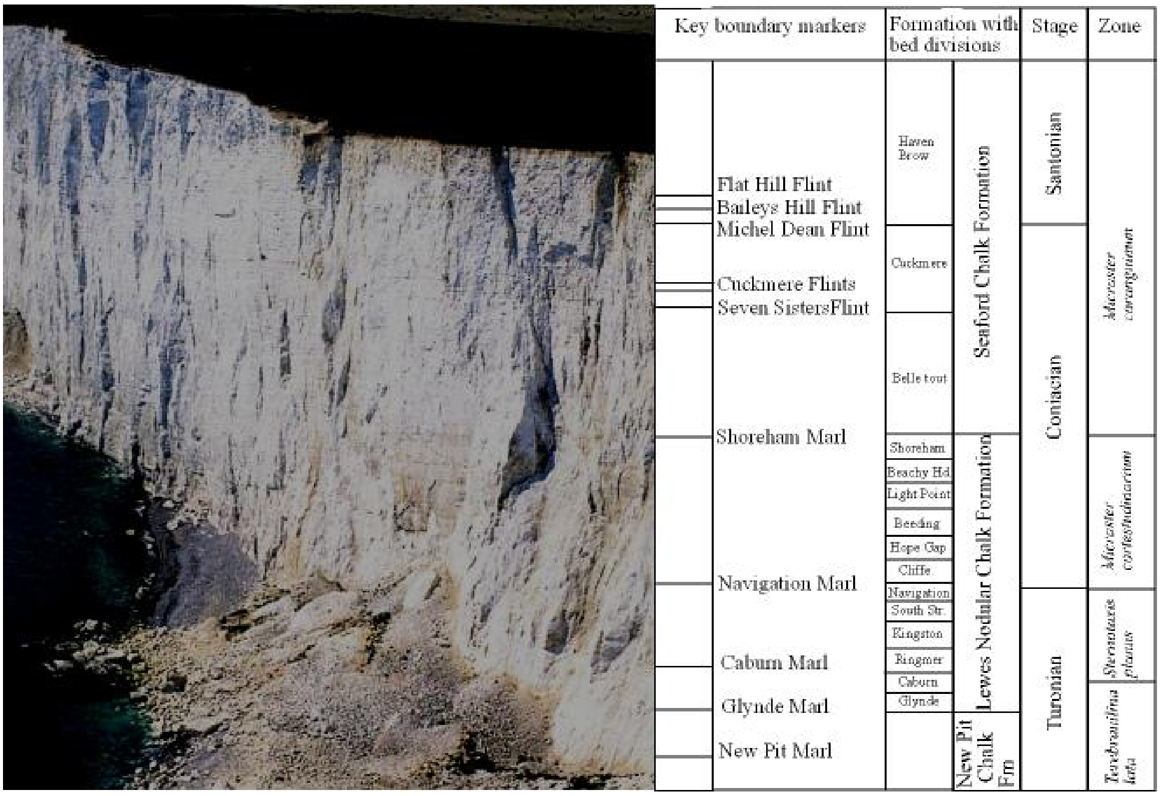


Figure 4.3. Beachy head research site stratigraphy.

Local zones of intense fracturing are also present and one of these is located immediately under the Beachy Head research site opposite the lighthouse (Figure 4.7). Here a wide zone with two complementary sets of steeply dipping shears (faults) is present, one with a NW strike and the other with a NE strike. Strongly developed sub-horizontal slickensiding indicates a component of strike-slip shearing with nearly N-S compression and WNW – ESE extension (Figure 4.8). These fractures which persist right through the cliff are the locus of deep weathering with karst development (a cave systems is present here close to beach level).

A further intense zone of fracturing is present at the very top of the cliffs and results from more recent periglacial activity during the ice age(s).

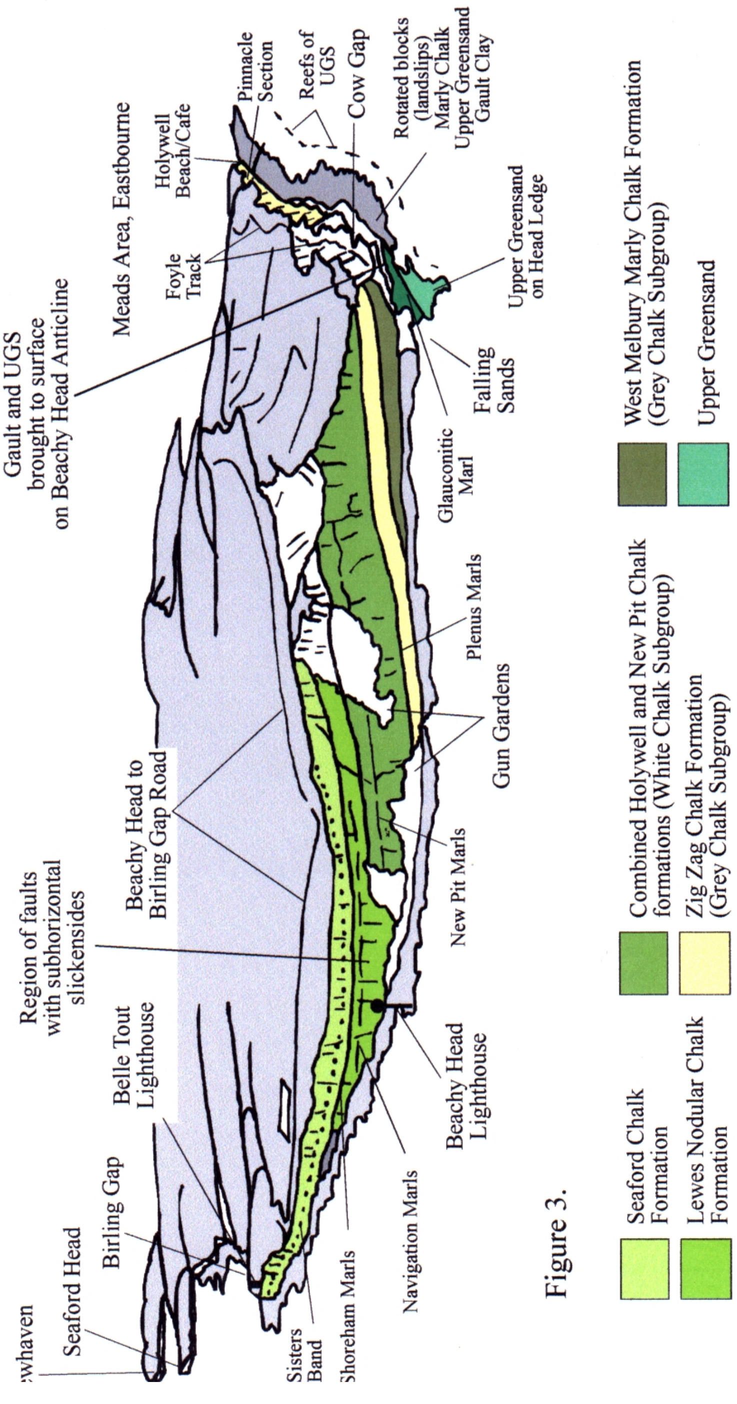


Figure 4.4. Geological Map of the cliffs from Beachy Head to Birling Gap (Mortimore 1997).

Figure 4.5. Sub-vertical orthogonal fracture sets in the Seaford Chalk, Birling Gap.

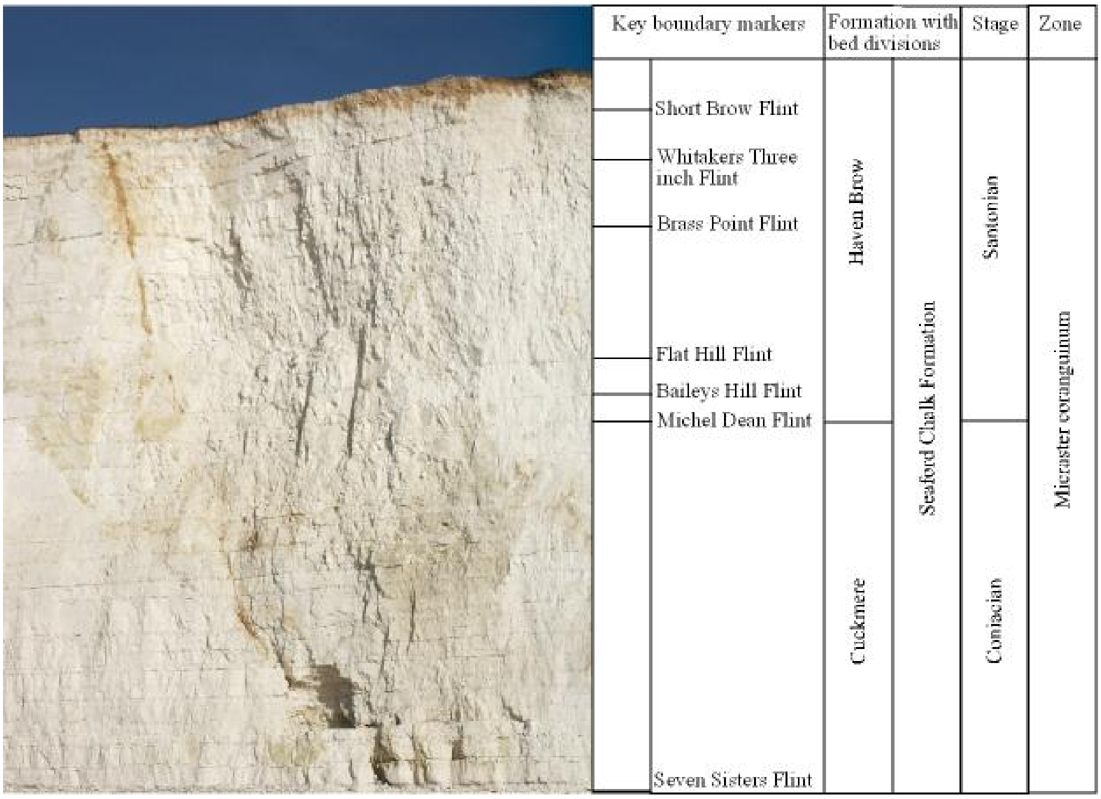


Figure 4.6. Stratigraphy of the Birling Gap research site.

Figure 4.7. Intensely fractured, sub-horizontal slickensides in faults, Lewes Nodular Chalk, Beachy Head.

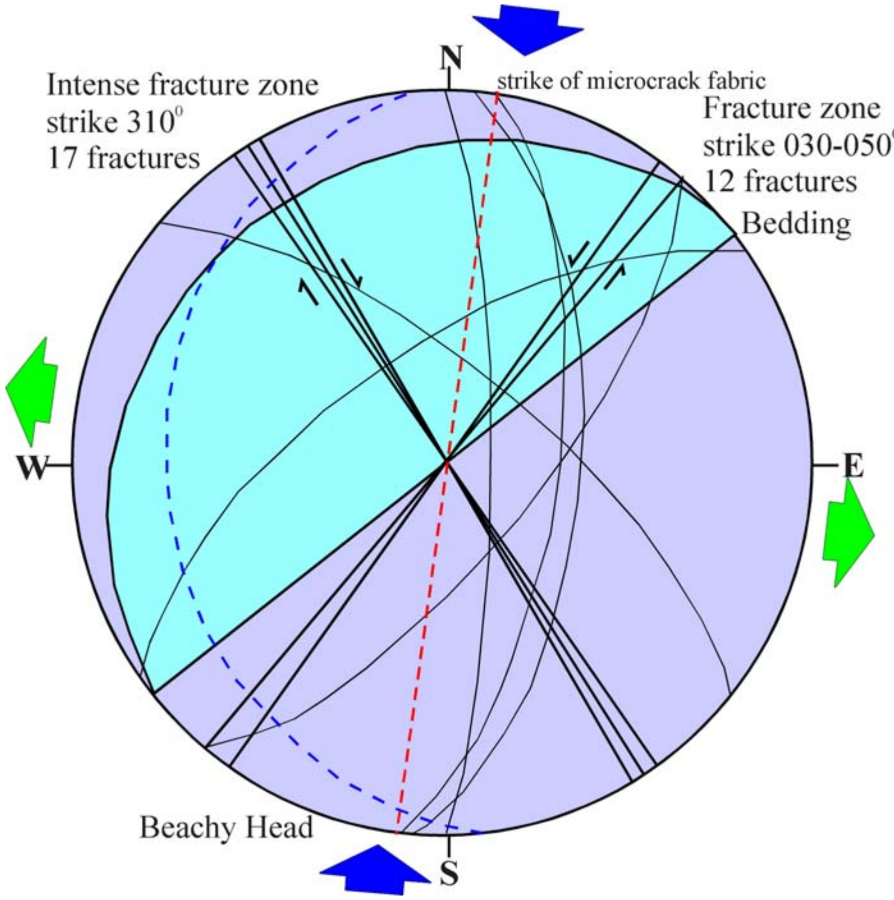


Figure 4.8. Orientation of bedding dip, complementary faults and vein fabric at Beachy Head, Sussex. The sense of direction on the strongly developed sub-horizontal slickensiding is shown by the arrows on the fault strike directions. The other arrows show the direction of compression and extension (From Mortimore, 1979, 2004).

The structure of the chalk and chalk weathering in the PROTECT sites has been found to be closely related to the overall geomorphological setting. From Birling Gap to Beachy Head many types of weathering can be observed, the deepest of which is in the valley at Birling Gap where the weathering is over 20 metres deep. However weathering in the cliff tops and slopes is frequently less than one metre deep. The different types of weathering recognised include:

- Involutions on valley sides.
- Cryoturbated chalk.
- Closely spaced fractures softened chalk and putty fill along fractures, ranging from matrix to clast supported.
- Dissolution features, often with Clay-with-flint fill.
- Clay-filled dissolution along faults.

The sediments mantling the weathered surface or reworked as part of the weathering process include flinty coombe deposits and wind-blown loess.

4.1.2 Mesnil-Val, Normandy

The Chalk cliff at Mensil-Val is entirely in the Lewes Nodular Chalk Formation. This is not a homogeneous unit and contains several different layers, which affect the physical properties and fracturing. For the purposes of the PROTECT investigations the cliff has been divided into three engineering geology units. The lowest unit, beneath the Lewes Marl, is a coarse chalk with nodular beds and appears in the cliff as a fairly massive unit with widely spaced, near vertical fractures which stop upwards at the Lewes Marl (strata-bound fractures). A unit above the Lewes Marl, up to the Navigation Hardgrounds is characterised by a weak layer of variable thickness. This stands out in the cliff as a zone of indentation which can be traced many kilometres along the cliff. Above the weak unit the Chalk is more homogeneous with bands of nodular chalk and flint bands. The topmost 10m is characterised by an intense zone of periglacial fracturing (Figure 4.9).

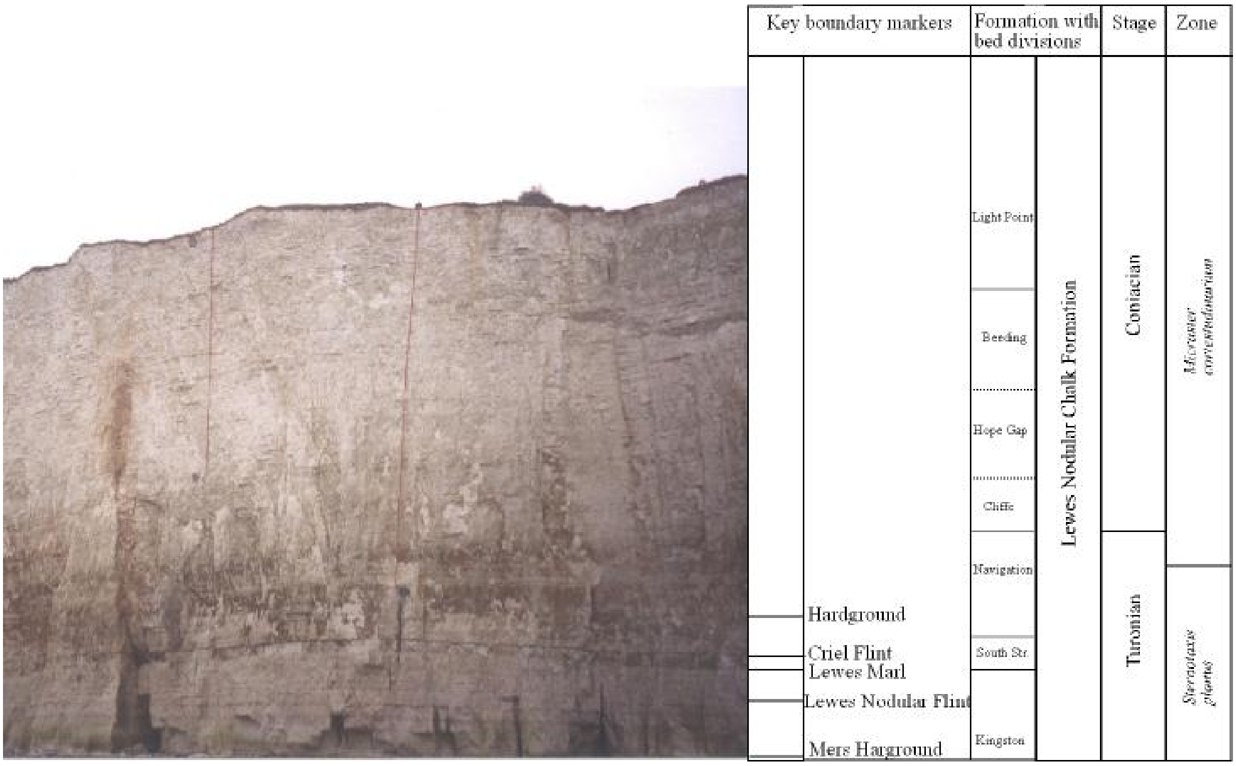


Figure 4.9. Stratigraphy of the Mensil-Val research site.

Sets of persistent fractures cross sub-vertically through the Lewes Nodular Chalk Formation. These tend to be steeply inclined conjugate sets and are typical of the Lewes Chalk both at Mesnil-Val and Beachy Head. It was the consistent presence of these persistent fractures that led to the Mesnil-Val site being used. The acoustic emission geophones were located close to fractures and at various levels in the cliff, one in the 'weak' zone.

Many of the flint bands, hardgrounds and marl seams in the Lewes Chalk act as impervious zones and the water runs along top surface of the flint band by utilising joints and dissolving the chalk around these features creating underground streams and dissolution tubules. The caves created by this process are often full of poorly consolidated chalk debris, sand, silt and clay. These karstic features have been mapped at Mesnil-Val.

At all three of these research sites in the Anglo-Paris Basin there is a section of more or less intensely fractured weathered chalk near surface. This is most notable at Mensil-Val where deep cryoturbated features have been identified in the cliff top. These slope towards the valley, sub-parallel to each other and seem to have an effect on the AZR. The importance of a clear understanding of the stratigraphy of the entire site is importance when categorising the cliff into sections (Figure 4.10).

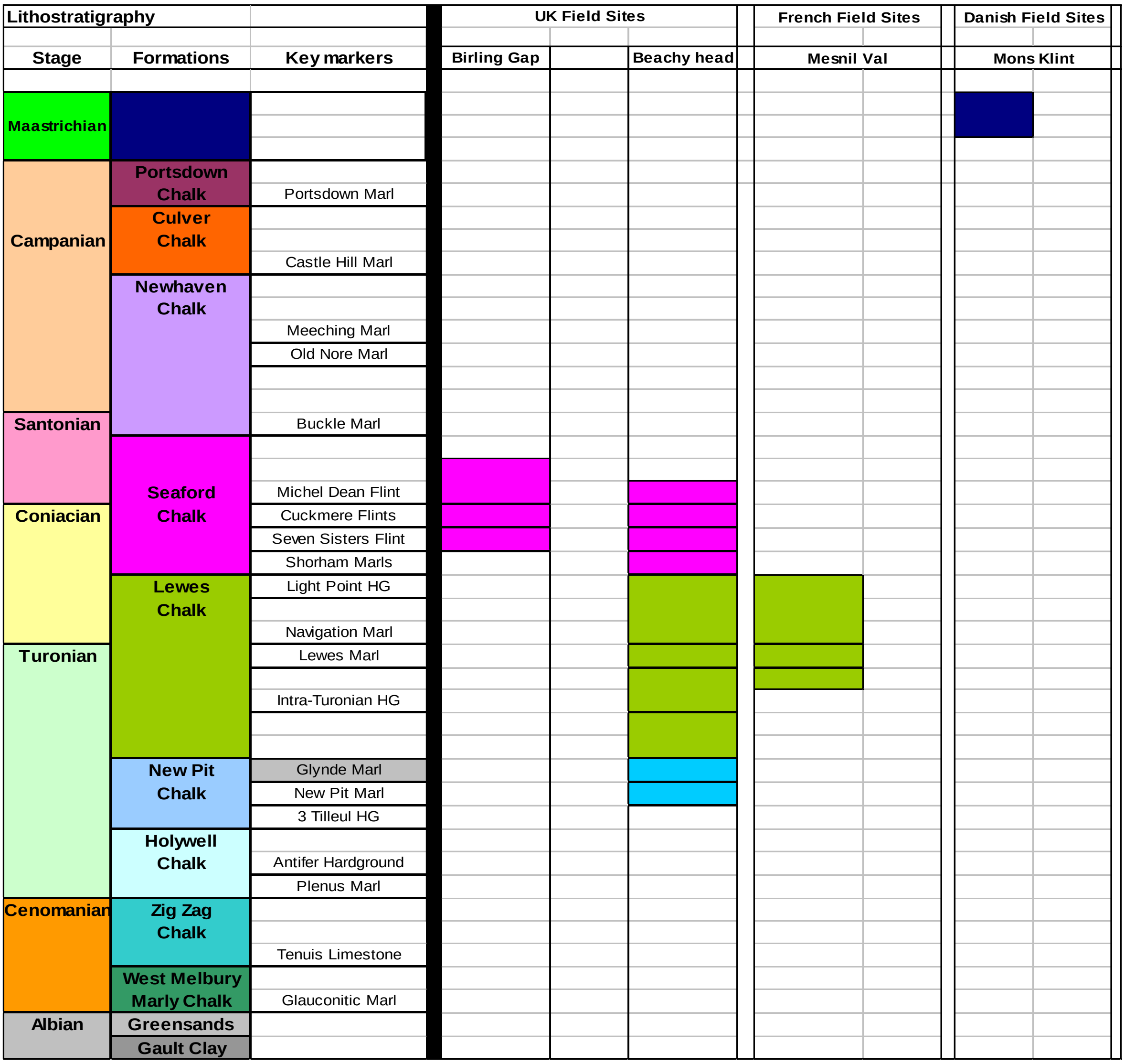


Figure 4.10. Stratigraphic comparison of all the research sites.

