Structural Geology and Fracture Patterns in the Chalk of Sussex, UK

presented by

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ABSTRACT

Chalk is the main rock-type that forms the downland of Sussex. This Final Year Geology Project evaluates fracture patterns, physical properties, geochemical and mineralogical compositions of the chalk, and links these aspects to cliff failure and to its hydrogeology and aquifer characteristics. The coastal cliffs from Brighton to Newhaven are susceptible to collapses due to a steeply inclined fracturing that has a dip average of 63°. Scanline surveys enabled the collection of fracture data that could be interpreted using the software DIPS. Also, combining Portable X-Ray Fluorescence (PXRF) and X-Ray Powder Diffraction (XRD) results, it was possible to measure the semi-quantity of illite in the marly chalk seams of the Newhaven Chalk Formation. As a small amount of this clay mineral is present, it might have a minor contribution to chalk cliff instability. The failure of the chalk cliffs is induced by the combination of their lithological characteristics (including structural features), overlying sedimentary material, and weathering processes which include the effects of rainfall and wave action. Collating all of this data enables one to locate the areas most susceptible to collapse, and to estimate the magnitude and frequency of collapses. Much of the Sussex coastline is in an urban area with nearby roads, leading to a significant risk to life and infrastructure. Geological characterization of the cliffs is therefore necessary to provide key data to inform risk assessment and remediation strategies.

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CHAPTER I

INTRODUCTION

This chapter briefly sets out the research's background, placing it in a general context, which is the field of study (I.1). Next will be presented the aims (I.2) and then the outline structure (I.3) of this Final Year Geology Project.

I.1) General Field of Study

England presents an extensive intermittent chalk cliff line that goes from Yorkshire to Devon. In East Sussex, the chalk cliffs along the coast from Brighton to Beachy Head (Figure 1.1) are part of the White Chalk Group (redefined as the Middle and Upper Chalks). Continuing from Beachy Head to Eastbourne, the stratigraphy goes down where the lithological units of the Grey Chalk Group (or Lower Chalk according to the traditional stratigraphy) have been mapped.

Although many studies involve this type of rock, there is a special concern about its instability. Most of it is located in urban areas and, due to structural and weakening mechanisms (e.g. wave erosion), the chances of cliff collapses are increasing with time. Also, some areas are not prepared in terms of infrastructure and engineering intervention to minimize risks, especially, to protect the population.
Every few years, large sections of chalk cliffs collapse and, the next day, they become headlines in the media, especially, if followed by severe losses or disruption of infrastructure or people. So, this issue has been attracting the attention of local authorities in order to minimize deaths and economic damage. For example, the area comprised by the cliffs from Brighton to Newhaven has a large population density, leading to concerns about how this section of coastline should be managed. Increasing geological and geotechnical studies have been carried out to understand what causes the collapses.
Cliff failures are a type of geohazard and if mitigation proposals exist and can actually be applied, much of public resources could be saved. But, to implement them, the hazard should be classified (e.g. low, medium and high) considering the following parameters:

1) Chalk lithology;
2) Overlying sediments (in this case they are clay, loess and clay with flints);
3) Weathering;
4) Magnitude and frequency of cliff failures;
5) Cliff height;
6) Chalk properties (density and porosity); and
7) Structural geology.

Turning, specifically, to the study area (subject of Chapter III), what motivates geotechnical studies are the lithostratigraphical changes because the same section may contain many chalk formations. Each of them has different densities, porosities and mass structures. Indeed, the structural geology aspect of the chalk influences most occurrences, styles and scale of collapses. So, a pre-existing network of fractures is a key structural parameter, which plays an important role in the stability of the Chalk of Sussex cliffs. As noted by Mortimore (1983) on the chalk cliffs of East Sussex (Figure 1.2), their failure is mainly controlled by minor fractures, major fractures and main faults. Consequently, they change the dip of strata, putting the cliff into a favourable position to collapse. However, folds can also affect their stability (as in the case of Newhaven town - one of the investigation sites for this work).
Discontinuities, in association with marine erosion, climate (and climate change), weathering, rainfall and other facts lead to collapses in East Sussex and modify the rate of cliff collapse development. In the past, heavy rain facilitated cliff failures at Peacehaven Steps, Telscombe Cliffs and behind Asda Supermarket in the Brighton Marina. Furthermore, there is the permanent erosion by wave action at the foot of the cliffs working as a conditioning factor to failures.

Cliff slope instability is a field for engineering performance. So, in order to protect the cliff base against wave attack and to strengthen the rock, coastal defense works have been demanded. For example, concrete walls were built in Peacehaven Steps (Friar’s Bay area) and Telscombe Cliffs between 1978 and 1984 and during the winter of 2000-2001 sections of the remaining chalk cliffs in the Brighton Marina (behind the Asda Supermarket) motived more coast protection works. Also, bolts were installed following the discontinuities orientations because either fractures or faults represent the weakest points of any type of rock. However, it is important to
make it clear that these engineering interventions do not completely eliminate slope failures in the Chalk of Sussex. They try to postpone the potential hazards and, consequently, more damage will be avoided.

Also, there is a further subject where this research fits. Generally, chalk’s porosity is very high. Through its porous nature the water flows down rapidly from the surface to empty spaces (cracks, discontinuities and cavities), forming dissolution features (e.g. karstic pipes). Also, its high levels of porosity make it a potential aquifer because it stores and, thanks to weaker planes (discontinuities), transmits groundwater. So, it is the Chalk of Sussex groundwater which provides much of the tap water used in Southeast England.

In conclusion, questions on why cliff collapses occur, where they are most likely to happen and how intense (magnitude) they will be can only be answered by geological research.

I.2) Aims

This Final Year Geology Project concentrates on the Chalk of Sussex, but the research/investigation, fieldwork and sites for data collection took place specifically at the chalk coastal cliffs from Brighton to Newhaven, East Sussex, England, UK. At this section of cliff, the dominant formation is the Newhaven Chalk (Figure 1.3), a soft to medium hard white chalk, sometimes very smooth, in which marl seams and flint bands work as boundary features. Also, the transition zone between rock and soil is usually marked by sub-Palaeogene erosion. So, on the top of outcrops, it is possible to identify Palaeogene sediments such as clays and sands.
Two main questions that lead to the achievement of the project aims are:

1) How do the fracturing characteristics of the Chalk of Sussex reflect their lithological, structural and geomorphological setting?

2) What are the implications of the fracture patterns for the engineering geology and hydrogeology of the Chalk of Sussex?

I.3) Outline Structure

The structure adopted to construct this report will follow the chapters below:

- Chapter I: Introduction
- Chapter II: A Review of Existing Literature
- Chapter III: Location and Site Description
- Chapter IV: Methods
- Chapter V: Results
- Chapter VI: Discussion
- Chapter VII: Conclusions
CHAPTER II

A REVIEW OF EXISTING LITERATURE

This Final Year Geology Project will address two main topics:

1) The relationship between fracture patterns, lithological, structural and geomorphological setting of the Chalk of Sussex; and

2) Implications of the fracturing for the engineering geology (geotechnical aspects) and hydrogeology of the chalk.

<table>
<thead>
<tr>
<th>Subsections</th>
<th>Subject of the Subsections</th>
</tr>
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<tbody>
<tr>
<td>II.1</td>
<td>Primary information about the Chalk of Sussex with focus on lithology, sedimentation and stratigraphy.</td>
</tr>
<tr>
<td>II.2</td>
<td>Structural Geology of the Chalk of Sussex with specific attention to the fracture pattern.</td>
</tr>
<tr>
<td>II.3</td>
<td>Geotechnical concerns regarding cliff collapses, rock falls and cliff retreat. Also, it will discuss the physical properties of the chalk in relation to hydrogeology matters.</td>
</tr>
</tbody>
</table>

Therefore, in this chapter the pertinent literature will be reviewed comprising the following subsections:
II.1) Lithology, Sedimentation and Stratigraphy

Since this Final Year Geology Project deals with the Chalk of Sussex, it is necessary to explain about its lithostratigraphy. The Chalk of Sussex, also known as part of the Chalk of Southern England, represents stratigraphically the exposed Chalk Group in the southern part of the country, which has different subdivisions. But, because this subject is not the focus of this work, here will be presented the traditional and also the modern lithostratigraphic subdivision of the Chalk of Sussex.

Traditionally, the widely recognized lithostratigraphy subdivision of the Chalk of Sussex comes from Jukes-Browne and Hill (1903, 1904). They established three divisions: the Lower Chalk, the Middle Chalk and the Upper Chalk (Figure 2.1).
Figure 2.1: Main lithostratigraphical subdivisions of the Chalk Group in England. In red, highlighting the nomenclature given by Jukes Browne and Hill (1903, 1904).


To build the stratigraphy above, the chalk was subdivided according to marker beds. Although in the Chiltern Hills this method works, unfortunately, going further away, it does not. Aldiss *et al.* (2012) listed three main problems encountered by this subdivision in terms of the mapping of the chalk. They are:

1) The Lower Chalk, the Middle Chalk and the Upper Chalk are not constant in terms of composition. There is a significant compositional variation from the
bottom to the top of the outcrops and vice-versa. For example, the lower part of the Lower Chalk is characterized by beds of hard limestone and soft enriched in clay marly chalk. Furthermore, these beds are rhythmically intercalated. However, this alternation is not very much evident in most of the upper part of the Lower Chalk (Grey Chalk). Instead, it contains massive amounts of bedded chalk with a lesser rate of clay and more regular composition than the middle part of the Lower Chalk (Chalk Marl). But, in the Middle Chalk the vertical variation in composition is substantially more pronounced due to the hardness (hard and sometimes very hard) of the Middle Chalk and the presence of nodular flints;

2) Impersistence of the marker beds used to divide the chalk; and

3) Thickness variations of the chalk. In general, the Upper Chalk’s thickness does not exceed 400 meters, such as, in Hampshire and Sussex. The Middle Chalk varies between 35 and 100 meters and, finally, the Lower Chalk which is 35 - 100 meters thick (Hopson et al., 1996). It is worth emphasizing that these thicknesses do not take into consideration tectonic structures in the outcrops. This means that if a marker is displaced by a fault, possibly, the orientation of the displacement will not be recorded by the next marker. Nowadays, this kind of information is easily obtained thanks to modern chalk stratigraphy (Bristow et al., 1997; Mortimore, 1983, 1986a - Figure 2.2) because it includes structural features.

