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INSTITUTE OF GEOLOGICAL SCIENCES

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TABLES

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R. W. GALLOIS

SUMMARY

The results of stratigraphical and engineering studies on the Jurassic, Cretaceous and Quaternary sediments of the southern part of The Wash and the adjacent land area are presented. The work was carried out as part of the Wash Water Storage feasibility study and was designed to assess the suitability of these sediments as a tunnelling medium down to depths of 150 m over an area of more than one thousand square kilometres. The stratigraphy of the Oxford Clay, West Walton Beds, Ampthill Clay, Kimmeridge Clay, Lower Cretaceous, Pleistocene and Recent deposits is described. It is suggested that the glacial deposits of Fenland fill a pre-Glacial valley system.

The engineering properties of the various sediments are described and their probable performance in tunnels is discussed in relation to their stratigraphy, chemistry and geological history. Geophysical borehole-logging techniques, particularly total gamma-ray logging, have been extensively used in the work and their usefulness as site investigation tools is discussed.

On a etudié, du point de vue de la stratigraphie et du génie civil, les sédiments jurassiques, cretacés et quaternaires dans la partie du sud du Wash et son littoral, et on présente les résultats de ces études. Le travail faisait partie de l'étude de la practicabilité d'emmagasiner l'eau dans le Wash. On avait l'intention d'établir combien ces sédiments sont adaptés comme milieu pour le percement de tunnels jusqu'à 150 m de profondeur sur une étendue de plus d'un millier de kilomètres carrés. La stratigraphie de l'Oxford Clay, des West Walton Beds, de l'Ampthill Clay, du Kimmeridge Clay et des dépôts crétacés inférieurs, pleistocénes et récents est décrite. On suggére que les dépôts glaciaires de Fenland remplissent un système de vallées préglaciaires. Du point du vue du génie civil on décrit les qualités des sédiments divers, et leurs réactions probables en tunnels sont discutées par rapport à leur stratigraphie, chimie et histoire géologique. Dans ces travaux on a employé largement des techniques géophysiques d'enregistrement de trous de sonde, surtout l'enregistrement par rayons gamma totaux et on discute leur valeur comme outils de recherche pratique.

Die Resultate von stratigraphischen und Tiefbau-studien über die Jura-, Kreide- und Quartärsedimente vom südlichen Teil von «The Wash» und vom anliegenden Landgebiet werden gegeben. Die Arbeit wurde als Teil des Wash-Wasseraufbewahrung-möglichkeitsstudiums durchsetzt und wurde geplant, die Eignung von diesen Sedimenten als Tunnelbauvermittlung bis zu Tiefen von 150 m über ein Gebiet von mehr als tausend Quadratkilometern zu schätzen. Die Stratigraphie von Oxford Clay, West Walton Beds, Ampthill Clay, Kimmeridge Clay, Unterkreide, Pleistozän und neulichen Ablagerungen wird beschrieben. Man macht den Vorschlag, dass die Gletscherablagerungen von Fenland ein Vorgletschertalsystem füllen.

Die Tiefbaueigenschaften von den verschiedenen Sedimenten werden beschrieben, und man bespricht ihre wahrscheinliche Leistung in Tunneln mit Bezug auf der Stratigraphie, Chemie und geologischen Entwicklung.

Geophysischebohrlochloggenmethoden, besonders das totale Gammastrahlenloggen waren in dieser Arbeit weitreichend benutzt, und ihre Brauchbarkeit als Platzuntersuchungsgeräte wird besprochen.

Bibliographical reference
GALLOIS, R. W. 1979. Geological investigations for the Wash Water Storage Scheme. *Rep. Inst. Geol. Sci.*, No. 78/19.

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INTRODUCTION

HISTORICAL BACKGROUND

The idea of building a barrage across The Wash to create an enormous freshwater lake was first put forward over 100 years ago, but it was not until 1965 that the project began to be considered seriously as one of a number of alternative ways in which the future demands for water in the South-East might be met. It was at this time that the Institute of Geological Sciences was asked by the Ministry of Housing and Local Government to provide information on the geology of the floor of The Wash and its adjacent land areas for use in connection with the possible construction of a barrage across the mouth of The Wash. The geological information available at that time was extremely limited, being restricted to 19th-century small-scale geological maps of the land areas (Old Series geological

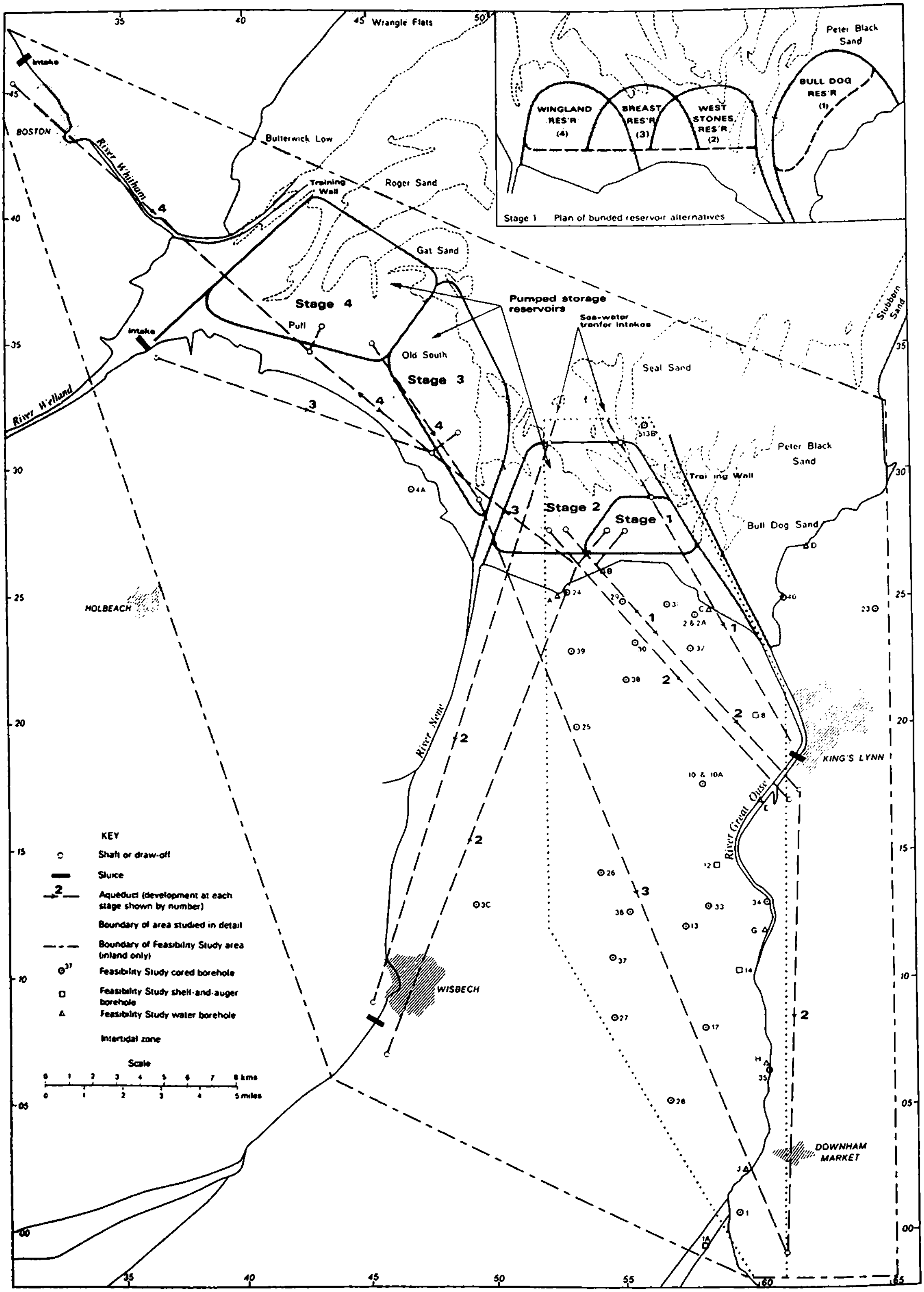

Figure 1 Plan of suggested developments and borehole site map

sheets 65 and 69), a scattering of borehole data on the land area and a small number of samples taken from the deep central channel of The Wash (Dingle, 1967). It was clear, however, even from this limited amount of information, that the solid strata cropping out on the floor of The Wash, together with their relationships to the Glacial and Recent deposits, could best be studied on the eastern side of The Wash where they crop out in a series of low escarpments running southwards from Hunstanton to King's Lynn and Denver. Primary six-inch geological surveying was therefore begun on Sheets 129 (The Wash) and 145 (King's Lynn) in 1965. This work was completed in 1971. Four continuously cored boreholes were drilled for stratigraphical purposes as part of the field survey, two of them at the nearest easily accessible points to the then possible line of the barrage, at Hunstanton and Skegness (Gallois *in* Institute of Geological Sciences, 1971).

In 1968 the Government authorised the Water Resources Board to undertake a desk study to assess the use of The Wash for possible future water storage. The Board's Report on the Desk Study (Water Resources Board, 1970) concluded that the construction of a barrage as originally envisaged was not economically practicable and that fresh water could best be stored in three or four bunded reservoirs at the southern end of The Wash. The Report further recommended that a full feasibility study should be undertaken to assess the engineering, economic, ecological and other factors that might be involved in the construction of these reservoirs.

The Secretary of State for the Environment authorised the Board to undertake the feasibility study in March 1971. The Institute was at that time completing the survey of the King's Lynn 1:50 000 Geological Sheet and, by virtue of its specialised local knowledge of the stratigraphy of the area, was invited by the Board to participate in the land-area investigation for the feasibility study.

SCOPE OF THE INVESTIGATION

The following report is concerned with only one part of the feasibility study, namely the assessment of the geological conditions likely to be encountered in the tunnel aqueducts connecting the possible reservoirs with their sources of fresh water. The Desk Study Report recommended that the feasibility study should be so designed as to enable a decision to be made whether or not to construct the first (Stage 1) bunded reservoir. The geological investigations described below are therefore concerned wholly with the assessment of the geological conditions beneath the area between the Stage 1 reservoir (as defined in the Desk Study Report, Map 1) and possible sources of fresh water from the River Great Ouse between King's Lynn and Denver (Figure 1). This is referred to subsequently in the text as the Stage 1 area.

The aims of the present work have been, firstly, to provide sufficient geological data to enable comparative assessments to be made between all possible tunnel aqueduct routes between Denver and the Stage 1 reservoir down to depths of about 150 m, and, secondly, to provide more general information on the geological conditions likely to be encountered along tunnel routes supplying alternative sites for the Stage 1 reservoir (Alternatives 1 to 4, WRB revised layout, December, 1972) and along routes supplying the Stages 2, 3 and 4 reservoirs (Figure 1). It has been borne in mind during the work that the most economical type of aqueduct construction available at the present time is that of standard 2.54-m (100-in) diameter tunnels, bored by a soft ground shield and lined with expanded concrete rings (Tattersall segments).

The work has also been designed to supply the stratigraphical and technical information necessary for the planning and execution of future site investigations for specific tunnel lines should approval for the construction of the reservoirs be given.

GENERAL GEOLOGY

The rock sequence of The Wash area can be divided into three parts, the Jurassic–Cretaceous solid rocks*, the Glacial deposits and the Recent deposits, each part consisting of sediments of different ages which are, for the most part, unrelated in their geographical distribution (Figure 2).

The geological structure of the area is simple. The Jurassic and Cretaceous rocks dip gently eastwards to east-north-eastwards, mostly at half a degree or less, and form a series of low escarpments running roughly north–south. The Cretaceous escarpment runs from Hunstanton, through the eastern part of King's Lynn and continues to Denver. The Jurassic escarpments run southwards from beneath the Terrington Marsh area to west of Denver but are now completely hidden beneath a cover of Recent deposits, locally over 20 m thick, which form Marshland and Fenland.

In Norfolk, the Lower Cretaceous consists mostly of weakly cemented sands and clayey sands (the Sandringham Sands) which are water-bearing. They would prove difficult to tunnel through with the equipment available at present and they form an effective eastern limit to the area of the feasibility study investigation.

The area beneath all four reservoir stages, together with their aqueduct tunnels, is floored by Upper Jurassic formations, the West Walton Beds and the Oxford, Ampthill and Kimmeridge clays. These formations consist almost wholly of clays. They do, however, contain thin beds of hard limestone at certain levels and local deposits of Upper Jurassic sandstone and reef limestone are known to occur not far distant from The Wash.

Superimposed on the Jurassic and Cretaceous escarpments is an old valley system which is now, for the most part, filled with Glacial deposits. East of a line from King's Lynn to Denver the positions of these old valleys can be clearly seen where they cut the Cretaceous escarpments. West of this line, in the area of interest to the feasibility study, they are completely hidden beneath Recent deposits. On the western and southern edges of Fenland, between Sleaford and Huntingdon, where Jurassic rocks come to the surface, glacially-filled valleys are again in evidence. On all three landward sides of the Fens these valleys appear to drain towards a major valley which formerly carried the combined waters of the present rivers Ouse, Nene, Welland and their tributaries, together with parts of the drainage of the Trent.

* The term 'rock' is used by geologists to cover almost all naturally occurring deposits, irrespective of their physical properties. For contractural purposes engineers classify such material either as 'soil', usually soft and loose, or 'rock', usually hard and rigid. In the wholly geological parts of this report, i.e. those parts dealing with stratigraphy or geological structure etc., the term 'rock' is used in the geological sense. Elsewhere, where the physical properties and probable engineering behaviour of the materials is discussed the terms 'soil' and 'rock' are used in the engineering sense.

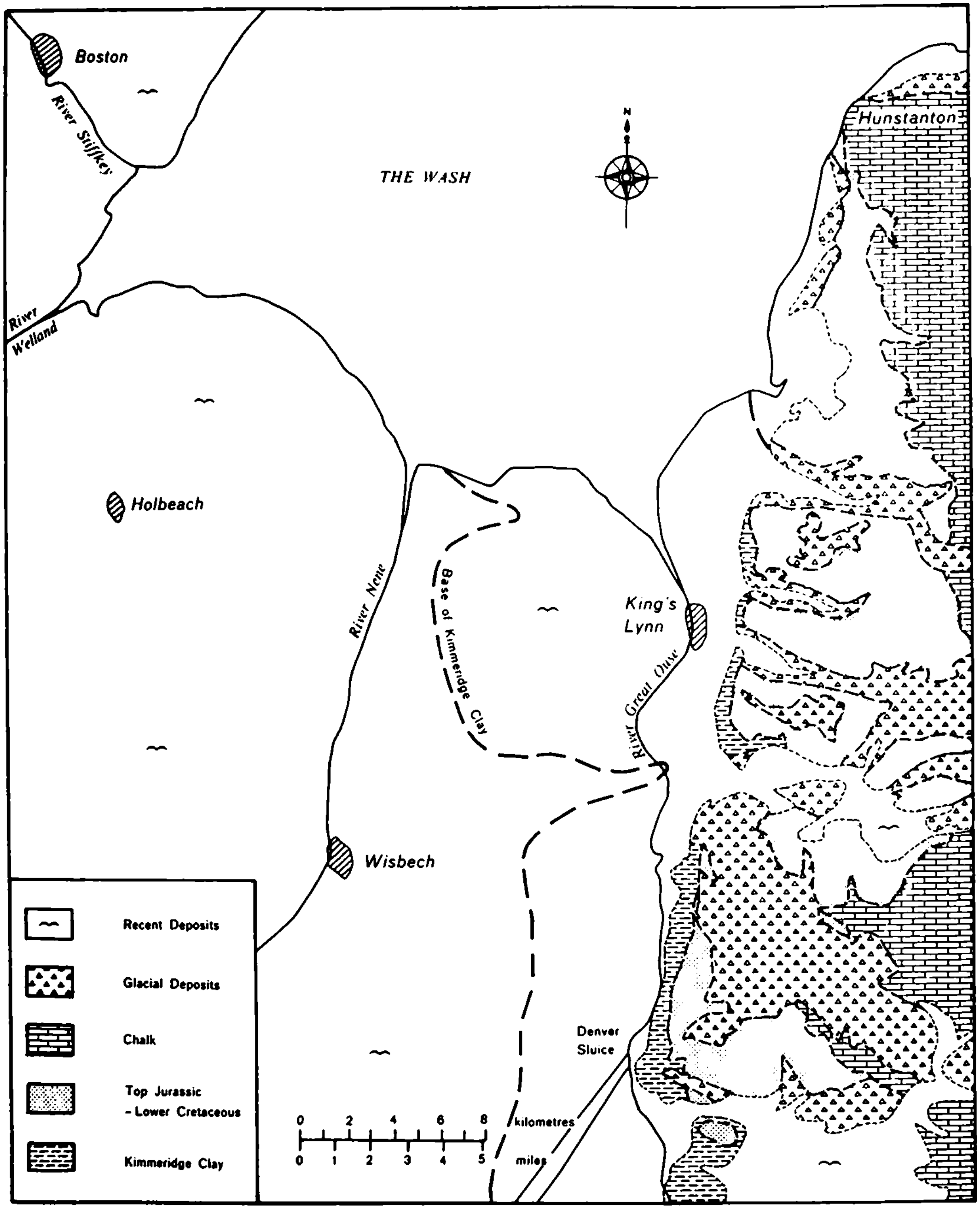

Figure 2 Geological sketch map of the Feasibility Study area

METHODS OF INVESTIGATION

The method of investigation used has been to establish standard lithological and palaeontological sequences for the full range of Upper Jurassic rocks likely to be encountered anywhere within the four reservoir stages or in their attendant aqueducts, by means of four continuously cored boreholes (Figure 1) at Denver (Bh. 1), Walton Highway (Bh. 3C), Gedney Drove End (Bh. 4A) and North Wootton (Bh. 23), ranging from 100 to 170 m in depth. These boreholes were drilled to such depths that they would provide extensive overlaps between those parts of the Upper Jurassic sequence thought to be of most interest, thereby enabling an assessment to be made of lateral changes in lithology that might be present within the clays. The Jurassic rocks and the Glacial deposits in an area approximately 15 km by 25 km, running from Terrington Marsh to Denver, were then examined in detail by means of a further 21 cored boreholes, ranging in depth from 30 to 80 m (Figure 1).

