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A geological model of the North Downs of Kent: the River Medway to the River Great Stour

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A geological model of the North Downs of Kent: the River Medway to the River Great Stour

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Key words

Chalk, geological model, Kent, North Downs, Palaeogene, drift.

Front cover

The mineralised Rochester Hardground (at the base of the hammer shaft), forming the top of the .Lewes Nodular Chalk, is overlain by the basal Seaford Chalk at the Doddington Pit, near Sittingbourne [TQ 921 567]. Dissolution cavities have formed along a marl seam .

Bibliographical reference

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Summary

This report describes the geological modelling of the North Downs in Kent, between the River Medway at Chatham and the River Great Stour at Canterbury, and north to the Thames estuary. This work was co-funded by the Environment Agency to support an investigation of the local hydrogeology, with particular reference to maintaining spring flow in the North Kent marshes.

Most of the area is underlain by the Upper Cretaceous Chalk Group. The Palaeogene Thanet Sand Formation, the Lambeth Group and the Thames Group occur in the north.

The project included a desk study revision of the Chalk of the North Downs, using the new Chalk lithostratigraphy. The revisions to the geology are shown on the 1:50 000 scale geological map which accompanies this report. Together with evidence from boreholes and from seismic surveys, the new outcrop patterns have been incorporated into a geological model, using both computer software (earthVision) and manual methods.

The introduction describes the background to the project. The subsequent chapter describes the sources for the data used in the model: published and unpublished geological maps, borehole records, seismic surveys, biostratigraphic collections and records, and the published literature.

Each Chalk formation present in the area is briefly described, noting its relationship to the older lithostratigraphic divisions, and to biostratigraphic zones. The local Chalk sequence extends from the base of the Chalk Group to high in the Seaford Chalk Formation.

The early Palaeogene formations (the Thanet Sand, the Upnor Formation, the Woolwich Formation and the Harwich Formation) and the major local superficial deposits are also briefly described. Apart from minor adjustments to the outcrop of the basal surface, no revision of these formations was done for this study.

An account of the processes that led to the generation of the geological model includes notes on their inherent limitations, and on the criteria used to subdivide the Chalk according to the new lithostratigraphy.

A discussion of the structure starts with observations on the kinds of influence exerted on the Chalk by tectonic structures, and on the difficulties of specifically identifying faults in the Chalk. Evidence for folding and faulting both subparallel to strike and subparallel to dip is described.

Geological factors influencing the local hydrogeology are noted. It is likely that most groundwater movement in the Chalk occurs in the Seaford Chalk and the Lewes Chalk. There is a distinct possibility that a dual control constrains the position of the major spring-line at the northern foot of the North Downs: a relatively impermeable, clay-rich facies in the lower part of the Thanet Formation is combined with concentration of groundwater flow on north-north-east trending fracture zones within the Chalk.

1 Introduction

The Environment Agency (EA) requested the British Geological Survey (BGS) to provide information on the geology of part of North Kent, to support an investigation of the local hydrogeology, with particular reference to maintaining spring flow in the North Kent marshes.

This report describes the structure of the Upper Cretaceous Chalk and the overlying early Palaeogene deposits of North Kent, with reference to a three dimensional (3D) geological model and a number of two dimensional (2D) surfaces portrayed as structure contour plots.

The area described in this report spans the Chalk outcrop from the River Medway at Chatham east to the River Great Stour at Canterbury. It also extends north across the Palaeogene outcrop to the Thames estuary, including the Isles of Sheppey and Grain (Figure 1). The North Downs escarpment forms the most prominent topographical feature. This is formed by the Chalk Group, which underlies most of the area. The Chalk dips gently northwards, progressively disappearing beneath a cover of Palaeogene and Quaternary deposits north of a line between Chatham and Canterbury.

Traditionally, the Chalk was divided into three units, effectively of formation status: the Lower Chalk, the Middle Chalk and the Upper Chalk. Named members or beds within these units, such as the Glauconitic Marl, the Melbourn Rock and the Chalk Rock (which occur at the respective bases of the three traditional units) were widely recognised (Table 1). However, following work by Mortimore (1986) and by Bristow et al. (1995), it was found that a more detailed lithostratigraphic subdivision of the Chalk was possible (Bristow et al., 1997). Following further discussion, it was proposed that the Chalk Group be divided into an older Grey Chalk Subgroup and a younger White Chalk Subgroup, the boundary between being placed at the base of the Plenus Marls, slightly below the base of the traditional Middle Chalk (Rawson et al., 2001). Each subgroup was further divided into formations (Table 1) which now form the basis for the mapping of the Chalk across southern England, and which are used in this study. The formations are described in Section 3.

The correspondence of biostratigraphic zones with the lithostratigraphic scheme used here is shown in Table 1, and described by Mortimore et al. (2001). The biostratigraphical significance of fossil material in the BGS collections and documented in the BGS memoirs is discussed by Woods (2002a).

A 3D geological model was constructed digitally using datasets from seismic surveys, borehole logs (both lithological and geophysical), digital topographic information, palaeontological records and geological field records, as outlined in Section 2. New geological boundaries subdividing the Chalk outcrop according to modern lithostratigraphy (Section 3) were compiled, using the criteria outlined in Section 6. This new linework was used, together with the other datasets, to compile a 3D computer model from which gridded surfaces and cross sections could be generated. In addition, surfaces representing the base of the Palaeogene, and two formation boundaries in the upper part of the Chalk were compiled manually.

The surface geology of the area is shown on the 1:50 000 scale geological map which accompanies this report.

A companion report discusses the Palaeogene deposits in more detail, and assesses the possibilities for improving the geological understanding of that part of the sequence (Aldiss and Farrant, 2002).

2 Data Sources and Acquisition

2.1 1:50 000 SCALE GEOLOGICAL MAPS AND OTHER PUBLICATIONS

Four 1:50 000 scale geological maps, published by the BGS, cover the project area (Figure 1). These maps are essentially reprints of the 'New Series' one-inch (1:63 360) sheets transferred onto new 1:50 000 scale base maps with only minor revision.

The maps all use the traditional three-fold subdivision of the Chalk: none show the new lithostratigraphic scheme developed for the Chalk over the last ten years (Sections 1 & 3). The relationship between the geological boundaries shown on the published maps with those newly compiled for the map which accompanies this report is described in relevant parts of Section 3. In summary, the base of the Chalk remains at the base of the Glauconitic Marl; the base of the Holywell Chalk is slightly lower than the base of the Middle Chalk; and the base of the Lewes Chalk is significantly lower than the base of the Upper Chalk (Table 1).

The classification of the Palaeogene deposits used on the published maps has also been revised (Ellison et al., 1994), as discussed in the companion report (Aldiss and Farrant, 2002).

Sheet 272 (Chatham) is based on six-inch scale (1:10 560) surveys in 1937-38 and was republished at 1:50 000 scale in 1977 with only minor revision. The memoir was published in 1954 and later reprinted (Dines et al., 1971).

Sheet 273 (Faversham) is based on six inch surveys in 1937-46 and republished in 1974 with only minor revision. The memoir was published in 1981 (Holmes, 1981).

Sheet 288 (Maidstone) is based on six inch surveys in 1946-50 and was republished in 1976 with only minor revision. The memoir was published in 1954 and later reprinted (Worssam, 1963).

Sheet 289 (Canterbury) is based on six inch surveys in 1938-55 and was republished in 1982 with only minor revision. The memoir was published in 1966 (Smart et al., 1966).

Other published geological literature which was consulted is noted where relevant, and listed in Section 10.

2.2 FIELD SLIPS AND STANDARDS

The area was geologically surveyed at 1:10 560 scale by S C A Holmes, H G Dines, B C Worssam, J G O Smart and F H Edmunds. Much lithostratigraphic and biostratigraphic data are recorded on the copies of the relevant 1:10 560 scale Ordnance Survey topographic maps annotated by the field geologist during the field survey. The data density and quality are variable, depending on the degree of exposure and on the surveyor.

These large-scale maps mostly show contours at a vertical interval of only one hundred feet [30.5 m]. This significantly constrains the precision with which the geological boundaries could be plotted.

Fair-drawn copies of the geological maps were compiled at 1:10 560. These maps, known as 'standards', are also annotated with local geological information. The 1:63 360 scale geological maps were compiled from the standards.

The field slips and standards are held in the National Geological Records Centre (NGRC) at BGS Keyworth.

2.3 BOREHOLE LOGS (LITHOLOGICAL)

Records of thousands of boreholes in the area between the River Medway and the River Great Stour are held in the National Geological Records Centre. These records are of variable age and quality and many were found to lack useful lithological (or lithostratigraphical) information, the descriptions being too vague, imprecise or inaccurate. Some 1454 borehole logs were found to provide information about at least one stratigraphic boundary, although not all of these could be incorporated into the 3D model or 2D contoured surfaces (Section 6.1).

Where possible, the level of each stratigraphic boundary recorded in these logs was determined and converted to elevation with respect to Ordnance Datum. In many cases only the level of the top Chalk surface could be determined. None of the boreholes had been previously interpreted using the new Chalk lithostratigraphy.

In the north of the area (on sheets TQ97NW, 97SW, 87SW, 87NE, 87NW, and 77SE) very few boreholes penetrate the base of the Lewes Chalk (Section 3.7). In order to constrain the deeper levels of the 3D geological model in that area, ‘phantom data points’ were introduced. Borehole logs intersecting the top of the Chalk beneath the Palaeogene were extrapolated downwards to the depth to the base of each of the new Chalk formations, using an estimated thickness for each. Although this is better than no data, it should be emphasised that the thickness of each unit is known to vary somewhat across the area, and so these ‘phantom data points’ are correspondingly uncertain.

2.4 BOREHOLE LOGS (GEOPHYSICAL)

Geophysical borehole logs (natural gamma and resistivity) were collated from BGS archives, the Environment Agency and Southern Water. These were interpreted in terms of the new Chalk stratigraphic units. The stratigraphic interpretation of the boreholes is based on work by Mortimore and Pomerol (1987) and Murray (1986) and is described more fully by Woods (Woods, 2001, 2002b).

2.5 SEISMIC DATA

The availability of seismic data in the region is shown in Figure 2. Most of the seismic surveys were carried out for hydrocarbon exploration of the Weald Basin in the late 1970s and early 1980s. However, the North Downs area was considered to be a poor prospect and most of the seismic surveys terminate a short distance into the Chalk outcrop. The seismic data that occurs within the area has been processed and interpreted for the respective bases of the Lewes Chalk, the Holywell Chalk and the West Melbury Marly Chalk.

2.6 BIOSTRATIGRAPHICAL DATA

Biostratigraphical determinations were obtained from BGS collections of Chalk Group macrofossils from 376 localities between the River Medway and the River Great Stour (Woods, 2002a). Where possible, the biozonal information, together with any associated lithological observations, have been used to infer the lithostratigraphic unit (or units) occurring at each locality. In some cases, it is possible to infer the relative position within a formation (e.g. ‘higher part of Lewes Chalk’). Elsewhere, there is insufficient material available for re-assessment, and the only basis for the lithostratigraphical interpretation of a fossil locality is the published biozonal diagnosis in the memoir. It is possible that a modern biostratigraphic assessment of these localities would reach a different conclusion.

Moreover, the biostratigraphic data is quite variable in distribution. There is a wealth of data points for the Lewes Chalk and Seaford Chalk formations, and a relative lack of data for the remainder of the Chalk sequence. The New Pit Chalk Formation in particular has only a few data points for the entire area. Furthermore, much of the dip slope is covered by superficial or Palaeogene deposits and so there are very few exposures of the Chalk other than in old pits and quarries along the sides of the valleys.

2.7 TOPOGRAPHIC MAPS AND DIGITAL TERRAIN MODELS

Ordnance Survey 1:10 000 scale topographic maps, including contours at a five metre vertical interval, and Digital Terrain Models were used as an aid to compiling the new Chalk linework and to identify possible fault zones and joint systems. The availability of good topographic information aided the identification of topographic features which appear to mark geological boundaries (Sections 3 & 6).