The proposed division of the chalk into nine formations by authors, such as, Bristow et al. (1997) and Mortimore (1983, 1986a) provides a clearer understanding of the English Chalk Group and its structures than older versions (Figure 2.1). This
chalk stratigraphy is very useful and has been helpfully applied to geological researches in engineering geology and hydrogeology.

In terms of deposition, the Chalk of Sussex, including its extension towards the Northern European coasts, was deposited in a marine environment. The sedimentation began in the first stages of the North Atlantic opening. Stratigraphically, the units belong from Cenomanian to lower Campanian stages (Mortimore & Pomerol, 1987). As said before, the traditional chalk stratigraphy has been replaced in the UK by the Southern Province Chalk Stratigraphy, which is used even by the British Geological Survey. The main difference between this new terminology and the traditional one is a lithostratigraphical concept based on key boundary markers. So, the mapping of chalk terrains was focused on flints bands, hardground and marl seams. Also, Mortimore et al. (2004a) included macro, micro and nannofossils analysis to support and define the new chalk lithostratigraphy in East Sussex. To illustrate the result of this revision, Figure 2.3 gives a condensed version of the lithostratigraphy of the Chalk of Sussex and key markers for each formation.
Figure 2.2: Comparison between the traditional chalk stratigraphy and modern versions, including key marker beds. Note: Us = Uintacrinus socialis Zone. Mt = Marsupites testudinarius Zone.

Markers, as the content of flint, marl and fossil, play an important role in the stratigraphy. They help to position and locate, in an accurate way, the chalk formations. Also, they represent boundaries within the formations. Regarding the fossils, it can be stated that they occur commonly within chalk formations, but it is...
very hard to identify them in the soil, where soil and chalk fragments appear in the same horizon. But, the fossils are better preserved in flint nodules layers than in the soil, making the identification between rock (chalk), flint bands, clay-rich beds and fossils easier. A practical example is the Lewes Nodular Chalk (redefined Upper Chalk), which was divided into two: upper and lower parts. Lewes Marl is the key boundary marker that separates both parts (Figure 2.2). As it is so essential to know about the chalk markers, it is necessary to have background knowledge about the types of rock associated with the Southern Province Chalk. So, Table 2.1 gathers together a summary regarding each formation and its characteristics (composition, types of fragments within the chalk and corresponding topography).

All markers cited above represent the notable features of the chalk formations. The majority of them have thin parallel bedding planes (in the order of decimeters) and identification is made by variations in the clay (Wray & Gale, 2006). It is the clay content, rich in carbonate, which is the main component of the chalk marl rhythms. In the literature, clay minerals are widely mentioned: illite, kaolinite and smectite. However, the mineral assemblage is different from one formation to another. Taking the results from Weir & Catt (1965), Young (1965) and Perrin (1971) as a proof of that statement, smectite tends to be the dominant clay mineral while illite presents subordinate amounts. This data belongs to younger chalk formations in Eastern England. In addition, a more recent study by Deconinck et al. (1989) showed a slow decrease in illite and kaolinite distributions only in Turonian Lewes Nodular Chalk Members, New Pit Chalk Member and Holywell Nodular Chalk Member (both also in Turonian age). Regarding the flint bands, it is important to mention two aspects: they reflect the chalk sedimentation, which is cyclical in all
formations, and, depending on the formation, are key features to understand their palaeoceanography and diageneses.

Table 2.1: Summary of all formations of the Chalk of Southern England including the rock’s composition, associated brash and topography.


<table>
<thead>
<tr>
<th>Formation</th>
<th>Typical composition</th>
<th>Characteristic brash*</th>
<th>Typical associated topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Chalk</td>
<td>White flinty chalk with common marl seams and some flint bands</td>
<td>Associated brash cannot be reliably distinguished from that of Culver Chalk on lithological grounds alone.</td>
<td></td>
</tr>
<tr>
<td>Culver Chalk</td>
<td>Soft white chalks without significant marl seams, but with some very strongly developed nodular, horn and semi-tubular flints</td>
<td>Tends to be more flaky than that from the Newhaven Chalk, but must not be reliably distinguished from lithological grounds alone. Some parts with abundant bioclastic debris, especially byssozoan debris.</td>
<td></td>
</tr>
<tr>
<td>Newhaven Chalk</td>
<td>Soft to medium-hard, blocky smooth white chalk with numerous marl seams and bands of flint nodules (generally smaller than those in the Seaford Chalk). Some beds rich in bioclastic debris occur at intervals.</td>
<td>Angular slaty fragments of smooth white chalk very similar in appearance to that of the Seaford Chalk but commonly much more voluminous although in smaller fragments; abundant Zopfina fossils near the base. The volume of flint and the frequency of large flint nodules is generally much greater than on the Newhaven Chalk. Some of the large flint bands are characteristic enough to be locally recognized in brash. Individual fragments of typical Seaford Chalk are smaller and more scattered than those of the Newhaven Chalk. Flints are generally larger and more abundant.</td>
<td>Forms steep ground in the face of the secondary escarpment. Base at a negative break of slope at the foot of that escarpment.</td>
</tr>
<tr>
<td>Seaford Chalk</td>
<td>Soft blocky smooth white chalk with abundant seams of large nodular and semi-tubular flint, with thin beds of harder nodular chalk near the base</td>
<td>Rought textured and rather flaggy in appearance. It tends to be more voluminous and rather dirtier than that derived from the New Chalk.</td>
<td>Forms extensive dip slopes between primary and secondary escarpment. Base at a very slight negative feature in front of, or at, or behind the crest of that escarpment.</td>
</tr>
<tr>
<td>Lewes Nodular Chalk</td>
<td>Hard to very hard, white to creamy or yellow/brown white chalky chalks and chalkstones, with interbedded soft to hard gritty white chalks and common seams of clay-rich chalk (marl seams). Regular bands of nodular flint, some large, occur more commonly than in the underlying beds.</td>
<td>The Chalk Rock (a variable sequence of mineralized hardgrounds, chalkstone and nodular chalk) occurs at or near base of formation.</td>
<td>Forms a convex slope at the top of the primary escarpment, commonly including the crest. Base at a positive break of slope.</td>
</tr>
<tr>
<td>New Pit Chalk</td>
<td>Smooth textured, rather blocky, massively bedded, firm white chalk, with regular thin beds of clay-rich chalk (‘marl seams’) and sparse smallish flints.</td>
<td>Fragments tend to be of very uniform, smooth, brittle white chalk of medium hardness, with little fissility. These break readily under the plough and so the chalk commonly shows numerous clean broken surfaces.</td>
<td>Forms the steepest ground in the face of the primary escarpment, typically with a uniform gradient. Base at a negative break of slope.</td>
</tr>
<tr>
<td>Holywell Nodular Chalk</td>
<td>Medium hard to very hard, nodular, white to creamy white chalk with beds and laminae of clay-rich chalk (marl), including flaser-laminated marl. A thin alternating sequence of clay-rich chalks and clayey limestones (Penux Marl) over耙 by very hard, creamy white limestone (Melbourne Rock) occurs at base of formation. The upper two-thirds is mostly conspicuous Oscillinae; most beds contain gritty shell debris, commonly pink, and some have myriads of inorganic bivalves preserved in three dimensions.</td>
<td>Roughter, more granular and rubby brush, compared with New Chalk. Flints are commonly too hard to easily be broken during normal cultivation and so tend to develop a rather granular appearance. In the absence of shell debris, the rather granular texture of typical Holywell Chalk distinguishes it from the smooth chalks of the successor New Pit Chalk.</td>
<td>Forms relatively gristy sloping ground in the mid part of the primary escarpment, which can slope either upwards towards or away from the escarpment. Base occurs at a weak negative break of slope, just below a strong positive break of slope.</td>
</tr>
<tr>
<td>Zig Zag Chalk</td>
<td>Soft to medium-hard, pale grey, blocky chalk with some thin resistant limestone beds near the base. Basal bed is either a fine-grained phosphatic calcarenite (Totternhoe Stone), or alite to calcarenitic chalk (the East End).</td>
<td>Rather sparse angular or blocky fragments of grey chalk.</td>
<td>Forms relatively steep ground low in the primary escarpment. Base at a negative break of slope.</td>
</tr>
<tr>
<td>West Meiddlebury</td>
<td>Numerous rhythmic alternations, each consisting of soft dolomite in grey clay-rich chalks (marls) passing up into grey clays and hard grey or brownish grey limestones. Glassy marine, clay-rich, locally sandy chalk at base (Glasstone Marl Member)</td>
<td>Rough, waxy limestone fragments locally voluminous; commonly fissured. Glassy and calcareous base found as brash in places, but is more common by hand auger samples.</td>
<td>Forms relatively gristy sloping ground in the lower part of the primary escarpment. Locally can form a subsidiary escarpment with a dip slope facing towards the primary escarpment. Base occurs at a weak negative break of slope.</td>
</tr>
</tbody>
</table>

* The term 'brash' is commonly used for rock fragments in the soil, especially those derived from local bedrock.
The “Typical Associated Topography” column in Table 2.1, making an association with cliff collapses and rock falls is significant. In next chapters, the link between the angle of the chalk slope and the type of collapse is will be highlighted.