ACKNOWLEDGMENTS
The work described in this account was jointly funded by the Water Resources Board and the Natural Environment Research Council. The author thanks the Central Water Planning Unit (as successors to the Water Resources Board for the management of the feasibility study) for permission to publish these details from the study and acknowledges the assistance of staff of the Unit's consulting engineers, Messrs Binnie and Partners, who supervised the drilling programme. Mr L. Standen-Batt of the Resources Division of the WRB geophysically logged several of the boreholes and the author is grateful for his assistance.

The inland drilling (Boreholes 1 to 40), comprising 25 cored boreholes and 5 shell-and-auger boreholes, was carried out by Foraky Ltd and an offshore cored borehole (Borehole 513B) was drilled by Wimpey Ltd. The soil test results quoted in this report are taken from a report prepared by the Wimpey Central Laboratory.

In addition to the feasibility study offshore cored borehole, the Continental Shelf Unit South of IGS drilled four cored boreholes within The Wash from the m.v. *Whitethorn* (Boreholes IGS 71/65, 71/66, 72/77 and 72/78) as part of the overall study of the geology of the area.

The stratigraphical interpretation of the Upper Jurassic clays, which forms a large part of the present report, is the result of collaboration between Miss Beris M. Cox of the Palaeontology Department of IGS and the present author: Miss Cox's assistance at all stages of the preparation of the report is gratefully acknowledged.

Mr D. M. Green, of the Laboratory of the Government Chemist, working under the direction of Dr R. J. Mesley, has analysed selected oil shale samples and has contributed a note on the chemistry of the Kimmeridgian oil shales. Messrs R. J. Merriman and G. E. Strong of the Petrographical Department have analysed selected clays and have provided an appendix on the clay mineralogy of the Upper Jurassic clays.

STRATIGRAPHY

In an investigation such as this where an exceptionally large volume of rock is being assessed, it is economically possible to examine only a minute part of the material under consideration, with an even smaller part available for geotechnical testing. In the case of the Stage 1 area, the borehole cores represent about one part in 500 million, and the soil-tested samples about one part in 250 000 million, of the total volume of the rock mass involved. It is therefore clearly necessary to make a number of fundamental assumptions about the nature of the strata being examined.

The most important of these assumptions is that the strata at any given stratigraphic level are sufficiently uniform for the lithologies observed in the boreholes to be correlated between them. In the case of the Upper Jurassic clays, the situation is complicated by the presence of thin limestones—one of the lithologies of most interest to the feasibility study—which commonly occur as lines of discontinuous doggers separated by clays. Furthermore, by virtue of their curved edges, such doggers are difficult to sample and are commonly lost in the coring process. Much of the stratigraphical and palaeontological effort in this study has therefore been directed towards determining the precise levels at which persistent and impersistent limestone bands occur. This has involved the detailed examination of the faunas and lithologies in the borehole cores in order to establish a standard sequence of faunal and lithological changes for the Jurassic rocks of the area. Such changes reflect events in the Jurassic environment; where these events are of a regional nature (e.g. changes of climate or sea-water temperature), they can give rise to lithological and faunal variations that can be correlated over much larger areas than that under consideration for the feasibility study. The recognition of such events can largely offset the problems arising from sampling failure.

Examples of lithological variations recorded in the cores include changes in the silt, calcium carbonate, kerogen and shell contents of the mudstones as shown by variations in texture and colour. Palaeontological examples include changes in relative abundance of particular bivalves or ammonites, sudden influxes of uncommon faunas (e.g. crinoids, echinoids, brachiopods) and interburrowed horizons. These changes probably occurred in response to events such as variations in rates of clastic influx, current strength and direction, water depth and temperature, and the climate of the land areas supplying the sediments and nutrients.

The Upper Jurassic clays of southern England were probably deposited in a relatively shallow, warm shelf-sea with interconnected subsiding basins separated by islands of low relief. During Upper Oxford Clay, West Walton Beds and Ampthill Clay times, these basins became locally shallow enough for coral reefs to form and for arenaceous sediments to be deposited adjacent to the islands. At other times (e.g. during the deposition of the Lower Oxford Clay and the Kimmeridge Clay) an open marine enviornment probably existed over most of southern England. Thus, although the sequences are wholly argillaceous within the area of the feasibility study, there are differences in the degree of detail with which lithological and faunal variations can be correlated within particular formations due to variations in the overall nature of the Upper Jurassic formations.

Changes in the general conditions of the depositional environment or the sediment source are also reflected in the distribution of clastic materials and their mineral compositions. The distribution of minerals derived from the radioelements in the uranium and thorium decay series, although usually present in quantities below the level of analytical detectability, can readily be studied by recording their gamma-ray decay emissions. Characteristic total gamma-ray signatures have been obtained for most of the boreholes (see section on geophysical logging techniques) and these have been used in conjunction with the lithological and palaeontological data to obtain progressively more detailed correlations between the boreholes.

A second assumption that has to be made in an investigation such as this is that the geological structure of the area is simple and that major faults or folds, bringing unsampled strata into the rock mass under consideration, do not occur between the boreholes. This assumption has been made for the feasibility study area after consideration of the structure of a much larger area.

The Glacial deposits, which consist of till, varved clay and glacial sand and gravel, vary considerably in lithology and in their stratigraphical relationships with one another. The pattern of their distribution and the nature of these variations cannot be deduced from the borehole data alone, but a number of generalisations can be made on the basis of evidence from the geological field survey of the area together with the inferred glacial history.

The Recent deposits have not been examined in detail in the present work since their generally poor engineering properties would probably require the use of special construction techniques everywhere within the inland area.

UPPER JURASSIC CLAYS

The Upper Jurassic clays of eastern England consist almost entirely of soft mudstones and calcareous mudstones laid down in a marine environment. Beneath Fenland and The Wash these beds form an almost unbroken argidlaceous sequence over 230 m thick which cannot readidy be divided on lithodogy alone. Elsewhere in Britain the middle part of this sequence is represented by limestones, sandstones and mudstones (the Corallian Beds) which separate a lower clay formation, the Oxford Clay, from an upper clay formation, the Kimmeridge Clay. In the feasibidity study area this middle part is everywhere present as sid mudstones (the West Walton Beds) and mudstones and calcareous mudstones (the Ampthill Clay).

The identification of these formations, and of subdivisions within them, depends in the present area upon the recognition of combinations of lithological and faunal characters. Fortunately, most of these marine mudstones carry a rich fauna of ammonites and bivalves, the ammonites being particularly useful for stratigraphical purposes.

The zones and thicknesses of the Upper Jurassic clay formations of the feasibility study area are given in Table 1.

Oxford Clay

The Oxford Clay subcrops beneath the Glacial and Recent deposits of Fenland in a broad belt, some 30 km in width, extending from Wisbech to west of Peterborough and from there running northwards beyond Spalding and Sleaford into northern Lincolnshire.

In areas adjacent to Fenland and The Wash it varies generally from about 60 to 90 m in thickness (Kellaways Beds excluded). In Cambridgeshire, boreholes at Bluntisham [TL 36 74] and March [TL 41 97] proved 91.4 m (300 ft) and 65.2 m (214 ft) of Oxford Clay respectively (Whitaker, 1922). At Warboys, Huntingdonshire [TL 308 817], Callomon (1968, p. 264) has estimated the full thickness of the formation from borehole and outcrop evidence to be about 70 m (230 ft). In the Severals House Borehole, in south-west Norfolk [TL 692 964] 61 m (200 ft) was recorded (Pringle 1923, p. 131). Kent (1947, p. 8) recorded 42.1 m (138 ft) of Oxford Clay in the North Creake Borehole, Norfolk [TF 856 386], although this figure is based on rock cuttings and geophysical information only. In Lincolnshire, the Oxford Clay at outcrop is generally about 90 m (300 ft) thick (Arkell, 1933, p. 351). In the present work only Borehole 1, (Denver Sluice) penetrated the full thickness of the formation, where 40.3 m were proved. Boreholes 3C (Walton Highway) and 4A (Gedney Drove End) penetrated about 17 m and 1 m of the Upper Oxford Clay respectively.

The Oxford Clay in the feasibility study area can be divided into a lower part comprised mostly of dark-grey mudstones with thin bituminous bands and an upper part consisting of paler, more calcareous and, locally, more silty mudstones. The conditions of deposition

Table 1 Zones and thicknesses of the Upper Jurassic clays of the Wash area

Formation	Stage	Zone	Details in feasibility study area
		Pavlovia spp.	Absent through erosion at base of Sandringham Sands
Kimmeridge Clay	Kimmeridgian	*pectinatus* *hudlestoni* *wheatleyensis* *scitulus* *elegans* *autissiodorensis* *eudoxus* *mutabilis* *cymodoce* *baylei*	Soft mudstones, calcareous mudstones and bituminous mudstones; 50 to 120 m
	Oxfordian	*rosenkrantzi*	Presumed absent through erosion at base of Kimmeridge Clay
Ampthill Clay		*regulare* *serratum* *glosense*	Soft mudstones and calcareous mudstones, silty in part; 36 to 55 m
West Walton Beds		*tenuiserratum* *densiplicatum*	Soft mudstones and calcareous mudstones with numerous cementstone bands; 10 to 15 m
Oxford Clay		*cordatum* *mariae*	
	Callovian (*pars*)	*lamberti* *athleta* *coronatum* *jasoni*	Soft mudstones and calcareous mudstones, bituminous in lower part; 40 to 70 m

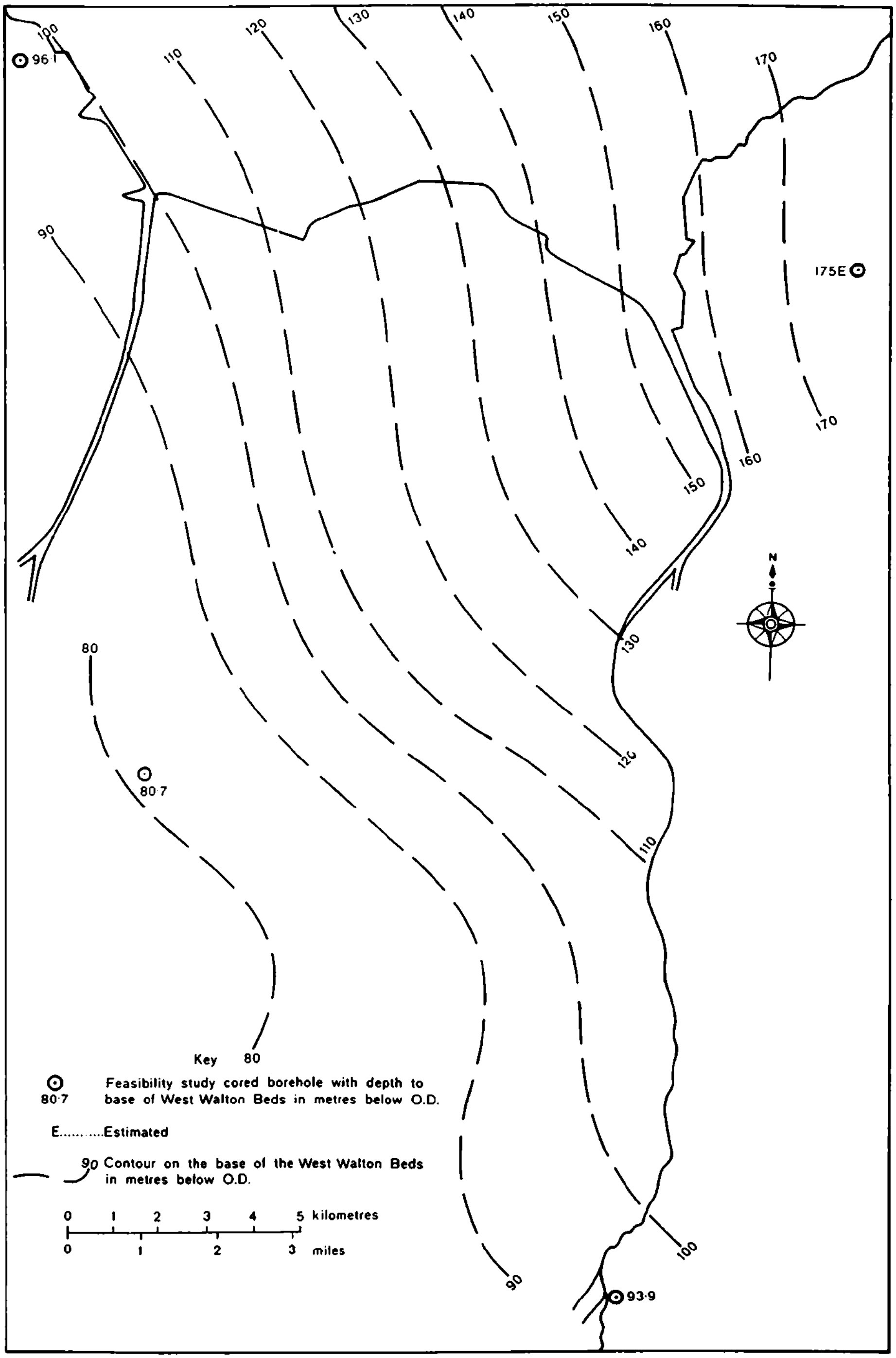

Figure 3 Structure contours on the base of the West Walton Beds, assuming a similar pattern of folding to that of the Kimmeridge Clay (Figure 6)

and palaeogeography in the lower and upper parts of the formation probably correspond closely with those of the Kimmeridge Clay and the Ampthill Clay respectively.

The lower part of the formation is well exposed in the extensive brick pits around Peterborough, where its stratigraphy has been described in detail (*see* Callomon, 1968, for summary). Its usefulness as a brick clay depends largely on the calorific value imparted by the bituminous bands: workings using the Fletton process are stratigraphically limited to horizons with these bands. The more bituminous bands are generally characterised by clusters of crushed small ammonites, and form a lithological and faunal assemblage similar to parts of the Kimmeridge Clay.