3 The Chalk Group

The Upper Cretaceous Chalk Group comprises predominantly soft to medium hard, white to off-white, very fine-grained and extremely pure, homogeneous, micro-porous limestones with subordinate beds of clay-rich chalk (marl), hardgrounds, calcarenite and flints. The nomenclature for the Upper Cretaceous utilised in this district is shown in Table 1, where its relationship to the traditional scheme is also given. The current nomenclature is a development of the schemes devised by Mortimore (1983; 1986) and by Bristow et al. (1995; 1997), and adopted by the Geological Society Stratigraphic Commission (Rawson et al., 2001). An alternative scheme of lithostratigraphic nomenclature proposed for the Chalk of the North Downs by Robinson (1986) is also shown in Table 1. Following discussion (Mortimore, 1987; Robinson, 1987), it is generally considered preferable to use a single scheme for the whole of southern England (Mortimore et al., 2001; Rawson et al., 2001). However, the relationships between the units used in this report and those used in Robinson's scheme are noted in the following, to assist understanding of Robinson's numerous measured sections, which provided essential local information on the thickness of the Chalk formations.

The Chalk is divided into nine formations, of which six are present in the North Downs, in two Subgroups. Each formation is distinct in terms of overall lithological composition (nodular chalks, smooth white chalks, chalk marls, flinty chalks and so on) and rock mass character (density, porosity, strength, fracture style). These properties are in turn thought to influence the hydrogeological and engineering characteristics of the Chalk. For example, the fracture style is thought to influence the fracture/fissure volume, and (together with the presence or absence of chalk putty derived from the softer chalks) so also the hydraulic conductivity (Section 8).

The total thickness of the Chalk in the North Downs of Kent is generally about 207 – 213 m, falling to a minimum of 203.7 m recorded at Sheerness. Variations are probably due to local changes in thickness of the Holywell Nodular and New Pit Chalk formations, but especially of the Grey Chalk Subgroup (Dines et al., 1971).

3.1 GREY CHALK SUBGROUP

The Grey Chalk is divided into two formations, the West Melbury Marly Chalk and the Zig Zag Chalk (Table 1). It is essentially equivalent to the traditional Lower Chalk except that the topmost part of that unit, the Plenus Marls, is now included with the overlying Holywell Chalk. The Grey Chalk crops out along the lower third of the North Downs escarpment.

The Lower Chalk (including the Plenus Marls) of the Chatham District is usually about 60 m thick or more, and overall between 53 m and 72 m (Dines et al., 1971). At Boxley, in the Maidstone District, it is estimated at 58 m, at Boxley (TQ75NE) about 55 m at Harrietsham, Lenham and Charing, but only about 49 m at Hart Hill, between Lenham and Charing.

3.2 WEST MELBURY MARLY CHALK FORMATION

The West Melbury Marly Chalk underlies gently sloping ground at the base of the North Downs escarpment. It consists predominantly of rhythmically bedded, pale to medium grey marly (clay-rich) chalks with thin beds of grey to brown limestone. Certain beds, particularly the main limestone beds, have been given informal names (Mortimore et al., 2001), or are designated by alphanumeric codes (Gale, 1989). The West Melbury Chalk corresponds to the lower part of the East Wear Bay Chalk Formation of Robinson (1986).

The base is marked by the Glauconitic Marl Member, comprising grey clay-rich chalk (marl) with variable proportions of glauconite and quartz sand, and up to 5 m in thickness. The lower boundary is placed at a strongly burrowed surface associated with a concentration of phosphatic nodules, overlying the clays of the Gault. The same boundary marks the base of the Lower Chalk in the traditional scheme.

The limestone beds in the lower part of the formation are often spongiferous and occasionally contain glauconite grains. A limestone rich in the ammonite *Schloenbachia* occurs in the middle of the sequence and is thought to be equivalent to the M3 limestone at Folkestone (Gale, 1989). The upper limestones of the West Melbury Chalk are generally poorly fossiliferous and lack sponges. The Tenuis Limestone occurs at the top of the formation (Mortimore et al., 2001).

The West Melbury Marly Chalk includes all the chalk of the Cenomanian *M. mantelli, M. dixoni* and *C. inerme* Zones and the basal part of the *T. costatus* Subzone (*A. rhotomagense* Zone). In terms of older biostratigraphic nomenclature, the West Melbury Chalk is approximately coincident with the *S. varians* Zone.

In the Chatham District the *varians* Zone is reckoned to about 30 m thick (Dines et al., 1971). In the Maidstone District it is estimated at 24 to 27 m thick (Worssam, 1963).

Outcrop patterns and borehole evidence suggest that the West Melbury Chalk varies between 20 m and 30 m in thickness. It is overlain conformably by the Zig Zag Chalk.

3.3 ZIG ZAG CHALK FORMATION

The Zig Zag Chalk crops out in the lower part of the North Downs escarpment. It is typically composed of soft to medium-hard, pale grey, blocky chalk with some beds of limestone near the base. No flints are recorded in the Zig Zag Chalk in this area.

The base of the formation is taken as the base of the ‘Cast Bed’, a distinctive pale brown silty chalk containing abundant small brachiopods (Bristow et al., 1995; Bristow et al., 1997; Mortimore et al., 2001). This typically coincides with a marked negative topographic feature.

The lower part of the formation has a higher clay content than the rest, and contains some thin limestone beds. It corresponds to the upper part of the East Wear Bay Chalk Formation of Robinson (1986). The upper part of the Zig Zag Chalk tends to be of pale grey to white, firm chalk with common *Inoceramus atlanticus*, *I. pictus* and the echinoid *Holaster subglobosus.* It is equivalent to Bed 7 and Bed 8 of Jukes-Browne (Jukes-Browne, 1880; Jukes-Browne and Hill, 1903) which together comprise the Abbot’s Cliff Chalk Formation of Robinson (1986). The top of this formation coincides with the top of the Zig Zag Chalk.

The base of the Zig Zag Chalk falls in the *Turrilites costatus* Subzone and the top is at the top of the *Calycoceras guerangeri* Zone. In terms of older biostratigraphic nomenclature, the Zig Zag Chalk is approximately coincident with the *H. subglobosus* Zone.

In the Chatham District the *subglobosus* Zone is about 24 to 30 m thick (Dines et al., 1971), as exposed at Wouldham. In the Maidstone District, it is about 27 m thick. The Abbot’s Cliff Chalk Formation of Robinson (1986) is 20.8 m thick at Peter’s Pit, Wouldham, but only 12.1 m thick just the south-east at Margett’s Pit, Burham (Robinson, 1986, p. 165). This difference was attributed to reduced sedimentation over the ‘Medway Axis’, a structural zone controlled in part by a NNW-SSE synsedimentary fault with easterly downthrow, on the eastern side of the River Medway.

Measured sections suggest that the Zig Zag Chalk varies between 15 m and 30 m in thickness (It reaches 33 m at Folkestone). It is overlain with slight disconformity by the Holywell Nodular Chalk.

3.4 WHITE CHALK SUBGROUP

The White Chalk subgroup is divided into seven formations, four of which are known to occur in this area. It is essentially equivalent to the combined traditional Middle Chalk and Upper Chalk, except that the base of the Middle Chalk was placed at the top of the Plenus Marls, and the base of the White Chalk (that is, the base of the Holywell Nodular Chalk Formation) is defined as the base of the Plenus Marls (Table 1). The youngest known chalk in the area is in the upper part of the Seaford Chalk Formation, although it is possible that a few metres of the Newhaven Chalk (or its lateral equivalent, the Margate Chalk) crops out in the extreme east. Between 150 and 180 m of the White Chalk is estimated to crop out in this district.

3.5 HOLYWELL NODULAR CHALK FORMATION

The Holywell Chalk underlies relatively gently sloping ground in the middle part of the North Downs escarpment, usually above a positive topographic feature marking the Melbourn Rock. The Holywell Chalk is relatively lithologically varied, comprising medium hard to very hard, nodular, white to creamy white chalk with beds and laminae of clay-rich chalk (marl), including flaser-laminated marls.

The basal member is the Plenus Marls, consisting of alternating beds of slightly greenish grey marls and marly limestones, resting with marked colour contrast on the eroded and burrowed surface of the Zig Zag Chalk. A standard succession of eight beds can be recognised at many localities (Jefferies, 1963). Estimates of thickness of the Plenus Marls from localities in North Kent vary considerably, suggesting that some sections might have been misinterpreted. Jefferies (1963, fig. 6) found a variation from about 2 m near the Medway, decreasing to less than 0.75 m to the east, then increasing to about 1 m near the Great Stour. His isopachyte map shows all occurrences in Kent to be less than 2.5 m, although he recognises local variation in detail. The Plenus Marls Member thus appears to be between 0.75 and 2.5 m thick in the North Downs.

The overlying Melbourn Rock comprises hard to very hard nodular chalk with marl seams, generally lacking fossil material. It has been estimated at 1.8 to 4.6 m in thickness. The upper two-thirds of the Holywell Chalk is mostly conspicuously fossiliferous: most beds contain gritty shell debris, some have inoceramid bivalves preserved in three dimensions. In the absence of shell debris, the rather grainy texture of typical Holywell Chalk distinguishes it from the smooth chalks of the succeeding New Pit Chalk. The unit also contains thin interbedded flaser marls but these are only readily apparent in exposed sections.

Robinson (1986) treats the Plenus Marls as a separate formation. The rest of the Holywell Chalk lies entirely within his Shakespeare Cliff Member (lower part of the Dover Chalk Formation).

The Holywell Chalk spans the Cenomanian/Turonian boundary; the boundary occurring close to the top of the Melbourn Rock. Biostratigraphically, the *M. geslinianum* Zone encompasses the Plenus Marls Member and the lowest part of the Melbourn Rock. The rest of the Cenomanian portion of the Holywell Chalk lies within the *N. juddii* Zone. The Turonian part of the Holywell Chalk is in the *Mytiloides* spp. Zone. In terms of older biostratigraphic nomenclature, the Holywell Chalk excluding the Plenus Marls is approximately coincident with the *I. labiatus* Zone.

In the Chatham District, the *labiatus* Zone is up to 27.5 m thick (Dines et al., 1971, p. 34). In the Maidstone District, the *labiatus* Zone is over 15 m at Detling, about 18.3 m at Harrietsham, and 18 to 21.3 m east of Lenham. With the Plenus Marls, the Holywell Chalk is generally about 20 m thick.

Geophysical log interpretation suggests the Holywell Chalk shows a consistent thickness of 16-20 m across the region. It is overlain conformably by the New Pit Chalk.

3.6 NEW PIT CHALK FORMATION

The New Pit Chalk Formation generally underlies steeply sloping ground within the upper part of the North Downs escarpment, above a persistent negative feature marking the top of the Holywell Chalk. It is composed of fairly pure massively bedded white chalks with pairs or groups of conspicuous marl seams. It is generally medium hard but softer than either the Holywell Chalk or the Lewes Chalk. Flints occur even to within a few metres of the base, but they are not a conspicuous part of the sequence. The included fauna is much sparser than in Holywell Chalk, mostly comprising brachiopods (both terebratulids and rhynchonellids) rather than abundant inoceramid bivalves. Specimens of *Mytiloides hercynicus/subhercynicus* are present but they tend to be flattened and typically lack any preserved shell.

The base of the New Pit Chalk is taken at the base of the Gun Gardens Main Marl, this being marked by the upward disappearance of abundant shell debris and, generally, of nodular chalk. It also approximates to first appearance of flints in the North Downs, and in the South Downs. In the eastern part of the North Downs, however, the lowest parts of the New Pit Chalk are nodular and contain chalk pebbles (intraclasts), and so were placed with most of the Holywell Chalk in the Shakespeare Cliff Member of Robinson (1986). The rest of the New Pit Chalk corresponds to Robinson's (1986) Aycliff Member (mid-Dover Chalk Formation).

In the standard sections in Sussex the formation extends up to the base of Glynde Marl 1 (Mortimore, 1986). In the North Downs, the nodular chalks characteristic of the Lewes Chalk come into the sequence a little higher, about 1 m above the topmost Glynde Marl (topmost Maxton Marl of Robinson, 1986).

Biostratigraphically the New Pit Chalk covers all but the highest part of the *Terebratulina lata* Zone. The base of the New Pit Chalk lies in the topmost part of the *Mytiloides labiatus* Zone of the traditional scheme.

The thickness of the New Pit Chalk observed on geophysical logs varies between 34 and 48.5 m, although 37-39 m seems more typical. The New Pit Chalk is more than 40 m thick at the eastern and western margins of the study area, thinning to a minimum of 34 m in the Fisher Street borehole. It is overlain conformably by the Lewes Nodular Chalk.