At the beginning of the twenty century, Brydone (1912, 1914, 1915 and 1930) released a pioneer idea: can any correlation be made between flint bands, chalk units and marl seams? His studies suggested that the marl seams of the cliffs along the coastline from Newhaven to Brighton were probably related, being present even in Hampshire. Years later, in the 1980s, there was a resistance to correlating these three markers because it was claimed that it was impossible. However, many important contributions to the studies of the Chalk of Sussex, including Mortimore (1997), have confirmed the fact that its stratigraphy repeats frequently, making possible the identification of a considerable number of bio and lithostratigraphic boundary markers. Also, through them, many correlations can be demonstrated.

The sedimentation of the chalk is strongly controlled by structural features such as anticlines and, mainly, fractures. Consequently, the sedimentation has a rhythmic character, which is well represented by the West Melbury Marly Chalk (lower part of the Lower Chalk - old stratigraphy). But, papers published by Felder (1981), Ditchfield & Marshall (1989) and Gale (1989) about Campanian and Maastrichtian alternated white/bioclastic chalk layers and marly chalks respectively have provided evidence of climate changes. In another words, the alternations in lithology, revealed by the rhythmic sedimentation, were caused by the Milankovitch Cycles. How have they concluded this? Firstly, in 1981, Felder showed a correlation between the oscillation of macrofossil concentration and the cycles, so for each cycle there is a corresponding variation in macrofossil rates. Secondly, Ditchfield & Marshall (1989) developed a pioneer study on water using $\delta^{18}$O, a
palaeothermometer, to determinate the temperature of the water when calcium carbonate was precipitated (sedimentation stage) and also temperature variations during this stage of chalk’s formation. Thirdly, to locate the rhythms according to geological time, Gale (1989) used these data, which can be used as well to make long distance correlation. Later, in 2006, Kennedy & Gale included the concept of eccentricity to strengthen the explanation of lithological variation within the chalk. So, in general terms, the geological community accepts the Milankovitch Cycles and also eccentricity as being the dominant control factors on chalk’s lithological variation.

Many groups of fossils characterize the Chalk of Sussex and they provide useful information about chalk’s origin (deposition from plankton) and what happened in the Upper Cretaceous. Generally, different ranges of invertebrate fossils represent the fossil content in the chalk. They can be: ammonites, belemnites, bivalves, brachiopods, crinoids and echinoids (Mortimore, 2011). Together with flint bands and marl seams, all these fossils can be used as zonal indices. Taking as an example one of the formations that is exposed in the area of this work, the Newhaven Chalk contains a type of echinoid named *Echinocorys*, which is the most useful horizon marker of this formation. Considering abundance throughout the horizons of the chalk, the inoceramid group of fossil bivalves (Figure 2.4) is the most abundant. It is very common to observe this particular group and also fragments of its shells in the outcrops of the Chalk of Sussex. Again, this fossil species is essential for recognition or verification of formations and members of the Chalk of Sussex. Furthermore, in the absence of ammonites and belemnites, bivalves are required for international correlation.
The study of macro fossils has opened new doors for advances in biostratigraphy, making possible the development of micro and nannofossils identification. The first ones to add them to the modern Southern Province Chalk lithostratigraphy and macrofossil stratigraphy were Bailey et al. (1983, 1984) and Mortimore (1986a). Biostratigraphies are usually more reliable and accurate than a simple stratigraphy containing rock types. In the Chalk of Sussex, the collection and application of micro and nannofossils in its stratigraphy have confirmed the existence of lithomarker beds (marl seams and flint bands). The importance of this kind of study is huge even for areas, such as, geochemistry, engineering geology and hydrogeology. As a summary, macro, micro and nannofossils within the Chalk of Sussex provide confidence about:

1) Recording key boundary markers for bed correlations;
2) Geochemistry analysis that can be applied to understanding the Upper Cretaceous ocean-climate change system;
3) Tectonic mechanisms in sedimentation;
4) Relationship between orbital forces caused by the Milankovitch Cycles and alternation of sedimentation according to pre-existent climate; and
5) Defining sedimentation rates in a smaller scale of geological time, preferably, within tens of thousands of years.

II.2) Structural Geology and Fracture Patterns

The Chalk of Sussex is characterized by many fractures although its beds have different fracturing intensity. The basal part of the Holywell Nodular Chalk Member is an example of intensive fracturing. Seismic sections show how numerous they are, proving tectonic control on sedimentary hinge-lines. One of the special characteristics is the way they can be found in the chalk exposures: very well distributed. During the fieldwork for this dissertation, the use of scanline survey for structural data collection has shown how frequent they are in the outcrops, no matter the chalk formations. Figure 2.5 illustrates conjugate and syn-sedimentary fractures that are present in the Newhaven Chalk Formation, which is the predominant formation of the study area.
Figure 2.5: A) It shows the early syn-sedimentary fractures filled with sheet flints in the Newhaven Chalk Formation. Photo by R. N. Mortimore taken in one of the cliffs in Brighton, East Sussex. B) Steeply inclined conjugate fractures at Newhaven Cliffs (Newhaven Chalk Formation). They die out towards the base of the Culver Chalk Formation. Photo by R. N. Mortimore.


The distribution and types of fractures go across the Anglo-Paris Basin, so the fracture pattern in Southern England is the same on the other side of the English Channel. The same occurs at the London Basin and Northern Province Chalk.

The first years of the 21st century saw the attention of authors such as Duperret et al. (2004), Genter et al. (2004) and Mortimore & Duperret (2004) turn to investigations of cliff stability through the typical palaeostress that surrounds all chalk formations along the eastern part of the coast of Sussex. Using Scanline Survey, a structural data collection method, they measured the orientation of every discontinuity (bedding planes, flint bands, joints, marl seams etc) along the chalk cliff sections. Due to its efficiency and the proposed aims of this project, it was used as one of the methodologies. Since strike and dip fracture measurements and their frequency provide answers to find alternatives to mitigate any rock fall type, it is relevant to examine the content of Table 2.2.
Table 2.2: Dominant fracture types associated with the Chalk of Sussex stratigraphy.

<table>
<thead>
<tr>
<th>Type of Fracture</th>
<th>Occurrence in the Chalk of Sussex Lithostratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclined Conjugate Fractures</td>
<td>• Newhaven Chalk Formation</td>
</tr>
<tr>
<td></td>
<td>• Belle Tout Member (Seafor Chalk Formation)</td>
</tr>
<tr>
<td></td>
<td>• New Pit Chalk Member</td>
</tr>
<tr>
<td></td>
<td>• Holywell Nodular Chalk Member</td>
</tr>
<tr>
<td>Vertical Fractures</td>
<td>• Culver Formation</td>
</tr>
<tr>
<td></td>
<td>• Haven Brow Member (Seafor Chalk Formation)</td>
</tr>
<tr>
<td></td>
<td>• Cuckmure Member (Seafor Chalk Formation)</td>
</tr>
</tbody>
</table>

In terms of palaeostress (Figure 2.6), Vandycke (2002) states that the chalk formations of East Sussex have suffered an extensional regime characterized by periodic compressional occurrences. These compressional events are associated with Eocene-Oligocene inversions. The inversions are a combination of compressional and extensional forces with the following respectively orientations: N-S and E-W. As a consequence, hanging wall anticlines were generated in the Eocene and Oligocene and also rocks exhumed from large depths. Although studies carried out on the palaeostress of the chalk are complex, they are capable of claiming the origin of the tectonic regime, which is the North Atlantic opening. Because of the North Atlantic opening, the palaeostress (tectonics) is characterized by a WNW-ENE extensional faulting, which was interrupted by periodically regional N-S and E-W inversions (Butler, 1998; Butler & Pullan, 1990; Chadwick, 1993; Vandycke, 2002).

The extensional regime mentioned above can be chronologically divided into four main events, according to Vandycke (2002):
1) Synsedimentary subsidence in the early Cretaceous;

2) There are two main preferential direction of extensional stress, N-S and E-W. Both correspond to the direction of the opening of the North Sea and the English Channel;

3) A NE-SW younger fault system. This set of faults is extensive, abundant and active since the Late Cretaceous, so is considered the most important fault system. It is also related to contemporaneous crustal forces (neotectonics); and

4) The N-S strike-slip system in East Sussex explains the origin of the faults. They are, mainly, the result of the Tertiary (Eocene-Oligocene) inversion.
Figure 2.6: Diagram showing the preferential directions of the typical palaeostress of the Chalk of Sussex in association with the lithological formations. The numbers represent different tectonic events in Sussex and are reported from oldest to youngest formations. (III): The same event occurred in Normandy (France). It is characterized by NNE-SSW extension and ESE-WNW compression. (IV): N-S compressional and E-W extensional events. (V): E-W extension.

Source: Duperret et al., 2012. How plate tectonics is recorded in chalk deposits along the eastern English Channel in Normandy (France) and Sussex (UK). Tectonophysics, 581, 163-181.
Gathering together knowledge about the Chalk of Sussex lithostratigraphy, especially from the formations exposed in the study area of this dissertation, and integrating structural geology features into them, it was possible to date the palaeostress. The following table (Table 2.3) associates a palaeostress event to a chalk unit within the study area and its main structural feature. Most of the structures in the table are faults because they keep intact traces of tectonic events in the crust. So, this data has enabled investigations on the palaeostress of the Chalk of Sussex.

