CHALK: A STRATIGRAPHY FOR ALL REASONS

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Geological maps of the Chalk country of England have been revolutionised by the British Geological Survey. The initial impetus for developing a new lithostratigraphy for the Chalk was, however, the need to provide a framework for major construction projects, particularly earthworks and tunnels, in relation to physical properties and rock mass character. Out of this research arose divisions appropriate for mapping because the geomorphology reflected the material and mass properties. Latterly, the detailed marker bed stratigraphy has successfully been employed to construct ground models for tunnels along the south coast and for the Channel Tunnel Rail Link. The same detailed stratigraphy is also being used to develop a hydrogeological stratigraphy for the Chalk aquifer.

The conspicuous 'stratigraphic' variation in the rock mass character of the Chalk reflects both lithological variation and tectonic controls. Understanding this variation and its causes makes the development of a mechanical or fracture stratigraphy possible. Such a fracture stratigraphy provides the means for modelling the Chalk as an aquifer, as an oil reservoir and aids prediction of ground conditions for slope, tunnel and earthwork design. Karst development in the Chalk is also closely related to its material and mass character, especially the lithostratigraphy and associated fracture styles.

A key factor in the development of the detailed lithostratigraphy was the recognition of marker beds, including marl seams, flint bands and macrofossil and trace fossil horizons, that could be consistently recognised in rock-core as well as field sections. Training geologists and engineers to recognise these features has been an important part of the successful application of this geological research to a wide range of industries.

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INTRODUCTION: PHILOSOPHY OF TOTAL ROCK ANALYSIS OF CHALK

The 1960s exposed our limited understanding of chalk behaviour in engineering situations (Anon, 1966, ICE Chalk in earthworks and foundations) by illustrating the peculiar and unpredictable way chalk broke down when mechanically handled. Such problems continued into the 1970s in both England and France resulting in several attempts at classification reported in La Craie (Masson, 1973, 1976), by Jenner and Burfitt (1975), Clarke (1977), Clayton (1977) and Ingoldby and Parsons (1977). All of the investigations concentrated on 'tests' to discriminate different types of chalk without considering its detailed geology. Having reached the new Millennium we are still waiting for the 'ultimate' test. Even simple tests for properties such as intact dry density and porosity have inherent problems because of the variable nature of chalk (Meigh and Early, 1957; Carter and Mallard, 1974; Lamont–Black and Mortimore, 1996). A completely fresh approach to predicting chalk engineering behaviour is required, one which recognises the importance of the basic field geology and the geological processes that chalk has gone through from its origins to its present day setting in the landscape.

During the 1970s ground investigations for major road schemes such as the A27 Trunk Road bypasses around Lewes, Brighton and Worthing and the construction of the A26 Cuilfail Road Tunnel at Lewes, reinforced how poor our knowledge of the Chalk geology really was. Chalk was simply described in terms such as '***white chalk with occasional cobble sized flints***' (Figure 1). The legend on borehole logs showed only one kind of lithology. Assumptions about stratigraphical level were at best related to fossil zones (e.g Clayton, 1977) or at worst to the three broad traditional divisions of Lower, Middle and Upper Chalk (Figure 2) shown on geological maps. In France, it was no better as the Upper Cretaceous stages of Cenomanian, Turonian and Senonian were the only units mapped in the chalk of the Paris Basin. These stages did not distinguish different lithologies. For example, the Cenomanian in each region of the Paris Basin (Figure 3) is a completely different material ranging from calcareous sands (Sarthe, southeast region), hard chalks with regular flint bands (Pays de Caux) to marls with a high percentage of clay and no flint (Aube and Marne northeast region). The Senonian (in the past taken as broadly equivalent to the Upper Chalk) could be several hundred metres thick containing many different lithologies. It was also widely assumed in England and France that flint bands and marl seams were local features that could not be correlated between field sections let alone identified and correlated from borehole cores.

The absence of any form of sensible stratigraphical framework made it impossible to compare one engineering site with another or come to any general conclusions about physical properties or rock mass character. Without a detailed stratigraphy it was also not possible to assess lateral variation in sediments, or possible causes of variation in the Chalk such as tectonic controls and sea-level fluctuations. The assumptions about absence of significant variation, particularly in the 'white chalk' were reinforced by a widely held view amongst geologists who considered the Chalk to be a rather boring homogeneous rock! Some horizons contained fossils of interest to palaeontologists but not of more general interest to the science! Even the classical work at Mundford, Norfolk (Figure 3) in the 1960s (Ward *et al.,* 1968), where marl seams were recognised and channels in the 'Middle Chalk' were illustrated, failed to stir the geological or engineering communities into greater interest in the Chalk. Aspects of the Mundford results such as increase in hardness/strength of chalk with depth and regular improvement in Engineering Grade with depth below the ground surface, were taken too literally and not applied with 'geological' common sense. Hardness or strength depends on lithology. At Mundford the ground profile went down through the 'Middle Chalk' from the softer, weaker New Pit Chalk Formation with marker marl seams to the harder, stronger Holywell Nodular Chalk Formation with the 'Melbourn Rock' at its base (Figure 2). In southern England, if a ground profile went from the Lewes Nodular Chalk Formation to the New Pit Chalk Formation the hardness/strength profile would be reversed going down from

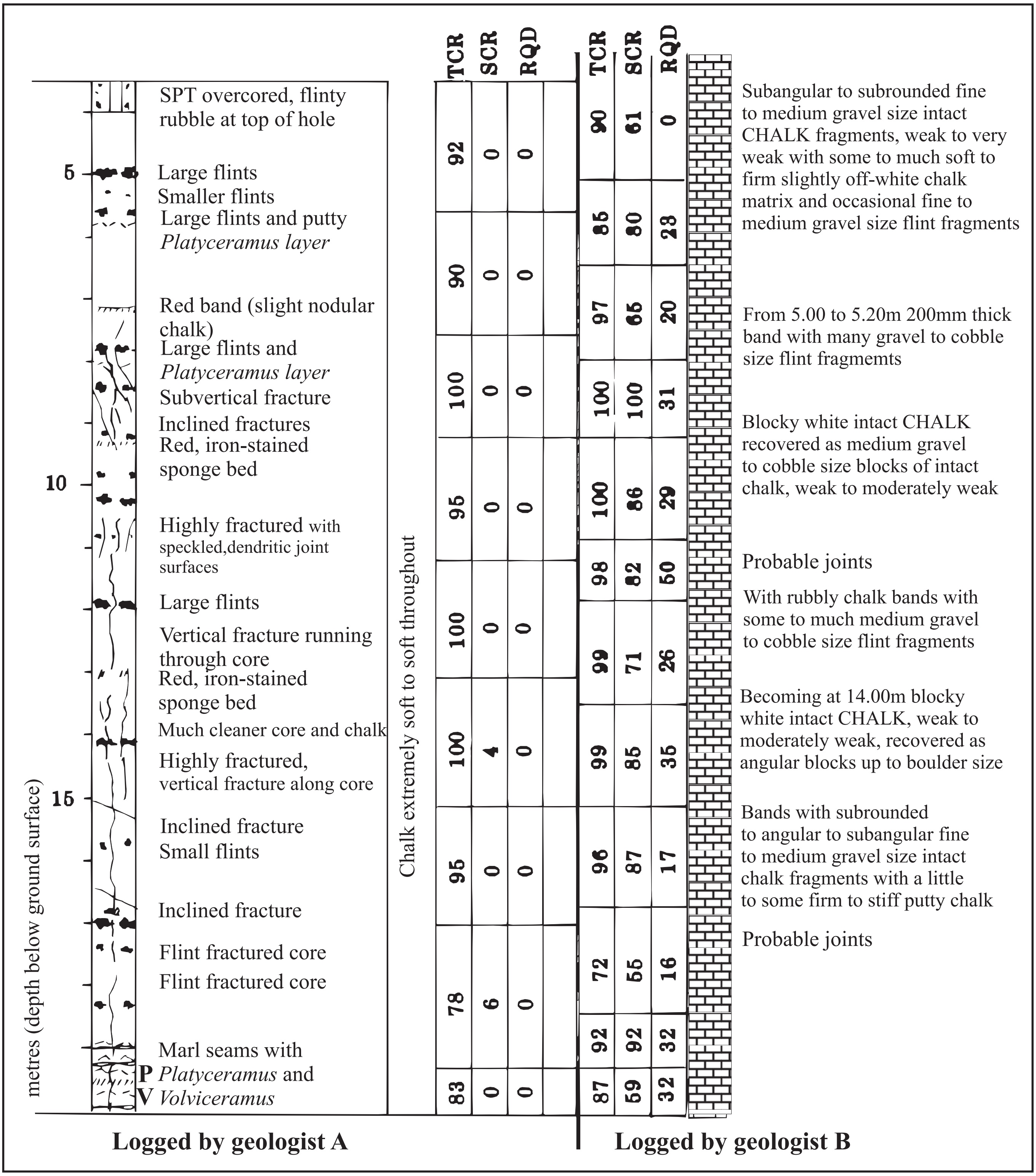


***Figure 1.** Parts of contrasting borehole log descriptions completed by two engineering geologists on the same core at different times.*

stronger to weaker material. There are many sites in the North and South Downs where there is no regular improvement of Engineering Grade with depth. Grade can reverse depending on fracture frequency, tectonic effects or geomorphological processes.

Ground investigations for the proposed construction of roads and tunnels in the South Downs were the starting point for a complete rethink of chalk geology and its relationship to engineering. As a key part of this rethink, it was realised that a new stratigraphy was required that more closely related to the lithological and mechanical properties of chalk than was the case with fossil zones or the traditional Lower, Middle and Upper divisions. However, it would not have been possible to erect a stratigraphy for the South Downs only, ignoring the rest of southern England and France. Nor could the engineering significance of any particular lithology be fully realised unless the research was actively involved in major construction projects in a wide range of chalk lithologies across the whole region. Initial studies in the North and South Downs and Chiltern Hills illustrated that there were indeed lithologies in the Chalk that could be recognised easily and correlated at least through southern England (Mortimore, 1977, 1983; Mortimore and Young, 1980).

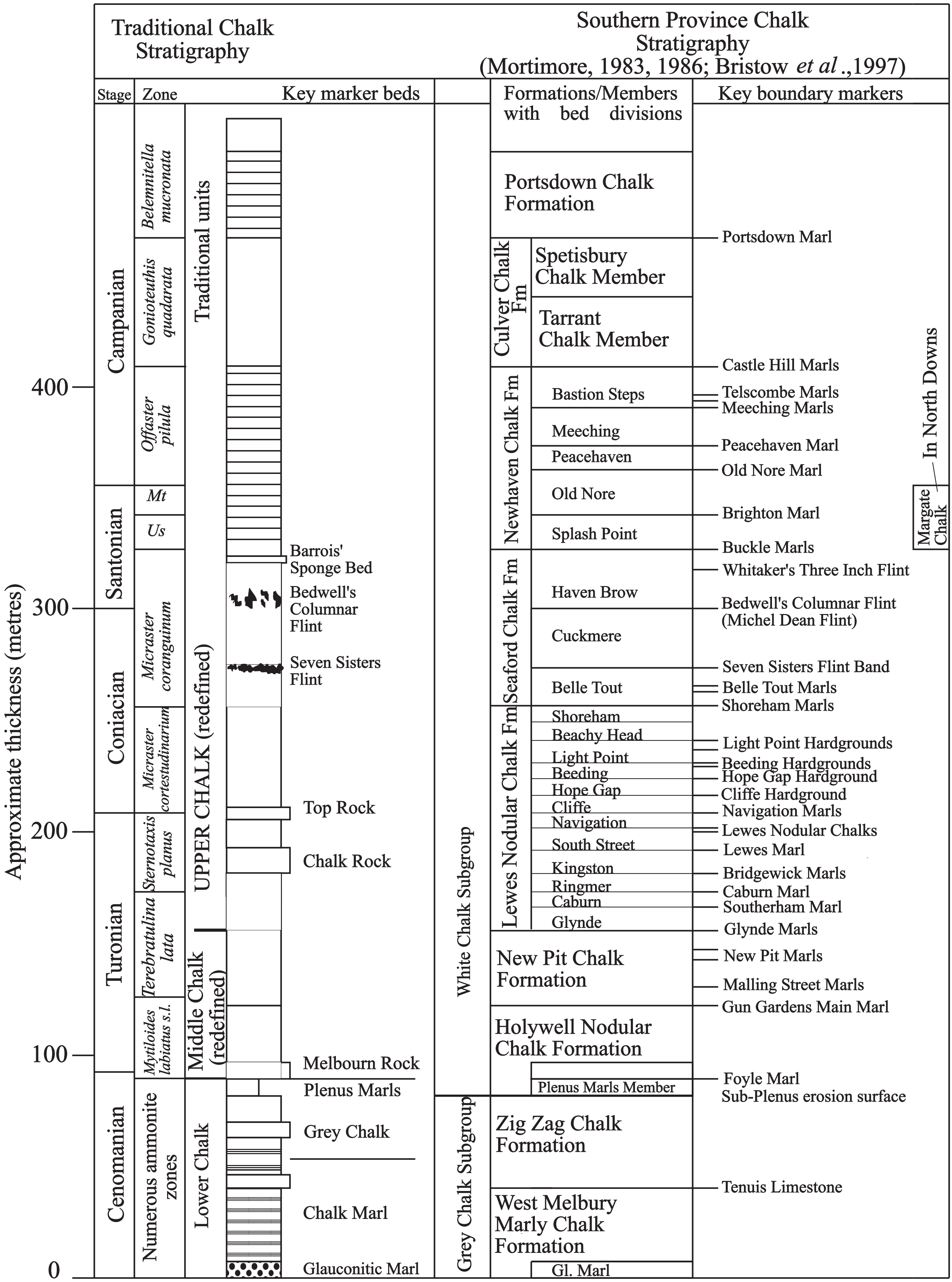


Figure 2. *Chalk lithostratigraphic units (subgroups, formations, members) are those used by BGS for mapping purposes. The traditional zones are also shown.*