4.2 MØNS KLINT; THE DANISH BASIN AND THE RINGKØBING –FYN-HIGH

Chalk forms the major part of a six kilometre long coastal cliff on the eastern Baltic shores of Denmark at Møns Klint (Surlyk and Hakansson, 1999). The cliffs are divided into a series of named cliff tops and valley bottoms with a number of coastal paths and staircases providing excellent access to the area that is heavily used by tourists. There have been many small and several large collapses since the first detailed sketches of the cliffs (Puggaard, 1851, Figure 4.11). Møns Klint still retains a remarkable resemblance to those sketches made over 150 years ago. The two PROTECT research sites are located (i) to the south at Jættebrink and (ii) midway along the Møns Klint section at Dronningstolen on the highest sea cliffs in Denmark where there was a fatality in 1994 as the result of a cliff collapse.

Møns Klint comprises chalk overlain unconformably by Pleistocene glacial deposits (tills and sands and gravels). The geological evolution of the Danish Chalk cliffs at Møns Klint is very different to the cliffs of the Anglo-Paris Basin. It is uncertain exactly where the Chalk, which has been transported by ice, originally formed. It was probably to the south of Møn in the Danish Basin or on the northern flanks of the Ring købing–Fyn-High. The Maastrichtian chalks of Møns Klint are generally softer and weaker than the Anglo-Paris Basin chalks but contain many sedimentological similarities such as marl seams, flint bands including giant cylindrical Paramoudra flints, thin hard grounds and nodular chalk beds and rhythmically bedded chalk. Synsedimentary, strata-bound fractures and shear surfaces are also present.

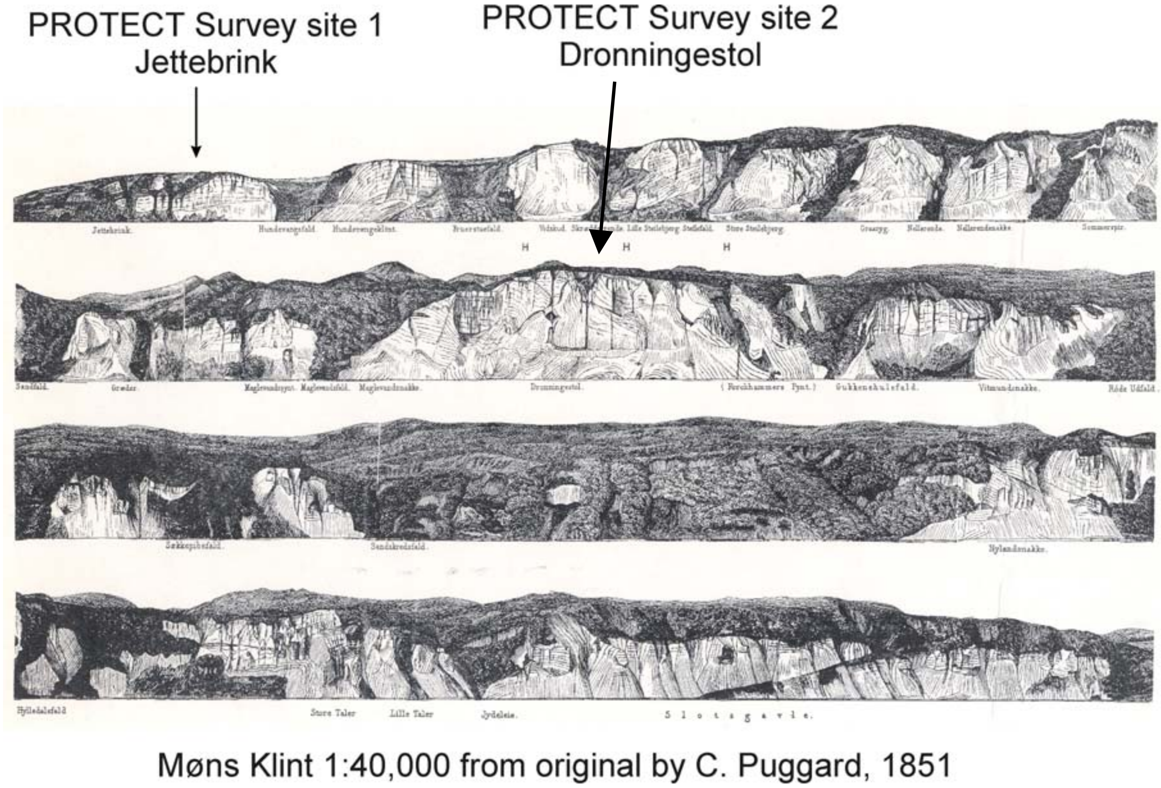


Figure 4.11. Puggard 1851 sketch of Møns Klint indicating the two PROTECT project research sites.

In addition to the Maastrichtian Chalk, Møns Klint comprises Pleistocene glacial sediments composed of tills, clay with scattered boulders, cross-bedded sands with marine shells and glacio-fluvial sand and gravel (Surlyk 1983). The Pleistocene deposits rest on the chalk with a sharp unconformity. Both the older chalk in the south and the younger chalk in the north have sharp unconformities suggesting considerable structural activity prior to emplacement of the thrust stack. There is also evidence that Quaternary sediments were deposited during glacio-tectonic thrusting within 'piggy-back' basins (half grabens) (Pederson 2000).

There is evidence of much syn-sedimentary and post-sedimentary structural deformation of the chalk throughout the end Cretaceous and Tertiary, but the overriding structural control at Møns Klint is glacio-tectonic deformation.

The Møns Klint glacio-tectonic thrust stack was emplaced from the south during the late Weichselian (20,000-13,000 BP) ice advance and a second deformation affects the northern section of Møns Klint as a result of the very latest Weichselian ice advance. Three broad structural settings are recognised:

1. The southern section is composed of a proximal imbricate fan, a series of stacked thrust faults dipping steeply to the south. This structural interpretation (Figure. 4.12 Pederson 2000) is supported by biostratigraphical work (Surlyk, 1972).
2. The central section is in the form of an antiformal stack.
3. The northern part is dominated by a flat lying foreland thrust involving younger strata, with glacio-tectonic compression occurring at a later stage from the East (Surlyk, 1983, Pederson, 2000).

Glacio-tectonic deformation only incorporates sediments deposited during or younger than the Maastrichtian chalk. The glaciotectonic transport model put forward for Møns Klint was a hill and hole model. The hill is the Møns Klint cliffs formed from the transported thrust slices. Approximately five kilometres to the south in the Baltic Sea is the hole, identified by the geological survey of Denmark in Greenland (Pederson. 2000) where the Chalk is originally thought to have been derived. Pederson has estimated the speed of glacio-tectonic transportation to be 1 to 10 metres per year, which is fast when compared to tectonic thrusting.

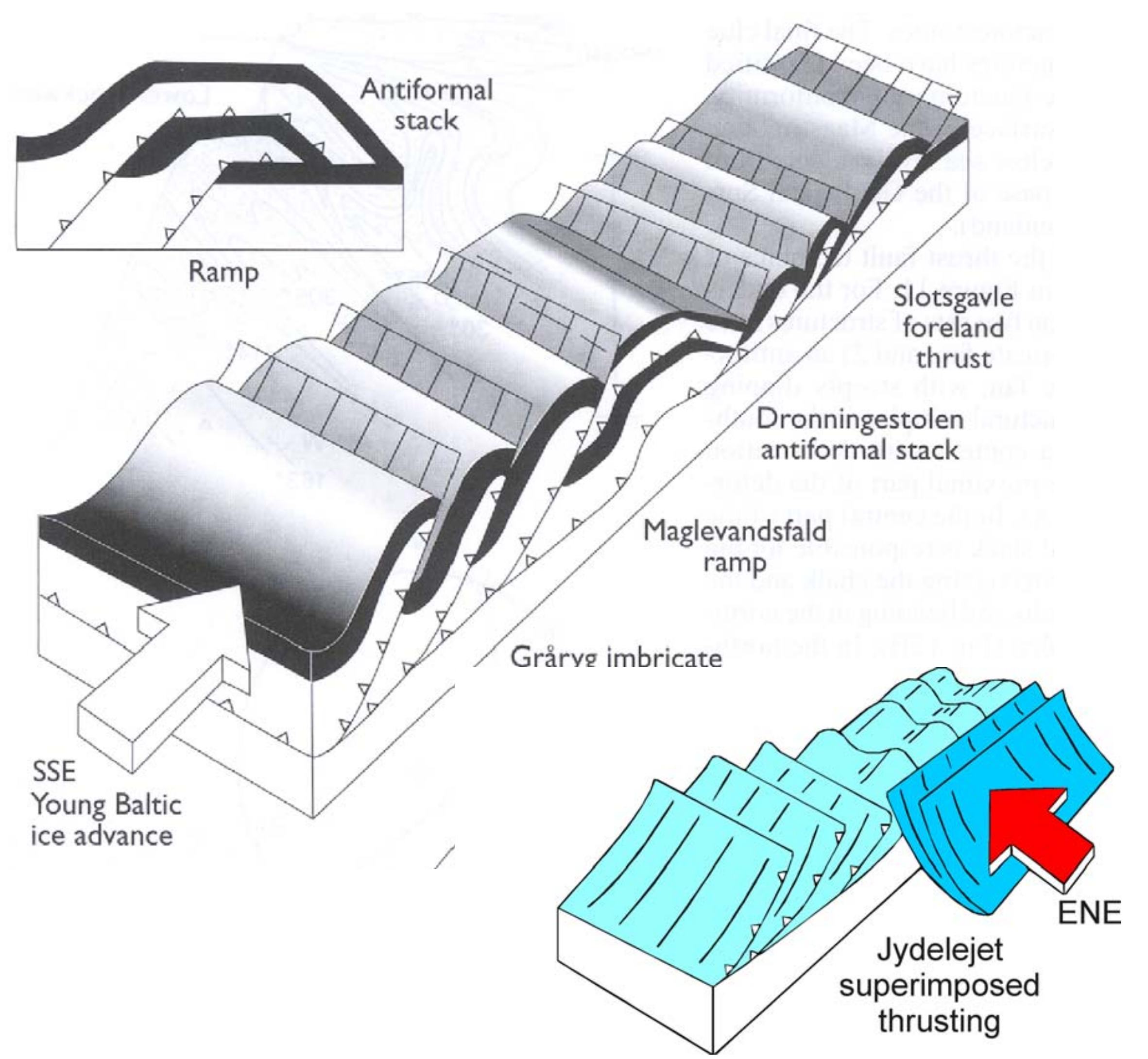


Figure 4.12. Simplified model for the superimposed deformation of Møns Klint. The main glaciotectonic complex may be regarded as a combination of an imbricate fan and antiformal stack. During a re-advance of the ice at the termination of the glaciation in Denmark the complex was superimposed by the thrusting from the east (Pederson, 2000).

One of the PROTECT research sites studied, is in the proximal southern section at Jætterbrink. The central section, including the PROTECT research site at Dronningestolen, starts with the Maglevandsfald ramp and ends in the north with the Dronningestolen antiformal stack. The distal section of the whole thrust complex is the most complex due to a second phase of glacial deformation. The northern section of the cliff is represented by flat-lying thrusts and bedding planes dipping gently to the south, although there has been some secondary orientation striking east to west due to the later ice advance.

As a result of the combination of sedimentary, tectonic and glacio-tectonic events the Chalk of Møns Klint contains several phases of fracturing and weathering which influences cliff instability and geophysical exploration results. These include (i) synsedimentary structures such as the sheet flints and intra-Chalk thrusts (ii) synsedimentary and penecontemporaneous micro-fabrics (iii) tectonic jointing (iv) periglacial fracturing and related structures in the uppermost layers (v) glacio-tectonic folding and thrusting. All of these geological aspects have been investigated as part of the PROTECT studies to provide a geological model for the interpretation of the geophysics.

4.3 LESSONS LEARNT FROM THE GEOLOGY TO APPLY TO THE GEOPHYSICAL INVESTIGATIONS

Geological studies at the PROTECT experimental sites illustrate that:

1. Each chalk formation has a style of sedimentation and fracturing which imposes constraints on the success of each of the geophysical techniques.
2. Different periods of fracturing can be recognised at all the sites.
3. The depth of weathering at each site is very different and much more site specific.

Hence the idea of geologically characterising each of the PROTECT sites has proved essential to the overall project.

5 Geophysical techniques used to investigate cliffs

As previously mentioned two geophysical techniques have been developed to investigate the cliffs. Azimuthal apparent resistivity, applied on the cliff top, has been deployed to monitor changes in anisotropy that may reflect fracture dilatancy with time. This is likely to constitute a long-term warning of cliff failure. Microseismic monitoring of acoustic crack emissions has been established in boreholes set into the cliff. This network should record acoustic crack emissions as the rock cracks in the lower part of the cliff and hence should constitute a short-term warning of impending cliff failure.

5.1 AZIMUTHAL APPARENT RESISTIVITY

It is known that fractures in hard rocks such as chalk and limestone occur in parallel sets, which impose anisotropic physical properties on the rock mass. The catastrophic failure of a cliff is likely to occur along one of these sets of fractures, at least in the upper part of the cliff. Increased tension (dilatancy) within the fracture network will increase the anisotropy of the rock mass. Hence, a relative measure of the increased anisotropy will indicate sections of cliff where the fracture tension is increasing. It is highly likely that increased tension within the fracture network will eventually lead to rock failure, although the timing (months or years) is not currently known. However, knowledge of fracture tension will help to identify vulnerable sections of coastline.

An apparent resistivity measurement is made by imposing a low energy direct current between two electrodes implanted into the ground surface. The resultant distribution of ground potential is measured between additional pairs of potential electrodes (Figure 5.1). When the resistivity of any material contained within the fractures differs from that of the host rock, the measured apparent resistivity will vary with the orientation of the electrode array. Measurements are made by rotating the electrode array through 180° or 360° and taking measurements along a sufficient number of azimuths to define any variation of apparent resistivity with orientation (Taylor and Fleming, 1988). The apparent resistivities (in ohm.m) for each electrode spacing are plotted against azimuth in a polar diagram. If the plotted figure is circular then either there are no measurable fracture sets or the volume of rock investigated was insufficient because the structure and material sampled were, to the limit of measurement, isotropic. This may well be the case for shallow depths, sampled at short spacings. If an ellipse results then the azimuth of the principal fracture set can be defined. For co-linear arrays, the major axis of the ellipse is coincident with the strike of the fractures, whilst for a square array the minor axis of the ellipse is parallel to the fracture strike. A measure of the anisotropy can be obtained from the ratio of the maximum and minimum apparent resistivities. For a square array, the coefficient of anisotropy, λ is defined as

$$\lambda = \sqrt{\frac{\rho_y}{\rho_x}} = \frac{\rho_{x_{app}}}{\rho_{y_{app}}}$$

where ρ_y is the true resistivity parallel to the fractures, ρ_x is the true resistivity normal to the fractures, $\rho_{x_{app}}$ is the apparent resistivity normal to the fractures and $\rho_{y_{app}}$ is the apparent resistivity parallel to the fractures.

If the measurements are repeated over a period of time, any variations indicate an alteration of the physical properties of the rock mass, one of which could be changes in dilatancy within the fracture network (Figure 5.1).

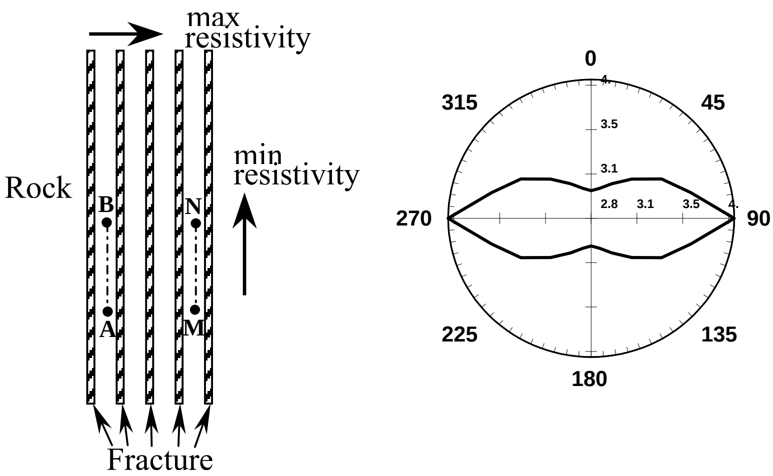


Figure 5.1. A set of parallel fractures will impose anisotropy on an apparent resistivity measurement, conducted through current electrodes A, B and potential electrodes M, N. When the electrodes are rotated about the centre of the square A, B, M, N and the results plotted against azimuth in a polar diagram, an ellipse results. The major axis of the ellipse is perpendicular to the fracture strike.

5.1.1 Electrode configuration

The majority of AZR measurements have been taken with the electrodes arranged colinearly (e.g. Nunn *et al*., 1983, Busby 2000). On a cliff top, space is restricted, so it may be more appropriate to consider a non-linear array. Three different electrode arrays were tried in order to find the array most sensitive to anisotropy. These comprised the Offset Wenner array (Barker, 1981), the Square array (Habberjam and Watkins, 1967) and the Arrow array (Bolshakov *et al.,* 1998). The trial site was located on chalk at Telscombe Tye on the east Sussex coast of the UK [NG 539.25, 101.65], near Telscombe Cliffs. The square array was the only array to give coherent results that indicated a strike for the chalk fractures. The direction obtained, 15^{o}, is in agreement with fracture mapping carried out in the Telscombe Tye area (R. Mortimore pers. comm.). A full account of the trial is given in Busby (2001).

Subsequent to the trial described above, the Square array was selected for all the cliff top measurements. Habberjam and Watkins (1967) have shown that with the electrodes arranged in a square they are more sensitive to anisotropy and require about 65% less surface area than an equivalent, rotated, colinear array. Lane *et al.,* (1995) have applied the azimuthal square array to the mapping of bedrock fractures and have extended the interpretational analysis. By using a switch box there are three electrode configurations for each square (Figure 5.2).

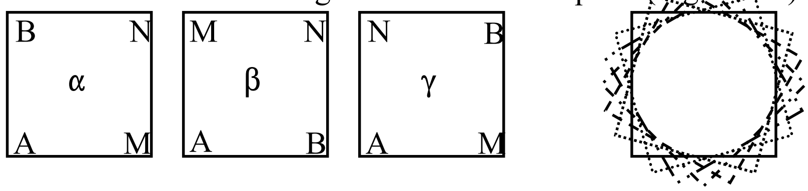


Figure 5.2. The α, β and γ configurations of the square array where A, B are current electrodes and M, N are potential electrodes. By rotating the array in increments of 15°, all orientations are defined with six configurations.