The upper part of the Oxford Clay consists of calcareous and very calcareous pale-grey mudstones characterised by a varied fauna that includes ammonites, crinoids, crustaceans, brachiopods, belemnites and oysters. This faunal and lithological assemblage suggests deposition in a more near-shore environment than the lower part of the formation and one might expect lateral lithological variations to occur at this level. The Upper Oxford Clay has little commerical value and is consequently less well exposed and less well documented than the Lower Oxford Clay. In addition, in many areas, the West Walton Beds rest disconformably on the Oxford Clay and locally much of the upper part of the sequence has been removed by erosion.

The Oxford Clay is generally at too great a depth to be of interest for tunnelling beneath the area explored in detail for the feasibility study. Estimated contours on the top of the Oxford Clay are given in Figure 3; it can be seen that the formation varies from 85 m to 150+ m below ground level in the Stage 1 area. In those parts of the area where it is nearest to the surface, the overlying Ampthill or Kimmeridge clays, which have been examined in more detail, are generally also available for tunnelling. The Ampthill Clay is separated from the Oxford Clay by the West Walton Beds (*see below*) and this last-named unit is likely to form a natural lower limit for tunnelling during Stage 1. During Stages 2, 3 and 4, the Oxford Clay might become important as a tunnelling medium (*see* p. 58).

It has not been possible to establish a generalised vertical section for the Oxford Clay of the feasibility study area because it was fully cored in only one borehole (Bh. 1). However, detailed correlations have been made between the Lower and Middle Oxford Clay sequences of that borehole and the exposures in the Peterborough area (Figure 4), which suggest that the lithological and faunal sequences at this stratigraphical level throughout the feasibility study area are likely to be similar to those at Peterborough. The Lower and Middle Oxford Clay thin eastwards towards Denver in a manner similar to the other Upper Jurassic formations.

Parts of the Upper Oxford Clay were cored in two boreholes, Boreholes 1 and 3C (Borehole 4A just penetrated the top of the formation). The only major exposure of Upper Oxford Clay near the present area is that at Warboys Brick Pit [TL 308 817], Huntingdonshire, where a sequence of 24.4 m of mudstones with thin limestone bands was recorded by Spath (1939, pp. 82–87).

The Upper Oxford Clay proved in the feasibility study boreholes consists of uniform poorly fossiliferous pale-grey calcareous mudstones. Only two cementstones were recorded (in Borehole 1) but the overall lithology is similar to that in which cementstones are particularly common in the Ampthill and Kimmeridge clays. Furthermore, the lithology and fauna of the Upper Oxford Clay in the boreholes are similar to those at Warboys, where eight bands or impersistent beds of limestone occur in 24.4 m of mudstone.

The limited evidence available suggests that the Lower and Middle Oxford Clay contains fewer stone bands than the Upper Oxford Clay.

The Upper Oxford Clay in Boreholes 1 and 3C was sparsely fossiliferous and lithologically uniform and the sequences could not be correlated in detail with one another or with Warboys. If subdivision of the Upper Oxford Clay was required at a later stage, it could best be carried out by coring the formation in the Wisbech area and by comparing the sequence there with those at Denver, West Walton and Warboys.

As with parts of the other Upper Jurassic clays, the Upper Oxford Clay thins towards Denver. At West Walton (Borehole 3C), 17.1 m was proved and the base not reached; at Warboys, the complete sequence is 24.4 m thick, whilst at Denver (Borehole 1) only 13.0 m is present.

West Walton Beds

The West Walton Beds and the Ampthill Clay are stratigraphically poorly known in comparison with the Oxford and Kimmeridge clays. Throughout much of England, beds of equivalent age (Corallian Beds) are present as limestones, sandstones and clays representing marine, shallow-water, reef and lagoonal environments.

In the area between Wheatley, Oxfordshire, and the Vale of Pickering, Yorkshire, the beds between the Oxford Clay and the Kimmeridge Clay are predominantly argillaceous. They are poorly exposed since they have little commercial value and their outcrop is largely drift-covered. The upper part of this argillaceous sequence has long been termed the Ampthill Clay following Seeley (1869). The lower part of the sequence, by virtue of its more variable silty and calcareous lithology, has given rise to a variety of local names such as Arngrove Stone, Elsworth Rock, Oakley Beds, St Ives Rock, Upware Limestone and Worminghall Rock, some or all of which may be synonymous. In recent years the term Elsworth Rock Group has been used for all the silty and calcareous beds between the Oxford and Ampthill clays. These beds have never been fully exposed and there is no type section. In the present work, the boundaries of this unit have been lithologically and palaeontologically defined and a new name, West Walton Beds, has been proposed (Gallois and Cox, 1977); the type section is taken in Borehole 3C (West Walton Highway).

The West Walton Beds were completely penetrated in three boreholes (Boreholes 1, 3C and 4A). A bed-by-bed description, based on these boreholes, is given in Appendix B.

In the area to the south of the feasibility study area, the West Walton Beds are lithologically very variable; they were probably deposited in current-agitated shallow waters close offshore to a land area fringed by coral reefs. Reefs occur at this stratigraphical level at Upware, Cambridgeshire, and clays with limestone bands rich in reef debris occur elsewhere (e.g. at Elsworth, Cambridgeshire).

Within the area examined in detail, the West Walton Beds consist of alternating interburrowed calcareous mudstones and silty mudstones with many lines of cementstone doggers. The formation thickens westwards and northwards across the area examined in detail, from 10.6 m at Denver (Borehole 1) to 14.1 m at Walton Highway (Borehole 3C) and 14.5 m at Gedney Drove End (Borehole 4A). This thickening is accompanied by a reduction in the number of cementstone bands recorded at this level in the

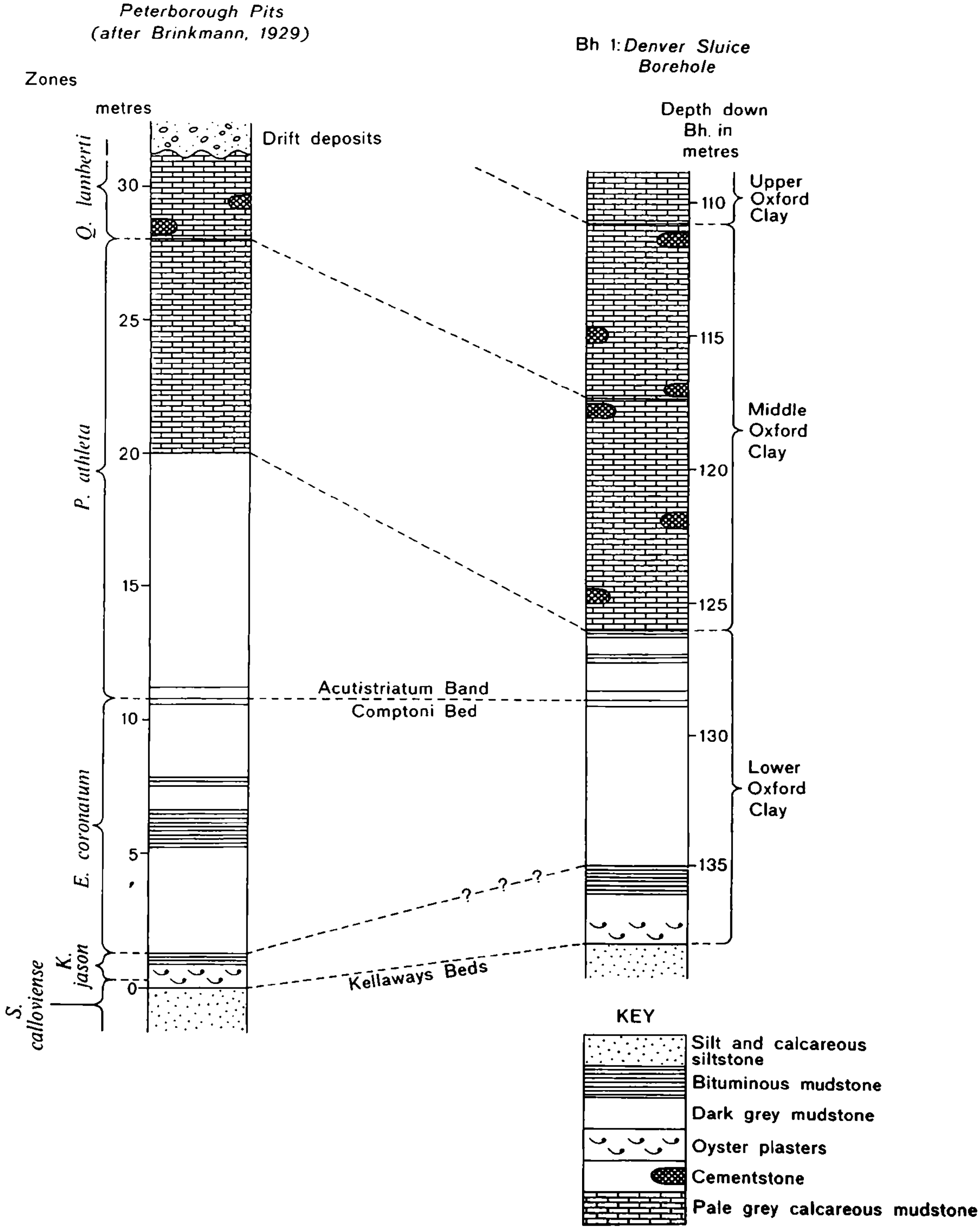

Figure 4 Correlations between the Lower and Middle Oxford Clay of the Peterborough area and the Denver Sluice Borehole

boreholes (7 at Denver, 4 at Walton Highway and 2 at Gedney Drove End) and by a general lessening of the silt content of the clays. These broad lithological changes probably reflect the passage from a more near-shore to a less near-shore environment and it seems likely that the suitability of the West Walton Beds as a tunnelling medium decreases towards Denver.

Correlations are difficult to make within the formation due to subtle lateral variations in lithology and to the discontinuous nature of the cementstone bands. The three sections examined are, however, sufficiently similar to suggest that any sudden major lithological change, such as the presence of local reef limestones, is unlikely to occur in the rocks between them.

The formation lies mostly at too great a depth to be of interest as a tunnelling medium on the eastern side of the area examined in detail for Stage 1 (Figure 5). In this area its upper surface is likely to form the lowest limit at which tunnelling could conveniently be carried out.

On the western side of the Stage 1 area and in the Stage 2, 3 and 4 areas it might be necessary to tunnel through the West Walton Beds if glacially filled valleys were to be avoided (*see* p. 58 for details). In these cases, it would be necessary to balance the additional costs of tunnelling through a sequence containing closely-spaced cementstone bands against other alternatives.

The West Walton Beds, by virtue of their higher silt content and their limestone bands, are likely to form the most permeable thick rock unit within the Upper Jurassic clays. No permeability measurement was made within the formation during the present work but provision should be made for such testing in any future site investigation for tunnel routes that might pass close to or through the West Walton Beds.

Ampthill Clay

Beneath the feasibility study area, the crop of the Ampthill Clay is entirely hidden by Glacial and Recent deposits. It probably extends north-westwards from the Wisbech area to south of Boston, and underlies much of the Stage 2 and parts of the Stage 3 areas. Beneath the Stage 1 area it occurs at depths of 20 to 90 m (Figure 6). A few boreholes in Fenland are thought to have penetrated the Ampthill Clay but the present work has provided the first good samples from the area.

The full thickness of the Ampthill Clay was penetrated only in Borehole 1; an almost complete sequence was cored in Borehole 23 and large parts of the sequence were cored in Boreholes 3C and 4A and in a number of other boreholes. The generalised vertical section of the Ampthill Clay, based on all these boreholes, is given in Figure 7. Bed-by-bed descriptions of the standard sequence, based mainly on the four boreholes listed above are given in Appendix B. These bed descriptions, which summarise the lithological and faunal sequences of the Ampthill Clay, have been used to make detailed correlations between the boreholes.

Much of the fossil material from the feasibility-study boreholes is better preserved and better documented stratigraphically than any previously obtained from the Ampthill Clay. Comparison has been made between this material and faunas from the Staffin Shales of Skye (Morris, 1968; Sykes, 1975) which confirms that the zonal scheme proposed by Sykes (1975; *in* Sykes and Surlyk, 1976) for the Middle and Upper Oxfordian sediments of Skye and east Greenland is applicable to the present area (*see* Gallois and Cox, 1977, for details).

The Ampthill Clay consists largely of soft mudstones and calcareous mudstones, silty in part, with a predominantly bivalve-ammonite fauna indicative of an open marine environment. Oysters, gastropods, echinoderm fragments and plant debris are common at certain levels, suggesting a more near-shore or near-reef environment than that of the Kimmeridge Clay.

The Ampthill Clay can be roughly divided into three parts on the basis of gross lithology. The lowest part is generally slightly silty and forms a passage down into the West Walton Beds; the middle part consists mostly of smooth mudstones and the highest part is characterised by erosion surfaces with phosphatic nodules, oysters and more silty mudstones. The formation thickens westwards and northwards away from Denver (36 m in Borehole 1) towards Gedney Drove End (estimated 55+ m) and North Wootton (estimated 52 m), but this thickening is not uniform throughout the formation. The lower and middle parts of the formation (Beds 1 to 29) appear to thicken in a regular manner (Figure 8), but the upper part (Beds 30 to 42) probably reflects minor earth movements and folding at the margins of the Ampthill Clay basin of sedimentation and thickens more rapidly and more irregularly (cf. Figure 9). Four persistent erosion surfaces were recorded in the upper part of the Ampthill Clay throughout the Stage 1 area (at the base of Beds 30, 33, 36 and 37, cf. Figure 7). Some of these combine at Denver as the basin margin is approached. A similar disconformity at the base of the Kimmeridge Clay accentuates the attenuation of the upper part of the Ampthill Clay (Figure 10).

Kimmeridge Clay

The Kimmeridge Clay crops out along the eastern margin of Fenland between King's Lynn and Denver and its subcrop underlies the Glacial and Recent deposits throughout the whole of the Stage 1 area and much of the Stage 3 and 4 areas (Figure 2).

The Kimmeridge Clay was probably deposited under quiet conditions in a relatively shallow shelf-sea between islands of low relief. Thin bands of distinctive lithology or fossil content in the Kimmeridge Clay can be correlated over great distances (Gallois and Cox, 1974; 1976). Comparison of the core samples from the feasibility study with those of the Institute's Warlingham Borehole in Surrey and with the cliff sections of Dorset has shown that many of these bands can be recognised throughout southern England.

Sandstone, sandy ironstone and reef-limestone occurs in the Kimmeridge Clay elsewhere in Britain, but each of these deposits is associated with local features such as a nearby land area (e.g. Abbotsbury Ironstone, Dorset), a positive axis (Elsham Sandstone, Lincolnshire) or a contemporary fault line (sandstones and reef-limestones of the Moray Firth, Scotland) (*see* Arkell, 1933, for details).