3.7 LEWES NODULAR CHALK FORMATION

The Lewes Nodular Chalk underlies the highest parts of the North Downs escarpment and much of the Chalk dip slope. It comprises interbedded hard to very hard nodular chalks and hardgrounds with soft to medium-hard grainy chalks and marls. The nodular chalks are typically lumpy and iron-stained, this iron-staining usually marking sponges. Rock fragments in the soil (brash) are rough and flaggy. The first regular seams of flint appear near the base and flints are a conspicuous part of the sequence. Most flints are nodular, but some tabular flints also occur. The flints are typically black or bluish black with a thick white cortex.

In exposed sections the Lewes Chalk can be divided informally into two units. The lower is mainly medium to high-density chalks and conspicuously iron-stained hard nodular chalks, whilst the upper is mainly low to medium-density chalks with regular thin nodular beds. The boundary between the two units is marked by the Lewes Marl and the Lewes Flints, an extensive system of black cylindrical burrow-form flints. The upper Lewes Nodular Chalk is further distinguished by the occurrence of the bivalve *Cremnoceramus* (Mortimore, 1986). There are several levels of tabular flint within an interval of 4 or 5 m in the lower part of the Upper Lewes Chalk.

The Lewes Nodular Chalk includes the top of the *Terebratulina lata* Zone, and all of the *Sternotaxis plana* (previously *Holaster planus*) and *Micraster cortestudinarium* zones.

The Lewes Chalk is very approximately equivalent to the lowest part of the traditional Upper Chalk. In the Chilterns, the Berkshire Downs and areas to the west, the base of the Upper Chalk was placed at the base of the Chalk Rock, but the Chalk Rock is absent in the more expanded sequence of the North Downs (where it is represented by perhaps as much as 40 m of strata). Instead, the base of the Upper Chalk has there generally been defined as the base of the *Sternotaxis plana* Zone, but this horizon may be difficult to recognise, and in practice it has been taken at the first appearance of the '*reussianum* fauna' or at the 'Basal Complex'.

The '*reussianum* fauna' is found only in certain beds in the nodular chalk of the basal *plana* Zone of southern England. It is named after the uncoiled ammonite *Hyphantoceras reussianum.* It largely comprises moulds of a variety of fossils and is unusual in that it includes aragonite-shelled molluscs such as ammonites and gastropods which are not generally preserved in other chalk facies. Hexactinellid sponges are also abundant (Gallois, 1965).

The 'Basal Complex' of the North Downs constitutes a thin succession of closely spaced marl seams associated with large, nodular flints (Mortimore and Wood, 1986, and references therein). In ascending order these beds comprise the Bridgewick Flints, the Bridgewick Marls, and the Bopeep Flints (Mortimore et al., 2001). The Basal Complex coincides with the maximum development of flints (including some flints of unusually large size) in the high Turonian throughout the English Chalk, at or about the base of the *plana* Zone (Mortimore and Wood, 1986, p. 10-11). In all areas this is overlain by beds with a maximum development of the *reussianum* fauna, and is underlain by a succession of chalks, some nodular, including several well-developed and laterally continuous discrete marls seams.

The Basal Complex can be traced throughout the North Downs and its base was used to define the base of the *Sternotaxis plana* Zone and thus of the base of the Upper Chalk in some previous accounts, notably those of the Geological Survey (Worssam, 1963, p. 72; Smart et al., 1966, p. 123; Dines et al., 1969; Dines et al., 1971, p. 39; Mortimore and Wood, 1986, p. 11; Holmes, 1987).

The base of the Lewes Chalk, however, corresponds to the appearance of indurated or nodular chalks above the New Pit Chalk Formation. This is taken as the base of the Glynde Marl 1 in Sussex, and elsewhere in the interval between the Glynde Marls and the Southerham Marls (Bristow et al., 1997).

In Robinson's stratigraphic scheme, the base of the Akers Steps Member (top of the Dover Formation) coincides with the change from underlying flintless soft white chalk with marl seams and rare beds of weakly nodular chalk to beds of nodular chalk with laterally extensive flint beds. This corresponds to the base of the Lewes Chalk and occurs about 1 m above the topmost of the Maxton Marls of Robinson (1986) (equivalent to the Glynde Marls of Sussex; Mortimore, 1986). Mortimore and Pomerol (1987) point out that the interval between the Glynde Marls and the Southerham Marls at Akers Steps (on the Kent coast) is considerably expanded, a feature that, they say, is found throughout much of Kent. This obscures the incoming of nodular chalks at this level. Robinson (1987) notes that the nodular chalks of the Akers Steps Member are represented inland by well-developed hardgrounds in localities including the A229 road cutting [TQ748 612], marking 'minor, areally restricted, synsedimentary structural features'.

In the terminology of Robinson (1986), the Akers Steps Member is overlain by the St Margarets Member (lower part of Ramsgate Chalk Formation) at the Crab Bay Marl. This (which is the same as the Caburn Marl of Sussex; Mortimore, 1986) occurs some 4 or 5 m below the Basal Complex. The thickness of the Akers Steps Member, together with this interval from the Caburn Marl to the Basal Complex, thus provides a value for the thickness of chalk of the *lata* Zone in the Lewes Chalk. The rest of the Lewes Chalk corresponds to the *plana* Zone and the *cortestudinarium* Zone. The top of the Lewes Chalk coincides with the top of the St Margarets Member.

In the standard Sussex succession the Lewes Nodular Chalk extends up to the base of Shoreham Marl 2 (Mortimore, 1986). A distinctive unit of chalk with the trace fossil *Zoophycos*, the Beachy Head Zoophycos Beds, occurs near the top of the Lewes Chalk. This can be traced northwards from Dover through the London Basin (where it is seen in borehole cores) (Mortimore et al., 2001). This unit is usually overlain by the two Shoreham Marls and the intervening bed of Shoreham Tubular Flints; conspicuous markers in both borehole core and exposures (Mortimore et al., 2001). However, at Rochester and some other localities, either or both of the Shoreham Marls may be occluded by the Rochester Hardground, developed over structural highs in parts of Kent and Surrey (Robinson, 1986).

During fieldwork for the present project, a previously unrecorded occurrence of the Rochester Hardground was found in a chalk pit some 1.3 km west of Doddington [TQ 921 567] (see cover picture). The hardground comprises a 40 cm bed of very hard, yellowish brown coloured chalk with a sharply defined top. A zone of small to medium sized tubular and thallassinoid flints which occurs between 60 and 100 cm below the top of the hardground is taken to represent the Shoreham Tubular Flints. A continuous subhorizontal fissure up to 5 cm in width, partly infilled by brownish clayey chalky sand, occurs just above the hardground, indicating that it has been a preferred horizon of groundwater flow. This flow horizon might coincide with a marl seam resting on or just above the hardground, perhaps Shoreham Marl 2. Two further subhorizontal fissures, although without any brownish infill, occur within two metres below the hardground.

This occurrence of the Rochester Hardground, some 7 km south by east of Sittingbourne, implies that it is present at the boundary between the Lewes Chalk and the Seaford Chalk in much of the western and central portions of the project area, and that it possibly occurs throughout.

According to Robinson (1986), the Akers Steps Member is 13.7 m thick at Detling (TQ791587), but over the Medway Axis it is only 10.6 m, and at Blue Bell Hill, it is 12.8 m thick. Estimates from Robinson’s Figure 23 suggest 10.3 m at the A229 road cutting, 12.3 m at Bores Hole, and 12.1 m at Upper Halling.

At Blue Bell Hill, the interval from the base of the Akers Steps Member to the Bridgewick Flints (Basal Complex) is 17.9 m, there being a 5.1 m section of *lata* zone chalk at the base of the St Margarets Member.

The St Margaret’s Member is 38.3 m on the East Kent Coast, and 43.2 m at the Rose and Crown Pit. It reduces to 32 m over the Medway Axis (Robinson, 1986).

In the Chatham District, the *plana* Zone chalk is about 16.8 m thick and the *cortestudinarium* Zone chalk is about 24.4 m thick (Dines et al., 1971). In the Maidstone District the *plana* Zone is 18.3 to 19.8 m in sections on Boxley Hill. At Hucking it is estimated at 21.3 m and eastward of Lenham, 13.7 to 15.2 m.

Thus the thickness of the Lewes Chalk could be as little as 32 + 10.6 = 42.6 m in thickness over the Medway Axis, but can be inferred to be as much as 43.2 + 17. 9 = 61.1 m elsewhere. It can generally be taken to be in the range of 40-50 m. It is overlain conformably by the Seaford Chalk.

3.8 SEAFORD CHALK FORMATION

The Seaford Chalk typically forms the long dip slopes of the North Downs. It is composed mainly of soft white chalk with common seams of small to very large flint nodules, and of tabular flint. In the Chatham District, occasional yellowish lumpy chalk is found at the top of the Seaford Chalk, but otherwise courses of harder chalk are only found locally in the bottom half. Distinct hard nodular beds are practically absent (Dines et al., 1971). A layer of putty chalk (soft, weathered or crushed chalk) may seal fractures and faults in the Seaford Chalk Formation. This may act as an aquitard, tending to seal faults and joints against the movement of water between adjacent parts of the aquifer. The flints are typically black to bluish-black, and mottled grey with a thin white cortex. They commonly contain shell fragments, and in some cases echinoids.

Many other beds within the Seaford Chalk contain macrofossils, of which inoceramid bivalves and echinoids are most significant biostratigraphically. For example, the lower part of the Seaford Chalk contains abundant fragments of the bivalves *Volviceramus* and *Platyceramus*, whilst the upper part contains *Cladoceramus* and *Platyceramus* (Mortimore, 1986). These fossils can be found in rock fragments in the soil (brash), as well as in exposed bedrock.

There are several key marker horizons present in the upper part of the Seaford Chalk. Whitaker's Three Inch Flint band is a prominent, nearly continuous single tabular flint seam about 10 m below the base of the Newhaven Chalk Formation (or of its lateral equivalent, the Margate Chalk Formation). This flint band has been recognised in several pits in the Selling area, particularly in the Fisherstreet – Boughton Street valley where it helps define the Seaford Chalk dip-slope.

'Whitaker's Three-Inch' contrasts with Bedwell's Columnar Flint, which is a conspicuous line of double flints with occasional vertical columns of flint. On the Kent coast it occurs about 13 m lower in the sequence, this interval diminishing to about 8.8 m in the Canterbury area and 7.5 m in the Medway area.

Barrois' Sponge Bed is a conspicuous 200-300 mm thick red iron-stained nodular sponge bed which occurs at the very top of the Seaford Chalk, defining the boundary with the overlying Margate Chalk on the Isle of Thanet (Mortimore et al., 2002). In the western North Downs, the top of the Seaford Chalk is marked by the Clandon Hardground, which is the lateral equivalent of Barrois' Sponge Bed, although this is not known to occur east of the River Medway. The relative induration reflects deposition over swells and basins (Mortimore et al., 2001, p. 292).

Biostratigraphically, the Seaford Chalk is co-extensive with the *Micraster coranguinum* Zone (Table 1). It crosses the Coniacian/Santonian boundary, marked by the incoming of *Cladoceramus* (Mortimore, 1986).

In the Chatham District, the *coranguinum* Zone chalk is about 48.8 m thick (Dines et al., 1971), and in the Maidstone District perhaps about 46 m (Worssam, 1963). The Seaford Chalk is about 48 m thick in the Medway area. The thickest Seaford Chalk inferred from geophysical logs is generally between 55 m and 60 m thick. It is overlain unconformably by the Thanet Sand Formation.

There is no evidence for the presence of crinoid zone chalk (Newhaven Chalk or Margate Chalk formations) in the Chatham District, and probably the top 12 m or so of *coranguinum* Zone chalk is missing beneath the Palaeogene (Dines et al., 1971, p. 38). Farther east, the topmost Seaford Chalk is preserved beneath the Palaeogene cover and it is possible the basal Newhaven Chalk occurs in the extreme east of the region.

4 The Early Palaeogene

The stratigraphic nomenclature used in this report follows Ellison et al. (1994). The formations are discussed further by Aldiss and Farrant (2002).

4.1 THANET SAND FORMATION

The Thanet Sand Formation, previously known as the Thanet Beds, or Thanet Sands, consists of bioturbated glauconitic silts and fine to very fine sands deposited in an inner marine shelf to coastal setting, above fair weather wave base.