Table 2.3: How useful fault planes are for palaeostress studies. The “Chalk Formation/Location” column locates a tectonic event which occurred in the Chalk of Sussex within a formation.

<table>
<thead>
<tr>
<th>Chalk Formation/Location</th>
<th>Structural Feature</th>
<th>Palaeostress Event/Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campanian Chalk Units exposed at Newhaven</td>
<td>• Conjugate NNE-SSW and NNE-SSW normal faults; and • NNW-SSE strike-slip faults.</td>
<td>Phase III</td>
</tr>
<tr>
<td>Newhaven Chalk Formation (at Newhaven)</td>
<td>According to Mortimore (2011) and Mortimore et al. (2004b) the following type of joints represents a pyramidal shape of fractures of the Newhaven Chalk Formation: • Master-joints oriented NNE-SSW and NNW-SSE.</td>
<td>Phase III</td>
</tr>
<tr>
<td>Newhaven Chalk Formation</td>
<td>In this formation, which contains a large number of marl seams, occur: • Conjugate and slickenside normal faults; and • Strike-slip faults.</td>
<td>Phase IV</td>
</tr>
<tr>
<td>Peacehaven</td>
<td>Large proportion of: • Normal and strike-slip faults.</td>
<td>Phase V</td>
</tr>
</tbody>
</table>
The bedding planes are another type of structural feature. In the Chalk of Sussex, they are horizontal and usually very thin (decimeter scale). Therefore, the chalk bedding can be identified by: flint nodule bands, marl seams (because they present variations in the carbonate content - clay), intercalated chalks with different hardness, thin clay (marl) beds originally from volcanic or detrital clay source and lack of surfaces (beds) because of small gaps during sedimentation.

Due to the subject of this work, faults will be given limited attention. In order to make the closest relationship between them and the project aims some factors may be considered:

1) During field work stage for this dissertation, faults were observed and pointed out. Even though they are not the main focus, it is relevant to say that the offsets caused by them are recorded as striation, slickensides and vertical displacements of flint bands. Below is Figure 2.7, taken in Newhaven (Sussex, UK), which illustrates a shear movement in the White Chalk (Turonian to Campanian). The displacement is evident because the marl layer is offset by a pair of normal faults filled with flint (unfortunately, the flint is not visible on the photo); and

2) Normal and conjugate strike-slip faults are the clearest evidence to support the palaeostress that has been acting on the Sussex coastline since the Upper Cretaceous. Beyond that, the current fault system of the Chalk of Sussex preserves very well the necessary evidence that tell the history of the tectonic evolution of the Northwest of Europe.
Figure 2.7: Conjugate normal faults in White Chalk units located in Newhaven, Sussex.


Taking the same reasoning given in relation to faults, the space devoted to folds will be limited. The chalk cliffs of the Sussex coastline are at the boundary of the Anglo-Paris Basin. The border of the basin concentrates a large number of en échelon folds. Furthermore, a set of meso-scale faults is contemporary with this folding system (Duperret et al., 2012). In addition, there is a very detailed article in the literature on megascopic structures as a result of ductile deformation of the Chalk of Sussex. This work was published in 1951 by Christopher Gaster. He identified the following sets of anticlines and synclines:

1) Henfield Syncline;
2) Pyecombe Anticline;
3) The Syncline of Mount Caburn;
4) The Anticline of Kingston (near Lewes);
5) Hollingbury Anticline;
6) Glynde Syncline;  
7) The Beddingham Anticline;  
8) Friar’s Bay (Peacehaven) Anticline;  
9) The Telscombe Syncline;  
10) Castle Hill Syncline and Seaford Syncline; and  
11) The Seaford Head Anticline.

Mortimore, one of the main specialists in the Chalk of Sussex, has been studying the East Sussex coastline since the 1970s. After publications in 1993 and 2001a, he disclosed a series of fracture data, mainly, from the coastal cliffs of the Newhaven Chalk Formation. In conclusion, he demonstrated that each area along the East Sussex coastline presents a unique fracture trend as shown below:

1) Large amounts of wispy and grey marl seams characterize the Newhaven Chalk Formation. Even if the concentration of marl seams is small or absent, conjugate sets of fractures are still a remarkable structural feature of this chalk unit. Besides that, sheet flint filling inclined conjugate pairs of fractures and main fracture set parallel to the bedding complement the characteristics of the Newhaven Chalk Formation fracture type;

2) Contrasting with the Newhaven Chalk Formation is an example from the Seaford Chalk Formation in which marl layers can be in particular units (e.g. Belle Tout Beds) or even absent. But, regarding the dominant fracture pattern in this
formation, it was established as being conjugate fractures filled with flint and also slickenside fractures; and

3) Exposed marls at Brighton Cliffs (Newhaven Chalk), from Saltdean to Rottingdean, contain impressive sheet flints filling fractures. Generally, they are on slightly displaced fractures (Figure 2.8), so it is possible to assert that flints are good markers of seismic disturbance as well as marl seams with flaser texture. This texture is the consequence of shearing stresses.

![Sheet flint replacing fracture walls](image)

Figure 2.8: Sheet flints filling fractures at Brighton Cliffs. Photo by R. N. Mortimore.


Mortimore (1993, 2001a) observing and illustrating (Figure 2.8) the fractures' walls being replaced by sheet flints, especially in the Newhaven Chalk Formation, Clayton (1986) described this fill as a chemical process.
II.3) Engineering Geology and Hydrogeology

In Southern England, chalk is exposed in different ways, but, in most of cases, occurs in cliffs and scarplands. Not surprisingly, it defines the landscape of the country. The geomorphological landscape formed by cliffs and scarplands is proof of the chalk’s durability. Is it stable enough even against future predictions about increase of sea level and rainfall rates? Engineering geology does its best to answer this and other questions on geohazards: is it possible to predict collapses, falls and landslides? And what about the retreat rate of the cliffs?

Due to physical properties, chalk represents the UK’s most important aquifer. Its water supplies both the public and private sectors. In order to preserve groundwater resources against any threats, the Environment Agency (1998) developed protection policies to secure both the quality and quantity of chalk aquifers’ groundwater.

For the engineering, as stated by Lord et al. (1994), chalk is an ultra-fine grained limestone and, depending on its composition, the content of carbonate can vary, leading to differences between pure and impure chalks (showing lower carbonate content, but higher magnesium concentration).

Chalk coastal cliffs in Brighton and adjacent areas (study area of this research) are continually subject to changes in stress because of internal and external factors. This has led to investigations on geological properties, features and materials (e.g. soils beneath, above and others that fill chalk valleys). Together, these factors constitute an active part of cliffs’ instability regime. Types, volumes and mechanisms of collapse have been investigated by workers such as Lamont-Black (1995), Lawrence (2007) and Mortimore et al. (2004a). Furthermore, all of them
agree that the probability of collapses depends on: chalk formation, rock mass properties, cliff face orientation and cliff height. So this information has been used to evaluate hazards in order to look for the most suitable mitigation plan. Yet Lawrence (2007) studied the fracture patterns in the Chalk of Sussex and concluded that it is one more important controlling factor for its instability (Table 2.4 and Figure 2.9).

<table>
<thead>
<tr>
<th>Chalk Formation</th>
<th>Fracturing</th>
<th>Type of Cliff Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newhaven</td>
<td>Steeply inclined with weathered surfaces.</td>
<td>Peacehaven</td>
</tr>
<tr>
<td>Lower Newhaven</td>
<td>Blocky and irregular.</td>
<td>Joss Bay</td>
</tr>
<tr>
<td>Upper Seaford</td>
<td>Smooth and planar.</td>
<td>Joss Bay</td>
</tr>
<tr>
<td>Seaford</td>
<td>Regular pattern with sub-vertical and orthogonal fractures.</td>
<td>Seven Sisters</td>
</tr>
<tr>
<td>Lewes Nodular</td>
<td>Very steep, resulting in large collapses.</td>
<td>Peacehaven</td>
</tr>
<tr>
<td>New Pit</td>
<td>Steeply inclined with conjugate fractures (some with evidence of slickenside faults).</td>
<td>Peacehaven</td>
</tr>
<tr>
<td>Holywell Nodular</td>
<td>Steeply dipping and closely spaced fractures. Evidence of slickenside in some conjugate fractures.</td>
<td>Peacehaven</td>
</tr>
</tbody>
</table>
Another issue that arouses engineering interest is cliff retreat. During the last 130 years, cliff retreat has been recorded along 22 km of the East Sussex chalk coastline, revealing an average retreat rate of 0.35 m y\(^{-1}\) (Dornbusch et al., 2008). Unfortunately, the cliffs are mostly in an urban area and near roads, so many scientists aim to study the cliff retreat rates to develop a prognosis (how long a time...
will be necessary for the cliffs to reach urban areas and affect people’s lives? Is there any remediation that can be done to postpone this process?).