The Kimmeridge Clay of the feasibility study area ranges from about 65 to 130 m in thickness and is much thinner than the sequences of the Warlingham Borehole or the Kimmeridge Bay cliffs. At Warlingham 217 m of Kimmeridge Clay was proved (Worssam and Ivimey-Cook, 1971) but the lower beds (Beds 1 to 17 of Figure 12) were cut out by faulting. At Kimmeridge Arkell (1947) estimated the full thickness of the formation to be more than 500 m. These regional variations in thickness are thought to be due to

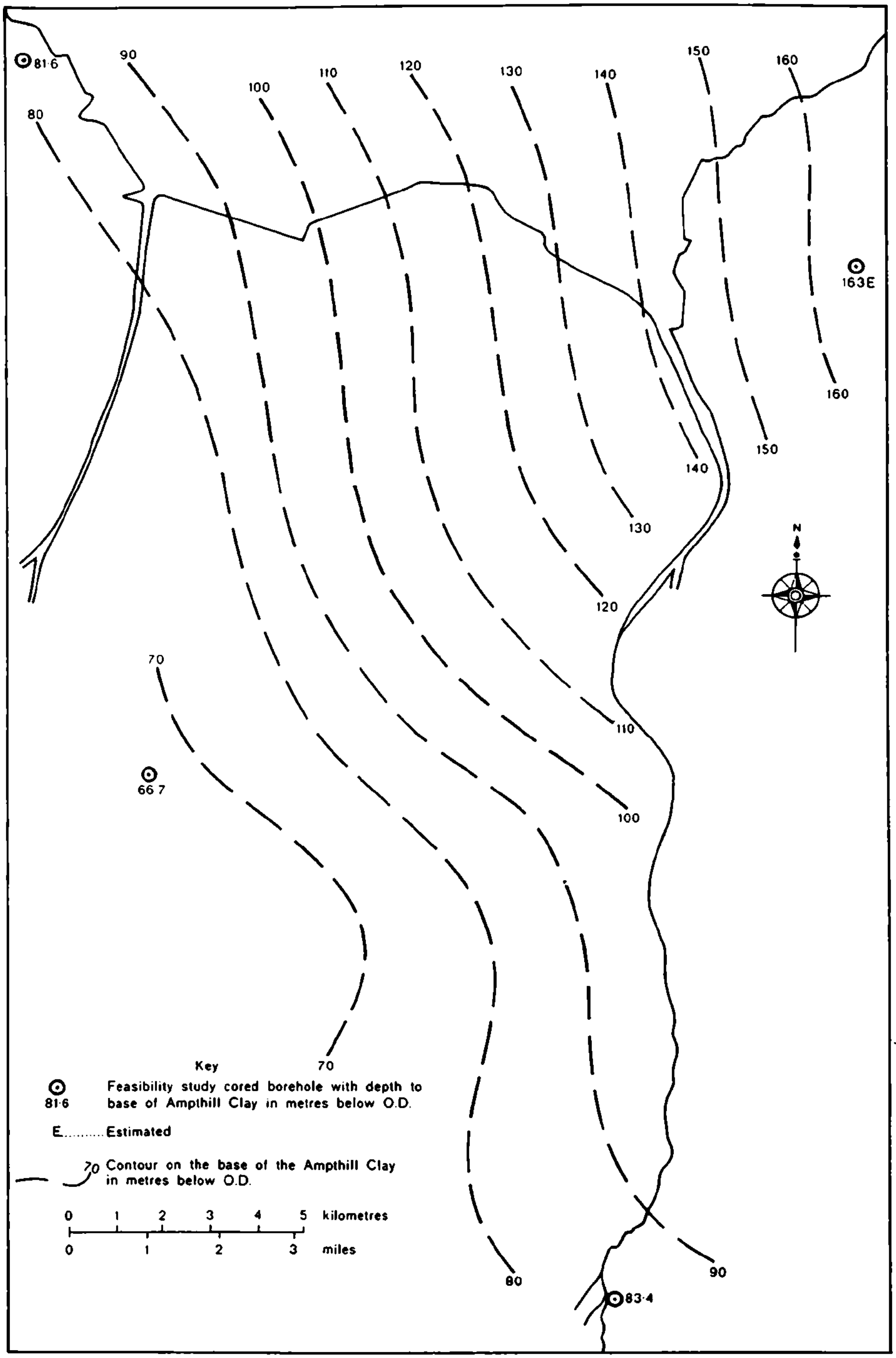

Figure 5 Structure contours on the base of the Ampthill Clay, assuming a similar pattern of folding to that of the Kimmeridge Clay (Figure 6)

differences in rates of subsidence within the Kimmeridgian area of sedimentation; Kimmeridge Bay is close to the axis of a subsiding trough and The Wash and Warlingham are on the stable flanks of an old massif (the London Platform).

Between Daseley's Sand (Borehole 513B) and Denver (Borehole 1), the Lower Kimmeridge Clay thins from an estimated 80 m to 42.3 m (cf. Figure 11), but does so without any change in lithology. There seems to be no evidence, such as faunal debris derived from fringing

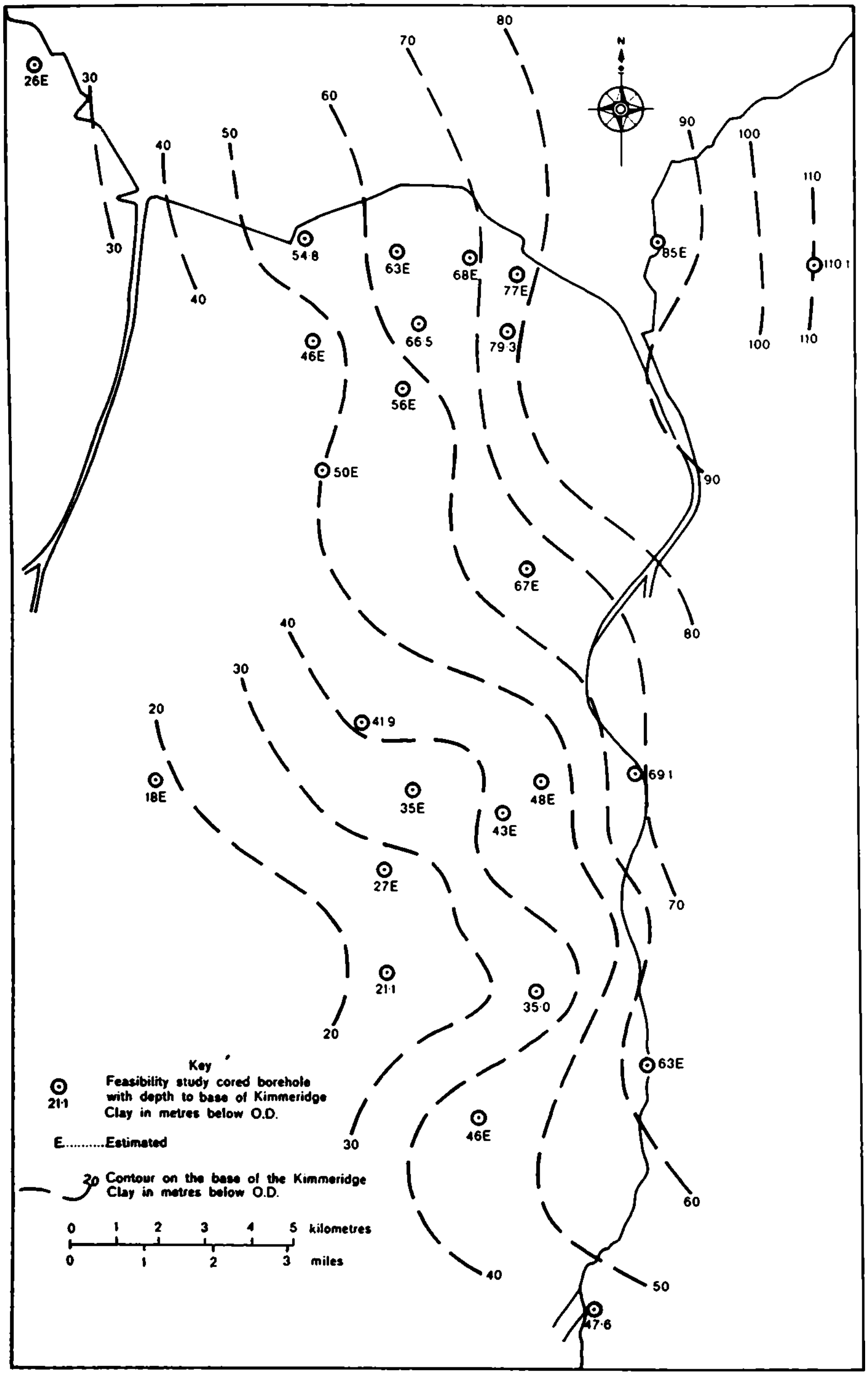

Figure 6 Structure contours on the base of the Kimmeridge Clay

reefs, coarser clastic debris or non-sequences, to suggest that this thinning indicates the approach to a shoreline. For the purpose of the feasibility study, it can be assumed that the lithologies within the Kimmeridge Clay are everywhere the same, despite the marked thinning between The Wash and Denver. Between Denver and Mundford [TL 779 932], Norfolk, some 18 km east-south-east of Denver, the Lower Kimmeridge Clay thins much more rapidly and becomes calcareous throughout; this thinning

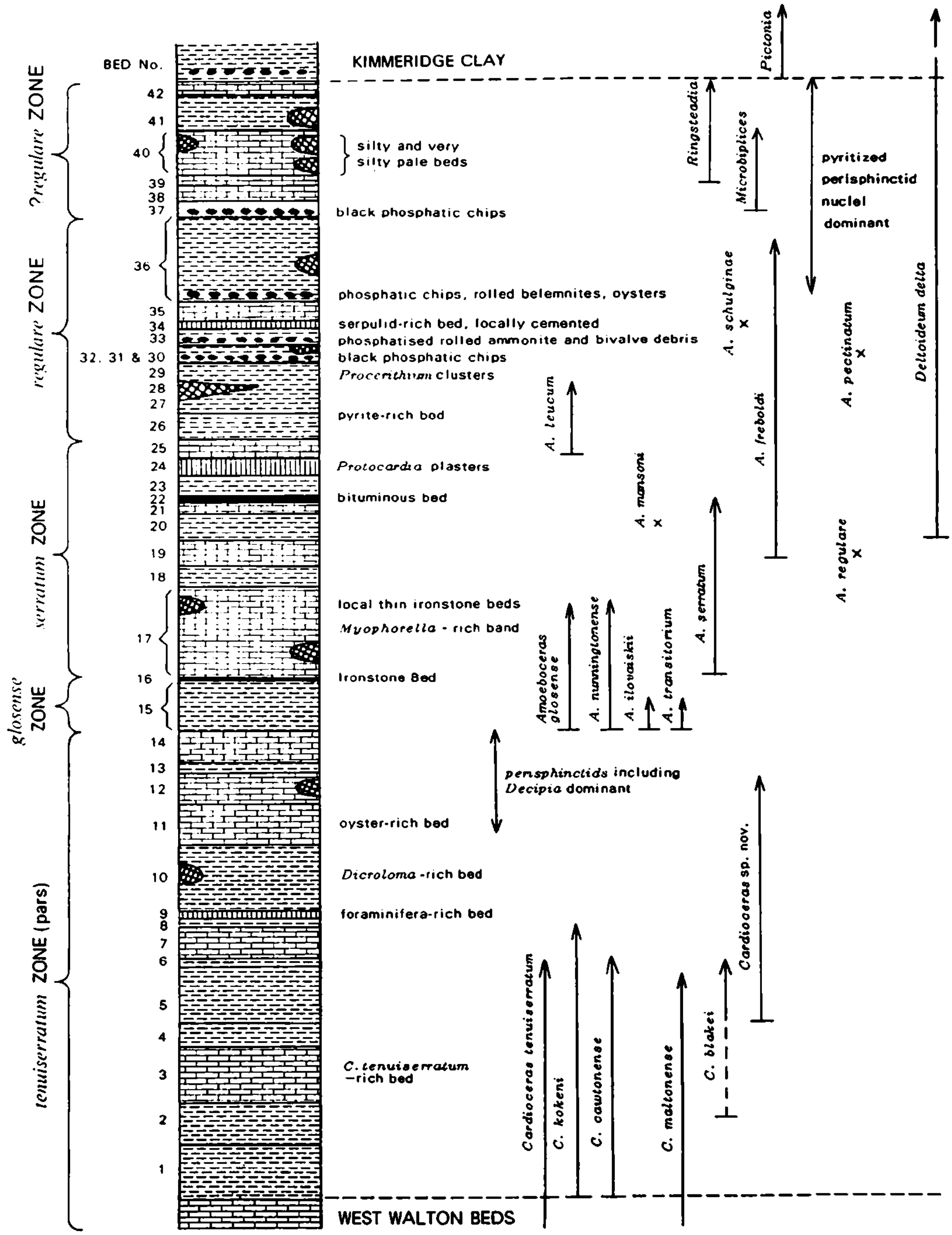

Figure 7 Generalised vertical section of the Ampthill Clay (Lithologies as on Figure 28)

probably does indicate the approach to a shoreline or to an area of shallows.

The Kimmeridge Clay of Norfolk and Lincolnshire is made up of a complex sequence of small-scale rhythms, generally 0.3 to 2.5 m thick, consisting of soft slightly calcareous mudstones, shelly mudstones and calcareous mudstones. Many of the individual rhythms can be correlated within the Wash area. Superimposed on this rhythmic sequence are broader lithological changes, from more to less calcareous and from more to

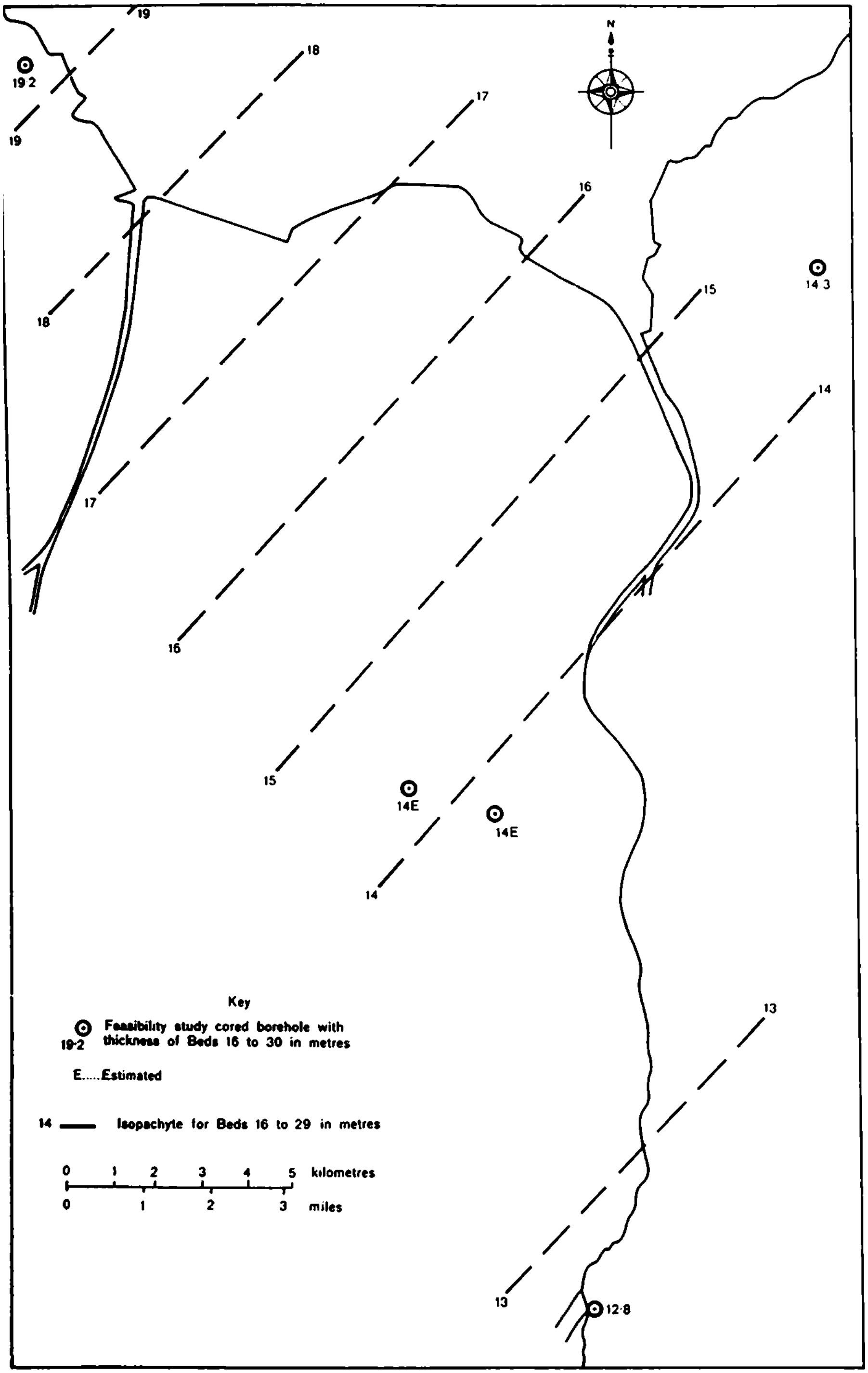

Figure 8 Isopachytes for Beds 16 to 30 of the Ampthill Clay

less bituminous, which can be regarded as larger-scale rhythms and which can be correlated between the Wash area and Dorset, a distance of some 300 km.