A thin pebble bed (the 'Bullhead Bed') is present at the base. It consists of unworn, green-coated flints in a matrix of bright green, glauconite-rich clayey sand and is typically 10 to 20 cm thick.

The clayey matrix of this unit may render it less permeable than the overlying sands and silts. Within the project area, the Thanet Sand Formation is thicker and more argillaceous in eastern sections.

As discussed by Aldiss and Farrant (2002), there is, generally, a layer of sandy or silty clay in the lower part of the Thanet Formation in North Kent. Between Sittingbourne and Faversham this is as much as 19 m thick, albeit with some relatively thin sand or silt interbeds. The clayey unit is pinched out eastwards from Faversham, but apparently continues northwards and southwards. It also diminishes westwards from Sittingbourne.

The presence of springs emerging from within the upper part of the Thanet Formation north-east of Newington implies that relatively clay-rich beds occur at least locally in that part of the sequence.

The thickness of the formation is greatest in North Kent, where it generally ranges from about 20 m up to 30 m, increasing to as much as 37 m in the Canterbury district. It is overlain unconformably by the Upnor Formation: in places significant parts of the Thanet Formation were removed by erosion prior to deposition of the Lambeth Group (Curry, 1981).

4.2 UPNOR FORMATION

The Upnor Formation, previously known as the Woolwich Bottom Bed or similar, is typically composed of variably glauconitic, fine to medium-grained sand with beds and stringers of well-rounded, black flint pebbles. When fresh, the sands are dark grey brown to dark green, depending on the proportion of glauconite (which can exceed 25 per cent). They weather pale brown to yellow brown, but the glauconite remains dark green. The sands are extensively burrowed but locally cross-bedding remains.

The base of the formation rests unconformably on the Thanet Formation. The boundary is generally sharply defined, being marked by an upward change to medium-grained sand, with burrows of glauconitic sand extending as much as 0.5 m downwards into the Thanet Formation. A basal flint pebble bed is usually present. In the far east of the London Basin, bioturbation has resulted in a gradational junction, and in north-east Kent the grain size contrast is difficult to pick out.

The formation was deposited in a marine shelf to coastal environments, predominantly with high energy, and partly influenced by tidal currents (Ellison et al., 1994).

At Upnor, the formation is about 7.5 m in thickness. In much of North Kent, the topmost part was locally removed by erosion prior to the deposition of the Harwich Formation.

The upper boundary is generally well-defined, being overlain conformably by the Woolwich Formation.

4.3 WOOLWICH FORMATION

Previously part of the Woolwich and Reading Beds, the Woolwich Formation consists largely of grey to grey-brown, interlaminated fine-grained sands, silts and clays, deposited in a variety of marginal marine, low to high energy environments, with some freshwater deposits. Plant debris is common. Sporadic burrows occur throughout but bioturbation is more common in the higher beds in which sparse glauconite has been recorded. Shelly beds, particularly in the basal couple of metres, consist of shells in a dark grey clay matrix. Grey clay with shelly beds and minor sand and silt interbeds is characteristic (Hester, 1965, quoted by Ellison, 1983). The Woolwich Formation is the most laterally variable of the Palaeogene units in North Kent (Ellison, 1983; Aldiss and Farrant, 2002).

The Woolwich Formation is generally around 11-12 m thick in north-west Kent, where the top has been removed by erosion beneath the Harwich Formation, but can reach 18 m in the

Chatham district. Its base is sharp, with burrows extending as much as 0.5 m into the Upnor Formation.

In the eastern part of the Chatham district, the Woolwich Formation consists mainly of sand but from the Newington area [TQ 85 65] westwards clay beds occupy up to about one-third of the unit, especially near the top and the base (Dines et al., 1971). The presence of such clay beds might have a controlling influence on springs emerging from within the Palaeogene outcrop, for example north-east of Newington.

In North Kent the Woolwich Formation was wholly or partly removed by erosion prior to deposition of the Harwich Formation (Holmes, 1981).

4.4 HARWICH FORMATION

The Harwich Formation was previously known generally as the London Clay Basement Bed, in North Kent as the Oldhaven Beds and in the London area as the Blackheath Beds. It consists mainly of highly glauconitic silty sands, sandy silts and sandy clayey silts, about 10 m in thickness, but a unit of fine-grained, glauconitic, cross-bedded sands (the Oldhaven Beds) is developed in parts of north Kent and south Essex. This includes pebbles near the base. The base is sharply defined, formed by a planar or slightly undulose discontinuity with a basal lag of rounded flint pebbles and fine to coarse quartz grains in a finer glauconitic matrix. Burrows commonly extend down into underlying beds.

The formation was deposited on a shallow marine shelf, with slow, interrupted sedimentation, and periodic storm-generated activity.

The thickness is laterally variable, ranging from 2.5 m up to about 10 m in North Kent. The Harwich Formation is overlain disconformably by the London Clay.

5 Superficial Deposits

The Quaternary superficial (drift) deposits were not mapped or revised during this study. Further details are available in the memoirs for the region. Across the Chalk outcrop, the most widespread superficial deposits are Brickearth, Head and Clay-with-flints.

5.1 BRICKEARTH

Brickearth typically comprises a reddish brown, variably sandy or clayey silt, with a small proportion of chalk or flint gravel. It tends to be massive or weakly bedded, and fairly homogeneous. Most of the brickearth seen at the surface is considered to have been redeposited by solifluction processes (Head Brickearth) or by fluvial processes (River Brickearth), or both. The brickearth deposits often show a lithological resemblance to the solid formations upon which they lie. Thus deposits partly derived from the Thanet Sands are generally of a fine sandy nature.

Brickearth forms a discontinuous but widely developed blanket in excess of 1 m in thickness, overlying either bedrock or other types of superficial deposit. Parts of the original deposit have been removed for brick-making.

Where the local brickearth sequence exceeds about 2 m in Kent and Essex, there is usually a distinct upper non-calcareous part and a lower calcareous part of the sequence. Although one might assume that this layering has arisen by leaching of the calcareous fraction by water percolating downward from the surface, recent work by BGS suggests instead that the lower layer is a primary aeolian deposit, and that the upper is a solifluction (head) deposit. Both layers are composed principally of silt, although the upper layer tends to contain rather more clay.

5.2 HEAD

Head deposits accumulated largely by solifluction and hillwash, mainly under periglacial conditions during the Quaternary glaciations. They are heterogeneous but are typically composed of very gravelly silty, sandy clay or diamicton, ranging to clayey sandy gravel. The composition of head varies according to the local sources of material and details of landscape evolution.

In the present area, head is ultimately derived by erosion of the Chalk and Palaeogene strata, but may well include material reworked through older Quaternary deposits such as clay-with-flints, older head deposits and, probably, older fluvial deposits (some of which may be locally absent now due to erosion). The deposits thus show a great diversity in composition from almost pure chalk rubble to resorted sands from the Palaeogene. The clasts are primarily nodules and frost-shattered fragments of flint of a wide range of sizes, commonly cobble or coarse gravel-sized. In comparison with the clay-with-flints, head generally includes a greater proportion of frost-shattered flints. A small proportion of the very well-rounded flint pebbles derived from the Palaeogene is commonly also present but this tends to be less than in the clay-with-flints.

5.3 CLAY-WITH-FLINTS

The clay-with-flints is primarily a *remanié* deposit created by modification of remnants of the original Palaeogene cover, together with dissolution of the underlying Chalk. It is typically composed of orangish brown or reddish brown clays, sandy clays and loam, containing varying amounts of flint nodules and pebbles. The deposit often approximates to brickearth with few flints where it rests on outliers of Thanet Sand. At the base of the deposit the matrix becomes stiff, waxy and fissured, and of a dark brown colour, with relatively fresh nodular flints stained black by manganese compounds or dark green by glauconite.

The clay-with-flints has been modified by periglacial processes, but unlike the head deposits is considered to have undergone little lateral movement. The basal surface of the deposit approximates to the sub-Palaeogene unconformity but the clay-with-flints can be carried some distance below that level in solution pipes. Deposits are estimated to be generally between 1 m and 5 m thick, but tend to be much thicker within solution pipes. These can extend 10 m or more into the underlying Chalk.

6 Geological Modelling

6.1 THE MODELLING PROCESS

The three dimensional (3D) geological model comprises a series of seven layers, representing the six Chalk formations and the Palaeogene up to the base of the London Clay (Figure 3).

Data on the position of the surfaces bounding each layer was compiled from the sources described in Section 2. The ground surface was modelled using a hydrologically corrected digital terrain model derived from the Centre for Ecology and Hydrology. This DTM is based on the Ordnance Survey (OS) 1:50000 Panorama dataset with analysis performed to integrate the OS DTM with river network information and remove hydrological anomalies in the data. The DTM provided elevation data at a 50m (Easting, Northing) resolution.

The intersection of each geological surface with the ground surface is shown by the geological map. Lines delineating the base of the London Clay and the base of the Thanet Sand Formation were taken unmodified from the DiGMapBG-50 database, which is a digital version of the published 1:50 000 scale geological maps. Linework for the base of each of the Chalk formations was newly compiled manually, as described in Section 6.3, and digitised.

Lithological or lithostratigraphical records for boreholes within the area were scrutinised for information on the formation boundaries, and the depth of each boundary within the borehole recorded. The National Grid coordinates for boreholes with useful information were taken from the BGS Single Onshore Borehole Index (SOBI), where possible, or from the original borehole record where not. The ground surface level (relative to Ordnance Datum) was taken from the borehole record, where recorded, or from its recorded position on a 1:10 000 scale Landplan topographic map, where not.

Geophysical boreholes were scrutinised in a similar way. The geophysical records for each borehole were first interpreted individually, but then each interpretation was compared with that of its nearest neighbours, as a further check on the consistency of the interpretation.

Inaccuracies can occur in any aspect of the borehole data: in the original record, in its subsequent interpretation, in the recorded location of the borehole, or in the ground elevation at the borehole site. Borehole records which give rise to obvious anomalies in the modelled surfaces are first checked for inaccuracy but if no correctable errors can be detected, then the record is discarded. This is a subjective process but it tends to lead to a model based on a relatively self-consistent dataset. However, borehole records which are somehow incorrect but which are nevertheless consistent with the model will generally remain unsuspected.

Each seismic reflection profile was interpreted for the base of the Upper Chalk, the base of the Middle Chalk and the base of the Lower Chalk. The seismic picks represent a reasonable approximation to the bases of the Lewes, Holywell and West Melbury chalks.

Each seismic profile was then digitised and the two-way-travel-time (twtt) values loaded to LOCSEC, an in-house locations and sections database. The twtt values for each horizon were then exported to Earthvision as xyz data and depth converted using interval velocities from surface to the seismic pick. The velocities were obtained from a study of borehole information in the area, but given the paucity of information, included data from the chalk of southeast England in general. The depth-converted values for the three horizons were then supplied in digital format for inclusion in the subsurface modelling.

6.2 LIMITATIONS OF THE MODEL

The quality of geological models constructed using earthVision is highly dependent on the data that is used to construct them. In this study area, the quality and quantity of the data available to define the position of each geological surface in the model is spatially very variable (Section 6.3). Data is generally of reasonable or high quality at outcrop, but the number and quality of the borehole records is generally poor except in the vicinity of pumping stations, where there is commonly a concentration of good quality records. In some cases uncertainty about the location of the borehole and its elevation contribute to the inaccuracy of the Earthvision model.

Furthermore, many of the boreholes provide information only about certain stratigraphic horizons. Thus each modelled surface will have a different array of data points, and so each surface may not lie parallel to those above and below. In extreme cases, where the modelled surfaces are insufficiently constrained by data they may converge to an unrealistic extent. This is apparent in some sections through the model (Figure 3). In addition, over much of the area the density of data points is not sufficient to delimit fault zones and fold structures. These deficiencies in the data set do not enable a realistic 3D geological model to be constructed for all surfaces covering the whole area.

For these reasons, structure contour maps of three key surfaces (base Palaeogene, base Seaford Chalk and base Lewes Chalk) were prepared manually. These are based on the same data as used in the computer model, but the contours were interpolated by the project geologists. These surfaces created were then gridded to produce the model output.