Finally, the hydrogeology of the Chalk of Sussex. Features known as dissolution pipes are very common in this rock type. They are the most frequently occurring natural dissolution features in chalk and they are responsible for enhancing storage and transmission of groundwater. Edmonds (2008) showed the importance of mapping karstic structures to help manage chalk aquifers through tools, such as, aquifer vulnerability maps. Within the study area of this dissertation, the town of Newhaven has some outcrops (Newhaven Chalk Formation) where dissolution pipes constitute a large network of caves.
Chapter III will provide a brief description of the location where this work took place. As previous chapters mentioned, the coastline between Brighton and Newhaven, passing through Peacehaven, was chosen to be studied (Figures 3.1 and 3.2). Along this section, there are 11 kilometers of cliff exposures and wave-cut platform. In terms of geology, they belong to the Newhaven Chalk and Culver Chalk Formations (both White Chalk Group) and, chronologically, go from Upper Santonian to Lower Campanian. Also, on top of the outcrops, especially in Brighton (Marina) and Newhaven (Castle Hill), there are Palaeogene sediments of considerable thickness, enabling easy identification. Evidence for fracturing distribution and how it behaves can be found along this coastal section as well.

Figure 3.1: Geological section of the Brighton to Newhaven cliffs showing formations and beds of the Chalk of Sussex that correspond to this coastline section. Red circles represent the studied sites. Source: British Upper Cretaceous Stratigraphy, Geological Conservation Review, Volume 23, Chapter 3.
The Cretaceous chalk is the striking geology of the region. It composes the landscape characterized by the North and South Downs (Wooldridge & Goldring, 1953), which are the most distinct geomorphological features in the county of Sussex (Southeast England, UK). Furthermore, both the geomorphology and topography of the study area are controlled mainly by the Friar’s Bay Anticline, with natural headlands on its axes, and the Newhaven Syncline, which axes of which is occupied by the River Ouse (Mortimore, 2011; Mortimore & Pomerol, 1991). Due to the formation of river valleys, the chalk erosion is high and brings concern about rock failures in Newhaven (Castle Hill). There, the overlying sediments (London Clay and the Lambeth Group composed of sandstone) absorb rainwater, increasing its density. At some points, the chalk strength is not be able to hold up the rock mass hence failures constantly occur in this location (Figure 3.3).

Usually rivers are seated on fault planes and this is not different in this study area. Mortimore et al. (2004b) suspect that the River Ouse, the main drainage, follows a strike-slip fault in a N150E direction. So, the faulting pattern in Newhaven shapes the geomorphology of its valleys and builds a drainage network. Moreover, this set of faults has segregated chalk fragments in Brighton and Seaford. In addition, there are more aspects that contribute to the typical morphology and topography of the study area, for example:

1) Different topographical level of formations and members of the Chalk of Sussex;

2) Erosion/weathering;

3) Effects of Quaternary processes (deposits covering the top of outcrops); and

4) Attitude of faults.
Despite its extent, the investigation site is continuous and accessible, being helpful for field work and data collection. However, care in checking tide times is essential. The tides do not hinder the work at Brighton, Peacehaven cliffs and steps and Newhaven, but, if the area of Friar’s Bay (Peacehaven) is the site of study, it is highly recommended that one is aware of tide times and work there during periods of low tide.

In summary, Gaster (1951) would conclude that geomorphological and topographical characteristics are strongly controlled by faults systems. It will be its strike and dip measurements that are responsible for giving variations in the topography, which will determine morphological features. Finally, it is important to highlight chalk’s porosity as one more factor that contributes to the geomorphology of the study area. Thanks to its great porosity, rainwater drains down rapidly and it is stored, setting the Chalk of Sussex as the principal aquifer in the UK (Figure 3.4). But, on the other hand, water starts to dissolve the calcium carbonate present within the chalk. Besides increasing the chance of collapses, dissolution features develop. The most frequently features recorded in chalk are caves and dissolution pipes. So, that is the reason for dry and dissected landscapes between Brighton and Newhaven.
Figure 3.2: Regional and detailed location maps of the study area (Brighton to Newhaven coastline, East Sussex, England, UK). The three red stars indicate the sites of investigation and data collection.

Figure 3.3: Map showing the study area with simplified geology (Cenozoic and Quaternary deposits not included). It also includes the main structures responsible for shaping the topography at this area: the Friar’s Bay Anticline and the Newhaven Syncline. The white line is the drainage (River Ouse).

Source: Duperret et al., 2012. How plate tectonics is recorded in chalk deposits along the eastern English Channel in Normandy (France) and Sussex (UK). Tectonophysics, 581, 163-181.
Figure 3.4: UK’s Hydrogeology Map. The red star highlights the county of Sussex where this study was based and the importance of chalk as an aquifer for water supply.


Below, there is a selection of photographs taken during field work that illustrate some key features of the study location.
Figure 3.A: Typical marl seam, Peacehaven Steps.

Figure 3.B: Fracture filled with flint, Brighton Marina.

Figure 3.C: Platyceramus (inoceramid bivalve), Peacehaven Steps.

Figure 3.D: Conjugate fractures in Chalk, Brighton Marina.

Figure 3.E: Brighton Marina.

Figure 3.F: Newhaven (Castle Hill).
CHAPTER IV

METHODS

In order to attempt to find the fracture characteristics of the study area and relate it to engineering geology and hydrogeology subjects various methods have been used. They are described below.

IV.1) Field Work
This Final Year Geology Project started with field work at the study area. Walking around the coastal sections between Brighton and Newhaven, observations notes were recorded in a field notebook. The most important annotated information comprises outcrop descriptions, which may include the main characteristics of the rock such as colour, grain size, roundness, identification of the chalk formation if it is possible, weathering grade, etc. Also, sketches were drawn and photographs taken in order to complement the field notes. A few sedimentary logs using key litho and biostratigraphical marker horizons at determined localities were required to increase the quality of detail of the notes and to check the stratigraphy. In terms of data collection, rock mass data through scanline surveys were done.

IV.1.1) Scanline Fracture Surveys
It demands a 30 meters tape along the outcrop, however in Peacehaven Steps (Friar’s Bay) it was not possible to straighten out the tape to 30 meters because of the steps. So, there, the scanline had to be done step by step and because of that it
reached more than 30 meters. On the other hand, at Peacehaven, at the end of the coastal defenses, the scanlines were done during low tide. First, this method aims to measure the orientation of every discontinuity (for example, bedding planes, faults, fractures, joints and marl seams) along 30 meters of chalk sections. But, due to the subject of this project, only main and minor fractures set on the cliff faces have been recorded. Secondly, any relevant detail of the fractures has to be annotated and, if marl seams are present, they must be included as well. During the scanlines characteristics as apperture, fill of fracture veins (fractured chalk and flint are the dominating type of fill) and persistence were all noted. Also, comments about distinguishing features have been written to improve the quality of collected data.

IV.2) Desktop Work
At this stage all information from the Scanline Fracture Surveys was analysed using a computer program named DIPS. Version 6.0 of DIPS was used, in which all fracture measurements were plotted for the interactive analysis and visualization of its orientation. Furthermore, no distinction was made between main and minor fractures, so they were plotted together into stereographical projections (Schmidt plot in Lower Hemisphere). Regarding the nomenclature of the fracture measurements, it is important to mention which one was used. Although the DIP DIRECTION is the most common way to represent the attitude of any geological feature, all measurements for this work have been taken recording firstly the STRIKE and secondly the DIP (STRIKE/DIP) with the right hand measuring technique.
IV.3) Laboratory Work

The laboratory work was developed on the chalk formations that comprise the study area. But, before that, samples of Newhaven Chalk and Culver Chalk Formations were collected during field work in order to analyse them for elemental and mineralogical composition. In total, three samples were collected and analysed using Innov-X 6500 Portable X-Ray Fluorescence (PXRF) and X-Ray Powder Diffraction (XRD). The first technique tests the chemical composition of the sample/material in parts per million (ppm). Also, the PXRF provides measurements around twenty elements in small samples whereas the XRD is an analytical technique which identifies mineral(s), in another words, it provides the mineralogical composition of what is being analysed (clay in this case). It is worth emphasizing that each sample was collected at different localities of the study area. The sample collection work aimed at acquiring samples from the marl seams, but, unfortunately, in Newhaven (Castle Hill) marl seams were not identified, at least along the studied sections, so, there, one sample was collected in clay rich portions of the very weathered chalk. Finally, the last two samples came from different marl seams: one of them was collected at Brighton Marina and the other one at Peacehaven Steps (Friar’s Bay).
CHAPTER V

RESULTS

This chapter will present all the data obtained during the development of this dissertation. The results come primarily from data collected in the field, which, after application of the methods described in Chapter IV, could be processed and then be discussed and interpreted. Furthermore, the results lead to a conclusion based on answering the research questions (Chapter I).

First it will be presented the analysis of structural data through DIPS and, next, the mineralogical (XRD) and geochemical (PXRF) compositions of three collected samples from marl seams except the one collected in Newhaven (it is likely to be the London Clay).