The α and β configurations are perpendicular measurements. The γ measurement serves as a check on the accuracy of the α and β measurements since in a homogeneous anisotropic medium,

$$\rho_{a\gamma} = \rho_{a\alpha} - \rho_{a\beta}$$

where ρ_a = apparent resistivity in Ω.m. Apparent resistivity is calculated from the measured potential difference (ΔV) and current (I) by the relation;

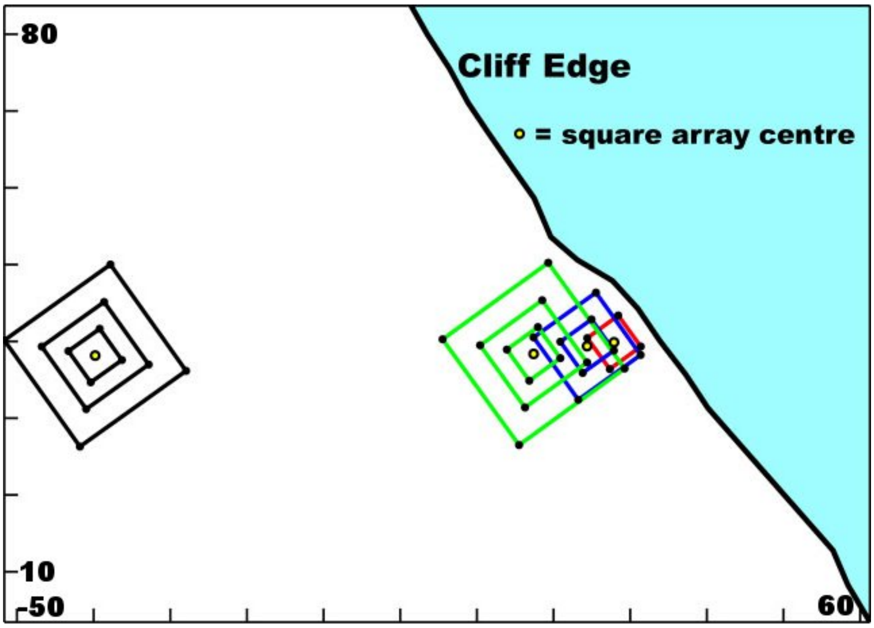
$$\rho_a = \frac{2\pi a \Delta V}{(2-\sqrt{2})I}$$

where ‘a’ is the Square array side length in metres. If the square is rotated about its centre point in increments of 15°, it requires only six rotations to define all orientations. The direction of fracture strike occurs perpendicular to the direction of maximum resistivity; the opposite situation to that of co-linear arrays.

The volume of rock involved in the measurement (and hence the number of fractures crossed) as well as the depth of penetration are determined by the array spacing, that is, the length of a side of the square. In practice all array spacings at a particular orientation would be completed before rotating the array.

5.1.2 Measurement procedure

The cliff top sites used for the measurements all comprised flat lying chalk overlain by very thin drift. Chalk is highly fractured and its permeability arises from the fracturing. On each cliff top, three sites perpendicular to the cliff face were established and a control site was setup approximately 50 m from the cliff (Figure 5.3). Those sites near the cliff edge (Sites A, B and C) should sample ground that is likely to be affected by fracture dilatancy. The maximum electrode spacing (side of the square) for the three sites near the cliff face was set so that nearest approach of an electrode to the cliff edge was about one to two metres. Some temporal variations are likely to be observed due to influences such as seasonal changes in saturation levels, but these should also be observed at the Control Site. A time series was built up by repeating the measurements every two months for a period of two years.



Four centres

Site A: a = 5 m

Site B: a = 5, 10 m

Site C: a = 5, 10, 20 m

Control: a = 5, 10, 20 m

Where 'a' = the side of the square.

For Sites A, B and C the outer electrode approaches to within 1 to 2 m of the cliff edge.

Figure 5.3. Deployment of the square array on the cliff top with three soundings near the cliff edge and a control sounding set back from the cliff edge.

5.1.3 Azimuthal apparent resistivity results

The main results from the AZR are described below:

5.1.3.1 Geoelectric Modelling

The apparent resistivity data need to be corrected for the effect of the cliff edge. The rotated square array measurements were simulated using a 3D finite difference approach (Jackson *et al.*, 2001) incorporating the surveyed cliff co-ordinates at a resolution far in excess of the surveyed points. From this a correction was developed for the infinite resistance afforded by the cliff and applied to the data. The modelling approach was to input the actual co-ordinates of the cliff and test whether the resistivity at each node of the forward model should be set to be infinitely large (i.e. air). Angular variations were modelled by rotating the cliff around the nodes of the forward model in 15^{o} increments. This ensured that the same high-density grid always represents the parts of the model where the current density is highest. The application of the correction generates a reduction to the apparent resistivity measured. Corrections as high as 50% were calculated for the 5 m square array closest to the cliff, compared to the homogeneous case (i.e. no cliff present). Moving away from the cliff these differences decreased as expected, to a few percent for those arrays that did not expand as far as the cliff edge. At the control sites the corrections were negligible.

5.1.3.2 Azimuthical Apparent Resistivity

The orientations of greatest (and least) anisotropy have remained constant at each of the sites (A, B, C and Control) at the five locations over the two years of measurements. For those sites that are anisotropic, fracture orientations have been estimated based on the assumption that the anisotropy is due to fracturing and these are tabulated in Table 5.1. At the UK and French locations the fracture orientations obtained adjacent to the cliff are sub-parallel to the cliff face. At Beachy Head and Birling Gap it occurs in a zone about 10 m wide, but at Mesnil-Val it widens to about 20 m. At Jættebrink a number of fracture orientations were obtained near the cliff face. The chalk here has been highly deformed by glaciotectonics and these results are consistent with the geological mapping that indicates a highly fractured rock mass with many fracture sets at different orientations, but of low persistence. At Dronningestolen the Site B results suggest a fracture orientation at a high angle to the cliff with no cliff parallel fractures. However, the anisotropy in the ground may not be due to fracturing, but may be caused by moisture variations in the near surface arising from the trees at this site. The results from Site A were very variable and cannot be relied upon.

Location	Derived fracture orientations		Coefficient of anisotropy (λ) at distance from the cliff
	Adjacent to the cliff	At distance from the cliff	
Beachy Head (UK)	92 ± 0.5°	151 ± 2°	1.15 ± 0.02
Birling Gap (UK)	115 ± 1°	72 ± 0.3°	2.02 ± 0.03
Mesnil-Val (France)	55 ± 1°	16 ± 2° & 117 ± 1°	1.96 ± 0.08 & 1.90 ± 0.08
Jættebrink (Denmark)	-	5 ± 1°	1.38 ± 0.008
Dronningestolen (Denmark)	54 ± 1°	23 ± 2°	1.19 ± 0.009

Table 5.1. Fracture orientations and coefficients of anisotropy obtained from the azimuthal apparent resistivity data. Those adjacent to the cliff were derived from Sites A and B at Beachy Head and Birling Gap, from Sites A, B and C at Mesnil–Val and Site B at Dronningestolen. The Control Site data were used for the estimations away from the cliff. The error quoted is the standard error in the mean, σ_m, derived from $\sigma_m \approx \frac{s}{\sqrt{(n-1)}}$ where s is the standard deviation of n measurements.

Away from the cliff, at the Control Sites, for the UK locations the derived fracture orientations correspond to the tectonic fractures and are consistent with the mapping of fractures at the cliff face. The data indicate that for the two mapped fracture orientations within the Seaford Chalk, those on an azimuth of 150° dominate at Beachy Head whilst those striking at 70° are dominant at Birling Gap. The increase in the coefficient of anisotropy from Birling Gap to Beachy Head may represent an increase in fracture density (on the scale of the measurements) of the dominant fracture set, although this has not been confirmed by fracture mapping. At Mesnil-Val two fracture orientations are evident in the data and produce similar values for the coefficient of anisotropy. However, there is a discrepancy between these orientations and the mapped tectonic fracture strikes that is discussed in Section 7.

At Jættebrink a fracture orientation of 5° was measured at the Control Site, but cannot be verified by fracture mapping. The results from Dronningestolen indicate a fracture orientation at 23°. These orientations do not agree well with the fracture mapping and there could be a number of reasons for this:

1. The fracture orientation at the top of the cliff is different to the base. At Jættebrink there is a thrust dividing the top and bottom of the cliff. This can be seen in field stretches and photographs.
2. Fracture frequency and style indicates a far higher intensity of fracturing than at the other sites.
3. Fracture persistence is generally far less than at the other sites.
4. The chalk is of a different age and therefore behaves differently.
5. The fracture surfaces are not well developed and therefore the resistivity across the fractures changes very little to that of the chalk mass as a whole.
6. The chalk at the top of the cliff has been deeply weathered.

Møns Klint chalk has sub-vertical, sub-perpendicular fracture sets. Comparing this with the other sites it could be suggested that these fracture groups were pre-existing before the thrusting and that the glaciotectonics has only increased the frequency of this group.

Graphical plots of the variations of the coefficient of anisotropy (λ) with time for three locations are shown in Figures 5.4 – 5.6. Beachy Head and Mesnil-Val display strong seasonal variations, especially towards the cliff edge at Beachy Head. Values peak in the summer with minimum values in the winter. A similar pattern is seen at the Control Site although at Beachy Head the magnitudes are much less and there is a gradual increase over the monitoring period. At Mesnil-Val, the Control site 'a' = 20 m measure shows the same magnitudes and pattern of variation as Site A. A cliff fall occurred at Mesnil-Val on June 23 2002 and this is not apparent in the variations of the coefficient of anisotropy. However, at Birling Gap a cliff fall occurred between 5 March and 23 April 2002 and is associated with a large decrease in the coefficient of anisotropy at Site A and significant reductions at Site B. There is no associated reduction in the coefficient of anisotropy at the Control Site. A further cliff fall at Birling Gap occurred on 9 January 2003, but there is no indication of it in the time series of the coefficient of anisotropy. Seasonal variations are much less than at Beachy Head and Mesnil-Val, but the same cycle is evident particularly in the control data. At Jættebrink there are no clear trends in the variations of the coefficient of anisotropy. At Dronningestolen a seasonal trend is shown with a peak in summer and lower values in the winter. No cliff falls occurred at Beachy Head or the Danish locations during the two years of measurements.

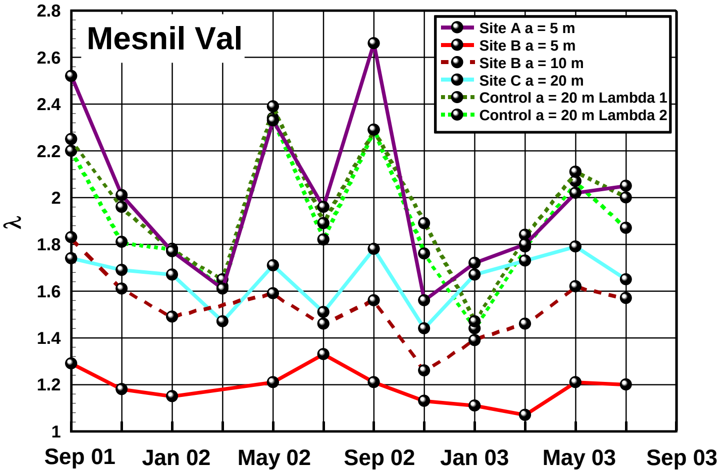


Figure 5.4. Temporal variation of the coefficient of anisotropy at Mesnil-Val.

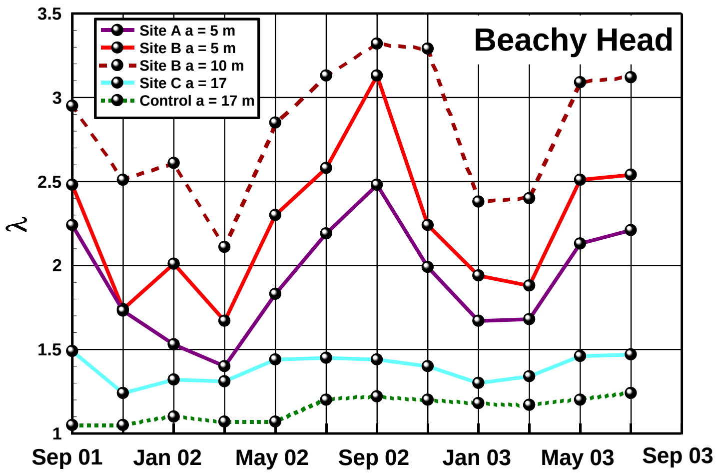


Figure 5.5. Temporal variation of the coefficient of anisotropy at Beachy Head.

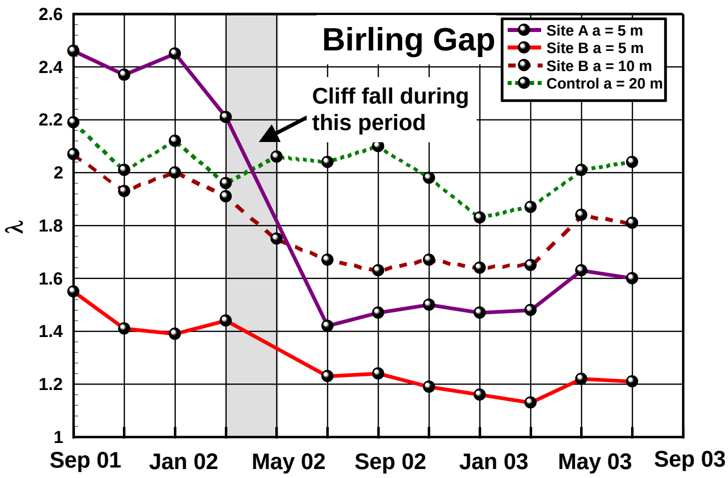


Figure 5.6. Temporal variation of the coefficient of anisotropy at Birling Gap.

5.2 MICROSEISMIC MONITORING

A microseismic monitoring system was only installed at the French research site at Mesnil-Val. Over two years of continuous data were recorded until the system was turned off in June 2004.

5.2.1 Microseimic data collection

The emission of a seismic signal has been used to detect developing cracks in rock in deep coal mining, in abandoned mines (Senfaute *et al*., 2000) and in hot dry rock geothermal projects. The challenge in the PROTECT research project was to adapt the microseismic technique to cliffs where the overburden stresses induced by the rock mass were likely to be lower than in underground deep mines. The acoustic signals from crack development in chalk would probably be weaker in cliffs than in underground mines because of attenuation caused by the high frequency of open fractures in weathered chalk.

Acoustic emissions from developing cracks were measured with accelerometers and geophones. Since the wavelengths of the seismic signals generated during the rupture of chalk were not known, a broad frequency band-width was selected. A network of five microseismic stations (accelerometers and geophones) was installed in the cliff at Mesnil-Val. Anticipating strong attenuation of the seismic signal in chalk, a maximum spacing of about 50 m was chosen between stations. The network comprised two stations in vertical boreholes, drilled from the top of the cliff, and installed to a depth of 10 m and located 10 m from the cliff edge. A further three stations in horizontal boreholes were drilled from the cliff face to a depth of 6 m (Figure 5.7). Results were recorded continuously from January 2002 to May 2004. In addition, temperature and humidity sensors and extensometers were located in the cliff. A weather station was established on the cliff top. Due to the high cost of installation, microseismic recorders were only located at Mesnil-Val and not in the UK and Danish research sites.

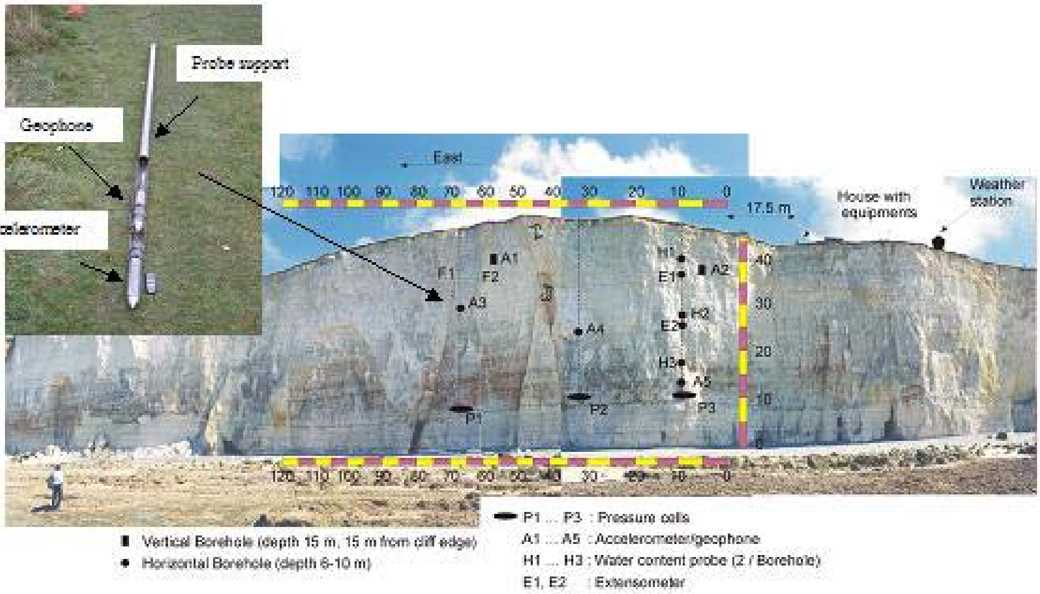


Figure 5.7. Location of monitoring network at Mensil-Val and accelerometer/geophone station installation design.

5.2.2 Microseismic activity recorded

Significant seismic activity was recorded twice per day at Mesnil-Val, at the hours when the sea was highest for periods of 2 to 3 hours. Analysis confirmed a strong correlation between tide and seismic triggering (see Figure 5.8). Hence, it is possible to conclude that these recordings are related to the action of high tide on the face of the cliff. Microseismic events were also recorded at low tide. These events are considered as independent of the action of the sea. Spectral analysis of the signals showed significant differences between these events and those recorded during high tide. The intensity of the high tide events was so large that it was not possible to record the other type of event during periods of high tide.

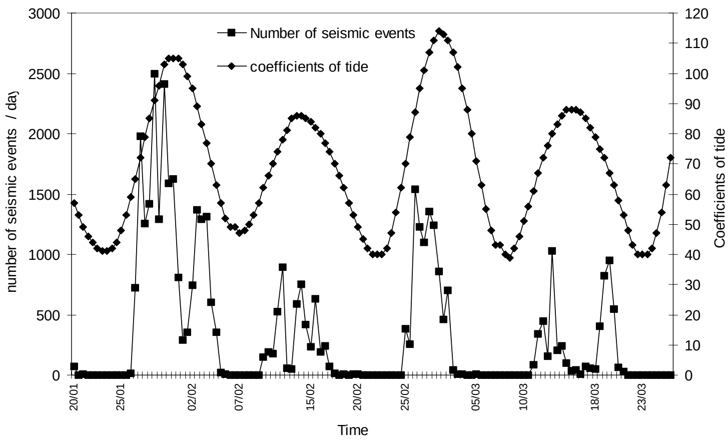


Figure 5.8. Correlation between seismic events number and tide coefficient.

A cliff collapse occurred on 23 June 2002 at Mesnil-Val. An estimated 2700 m^3 of chalk dropped from a maximum height of around 50 m. It occurred at the center of the monitored zone (see Figure 5.9). In the 15 hours preceding the collapse strong seismic pre-cursors were recorded on one of the accelerometers (Figure 5.9).

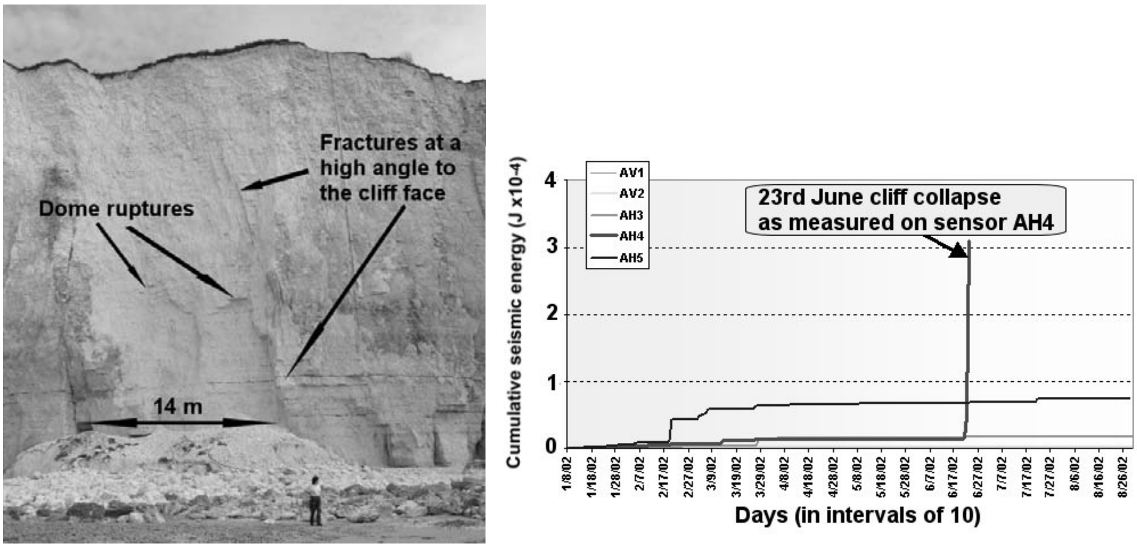


Figure 5.9. The cliff collapse at Mesnil-Val with a plot of the cumulative seismic energy recorded over eight months. AV are stations in vertical boreholes, AH are in horizontal boreholes.