6.3 MAPPING THE NEW CHALK LITHOSTRATIGRAPHY

6.3.1 General procedure

New or revised linework to depict the new Chalk formations (Sections 1 & 3) was compiled using data from many of the sources outlined in Section 2. The 1:10 560 scale standards and selected field slips were enlarged to 1:10 000 scale on a large-format photocopier. The existing lines for the base of the Lower Chalk, Middle Chalk and the Upper Chalk were traced from these enlarged maps to 1:10 000 scale OS Landplan maps on a light table, matching the positions of local topographic features to make small adjustments of scale or registration, where required.

Relevant information from biostratigraphic records, annotations on field slips and the available literature was also plotted onto the 1:10 000 scale base-maps. New linework for each Chalk formation was then constructed, as described in the following sections.

No fieldwork was undertaken to support this study and so there was virtually no opportunity to check the new interpretations in the field. Field mapping of the Chalk formations depends on the interpretation of small to medium-scale topographic features which can normally be located much more accurately on the ground than on the 1:10 000 scale topographic maps, even if they can be identified on the maps at all. For these reasons, the new linework should be regarded as an approximation which could significantly improved by detailed field mapping.

6.3.2 Base of West Melbury Marly Chalk Formation

The Glauconitic Marl is readily recognisable in the field, as is the contrast between the Gault and the Chalk. The existing mapped boundary for the base of the Lower Chalk is thus considered to be reasonably reliable, although it is commonly covered by superficial deposits and the accuracy with which it was mapped would also be limited by the less detailed contours shown on the 1:10 560 scale maps. Also, in some places, this boundary appears to have been placed at a spring-line without any corroborative evidence, although springs can occur above the base of the West Melbury Chalk. In adopting the mapped base of the Lower Chalk as the base of the West Melbury Chalk, adjustments have been made locally to make it consistent with the modern five metre contours, while taking account of where the Glauconitic Marl has been recorded on field slips.

In boreholes, this boundary can usually be accurately located in both lithological and geophysical logs, although in this area no geophysical logs penetrating the base of the Chalk are available. The boundary is also identifiable on seismic sections. Even so, there is little information to show its position in the 3D model other than on the scarp face and in the Great Stour and Medway valleys.

6.3.3 Base of Zig Zag Chalk Formation

The base of the Zig Zag Chalk has not been previously surveyed in the North Downs. Neither the Cast Bed (at the base of the formation) nor the Tenuis Limestone which immediately underlies it were recorded during the original large-scale survey. Furthermore, none of the geophysical logs penetrate this boundary, nor is it recorded on any of the lithological borehole logs.

The new boundary was constructed by inference from published estimates for the thickness of the approximately equivalent biozones (Sections 3.2 & 3.3), which indicate that the West Melbury Chalk and the Zig Zag Chalk are of approximately equal thickness. The base of the Zig Zag Chalk was therefore placed at a level equivalent to about half the vertical distance between the new mapped base of the Holywell Chalk (Section 6.3.4) and the new mapped base of the West Melbury Chalk (Section 6.3.2), constrained where possible by the limited biostratigraphical data for individual localities.

This level was found to correspond to a broad negative break of slope lying above the locally developed spurs in the West Melbury Chalk outcrop. In general, the ground above this topographic feature slopes more evenly and more steeply than the ground below. These characters are consistent with landforms associated with the two formations of the Grey Chalk in other parts of southern England.

The absence of any positive observations of this boundary, particularly in the subsurface, make it the least well-constrained of any in the 3D model.

6.3.4 Base of Holywell Nodular Chalk Formation

This is close to the base of the traditional Middle Chalk, differing only in that it is taken between 0.75 and 2.5 m lower, at the base of the Plenus Marls. Both the Plenus Marls and the Melbourn Rock are easily identifiable in the field where exposed, and the Melbourn Rock gives rise to a characteristic topographic feature. The previously surveyed line for the base of the Middle Chalk is therefore probably very reliable, although the accuracy with which it was mapped would be limited by the less detailed contours shown on the old 1:10 560 scale maps. This boundary is easily identified on geophysical and lithological logs, and from seismic records.

As the variation in the thickness of the Plenus Marls is poorly known, and as it is likely to be less than 10 percent of that of the whole Holywell Chalk, the existing line for the base of the Middle Chalk was taken as the base of the Holywell Chalk, with some minor local adjustments to improve consistency with the modern five metre contour set. The resulting line has no clear relationship with the topography as expressed by the five metre contours.

This boundary is quite well constrained in the 3D model, both by surface mapping and from borehole and seismic data. However, the density of data points becomes sparser in the north of the project area, as the thickness of overlying strata increases and here the model becomes less reliable. Many of the data points north of the Chalk outcrop were calculated using thickness estimates.

6.3.5 Base of New Pit Chalk Formation

The base of the New Pit Chalk has not been previously surveyed in the North Downs, although the corresponding lithological change from hard nodular fossiliferous chalk to softer smooth white chalks is noted locally on the field slips.

Thickness estimates for the Holywell Chalk and the New Pit Chalk suggest that they are approximately in the proportion three-fifths to two-fifths, the New Pit Chalk being the thinner (Sections 3.5 & 3.6). The base of the New Pit Chalk was therefore placed at a level corresponding to 40-45 per cent of the vertical interval between the revised base of the Holywell Chalk and the revised base of the Lewes Chalk, but constrained by the lithological and biostratigraphical data for individual localities.

This level was found to correspond to a distinct negative break of slope between a uniform steep slope above, and a more irregular, less steep slope below. Some low spurs are developed on the outcrop of the Holywell Chalk, whereas none appear on the New Pit Chalk outcrop. These characters are consistent with landforms associated with the two formations in other parts of southern England.

The base of the New Pit Chalk can be identified on geophysical logs but is rarely recorded on lithological logs, and is not identifiable on seismic records. Thus there are few reliable data points in the 3D model for this boundary, other than those representing the surface outcrop along the scarp face and along the Medway and Great Stour river valleys. In the area of the dip slope, the data are much sparser and the model is correspondingly less reliable. Many of the data points north of the Chalk outcrop are calculated using thickness estimates.

6.3.6 Base of Lewes Nodular Chalk Formation

This approximates to the old Middle-Upper Chalk boundary, except that the base of the Lewes Chalk is taken significantly lower. During the large-scale surveys of this area, the base of the

Upper Chalk was placed at the lowest appearance of the distinctive *reussianum* fauna, which occurs in association with the 'Basal Complex' (Section 3.7). Numerous occurrences of the *reussianum* fauna are marked on field slips. The surveyed line for the base of the Upper Chalk is therefore probably fairly reliable, although the accuracy with which it was mapped would be limited by its common occurrence in relatively steep, wooded ground, and by the less detailed contours shown on the old 1:10 560 scale maps. Also, large sections of the boundary are covered by superficial deposits, especially in the eastern part of the area.

Before the new line marking the base of the Lewes Chalk was constructed, the existing line for the base of the Upper Chalk (i.e. the base of the *plana* Zone) was adjusted to be consistent with the modern five metre contour set, and with biostratigraphic and lithological observations. To the north and west of Burham [TQ 72 62] the base of the Lewes Chalk was then placed 15 m below this revised base of the *plana* Zone, between Burham and Charing it was placed 18 m lower, and to the east of Charing between 10 and 15 m lower. These figures correspond to the local thickness of *lata* Zone chalk within the Lewes Chalk (that is, the thickness of the 'Akers Steps Member' of Robinson (1986), plus five metres to represent the strata between the base of the St Margarets Member and the Basal Complex - Section 3.7).

This new line for the base of the Lewes Chalk tends to occur just at the top of the steepest slope at the top of the escarpment (typically in the narrowest contour interval), that is, at the positive break of slope at the top of the New Pit Chalk outcrop. The base of the Lewes Chalk bears the same relationship to associated landforms in other parts of southern England.

This boundary can be identified on lithological, geophysical and seismic logs. It is also well constrained by its outcrop pattern along the scarp face. However, north of the M2 motorway, the data becomes sparser and the 3D model is correspondingly less reliable. Many of the data points north of the Chalk outcrop are calculated using thickness estimates derived from borehole data and thus should be treated with caution.

6.3.7 Base of Seaford Chalk Formation

The base of the *coranguinum* Zone, here taken as the base of the Seaford Chalk, was surveyed in the Maidstone and Canterbury districts (but not in other parts of the project area) and presented on small-scale maps in the corresponding memoirs (Worssam, 1963, fig. 12; Smart et al., 1966, fig. 2). This biozonal boundary appears to have been recognised in part by biostratigraphic criteria, and in part by the corresponding lithological change from hard nodular chalks to softer smooth white chalks. Relevant information has been recorded at numerous localities where the Lewes Chalk or the Seaford Chalk were exposed, although most of these are in dip slope valleys. There are few data from the broad drift-covered interfluve areas.

In unexposed ground just west of Doddington, there seems to be a clear topographic expression of the Rochester Hardground, marking the contact between the Lewes Chalk and Seaford Chalk formations. It is not clear, however, whether this persists throughout the outcrop, and if so whether it was recognised by the original surveyors. It is possible that in unexposed ground the base of the *coranguinum* Zone was placed only by reference to information from exposures, and not by 'feature mapping'.

The position of the new line for the base of the Seaford Chalk was guided by the existing small-scale maps of the base of the *coranguinum* Zone. Where it crops out high on valley sides the boundary was placed at a positive topographic feature, constrained by the lithological and biostratigraphical data for individual localities, although it is difficult to do this consistently. Structure contours were then constructed for these sections of the outcrop and used to project the boundary line through the lower-lying parts of the valleys, and across drift-covered interfluves.

This approach assumes a relatively low, uniform dip. At least one significant error is known in the new mapped line for the base of the Seaford Chalk, in the vicinity of a large chalk pit west of

Doddington [TQ 721 567] where the boundary has been displaced by faulting, or by local dips of up to 15º.

Although the base of the *coranguinum* Zone, or the base of the Seaford Chalk, traces a rather indented outcrop pattern as it crosses the valleys of the North Downs dip-slope, and so should provide good constraint for the subsurface model, there are several factors which limit the accuracy with which it can be surveyed. Where it occurs on dip slope interfluves, the Seaford Chalk is extensively covered by superficial deposits, whose thickness is in general not great, but poorly known. Also, there is generally only a small difference between the slope of the land surface and the angle of dip of the base of the Seaford Chalk. Minor changes in the slope, the angle of dip, or of the thickness of superficial deposits can make relatively large changes to the outcrop pattern. (Conversely, such minor changes should have little effect on the 3D model).

Nevertheless, the new mapped boundary was found to mark a change in the topographic profile of dip slope valleys. Valleys developed within the Lewes Chalk are quite narrow with steep sides, whereas in the Seaford Chalk they tend to be shallower, broader and with rounded slopes. These characters are consistent with landforms associated with the two formations in other parts of southern England.

Although this boundary can be identified from geophysical logs, it is rarely recorded on lithological logs, and is not picked on seismic records. Thus there are few reliable underground data points. Accurate modelling of the corresponding surface is difficult.

6.3.8 Base of Palaeogene

The base of the Thanet Sand Formation mapped during the original large-scale surveys remains essentially unchanged except for some minor modifications to maintain consistency with the modern five metre contours. However, it should be noted that in many parts, the basal contact is obscured by superficial drift deposits and is there likely to be less accurately surveyed. Furthermore, the contact is likely to be highly irregular locally, due to the presence of dissolution pipes in the underlying Chalk.

This surface is well constrained by data from many borehole logs and by the complex shape of its outcrop pattern.

7 Structure

7.1 GENERAL CONSIDERATIONS

Tectonic activity during deposition has influenced the thickness of the Chalk sequence and its lithological composition on a local or regional scale. There is growing evidence that tectonic and eustatic movement occurred in phases throughout the Upper Cretaceous (Mortimore and Pomerol, 1987, 1991; Mortimore et al., 1998; Evans and Hopson, 2000). Four major tectonic phases (demonstrated in Germany and in the eastern Anglo-Paris basin) caused local channelling and slumping, and the local formation of hardgrounds and phosphatic chalks, as well as variations in marl development throughout southern England. Some characteristics of the Chalk in the present area may be a consequence of this tectonic activity.

In some parts of southern England, faulting within the formations beneath the Chalk becomes attenuated upwards, apparently passing into broad anticlinal folds. Where faulting does occur in the Chalk, the displacement may have been accommodated by movements of numerous small faults within a zone some tens, perhaps hundreds, of metres wide, rather than on a few discrete fault planes. In unexposed Chalk terrain, it is rarely possible to distinguish a broad, gentle anticlinal fold from a broad fault zone. Indeed, it is difficult to demonstrate the existence of faults in unexposed Chalk by geological field survey unless the faults are relatively large.