In the upper part of the Kimmeridge Clay, the idealised small-scale rhythm is made up of brown or brownish grey, fissile, bituminous-smelling mudstone (referred to below as oil shale) which is usually shelly and rich in both calcareous and chitinous microfossils; this passes upwards first into dark-grey fissile shelly mudstones, characterised by plasters of small bivalves

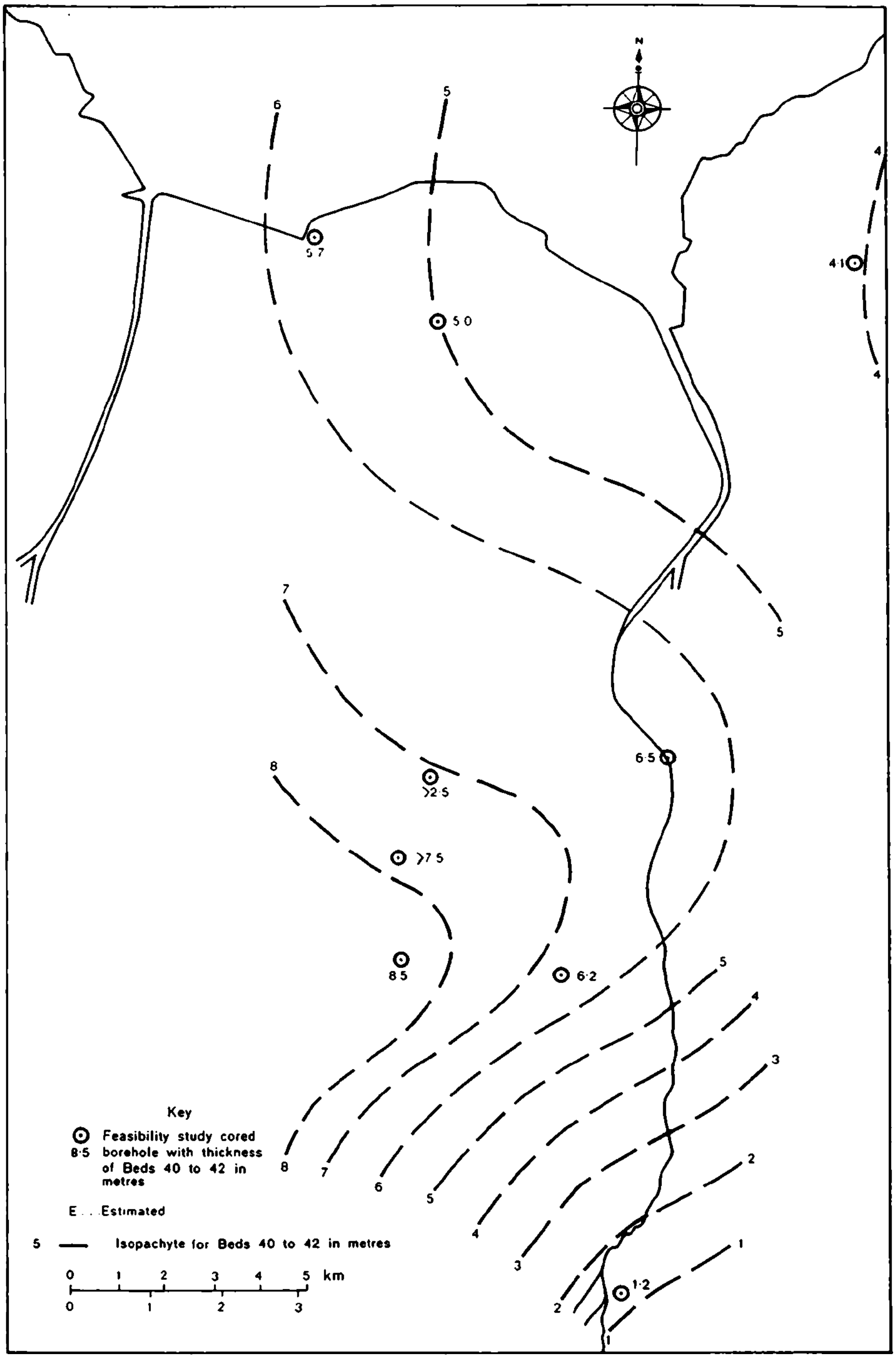

Figure 9 Isopachytes for Beds 40 to 42 of the Ampthill Clay

and small (finely-ribbed) ammonites, and then into dark, blocky, almost barren mudstones containing scattered oysters and larger (more coarsely-ribbed) ammonites. These last named mudstones become paler upwards by increase in calcareous content, and culminate in pale-grey mudstones with a subconchoidal fracture which locally contain a continuous tabular bed or line of doggers of muddy limestone.

In the lower part of the Kimmeridge Clay, oil shales become progressively less common with depth and

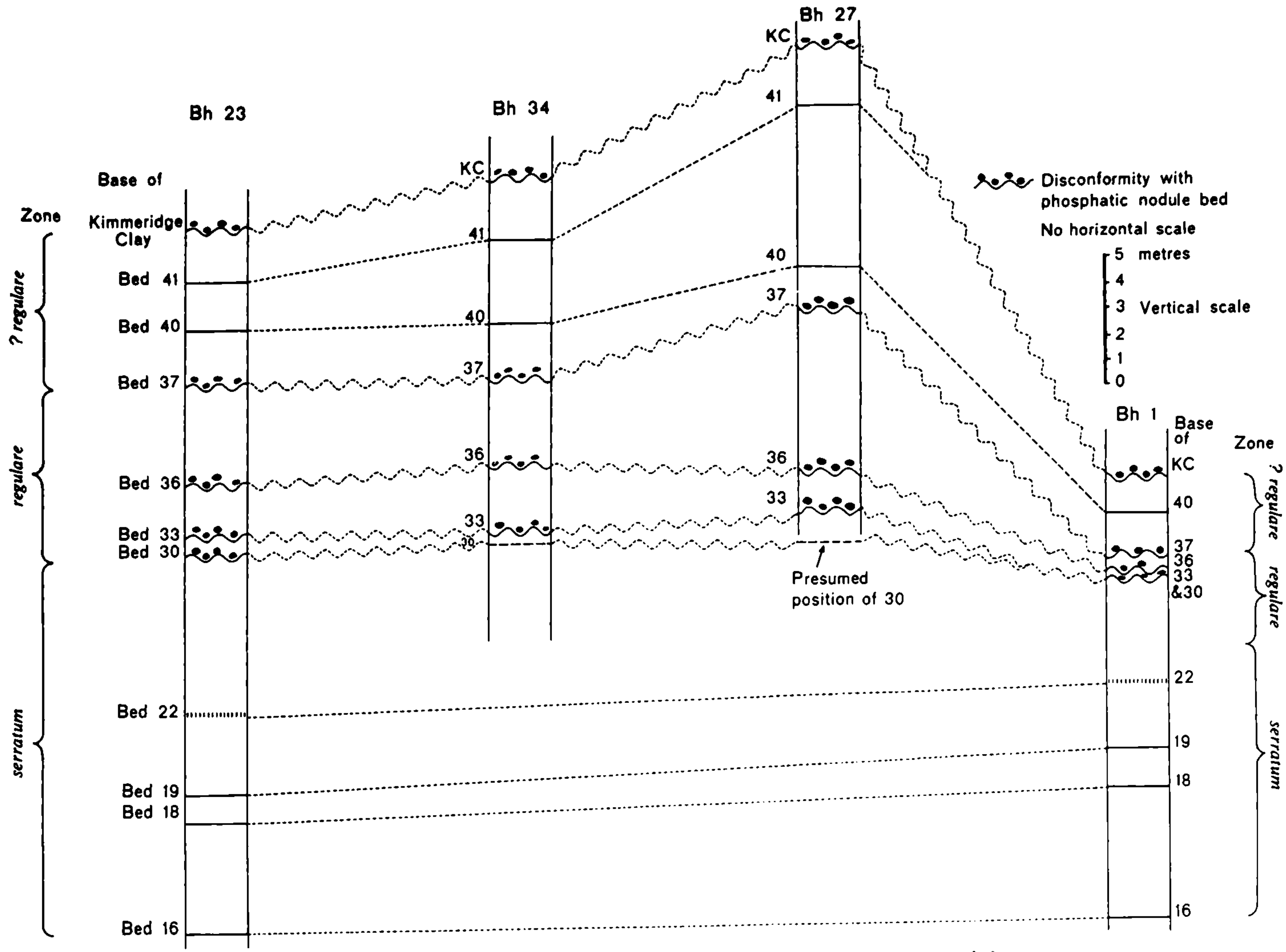

Figure 10 Attenuation of the upper part of the Ampthill Clay due to intraformational non-sequences and the overstep of the Kimmeridge Clay (after Gallois and Cox, 1977)

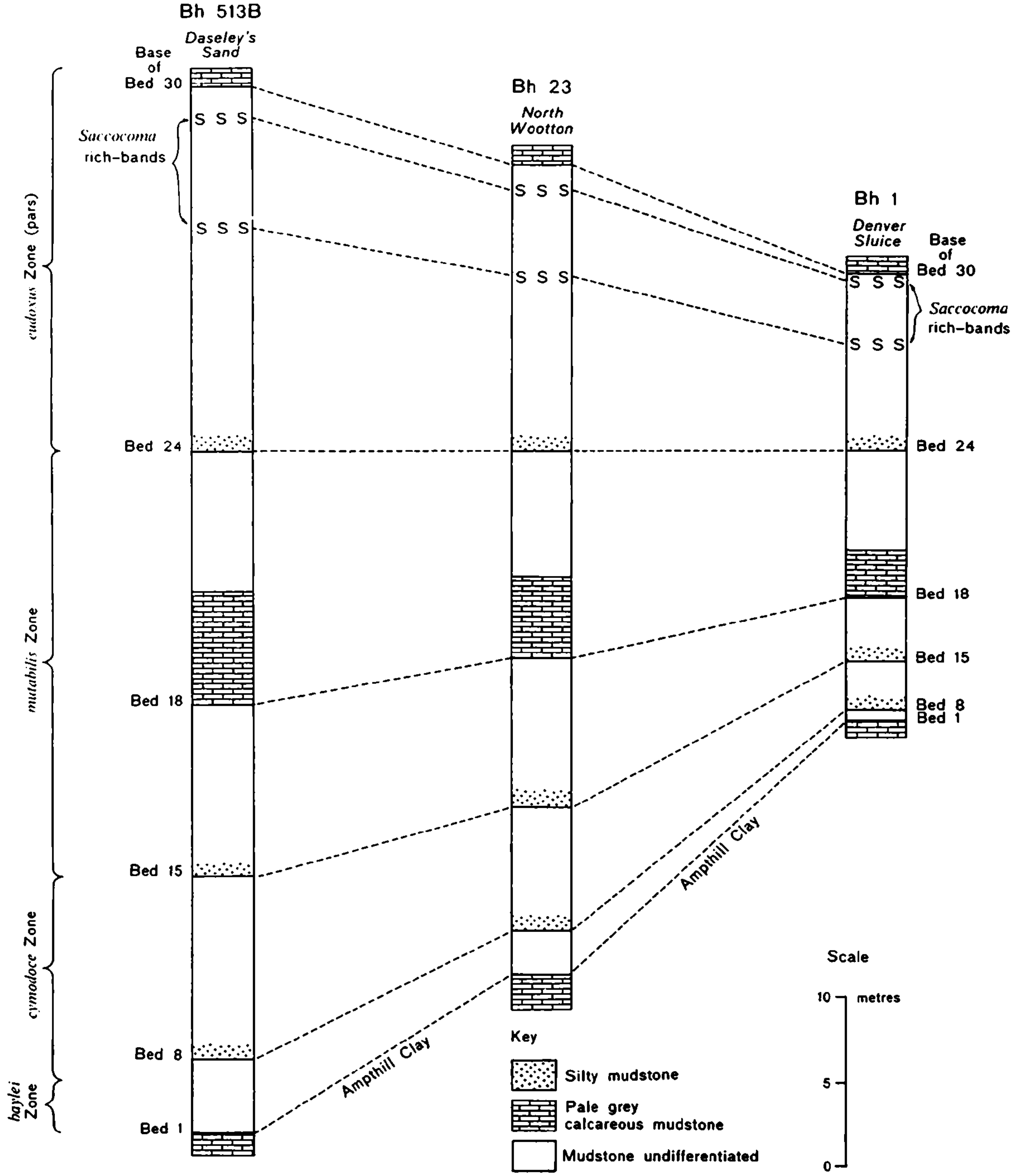

Figure 11 Attenuation in the Lower Kimmeridge Clay between Daseley's Sand (Bh. 513B) and Denver Sluice (Bh. 1)

their place in the rhythms is taken by silty mudstone bands, each of which marks a minor, but widespread, unconformity. Within the rhythms, the oil shales, the pale calcareous beds and the silty beds are the most easily identifiable lithologies and in Figure 12 they are used to illustrate the detailed stratigraphy of the cored boreholes.

The Kimmeridge Clay differs from the Ampthill Clay in that it contains a greater range of lithologies so that, whilst many individual hand specimens could equally well belong with either formation, it is usually clear in any core more than a few metres in length which formation is concerned. Some lithologies, such as oil shale and certain smooth dark-grey mudstones, are

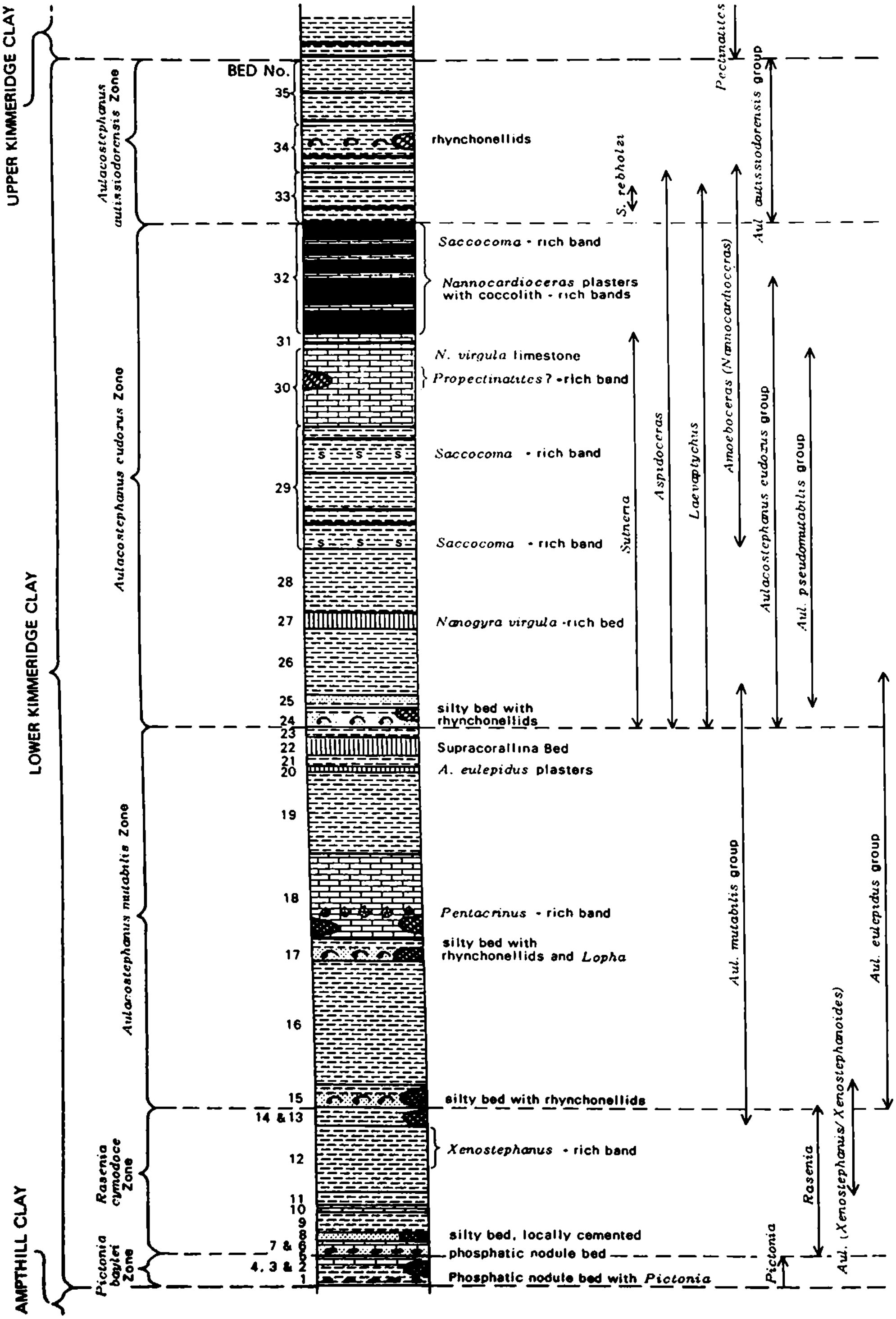

Figure 12 Generalised vertical section of the Lower Kimmeridge Clay (Lithologies as on Figure 28)