This accelerometer (AH4) was damaged by the collapse and ceased to function. The collapse occurred during a low tide, and most of these seismic pre-cursors can therefore be considered to be independent of the action of the sea. Prior to the collapse of June 23 2002, 343 seismic events were recorded during the 6 months period before the collapse, 224 seismic events were recorded on June 23 (one day) and 281 seismic events recorded in the 29 months period after the collapse. The low seismic activity observed after the collapse indicated that the monitored zone had become stable. This observation was backed by site visits as no other rock fall was recorded. A seismic attenuation study was conducted on the cliff at Mesnil-Val using explosive charges on the cliff top and geophones on the cliff top and on the beach. These tests demonstrated that after 30 meters the signal had reduced by approximately 90%. The analyses indicate that the radius of the monitored area will be less than approximately 15 meters from any seismic sensor in chalk.

5.2.3 Failure mechanisms from microseismic signals

The recorded microseismic signals provided the first information on failure mechanisms associated with cliff collapse. The doublets technique or multiplet selection was applied to the data to identify the seismic events families, supposing that each family belongs to the same failure mechanism. Multiplets were defined as a set, while a doublet was a pair of similar-appearing events. The objective was to characterize the degree of similarity of a pair of events using the modulus of the coherency spectrum, which is the smoothed cross-spectrum normalized by the smoothed autospectra of each windowed seismogram. The smoothing function of the spectral densities is given by Fourier transform.

The multiplet selection technique was applied to microseismic events recorded on June 23rd, before the collapse. Only events that were recorded during low tide were considered to eliminate the possible signature associated with the action of the sea. Four seismic event families were identified (59 events) and 175 events were excluded. Each seismic event family contained one specific frequency spectrum. Figure 5.10 shows an example of the frequency spectrum of each event family. Family 1, for example occurred only in the beginning of microseismic activity (the frequency-band is between 500 Hz and 1.5 kHz). Families 3 and 4 occurred just before the cliff collapse and recorded higher frequencies. They may be associated with the shear surface mechanism, which took place just before the collapse. These results suggest several rock fall phases. The most important rupture phase may be associated with the seismic event families identified by multiplets selection.

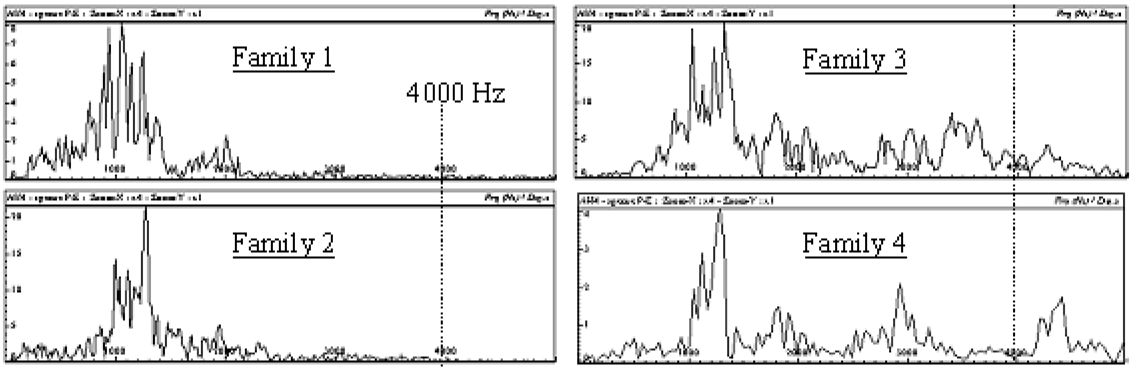


Figure 5.10. Example of the frequency spectrum for each seismic event family.

5.2.4 Laboratory induced acoustic emissions

In order to increase the understanding of failure mechanisms that lead to collapses a study was carried out of acoustic emissions induced in samples from the chalk cliffs. Chalk blocks from each of the three geological levels identified in the Mesnil-Val cliff were collected for laboratory testing. Two samples were drilled from each geological level, resulting in a total of six samples. All samples were cut as a cylindrical core 140 mm in height and 70 mm in diameter. Laboratory tests were carried out in uniaxial compression with cycles of loading and unloading. The total porosity of chalk was high suggesting a low mechanical strength, which is confirmed by the low values of the failure strength obtained during the tests. Analysis of the acoustic emission rate allowed the identification of several phases of the sample deformation (see Figure 5.11). These were:

- A phase of pore closing, with virtually no acoustic emissions.
- A significant elastic linear phase, which is prolonged almost until peak strength, with very few acoustic emissions .
- A short inelastic phase during which acoustic emissions are generated. This phase is clearly highlighted by significant increase in the acoustic emissions rate (point A, Figure 5.11). Acoustic emissions may be associated with the creation of new ruptures. For the chalk analysed this phase begins rather slowly, the point A is located between 76 and 90 % of the failure strength.
- A rupture phase with several macro-ruptures. These macro-ruptures are accompanied by significant peaks in acoustic emissions (point B, Figure 5.11).
- A post-peak phase that may be associated with shearing. The acoustic emissions are still important at the beginning of this phase but decrease quickly and disappear.

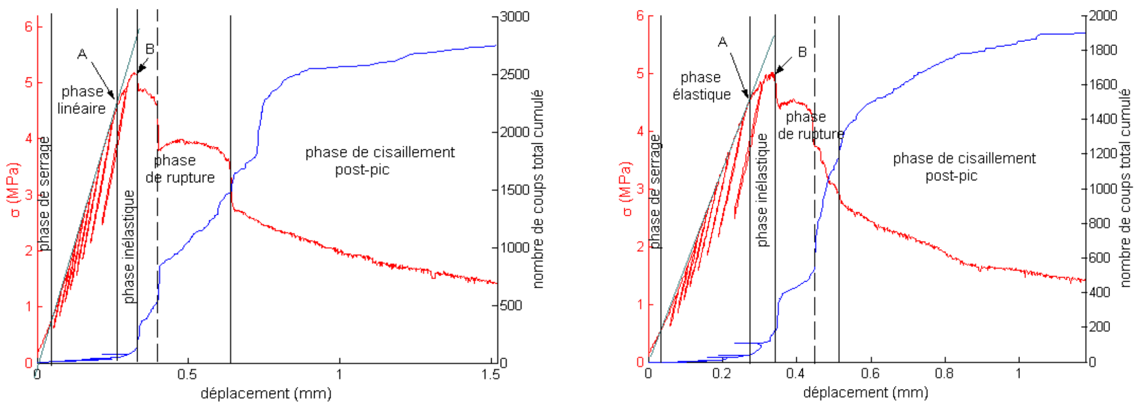


Figure 5.11. Evolution of cumulative acoustic emission rate during the deformation for two chalk tests. The blue curve is the acoustic emission rate.

It has also been observed that the strongest events appear in the inelastic zone and near to the failure strength.

The correlation between the data recorded in the field and laboratory data are complex for a number of reasons:

- The timescale of events; since the rupture studied in the laboratory occurred over a few minutes, whereas the rock fall on site occurred over one day.
- The spatial scale, since a laboratory sample was 140 mm in height and the cliff face is 50 m in height.
- In the laboratory the tests were carried out in uniaxial compression with an imposed constant deformation speed. The observations on site and the initial modeling suggest that the cliff-fall happened in several phases and probably under its own weight.

Analysis of the acoustic emission data, however, indicates significant similarities between the ruptures observed in the laboratory and those due to the cliff fall. At these two scales, there is a clear exponential increase of the seismic event numbers and of the energy released before the final rupture (see Figure 5.12).

Figure 5.13 shows the evolution of the frequency spectrum for seismic events recorded in the laboratory and at the experimental site due to the cliff collapse. The laboratory results highlight the fact that the signal frequencies move towards the high frequencies during the linear phase until the inelastic phase when the frequencies are highest. These high frequencies, just before the rupture, may be associated with the creation of new cracks. After the rupture peak and during post-peak phase, the signal frequencies are lower. On site, the evolution towards the highest frequency spectra was observed a few hours before the rock fall. There were two peaks of maximum frequency spectrum. A peak one hour before the rock fall, which would be associated with the creation or with the slip of the ruptures, and a peak at the time of the rock fall. Approximately 50 minutes before the collapse of the cliff there is a clear evolution of the frequency spectrum from low to high frequencies. After this highest frequency peak, a significant reduction in frequency was observed. It may be associated with the extension of ruptures that would generate low frequencies and/or very fractured zones that would filter out the high frequencies. This significant fall in frequency after the maximum frequency peak was also observed in the laboratory in the post rupture phase.

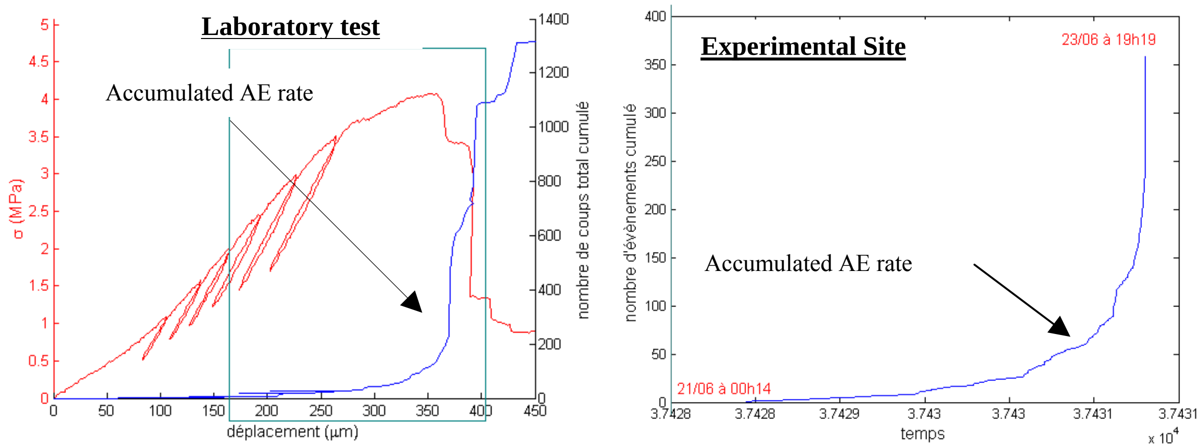


Figure 5.12. Acoustic emission activity during uniaxial compression tests and during the cliff collapse at the experimental site.

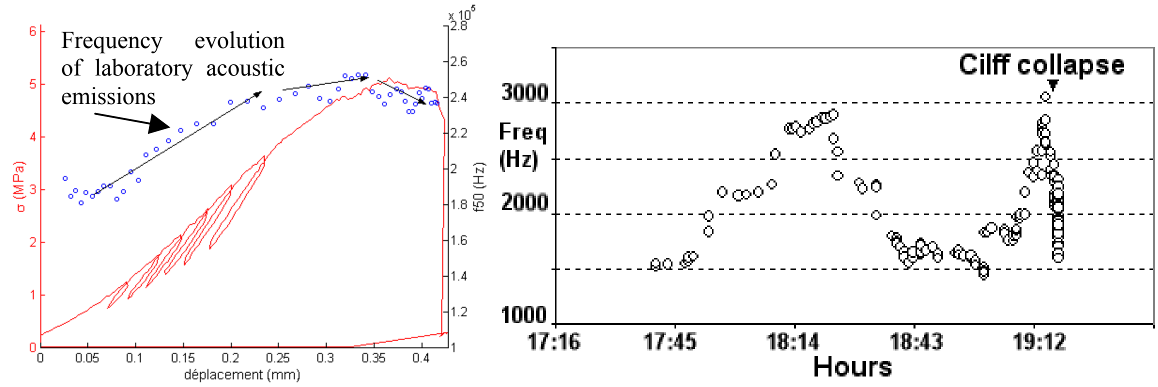


Figure 5.13. Frequency evolution of acoustic emissions in the laboratory and from the cliff collapse.

6 Methods used to verify, compliment and assist interpretation of experimental tools

It was necessary to verify the results of the experimental techniques as accurately as possible and hence several methods were employed to establish the accuracy of the tools under development. Many of these methods had not been used as coastal zone management tools in relation to cliff slope stability. Some of the results and methods used were found to be very good indicators of impending cliff collapse in themselves or helped to better understand the causes leading to different types of collapse. The best results were obtained when all the data were combined into a holistic approach of predicting cliff collapse. These experiments, methods and tests are described below:

6.1 DETAILED GRID SURVEYING: MONITORING SYSTEM FOR DIRECT VERIFICATION OF PRECURSOR MOVEMENTS IN THE TERRAIN AND ACTUAL COLLAPSE OF CLIFFS

After the selection of the research sites in May 2001 test grids were established at the research sites for the purpose of regular topographic measurements to detect possible cliff top movement. The monitoring test grids at Møns Klint, Denmark were established May 2001, whilst the UK and French research site grids were established in August 2001. This was later than hoped due to delays caused by the Foot and Mouth epidemic in the UK that resulted in limited access to the research sites. Thereafter the grids were measured in September 2001 and regularly measured in January 2002, May 2002, September 2002, January 2003, May 2003 and September 2003.

The grid consisted of a number of fixed points marked with wooden pegs hammered down into a small-drilled hole in the chalky soil. The top of the pegs were marked with red paint and a small nail marking the precise position of the grid point. Subsequently the grid points were measured with a Leica electronic total station (TC600, theodolite) with mirror prism distance calibration. In addition to the grid points a number of established fix points were identified and measured. Details of the grids are given by Pederson *et al.*, 2002 and are summarised below.

6.1.1 Beachy Head

At this site there was a cliff block separated from the main cliff surface by a 20 cm wide-open fracture in the south-western part of the Beachy Head grid. However no collapse occurred at Beachy Head during the two years of measurements. This research site showed the least movement of all the sites. The monitoring of the grid showed that no significant movements were observed (Figure. 6.1).

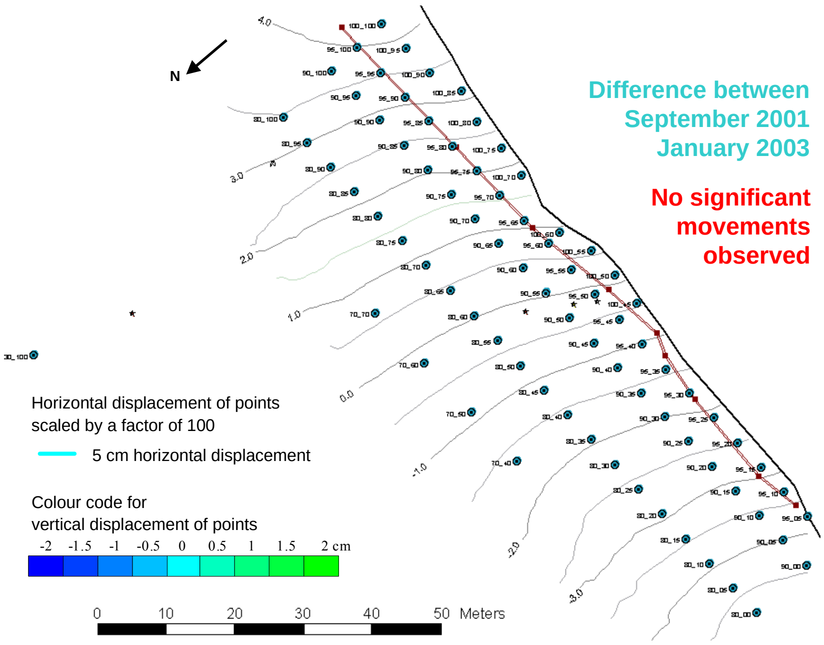


Figure 6.1. Grid established at Beachy Head, no significant movements observed.

6.1.2 Birling Gap

A feature at the Birling Gap research site is the prominent vertical fault striking more or less north-south, entering the grid at the cliff edge in the south-east corner of the field and crossing the wave cut platform to the south (Figure 6.2). The cliff edge of the Birling Gap research site was measured several times for verification of the cliff collapses from the top of the cliff. During the project period none of the grid points were lost, but two marked collapses happened between the middle of January 2002 and May 2002. From the edge measurements the largest of these collapses was estimated at 500 m^3. The three grid points nearest to this collapse showed marked displacements towards the cliff edge from January 2002 to May 2002. In September 2002 these points had accumulated a horizontal displacement of about 5 cm towards the cliff edge (south-west, see Figure. 6.3). Between September 2002 and January 2003 a fracture system developed along the vertical fault system, and significant horizontal displacement was recognised in the south-eastern corner of the Birling Gap grid. It is predicted that this fracture will develop into a major failure and will be the location of the next collapse at Birling Gap.

Figure 6.2. Large fracture developing in the cliff top at the Birling Gap research site. Also note the fault running along the wave cut platform that intersects the research site.

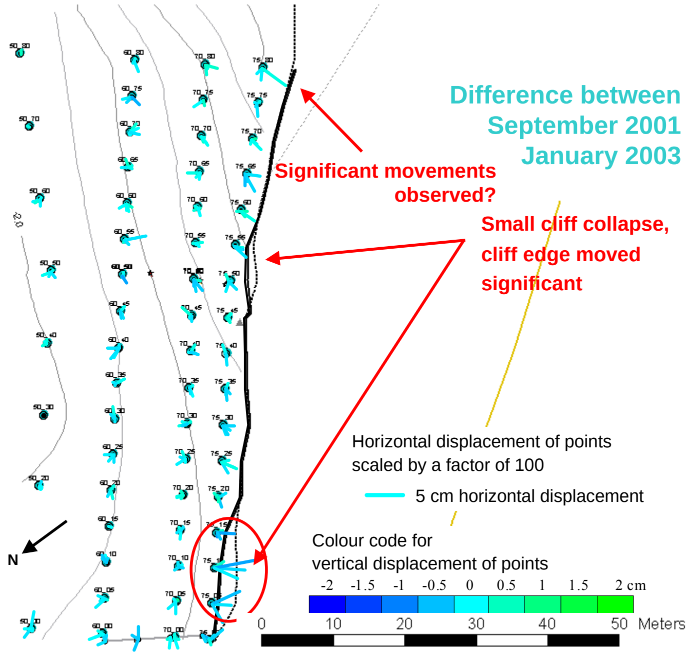


Figure 6.3. Grid established at Birling Gap, significant movements were observed in several areas of the site related to cliff collapse and fracture dilation.

6.1.3 Mensil-Val

The Mesnil-Val research site is characterised by an upright, high angle steeply dipping conjugated fracture system, which strikes nearly perpendicular into the cliff below the central part of the field. The major collapse in June 2002 was bounded by fractures. Subsequent to the collapse the edge of the cliff was re-measured for the calculation of the chalk mass involved in the collapse (ca. 2700 m^3).

The verification of the collapse in June 2002 was documented by the measurements in May 2002, where no significant movements were recorded. The measurements in September, where two grid points were missing in the rock fall and a significant movement was recorded on the grid points nearest to the head of the rock fall (Figure. 6.4). Apart from this no other significant movements were observed.

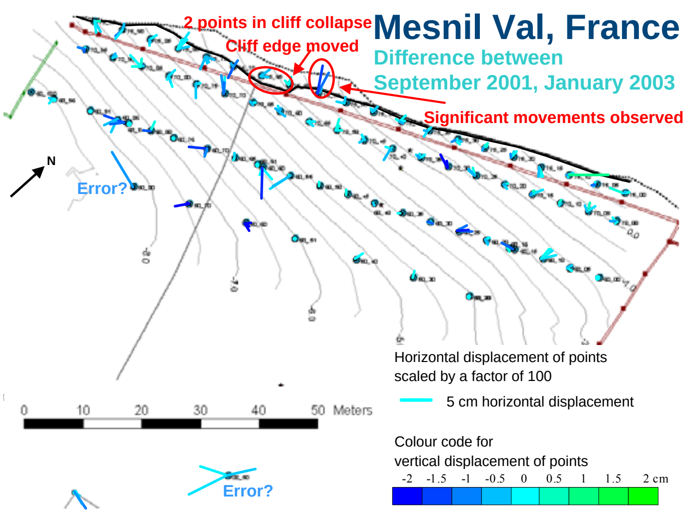


Figure. 6.4. Grid established at Mensil-Val. Considerable movement was observed in the area of the June 2002 collapse.

6.1.4 Dronningestolen

The Dronningestolen research site is situated on top of the highest chalk cliff selected for the project. Furthermore it is located close to the rock fall in 1994, which killed a French woman. The site was the most difficult to measure due to the dense wood and vegetation. During the project no significant movements were observed in the measured grid (Figure. 6.5).