In the present area, this problem is exemplified in a small area west of Doddington. There, the western end of a chalk pit [TQ 721 567] exposes a series of small fault zones, each with an easterly downthrow of about one metre, in strata dipping at no more than 4º. The same pit exposes the base of the Seaford Chalk. Some 250 m west of the pit, the base of the Seaford Chalk occurs about 28 m higher, indicating either a local increase in dip to about 15º on the short limb of a strike-parallel fold pair, or the presence of one or more unexposed faults with an accumulative throw of about 10 metres. The intervening ground is steep and covered by woodland, and provides no evidence to resolve the structure.

However, this difficulty in distinguishing between the effects of folding and faulting is probably not of critical importance in the present context: folding that does occur in the Chalk of North Kent is very gentle, and it seems likely that in most local folds the Chalk will have undergone some brittle fracture and sufficient minor faulting to influence the local hydrogeology.

In the same way that small faults and folds at outcrop will remain undetected by field survey of the relatively widely-spaced, coarse topographic features delineating the relatively thick Chalk formations, the sparse distribution of subsurface data does not allow the delineation of any but the most obvious structures in the 3D model. The wavelength of the small to medium-scale folds in the Chalk is less than the general spacing of the boreholes in the area.

7.2 REGIONAL DIP AND FOLDING

7.2.1 Regional dip

Within the project area, the Chalk generally dips to the north-north-east at between 0.5º and 3º. The steepest dips seem to occur along the main North Downs escarpment and the dip slope immediately to the north.

Structure contours on the base Palaeogene surface suggest that the regional dip in those younger strata is generally similar, usually being between 1º and 1.5º. It locally increases to 2º in the outcrops around Rochester and to the west, and within about five kilometres of the River Great Stour in the east of the area. In most of the area this surface dips towards the north-north-east, changing more towards the north-east between Rainham and the Higham syncline in the north-west of the area (Figure 4).

Steeper dips have been recorded at exposures in large quarries. For example, in the Burham quarries bedding in the Chalk dips locally at as much as 6º or 8º (Dines et al., 1971). The extent and significance of such relatively steep dips is not clear, however, although they might reflect proximity to faults controlling the ‘Medway axis’ of Robinson (1965) (Section 7.3).

Superimposed on this overall pattern, there is evidence for folding both approximately perpendicular to, and parallel to, the regional dip.

7.2.2 Strike-parallel folds

In the north-west of the area, the major Cliffe anticline extends east-south-east towards the Hoo peninsula, diminishing in amplitude and fading towards Sheerness. The corresponding syncline passes through Higham to the south, extending eastwards along the northern side of the Medway estuary, and then likewise gradually fading out (Figure 4).

An anticline trends approximately north-west–south-east along the line of the Luton valley, south-east of Chatham (Figure 4). The existence of this fold is inferred from the occurrence of the Lewes Chalk in several places in the south Chatham area at levels higher than would be expected if the regional dip observed at the escarpment nearby continued northwards without deflection. The same evidence could instead be interpreted in terms of a southwards-throwing fault zone in the Luton valley, but the presence near Darland [TQ 7802 6554] of *planus* Zone chalk dipping at 3º to the south-south-west suggests that there is a corresponding syncline, forming a south-facing fold pair. Nevertheless, the strikingly linear nature of the Luton valley suggests that sub-parallel faulting has also occurred, close to the axes of this fold pair.

In the north-west the Luton valley structure probably controls the course of the River Medway along the Lighthouse Reach. To the south-east, it can be traced as far as Wigmore [TQ 796 647], where either its amplitude simply diminishes or it is truncated by a north-north-easterly fault zone (Figure 4).

There is some evidence, however, that a co-linear structure does continue to the south-east, subparallel to strike. In general, the north-facing interfluve slopes of the North Downs are notably planar, dipping at about 1º. Inspection of the five metre contours on 1:10 000 scale topographic maps shows that these regular slopes are interrupted by a linear 'steep zone' in which the slope of the ground increases to between 2º and 4º (Figure 4). The relatively steep ground just north of the Luton anticlinal axis apparently forms the western end of this zone, which then continues south-east in approximate alignment with the Luton Valley structure.

This steep zone might appear at first sight to be a consequence of surface processes, without any particular relationship to the underlying bedrock structure. In several places, however, the steep zone has been offset on north-north-easterly lines of faulting (Figure 4), suggesting that it does arise from some bedrock structure. The base of the Seaford Chalk coincides with the steep zone in some places, suggesting that it might be a consequence of the lithological contrast between the Seaford and the Lewes chalks, but elsewhere not. The steep zone could conceivably mark a gentle strike-parallel fold pair, but (A) there is no positive evidence for the corresponding increase in dip in the Chalk, (B) a fold would not expect to persist with such marked linearity, and (C) such a fold pair would be north-facing, the opposite direction seen in the Luton valley fold pair. It seems most likely, therefore, that the topographic steep zone marks a persistent fault zone trending at approximately N120° across the regional dip slope (Section 7.3).

A strike-parallel syncline is said to extend from near Rainham [TQ 82 65] to near Stockbury [TQ 84 61] or Hartlip [TQ 83 64] (Dines et al., 1971, p. 8), but no specific evidence to confirm this was noted during the present project.

The outcrop pattern of the Woolwich Formation outlier east of Sittingbourne [TQ 946 642] suggests a local southerly dip direction, which has been attributed to a small anticline just to the north (Dines et al., 1971)

The western end of a strike-parallel fold structure, oriented north-west – south-east along the lower part of the Petham valley to the east of the area, intersects the Great Stour valley. This may extend west to the Selling area as a shallow monocline, where it gradually fades. Its influence can be seen in the Old Wives Lees area where the dip is almost horizontal and locally oriented southwards but dips north at 3.6° further towards Boughton Street. A short distance to the west, in the lower part of the Fisherstreet – Boughton Street valley, the regional northerly dip is quite well constrained by exposures of Whitaker's Three Inch flint band and at 0.8° appears unaffected by local folding.

7.2.3 Dip-parallel inflections

Evidence for minor inflections caused folding or faulting, or both, on axes approximately parallel to the regional dip is seen in offsets of two major topographic features, and in the analysis of structure contours (Figure 4). Faulting is discussed in the following section, although (as noted in Section 7.1) in many places the effects of folding and faulting can be difficult to distinguish.

Structure contours for the base of the Palaeogene can be constructed with some confidence (Section 6.3.8). This surface is made up of a series of planar elements, separated by linear inflections (marked by bends or faulted displacements in the contour set), trending north-north-east to south-south-west (Figure 4). Between Bobbing (just west of Sittingbourne) and Hernhill (east of Faversham), there are four pairs of such deflections, corresponding to four very gentle east-verging fold pairs, or four broad fault zones, each down-thrown to the east. Four similar but apparently unpaired lineaments occur to the west of Newington, one of which coincides with the Medway valley.

These lineaments appear to control subtle changes in the direction of dip and may have an important control on groundwater flow, by dividing the Chalk into a series of structural 'blocks'.

Pairs of inflections respectively east and west of Faversham (Figure 4) correspond to dip-parallel folds described by Holmes (1981, p. 8), where some evidence taken in older publications to indicate folding is critically discussed.

Cross-sections of the Maidstone district presented by Worssam (1963, fig. 5) show a number of broad very gentle folds in the Harrietsham area trending north-east to south-west in the Lewes and Seaford Chalk. The presence of these structures was inferred from mapping of the biostratigraphic zonal boundaries but it appears likely that the accuracy of that mapping was not sufficient to demonstrate the exact location of the displacement of the corresponding surfaces, or whether it is a consequence of folding or of faulting.

7.3 FAULTING AND FRACTURING

In common with other Chalk terrains in southern England, very few mappable faults have been recognised within the project area. Those which have been identified previously are mostly of no great extent, and occur either along the scarp face or in the Medway valley.

Although many of the chalk quarries expose faults, the majority of these have displacements of five metres or less, and they cannot be traced beyond the exposure. Although the common occurrence of minor faulting of this kind in exposures suggests that it may be a ubiquitous feature of the Chalk, especially in the harder Chalk units, such as the Holywell Nodular Chalk and the Lewes Nodular Chalk formations, it is rarely possible to demonstrate the existence of faults of less than five metres displacement in unexposed ground on the Chalk, even during detailed field surveys.

The north-easterly-trending reaches of the Medway valley through the Chalk outcrop are controlled by a fault zone running along the axis of the valley. This is likely to be a complex structure consisting of several interlinked faults. Borehole evidence from the site of the new Medway Bridge [TQ 724 670] shows faulting down-thrown to the west.

Marked variations in the thickness of some units in the Chalk has been found a few kilometres to the east of the River Medway. This has been attributed to reduced sedimentation over the 'Medway Axis', a structural zone controlled in part by a NNW-SSE synsedimentary fault with easterly downthrow, between the chalk pits at Wouldham and Burham on the eastern side of the River Medway (Robinson, 1986, p. 165).

Few faults can be confidently located by desk interpretation alone, but construction of structure contour maps for the base of the Palaeogene, the base of the Seaford Chalk and the base of the Lewes Chalk does suggest the presence of several previously unrecognised faults (Figure 4). These strike between north-north-east and east-north-east, being down-thrown either to the east or to the west by between about 3 and 15 metres. The occurrence and orientation of these faults has not been tested by fieldwork, although Dines et al (1971) note that faults of up to five metres throw seen at exposures in the Chatham area typically lie perpendicular to strike. The estimated amount of down-throw is particularly dependent on the details of the interpreted structure contours.

In Section 7.2.2, it was suggested that a topographic 'steep zone' crossing the North Downs dip slope approximately parallel to strike marks a fault zone (Figure 4). Field evidence for this was found in the chalk quarry west of Doddington [TQ 721 567] which is aligned with this zone of topographic steepening. The western end of the quarry exposes a series of subvertical fracture zones aligned between N351° and N307° degrees. These zones include several minor faults which displace flint bands down to the east by between about 0.5 and 2 m. North-north-east trending offsets in this topographic 'steep zone' can also be attributed to faulting.

The linear inflections noted in the basal Palaeogene surface (Section 7.2.3) probably mark fault displacement at depth, and many, if not all, could be associated with near-surface concentrations of subvertical fractures. Some of these lineaments appear to be aligned with faults inferred from other evidence, or with offsets in the North Downs escarpment (Figure 4).

The North Downs escarpment is characterised by lengthy linear sections closely parallel to strike, separated by short intervening sections oblique to strike in which geological boundaries change height relatively rapidly (Figure 4). In one place, near Blue Bell Hill in the west of the area, there is evidence for coincident fault displacement of the base of the Lewes Chalk. On present evidence faulting can only be suspected at the other deflections of the escarpment.

It is assumed that drainage lines tend to follow major fractures within the Chalk, although the regional dip presumably also exerts a strong influence on valley orientation. Two strong preferred orientations are apparent in linear elements of the local drainage: one trending north-east - south-west, most clearly developed in the valleys south of Sittingbourne and Faversham, including that of the River Great Stour, and a second trending north-south. Two minor sets also occur: east-west and approximately north-west – south-east. These fracture zones may have a significant influence on water movement within the aquifer, even though faulting within them may be minor in terms of vertical displacement.

8 Hydrogeological characteristics of the Chalk

The Chalk is the major aquifer in the region. It receives most of the recharge in the project area. Groundwater in the Chalk emerges at springs at the northern foot of the Downs. Most of the largest springs occur at the contact between the Seaford Chalk and the overlying Palaeogene deposits, although there are some either within the Chalk or in the Palaeogene.

The hydrogeological characteristics of the Chalk aquifer are thought to be influenced by several aspects of rock mass character, such as hardness (itself a function of chalk density), porosity and fracture style, which are to a large extent functions of the lithological assemblage found in each Chalk formation (Mortimore et al., 1990; Mortimore, 1993). In turn, the fracture style is thought to influence the fracture/fissure volume, and so also the hydraulic conductivity.

For example, the New Pit Chalk Formation, composed of fairly uniform, medium-hard chalks with sporadic marl seams, typically develops a network of steeply inclined conjugate joints. The joints serve to concentrate groundwater movement through the relatively brittle rock mass, until it meets a marl seam which has deformed plastically. Such marl seams tend to act as loci for bedding-parallel groundwater movement and solution-widened cavities commonly develop along them (Mortimore 1993). In the Lewes Chalk, by contrast, the harder nature of the nodular chalk gives rise to more open joints. These are prone to dissolutional widening and may form significant conduits for groundwater flow.