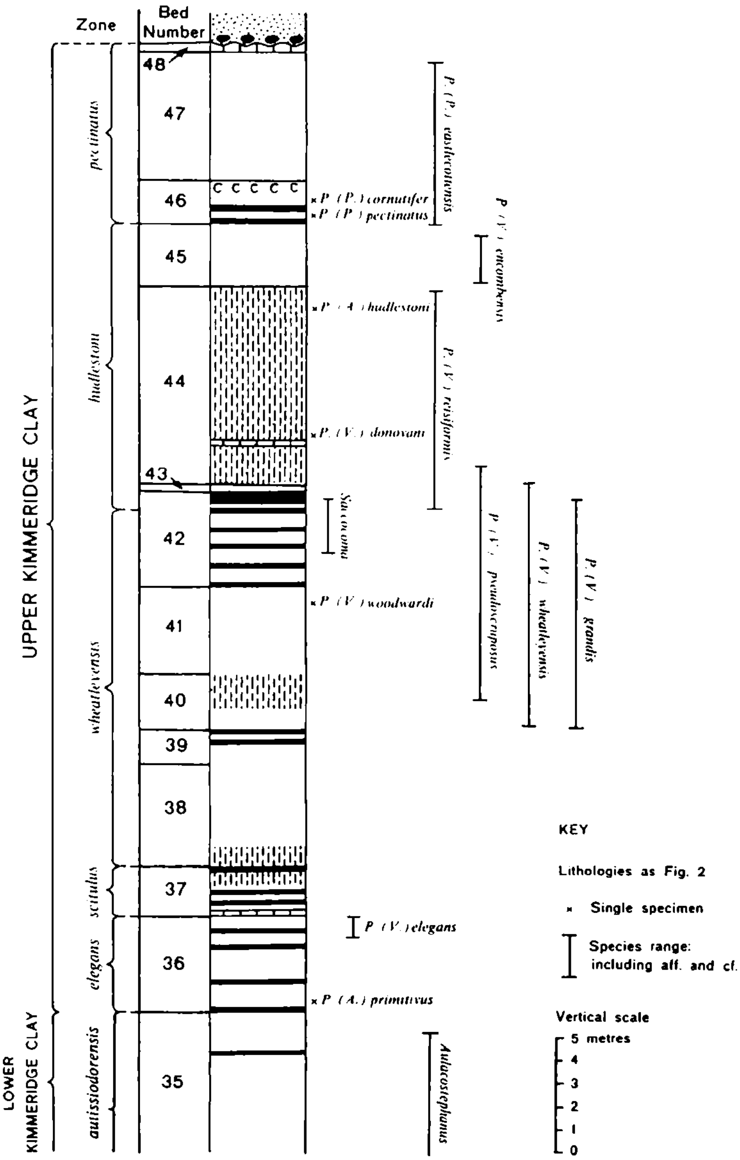

Figure 13 Generalised vertical section of the Upper Kimmeridge Clay (Lithologies as on Figure 28)

almost exclusively confined to the Kimmeridge Clay, and others, such as very plant-speckled or very pyritic mudstones, to the Ampthill Clay.

The faunas of the two formations are readily distinguishable at almost all levels. The Kimmeridge Clay is characterised by a rich and varied fauna of bivalves and ammonites in marked contrast to that of the Ampthill Clay which is commonly sparse in numbers and always more limited in variety. The Lower Kimmeridgian has been zoned using species of the ammonites *Pictonia*, *Rasenia* and *Aulacostephanus* (Table 1) and its faunas are well documented. Other ammonites such as *Xenostephanus*, *Sutneria*, *Amoeboceras* (*Nannocardioceras*) and *Aspidoceras*, the aptychal plate *Laevaptychus*, bivalves such as *Astarte*, *Lopha* and *Nanogyra*, rhynchonellid brachiopods, and the crinoids *Saccocoma* and *Pentacrinus* characterise specific levels and enable the broad zonal divisions to be subdivided.

The fauna of the Upper Kimmeridge Clay is much less varied than that of the Lower Kimmeridge Clay and is more difficult to use for the zonation of borehole cores because of the rarity of determinable ammonites. Despite this problem, the zonal scheme devised for Dorset on the basis of the perisphinctid ammonite faunas (Cope, 1967) has recently been shown to be applicable both to the Warlingham Borehole (Callomon and Cope, 1971) and to the Wash area (Cope, 1974).

The stratigraphy of the Lower Kimmeridge Clay is summarised in the generalised vertical section (Figure 12); bed-by-bed descriptions of the standard sequence

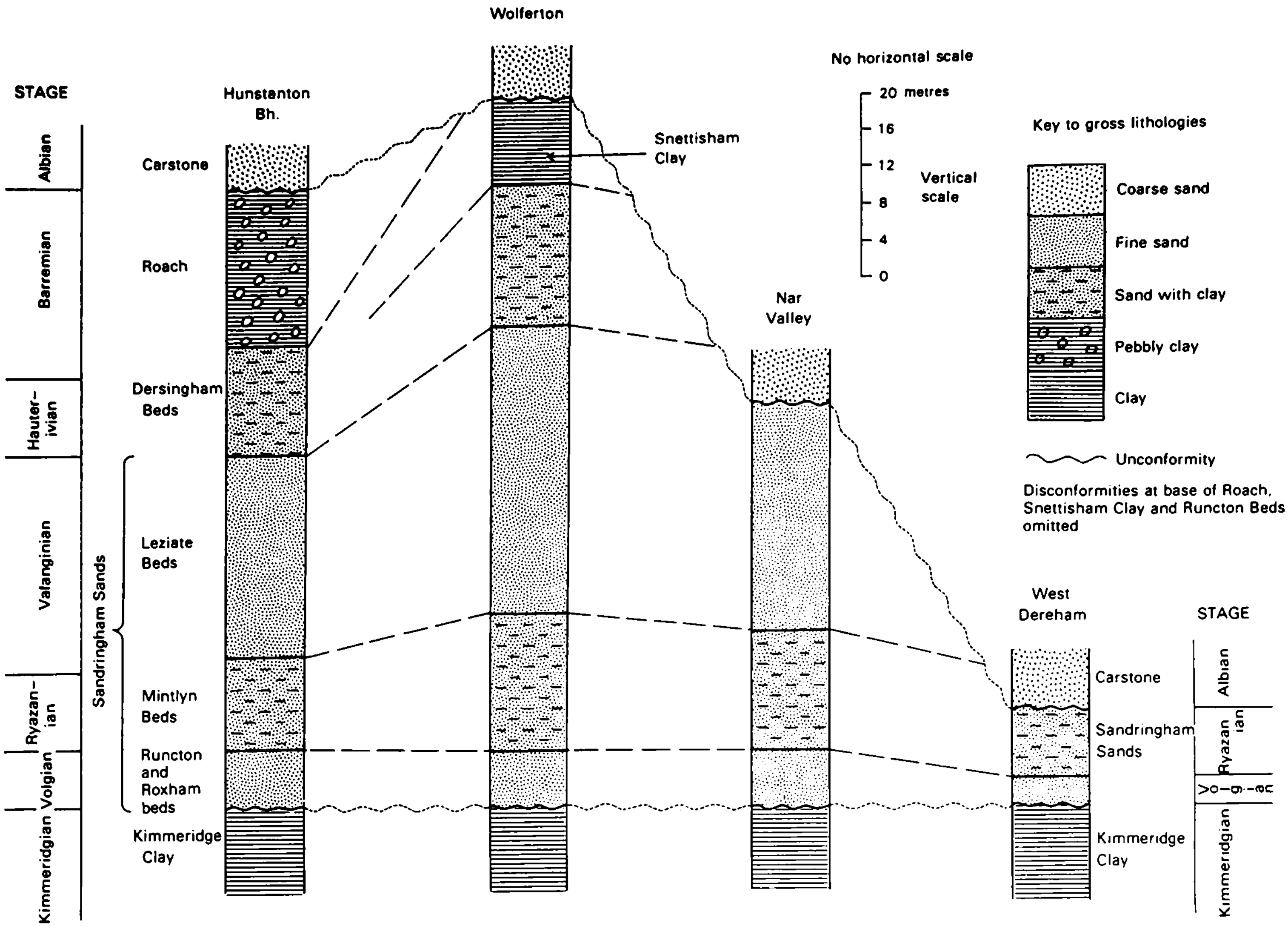

Figure 14 Generalised vertical sections of the top Jurassic–Lower Cretaceous rocks of west Norfolk

are given elsewhere (Gallois and Cox, 1976). The formation was extensively explored in the present work; it was completely cored in Boreholes 1 and 23 and partially cored in several other boreholes. The sequence has been divided on the basis of lithological and faunal features into 35 distinctive beds, each of which has been recognised throughout the area. The purpose of constructing this classification has been firstly to identify as precisely as possible the levels at which cementstones occur or might occur (*see* pp. 43–45) and secondly, to provide a standard sequence of sufficient detail to enable the stratigraphical position of any future tunnel to be accurately monitored. This second aim could be particularly important in a tunnel that encountered small faults (about 5 m throw) or minor changes in dip.

The stratigraphy of the Upper Kimmeridge Clay of the Wash area has recently been described in detail in a number of IGS land and offshore boreholes (Gallois, 1973; Gallois and Cox, 1974; Cope, 1974) and it has been possible to consider the formation as a tunnelling horizon for the feasibility study largely on the basis of this earlier work.

In the present work, the Upper Kimmeridge Clay was fully cored only in Borehole 23, where the lithological and faunal sequences can be matched in detail with those of the generalised vertical section deduced from the earlier IGS boreholes. Furthermore, this sequence has been correlated in detail with those of the Warlingham Borehole and the Dorset type section, and it is likely to be constant throughout the feasibility study area. A detailed description of the Upper Kimmeridge Clay sequences in two Institute boreholes within The Wash (IGS 71/65 and IGS 71/66) is given by Gallois and Cox (1974), and the sequence is summarised in Figure 13 and Appendix B.

LOWER CRETACEOUS

The Lower Cretaceous deposits of Norfolk crop out in a series of low escarpments running north-south from Hunstanton, via the eastern part of King's Lynn, to Denver. They consist predominantly of arenaceous sediments which were laid down in shallow, current-swept, near-shore, marine environments and their stratigraphy is complicated by lateral lithological variations and by intraformational unconformities. Whitaker and Jukes-Browne (1899, pp. 5–27) described the lithologies of the Lower Cretaceous that can be seen at outcrop along the eastern edge of the feasibility study area and Casey and Gallois (1973) have described the sequences proved in recent boreholes and temporary sections in the same area. A generalised vertical section of the Lower Cretaceous rocks of the area between Hunstanton and West Dereham, the limits of the Norfolk outcrop, is given in Figure 14 and the relationship of the Norfolk sequence to those of the central Wash and Lincolnshire is summarised in Table 2. Detailed descriptions of Boreholes IGS 72/77 and 72/78, which cored the full thickness of the Lower Cretaceous in the central Wash, are given by Gallois and Morter (Appendix A *in* Wingfield and others, 1978) and a summary of the Lower Cretaceous stratigraphy of the area is given in Wingfield and others (1978, fig. 2).

The lowest part of the Sandringham Sands (Roxham Beds) consists of loose, water-bearing, fine-grained sands with a bed of densely calcite- and pyrite-cemented sandstone, up to 1.5 m thick, at the base. This bed marks the natural upper stratigraphical limit at which tunnelling could be easily carried out. The Sandringham Sands rest unconformably on the Kimmeridge Clay and progressively cut out the higher parts of the clay in a southerly direction between Hunstanton and Denver (Gallois, 1973, fig. 4b).

Table 2 Correlation of the Lower Cretaceous sequences of the Wash area (excluding the Red Chalk and Gault)

Stage	East Lincolnshire	Central Wash	West Norfolk
Albian	Carstone	Carstone	Carstone
Aptian	Sutterby Marl	Sutterby Marl	non-sequence
	Skegness Clay	Skegness Clay	
Barremian	Roach	Roach	Roach
	Tealby Beds	Tealby Beds	Dersingham Beds including Snettisham Clay
Hauterivian			
	Claxby Beds	Claxby Beds	Leziate Beds
Valanginian			
	Hundleby Clay	Mintlyn Beds	
Ryazanian	Upper Spilsby Sandstone	non-sequence	Mintlyn Beds
	non-sequence		
Volgian	Lower Spilsby Sandstone	Roxham Beds and ?Runcton Beds	Roxham Beds and Runcton Beds
Kimmeridgian	Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay

However, this effect is small and regular and nowhere within the area adjacent to the feasibility study area does this unconformity cut down as far as the base of the *hudlestoni* Zone. Furthermore, the unconformity appears to be planar and there is no evidence to suggest that the base of the Sandringham Sands has anywhere cut irregular channels into the Kimmeridge Clay or that the unconformity is accompanied by weathering or fracturing that has impaired the properties of the clay for more than 1 to 2 m below the junction.

The only part of the feasibility study area that might be underlain by Lower Cretaceous rocks is the northern part of Stage 1, Alternative 1 — Bull Dog Sand (*see* p. 58).

GLACIAL DEPOSITS

The nature and distribution of the Glacial deposits within the feasibility study area will be an important factor affecting the choice of tunnel routes at all four reservoir stages. The present work has involved the study of the Glacial deposits in only a small part of that area but it has produced a number of results that are applicable to the glacial history of the Wash and Fenland area as a whole.

Glacial deposits are almost always too variable laterally, both in lithology and thickness, to be satisfactorily explored by means of boreholes alone. This has proved to be the case in the present work. Whilst the borehole cores have provided valuable samples for lithological description and soil testing, the more important conclusions concerning the overall distribution of the Glacial deposits and the glacial stratigraphy of the area can be drawn only after consideration of evidence from the exposed areas on the edges of Fenland and the offshore seismic data.

The Glacial deposits of west Norfolk have a relict distribution with patches of thin drift occurring on high ground and thick drift in the valleys, which suggests that post-Glacial erosion is revealing a complex pre-Glacial or Glacial valley system.

On the eastern edge of Fenland between Dersingham and Denver, the Cretaceous escarpments are broken by four east–west valleys whose floors and sides are cut in Glacial deposits (Figure 2). At present these valleys carry small streams, the Babingley River, the Gaywood River, the Middleton Stop Drain and the River Nar, but the extent of the Glacial deposits shows that these valleys and streams were formerly much larger.

In order to interpret the borehole data and reach a conclusion about the nature and distribution of the Glacial deposits in the area, it is necessary to decide whether this valley system was formed beneath ice during a Glacial period (tunnel valleys) or by a river system before the Glacial period. If it is fluvial in origin then it is likely to have been considerably modified by the later glaciation. The choice therefore is between a tunnel-valley system and glacially-modified fluvial system.

Tunnel valleys are characteristically deeply-incised narrow valleys with undulating long profiles. Those of Denmark and the North German Plain, the classic areas for such features, are thought to have been formed by underloaded subglacial streams that followed courses roughly normal to the ice front, their erosive power being derived from debris-laden water acting under the hydrostatic head of a water table within the ice sheet. Their long profiles may therefore be deepest beneath the thickest ice, rising to the surface at the ice margin. Their emergence is usually accompanied by extensive spreads of coarse outwash material whilst the valleys themselves are generally filled with mostly water-sorted or water-laid materials.