V.1) Structural Data using DIPS

The data have been processed in two ways: stereograms and rose diagrams. Both contain the fracture orientation measurements of the three areas, which are Brighton (Marina), Friar’s Bay in Peacehaven and Castle Hill (Newhaven).
V.1.1) Stereogram of Fracture Orientation Measurement in Brighton

V.1.2) Stereogram of Fracture Orientation Measurement in Peacehaven
V.1.3) Stereogram of Fracture Orientation Measurement in Newhaven

V.1.4) Stereogram of Fracture Orientation Measurement in the Study Area
V.1.5) Rose Diagram of Fracture Azimuth in Brighton

V.1.6) Rose Diagram of Fracture Azimuth in Peacehaven
V.1.7) Rose Diagram of Fracture Azimuth in Newhaven

V.1.8) Rose Diagram of Fracture Azimuth, all measurements in the Study Area
V.1.9) Stereogram of Marl Seam Orientation, all measurements in the Study Area

V.2) Mineralogical Compositions of the Three Collected Samples using XRD

The highest peaks in the following graphics correspond to calcite and the rest to other minerals. The equipment is able to distinguish each one of them and produces a list named Peak List, which contains the position (in °2Th), height of each peak and other characteristics. The database of the XRD identifies the peaks and associates them to a mineral. Each peak has its own Reference Code, so, for each reference code, there is a compound with a chemical formula. Also, the XRD provides the minerals semi-quantity within the samples as a percentage. All this information is given in the Pattern List and it is in the Appendices of this work as well as the Peak List (both are part of a report). Moreover, the output data is generated through graphics that show Intensity x 2Theta (°).
V.2.1) Graphic Corresponding to Marl Seam in Brighton

V.2.2) Graphic Corresponding to Marl Seam in Peacehaven
V.3) Geochemical Compositions of the Three Collected Samples using PXRF

The Table 5.1 below was generated after the analysis of the Chalk of Sussex samples using the PXRF and is the output format to process the data. All elements shown on the table correspond to the geochemical composition of the three listed samples collected in Brighton Marina, Peacehaven Steps and Newhaven and they are in order of increasing atomic number from left to right. Regarding the red and black colours, it is important to explain that numbers in red colour indicate values below the detection limit, which is three times the +/− value (other spreadsheet located in the Appendices), so they are unreliable. However, black-coloured numbers are reliable. Also, the abbreviation “nd” means NOT DETECTED. It is worthwhile to remember that the elements’ concentrations are in parts per million (ppm).
Table 5.1: Geochemical composition of marly samples measured using a PXRF.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Brighton Marina Marly Chalk</th>
<th>Peacehaven Steps (Friar’s Bay) Marly Chalk</th>
<th>Newhaven Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>513</td>
<td>14135</td>
<td>32166</td>
</tr>
<tr>
<td>K</td>
<td>3155</td>
<td>1955</td>
<td>4407</td>
</tr>
<tr>
<td>Ca</td>
<td>399223</td>
<td>459160</td>
<td>300255</td>
</tr>
<tr>
<td>Ti</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Cr</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Mn</td>
<td>88</td>
<td>105</td>
<td>162</td>
</tr>
<tr>
<td>Fe</td>
<td>2274</td>
<td>934</td>
<td>7958</td>
</tr>
<tr>
<td>Co</td>
<td>25</td>
<td>nd</td>
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</tr>
<tr>
<td>Ni</td>
<td>5</td>
<td>26</td>
<td>3</td>
</tr>
<tr>
<td>Cu</td>
<td>nd</td>
<td>nd</td>
<td>4</td>
</tr>
<tr>
<td>Zn</td>
<td>87</td>
<td>65</td>
<td>74</td>
</tr>
<tr>
<td>As</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Rb</td>
<td>10</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Sr</td>
<td>519</td>
<td>602</td>
<td>458</td>
</tr>
<tr>
<td>Zr</td>
<td>27</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>Mo</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Ba</td>
<td>20</td>
<td>nd</td>
<td>56</td>
</tr>
<tr>
<td>Pb</td>
<td>10</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>
CHAPTER VI

DISCUSSION

As the literature mentions, especially through Mortimore (1978, 1993 and 2001a), fracturing is one of the most remarkable structural characteristic of the Chalk of Sussex and it is not randomly distributed along the coastal cliffs between Brighton and Newhaven. In fact, in this coastal section, inclined conjugate fractures are strongly striking in the Newhaven Chalk Formation, which is the predominant formation. Although, there is also the Culver Chalk Formation, with a lack of marl seams and a general absence of conjugate joint sets at its base. However, the scanline surveys did not make a distinction between the types of fracture (whether they are fractures, joints or master joints). They were recorded as fractures every time they showed up on the line of the 30 meters tape along the outcrops.

The results of the applied methodology using DIPS are consistent with and coherent to other studies. All fracture orientations were plotted in lower hemisphere equal-area stereograms and each point represents a fracture plane. The fracture orientation of the study area indicates a common fracture trend, but, depending on the number of measures and on the area, the concentration of fracture sets could be less or more intense in a particular direction/orientation. So, according to the fracturing data processed in the DIPS software, all three areas (Brighton Marina, Peacehaven Steps and Newhaven Castle Hill), where fracture attitude have been measured, show a common pattern: NE direction. In another words, the fractures along the coast between Brighton and Newhaven are concentrated in the NE
quadrant of the stereograms. Although the main fracture orientation is NE, in
Brighton and Peacehaven the most dense concentrations of fractures are NNE (see
Chapter V). Furthermore, it is possible to infer that the most significant set follows
the N154E trend (Table 6.1).

Table 6.1: Averages of STRIKE/DIP fracture measurements taken at the investigation sites of this study.
The Total Average considers all sites and was calculated as follows: Average_Strike: 164° + 149,2° +
149,5° = 154° and Average_Dip: 67,5° + 52,4° + 68,5 = 63°.

<table>
<thead>
<tr>
<th></th>
<th>Brighton (Marina)</th>
<th>Peacehaven (Friar’s Bay)</th>
<th>Newhaven (Castle Hill)</th>
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<tbody>
<tr>
<td>Averages:</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>• Strike -&gt; 164°</td>
<td>• Strike -&gt; 149,2°</td>
<td>• Strike -&gt; 149,5°</td>
<td></td>
</tr>
<tr>
<td>• Dip -&gt; 67,5°</td>
<td>• Dip -&gt; 52,4°</td>
<td>• Dip -&gt; 68,5°</td>
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<tr>
<td>Total Average:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Strike -&gt; 154°</td>
<td>• Strike -&gt; 154°</td>
<td>• Strike -&gt; 154°</td>
<td></td>
</tr>
<tr>
<td>• Dip -&gt; 63°</td>
<td>• Dip -&gt; 63°</td>
<td>• Dip -&gt; 63°</td>
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</table>

Mortimore et al. (2004b) summarizes that the coastal chalk cliffs from Brighton
to Newhaven have a general fracture direction, but can be variable from one area to
another because of some aspects such as the number of fractures and
concentration of a determined style of fractures. The data results of this work confirm
this, however, in Peacehaven the dip average does not correspond to other studies.
For example, Mortimore et al. (2001) states that the fracture dip is usually between
60° and 70°, which characterizes fractures being steeply inclined. It is relevant to
emphasize the fact that this dip average is valid for sets of conjugate fractures as
well. But, looking back to Table 1, the dip average in Peacehaven does not reach
even 60°. Locally, the fracture pattern in Peacehaven is slightly different: fractures are more likely to be horizontal than in Brighton Marina and Newhaven (Castle Hill) and, consequently, they are not very steep. Yet, if the Total Average is considered, the dip in Peacehaven crosses over the 60° and remains in the interval between 60° and 70° as shown in the article by Mortimore et al. (2001).

Another important characteristic of the fractures in the study area is the fill. Commonly, they are filled by flint (Figures 6.1, 6.2 and 6.3) and, sometimes, by chalk, which is found fractured (Figure 6.4). Also, during field work, it was found that some fractures contained iron oxide and fossils (mainly sponges and bivalves). Furthermore, conjugate fractures are frequently seen filled by fractured chalk (Figure 6.4) or by flints (Figure 6.5) along their length and the subhorizontal bedding planes are parallel to the fractures (Figure 6.6).

Figure 6.1: The geological hammer points to a small fracture in the Newhaven Chalk Formation, possibly a syn-sedimentary fracture, which is filled by flint. Photo taken at Castle Hill outcrops (Newhaven).
Figure 6.2: Sheet flint in steeply inclined fracture in the Newhaven Chalk Formation. Photo taken at Peacehaven Steps (Friar’s Bay).

Figure 6.3: Fracture filled with flint in the Newhaven Chalk Formation. Thickness of the fracture: 2,3 cm. Length of the fracture: > 1,5 m. Strike/Dip = 278°/14°. Photo taken at Brighton Marina.
LEFT: Figure 6.4: Conjugate fractures filled with fractured Newhaven Chalk. Photo taken at Peacehaven Steps (Friar’s Bay). RIGHT: Figure 6.5: Conjugate fractures filled with flint in the Newhaven Chalk Formation. Thickness of both: from 1.0 to 2.0 cm. Length of both: 4.0 m and 2.5 - 3.0 m the other one. Photo taken at Brighton Marina.

Figure 6.6: Subhorizontal bedding parallel to sheet flint in the Newhaven Chalk Formation. Photo taken at Peacehaven Steps (Friar’s Bay).
The frequency of fractures in the outcrops of Castle Hill, in Newhaven, is lower than in Brighton and Peacehaven. There, the fracturing is not very intense, in contrast to the situation in Brighton and Peacehaven. In Castle Hill, fractures are not completely absent, but their number is considerably lower compared to the other two investigation sites and because of that it is more difficult to find fractures filled with flints or any other type of fill. This may be clearly seen in the stereograms in Chapter V. At Newhaven (Castle Hill), 85 attitudes of fractures were measured while 271 and 356, respectively, were measured at Brighton (Marina) and Peacehaven (Friar’s Bay). Therefore, at Castle Hill, the Newhaven Chalk Formation is less fractured and marl seams are not strongly developed. However, two features of its outcrops should be noted: regular flint bands and Palaeogene sediments overlaying unconformably the Culver Chalk Formation (Lower Campanian).

In order to make a link between fracture pattern and civil engineering aspects, the information provided in the previous paragraph suggests that the investigation sites are likely to have different classifications/types of cliff collapses. Although in all of them the probability of failure exists, in Newhaven, the triggering factor is not the fracturing, but the stress caused by the weight of the Palaeogene unconformity and overlying sediments (clay and sand) on the top of the Newhaven Chalk Formation.