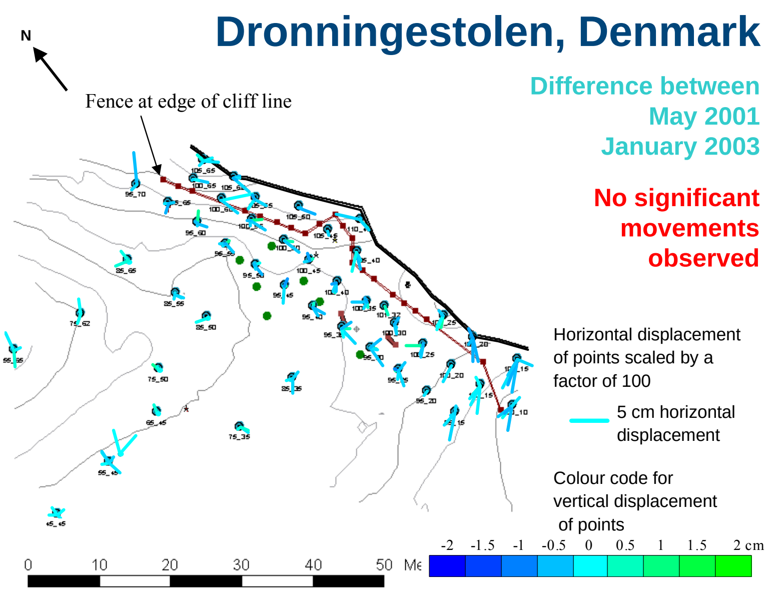


Figure 6.5. Grid established at Dronningstolen. No significant movements were observed.

6.1.5 Jættebrinken

This part of the Møns Klint cliff section was formerly regarded as relatively stable. However, in January 2004 a rock fall of about 3500 m^3 took place immediately north of the research site (Figure. 6.6). Small movements of the grid points towards the cliff edge were observed between May and September 2002, but due to the range of uncertainties in the measurements, this observation is questionable (Figure. 6.7). The study of the rock fall slip-surface indicates that the development of fractures in the cliff had been taking place over a long period in which iron hydroxides precipitated from ground water on the fracture surfaces. The rock fall was a vertical collapse with gravity spreading of breccia to form the landslide toe.

Figure 6.6. Cliff collapse at Jættebrinken in January 2004.

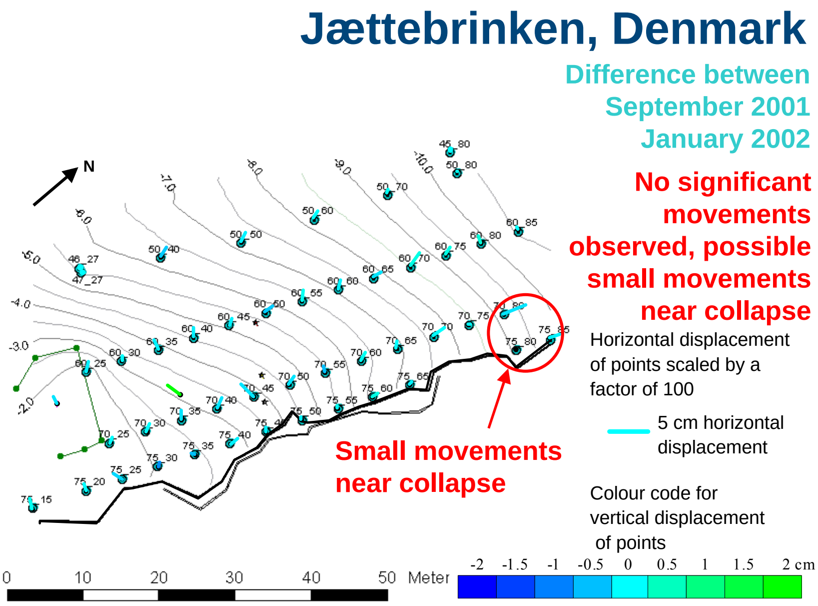


Figure 6.7. Grid established at Jættebrinken. Small movement were observed prior to the January 2004 collapse.

6.1.6 Topographic surveying results

The concept of establishing test grids, which were regularly measured with a theodolite total station, has provided a reliable documentation of cliff collapse (Table 6.1). Few precursor movements were observed. However with more frequent measurements it is possible that fracturing ahead of a slide could easily be observed. The method is relatively simple and could easily be improved to form a low cost indicator of the development of vulnerable cliff edges.

Research Site	Cliff collapses and movement
Beachy Head, UK	No cliff collapses or movements observed
Birling Gap, UK	Cliff collapses and significant movements observed
Mensil-Val, France	Cliff collapses and significant movements observed
Dronningestolen, Denmark	No cliff collapses or movements observed
Jættebrinken, Denmark	Cliff collapses and possible movements observed

Table 6.1 Summary of cliff edge movement observed at each of the research sites.

6.2 SCANLINE FIELD SURVEYS

From work completed prior to the PROTECT Project in the INTERREG II ROCC (Risk of Cliff Collapse) Project (Mortimore *et al.*, 2001) it was known that one of the most important areas of study were fractures and the importance of fractures to the AZR. It was considered important to study these further, to determine whether there was a relationship between these features and the larger fractures and to see if the fractures influenced the Azimuthical Resistivity and had any effect on cliff instability and collapse.

When discussing fractures it is important to use the correct nomenclature. Although this debate goes back some time Nevin (1942) said:

"*The joint in the rock, thin as hair, and straight as a measuring rod, that piece of petrified geometry, promises much, yet discloses little.*
Nevin (1942)

Hopefully the understanding of these "*joints*" has moved on substantially and they now disclose far more information to us.

Hobbs *et al.,* (1976) expands on this by stating that joints usually occur as families of fractures with more or less regular spacing in a given rock type. Thus a fracture can be defined as one of the ways in which rocks yield to deforming movements from any source, therefore cracks, joints faults or other breaks are all types of fracture. The term joint can be used if there is no visible displacement along the structure, but if displacement is observed the term fault should be used.

Traditionally, by studying the orientations of fracture systems within a regional rock assemblage, it is possible to uncover information regarding the orientation of past regional stressed directions involved in brittle deformation (Pollard and Aydin, 1988). Fracture orientation data is generally gathered by measuring strike and dip of the large number of fractures within a study area. However the PROTECT Project went into far greater detail collecting far more data.

6.2.1 Methodology

Scanline fracture surveys were carried out at all the PROTECT Project research sites in the UK, France and Denmark. This was done directly or as closely as possible at the base of the cliff under the research sites. A representative site was selected and a 30m tape was laid out along the base of the cliff. Working systematically along the tape all the visible fractures were measured. The data collected was recorded on a log that included:

- Strike,
- Dip,
- Dip direction,
- Persistence of fracture,
- Aperture of Fracture (including types of fill),
- Chalk type,
- Type of fracture,
- Any other comments,

This data was then used and put into sterograms for ease of interpretation.

6.2.2 UK research sites

The UK chalk cliffs have been described in previous studies and so it was known that certain chalk formations were dominated by certain fracture styles and to a lesser extent the approximate direction of the fractures was also known. It is generally accepted that the Newpit Chalk Formation and Lewes Nodular Chalk Formation are traditionally expected to have steeply inclined conjugate fractures. The Seaford Chalk Formation however, is renowned for its sub-vertical, sub-perpendicular fracture sets before moving upwards into Newhaven Chalk Formation and back into well defined conjugate fractures.

A scanline survey was taken at the base of the cliff at the Birling Gap Research site where the fractures are sub-vertical and sub-perpendicular to each other. The main fracture set is (Figure 6.8), 073^{o}/88^{o}S.

The other main direction of fracture orientation is, 145^{o}/84^{o}W

The orientation can be seen strongly in the Seaford Chalk Formation in the surrounding area such as the scanlines done at Belle Tout and in the Birling Gap valley thus supporting this evidence.

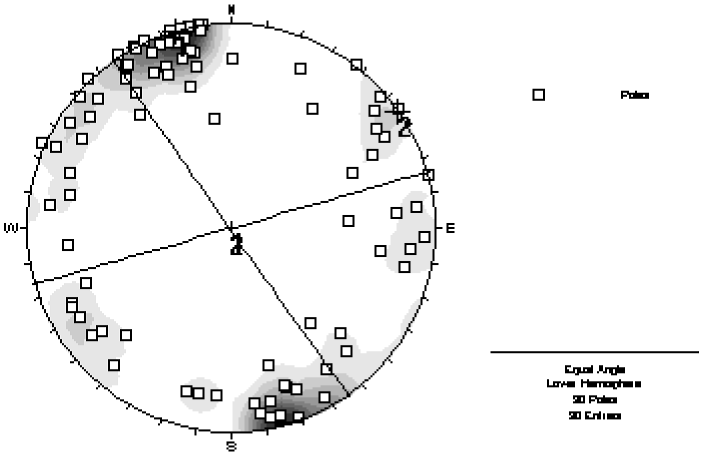


Figure 6.8. Birling Gap fracture survey, polar stereo-plot of bedding and joints.

A scanline survey at the base of the 110 m cliff under the PROTECT Research site at Beachy Head was in the Lewes Nodular Chalk Formation, whilst the top of the cliff is composed of the Seaford Chalk Formation.

The major fracture orientation at this site had a strike and dip of (Figure 6.9) 144°/79° NE .

There is a subsidiary fracture orientation with a strike and dip of 052°/82° E.

This corresponds very closely to the main fracture directions at Birling Gap. Also in this set is a very steeply inclined set of large conjugate fractures. It is also worth noting that the bedding is striking 015° with a dip of 18° W.

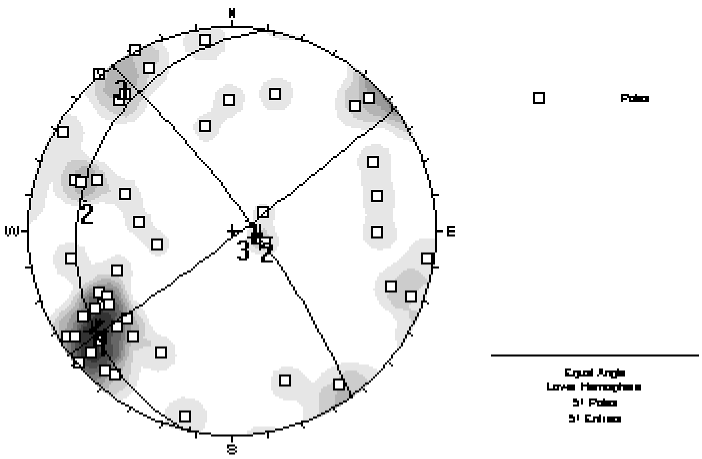


Figure 6.9. Beachy Head fracture survey, polar stereo-plot of bedding and joints.

6.2.3 Mensil-Val, France

This cliff section is entirely composed of Lewes Nodular Chalk and so the research site at this locality is on the oldest chalk of any of the project sites. From this site the fracture orientations are sub-vertical and very steeply inclined large conjugate sets, which are sub-perpendicular to each other with orientations of (see Figure 6.10):

Scanline 1 $134^{o}/82^{o}$NE
Scanline 2 $134^{o}/84^{o}$SW

and

Scanline 1 $66^{o}/72^{o}$N
Scanline 2 $48^{o}/84^{o}$NE

It should be noted that this fracture style, type and orientation is similar to the UK sites.

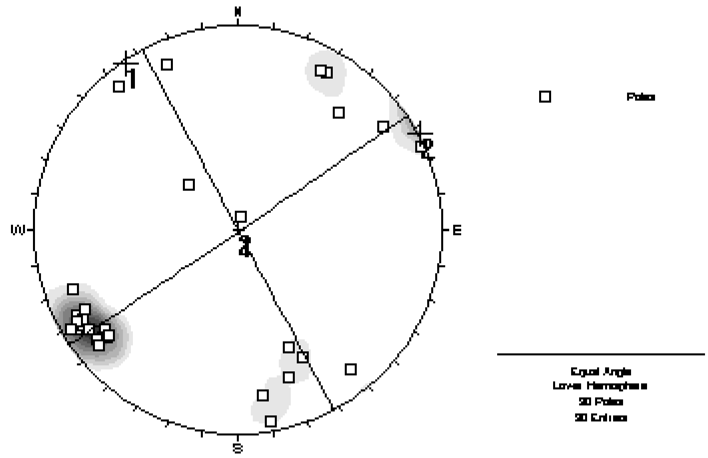


Figure 6.10. Mensil-Val, fracture survey 1, polar stereo-plot of bedding and joints.

6.2.4 Møns Klint, Denmark

Due to the glaciotectonics and the arrangement of the imbricate thrust fan and antiformal stack, this site has been the hardest to understand when it comes to the fracture style, type, persistence and frequency, which are important factors when trying to understand the mechanisms involved in cliff collapse. At Møns Klint several scanlines were taken. Due to the steep dip of the bedding, generally dipping about 20^{o} - 40^{o} to the south, the general fracture strike direction could be seen, but the fracture type was very difficult to interpret. Two fracture trends with strikes northwest and northeast can clearly be seen in all the scanlines (Figure 6.11).

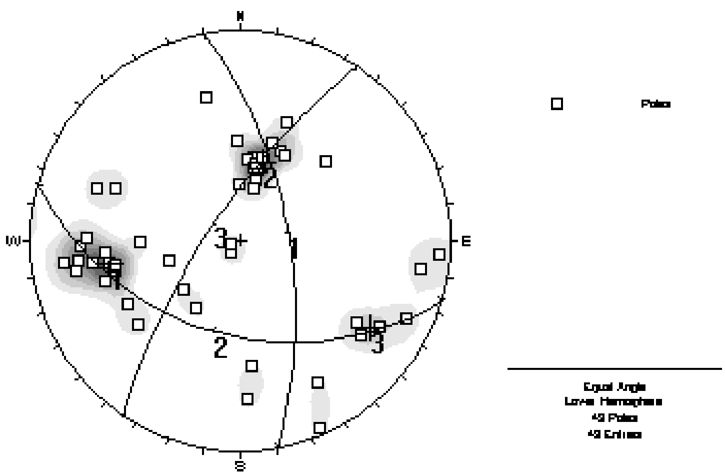


Figure 6.11 Hundevænklint fracture survey, polar stereo-plot of bedding and joints.

Figure 6.12 shows that fracture direction and fracture types become far more obvious after flattening out the bedding.

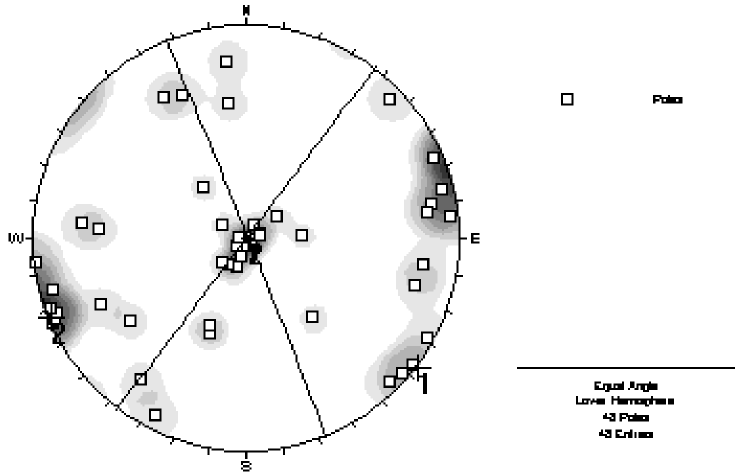


Figure 6.12. Hundevænklint flattened out bedding fracture survey, polar stereo-plot of bedding and joints.

For all the sites measured at Møns Klint the fracture system was dominated by sub-vertical, sub-perpendicular fracture sets. Broadly, the strike of these fracture sets was 285^{o} to 340^{o}. The other set was sub-perpendicular to this, striking at 20^{o} - 45^{o}. Another main set of fractures run sub-parallel to the bedding but were not bedding surfaces.

6.3 MICRO-FRACTURES AND VEIN-FABRICS

Brodie *et al.,* (2002) describes micro-scale fractures to be observable on the thin section or smaller scale. However Márquez and Mountjoy (1996) describe micro-fractures that could exist up to 6 cm in length with an aperture of around 1 mm. It seems a standard classification scheme for the description of fracture size is dependent on the type of fracture and may be relative to the investigation.

It is convenient for this report to classify micro-fractures on a centimetric scale. Investigations showed that the micro-fractures varied from locality to locality. To overcome this problem the property of continuity was considered. It was decided that to be classified a "micro-fracture" it should be stratigraphically contained within the formation in which it formed.

6.3.1 Micro-Fractures

A wide range of micro-fractures can be observed on the centimetric scale. The most simplistic of these are small fractures running through the rock mass. More complex micro-fractures can be observed related to syn-sedimentary tectonic movements within the sediment, in turn related to tectonic phases within the Cretaceous (Mortimore, 1997):

- Ilsede tectonic phase in the late Turonian to Early Coniacian, comparable to the Lewis Nodular Chalk Formation.
- Wernigerode tectonic phase in the late Santonian to Early Campanian, comparable to be Newhaven Chalk Formation.
- Peine tectonic phase in the late Campanian, comparable to Culver and Portsdown Chalk Formations.

Mortimore and Pomeral (1997) described many small-scale synsedimentary features in the chalk at the time of these tectonic events, before the chalk sediment had completely consolidated, that could be related to these global Late Cretaceous tectonic events. One of the features identified was sub-horizontal sliding along marl seams and within chalk beds. Within and around these areas of movement especially within the Lewes Nodular Chalk Formation, related to the Werngerode tectonic phase, the slightly harder chalk nodules did not flow as freely as the rest of the sediment and as a result have fractured (Figure 6.13, Mortimore pers comm 2004). These micro-fractures show roughly the orientation, compression and tectonic phases of the Wernigerode tectonic phase in the same way as the macro fractures.

Figure 6.13. a) Micro-fractures in hard nodules resulting from syn-sedimentary soft sediment sliding in the softer surrounding sediments during Wernigerode tectonic phase. b) Dieppe harbour, France, Lewes Nodular Chalk Formation.

6.3.2 Defining rock fabric

It is well-known that micro fabrics such as the vein fabrics provide important clues to the nature of rock deformation (Twiss & Moores, 1992). The term "fabric" is described by Hobbs *et al* (1976) as including the complete spatial and geometrical configurations of all components that make up a rock. Patterson and Weiss (1961) had already expanded on this idea and submitted that the individual parts referred to are not considered rock fabrics unless they are constantly repeated throughout the rock mass. For example, a bedding plane that only repeats itself a few times throughout a succession is not considered as contributing to a rock fabric; but if the bedding planes were repeated many times throughout a large area then they would be described as contributing to the rock fabric.

The fabric elements of a rock mass are vectorial, such as grain size or crystallographic planes, i.e., they have both magnitude and direction. So the fabric to be defined is the textures and structures of the rock. This fabric is then used to gain information about the geological processes that produced a particular rock or syn and post sedimentary processes which the rock has undergone. Petrofabric diagrams can be used to put the components of a rock fabric in the form of an equal-area or sterographic projection. A classic description of fabric and its elements may be gained from Sherbon Hills (1963). He states:

"The essential notions in petrofabric analysis relate to the definition of fabric in terms of fabric elements fabric components and to the orientation of the fabric in space."

Sherbon Hills (1963) p. 392

6.3.3 Methodology

It was essential that suitable sites were found for the collection of micro-fracture data due to the problems of finding a fresh face with suitable exposure. The best exposed micro-fractures were on ledges or under overhangs. This allowed for the best possible 3-dimensional view to the micro-fracture orientation. The data was collected using a compass clinometer recording the:

- Strike
- Dip
- Dip direction
- Type of fracture

This data were recorded onto a micro-fracture log.

The Vein-fabric data was collected on the wave cut platform during low tide. The same range of data was collected for the vein-fracture as for the micro-fractures plus orientated plans of the vein-fabric persistence and relationship to the each other. This data was then plotted on sterograms to give a visual representation of the data.

Orientated blocks of chalk were also collected from the cliffs to measure and study these fabrics in the laboratory. A modified version of the Bushinsky (1947) oil technique was developed. The blocks were sawn in half to create a smooth flat surface and a light oil (WD40) was sprayed onto the surface to display the fabric.

6.3.4 Results of Micro-Fabric analysis

The relationship of the fractures to the micro-fractures and the vein-fabric and this relationship to cliff stability and the AZR are intriguing. A micro-fracture survey was taken at the base of the cliff at the Birling Gap PROTECT research site. The fractures are sub-vertical and sub-perpendicular to each other. The main fracture set is (see Figure 6.14) $078^o/90^o$ S

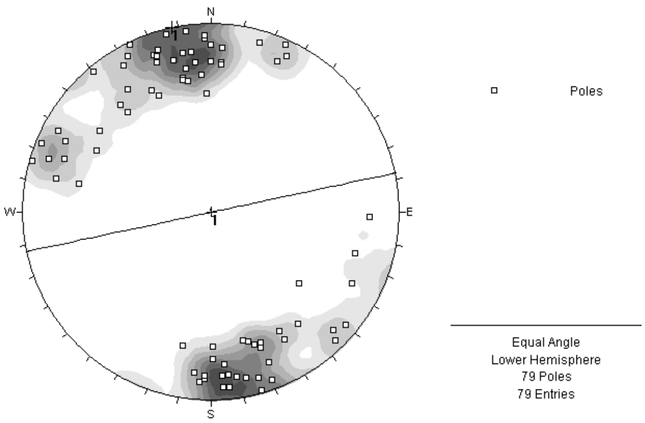


Figure 6.14. Birling Gap fracture survey, polar stereo-plot of micro-joints.