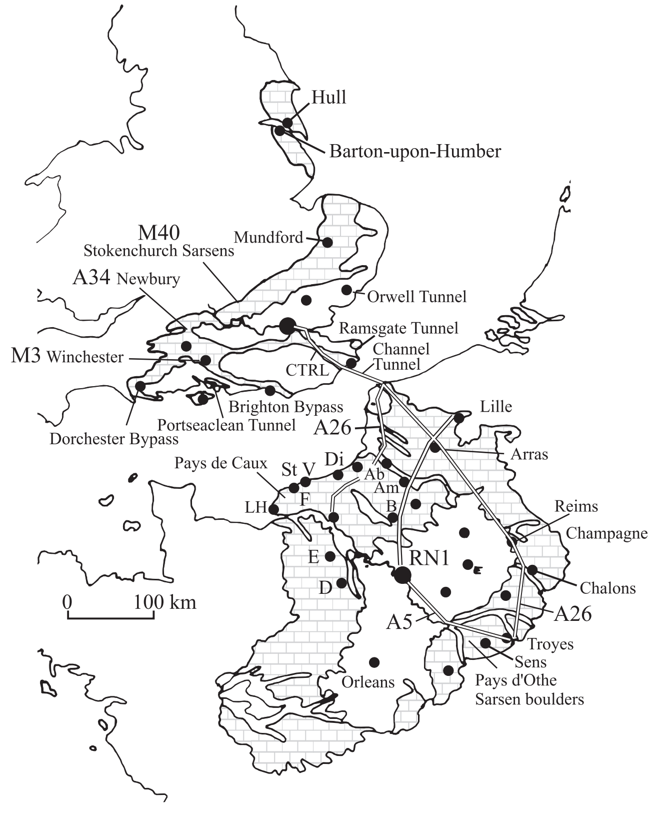


Figure 3. *The Chalk in England and the Paris Basin and construction projects where the research has been applied. CTRL - Channel Tunnel rail Link, Di - Dieppe, St V - St Valery, F - Fécamp, LH - Le Havre, Ab - Abbeville, Am - Amiens, B - Beauvais, E - Evreux, D - Dreux.*

A further key feature of lateral variation along strike and across dip also emerged. Lateral variation was first appreciated when a correlation between the Lewes chalk pits and Upper Beeding Quarry, Shoreham Cement Works, Sussex, illustrated major changes in lithology at particular horizons. Condensation was marked in parts of the succession leading to the formation of massive rock bands at Shoreham (Mortimore, 1979, 1986a, 1986b; Mortimore and Young, 1980). Correlation using geophysical borehole logs also illustrated this same condensation and 'hard' chalk development in the Sompting Borehole compared to Brighton boreholes (St. Peter's Church and Victoria Gardens, see below). It was apparent from these initial results that a study of one aspect of chalk geology or engineering would not be sufficient. A 'Total Rock' approach was required, taking the Chalk as a medium for investigating all aspects of its geology and engineering. It was also realised that such an approach would require a long period of research and a twenty–year programme to develop the geological frameworks was initiated. The first essential framework in this 'Total Rock' study was the stratigraphy. This paper summarises the results from more than twenty five years of investigation and application of the stratigraphy to construction of roads, railways, tunnels, slopes and groundwater in all units of the Chalk in southern England.

Construction of a new stratigraphy

A huge controversy surrounded the introduction of a new stratigraphy for the Chalk. One referee wrote .. '*the author has put a lot of lines into a pile of sediments without any justification'*. Justification there was in plenty, but as often happens with something new, the geological community felt that one of their 'better known rocks', the Chalk was being unnecessarily subdivided. Suddenly, from three simple mapping units, Lower, Middle and Upper, within which there were twelve biostratigraphical zones, there were to be nine mapping units, numerous bed divisions and hundreds of marker beds! In fact the stratigraphy was constructed gradually using three lines of evidence. The lithostratigraphy was devised on the basis of recognising broad units of chalk, some nodular some not, some with marl seams, some with no or few marl seams. These lithologies also defined units with different styles of fracturing and, therefore, styles of weathering and feature forming potential. The key to the lithostratigraphy, however, was the individual marl seam, hardground or flint band. Many of these could be correlated over vast distances, thousands of square kilometres from Sussex to Yorkshire, from Devon to the Yonne. Essential supporting evidence for any correlation was provided by the macrofossils. Purely lithological recognition of a bed was possible by knowing in detail the form and character of flints within a particular band, the association of a particular group of flints with a certain type of marl seam. For example, the Lewes Marl with its associated tubular flints was recognised in Hooken Cliff, Devon (Mortimore *et al.*, 2001) and in Autoroute A26 cuttings north of Troyes in the Aube (Mortimore and Pomerol, 1996). The same species of the sea urchin *Micraster leskei* and the inoceramid bivalve *Mytiloides striatoconcentricus*, occurred in all places where this marl was recognised. These detailed litho– and biostratigraphical features were the keys to core-logging and construction site evaluation. Having established these stratigraphical details, and proved that this character of the rock was retained over vast distances, it was then also possible to link the broad and detailed lithostratigraphy to geophysical borehole logs.

Gray (1965) identified a number of marker beds in the BGS Leatherhead Borehole, Surrey, which he designated with letters. Gray considered that these might be useful markers for correlation in the Chalk and recognised them in other boreholes in the London Basin but he did not specifically relate them to a Chalk lithostratigraphy. This came later. Leatherhead was in an area where the Chalk is relatively condensed and many marker beds were missing. Southern Water Authority (SWA) had great numbers of water-well logs for the region, mostly the 16"/64" resistivity and natural gamma logs, and many old 'Stow' logs. These were used as part of the research programme, in some cases supported with cored boreholes, to illustrate the succession of marl seams and nodular chalks and to then extend the correlation into the subsurface (Mortimore 1979, 1986a, 1986b; Mortimore and Pomerol, 1987). The key boreholes in this respect were the Candover series in the Itchen and Candover valleys near Winchester (Figures 3 and 4). Excellent SWA geophysical logs (16"/64"resistivity and natural gamma) were available for comparison with three cored boreholes. These illustrated the continuity of marker beds and broader lithological divisions, and by comparison with Sussex and Kent SWA logs, indicated that there was a succession of marker beds that could be recognised throughout the region. Some marker beds, or their geophysical spikes, were occluded in areas of stratigraphical thinning but returned once this area of thinning had been crossed. One anomaly occurred, however, which nearly threw the whole correlation into disarray!

Having identified the Lewes area of Sussex as exposing the most complete White Chalk succession in southern England this seemed the most sensible place to obtain standard geophysical borehole logs. Three boreholes (rock-roller open holes) were drilled in the Ouse valley at South Street, Lewes, Asham Quarries, Beddingham and Tarring Neville Quarry. The boreholes were drilled by East Sussex County Engineers SI Unit (a joint venture with the then Brighton Polytechnic Civil Engineering Department) and geophysically logged by the then Southern Water Authority as part of joint research with Brighton Polytechnic. The first, the South Street Borehole began at a known stratigraphic level, the Lewes Marl, in the former Chandlers Yard Quarry, South Street, Lewes (Mortimore, 1986b, 1997), and yielded an anomalous log. Two of the most conspicuous markers recognised everywhere else at that time, the spikes representing the Glynde and Southerham Marls, were either missing or giving an anomalous result! A re-log of the borehole gave the same result. It was, therefore, not an equipment failure. Five hundred metres south of the borehole, in what is now Cliffe Industrial Estate Quarry, Strahan's hardground and phosphatic chalk was known to occur

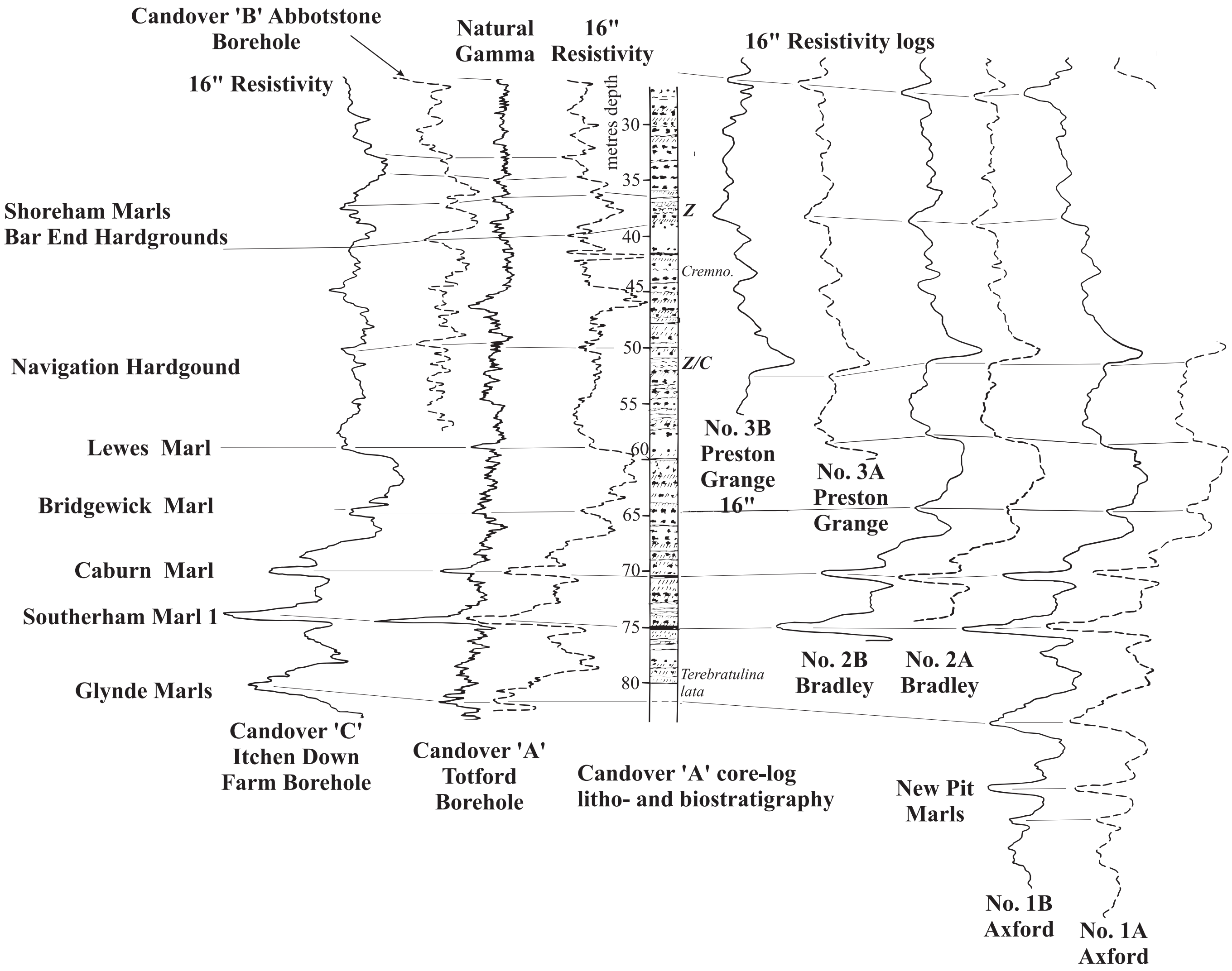


Figure 4. *The Candover boreholes near Winchester, provided the first firm evidence for a link between the lithostratigraphy of the Chalk in the Southern Province of England and the electrical resistivity and natural gamma geophysical borehole logs.*

in the steeply north dipping limb of the Caburn syncline but at this time (1977) it was not well exposed. The anomaly on the borehole 16" resistivity log indicating a hard chalk spike where marl spikes should have occurred, was interpreted (Mortimore, 1986b) as the continuation northwards of Strahan's hardground. This hardground had formed on a synsedimentary erosion surface cutting through the junction between the New Pit and Lewes Nodular Chalk formations. Having partly resolved the anomaly, the South Street Borehole provided invaluable further evidence of lateral variation in the Chalk and the tectonic setting for such anomalies. Subsequently in 1990, construction of the Cliffe Industrial Estate included re-excavation and cleaning of the old quarry faces, revealing the detailed stratigraphy of beds above and below Strahan's hardground, the phosphatic chalks and the anomalous channel fill (Figure 5; Mortimore *et al*., 2001, Southerham Pit figure 3.114).