In the area adjacent to the feasibility study area Woodland (1970) has interpreted the borehole data from the boulder clay plateau areas of central and east Norfolk as showing tunnel valleys cut in the chalk surface. Cox and Nickless (1972) have used a similar explanation to account for the extensive spreads of glacial sand and gravel in the Norwich area, and Sparks and West (1965) considered the buried valley of the River Cam to have resulted from subglacial erosion.

Horton (1970), on the other hand, concluded from a study of the glacially-filled valleys of the River Ouse between Stony Stratford and Huntingdon and the River Nene at Northampton, that ice advanced over a pre-existing valley system. Wyatt (1971) reached a similar conclusion concerning the origin of drift-filled valleys in south Lincolnshire. As supporting evidence Horton (1970, p. 26) has pointed out that recent geological surveying has indicated that in pre-Glacial times the Nene and Ouse catchment areas formed closed basins with outlets only into The Wash.

The results of the present work for the feasibility study, including that in the offshore area, support a pre-Glacial fluvial origin for the glacially-filled valleys of Fenland for the following reasons:

(i) The known glacially-filled valleys in the areas marginal to Fenland show no preferred orientation but appear to form a dendritic pattern draining towards a single outlet in The Wash.

(ii) In addition to those of the Nene and the Ouse, the catchment areas of the Babingley and Gaywood rivers are closed basins with outlets only into Fenland.

(iii) The shapes, and in particular the long profiles, of buried valleys cannot normally be determined from boreholes alone. In the offshore area, however, seismic profiling can provide a series of accurate and detailed sections across and along these valleys. Tunnel valleys are typically claimed to be gorge-like when formed in soft, easily erodible materials. In the offshore area, the buried valleys are commonly neither narrow nor particularly steep-sided and their shapes are often strikingly related to the hardness of the strata in which they are carved (Figure 15). The narrower parts of the valleys are controlled either by cementstone bands or by harder formations such as the Chalk. Elsewhere, in the soft Upper Jurassic clays, broad valleys occur with slopes of about 3° to 7°, comparable to the subaerial slopes that are formed in these materials at the present day. Between the valleys, hard bands in the Upper Jurassic and Lower Cretaceous form minor escarpments similar in shape and size to those of the adjacent land area.

Parts of some of the valleys are overdeepened or have abnormally steep sides (presumably due to glacial modification) and isolated drift-filled hollows (interpreted here as glacial scour hollows) occur beneath the eastern Wash (Figure 16). However, the overall rockhead surface appears to show many of the subtleties of form that are normally associated with fluvial erosion and subaerial weathering.

(iv) The long profile of only one major glacially-filled valley can be examined in the offshore sections. This profile is irregular in places but falls south-westwards, cutting across a series of Jurassic and

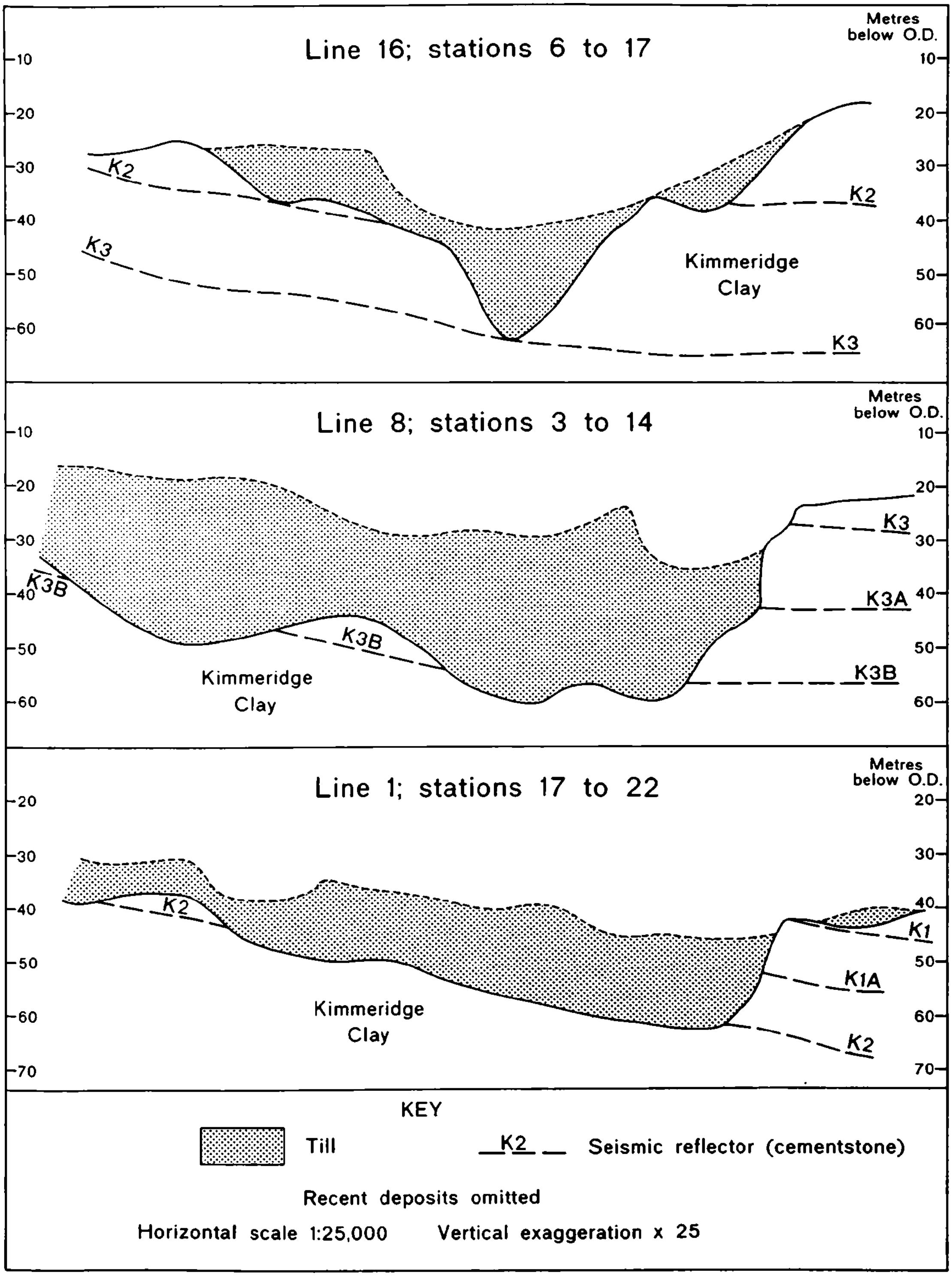

Figure 15 Examples of glacially-filled valleys in which the shape of the subglacial surface appears to be controlled by hard bands in the Kimmeridge Clay (*See* Wingfield and others, 1978, fig. 1 for positions of seismic lines)

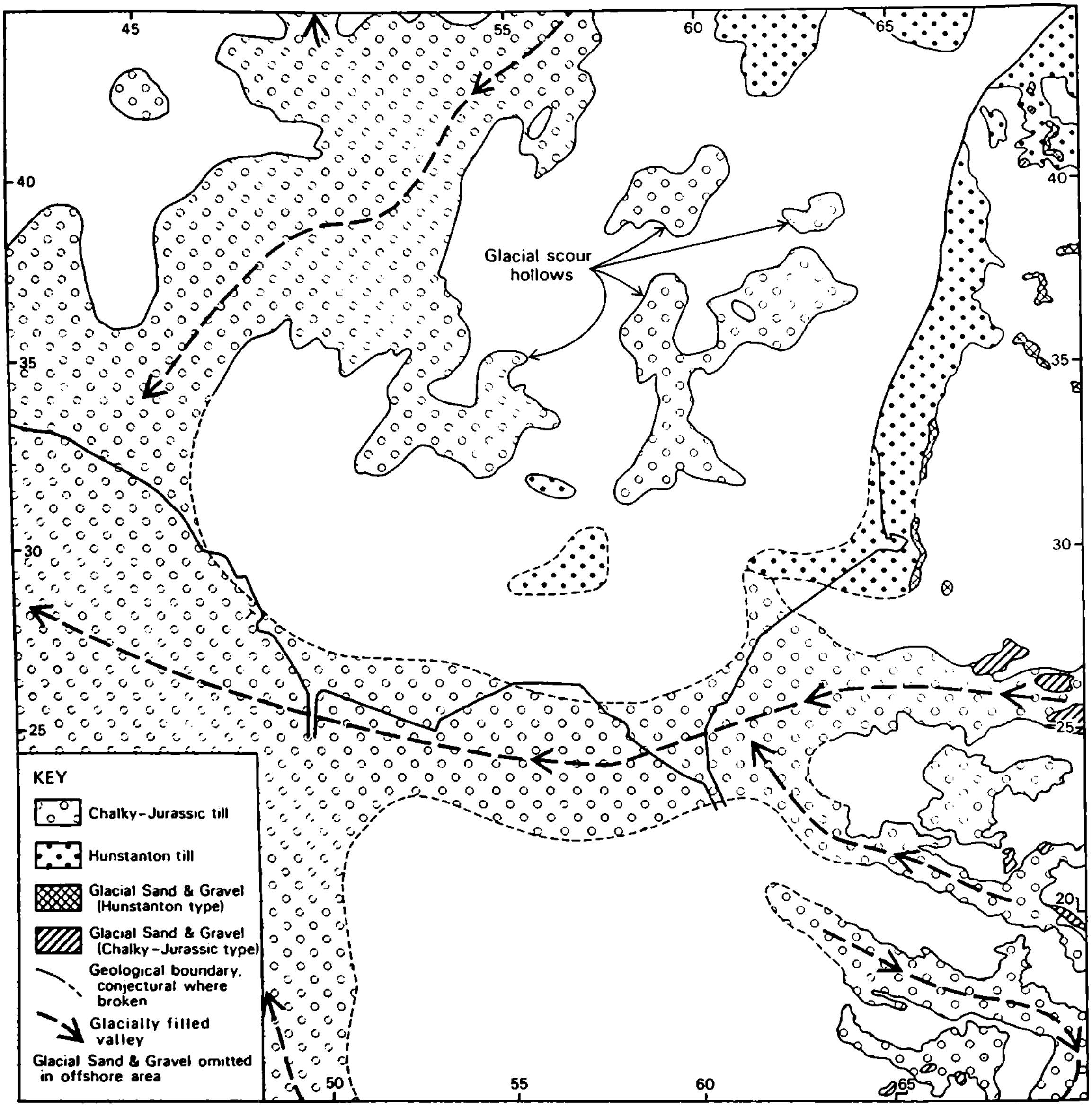

Figure 16 Distribution of Glacial deposits in the south-eastern part of The Wash and the adjacent land area

Cretaceous escarpments. Part of a second, much deeper valley, with a more westerly trend, was proved in the entrance to The Wash.

The evidence from the borehole data and the seismic work indicates buried valleys cut down to about 70 m below OD in the Terrington to Denver area, with a deeper central valley cut down to about 100 ± at 15 m below OD (Wingfield and others, 1978) beneath the mouth of The Wash. This latter figure is in accord with estimates of 100 m to 150 m (Donn, Farrand and Ewing, 1962) that have been made for the fall in relative sea level during the glacial periods.

(v) The lithology of the till in the King's Lynn area and within the buried valleys of the Babingley and the Nar, as proved in the feasibility study cored boreholes, is remarkably constant. The matrix is made up of a grey clay or slightly sandy clay derived from the Upper Jurassic clays and from sands of uncertain, but probable Lower Cretaceous, origin. The erratic pebbles are overwhelmingly chalk (usually more than 95 per cent, with flints, Upper Jurassic cementstones, Lower Cretaceous sandstone and ironstone, Red Chalk and Carstone making up almost all the remainder. This suggests derivation from the north-west—from the broad Upper Jurassic clay vale lying between the escarpments of the Lincolnshire Limestone and the Chalk. A more westerly source would have included more Triassic and Lower and Middle Jurassic rocks and a more northerly source, more flint from the Middle and Upper Chalk. It follows from this that the ice front probably lay to the south-east or the south of the present area, roughly parallel to the courses of the glacially-filled valleys of the Nar, Babingley and the central Wash.

(vi) Small amounts of varved clay and of apparently water-laid or water-sorted till occur in the upper parts of the glacial sequences within the buried valleys, particularly in that of the River Nar, but the bulk of the material is typical heterogeneous unsorted till which locally includes erratic rafts of Upper Jurassic clay several metres across. The contact of the till with the underlying solid in the valleys is almost everywhere gradational from chalky till to Upper Jurassic clay-rich till to disturbed *in-situ* Jurassic clay cut by polished shears.

Such sequences suggest that an existing land surface was overridden and mechanically disturbed by the ice, and was then preserved beneath its ground moraine. This sequence of lithologies and presumed events is markedly different from that generally envisaged for the erosion and infilling of tunnel valleys.

The evidence presented above, particularly (i), (ii), (iii) and (vi), combined with that of Horton (1970), points strongly to a pre-Glacial origin for the glacially-filled valleys of the feasibility study area.

The uniformity of the till in the present area, together with its relationships to the solid and other Glacial deposits indicate that it probably resulted from a single glacial episode. A second type of till, the Hunstanton till, is present in north Norfolk and beneath parts of The Wash (Figure 16); this is rich in Triassic, northern-England, and far-travelled igneous and metamorphic erratics. The relationship of the Hunstanton till to the Chalky/Jurassic till of the King's Lynn area cannot be determined directly, but the available evidence suggests that the Hunstanton glaciation was a separate, younger event. If this is so, the central Wash buried valley might have a more complex history than those of the southern Wash and the adjacent land areas.

The Hunstanton till does not extend as far south as the inland feasibility study area and does not affect the present work.

The apparent presence of a pre-Glacial valley system and a tunnel valley system beneath the Chalky/Jurassic till of adjacent parts of Norfolk is not incompatible. Boreholes have proved drift-filled valleys more than 100 m deep in the area just east of the present-day Nar–Wensum watershed (Woodland, 1970). Such valleys do not appear to extend westwards to breach the Chalk escarpment between Hunstanton and Stoke Ferry, but rise irregularly eastwards towards the position of a former ice front (Cox and Nickless, 1972). The present day watershed, between streams flowing westwards to the Ouse drainage and eastwards to the Yare drainage, approximately marks the dividing line between the areas of presumed pre-Glacial and subglacial drainage (Figure 17). This line lies a little to the east of what in pre-Glacial times must have been an impressive Chalk escarpment comparable to that of the present day Chilterns or the North or South Downs. The roots of this escarpment now occur as a belt of almost drift-free chalk separating the sparsely drift-covered areas of west Norfolk from the completely drift-covered till plateau of central Norfolk. Debris from the escarpment is scattered throughout the Chalky/Jurassic till of East Anglia. Large erratics which indicate the position of the former escarpment occur at Rising Lodge, King's Lynn [TF 668 230] where there are huge transported masses of Gault and Chalk; at Leziate [TF 677 192] where the till encloses a large erratic of Carstone and Gault; at The Howdale, Downham Market [TF 617 029] where there is a large erratic composed of Carstone, Red Chalk and Gault, and at Roslyn Hole, Ely [TL 555 808] where Skertchly (1877) recorded an enormous mass of Kimmeridge Clay, Lower Greensand, Gault, Cambridge Greensand and Chalk within the till.

Between the north Norfolk coast and Stoke Ferry the present day Chalk escarpment, although divided into two parts (a Lower Chalk and an Upper Chalk escarpment) and much lower than its southern counterpart, lies close to its presumed pre-Glacial position. It appears to have been eroded by ice moving from the north-west at an oblique angle to the escarpment. Between Stoke Ferry and Ely the former escarpment was eroded by ice rich in Triassic material (derived from the west) which moved onto it at right angles so that the escarpment was eroded back by over 10 km in places. This has given rise to the large embayment that is now occupied by Methwold and Lakenheath fens. Within this embayment the islands of Hilgay, Southery, Littleport and Ely probably mark the line of the former escarpment.