In the software DIPS, the data from the Scanline Fracture Surveys have been processed and the results are presented as stereograms and rose diagrams. As the stereograms report fracture measurements, the rose diagrams for each locality contain the same number of them and is another way to reinforce the statement of Duperret et al. (2012). These authors concluded that the coastline of East Sussex has WNW-ESE orientation, so, consequently, it matches with the fracturing direction of the region, including the plunge of folds, in which chalk units are folded. However,
for this work, ductile features have not been recorded even though their study would add more knowledge to achieve a better understanding of structural geology, palaeostress, tectonic reactivation and chalk cliff instability in the study area.

Moreover, since the Sussex coast is on the border of the Anglo-Paris Basin, it is reasonable to explore the folding in depth because this coastline is characterized by *en échelon folds*. Also, this complex system of folds contributed to reactivating meso-scale fractures during extensional and compressional events occurring in the Oligocene and Miocene (see Chapter II, Figure 2.6). But, the area of this project only contains evidence of Phases IV and V. Phase IV gathers a set of compressional (N-S direction) and extensional (E-W direction) forces relative to the Pyrenean tectonics during the Oligocene while Phase V corresponds to the E-W extension due to the opening of the north of the North Sea in the Middle Miocene. Also, both phases affected the Newhaven Chalk and Culver Chalk Formations (Brighton, Peacehaven and Newhaven localities).

So, returning to rose diagrams (Chapter V), it is possible to establish that the fractures are organized in two sets:

1) A dominating fracture system orientated NW-SE; and

2) A secondary fracture system orientated E-W.

Fractures with NW-SE orientation are present in all the three of the studied locations: Brighton (Marina), Peacehaven (Friar’s Bay) and Newhaven (Castle Hill), making this set the main fracture system of the study area. But, their concentration is higher and clearer in Castle Hill and, especially, in Brighton Marina. In the other hand, there is the subordinate or secondary fracture set with an E-W orientation, which affects
the area of Friar’s Bay in Peacehaven, including the steps. There, the fracture pattern is not very uniform as in Brighton (Marina) because there are fractures orientated in the following quadrants: NE-SW, E-W and NW-SE. However, most of the fractures follow the E-W direction, so it is considered the characteristic fracture pattern of Peacehaven. In order to illustrate what has been said previously, Figure 6.7 shows the fracturing behaviour of the study area in the format of a rose diagram, containing fracture azimuths collected in the chalk (mainly in the Newhaven Chalk Formation). This rose diagram reports, in total, 712 fractures from the investigation sites and it is the same as the one presented in Chapter V, whereas Table 6.2 gathers the numbers of fracture measurements that have been taken in each location.

![Figure 6.7: Rose Diagram of Fracture Azimuth in the Study Area.](image)
Table 6.2: Number of fracture measurements of each investigation site. They came from the Scanline Fracture Surveys.

<table>
<thead>
<tr>
<th>Brighton (Marina)</th>
<th>Peacehaven (Friar’s Bay)</th>
<th>Newhaven (Castle Hill)</th>
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<tbody>
<tr>
<td>• 271 fracture measurements taken.</td>
<td>• 356 fracture measurements taken.</td>
<td>• 85 fracture measurements taken.</td>
</tr>
</tbody>
</table>

In addition to fractures, marl seams’ orientation have been recorded in the field and also processed in the software DIPS. It generated only one stereogram that shows the preferential direction of the marl seams: NNE. But, the number of measurements is low and not enough to provide a realistic orientation scenario of the marl seams. Although they do not express the true pattern in which marl seams are orientated, the layers of marl can be studied to look for mechanical properties of the chalk. This subject will be discussed later because it depends on the results from the analysis of the marl seam samples. Next, it will be discussed the implications of the fracture patterns for the engineering geology and hydrogeology of the Chalk of Sussex.

In Brighton and in Peacehaven, the inclined conjugate joint sets are a remarkably brittle feature in the Newhaven Chalk Formation. Sometimes sheet flints are present along these fractures and are considered one of the more predisposing factors of cliff failure. The flint can be a bedding layer or filling a fracture, but still can influence/control the modes of failure. Also, it varies and its measurement requires care (usually this is done through point load or uniaxial compressive strength testing). Depending on the chemical state of the silica (if the flint is formed by opaline silica, quartz or chalcedony), its chemical properties and porosity will be different and
might or might not contribute to cliff failures. Testing flint strength would give more accuracy to the results of this project, but it has not been done. So, the high dip angle of fractures (67,5° in Brighton and 52,4° in Peacehaven) in association with flint bands or fractures filled with flint may potentiate the occurrence of collapses. On the other hand, there is the case in Newhaven. When the fracture data was processed, the programme DIPS revealed that Peacehaven has the highest dipping conjugate fractures within the study area. The dip of 68,5° characterizes a steeply inclined fracturing style and can be considered the same as at Brighton and Peacehaven. However, the differentiating aspect is the presence of sands and clays that constitute the Palaeogene layer on the top of the outcrops. In terms of rock mass, the sands are usually medium dense and the clays are weak. Together with vertical joints and pipes in the Culver Chalk Formation and conjugate fractures in the Newhaven Chalk, these sediments increase the chance of chalk blocks falling down the cliff in Newhaven.

According to Genter et al. (2004), a minimum of ten collapses occurred along the English coastline in the period between 1998 and 2001, including one episode at Brighton Marina, behind the ASDA Supermarket. Because of this kind of incident concerns about instability of coastal cliffs and how to manage them is calling the attention of many government agencies and local authorities. So, the physical properties (porosity, density and friction), style of fractures (angle of dip) and lithology (Table 6.3) in association with weathering and the fact that the chalk is the most frost-susceptible rock, make geologists and civil engineers intervene in order to avoid collapses and, consequently, minimize risks to people and material losses (Figures 6.8 and 6.9). Also, public signs warn the population about the danger of falling rocks (Figure 6.10) along the coast from Brighton to Newhaven.
Table 6.3: Relationship between features mapped on the coast from Eastbourne to Brighton and geohazards that may be caused by them. This coastal section contains the study area of this work.


<table>
<thead>
<tr>
<th>Lithostratigraphic units</th>
<th>Structure/geomorphology</th>
<th>Geohazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>based primarily on Juignet, 1974; Mortimore 1983, 1986; Mortimore &amp; Pomerol, 1987, 1988; 1996; Bristow et al. 1997; Mortimore et al. 2001b</td>
<td>1. Style of fracturing in each unit of the Chalk</td>
<td>Hazards related to the cliff top (includes variable deposits on the cliff top of Tertiary and Quaternary sediments and Sarsen stones and karst or calcite).</td>
</tr>
<tr>
<td>Biostratigraphic marker beds, zones and stages as applied to the Chalk (Birkelund et al., 1984; Mortimore, 1986; Mortimore &amp; Pomerol, 1987; Rawson et al., 1996; Mortimore et al. 2001b)</td>
<td>2. Faults and fault zones</td>
<td>Hazards related to the cliff face primarily controlled by rock structure and lithology with consequent control on karst development.</td>
</tr>
<tr>
<td></td>
<td>3. Cliff top profiles;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Extent of dissolution and karst development</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Valley profiles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Groundwater as springs in the beach platform and as emanations from the cliffs.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Hazards related to processes at the base of the cliff including marine erosion and undercutting related to styles of fracturing leading to different forms and sizes of cave.</td>
</tr>
</tbody>
</table>

Figure 6.8: Steel mesh on the chalk against rock falls - Civil Engineering Intervention at the Brighton Marina.
The characteristic fracturing of the study area is not variable from one location to another because the predominant lithology (chalk) and formation (Newhaven) remains the same. The fracture dips average of the three investigation sites is 63°, which belongs to the interval between 50° and 78° presented in the literature (Lamont-Black, 1995; Lawrence, 2007; Mortimore & Duperret, 2004; Mortimore et al., 2004).
Furthermore, it is possible to explain how the fractures reflect the geomorphological setting of the chalk through folding. So, the coastline between Brighton and Newhaven is unusual due to anticlines and synclines. These folds can reactivate fractures and usually their dips coincide with the bedding (marl seams) dips. Also, the steeply inclined angle of fractures (63°) in the study area makes them vertical and high. Normally, they are vertical cliffs 20 to 200 meters high and the fractures are parallel to the cliff face. Sunamura (1977, 1992) and Robinson (1977) defined the chalk cliff geomorphology as being a type of foreshore (wave cut platform). The angle of fractures shapes the cliffs and it is the main controlling factor for their collapse. In this case, the study area is affected by the Peacehaven Type of Cliff Collapse (Figure 6.11), as named by Mortimore et al. (2004b), which is characterized by large plane and wedge failures due to progressive block failures on steeply inclined (63°) conjugate sets of fractures. This type of cliff collapse can occur on protected and unprotected coastlines within the study area, especially in Brighton and Friar’s Bay (Peacehaven). Although it fits in Newhaven as well, there, in Castle Hill, the Palaeogene sandstones and mudstones bring concern about an extra hazard: landslides. So, not only failures, but also mudslides containing the London Clay and the toppling of sandstone (Lambeth Group) from top of the outcrops characterize this geohazard.
Figure 6.11: Simplified sketch showing, in red circles, the Peacehaven Type of Cliff Collapse Model. It affects the Newhaven Chalk Formation and it was built according to the chalk lithology and its own fracture pattern.