The evidence from the geophysical logs provided essential additional data in several respects. First, the logs confirmed the presence of marker beds of marl and nodular chalk and the succession of marls. They also illustrated which marker beds consistently produced the most conspicuous geophysical signatures and, in terms of gamma logs, indicated which marl seams might have volcanogenic origins. Secondly, the correlation framework of marker beds using field sections and geophysical borehole logs, illustrated the subsurface structure of the Chalk and greatly enhanced interpretations of tectonic structure and sedimentation history. Thirdly, the geophysical logs, in providing information in areas with very limited exposure, indicated where some exposures with uncertain stratigraphy must fit into the succession. This was particularly the case for the Chalk Rock succession in the Berkshire Downs and Chiltern Hills.

The isolated Chalk Rock exposure in Fognam Quarry near Lambourn, Berkshire, is difficult to place in a regional context because the next exposure of the same stratigraphy is many kilometres away. The Chalk Rock of this region comprises a succession of named hardgrounds (Bromley and Gale, 1982). For some (e.g. Gale, 1996), the basal Chalk Rock Ogbourne hardground formed within the New Pit Chalk Formation and the overlying sediment between it and the next hardground above, the Pewsey Hardground, was lost through winnowing leading to a reduced thickness of New Pit Chalk Formation. However, water-well geophysical logs in the nearby Lambourn Valley (Tate *et al*., 1971; Mortimore, 1987) illustrate the thicknesses of Holywell Nodular Chalk and New Pit Chalk formations that are present in the area beneath the Chalk Rock. As in the South Street Borehole, Lewes, the Lambourn logs also illustrate which marker beds are present or lost as a result of sedimentary processes in the region of maximum Chalk Rock development. It is evidence that cannot be ignored (e.g. Mortimore *et al*., 2001).

A fourth use of the geophysical borehole logs is in assessing potential engineering properties and potential engineering behaviour. A broad correlation exists between the resistivity and sonic log spikes and the porosity and density of chalk. This aspect has not been widely employed as the logs will vary in absolute values, depending on degree of fracturing and saturation as well as mineralogy and degree of cementation of the chalk. However,

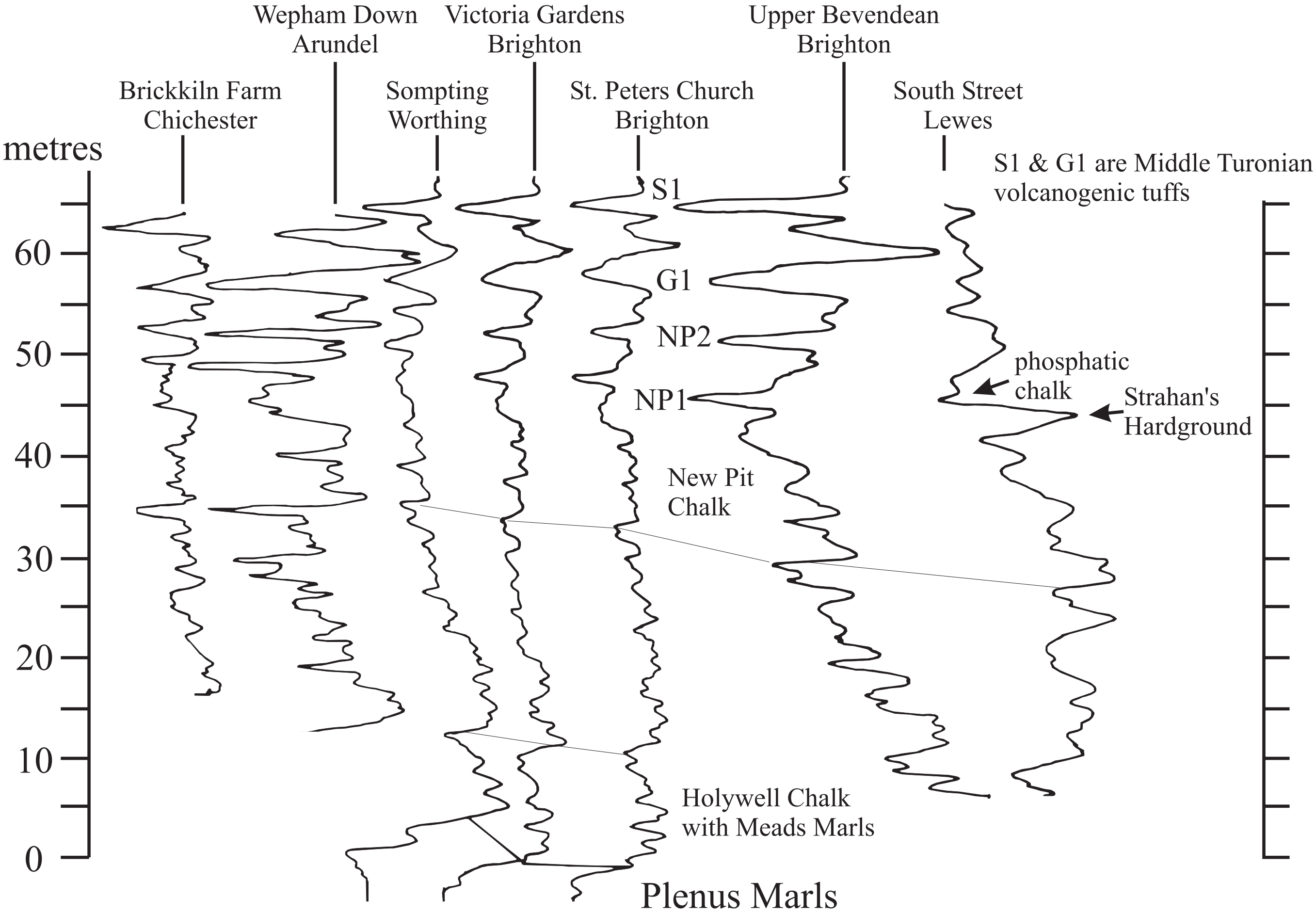


***Figure 5.** Correlation of 16" electrical resistivity borehole logs in the Turonian of the Southern Province, England. Based on Mortimore (1986b) figure 3.7. The South Street log is anomalous because of the presence of Strahan's hardground, channel and phosphatic chalk. Note the Middle Turonian volcanogenic marls forming conspicuous spikes on the logs*

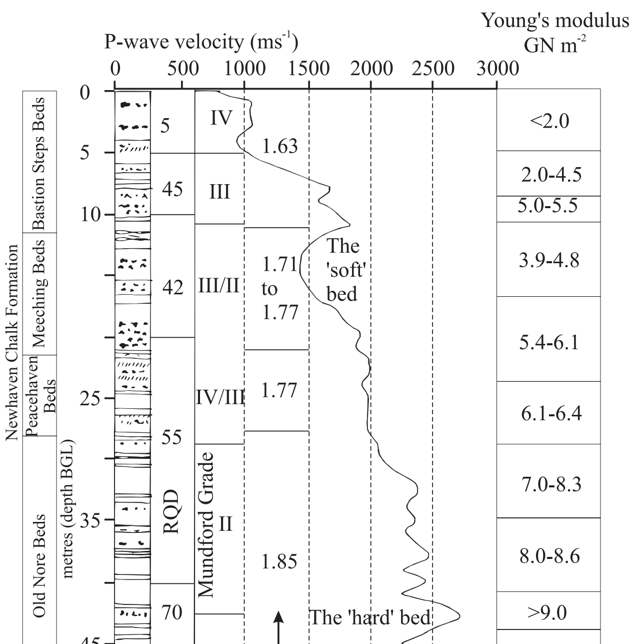


***Figure 6.** The A27 Southwick Tunnel site investigation: P-wave velocity profile (data from L.G. Mouchel and Partners, Downing et al., 1993).*

it is possible to recognise both local and regional physical characterstics such as horizons which will yield massive rock chalk or very soft chalk in tunnels and earthworks. An excellent use of geophysical borehole logs was made in the A27 Brighton Bypass Southwick Tunnel investigation (L.G. Mouchel and Partners Ltd., 1989). A nest of boreholes, including vertical (stratigraphic) and inclined (for fracture frequency analysis) boreholes, was used to carry out both cross–hole seismic and downhole velocity profiling (for both P and S waves). The results from the P–wave velocity profile (Figure 6) indicated locally higher velocity 'hard' and lower velocity 'soft' layers in addition to a general increase in velocity with depth. During construction of the tunnel and the adjacent cuts and fills it was possible to monitor the impact of these layers on mechanical handling. In the tunnel, the soft, low velocity layer balled up on the roadheader cutting tines and jammed in the muck conveying system. In contrast the hard, high velocity band generated dust problems. This same hard band proved exceptionally difficult to excavate in the Hangleton Cutting, yielding large, interlocking blocks (>1m^3 with inclined conjugate shear joints typical of the Newhaven Chalk Formation). In turn, these large blocks were difficult to place and break down to the required layer thickness in the embankment fills. This same hard bed is present in the Newhaven Chalk Formation coast sections at Peacehaven and Seaford. It is a bed characterised by an abundance of a particular nannofossil, *Micula* (Mortimore, 1979; Mortimore and Fielding, 1990).

A fifth use of geophysical borehole logs in the Chalk is the identification of water flow horizons using differential temperature and salinity logs alongside the lithological logs (resistivity, gamma, sonic). Flow horizons are closely related to

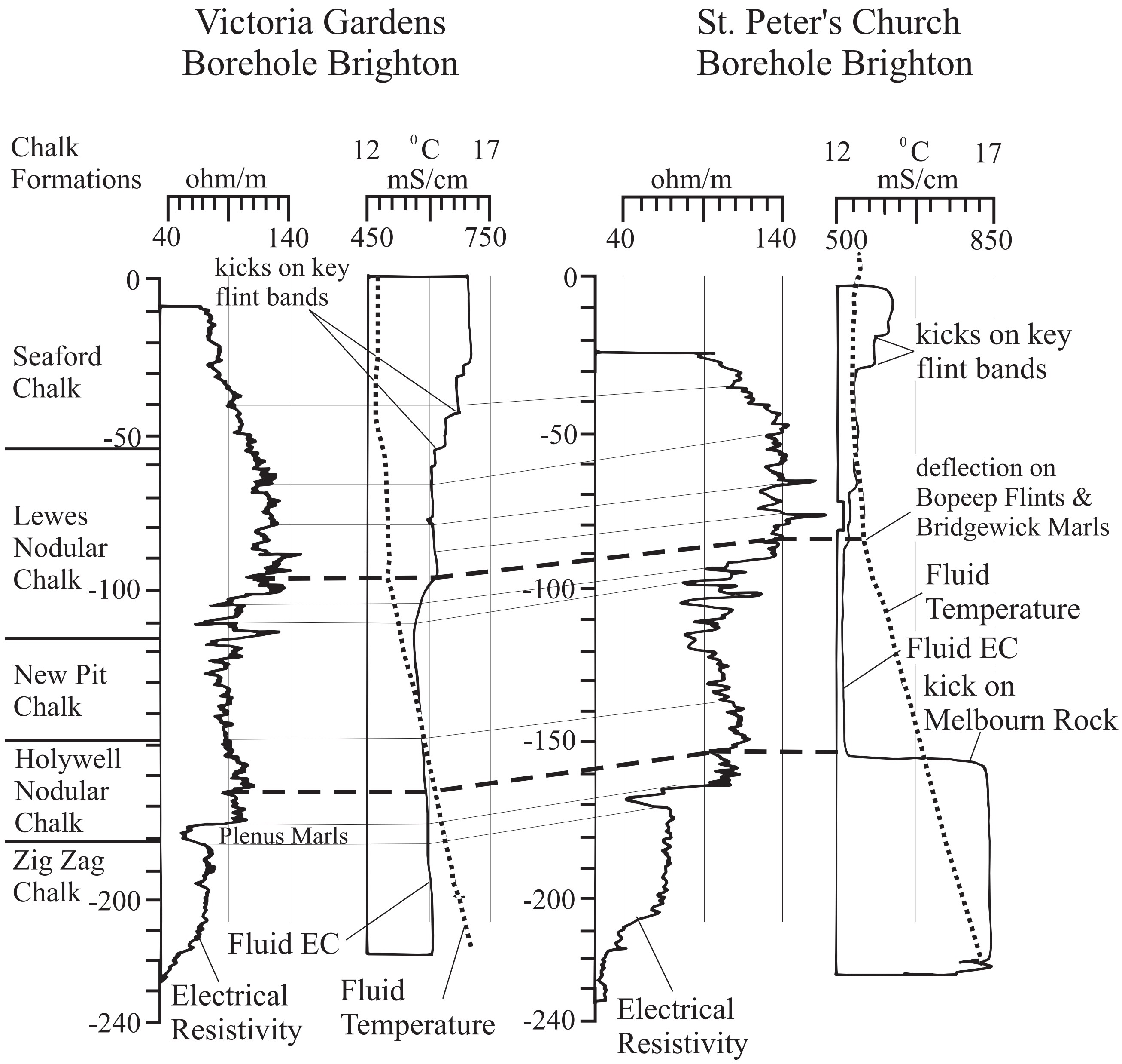


Figure 7. *Geophysical logs of boreholes in the Brighton area, South Downs, showing kicks in fluid conductivity (salinity) and temperature, related to groundwater flow along key lithological marker flint bands, concentrated rock bands, and marl seams. These logs illustrate that the aquifer is 'layered' in relation to the Chalk lithostratigraphy. The big temperature change is at about 80 m depth.*