This was the only family of micro-fractures identified although it is suspected that a set exists roughly perpendicular to this group corresponding to the main fracture set, but this set probably runs sub-parallel to the cliff line.

The vein fabric data were collected from the wave cut platform at Birling Gap, therefore stratigraphicaly positioned directly under the Seven Sisters Flint Band. This is approximately 3 m below the other survey carried out along this section. This is an important factor because it means this survey was measured in the Belle Tout Bed. The vein fabric again shows very similar trends to the other surveys in this area. The vein-fabrics are sub-vertical and sub-perpendicular. Two main vein-fabric sets were identified (see Figure 6.15) as $068^o/89^o$ S and $163^o/87^o$ W

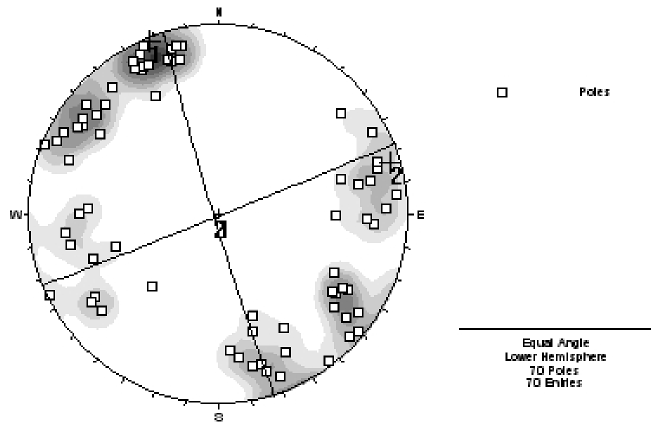


Figure 6.15. Birling Gap fracture survey, polar stereo-plot of vein fabric.

At Mensil-Val the data were collected from the wave cut platform in the Mers Hardground Beds of the Lewes Nodular Chalk Formation. Only micro-fracture data were collected from this locality. Three main micro fracture orientations were identified as 070^o/80^o, 050^o/80^o and 170^o/82^o.

6.4 MODELLING

In order to identify the key mechanisms of cliff collapse, digital modelling techniques were employed. Two methods were used, a limited equilibrium method and a distinct element method. The sites modelled were the Birling Gap research site in the UK and Mensil-Val research site in France as these two sites are very different. The Birling Gap research site is composed entirely of the Seaford Chalk Formation, with many flint bands and a sub vertical fracture system. The Mensil-Val research site is completely different, composed of the underlying Lewes Nodular Chalk Formation with a complex system of conjugate fractures, with some smaller sub-vertical fractures. None of the other research sites were modelled because there was insufficient data to generate models.

6.4.1 Liquid equilibrium method

The liquid equilibrium method uses a calculation code in a computer program called RESOBLOK developed by the French institution INERIS. The liquid equilibrium method is based on the assumption that failures occur along rock fractures and that these fractures are the controlling parameters of collapses. Based on site data, randomly generated fractures were used to describe both quantitative (volume of cliff collapses, number of collapsed blocks, mean volume of collapsed blocks, etc) and qualitative data (shape of collapse, fractures controlling the collapsed shape). The model input parameters include material density, cohesion and friction angle of the joints. For the model to run the blocks were assumed to be completely rigid. Many cliff collapse simulations were run to test a range of randomly generated fractures sets. Each run was undertaken until the cliff returned to stability. A statistical description of the results was obtained in three dimensions allowing the true shape of the collapse to be shown. However the limitations of the program were in the number of blocks that could be generated, with a maximum of 4000 blocks, a low number for the highly fractured chalk.

6.4.2 Distinct elements method

The distinct elements method uses the ITASCA company distinct elements programme UDEC to examine the stress mechanisms involved in cliff collapses. The model assumed that each block can deform. At the same time, the model allows each block to slip along the fractures, thus allowing both fractured controlled failures and plastic failure to be detected. Unfortunately, the model required a great deal of data input and some figures had to be estimated from typical figures reported in the literature. Furthermore the model only operated in two dimensions thus losing any information on the shape of the collapse.

No matter how "realistic" the models are, the results obtained cannot be taken for granted, as they come from simplified and idealise structures prescribed to a complex phenomenon.

6.4.3 Birling Gap – liquid equilibrium method

Some interesting points can be drawn from the modelling. As expected the shape of the collapse was disaffected by the stratification and fracture systems within the rock. The effect of the spacing between fractures appeared to be limited. The volume of the collapses were similar to those observed in the field, most commonly single blocks of several m^3. The largest collapses recorded by the model were almost $1,500m^3$ (Figure 6.16a and 6.16b). No collapse larger than this has been observed at the Birling Gap research site which the model was designed to simulate. Although larger collapses have occurred in this formation, type and height of cliff the angle of fracture in relationship to the cliff face may not be the same. Occasionally far larger collapses have occurred in cliffs of these heights and type but larger collapses could have been restricted by the edge effects of the model. The limit equilibrium results indicate that the failure mechanisms in the Seaford Chalk Formation, as seen near Birling Gap, are mainly controlled by the fracture sets.

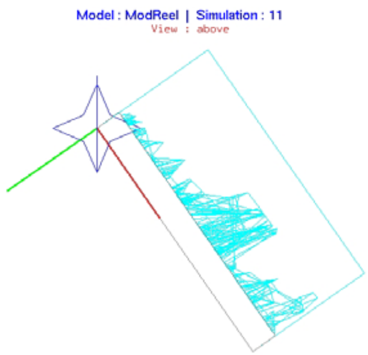


Figure 6.16a. Plan view of wedge shaped collapse as obtained through a RESOBLOK simulation of the cliff at Birling Gap.

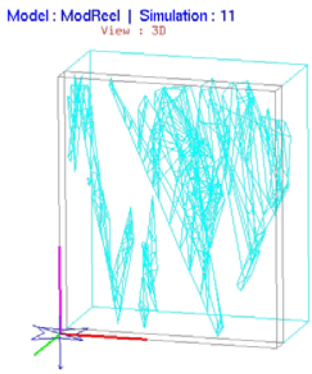


Figure 6.16b. Cliff face view of wedge shaped collapse as obtained through a RESOBLOK simulation of the cliff at Birling Gap.

6.4.4 Birling Gap - distinct elements method

A cross-section of one of the RESOBLOK simulations from the zone of the collapse in the liquid equilibrium analysis was converted to a UDEC file, and then placed into a bigger structure to avoid any possible boundary affects and bedding and jointing were added to the model (Figure 6.17).

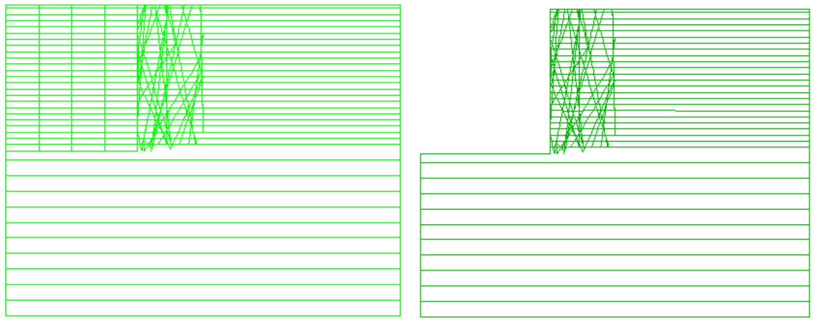


Figure 6.17. Example of cross-section in UDEC, before and after the removal of the stabilisation steps.

The whole model was assumed to be saturated with water and as the cliff was the Seaford Chalk Formation, the same material properties were assigned to the whole model. However, several joint properties were defined and assigned to different layers that form the cliff, following the assumption that joint behaviour varies between layers and beds. Several slices representing former collapses were placed in front of the cross-section. Slices were removed one by one, with several calculation steps in between to allow the model to stabilise between each removal operation (Figure 6.17). When all slices had been removed a greater number of calculation steps were used to run the real simulation.

6.4.5 Birling Gap modelling results

As slices were removed the vertical and horizontal stresses increased near the cliff face especially at the base (Figure 6.18), depending on the calculations used, weaker models showed the creation of several plastic deformation points, where stronger models stayed in elastic deformation domains. The plastic strain tended to be at a higher angle to the fractures (Figure 6.18). After the last calculations step, the plot of the displacement suggested that the lower part of the cliff tended to be “thrown away” following a horizontal movement, whereas the upper part of the cliff showed movements which were more vertical. This movement suggested a flow slide mechanism.

The model showed that as slices were removed, the cliff fracture apertures started to move in the RESOBLOK cross-section. The opening started as soon as the first removal step had occurred. This meant that fractures were opening 20 to 30 metres back from the cliff face.

Both the RESOBLOK and UDEC models attributed the failure of the cliff to block falls suggesting a slip along the fractures but that this mechanism when the chalk is soft enough means the material deforms under plastic deformation. It is therefore linked to fracture failure and material failure. Material failure is steeper than the slipping direction of the blocks which would induce collapses. This would tend to suggest that thinner wedges of the chalk collapse, than were observed in the RESOBLOK models. Thinner wedge collapses tie in better with field observations.

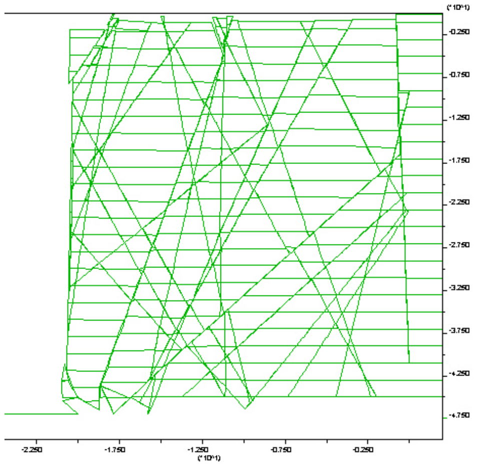
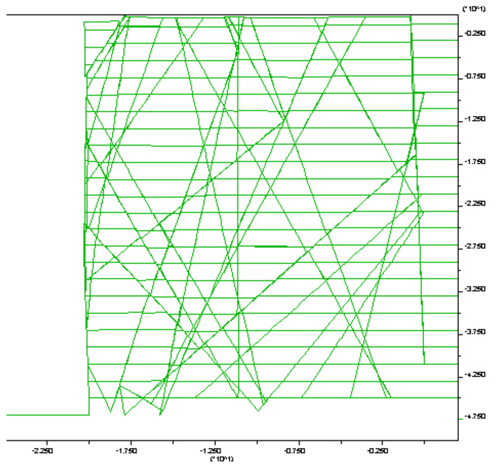
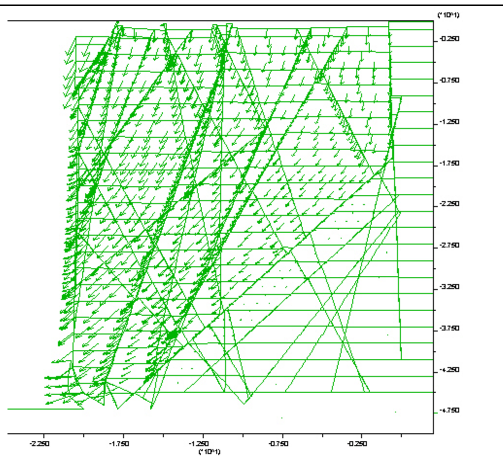
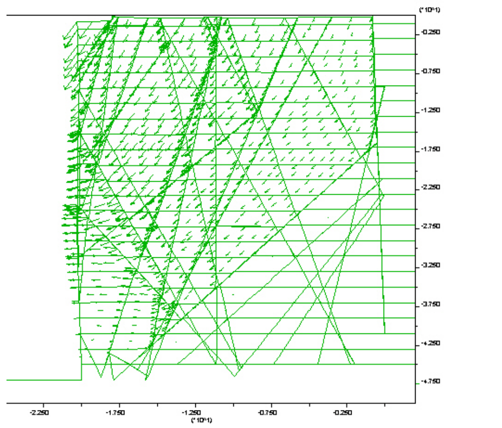
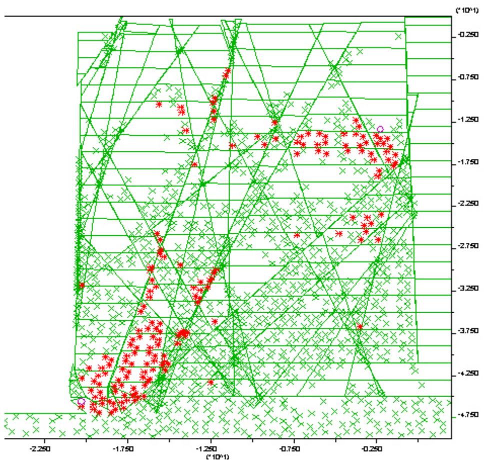
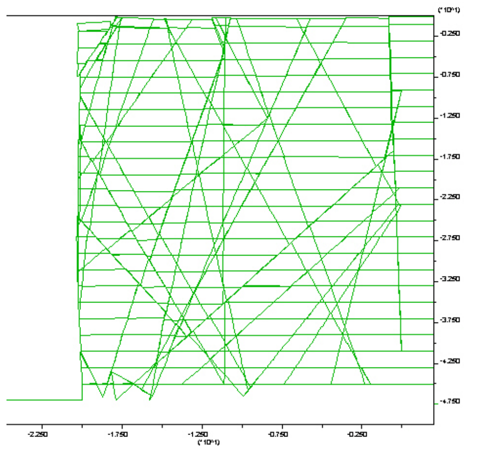
Distinct Elements method results – Birling Gap site		
Model	**BGSat1**	**BGSat2**
Block plots after 10 000 calculation steps		
Displacements vectors after 10 000 calculation steps		
Plastic strain points after 10 000 calculation steps.		

Figure 6.18. Distinct element calculation results, Birling Gap research site.

6.4.6 Mensil-Val – liquid equilibrium method

One of the main differences between the modelling of this research site and the Birling Gap research site was the scale of the collapses, the blocks involved in the Mensil-Val collapses were more numerous and larger. As can often be seen in the field the lateral extent of the collapses was generally controlled by master joints that affected the whole height of the cliff and dipped to the west (Figure 6.19).

The model showed that many of the collapses started at the base the cliff but died out before the cliff top, which was frequently seen in the field at Mensil-Val. The largest collapses involved the entire cliff although the retreat was occasionally up to 20 metres into the cliff, which is unrealistic and has never been observed in the field.

Figure 6.19. Collapse naturally controlled by West dipping master joints, Puys, France.

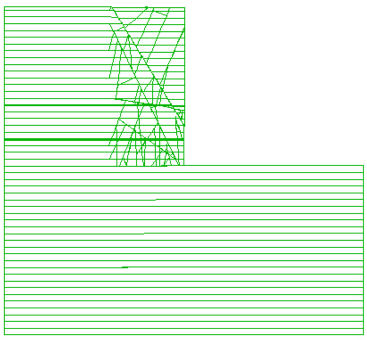
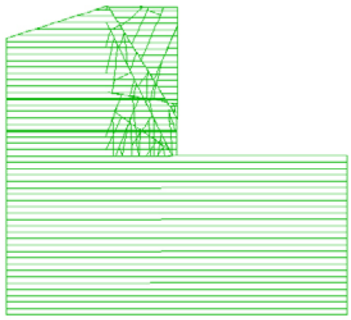
6.4.7 Mensil-Val - distinct elements method

The simulation process employed for this model was the same as for the Birling Gap model. A cross-section was taken from one of the RESOBLOK models and imported into a UDEC model. The simulation process of removing progressive blocks was also identical.

6.4.8 Mesnil-Val modelling results

As in the Birling Gap models the vertical and horizontal stresses concentrated at the base of the cliff and this caused the chalk to undergo plastic deformation. Most commonly plastic deformation occurred along the marl seams where they intersected major fractures implicated in the slipping process leading to a collapse (Figure 6.20). The models showed an average displacement of 65 cm, regardless of the fracture geometry or properties after the last calculation step. The displacement vectors were all parallel to the major fracture surface along which slipping occurred indicating that the cliff failure was controlled by a major fracture slipping process. Fracture apertures can be seen opening from the removal of the first block, but only along the major fractures and up to 15 metres back from the cliff edge.

In the Mensil-Val model an attempt was made to simulate the true cliff top profile, a 30^{o} slope dipping inland. Other than a very slight change in displacement directions during the slice removal process the effects on the model were almost null.

Distinct elements calculation results – Birling Gap site		
Model	**Simplified profile**	**Real Profile**
Initial model		

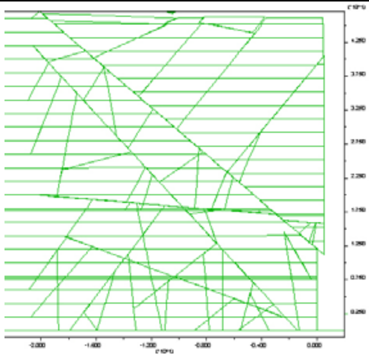
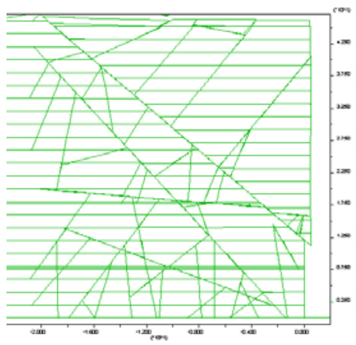
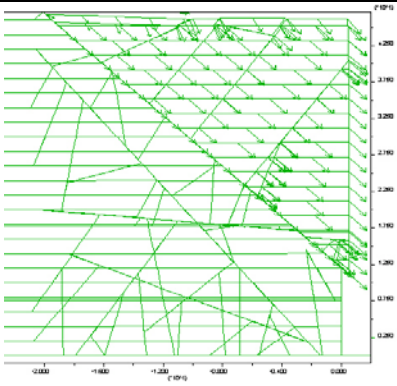
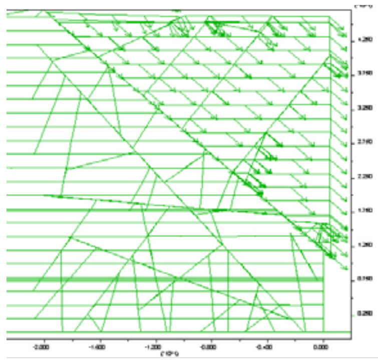
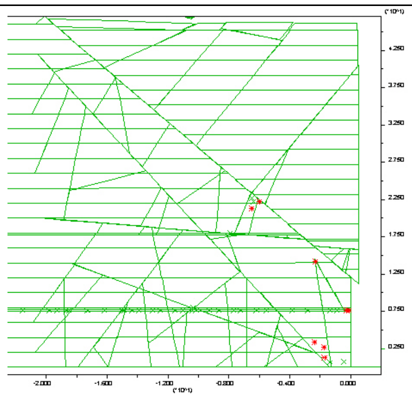
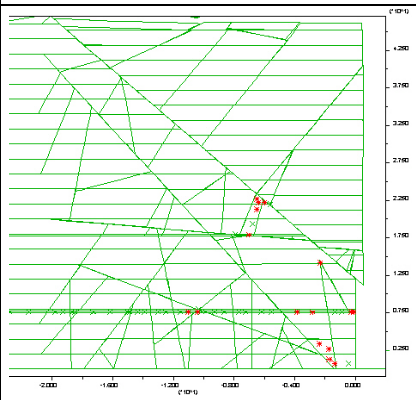
Block plots after 10 000 calculation steps		
Vecteurs déplacement à la dernière étape de calcul		
Plastic strain points after 10.000 Calculation steps		

Figure 6.20. Distinct element calculation results, Mensil Val research site.

6.5 LABORTORY TESTING

As part of the PROTECT project a laboratory based investigation was undertaken to better understand the mechanical properties of the chalk cliffs in general and more specifically at the project research sites, thus helping to better understand the causes, processes and mechanics involved in chalk cliff collapse. The laboratory testing involved a series of uniaxial and triaxial testing to establish stress paths for chalk cliffs in different types of chalk.

It is generally recognised that the behaviour of soil and rock depends not only on the applied stress level, but also on the applied stress path experienced during loading. Whilst the use of stress path testing is now fairly well established for the testing of soil samples, it is still rarely applied in the field of rock mechanics. However, there are many instances where the application of laboratory test data based on uniaxial and triaxial testing (conventional compression tests) is not readily applicable. In the case of rock slope stability, the failure of a rock slope results in a reduction in lateral stress experienced by the material adjacent to the failed zone. It is therefore apparent that uniaxial compression tests are not representative of the in situ stress paths experienced in the vicinity of the slope face.

A numerical study was performed in order to better quantify the in situ stress paths experienced adjacent to the rock slope. From the results of this study it was possible to perform a set of laboratory triaxial tests where the applied stress paths were more representative of those experienced in situ. The results of this test programme could then be compared to those obtained by conventional compressional tests.