The presence of other individual beds of relatively impermeable material, such as flint bands (especially tabular flints), hardgrounds and sponge beds, is also likely to be hydrogeologically significant. Major flint bands such as the Seven Sisters Flint or 'Whitaker's Three Inch' in the Seaford Chalk can be expected to impede downward flow within the vadose zone and so become significant groundwater flow horizons. Consequently, cavities can occur perched along tabular flints or hardgrounds within the Lewes Nodular and Seaford Chalk formations. Examples of these can be seen at a pit near Doddington [TQ 721 567] (see cover).

The particular horizons followed by groundwater flow can be expected to vary laterally, depending on several factors such as whether a horizon is laterally extensive, its orientation relative to the hydraulic gradient, and whether it is intersected by fractures themselves acting as conduits. Solution cavities may be oriented either parallel to dip, or oblique or perpendicular to it depending on the direction of the maximum hydraulic gradient. Most karstic solution occurs close to the water table, so the extent of karstic development will also depend on its present and past position and the amount by which it has fluctuated.

Fracture zones are likely to create significant anisotropy within the aquifer. For example, the western end of the chalk quarry west of Doddington [TQ 721 567] exposes a series of subvertical fracture zones, including minor faults, over a width of about 25 m. There is a strong contrast between the subvertical tectonic fabric in the western part of the quarry and the bedding-parallel joints and fissures seen nearby. Some of the fault planes are marked by open fissures, whereas others are lined by chalk and flint breccia, and 'puggy' chalk. The occurrence of brown-coloured sandy clay within parts of these fracture zones indicates that they once acted as groundwater channels, whereas the broken and weathered materials lining the faults would presumably have strongly inhibited movement of groundwater across the fracture zone.

Direct point recharge into swallow holes in the Chalk can be observed in the Selling area, between Faversham and Canterbury. Here, streams draining the Palaeogene scarp on the southern and western sides of the Blean (Joan Beech Wood) and the outlier near Selling sink underground on reaching the Chalk. Large karstic conduits are known in the Medway region, notably at Strood water works on the western side of the Medway. Recharge from the Thanet Sand Formation into the Chalk is likely to occur along the 'feather edge' of the Palaeogene outcrop, especially where dissolution has enhanced the permeability of the Chalk.

Many of the large springs at the northern foot of the Downs occur in the Chalk, close to the contact with the overlying Thanet Formation. These include the springs at Sittingbourne [TQ 911 640], Osiers Farm [TQ 963 630], and Hawkes and Beetles Farm [TQ 984 628]. Reappraisal of the geological mapping of the ground surrounding three other major springs, which the published maps show to be occur within the Thanet Formation outcrop, at Bapchild (St Thomas a Becket's spring) [TQ 931 632], Oare Creek [TQ 001 622] and Fairbrook [TQ 055 606], suggests that they too lie within the Chalk. The presence of this spring-line can be attributed to sandy and silty clay in the lower part of the Thanet Formation (Aldiss and Farrant, 2002). It seems possible that the upper part of the Thanet Formation, together with the other arenaceous early Palaeogene formations, is at least partly hydraulically separated from the Chalk between Otterham and just east of Faversham, and also possibly further east. However, the actual extent of groundwater flow between each unit remains unknown.

Moreover, as discussed in Section 7, the base of the Palaeogene has been gently deflected on a series of north-north-east – south-south-west trending axes, particularly in a zone covering Sittingbourne and Faversham (Figure 4). This zone, which can be expected to include a corresponding concentration of fracture zones in the Chalk, also includes most of the major springs. Some lie immediately adjacent to the individual axes of inflection marked on Figure 4, and so might be supposed to coincide with major fracture zones. However, these fold axes can be plotted only rather approximately and so the degree of alignment of a particular spring with a specific fold axis should not be treated with any great significance. Nevertheless, the coincidence of the main concentration of springs with this zone of gentle flexuring suggests a controlling relationship, although there is no specific evidence its nature. There are two main possibilities: firstly, that there some underlying structure which has somehow controlled the distribution of the clay-rich facies in the lower Thanet Formation, and secondly, that the major springs do indeed lie on fracture zones, perhaps having developed karstic cavities, which have acted as conduits for groundwater flow. Such fracture zones would not be expected to have propagated through the largely unconsolidated Palaeogene sequences.

If there is indeed a dual control on the position of the North Kent spring-line, and of the individual springs within it, it may be that the bulk permeability of the lower Thanet Formation is greater than would appear to be case if that were the sole, or major, control.

A few perennial springs do occur within the Thanet Formation or the Woolwich Formation, notably at Halstow. These, together with such ephemeral springs which also arise within the early Palaeogene outcrop, likewise indicate the presence of intraformational aquitards, presumably clay-rich strata.

9 Conclusions

The geological maps of the North Downs in Kent have been revised to incorporate the new Chalk lithostratigraphy. The presence of the lowest six new Chalk formations can be recognised from existing geological descriptions of the area, and their outcrop patterns mapped using available published and unpublished evidence. The new linework should be regarded as an approximation which could significantly improved by detailed field mapping.

This improved subdivision of the Chalk has been used in conjunction with borehole and seismic data to produce a three-dimensional geological model of the area. However, the scarcity of reliable borehole data does not permit a high quality, accurate, detailed model to be constructed by computer. The model presented should be viewed with this in mind and used with caution. Two-dimensional structure contour maps were compiled from outcrop data and borehole data for the base of Palaeogene, base Seaford Chalk and base Lewes Chalk using traditional manual methods. These give a more accurate picture of the structure, and show the likely position of some fold and fault axes. However, the wavelength of the small to medium-scale folds in the Chalk is less than the general spacing of the boreholes in the area. This sparse distribution of subsurface data does not allow the confident delineation of any but the most obvious structures.

Within the project area, the Chalk generally dips to the north-north-east at between 0.5º and 3º. The regional dip of the basal Palaeogene surface is generally similar, being mostly between 1º and 1.5º and locally increasing to 2º in the west, and in the east of the area.

There is evidence for folding and faulting both approximately perpendicular to, and parallel to, the regional dip. In many cases, it is not possible to state confidently that a particular perturbation of the strata is caused by a fold or a fault, but this difficulty is probably not of critical importance in the present context: it seems likely that in most local folds the Chalk will have undergone some brittle fracture and sufficient minor faulting to influence the local hydrogeology.

In particular, there is a series of north-north-east – south-south-west oriented linear structural zones (marking folds, or fracture zones, or both) which appear to control subtle changes in the direction of dip and may have an important control on groundwater flow by dividing the Chalk into a series of structural ‘blocks’.

Two strong preferred orientations are apparent in linear elements of the local drainage, taken to mark subvertical fracture zones. They trend north-east - south-west, and north-south. Two minor sets also occur: east-west and approximately north-west – south-east. These fracture zones may have a significant influence on water movement within the aquifer, even though faulting within them may be minor in terms of vertical displacement.

The Chalk is the major aquifer in the region. The hydrogeological characteristics of the Chalk are thought to be influenced by aspects of rock mass character, such as hardness, porosity and fracture style, which are to a large extent functions of the lithological assemblage found in each Chalk formation. Most of the groundwater movement in the Chalk is likely to be derived from flow in the Seaford Chalk and Lewes Chalk formations. Enhanced flow is particularly likely along major tabular flints horizons, hardgrounds, and marl seams, and along fractures in the Lewes Chalk. Karstic groundwater flow is particularly likely in the eastern part of the region, where swallow holes are known.

Groundwater in the Chalk emerges at springs at the northern foot of the Downs. Most of the largest springs occur at the contact between the Seaford Chalk and the overlying Palaeogene deposits, although there are some either within the Chalk or in the Palaeogene.

The presence of this spring-line can be attributed to sandy and silty clay in the lower part of the Thanet Formation. It seems possible that the upper part of the Thanet Formation, together with the other arenaceous early Palaeogene formations, is at least partly hydraulically separated from the Chalk between Otterham and just east of Faversham, and also possibly further east. However, the actual extent of groundwater flow between these aquifers remains unknown.

It is possible that in addition the major springs lie on fracture zones in the Chalk, which have acted as conduits for groundwater flow.

This suggests that a dual control operates on the North Kent spring-line, and of the individual springs within it, implying that the bulk permeability of the lower Thanet Formation could be greater than would appear to be case if that were the sole controlling factor.

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Table 1: Correlation of biostratigraphical and lithostratigraphical classification schemes for the Chalk of southern England

Stage	Foraminiferal Zones* UKB	Foraminiferal Zones* BGS	Macrofossil Zones	Macrofossil Subzones	Traditional southern England subdivisions	North Downs Robinson (1986)	South Downs Mortimore (1986)	Dorset Bristow et al. (1995)	Southern England Bristow et al. (1997)	Southern England Rawson et al. (2001)
Campanian (pars)	17 & 18 (lower)	21	*Belemnitella mucronata s.l.*				Portsdown		Studland Ck; Portsdown Chalk	Portsdown Chalk Formation
	16	20	*Gonioteuthis quadrata*	'post *A. cretaceus* beds'; *Applinocrinus cretaceus*; '*Hagenowia* Horizon'			Culver	Spetisbury; Tarrant	Spetisbury Ck; Tarrant Chalk	Culver Chalk Fm: Spetisbury C M; Tarrant Chalk Member
	15 (upper)	19	*Offaster pilula*	'abundant *O. pilula*'; *Echinocorys depressula*	Upper	Ramsgate Chalk Formation: Margate Member	Sussex White Chalk: Newhaven	Upper Chalk: Blandford	Upper Chalk: ? Margate Chalk / Newhaven Chalk	White Chalk Subgroup: ? Margate Chk Mbr / Newhaven Chalk Formation
Santonian	uppermost 14 & lower 15	18	*Uintacrinus anglicus*; *Marsupites testudinarius*; *Uintacrinus socialis*							
	14 (rest); 13; 12 (upper); 12 (l & m)	17; 16; 15; 14	*Micraster coranguinum*			Broadstairs Member	Seaford		Seaford Chalk	Seaford Chalk Formation
Coniacian	11	13	*Micraster cortestudinarium*		Top Rock	St Margarets Member	Lewes	Lewes	Lewes Nodular Chalk	Lewes Nodular Chalk Formation
Turonian	10 (upper)	12	*Sternotaxis plana*		Chalk Rock					
	10 (lower & middle)	11	*Terebratulina lata*		Middle: Spurious Chalk Rock	Dover Chalk Fm: Akers Steps Member; Aycliff Member	Ranscombe: New Pit Beds	Middle Chalk: New Pit	Middle Chalk: New Pit Chalk	New Pit Chalk Formation
	10 (basal)	10								
	9 (modified)	9	*Mytiloides* spp.			Shakespeare Cliff Member	Holywell Beds (U, M, L)	Holywell	Holywell Nodular Chalk	Holywell Nodular Chalk Formation
U	8 (upper) & 9 (basal)	8	*Neocardioceras juddii*		Melbourn Rock		Melbourn Rk			
Cenomanian U	8 (lower)	7	*Metoicoceras geslinianum*		Plenus Marls	Plenus Marls Fm		(Plenus Marls)	(Plenus Marls)	(Plenus Marls Member)
M	7 (modified)	6	*Calycoceras guerangeri*		Lower: Grey Chalk	Abbots Cliff: Capel-le-Ferne Member	Lower Chalk	Lower Chalk: Zig Zag	Lower Chalk: Zig Zag Chalk	Grey Chalk Subgroup: Zig Zag Chalk Formation
	6	5	*Acanthoceras jukesbrownei*			Hay Cliff Member				
	5	4	*Acanthoceras rhotomagense*	*Turrilites acutus*; *Turrilites costatus*						
	4	3	*C. inerme*		Chalk Marl	East Wear Bay Chalk Fm		West Melbury Chalk	West Melbury Marly Chalk	West Melbury Marly Chalk Formation
L	3	2	*Mantelliceras dixoni*							
	1 & 2	1	*Mantelliceras mantelli*	*Mantelliceras saxbii*; *Sharpeiceras schlueteri*; *Neostlingoceras carcitanense*						
					Glauconitic Marl	Glauconitic Marl	Glauconitic Marl	Melbury Sst	Glauconitic Marl	(Glauconitic Marl Member)
Upper Albian (pars)			*Stoliczkaia dispar*	*M. (D.) perinflatum*; *M. (M.) rostratum*	Upper Greensand		Upper Greensand	UGS: Boyne Hollow Chert	Upper Greensand/Gault	Upper Greensand/Gault