Figure 8. *Groundwater flow in the Chalk related to bedding features such as semi-continuous flint bands (Bruneval, Antifer, France).*

particular beds of chalk (Figures 7 and 8; see groundwater below). A sixth and increasing use of high resolution logs, particularly microresistivity, is for anlaysisis of cyclic sedimentation in the Milankovitch waveband (Niebuhr, 1995). Microresistivity has proved to be particularly useful in Northern Province Chalks in the north Linclonshire Wolds where every single bed can be identified (Figure 9) and very detailed sedimentological analysis is possible.

Despite the successes for stratigraphic interpretations using geophysical borehole logs there are parts of the succession which pose problems. Units of chalk without marl seams or contrasting lithologies, such as parts of the Seaford and Culver Chalk formations, are exceedingly difficult to interpret. Ideally, a borehole log needs to include sections of stratigraphy above and below these 'barren' formations. Attempts at correlating borehole logs through the 'high' Chalk of Hampshire and Dorset were abandoned (Bristow *et al.*, 1997), as every borehole seemed to be different. This is probably because there is extensive lateral variation including huge synsedimentary submarine channels in this part of the succession leading to numerous 'local stratigraphies'.

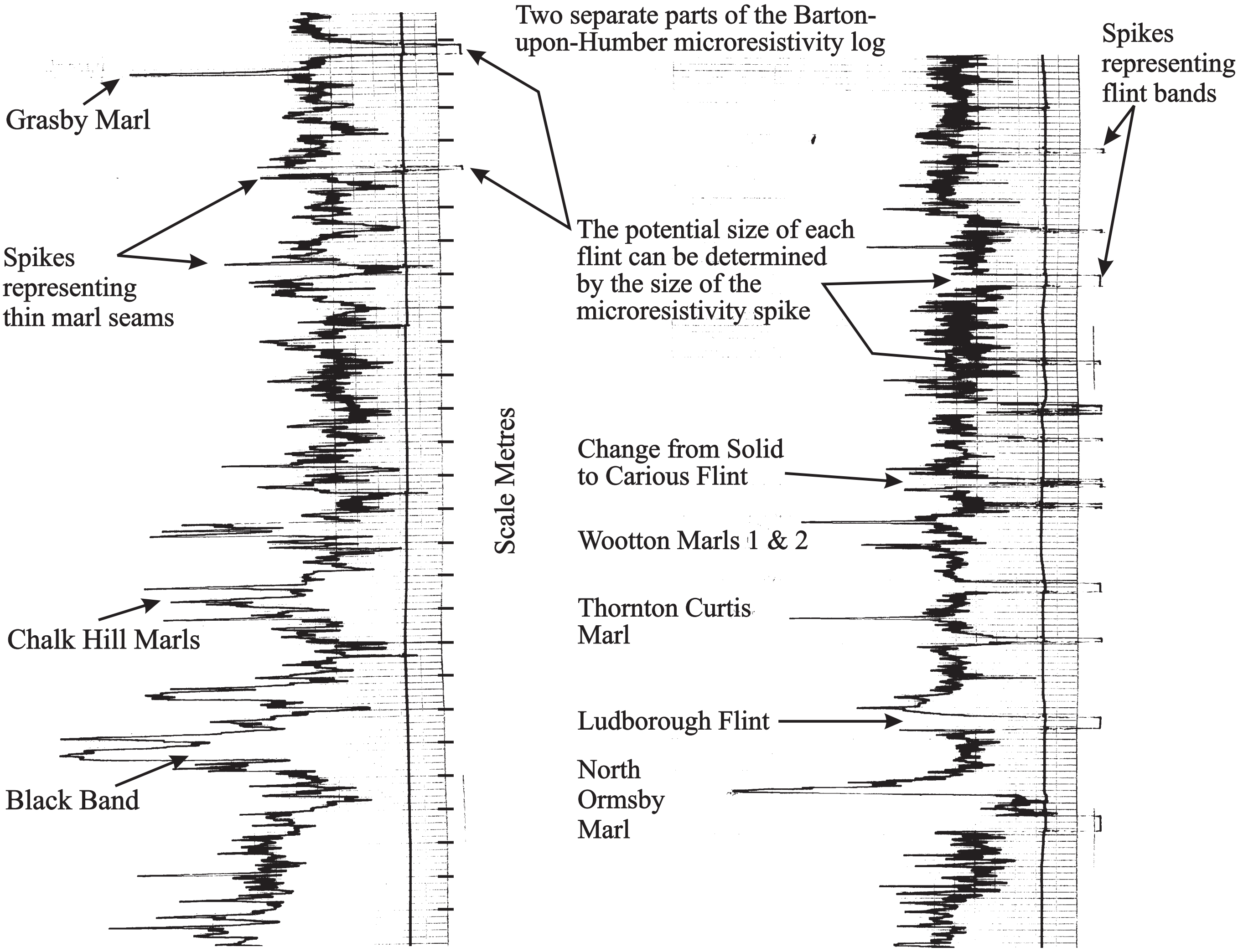


Figure 9. *Detailed lithostratigraphy that can be interpreted from geophysical logs in the Chalk: marl seams and size of flints are indicated by the microresistivity log for Barton-upon-Humber, Lincolnshire (lithostratigraphy of Wood and Smith, 1978).*

Combining field sections, cored boreholes and geophysical borehole logs, the lithostratigraphy for the White Chalk Subgroup of southern England was built around the most complete sections that could be identified which, at that time, were in Sussex and Hampshire (Mortimore, 1983, 1986a). Subsequently, the British Geological Survey began mapping the Chalk in Dorset in the early 1990s, recognising land features that were also visible on aerial photographs and satellite images. The two stratigraphies were combined for mapping purposes for the whole of southern England (Bristow *et al.*, 1997) as it was found that the geomorphological features were an expression of the lithological units recognised in Sussex and elsewhere. The stratigraphy for the onshore Chalk in the UK was formally ratified by a joint BGS and Geological Society stratigraphic commission in 1999 (Rawson *et al.*, 2001). This stratigraphy is now being applied to the French Channel coast from the Siene to the Somme to assist cliff stability hazard analyses (Mortimore, 2001).

Stratigraphies for engineering

Stratigraphy for core-logging

For most engineering projects core-logging involves following a set procedure proscribed in BS 5930 (1981). For the chalk, this procedure masks the most important element for interpreting the ground conditions, the various layers including flint bands, marl seams and nodular beds (i.e. the lithostratigraphy). The Chalk is sufficiently well known for it to be realised that it is a layered sedimentary rock and flint bands occur in regular layers! Flint, however, frequently gets stuck in drill bits and causes local destruction of core. SPT/CPT and or HPD test sections can also reduce core to a putty. Hence chalk core is frequently incomplete and partly destroyed making systematic logging, particularly fracture logging, difficult. Even in these seemingly unfavourable conditions it is possible to recognise a sufficient number of stratigraphic marker beds to be able to place a site in its correct position in the rock column and relate it to local field exposures. Every piece of evidence, from wispy marls, shell fragments of fossils and the trace fossils is used to identify the stratigraphic horizon. For this purpose, the profession (including Geology and Civil Engineering) must recognise the need for geologists to have the training and time to log this aspect of the core. Once one marker bed has been identified others can be looked for and all the boreholes placed in correct stratigraphical position so that tectonic structure and lateral variation can be assessed. Equally, a knowledge of the stratigraphy will allow a first appreciation of possible ground conditions in terms of chalk properties and rock mass character (see fracture stratigraphy and karst stratigraphy below). Such an appreciation always needs to be confirmed by testing and further field logging.

Some parts of the stratigraphical column are easier than others to identify from cores and field exposures. There are horizons where shallow boreholes (10-20 m deep) may be insufficient and at least one deeper, stratigraphic borehole should be considered. For the CTRL London Tunnels this was a very successful strategy. Most of the boreholes only penetrated a few metres into the Chalk beneath 40 m of Palaeogene sediments. The core recovered from these short intervals came from the

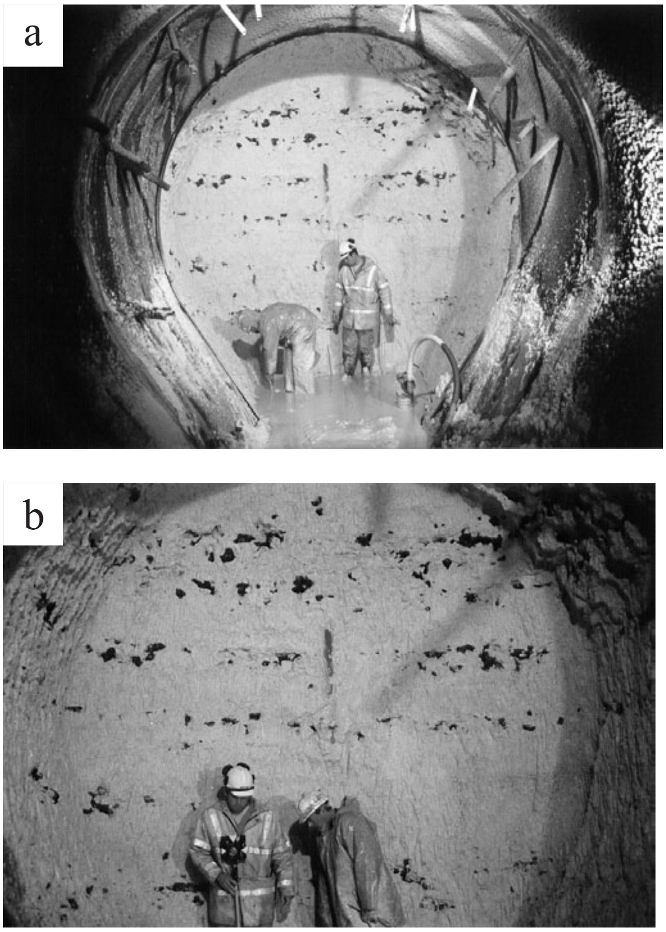


Figure 10. *Analysis of percentage flint in a tunnel face (in this case 25%), requires knowledge of the detailed flint stratigraphy.*

'barren beds' of the Seaford Chalk Formation and it was not possible to be sure of specific level without some deep boreholes penetrating the Belle Tout Marls and associated richly–shelly beds towards the base of the Seaford Chalk Formation. Once those markers had been recognised it was relatively easy to place the remaining beds in their correct stratigraphical position (Mortimore, 1996).

Flint stratigraphy

Flints pose particular problems for drilling (drill bit wear, core destruction, time on site), and borehole tests (e.g. High Pressure Dilatometer (HPD) damage to the lantern). A strategy for a site investigation should, therefore, include an assessment of the flint stratigraphy so that costs, time and appropriate stratigraphic levels for tests can be considered. This may require a staged approach with preliminary boreholes used to identify the stratigraphy before the numbers and depths for tests and further boreholes are decided upon.