6.5.1 Experiment methodology

Samples were collected from selected horizons near or at project sites in the UK, France and Denmark. As soon as the samples were collected they were wrapped in tin foil to prevent moisture loss on transportation back to the laboratory. As far as possible insitu, representative samples were collected. In the UK the sampling concentrated on collecting 20 – 30 kg samples from beneath the Birling Gap field site. Stratigraphically this corresponds to near the cliff top at Beachy Head. Samples were also collected from Hope Gap, which is stratigraphically similar to the Lewes Nodular Chalk in the Beachy Head site and comparable to the Lewes Nodular Chalk at Mensil-Val. Once back in the laboratory samples were taken immediately and natural moisture content (NMC), saturated moisture content (SMC) and intact dry density (IDD) tests were undertaken and calculated.

The preparation of specimens and experimental techniques adopted were as far as possible in accordance with BS1377 Parts 1 to 8 (BS 1377 1990). Intact specimens, prepared as right cylindrical plugs 76 mm in height and 38 mm in diameter, were cut from blocks of chalk using a diamond tipped core drill. The ends were prepared on an Abwood surface planner fitted with a diamond-planing wheel, the plugs being clamped in a V block to ensure squareness of ends.

Saturation was effected by placing plugs in a desiccator and saturating them in stages under vacuum with de-aired water, being kept in this state for at least 7 days before testing. The saturated weight of the plug to be tested was measured after removing surplus water, and the dimensions were measured with a vernier gauge. The sample was then prepared and tested in the triaxial rig. The triaxial tests undertaken were conducted with a 1700 kPa triaxial soil cell and a 100 kN load frame, manufactured by Wykeham Farrance. Test data was logged automatically.

The representative plugs from the different geological sites were tested at a number of different conditions that simulate different depths, differing amounts of loading and differing saturation levels within the chalk cliff. The samples were tested in quick undrained triaxial tests, with differing cell pressures of 78 kPa, 469 kPa and 970 kPa simulating plug depths within the cliff face of 5, 30 and 60 m, a combination of saturated and dried samples were tested.

6.5.2 Laboratory Results

All the sample blocks were tested for NMC, SMC and IDD. The results show most of the coastal cliff samples were at or near saturation. The samples collected from the Seaford Chalk had IDD's of between 1.46 to 1.86 g cc^{-1} but the vast majority of samples were 1.5 to 1.65 g cc^{-1} and so therefore fall into the category of low to medium density chalk. The Lewes Nodular Chalk samples from Beachy Head and Hope Gap were consistently high density chalks, but the Lewes Nodular Chalk Formation at Mensil-Val fell into the region of medium density chalk and the samples from Møns Klint were generally low density.

In total 182 plugs were cored of these 48% or 88 of the plugs did not meet the rigorous standards employed during testing. This was due to a number of reasons the most common being, breaking during or after coring or flaking during saturation.

All the dry samples were generally 2 to 4 fold stronger than samples that were saturated, the changes in cell pressure between 78 kPa to 970 kPa increased the axial stress peak strength by up to 50% (Table 6.2).

It was found saturated plugs from the cliff base at the Birling Gap research site, which corresponds to near the top of the cliff at Beachy Head, had an average axial stress peak strength of 3.9 kN and the dry plugs had a average axial stress peak of 7.9 kN (Table 6.2). Open fractures are often identified throughout the cliff suggesting another key factor in cliff stability was the axial stress post peak strength. The saturated samples had post peak strength of 1.9 kN and the dry samples had post peak strength of 3.7 kn.

The plugs tested from the Lewes Nodular Chalk, above the Hope Gap Hard Grounds in the cliff at Beachy Head and stratigraphically correspond to the base of the cliff at Mensil-Val, were taken from one of the softer beds in the Lewes Nodular Chalk. The average axial stress peak strength for saturated samples was 3.6 kN and for dry samples 5.3 kN (Table 6.2). The axial stress post peak strength was 2.7 kN for saturated samples and 3.9kn for dry. This can be compared to Mensil-Val where samples were collected from a similar horizon and the axial stress peak strength was 3.2 kN for saturated samples and 9 kN for dry samples (Table 6.2). The average axial post peak strength was 2 kN for saturated samples and 7.3 kN for dry samples.

The plugs tested from Møns Klint in the Maastrichtian chalk had a saturated average axial stress strength of 3 kN and a post peak average axial stress strength of 2.4 kN. This chalk was the weakest from all the sites, probably due to deposition and post deposition tectonics and glaciotectonics.

Locality	Chalk		saturated			Dry		
		Cell pressure kpa	80	470	970	80	470	970
Birling gap	Seaford		2.97	2.8	4.04	7.24	9.74	9.8
Shoreham	Seaford		3.17		6.77	11.37		18.47
Shoreham salt sat	Seaford		2.84		4.02			
Hope Gap	Lewes		2.26	3.82	4.85	4.96		5.63
France	Lewes		2.34	4.31	3.22	7.73		10.26
Shoreham	Lewes		4.31			7.95		
Shorham salt sat	Lewes		1.98					
Beachy Head	Newpit		2.05		4.75			
Denmark	Maastrichtian		2.36	2.99	3.05	6.48		11.03

Table 6.2. Average peak fracture strengths (in kN) of chalk plugs tested in Triaxial cells.

6.5.3 Salt saturation of samples

Studies of the chalk carried out during the project on Seaford Chalk Formation samples using a Scanning Electron Microscope (SEM) found large salt crystals forming within the chalk and disrupting the matrix of the material (Figure 6.21). Using a centrifuge, pore water from the samples was spun off. Depending where the samples were taken from, the water contained up to 8 times the amount of salt found in seawater and were often at water salt saturation levels (Table 6.3). Therefore a laboratory based investigation to better understand the mechanical properties of the chalk cliffs in relation to the effects of sea salt saturation on the strength and stability of the sea cliffs at the Birling Gap research site was established. The laboratory testing involved a series of undrained triaxial tests to establish stress paths for chalk cliffs in the Cuckmere Bed of the Seaford Chalk Formation, between the Seven Sisters Flint Band and the Cuckmere Flint Band.

Salinity tests of chalk pore water					
Sample	Grid Reference	Locality	Chalk Formation	Description	Salinity (ppt)
BGS 1	TV 5566 9569	Birling Gap	Seaford Chalk	Base of cliff at Geophysics site	232
BGS 2	TV 5531 9605	Birling Gap	Seaford Chalk	At sampling area, base of cliff	234
BGS 3	TV 5566 9569	Birling Gap	Seaford Chalk	Top of cliff at Geophysics site	no pore water extracted
BGS 4	TV 5563 9574	Birling Gap	Seaford Chalk	Top of cliff west of geophysics site 16m back from cliff edge	45

Pore water was extracted from samples using a centrifuge the salinity was tested using a American marine, Pinpoint Salinity Monitor.
The salinity meter was calibrated before use
Seawater salinity is approximately 35ppt

Table 6.3. Pore water extracted from samples using a centrifuge and tested for salt concentration.

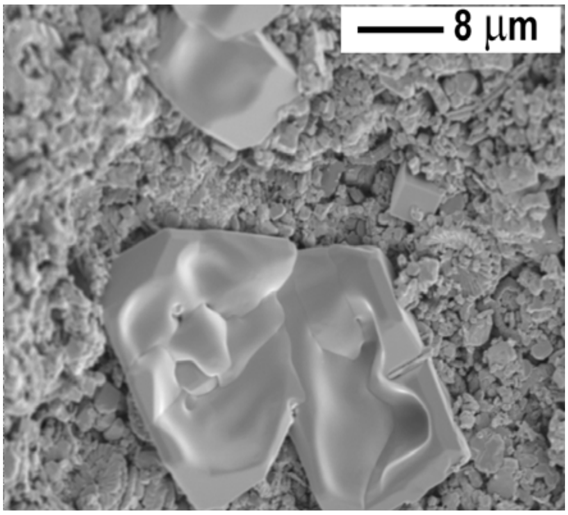


Figure 6.21. SEM image of salt crystals growing in the chalk matrix.

Samples from the Birling Gap research site, were compared with samples from the same stratigraphy collected at the Shoreham Cement Works, West Sussex. Laboratory samples were taken immediately and natural moisture content (NMC) and saturated moisture content (SMC) tests were done. The plugs from the samples were prepared in accordance with BS1377 Parts 1 to 8 (BS 1377, 1990).

Saturation of the coastal Birling Gap plugs was effected by placing plugs in a desiccator and saturating them in stages under vacuum with de-aired water for at least 7 days before testing. The quarry samples were spilt into two groups. Group 1 was saturated in de-aired water, but group 2 was saturated in sea water corrosion test mixture DEF 1053/B.S 3900/ B.S 2011, BDH, Laboratory Supplies UK. After saturation the samples were dried in an oven at 60^{o}C; this process was repeated 3 times. The saturated weight of the plug was measured after removing surplus water and the dimensions were measured with a vernier gauge. The samples were then prepared and tested in the triaxial rig.

Quick undrained triaxial tests were carried out on the 3 differently prepared families of samples:

1. Birling Gap coastal saturated plugs
2. Shoreham Cement Works inland saturated plugs
3. Shoreham Cement Works inland salt saturated plugs

All the plugs were tested under the same conditions in the same triaxial rig, the average axial stress peak strength for the different families revealed some very interesting results. The Shoreham Cement Works inland plugs had the highest average axial stress peak strength of 4.9 kN and the Birling Gap coastal plugs had the lowest average axial stress peak strength of 2.9 kN only 60% the strength of the Shoreham Cement Works samples. The Shoreham Cement Works inland salt saturated plugs provide evidence that the weakness in the coastal samples is at least partly due to the influence of the salt from the sea on the chalk. These samples had a average axial stress peak strength of only 3.4 kN far closer to the strength of the coastal samples than the other non-salt saturated Shoreham Cement Works samples which came from the same block of chalk.

6.6 ENGINEERING GEOLOGY OF THE RESEARCH SITES

The weathering, fracturing, engineering grade and fieldwork led to the subdivision of the cliff into several units at the research sites in the UK and France. These divisions all had their own properties and were found to affect the type of cliff collapse and coastal zone instability issues at each site. They also affected how well the instruments and experimental methods worked.

6.6.1 Birling Gap

Birling Gap was the simplest of the research sites investigated using this method. The entirety of the cliff is composed of the Seaford Chalk Formation, and several key marker flint bands were easily identifiable in the cliff face, the IDD's were all very similar and the chalk was considered to be medium density (Lord *et al.,* 2002). The homogenous nature of this cliff face meant from an engineering geology perspective it only needed to be divided into two units. The 1.5m deep weathered zone characterised by cryoturbation involutions and highly fractured Seaford Chalk Formation with a very thin drift. The rest of the cliff is a homogenous soft white chalk with nodular and sheet flint bands. The cliff was composed of sub-vertical continuous fractures some of these died out at the Michel Dean Flint that separates the Cuckmere and Haven Brow beds (Figure 6.22).

At the cliff face the majority of the chalk was not saturated, only the bottom 9 m of the cliff was near or at saturation. The pore water contained up to 234 ppt salt, which is near salt saturation in water. Even on the cliff top, 16 metres inland, the chalk in the weathered zone, had a pore water content of 45 ppt salt (Figure 6.22, Table 6.4).

6.6.2 Mensil-Val

The Mensil-Val research site is composed of Lewes Nodular Chalk Formation. The cliff was subdivided into four engineering zones based on IDD, the engineering grade, the weathering and the fracture style (Figure 6.23). The base of the cliff is represented by engineering unit MV1 (Figure 6.23) this unit has many caves that generally terminate at the top of this unit against Lewes Marl and follow steeply inclined conjugate fractures sets some of which terminate at Lewes Marl and others carry on through it. Unit MV2 is characterised by a soft zone (Figure 6.23) this can be seen in the cliff face as a continuous concave unit and by the lowest IDD in the cliff. Unit MV3 lies between the soft zone and under the weathered zone. Sets of steeply inclined conjugate fractures can be observed in the upper cliff. Although it is intensely weathered in MV4 the fracturing can still be observed through the weathering. As a result of the weathering there are many sub-horizontal small-scale fractures developed, it has an engineering grade from DC to C4 (Lord *et al.,* 2002), and deep cryoturbated involutions can be observed. The weathering deepens into the valley profile.

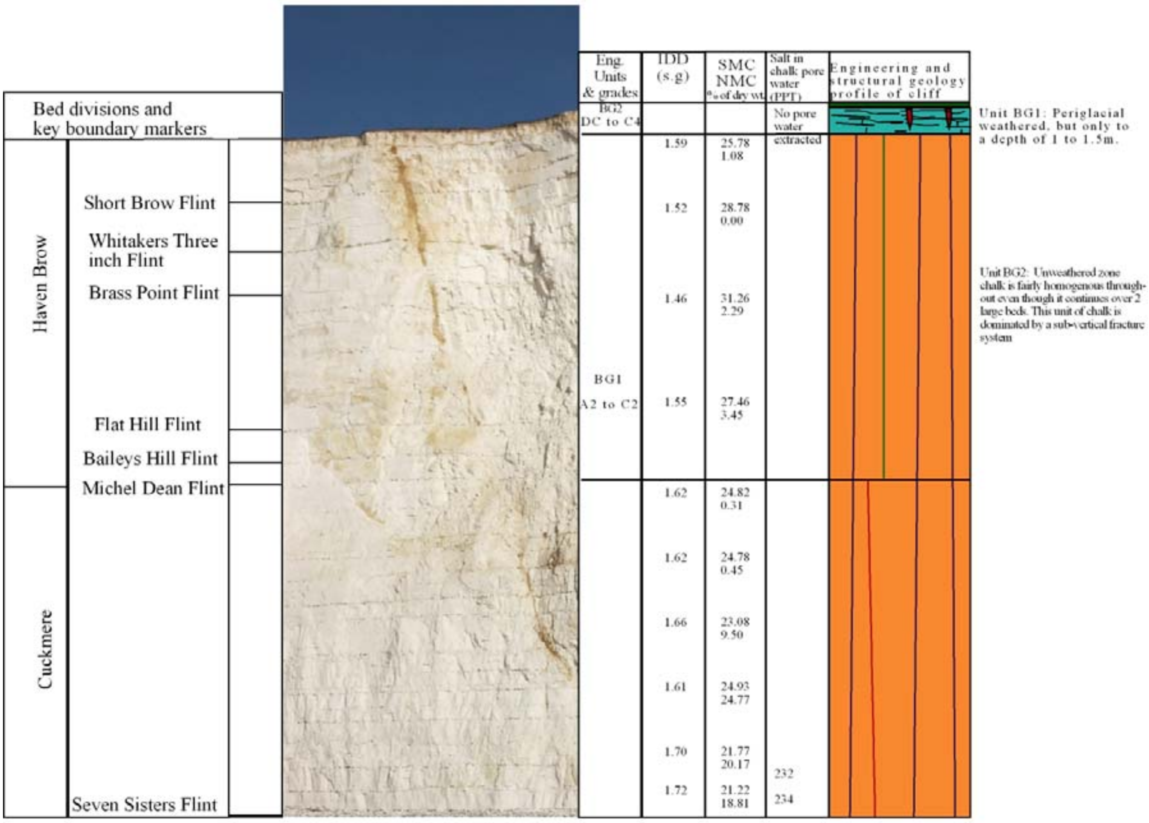


Figure 6.22. Birling Gap research site engineering geology stratigraphy, for the purpose of studying cliff slope instability.

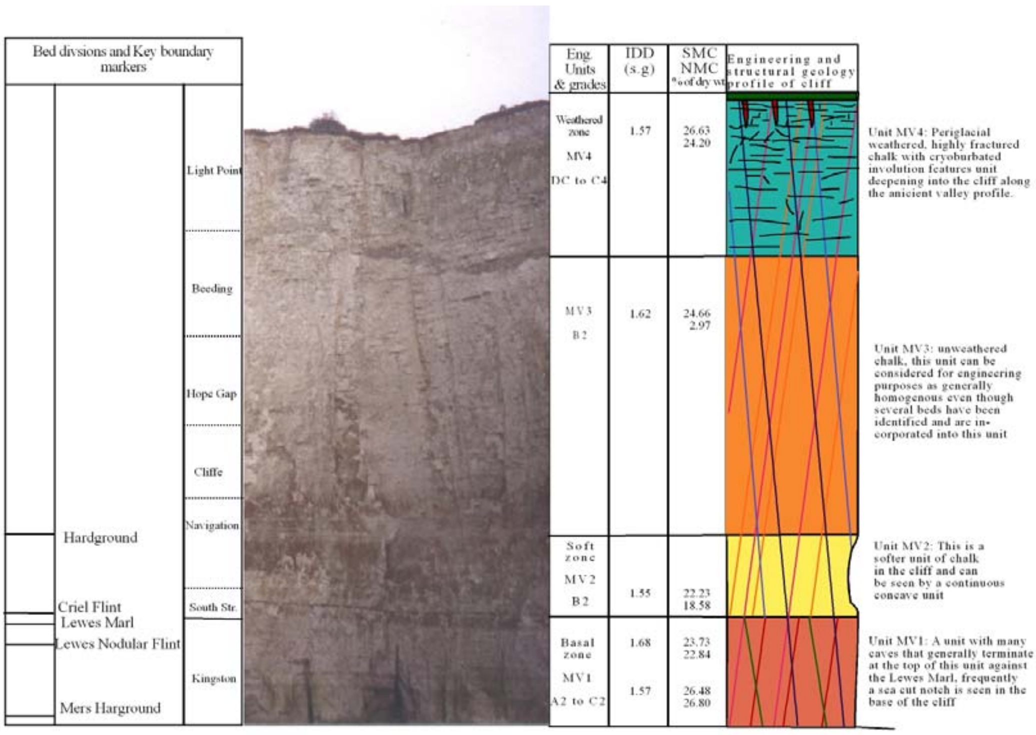


Figure 6.23. Mensil-Val research site engineering geology stratigraphy, for the purpose of studying cliff slope instability.

6.6.3 Beachy Head

Beachy Head research site is the most complex to split up into engineering zones, due to the height of the 110 m cliff. Often the engineering units have been split along the formation boundaries because this is where changes in the rock properties also occur. Three of the chalk formations can be found in this cliff. The top of the New Pit Chalk Formation, the Lewes Nodular Chalk Formation and, at the top of the cliff, the base of the Seaford Chalk Formation. The cliff was divided into 5 engineering units; at the base of the cliff, BH1 (Figure 6.24) is the New Pit Chalk Formation with an engineering grade of A1. It is a high-density chalk and was generally close to or at saturation. The fracture system was conjugate style fractures at a lower angle than the overlying Lewis Nodular Chalk Formation.

The Glynde Marl separates the New Pit Chalk Formation from the Lewes Nodular Chalk Formation and also separates the engineering units. The second engineering unit BH2 (Figure 6.24) coincides with the entire Lewes Nodular Chalk Formation and is characterised by a very steeply inclined conjugate fracture system. Units BH1 and BH2 can easily be seen in the cliff where the cliff face is slightly inclined, dipping steeply out to sea.

Above BH2 the Seaford Chalk Formation and the third engineering unit, BH3 are present. BH3 begins at the base of the Seaford Chalk and is made up of the entirety of the Belle Tout Beds. It can easily be identified by the sub-vertical fracture system that runs through it. Although some of the steeply inclined conjugate fractures from BH2 are present in this unit, they generally terminate at the top of this unit against the Seven Sisters Flint Band. The next engineering unit (BH4) is composed of the remaining Seaford Chalk Formation, found in the cliff top beneath the weathered zone (BH5). This like the cliffs at Birling Gap, is characterised by medium density, sub-vertically fractured homogenous chalk (Figure 6.24). Both BH3 and BH4 can be seen in the cliff as the upper vertical part of the cliff face. The highest engineering unit in the cliff, BH5, is the weathered zone, 2 – 3 m deep and characterised by cryoturbation involutions and highly fractured Seaford Chalk with a very thin drift.