Regarding the hazards brought by cliff collapses, within the study area, they normally are:

<table>
<thead>
<tr>
<th>Brighton (Marina)</th>
<th>Peacehaven (Friar’s Bay)</th>
<th>Newhaven (Castle Hill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope failures in dry valley-fills and spalling of chalk and flint due to the weathered state of the chalk.</td>
<td>Plane and wedge collapses caused by a complex system of conjugate fracture sets (could involve the entire cliff or part of it) and spalling of chalk and flint due to the weathered state of the chalk.</td>
<td>Slides containing mud and sand from cliff top, plane failures due to karst features (caves) and spalling of chalk and flint due to the weathered state of the chalk.</td>
</tr>
</tbody>
</table>
Finally, the hydrogeology of the chalk consists of an aquifer and it has a karstic nature, which controls the flow of groundwater. At Castle Hill, there are caves (Figure 6.12) formed by the dissolution of the calcium carbonate found within it. Furthermore, these caves store and transmit groundwater. Unfortunately, its consumption is not suitable for people because it contains the London Clay. Thanks to PXRF analysis of a sample from Newhaven, it was possible to confirm that the collected material is not the Newhaven Chalk, but the London Clay. The results of this analysis showed concentrations of 3.2% of sulfur (S) and 7958 ppm of iron (Fe) that are associated with pyrite (FeS$_2$). Even though the proportion of the London clay mixed into the water is low, the presence of pyrite makes the water completely unsuitable for human consumption. A considerable number of studies are being carried out relating to the vulnerability of the karstic chalk aquifer and its conservation. The elaboration of groundwater models is becoming very necessary to propose protection approaches for it (Edmonds, 2008) and one of them is the maintenance of its recharge capacity.

Figure 6.12: Both photographs show dissolution pipes (karsts/caves) in Castle Hill outcrops (Newhaven).
In order to complete the analysis of the results, it is necessary to interpret the data processed using the XRD and PXRF. First, the XRD identified clay within the samples from Brighton (Marina) and Peacehaven Steps (Friar’s Bay), but it represents the smallest part of them. Both samples contain almost 100% of calcite, which means they are almost pure chalk. So, despite these samples being from seams, they can be considered a marly chalk because carry more chalk than marl. Regarding the last analysed sample, over half of the mineralogical composition of the Castle Hill sample is calcite. However, the clay content is the highest compared with the previous two samples already mentioned. Secondly, the PXRF showed highest concentration for sulfur (S) in the Castle Hill sample, therefore it matches with the results from the XRD, in which gypsum was identified. Thus, both piece of equipment provided accurate results on mineralogical and geochemical compositions of the three collected samples because their results support/complement each other. Also, they proved that the sample from Castle Hill comes from the overlaying sediments enriched by clay due to the presence of gypsum, a calcium sulfate dehydrate (CaSO₄ 2H₂O) and very soft mineral. Next, on Table 6.4, there are the results from the XRD and PXRF and how they confirm each other.
Table 6.4: XRD and PXRF results comparison.

<table>
<thead>
<tr>
<th>Where has the sample been collected?</th>
<th>First thought:</th>
<th>XRD has identified:</th>
<th>PXRF has revealed:</th>
<th>Proven evidence:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton (Marina)</td>
<td>At the marl seams.</td>
<td>Calcite (CaCO\textsubscript{3}) at 90%; Quartz (SiO\textsubscript{2}) at 6%; and Illite (KAl\textsubscript{2} (Si\textsubscript{3}Al)O\textsubscript{10}(OH)\textsubscript{2}) at 4%.</td>
<td>40% of Ca; 3155 ppm of K; and 2274 ppm of Fe.</td>
<td>Clay content is low, so marl seams are marly chalk.</td>
</tr>
<tr>
<td>Peacehaven Steps (Friar’s Bay)</td>
<td>At the marl seams.</td>
<td>Calcite (CaCO\textsubscript{3}) at 92%; Quartz (SiO\textsubscript{2}) at 6%; and Illite (KAl\textsubscript{2} (Si\textsubscript{3}Al)O\textsubscript{10}(OH)\textsubscript{2}) at 2%.</td>
<td>46% of Ca; 1955 ppm of K; and 934 ppm of Fe.</td>
<td>Clay content is low, so marl seams are marly chalk.</td>
</tr>
<tr>
<td>Newhaven (Castle Hill)</td>
<td>In the chalk.</td>
<td>Calcite (CaCO\textsubscript{3}) at 60%; Quartz (SiO\textsubscript{2}) at 25%; and Gypsum (Ca (SO\textsubscript{4})(H\textsubscript{2}O)\textsubscript{2}) at 15%.</td>
<td>30% of Ca; 4407 ppm of K; 7958 ppm of Fe; and 3.2% of S.</td>
<td>Clay content is higher and calcite content is lower than in Brighton and Peacehaven, as expected. Also, the XRD has identified gypsum and not illite. The presence of this mineral is due to the chemical element S detected by the PXRF.</td>
</tr>
</tbody>
</table>
According to the results, the XRD (supported by the PXRF analysis) identified illite, which is the most common clay mineral fraction in chalk (Lord et al., 2002). This type of clay mineral has been incorporated during compaction and cementation of the chalk and gives an insight into the palaeoenvironment of the rock and it is also evidence for sea-level change during the formation of the chalk in the coastline of East Sussex (Deconinck & Charnley, 1995; Kimblin, 1992; Lindgreen et al., 2002; Wray & Gale, 2006). So, in this case, illite derives from detrital material due to the presence of zirconium (Zr). Fe values are good proxy for detrital material as well and these show the same trend as K: Newhaven > Brighton (Marina) > Peacehaven.

Density, hardness, porosity and strength of the marl seams can enable one to assess mechanical characteristics of the chalk for engineering purposes. However, the marl seams, which in fact, are marly chalk as XRD and PXRF analysis have shown, contain less than 10% of illite and, perhaps, this parameter is not very useful in order to explain what drives chalk cliff failures. A better parameter, which is the fracture orientation and other characteristics, such as, frequency and aperture, including lithological aspects and weathering give more cohesive arguments to offer a solution for the project research questions. However, the "marl seams" (marly chalk seams) are important because they can be used as one more feature to show the differences that distinguish the localities of this work. For example, in Brighton and Peacehaven clay layers have been identified, especially in Friar’s Bay where the seams are more persistent, but both are part of the Newhaven Chalk Formation. In contrast with these two places, the outcrops at Castle Hill showed the same formation, yet a high level of alteration caused by erosion and weathering. So, there, even if clay layers do exist, it was not possible to recognize them. Possibly, most of the clay component came from the Palaeogene mudstones, known as the London
Clay. Also, according to the results, the chalk chemistry in Castle Hill is different: while it is less pure and includes gypsum unlike that in Brighton and Peacehaven. In these last two, the chalk almost reached 100% of calcite with negligible traces of illite (less than 10% - 4 and 2% respectively).

In terms of mechanical properties, the illite marls of Brighton and Peacehaven are poorly plastic, and hence are considered a strong material although it presents low permeability. But, in Newhaven, the gypsum (within the chalk), a soft material that creates pressure over the rock mass, can be a different controlling aspect for chalk slope instability.
CHAPTER VII

CONCLUSIONS

Fracture measurements were taken on three sites along the East Sussex coastline: Brighton (Marina), Peacehaven (Friar’s Bay area) and Newhaven (Castle Hill). Their structural analysis revealed the respective striking orientations: NNE/SSW, NE and NE/SW. So, from this it is possible to assert that the majority of fractures are concentrated in the NE direction, in which the most common trend is N154E. But, the fracture patterns lie on NW-SE and E-W directions, the first one being the main (most common) pattern and the second one, the subordinate pattern. Also, it is correct to say that the fracture attitudes of the study area are orientated in the direction WNW-ESE (aggregating both patterns - the dominating and the secondary). The results from the Scanline Fracture Surveys also suggest a strong presence of conjugate fractures, marl layers and vein networks (fractures filled with flint and fractured chalk). Furthermore, together, all these aspects work as controlling mechanisms for chalk cliff collapses.

However, the dip average (63°) of the cliffs from Brighton to Newhaven suggests fractures parallel to the coastline that are steep and inclined, producing a particular type of cliff collapse known as the Peacehaven Type. Also, the magnitude and frequency of the collapses are closely related to weathering and particular features at the top of cliffs, especially in Castle Hill, where the weathered Palaeogene layers contain the London Clay (muds) and the Lambeth Group (sands).
XRD and PXRF analysis showed evidence that the seams from Brighton (Marina) and Friar’s Bay are not formed by marls, but in fact, are marly chalk. Therefore, they are more permeable and capable of storing more water, principally because of the intense fracturing through which the water flows. Furthermore, the geochemical composition analysis of the chalk at Castle Hill showed high levels of Fe and S, thus the consumption of its water is not recommended. Also, the marly chalk seams are enriched with illite and hence are likely to have high fluid pressures and solution weakened chalk above them. Usually, this clay mineral contributes to chalk cliff instability, however, in this case, it is not a determinant factor because the Newhaven Chalk Formation marls in Brighton and Friar’s Bay have less than 10% of illite.

In order to obtain more accurate results, the subject raised by this Final Year Geology Project allows further enquiry on, for example, use of GIS techniques and aerial photography for fracture analysis, and strength tests to check physical and mechanical properties of the chalk, such as Point Load Test (PLT).

Finally, the occurrence, magnitude and frequency of chalk cliff collapses involve a range of factors. Predominantly, the cliff falls are caused by:

- Structural features (folds, faults, joints);
- Geology and rock matrix properties;
- Climate change and marine erosion (salt from seawater might make a considerable contribution);
- Weathering caused, especially, by the groundwater that flows through the discontinuities, weakening the chalk; and
- Human activity (is not linked directly with cliff collapses although it increases its impacts and frequency).
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