Flints also cause problems for tunnelling machines. As part of the analyses for determining the successful deployment of different types of tunnelling machine a risk assessment may include a detailed study of flints to identify the size of flints, strength of flints and percentage flint in a tunnelling face (Figure 10). The size of flint in a particular band is relatively consistent over a distance of many kilometres and bands of very large, Paramoudra flints are stratigraphically restricted. Similarly, the stratigraphic position of bands of semi-continuous, thick (150-200 mm thick) flints is known. Once the stratigraphy is known for a site the types of flint can be predicted for the full length of the tunnel. The smaller the diameter of tunnel the more critical large flints become. A typical case was the Shoreham Harbour Tunnel, Sussex, which was under construction when, during shaft sinking, flint bands at about 1.8 m intervals were encountered. Critically,

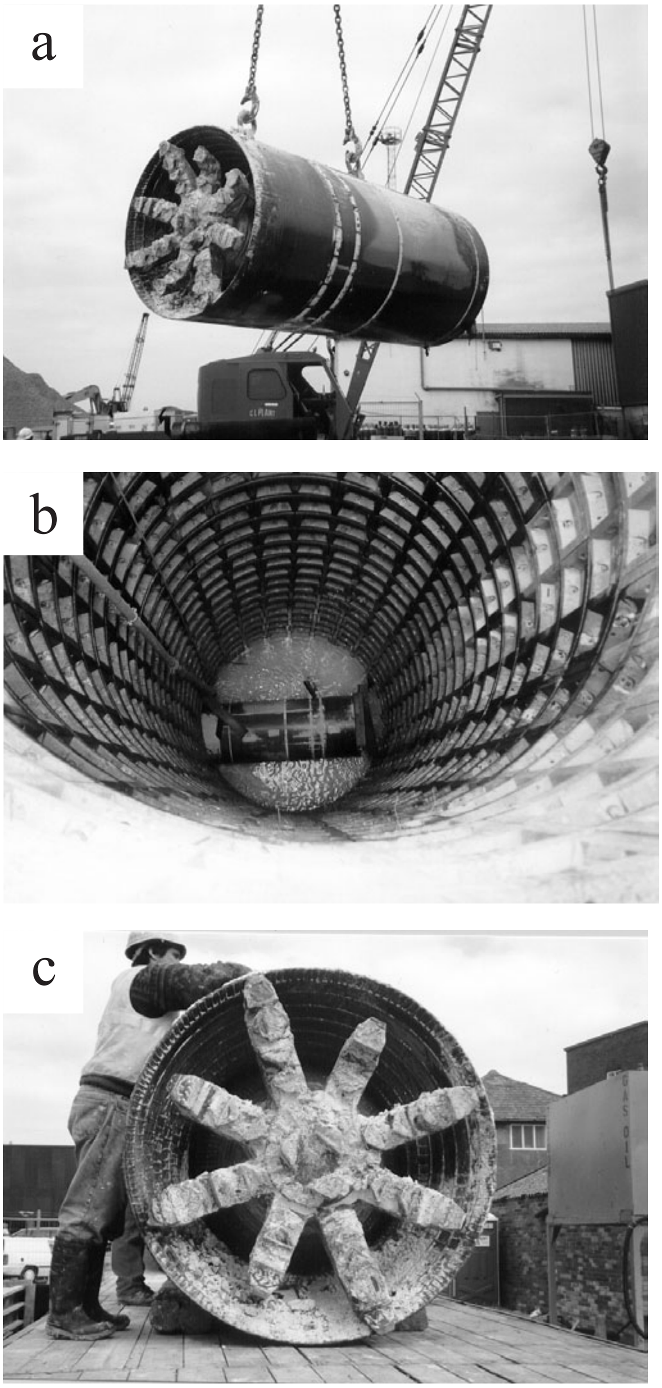


Figure 11. *The Shoreham Harbour Siphon Tunnel. An Iseki Unclemole, driven remotely from the ground surface, was used to bore this 210 m long tunnel in the Culver Chalk Formation beneath the entrance to Shoreham Harbour. The size, strength and frequency of flint bands were critical parameters for the successful use of this machine. The flint stratigraphy needed to be known. (a) Recovering the Unclemole from the North Shaft. (b) Inserting the Unclemole in the softeye at the South Shaft. (c) The recovered Unclemole showing the wear caused by the flints.*

a large (100-200 mm thick) semi-continuous flint was encountered in the "soft-eye", the launching depth for the tunnelling machine. This led to a reassessment of the Iseki Unclemole's ability to successfully complete the 1.2 m diameter 210 m long tunnel drive under the sea. The Unclemole (Figure 11) was capable of handling flints up to 330 MPa in strength but the large "soft-eye" flint gave an average strength of 500 MPa and ranged up to 700 MPa. To assist in the assessment the detailed flint stratigraphy in the boreholes was required and this needed to be linked to cliff and particular fracture styles and the presence of thin marl seams suggested marked stress redistribution effects. In addition, the Bridgewick Marl 1 and overlying very large semi-continuous Bopeep Flint Band were surfaces of major dissolution effects in the North Portal part of the tunnel drive. Similarly, modelling water pressure effects on chalk slopes (Duperret *et al*., 2001), illustrated the influence of just one marl seam, acting as an aquiclude within the cliff, on slope stability.

Fracture stratigraphy

Each major lithological unit of the Chalk has its own fracture characteristics. These differences include style, dihedral angle between conjugate sets, frequency and nature of aperture fill (e.g. sheet flint fill is a characteristic of the Newhaven Chalk Formation). On the Sussex coast this is well illustrated by the contrast between the Seaford and Newhaven Chalk formations (Figure 12). Exactly the same contrast in the same formations is found on the French coast between Veulettes-sur-Mer and Veules-les-Roses. Conjugate, slickensided or polished fractures are a feature of formations with marl seams in contrast to 'clean' formations without marl seams, which are characterised by predominantly vertical fracture sets. Variations do occur, particularly within the Lewes Nodular Chalk Formation. Variations are related to lateral changes in sedimentation. For example, some units of Chalk within a formation are only locally developed as channel fills and result in a local fracture style and frequency developing. Other variations are bed specific. Hardgrounds are generally more intensely fractured than the surrounding softer chalk. Other variations are related to local tectonic effects and to weathering but these tend to be an addition to the underlying 'formational' fracture characteristics.

Many of the clearly visible fractures are mimicked by a less clear vein fabric (Mortimore, 1979). The vein fabric can have a marked effect on the results from laboratory strength testing, as chalk of a particular intact dry density may fail at a lower applied stress level than expected for its density. The vein fabric is again a feature of particular parts of the rock column (Figure 13).

Karst stratigraphy

Most chalk karst features are related to dissolution on the Sub-Palaeogene or Sub-Quaternary surface and formed as vertical pipes. Less well known is the deeper karst in the Chalk which has a strong stratigraphical control related to particular beds in the Chalk. This type of karst has a profound effect on engineering operations and groundwater movement.

Hardgrounds, semi-tabular flint bands, sheet flints and marl seams can all act as local surfaces above which karstic openings can develop. The elevation of any such surface can change depending on the sedimentology as well as tectonic dip. The coastal cliff section west of Veulettes-sur-Mer exposes hardgrounds that have formed on synsedimentary erosion surfaces (Figure 14). Karstic openings and cave systems follow these surfaces through the exposure.

In the Chalk cliffs on the west side of Dieppe, the semi-continuous, 150-200 mm thick Seven Sisters Flint band has a spectacular karst system developed above it related to an underground stream. The stream was fed by a series of dissolution pipes in the top of the 60 m high cliffs (Figure 15).

Sheet flints form thin (20-50 mm thick) continuous subhorizontal layers (Figure 16). These impermeable layers commonly have karst systems developed above them. One such system encountered on the A27 Brighton Bypass in Great Wood Cutting contained an up to 2 m thick unit of altered chalk (Lamont-Black and Mortimore, 2000). Such loss of material can affect earthworks cut and fill balance calculations as well as producing wet, 'putty-chalk' conditions.

Groundwater stratigraphy

There are several aspects to the groundwater stratigraphy in the Chalk. Each of the Chalk formations, because they have particular fracture styles and frequencies, also have different aquifer properties in terms of storativity, transmissivity and groundwater fracture flow characteristics. An estimated fracture volume per chalk formation in the South Downs is based on fracture data collected in local quarries, sea-cliffs and from road cuttings. The nature of a fracture surface or fill material (rough or smooth,clean chalk surface, polished, clay-smeared, slickensided or sheet-flint fill surface), is likely to control both flow characteristics and the rate of interaction between the pores and the fractures.

In addition, each type of chalk lithology has a different pore structure based on the type of nannofossil that forms the bulk of the rock and the type and degree of diagenesis that has taken place. A texture analysis of the chalk, related to physical property measurements (intact dry density and porosity), illustrates the possible range of chalk material (Mortimore, 1979; Mortimore and Fielding, 1990).

As in the case of karst development indicated above, certain beds of chalk act as local horizons of groundwater flow in both the saturated and unsaturated zones (Figures 7 and 8). These flow horizons can be identified throughout the region by comparing resistivity and gamma-ray borehole logs with salinity and differential temperature borehole logs (Figure 7).

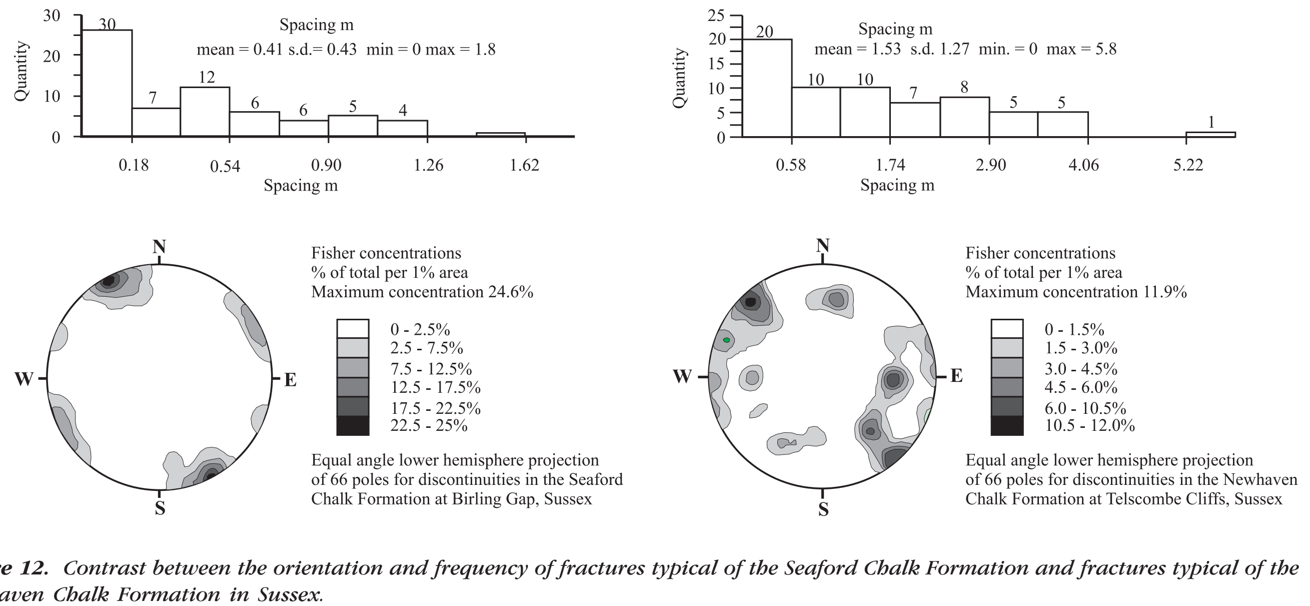


***Figure 12.** Contrast between the orientation and frequency of fractures typical of the Seaford Chalk Formation and fractures typical of the Newhaven Chalk Formation in Sussex.*

quarry exposures in the area where the flints could be studied, collected and tested. Extra boreholes would be needed to confirm the stratigraphy. The strategy was as follows.

(i) The first stage was a re-examination of pre-existing boreholes to obtain the detailed stratigraphy, to establish the dip of strata and to determine whether faults were present which might bring large flints into the tunnel face. Unfortunately, because the site investigation had been completed several years previously, not all cores were still available, nor were the cores kept in good conditions. It was necessary, therefore, to augment the available core data with two further boreholes. These needed to be deep enough to be sure of encountering, critical, easily recognised marker beds.

(ii) The second stage, following the field and core logging exercise, was to review flint band frequency, flint type and flint size at the tunnelling horizon. All likely geological variations and data errors were also needed to be considered such as lateral change in thickness of chalk between flint bands, faulting, change in dip, depth errors to flint bands in the core boxes as well as possible levelling errors.