*** Foraminiferal Zones after Hart et al., (1989) (UKB zones) and Wilkinson (2000) (BGS zones). Not to scale.**

Figure 1: Location and solid geology of the project area (based on published BGS 1:50 000 geological maps)

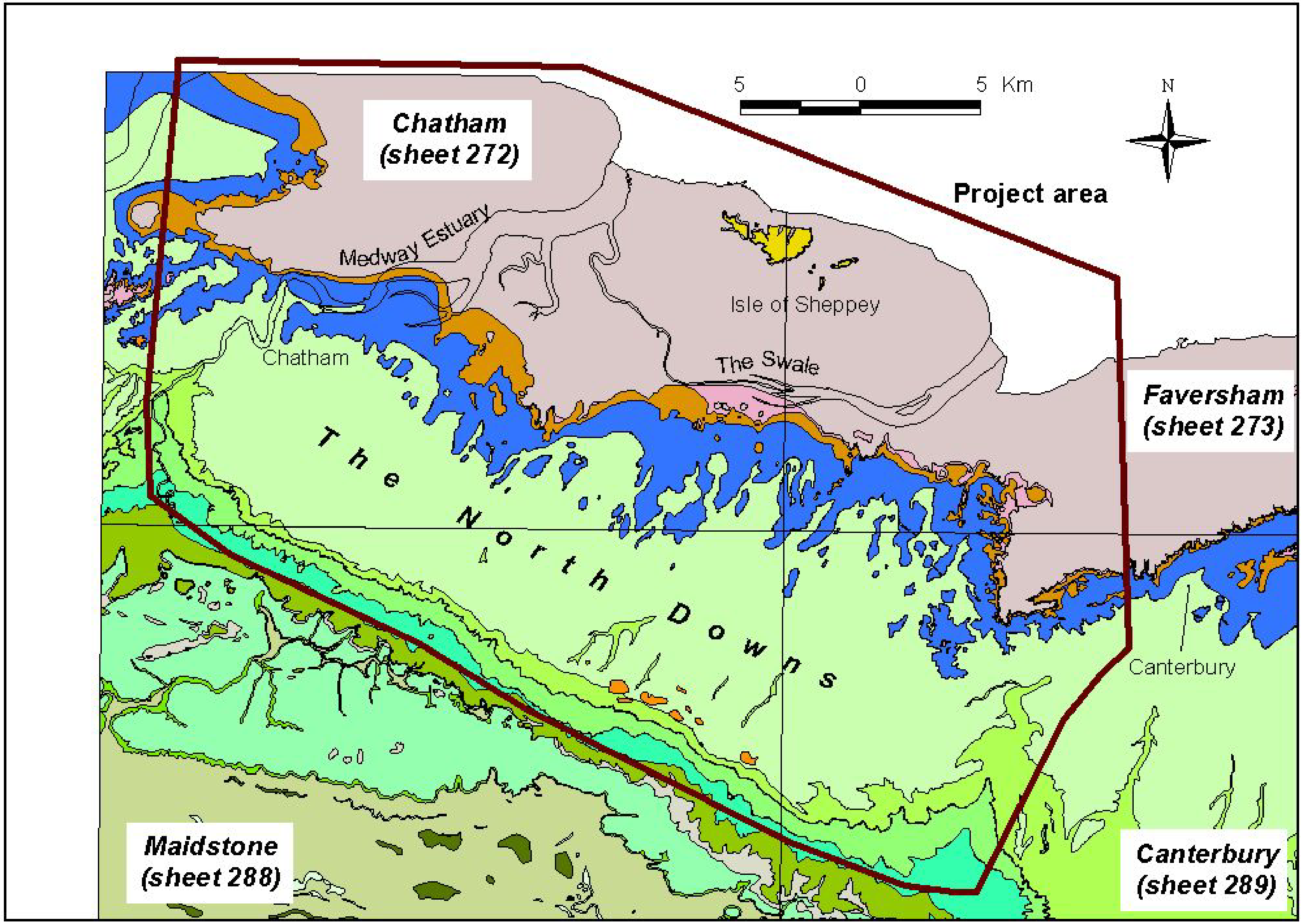
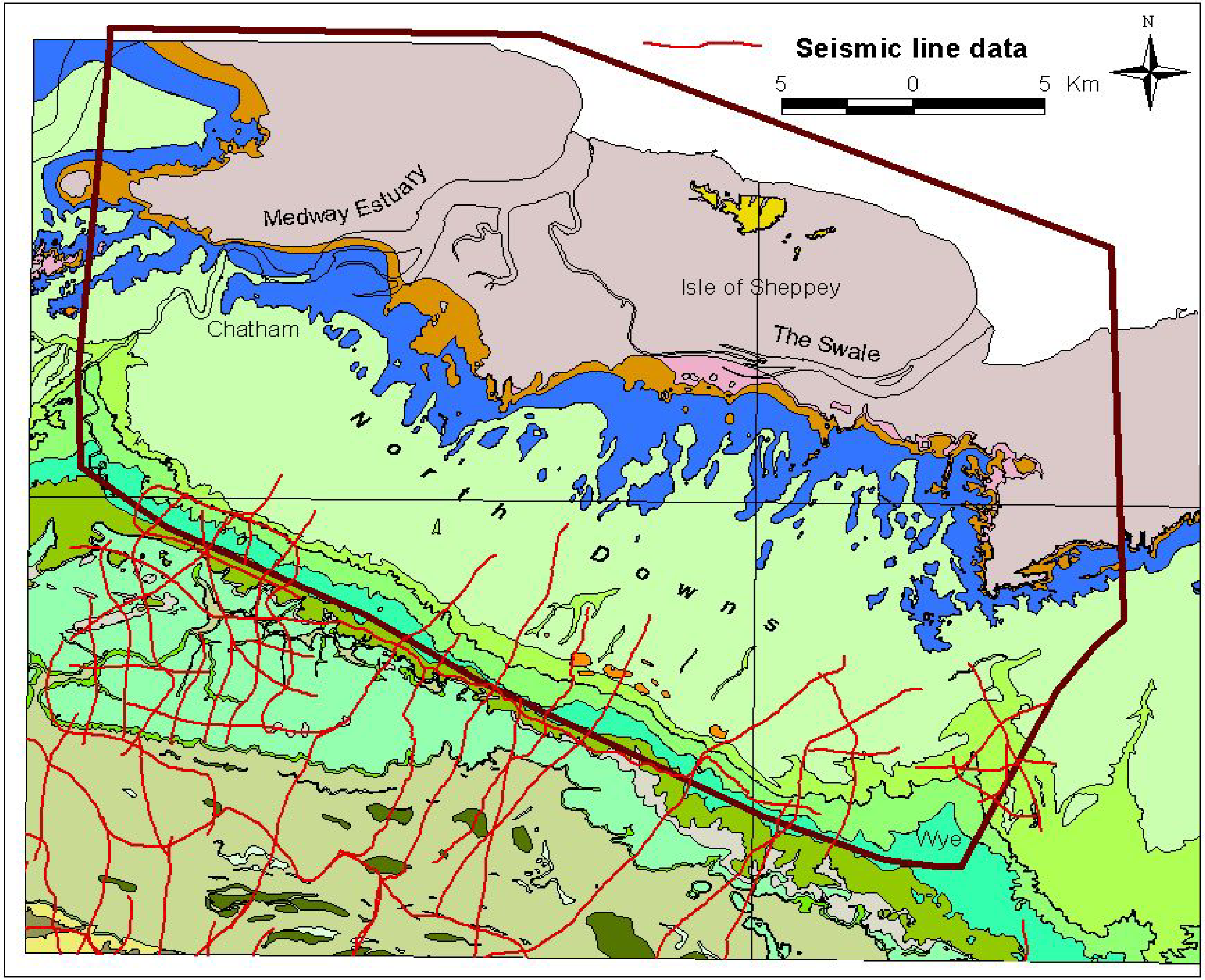


Figure 2: Solid geology based on published 1:50 000 scale geological maps, showing location of seismic data.



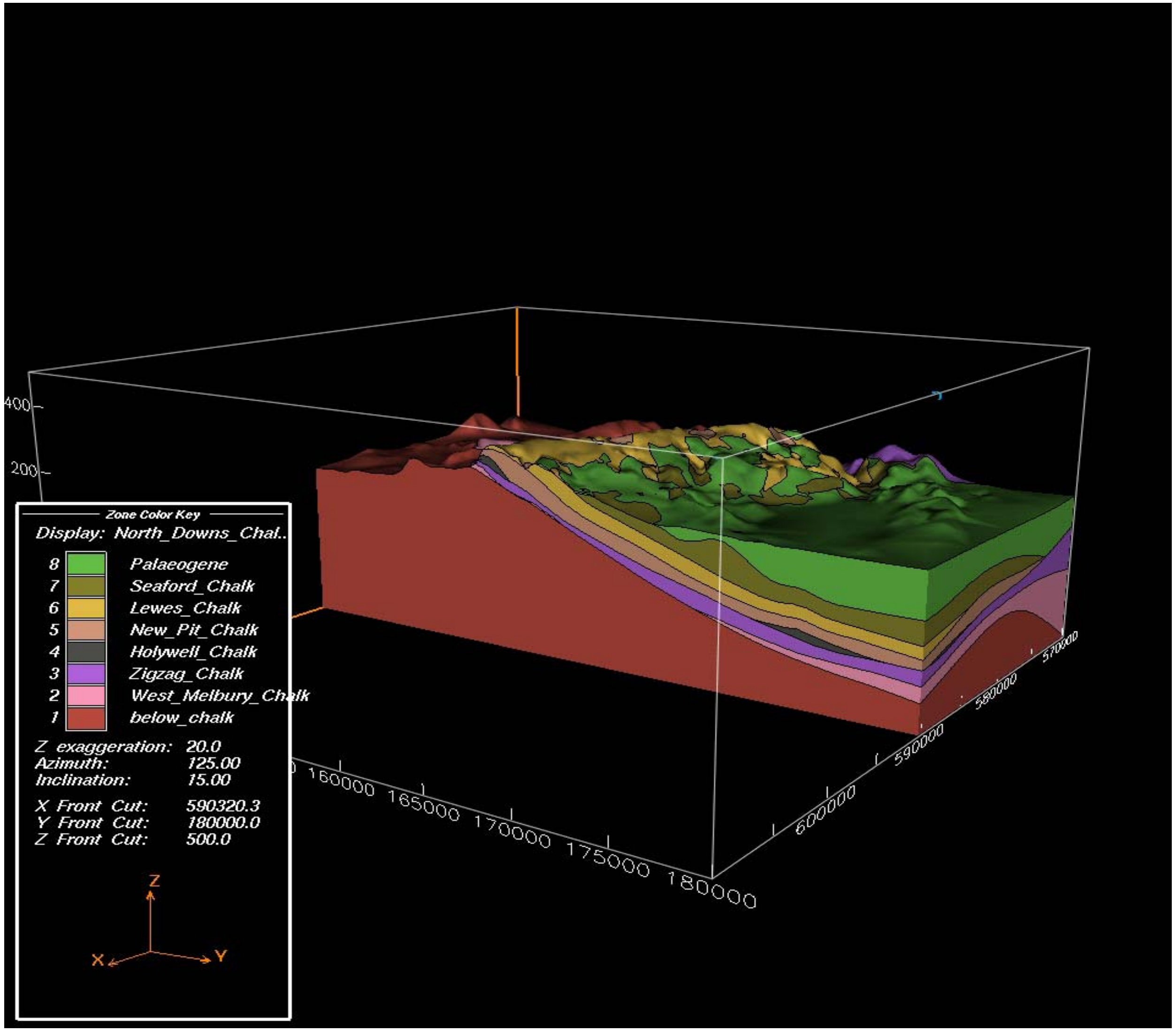


Figure 3: Section through the North Downs earthVision model looking west.

Note that using the earthVision modelling package with the sparse point data available causes convergence between the base Chalk and base Zigzag surfaces and the base New Pit and base Holywell surfaces.