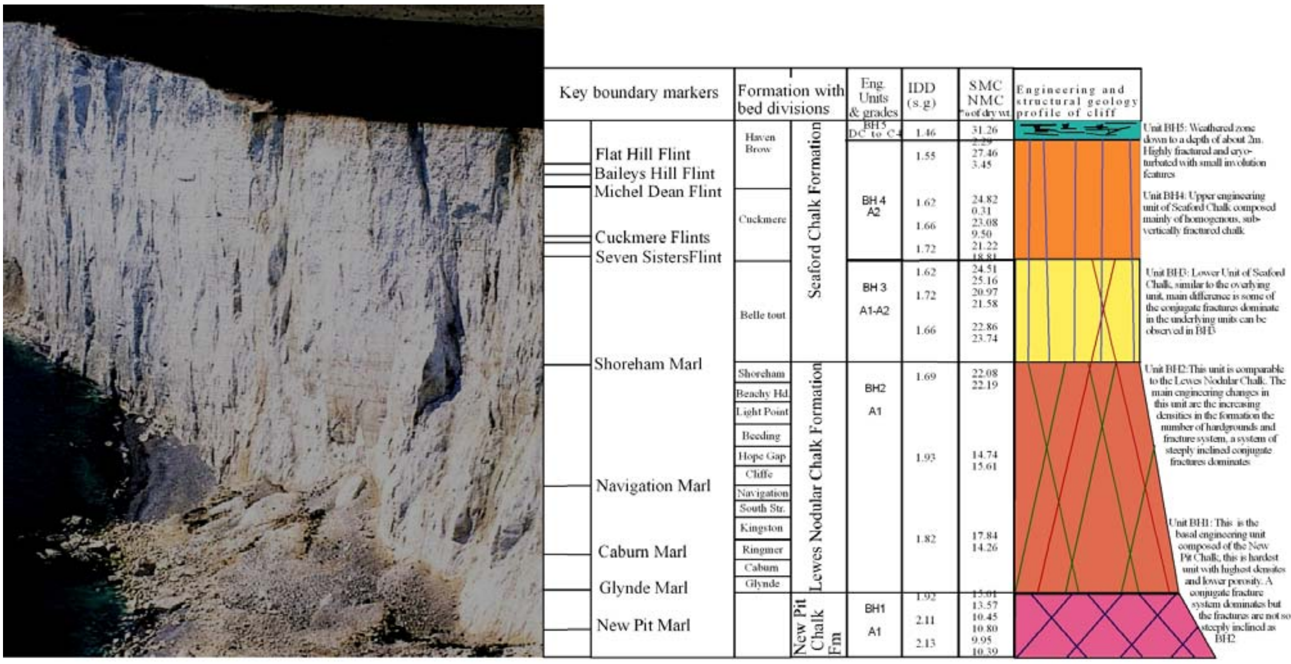


Figure 6.24. Beachy Head research site engineering geology stratigraphy, for the purpose of studying cliff slope instability.

7 Discussion

All of the geological and geophysical methods used for the PROTECT investigations have produced results that are useful when trying to predict imminent cliff failure. Their value increases when the results are combined and a holistic approach is taken. The multidisciplinary approach on this project provides the possibility of understanding mechanisms of coastal cliff failures and providing tools for predicting potential cliff collapses.

7.2 ENGINEERING GEOLOGY

Description and classification of rock for engineering purposes, and the chalk in particular, has developed greatly in the last decade (Lord *et al.,* 2002). Techniques employed during this investigation were learnt from major engineering projects in the UK, applied and adapted by the INTERREG II ROCC (Risk Of Cliff Collapse) programme and modified for the PROTECT project. Interpretation of the lithostratigraphy was an important first step in the project. Knowledge of the chalk stratigraphy of the cliff section provided a framework for all other investigations and aided interpretation of results. A second step was applying the CIRIA grades which included density description and rock fracture analyses.

Once the lithostratigraphy had been mapped, the cliffs were divided into several engineering units based on:

- The nature of the chalk layering (low and high density layers)
- Presence of hardgrounds or rock bands
- The nature (continuity) and size of flint bands and marl seams
- Hydrogeological features such as local perched water and spring lines/points
- Weathering zones especially periglacial affected parts of the cliffs
- Zones approaching an imminent state of collapse

7.3 FRACTURE (DISCONTINUITY) ANALYSES

The majority of fractures at all sites followed a series of orientations, regardless of size (persistence) of the fracture. Vein-fabrics, micro-fractures, fractures, master joints and faults all followed the major fracture orientations. This suggests that synsedimentary, depositional and tectonic processes were responsible for establishing the present fracture systems that shapes coastlines, dictates the type of cliff instability and even affects the periglacial weathering. Scanline surveys provided an interpretation of the 3D fracture system within the cliff and made it possible to interpret fracture directions and style of fractures within the cliff.

During the fieldwork at the research sites fracture aperture could be seen in the base of the cliff. Large fractures and movements could be frequently observed in the cliff top as the soil splits apart due to the stresses and loading on the newly exposed cliff face. This suggests fracture failure ranges from instantaneous to progressive and can be observed in the entire cliff face.

The surveys have shown that although all the research sites are on chalk, the material behaves very differently at each of the sites. The orientation and types of fracture act as major controls on the type, style and size of the cliff collapses and these fractures can be related to early tectonic and sedimentological controls.

7.4 LABORATORY TESTING

Index tests of intact dry density and moisture content were carried out on samples, providing detailed information on the material in the cliffs and supporting the CIRIA Grade classifications.

All the research sites had low-density chalks in the cliff face. To investigate some of the relationships with chalk fracture and cliff collapse a series of triaxial compression tests were undertaken in the laboratory. The chalk at all the research sites was relatively soft and generally fractured along pre-existing vein-fabrics, micro-fractures or fractures. The samples from Møns Klint were consistently the weakest samples and were also far more intensely fractured than samples from any of the other research sites. The chalk from the sites in the UK and France were comparable in strength before fracturing although they were from different formations. Even within the core the fracture angle was comparable to the angle of fractures that can be seen in the cliffs from where the cores were collected. The results showed that the saturated chalk was 50% to 90% weaker than the dry chalk, and this confirms the results from previous testing (e.g. Mortimore & Fielding, 1990; Mortimore *et al*., 2004) the NMC and SMC tests proved the chalk in the cliff face was near to or at saturation.

7.5 MODELLING

To assist in interpretation of cliff collapse mechanisms and the likely volumes of rock involved, various slope modelling programs were applied. Attempts were made to model the cliffs in terms of the types, styles, volumes and causes of collapse. Due to complexities of making a realistic model of the cliffs only the two simplest cliff sections could be modelled, Birling Gap in the UK and Mensil-Val in France, using RESOBLOK and UDEC. RESOBLOK is an in house rock fracture modelling programme developed by the Ecole des Mines, Nancy. Initial results in RESOBLOK were imported into UDEC to investigate two-dimensional cross sections of the cliffs. The modelling results showed the scale of collapse that could be expected. At Mensil-Val the blocks that failed were bounded by conjugate fractures and local block failure led to weakening the surrounding area. These model results compared closely with field observations of failures. Some similarities could be drawn between field observations and the numerical modelling collapse styles at Birling Gap. For this type of rock slope modelling more research is required on the liquid equilibrium and distinct element calculation codes. Judging by the results obtained from this work, numerical simulations cannot be used independently as a predictive tool, and do not replace the accurate and regular field surveys at the research sites.

7.6 AZR AND FRACTURE SURVEYS

In the UK the Azimuthical Resistivity (AZR) geophysics has proved to be a very useful tool in identifying the main orientation of the tectonic fracture sets in the cliff. At Birling Gap the AZR data predict a fracture set striking at 074^{o}. This result, on the cliff top, is the same (within an error of 1^{o}) as the fracture orientation mapped at the base of the cliff.

The major fracture sets at Birling Gap and Beachy Head are of the same type, style and orientation. However the dominant fracture set identified in the Azimuthal Resistivity surveys has changed from North East at Birling Gap to North West at Beachy Head. The change in the orientation of the cliff face means the scanline has a built in bias and is measuring the opposite set of fractures and is possibly part of the reason the geophysics is picking up the opposite set of fractures. Most likely because the fractures are dilating easier as the cliff face opens, relaxes and is exposed over time. The evidence of fault and slickensides in the area also suggests a tectonic relationship. The different orientation of the cliff can be seen from a map or from the strike of the scanline survey orientation.

A scanline survey at the base of the cliff under the research site at Beachy Head was in a different chalk formation to the top of the cliff and the research site. It would not have been surprising to see a completely different fracture orientation and set to the research site at the top of the cliff. The scanline picked the fracture orientation suggested by the geophysics almost perfectly, indicating the persistence of large-scale tectonic fractures.

The fracture style, type and orientation at Mensil-Val is very similar to the UK sites. It is possible this is because the sites in the UK and France have been in the same tectonic setting .

Results from scan-line surveys and Azimuthical Resistivity surveys at Mensil-Val do not compare. This suggests that the Azimuthical Resistivity is picking up something different that needs further investigation. From fieldwork several reasons have been identified which could explain this. The Mensil Val site is on the steep slopes of a valley and therefore the periglacial weathering of the chalk is very deep. This can be observed from field observation and also in the P-wave velocity of the seismic testing on the site. Large parallel cryoturbated chalk and clay solution features have been identified running though the site and may have affected the AZR.

7.7 AZR AND PERIGLACIAL WEATHERING

The AZR technique works by identifying the dominant fracture direction in the topmost layers of the chalk. These topmost layers are where past cold climate conditions have had greatest effect. Comparisons of the AZR results and engineering geology recorded on the cliff top have proved crucial. The depth and style of periglacial weathering is probably a factor in obtaining good results and thus interpreting the AZR. At Birling Gap, located on an interfluve, the periglacial weathering is less than 2 m deep with the chalk being highly fractured, but other than this relatively undisturbed. At Beachy Head the periglacial weathering is slightly deeper, about 3 m, on the flanks of a small valley, but this does not seem to affect the AZR results. However, at Mensil-Val, periglacial weathering penetrates the chalk far deeper, on the flanks of a large dry valley, and this appears to influence the AZR .

At the Møns Klint research sites the AZR results do not follow the apparent fracture orientations. This is probably caused by the intense periglacial and glacial fracturing of the Chalk, the high angle of dip of the Chalk and the effect of trees, particularly at the Dronningestolen research sites.

The results suggest that the AZR works best at sites where the weathered profile is shallow (<2m), and bedding dip is close to horizontal. In these circumstances the AZR is able to pick up the orientation and dilatency of fractures within the cliff and can, therefore, be used as a predictive tool. The AZR also works better at sites with no trees and widely spaced (>200mm) fractures sets.

7.8 TECTONIC FRACTURING ON THE EAST SUSSEX COAST OF THE UK

The Beachy Head and Birling Gap research sites are only 2.5 km apart and both are located on the Seaford Chalk Formation. However, the estimated azimuths of the primary tectonic fracture sets are different and the coefficient of anisotropy calculated for Birling Gap is much larger than that for Beachy Head. The initial differences are a prime example of the importance of a holistic study such as the PROTECT project and the importance of recording in detail the Engineering Geology. At first it was thought that the data show a progressive change in strike of the primary fracture set and an increase in the coefficient of anisotropy, from Beachy Head to Birling Gap. The scanline data collected from the cliff faces shows that there are two major sub-vertical, sub-perpendicular fracture sets at Birling Gap and Beachy Head that strike approximately 70 ^{o} and 150 ^{o}. At both research sites the change is not a change in the orientation of the fractures but a change in the dominance of a fracture set. The joint surveys indicate that the 150 ^{o} trending joint set is dominant at Beachy Head and those striking at 70 ^{o} dominate at Birling Gap. Intermediate fracture strikes recorded at two sites between Beachy Head and Birling Gap may result from the orientation of greatest fracture connectivity due to the influence of two similar fracture sets. The increase in the coefficient of anisotropy may represent an increase in fracture density (on the scale of the measurement) of the primary fracture set.

7.9 COMPARISONS WITH ROCK PROPERTIES AND METEOROLOGICAL DATA

This section attempts to interpret the results obtained from the azimuthal apparent resistivity measurements. In the previous sections AZR anisotropy has been examined, with the conclusion that orientation of the predominant joint set plays a major role in determining anisotropy. Other possible explanations for the variations observed could be changes in rock properties and/or meteorological effects.

7.9.1 Mensil-Val

There are no indications in the measures of anisotropy of the cliff fall of 23rd June 2002. This implies that a fall outside of the area of direct investigation is not detectable with azimuthal apparent resistivity. The implication is that fracture dilatancy is limited to the block constrained by the conjugate fractures and these fractures limit the lateral extent of the fall.

At Mesnil-Val there is a discrepancy between the fracture orientations estimated from the azimuthal apparent resistivity survey and those measured by scanline surveys. A resistivity imaging survey carried out at Mesnil-Val highlighted a conductive feature that passes through the Control Site and strikes at ~20 °. This orientation coincides with cryoturbated features that are a result of recent periglacial activity. They are oriented down slope towards the valley but also face slightly down hill in the direction of the valley. These results are summarised in Table 7.1. Hence, there is a correlation between one of the orientations measured by the azimuthal apparent resistivity survey and the conductive feature measured by the resistivity imaging and presumed to be a periglacial, cryoturbated lobe. However, it is unclear as to why only one cryoturbated lobe was imaged by the resistivity as these features occur in a parallel set down the valley side. In addition, the conjugate orientation measured by the azimuthal apparent resistivity survey remains unexplained. It is possible, but unlikely, that a synsedimentary shift in the direction of tectonic activity resulted in a change in fracture direction from the base to the top of the cliff. In this case the conductive feature measured by the resistivity imaging would be a weathered fracture filled with clay.

Type of measurement	Orientation of feature		Type of feature
	Strike 1	Strike 2	
Scanline surveys	40 °	138 °	Fracture orientations
Azimuthal apparent resistivity	16 °	117 °	Probably periglacial features
Resistivity imaging	24 °		Probably periglacial features
Periglacial mapping	20 °		Cryoturbated lobes

Table 7.1. Strike of surface features measured at Mesnil-Val.

Temperature sensors and extensometers were also placed in horizontal boreholes into the cliff face at Mesnil-Val. Temperatures were measured at depths of 3 and 6 m and the extensometers operated over lengths of 4 and 6 m. An example of these data is shown in Figure 7.1. The average monthly air temperature shows, as expected, a peak in the summer and a trough in the winter. The temperature sensors within the cliff demonstrate that the air temperature is driving rock temperature. It is well known that to depths of around 15 m, atmospheric temperatures drive rock temperature changes. There is a phase shift of 1 to 2 months between the temperature variations at the cliff face and those at a depth of 3 m and 4 months between the cliff face and those at a depth of 6 m. From these differences an average thermal diffusivity of 5.98×10^{-3} cm^2 s^{-1} has been calculated, which is consistent with fractured chalk. In turn, rock temperature is driving an expansion and contraction of the rock mass that has been measured by the extensometers. The movements are extremely small, but there is a clear maximum expansion in

February and minimum contraction in September. Hence, it would appear from the seasonal variations in the coefficient of anisotropy (peak in the summer and trough in the winter) that the expansion of the rock mass is taken up by a contraction of the fractures.

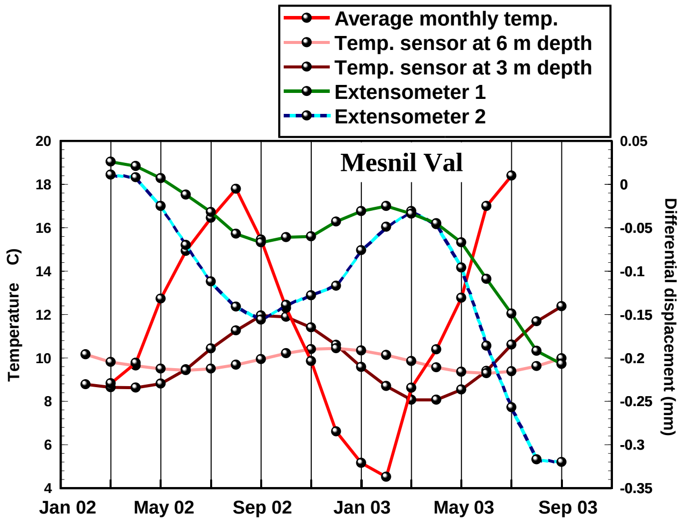


Figure 7.1. Air temperature, rock temperature and extensometer data from Mesnil-Val. The rock temperature sensors were emplaced in a horizontal borehole drilled into the cliff face.

7.9.2 Birling Gap and Beachy Head

A cliff parallel fracture set has been interpreted near to the cliff edge at Birling Gap and Beachy Head. This zone is around 10 m in width. The seasonal variations in the coefficient of anisotropy are small at Birling Gap, but large at Beachy Head, with peaks in the summer and troughs in the winter. Average apparent resistivities are constant with time at both sites, but with a low in the winter of 2002/2003. At Beachy Head there is a distinct increase in resistivity towards the cliff edge, whilst at Birling Gap there is no obvious resistivity gradient.

Two small cliff falls occurred at Birling Gap during the period of measurements. The first between March and May 2002 showed a large change in the coefficient of anisotropy at the research site. This change has been interpreted as resulting from the cliff fall and probably indicates a change in dilatancy within the fracture network. The second fall on 9th January 2003 was also small and occurred outside the zone of resistivity measurements. There is no indication of the fall in the measures of anisotropy. Hence, as at Mesnil-Val, it appears that tectonic fractures may limit the extent of the fracture dilatancy. No cliff falls were reported from the Beachy Head site during the two years of measurements.

7.9.3 Jættebrink and Dronningstolen

At Jættebrink, no consistent fracture orientations were recognised in the AZR data and this appears to be consistent with the mapping that found many fractures of low persistence at different orientations. There are no clear patterns to the measures of anisotropy except at Site A where there are peaks in the winter and lows in the summer, the opposite pattern to Mesnil-Val and Beachy Head. The average apparent resistivity data show peaks in the winter and lows in the summer. At Dronningestolen a number of fracture orientations are interpreted, all at a high angle to the cliff face. Hence there appear to be no cliff parallel fractures although the Site A results are very unreliable, possibly reflecting the influence of the trees. The coefficients of anisotropy display a seasonal variation with highs in the summer and lows in the winter. The average apparent resistivity data also show peaks in the winter and lows in the summer.

Monthly weather statistics from a local weather station show air temperature variations with mid-summer peaks suggesting that variations in the coefficients of anisotropy at Dronningestolen are driven by rock temperature. The unusual pattern from Site A at Jættebrink cannot be explained. The rainfall data shows a clear pattern of wet summers and dry winters that may explain the pattern of average apparent resistivities.

8 Conclusions

The microseismic data have demonstrated that there is a significant increase in seismic energy emitted from cracks within the rock mass in the hours before a cliff collapse. At Mesnil-Val this increase occurred over the 15 hours before the collapse. Azimuthal apparent resistivity data has identified a fracture set sub-parallel to the cliff face in the zone immediately adjacent to the cliff. It is likely that the acoustic crack emissions are being emitted from this fracture set. Analysis of the seismic data indicates that different phases of the failure can be identified by distinct seismic families. Comparisons with laboratory induced acoustic crack emissions has demonstrated that high frequency seismic signals are emitted as the rock cracks and that this increase in frequency might be used as an indicator that a collapse is imminent. The high porosity of chalk was found to lead to rapid attenuation of the seismic signals. The distance between accelerometers in a monitoring network on a chalk cliff would have to be less than 30 m. Such indications would constitute a short-term warning of impending cliff collapse.

The 2002 cliff fall at Birling Gap, where ground from within the circle of measurement was lost, produced a large temporal change in the coefficient of anisotropy, estimated from the azimuthal apparent resistivity measurements. This has been interpreted as a reduction in fracture dilatancy as a result of the cliff fall. The Mesnil-Val and Birling Gap 2003 cliff falls did not show temporal changes in the coefficient of anisotropy. Ground outside of the circle of measurement was lost and it is likely that the tectonic fractures limit the extent of both the fall and the dilating fractures. Hence a consistently high value of the coefficient of anisotropy near the cliff edge may constitute a long-term warning of impending cliff collapse.

Many of the sites showed seasonal variations in the coefficient of anisotropy with peaks in the summer and troughs in the winter. The Mesnil-Val temperature monitoring suggests a correlation between these variations and rock temperature. The thermal diffusivity of the rock is such that the maximum expansion of the rock mass, as measured by the extensometers at Mesnil-Val, occurs six months after the maximum air temperatures. The data indicate that the expansion leads to fracture contraction with associated minimum values of anisotropy in the winter. It is unclear why the magnitudes of the seasonal variations are so large between different sites.

Scanline surveys have recorded the orientations and persistence of tectonic fractures at the base of the cliffs at all of the research sites. These data have indicated that at the UK sites, tectonic fracture orientations are being measured at the Control sites with azimuthal apparent resistivity. At Mesnil-Val it is less certain and the lineament orientations derived from the azimuthal apparent resistivity data may be due to periglacial cryoturbated features. In Denmark, at Møns Klint, the results are more uncertain, reflecting the glaciotectonised nature of the chalk.

Laboratory testing was carried out on chalk samples from all the sites. The chalk was relatively soft and generally fractured along pre-existing vein-fabrics, micro-fractures or fractures. The samples from Møns Klint were consistently the weakest samples and were also far more intensely fractured than samples from any of the other research sites. Although they were from different formations, the fracture angle within the laboratory core was comparable to the angle of fractures that can be seen in the cliffs from where the cores were collected. The results showed that the saturated chalk was 50 to 90% weaker than the dry chalk. Chalk samples saturated with saline water were found to be significantly weaker than similar samples saturated with de-aired water. It has been noted how frequently collapses occur along coastal sections, yet inland quarries of similar chalk appear relatively more stable. Hopefully this study goes some way to proving that salt is a major contributing factor to the weakening of chalk coastal cliffs.

Topographic ground surveys have measured movement of marker pegs as tension fractures developed on the cliff top. Such surveys allow both the rate and direction of movement to be calculated. During the project these data have allowed changes in the cliff lines resulting from cliff falls to be measured accurately and have provided excellent ground control for the geophysical measurements.

The research has been successful in establishing that there are measurable changes in the rock mass prior to a cliff collapse.

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