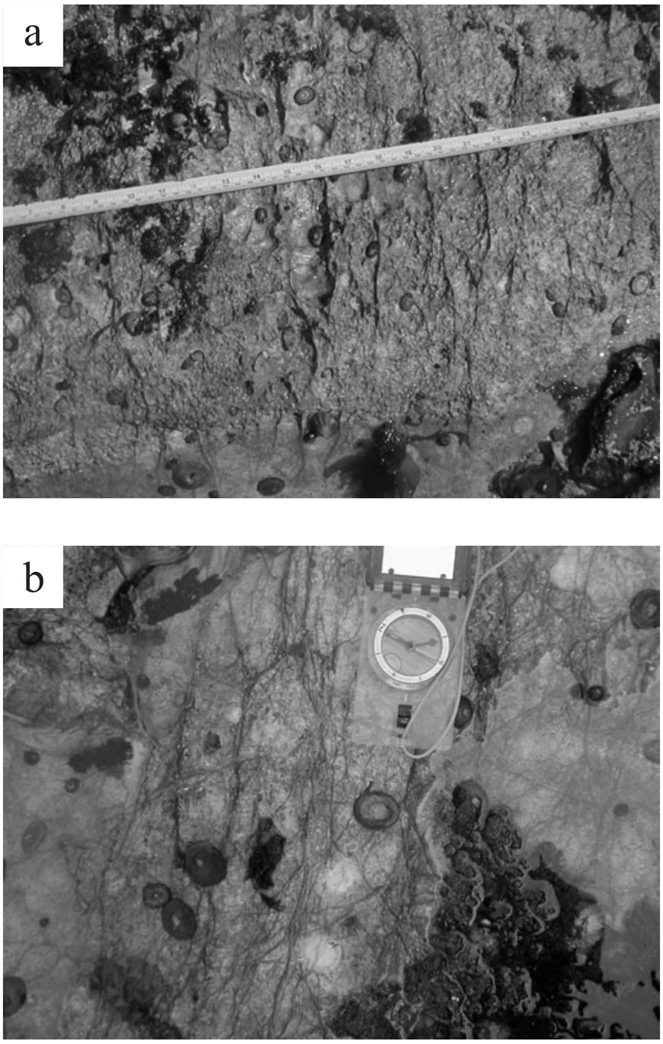


Figure 13. *Vein fabric typical of many levels in the Chalk. Calcite veins have a preferred orientation (Mortimore, 1979) and influence strength tests.*

The results of the analyses (Brighton University and Mott MacDonald, 1994) were used to make decisions on the machine design and tunnelling horizon. The Iseki Unclemole was sent back to Japan to be reinforced and by re-aligning the tunnel elevation a tunnelling horizon that avoided most of the larger flint bands was chosen. The success of this exercise was entirely related to being sure of the stratigraphy. The tunnel was constructed in the lower part of the Culver Chalk Formation (Tarrant Chalk Member). In three boreholes, the distinctive marl seams at the top of the Newhaven Chalk Formation including the Meeching, Telscombe, Castle Hill and Pepper Box marls, were all recognised. In addition, the conspicuous flint bands in the basal Culver Chalk Formation including Castle Hill Flint bands 4 and 5 and the Lancing Flint Band, were identified in all boreholes. This marker bed stratigraphy made the correlation and determination of all other aspects of the geology of the site possible.

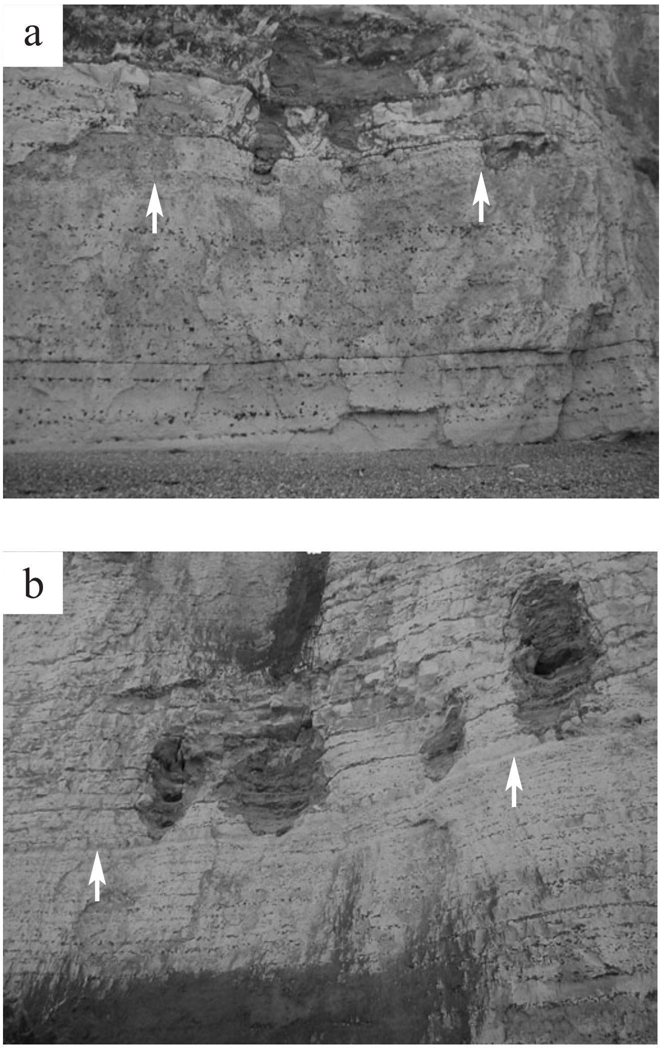


Figure 14. *Karst features in chalk related to bedding structure: a hardground forms the floor to the dissolution effects and a sediment-filled cave system develops upwards from this surface, Veulettes-sur-Mer, France. (a) and (b) the arrowed surface is a hardground in the Belle Tout Beds of the Seaford Chalk Formation*

Marl seam stratigraphy and numerical modelling

Marl seams are often missed in core-logging. They are also frequently 'spun-out' during drilling. Marl seams, however, are vital as marker beds, as aquicludes and as bedding features which cause redistribution of stresses around tunnel openings. This was well illustrated for the Channel Tunnel Rail Link (CTRL) North Downs Tunnel through the Holywell Nodular Chalk, New Pit Chalk and Lewes Nodular Chalk formations (Watson *et al*., 1999; Warren & Mortimore, in press). In UDEC and 3DEC modelling for the North Downs Tunnel the combination of

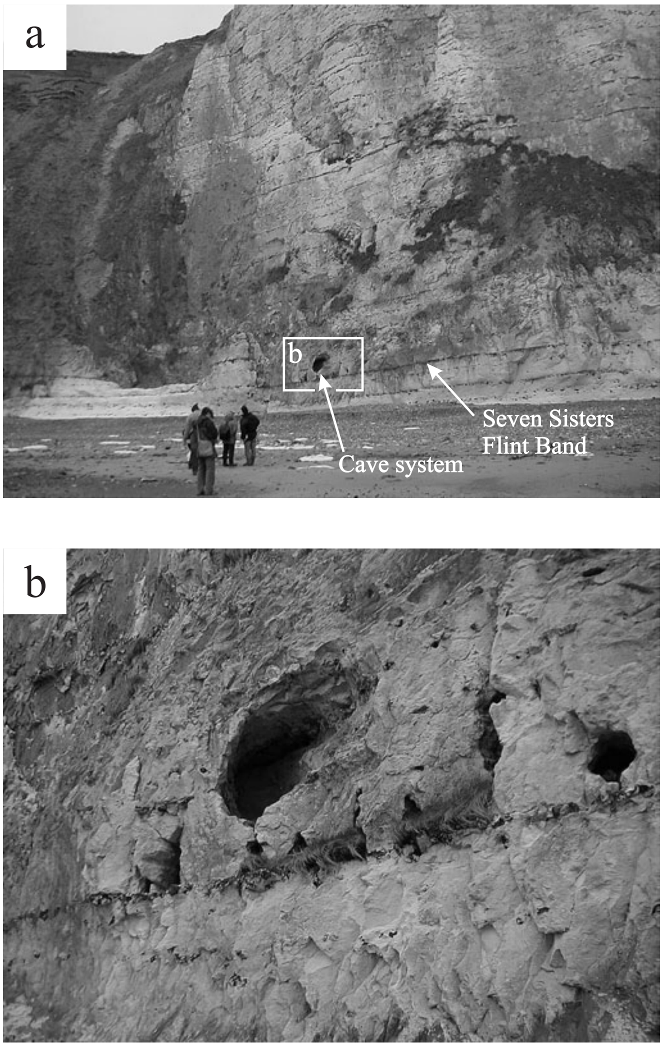


Figure 15. *Karst developed above the Seven Sisters Flint band, Dieppe. An underground river, fed by an overlying dissolution pipe system, flowed almost parallel to the present cliff line.*

Slope stability stratigraphy

Slope failures in the Chalk of Europe occur regularly with a variety of scales and mechanisms. Hutchinson (1971) illustrated a common type of failure at Joss Bay in Kent. Hutchinson (1988) also identified the potential for chalk to produce flow slides at lower volumes of failing rock than in any other rock type. What has not been illustrated before is the relationship between style, mechanisms and scale of failures to the lithostratigraphy.

As each formation has its own style of fracture and characteristic fracture surface or fill, slope failure mechanisms are very closely related to the formations. This difference is illustrated by cliff and quarry face profiles. The Seven Sisters typically have a vertical cliff profile related to vertical joint sets in the Seaford Chalk Formation (Figure 17). This same style of fracture is present in the Seaford Chalk Formation on the French coast at Yport, St Valery and Veulettes-sur-Mer. In contrast, the Holywell, New Pit and Newhaven Chalk formations have conjugate, slickensided or clay smeared fractures and these produce a pyramidal form of slopes in an irregular cliff profile (Figure 18). Some horizons within the Holywell and New Pit Chalk formations are more intensely fractured with conjugate sets. These include the Meads Marls-Holywell Marls interval and the Glynde Marls interval. This results in very dangerous cliff faces with many slides. Similarly, in the Newhaven Chalk Formation the interval containing the Roedean and Rottingdean Marls is more intensely fractured along the coast between Newhaven and Brighton. However, in the Newhaven Chalk sheet-flint fills are common, producing a potentially different shear strength compared to the Holywell and New Pit Chalk formations (Figure 19).

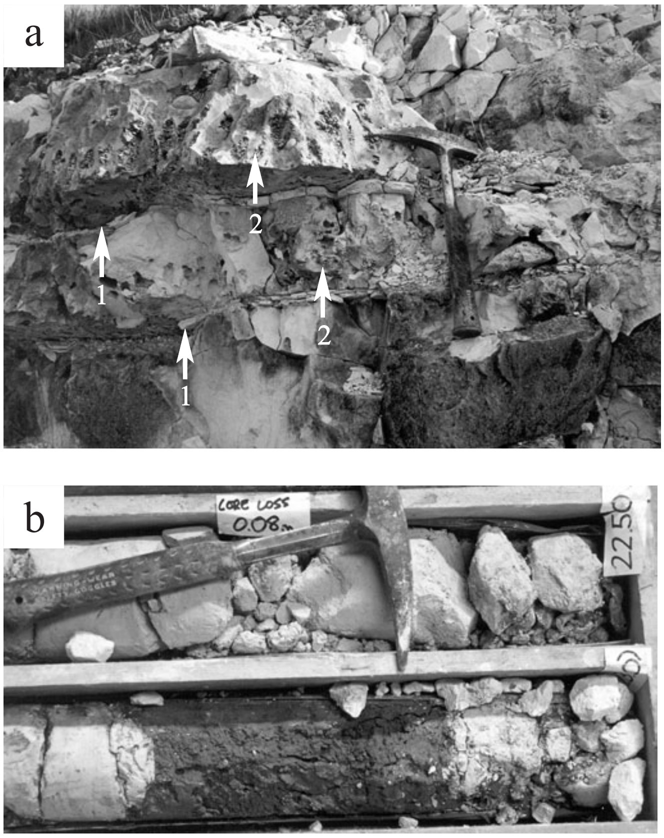


Figure 16. *(a) Sheet flints (1) and tubular karst (2), North Barn Quarry, Dorset. These layers of karst develop very hard (calcreted) chalk which form layers that can be traced across the Downs. (b) Sheet flints, tubular karst and karst developed above the Bridgewick Marl recovered in borehole cores.*

Slope failures during construction at the north portal of the Cuilfail Tunnel, Lewes, occurred on the 60-70^0 dipping, clay-smeared, slickensided conjugate fracture sets in the upper beds of the New Pit Chalk Formation. Collapse of cliffs at Compton Bay, Isle of Wight (Barton, 1990) is controlled by the same style of inclined conjugate joint sets in the Holywell Nodular Chalk and New Pit Chalk formations. Slope failures in foundation excavations and in cuttings on the A27 Brighton Bypass at Great Wood and Marquee Brow (Lamont-Black, 1995) were caused by clay-smeared, conjugate fractures in the Newhaven Chalk Formation. In contrast, the M25 chalk slopes in Highlands Farm and Addlestead Wood cuttings, Leatherhead, are in the Seaford Chalk Formation with predominantly vertical joint sets and slope failures are limited to relatively small scale spalling of chalk and flint fragments.

In addition to the control exerted on mechanisms of slope failure by the style and type of fractures in each Chalk formation, the nature of the material resulting from a slope failure is also stratigraphically controlled. The pure white, vertically jointed Seaford Chalk Formation produces smaller blocks and a higher percentage of fines than the more massive Lewes Nodular Chalk Formation (e.g. the Puys failure, Dieppe, Duperret *et al*., 2001).

Earthworks stratigraphy

Chalk earthworks, involving excavation, transportation to the fills, placing and compaction to a specification has been a problem ever since heavy plant was returned from the African Ground Nut scheme in the 1950s and was employed on chalk. ‘Soft’ chalk, yielding high percentages of fines and producing ‘putty’ conditions resulting in delays and knock-on costs, led to restrictive specifications which, like the Mundford Grading Scheme (see above), were applied indiscriminately to all chalk earthworks. Other chalk earthworks on the A26/A27 (1976-79) junction, the material used from the Round Hill Tunnel,

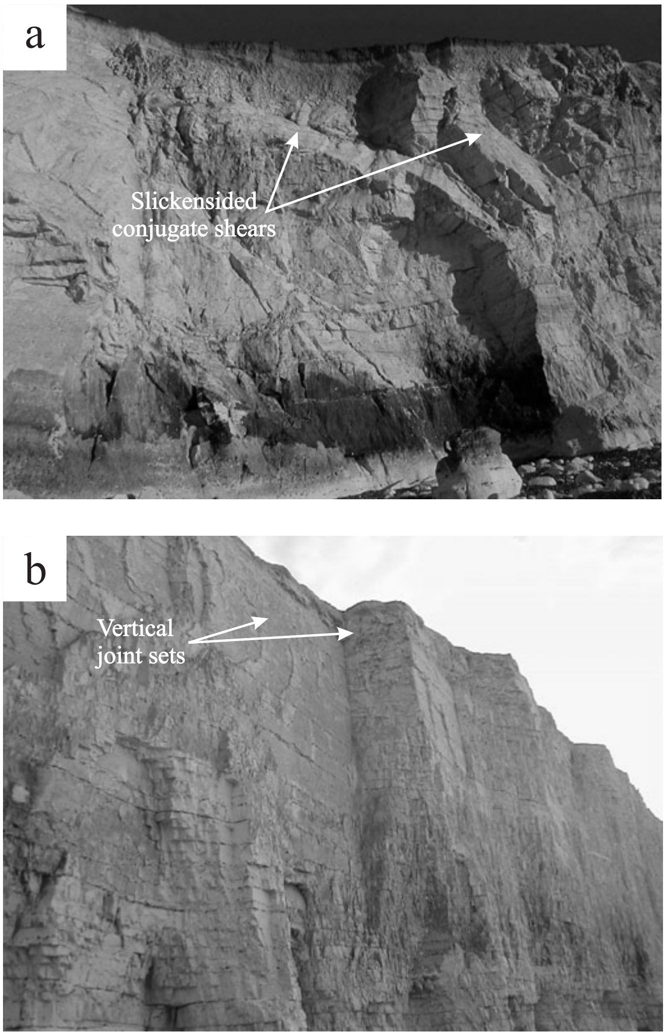


Figure 17. Contrasting cliff profiles related to fracture styles in different Chalk formations. a. Newhaven Chalk Formation, Seaford Head, predominatly slickensided, conjugate shear joints b. Seaford Chalk Formation, Seven Sisters, Sussex, predominantly vertical joint sets.

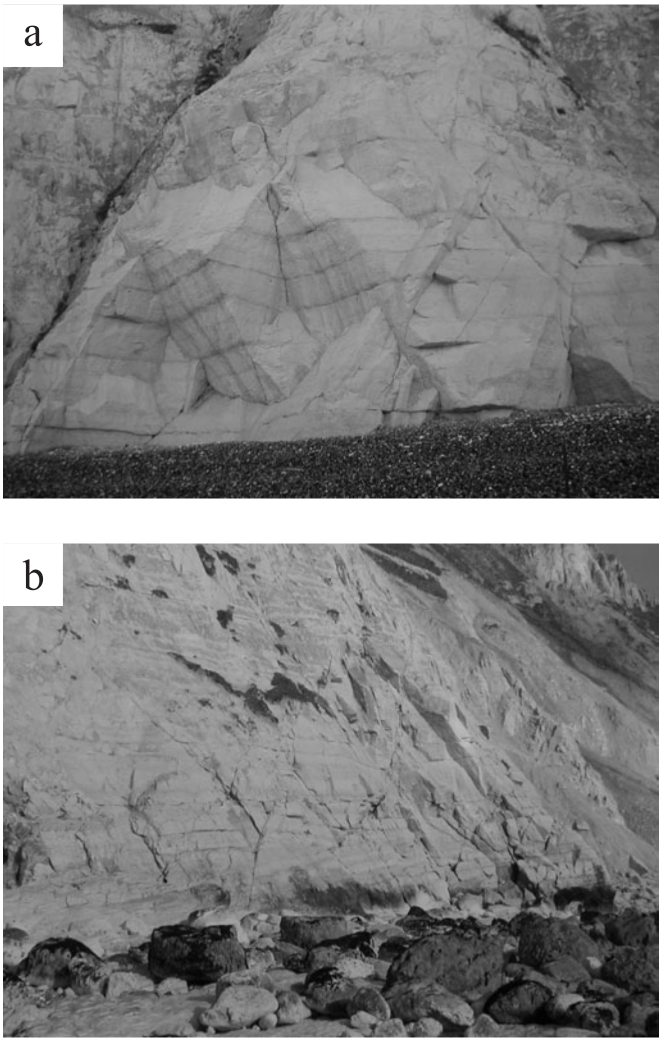


Figure 18. Comparable cliff profiles related to the same fracture style in the same Chalk formation (conjugate, slickensided shears). a. Holywell Nodular Chalk Formation, St. Martin Plage, Seine Maritime, France b. Holywell Nodular Chalk Formation, Beachy Head, Sussex.

Folkestone, and the material from the M3 Twyford Down Cutting (Figure 20) yielded massive, blocky chalk (>1 m^3). Excavation, even with the largest CATs, was sometimes difficult. At the A27 Southerham Roundabout, Lewes, massive Chalk from the very thickly bedded Jukes-Browne Bed 7 and from the Lewes Nodular Chalk Formation in Cliffe cuttings, required extra plant (peckers and hydraulic jacks) to break blocks down into a manageable size before placing in the fills. Compaction of large blocks of hard nodular chalk from the Lewes Nodular Chalk Formation at Home Farm Industrial Estate, Moulsecoombe, Brighton, required additional compaction methods to form the stable embankment on which the industrial estate was partly constructed. At the same stratigraphic level through the Lewes Nodular Chalk Formation in the M3 Twyford Down, heavy plant was used to track over the lumpy fill as a pre-compaction method of breaking the material down.

A plot of 'soft' and 'hard' chalk earthworks against the stratigraphy produces a strong correlation. In some situations there may be limited layers of 'soft' chalk interbedded with harder bands or vice versa (Figure 21). There are regional differences that must also be considered related to Upper Cretaceous palaeogeography (Mortimore *et al*., 1990, 2001).

Discussion

Stratigraphy has proved to be the fundamental framework for investigating all applied aspects of the Chalk. On a small-scale the marl, flint and fossil associations provide a correlation framework essential to core-logging and construction of engineering and hydrogeological cross-sections. Macro-fossil biostratigraphy is an essential support. Some horizons are unmistakable, including trace fossils such as *Zoophycos*, Cuilfail *Zoophycos* and Beachy Head *Zoophycos*. The absence of macrofossils producing barren beds is equally useful. Carter and Hart (1977) and Harris *et al*. (1996) illustrated how microfossils could be used to aid correlation of the chalk on construction projects. Harris (Channel Tunnel) and Wright (Ipswich Orwell Tunnel, in prep) have refined and developed the micro-biostratigraphy for parts of the succession to assist in 'bio-steering' tunnelling machines through difficult ground, to stay in a particular part of the column or to avoid flints. Bailey and colleagues at Network Stratigraphic Consulting Limited (pers. comm) have developed the nanno and micro-biostratigraphy for the North Sea Chalk reservoirs to such an extent that they can bio-steer drill-strings during horizontal well construction under hydrocarbon fields for water flooding operations.

Despite the successes, the uses and limitations of each aspect of the stratigraphy need to be considered. While it can be used very widely, there are parts of the Chalk column where the lithostratigraphy on its own is not easy to apply and fossils must also be used. There are also parts of the column where microfossils are of limited use, only providing very broad horizon identifications (e.g. in the Upper Santonian crinoid zones). With the greater knowledge we now have, it is possible to divide up the

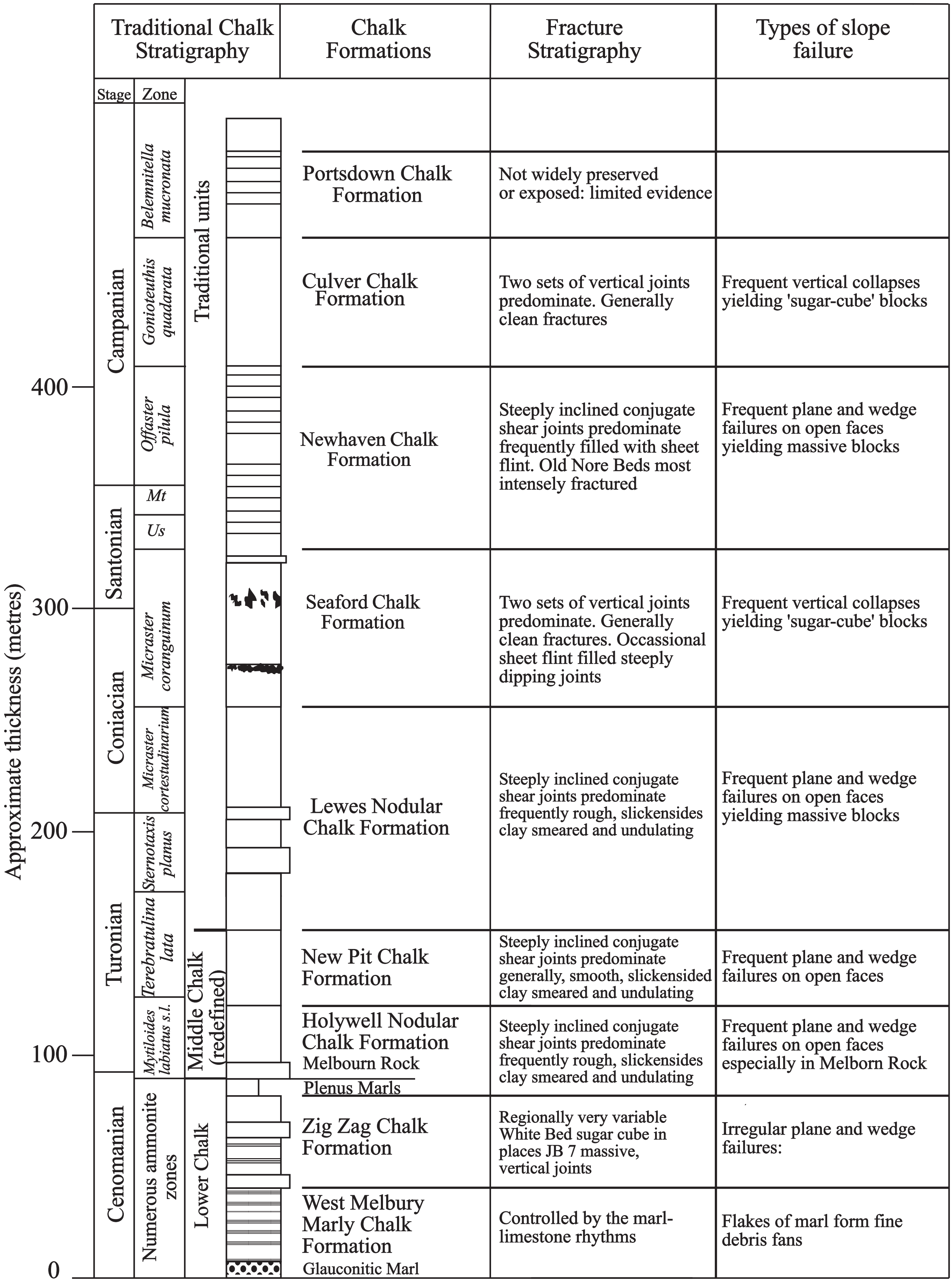


Figure 19*. Fracture stratigraphy for the Chalk of southern England.*

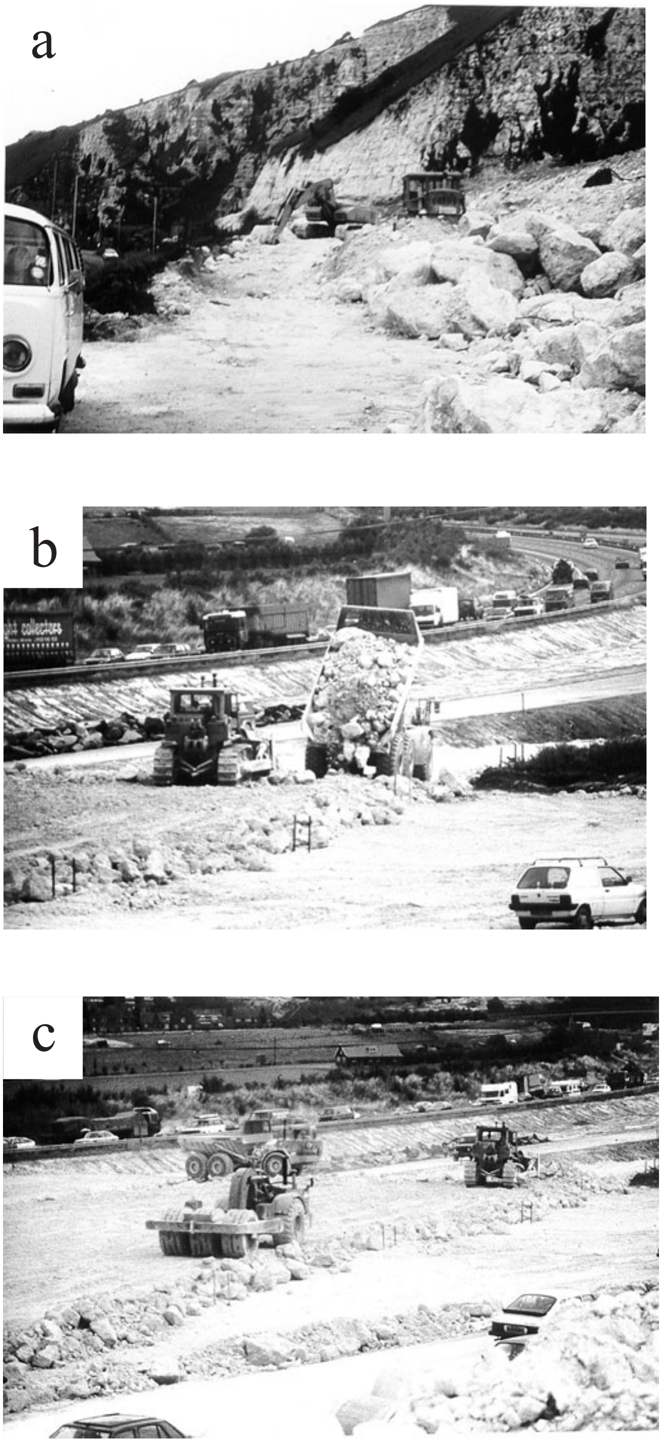


Figure 20. *Most Chalk earthworks in southern England take place in the Seaford Chalk Formation in 'soft' chalks. Where the Lewes Nodular Chalk Formation has been encountered in Sussex and Hampshire then 'hard' blocky chalks have resulted which required methods of block reduction not normally included in Chalk earthworks specifications. (a) A26 South Street, Lewes large blocks (>1 m^3) from the Lewes Nodular Chalk Formation required peckers and hydraulic jacks to break blocks before being transported to the fill areas. (b) Large blocks (>1 m^3) from the Lewes Nodular Chalk Formation in the Twyford Down cutting required extra trafficking in the fill areas with the caterpillar before compaction with the roller. (c) The majority of Chalk earthworks highway embankment construction specifications require Chalk to be placed in 200-300 mm layers prior to compaction. Knowing which stratigraphic layers will yield large blocks assists earthworks planning.*

rock column illustrating which method or combination of methods is the most appropriate to identification of the stratigraphic level.

Having developed a Chalk lithostratigraphy that can be applied to large-scale features and geological mapping (Bristow *et al.*, 1997) and to engineering ground profiles, the next stage is the production of more specialist maps showing the distribution of flint, marl and nodular chalk with a summary engineering stratigraphy and palaeogeography. Material properties of porosity/density also show a strong stratigraphic and palaeogeographic distribution (Mortimore *et al.*, 1990; Mortimore and Pomerol, 1998; Bloomfield *et al.*, 1995). The broad and local controls on chalk sedimentation history and physical property distribution (e.g. the relationship between density and bedding dip, Mimran, 1975) also need to be investigated and mapped.

The stratigraphic analysis of fracture distribution in the Chalk further illustrates the importance of having a stratigraphic framework for collecting data. Differences that have been observed between Chalk lithological units includes style, dihedral angle, frequency – and nature of fracture fill material. While this aspect of the Chalk has been tested in southern England and the Paris Basin, further work is required to establish what happens on the Anglo-Brabant Massif of the Chiltern Hills and East Anglia (Mortimore *et al.*, 2001).

There has been a general assumption that Chalk karst is primarily related to the development of vertical dissolution pipes developed from the sub-Palaeogene or sub-Quaternary surface. However, the major, deeper-level karst horizons illustrated here show a strong relationship with stratigraphy and predicting such horizons has proved possible once the overall stratigraphy and geological setting has been established.

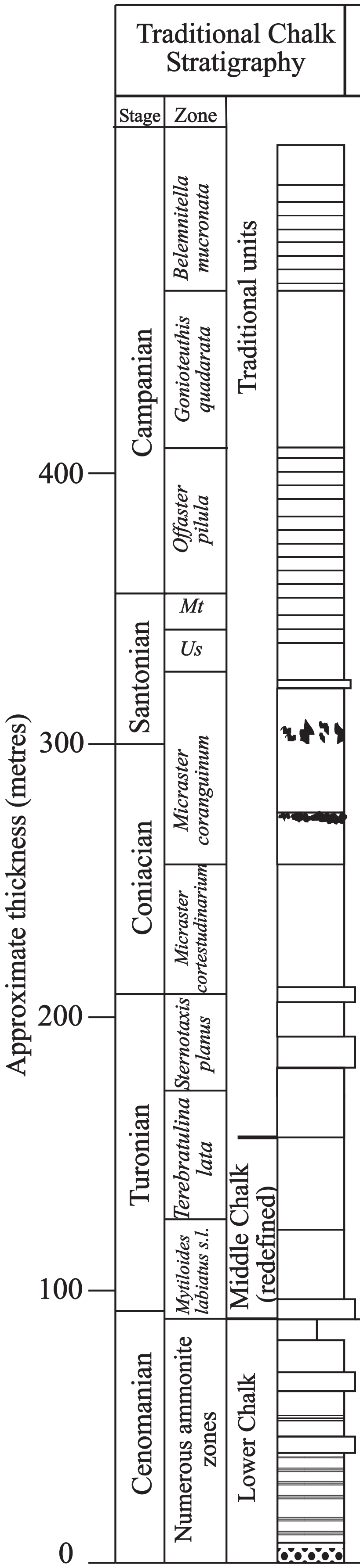
Monitoring the engineering performance/behaviour of chalk in earthworks, tunnels and slopes has shown that the stratigraphy can be usefully applied. There are, however, local lateral differences that must also be considered (Mortimore *et al.*, 1996). This requires knowledge of chalk sedimentary processes and tectonics as well as stratigraphy.

Conclusions

This study of the Chalk, taking a basin analysis approach, illustrates that a regional engineering geology is possible once a reliable stratigraphic framework has been established.

Are our expectations too great? We cannot yet always be specific about the geology at a point in a tunnel in terms of fracturing and potential block-release. However, we can provide better data that enhances predictive models. Machines need specific conditions for optimum operational efficiency and have reduced tolerances to variable ground conditions. As machines, construction processes and aquifer development and protection become more sophisticated and demanding we need more geological data not less. The successful use of computer generated numerical models such as UDEC/3DEC or VULCAN, also requires real geological field data. With the current stratigraphical information it is possible to provide that data and, for example, divide lengths of tunnel, cliff or cutting into sections with a particular geology, providing a more accurate basis for costing alternative construction methods. This would not have been possible 20 years ago.

In the past, the right geological information has not always been obtained or recorded from the Chalk and this has led to great information loss in the UK. This work is an attempt to redress that loss by being involved with construction projects, recording temporary exposures, logging as many cores as possible and contributing to the interpretation of geophysical borehole logs. The stratigraphic framework that has developed as part of this work is being continually refined as each site investigation and construction project contributes new information. It is hoped that the next 20 years will see a new engineering geology and hydrogeology for the Chalk based around the detailed stratigraphy, sedimentology, tectonic structure and geomorphology in the form of maps and 3D models.



Chalk Formations	Stratigraphy in relation to excavation	Stratigraphy in relation to placement and compaction
	NB: 'soft' and 'hard' dig are contractors terms reflecting the ease with which mechanical shovels can break into the chalk	NB: 'soft' ground 'putty' chalk and 'spongy' embankments are contractors terms for different types of 'instability' of chalk developed during earthworks
Portsdown Chalk Formation	Not widely preserved, exposed or used	Not widely preserved, exposed or used
Culver Chalk Formation	'Soft' chalk excavation easily excavated with mechanical diggers	Readily breaks down to high percentage of fines yielding putty conditions and spongy fills (A35 Dorchester Bypass, M27 Portsdown)
Newhaven Chalk Formation	'Mixed soft and hard 'dig' Soft' chalk excavated easily hard dig difficult to break blocks out even where 3m high benched excavations are used. Interlocking blocks of hard chalk the result of conjugatejoint sets	Mixed 'soft' and 'hard' material placed ranging from a high percentage of fines giving 'putty conditions (A27 Round Hill, Brighton) to many large blocks in the fill area requiring extra comapction (A27 Hangleton Cutting and adjacent fills)
Seaford Chalk Formation	'Soft' chalk excavation easily excavated with mechanical diggers.. Lateral variation - generally higher density, lower porosity in South Downs compared to North Downs	Readily breaks down to high percentage of fines yielding putty conditions and spongy fills (A249 North Downs borrow pit; M25 Badgers Mount cuttings, Kent) Ideal material when harder (A27 Contract 1 Brighton; A27 Juggs Lane Cutting, Lewes)
Lewes Nodular Chalk Formation	'Mixed soft and hard 'dig' Soft' chalk excavated easily hard dig difficult to break blocks out even where 3m high benched excavations are used. Interlocking blocks of hard chalk the result of conjugate joint sets (M3 Twyford Down; A26 Lewes)	Mixed 'soft' and 'hard' material placed ranging from a high percentage of fines giving 'putty conditions to 'many large blocks in the fill area requiring extra comapction (M3 Twyford Down; A26 Lewes)
New Pit Chalk Formation	Medium to hard dig, using mechanical diggers; interlocking blocks	Nearly ideal material (e.g. lower part of M25 Polhill Cutting, Kent)
Holywell Nodular Chalk Formation Melbourn Rock	Generally hard dig with mechanical diggers	Where fresh and massive requires more compactive effort: often used as capping layer, obtained from local quarries
Plenus Marls Zig Zag Chalk Formation	Regionally very variable White Bed sugar cube in places JB 7 massive, hard dig (A27 Southerham Lewes)	Mixed 'soft' and 'hard' material placed: hard massive blocks, A27 Southerham, Lewes, A20 Roundhill, Folkestone
West Melbury Marly Chalk Formation Glauconitic Marl	Controlled by the marl-limestone rhythms	High percentage clay minerals optimum moisture content

Figure 21. *An Earthworks stratigraphy for the Chalk of southern England based on direct observations and records from major highway construction projects.*

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It would not have been possible to investigate the Chalk in the whole of the Paris Basin without the support of Dr. Bernard Pomerol, University Paris Val de Marne over more than 20 years. With Bernard, the new autoroutes A26 (Calais – Troyes), A5 (Montreau – Troyes) and A16 (Calais – Rouen), as well as hundreds of field sections were investigated and the engineering performance of the chalk observed. Latterly, Anne Duperret (Le Havre) and many colleagues at BRGM in Orelans (Albert Genter) and Brest (Pierre Watramez) have contributed to the investigation of Chalk cliff stability along the Channel coast.

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