To the east of the presumed line of the former Chalk escarpment the rivers Wissey, Lark and Cam have buried valleys that have been interpreted as subglacial valleys draining south-eastwards or southwards (Woodland 1970, plate 1). To the west of the former escarpment the rivers Babingley, Nar and Gt Ouse appear to have pre-Glacial valleys infilled by glacial deposits (Figure 17). The Chalk escarpment seems therefore to have been a temporary barrier to the ice movement and to have separated an area of predominant erosion in the west from one of deposition in the east. The pre-Glacial valleys are interpreted as scarp-slope valleys that have suffered little glacial modification and the tunnel valleys may be former dip-slope valleys that have undergone extensive modification.

Contours on the rockhead surface beneath the area examined in detail, based on the assumption that the valleys in the feasibility study area are glacially modified pre-Glacial valleys, are given in Figure 18. An interpretation based on a tunnel-valley assumption would assume that the thicker drift sequences were filling lines of isolated hollows separated by cols.

The important difference between the two interpretations—that which would affect the choice of possible tunnel aqueduct routes and the design of any future site investigation, is that the one enables confident predictions to be made and the other does not.

In the pre-Glacial valley assumption, the valley floor will be irregular (due to glacial modification) but will tend to fall continually seawards. It is unlikely to extend much below the base level to which the original river was graded (i.e. about 100 m below OD in the case of the main pre-Glacial Ouse valley, 70 to 100 m below OD in its tributaries). In the tunnel-valley assumption, there is theoretically no limit to the depth to which erosion can occur if a sufficiently large hydrostatic head and volume of water are available. Furthermore, the valleys formed need not be continuous. They may have blind ends or be connected to similar valleys by high cols. Where continuous, they may locally fall either towards or away from the direction of the ice front. It would be almost impossible to locate all such valleys in an area the size of the feasibility study area using boreholes alone and, once located, it would be extremely difficult to define their maximum depths.

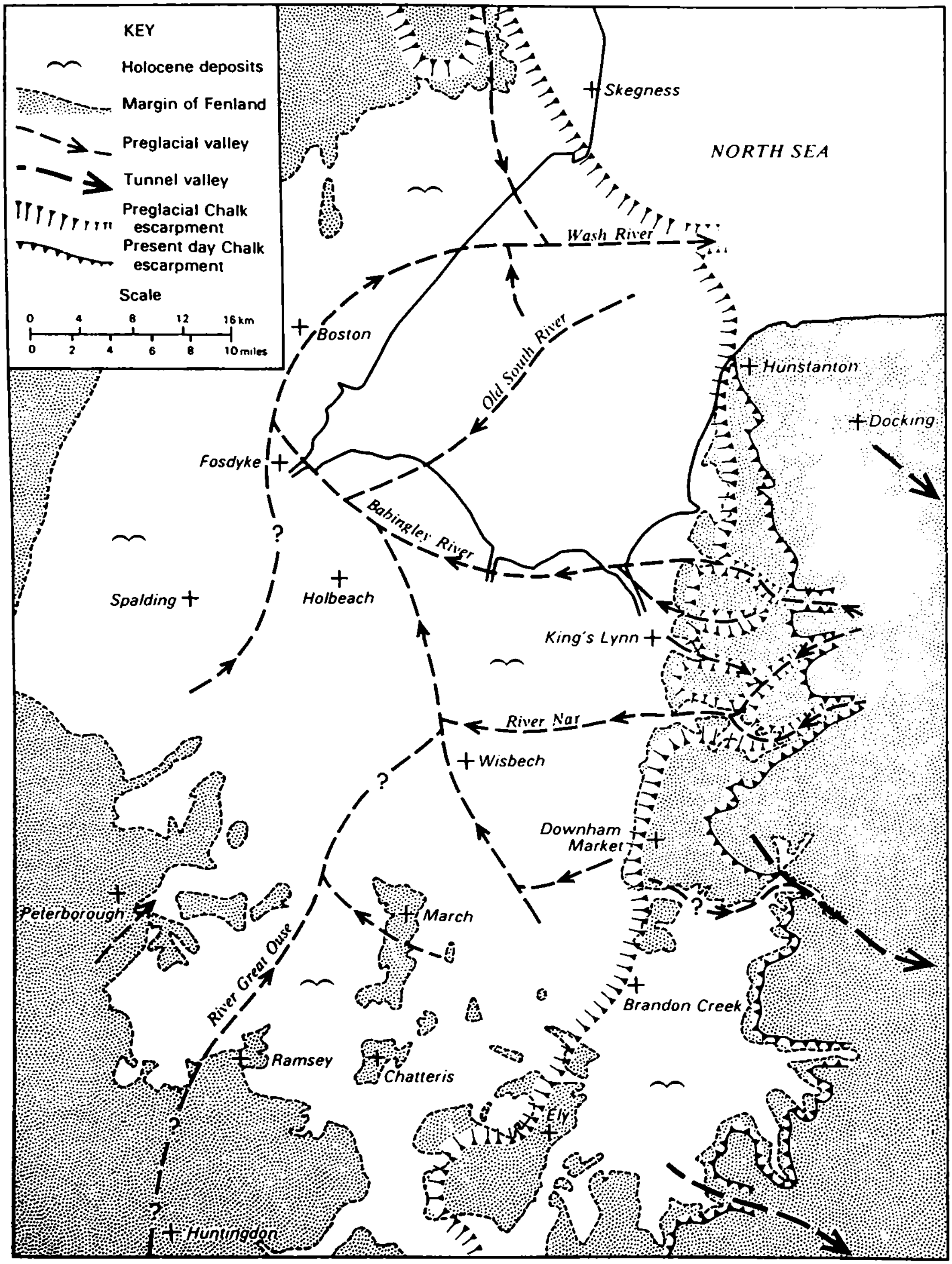

Figure 17 Possible pre-Glacial and subglacial drainage system of Fenland and The Wash

Details of the glacially-filled valleys

The evidence used in determining the presumed positions of the glacially-filled valleys that are thought to cross the feasibility study area is summarised below.

(i) The glacially-filled Babingley valley rises near Great Massingham [TF 780 210] and from there runs westwards to Grimston as a chalk valley floored by flint-rich gravels and with patches of similar drift on the sides. Boreholes at Grimston (IGS Well Catalogue no. 146/404a) and Congham (146/8) proved up to 55 m of drift. They appear to be sited within a well defined, steep-sided valley, since Lower Chalk crops out close to both boreholes. At Congham, the valley must turn northwards to follow a broad outcrop of till that links Congham with the present day valley of the Babingley River, because all possible southerly and westerly courses are blocked by an unbroken outcrop of Gault.

The glacially-filled Babingley valley joins that of the present river near the old flax mill [TF 693 256] where a borehole (145/73a) proved the drift to be more than 30 m thick. The easterly continuation of the present Babingley valley through Hillington to Harpley Dams appears to be a more recent feature, floored only by thin drift deposits.

Between the old flax mill and Castle Rising, the glacially-filled valley is again well defined and 1.25 to 1.5 km wide. Here, it is cut in Lower Cretaceous rocks and infilled by Chalky/Jurassic till and glacial sand and gravel. West of Castle Rising the valley passes beneath the Recent sediments of the marshlands and its course is presumed to continue almost due west via Boreholes 40 and 2A across the Stage 1 area. Seismic profiles along the River Gt Ouse (Floyd, 1973) were difficult to interpret where the glacially-filled Babingley valley is thought to pass beneath the river. A glacially-filled channel, about 70 m deep, can be made out in the section between West Bank Beacon [TF 598 241] and Admiralty Point [TF 590 255], although not clearly enough for the shape of the valley to be determined. The valley probably continues westwards from the R. Nene towards Boston and may unite with the Old South glacially-filled valley near Holbeach St Marks.

The limited amount of evidence available suggests that the cross profiles of the glacially-filled Babingley valley are similar to those of the glacially-filled valleys proved by the offshore seismic work, being narrow and steep-sided in the Chalk, less narrow and steep in the Lower Cretaceous and broad with ill-defined boundaries in the Upper Jurassic clays.

(ii) The glacially-filled Gaywood valley starts at Roydon Common [TF 690 218] and runs southwards and then westwards beneath the valley of the present day Gaywood River to Gaywood Bridge [TF 638 214]. For most of its length, the glacially-filled valley is about 1 km wide and probably has steep sides. An exposure on the King's Lynn bypass [TF 660 217], on the northern side of the valley, showed a vertical contact between Sandringham Sands and chalky till; field evidence indicates that very steep contacts occur throughout the length of the northern side of the valley. A cored borehole (145/17) close to the northern side of the valley at Reffley proved 30 m of Chalky/Jurassic till resting on Kimmeridge Clay.

West of Gaywood Bridge, the course of the glacially-filled valley is hidden by Recent deposits and there are insufficient borehole data to indicate its position beneath the northern part of King's Lynn. Seismic profiles along the river Gt Ouse clearly indicate Kimmeridge Clay at shallow depths for most of the section between West Bank Beacon and Wiggenhall St Germans bridge [TF 596 141] and it seems unlikely that the glacially-filled Gaywood valley passes beneath the Ouse. Only at Lynn Docks, where interference from quayside structures complicates the seismic records, might a narrow, glacially-filled valley have remained undetected. The glacially-filled Gaywood valley probably either turns sharply southwards at Gaywood to join the glacially-filled Middleton valley beneath King's Lynn or turns more gently northwards to become a tributary of the pre-Glacial Babingley to the north of King's Lynn.

(iii) The glacially-filled Middleton valley lies beneath the present valley of the Middleton Stop Drain and is well defined between Fairstead [TF 645 190] and Middleton Towers Station [TF 670 180]. The glacially-filled valley is about 0.5 to 0.75 km wide, probably steep-sided and cut through the Lower Cretaceous rocks into Kimmeridge Clay. A borehole in the middle of the valley near Fairstead [TF 6424 1888] proved 21.5 m of chalky till on Kimmeridge Clay. West of Fairstead, its course is lost beneath Recent sediments under King's Lynn; east of Middleton Towers, it rapidly broadens until, at East Winch, it merges with a wide tract of Glacial deposits which is connected to the Nar valley. Boreholes at East Winch (e.g. 145/77) have recorded up to 72 m of Glacial deposits resting on Kimmeridge Clay.

The apparent absence of thick drift deposits beneath King's Lynn, the indication (from seismic profiling data) that no glacially-filled valley passes beneath the Ouse in the King's Lynn area and the apparent easterly deepening of the valley all suggest that the Middleton valley ran eastwards from Fairstead to East Winch and from there southwards to Blackborough End to become a tributary of the pre-Glacial Nar.

(iv) In the Cretaceous outcrop area, where it can best be studied, the glacially-filled Nar valley is the longest and broadest of the valleys that might affect Stage 1 of the feasibility study. However, beneath the area examined in detail this valley appears to be no wider or deeper than that of the Babingley.

The start of the glacially-filled Nar valley is hidden beneath the thick Glacial deposits of the boulder clay plateau in the area of Litcham [TF 886 177] and it is not known whether or not the valley is a closed basin. West of Litcham, the presumed course of the glacially-filled valley is well defined with steep sides cut in Chalk. Wells within the valley, but close to the Chalk outcrop, at Lexham (146/20) and Castle Acre (146/194 and 146/238) proved drift deposits up to 60 m thick.

From Castle Acre to Narford [TF 765 140], the glacially-filled valley is generally well defined and 1 to 1.5 km wide. Westwards from there, its course beneath extensive spreads of Pleistocene and Recent deposits is uncertain but it probably turns north-westwards at Narborough to meet its tributaries, the Gaytonthorpe valley and the Middleton valley, in the West Bilney area. At West Bilney, it turns south-westwards and passes beneath the Recent deposits of Fenland near Blackborough End.

Several boreholes in the Setchey area have proved thick Glacial deposits, mostly till overlain by varved clay, beneath the valley of the present-day Nar. The seismic survey of the Gt Ouse proved thick Glacial sequences to be present everywhere between St Germans bridge [TF 596 141] and the railway bridge at St Mary Magdalen [TF 597 104]. The feasibility study borehole at Wiggenhall St Peter (Borehole 34) was sited on the basis of this work and proved 69 m of drift. Westwards from there Boreholes 13, 36 and 3A, thought to be on the flanks of this valley, proved thick Glacial sequences.

The field and borehole evidence suggests that where the glacially-filled Nar valley crosses the Stage 1 area, it is asymmetrical in cross profile with a very steep northern side and a relatively gentle southern side. Almost vertical contacts between the Glacial deposits and the Sandringham Sands occur in Blackborough End gravel pits [TF 676 145]. Between there and Setchey, the field relationships of the Glacial deposits and the solid rocks suggest similar steep contacts. At Setchey (159/20 and 159/25) and at Lordsbridge (Boreholes 13 and 33), the borehole evidence suggests a steep-sided glacially-filled valley.

None of the boreholes drilled within the Nar valley for the feasibility study encountered the interglacial Nar Valley Beds (Stevens, 1960) and it is presumed that although these deposits formerly covered much of Fenland, they were removed by late-Glacial or early Holocene erosion. More detailed investigation might prove scattered occurrences of them. The Nar Valley Beds include loose gravelly sands and soft clays and would be of engineering importance along a tunnel route. Within the Stage 1 area, occurrences of Nar Valley Beds are most likely to lie beneath Recent deposits on the flanks of the glacially-filled Nar valley in the Wiggenhall St Germans area.

The positions of the remaining glacially-filled valleys that might cross the feasibility study area have not been explored in the present work. The following notes on their occurrence are based on borehole records, offshore seismic data and published work. In the absence of detailed work specifically designed to explore the subglacial surface of Fenland it should be borne in mind that the evidence for many of these valleys must be largely conjectural. A possible interpretation of the pre-Glacial drainage system of the area is given in Figure 17. It is envisaged that this figure might provide a working model for use in planning any future investigation in the Stage 2, 3 and 4 areas.

The present day River Wissey follows the course of a glacially-filled valley which appears, from the limited borehole data available, to be locally up to 70 m deep. Boreholes at West Tofts (174/23), Stanford (174/77) and Hillborough (160/255) proved thick Glacial deposits, but since each of these sites is close to the boulder clay plateau area, it is unclear whether they lie in a westerly- or an easterly-draining channel.

Between West Tofts and Stoke Ferry, the glacially-filled valley is from 1.5 to 4 km in width, generally widening westwards. At Stoke Ferry the main valley probably continues north-westwards beneath the chalky till of the Boughton and Stradset areas. A tributary valley may turn southwards to pass through the narrow gap in the Chalk escarpment that separates Stoke Ferry from Whittington; from there it probably runs westwards to join a small glacially-filled valley at Fordham [TL 617 999]. Between Fordham and Littleport, site investigation boreholes suggest that Upper Jurassic clays are everywhere present at shallow depth beneath the Fenland.

The lower parts of the valleys of the rivers Lark and Cam are post-Glacial features cut in Recent deposits which rest on Upper Jurassic clays. However, both rivers overlie well documented deep, glacially-filled valleys in their upper reaches. It has been suggested that the buried valley of the Cam drained southwards and that the Lark drained south-eastwards 'ay from Fenland (Woodland, 1970, p. 540 and plate 28). The valleys of the Wissey, Lark and Cam are separated from the main part of Fenland by the outcrops (and subcrop at shallow depth) of the solid rocks between Ely and Fordham. There are, however, deep glacially-filled valleys within the Fenland area to the west of the presumed former position of the Chalk escarpment. Boreholes at Boston, Crowland, Long Sutton, March, Salters Lode (Borehole 1A) and Wisbech have proved thick drift sequences which may indicate the positions of valleys associated with a pre-Glacial Gt Ouse drainage system.

Horton (1970) has traced the glacially-filled valley of the Gt Ouse, which he interpreted as a pre-Glacial valley, from Stony Stratford as far north as Huntingdon. At Huntingdon the present-day natural course of the Gt Ouse turns sharply eastwards and enters Fenland at Earith. Downstream from Huntingdon, in the area where one might have expected to find evidence of a drift-filled pre-Glacial course, the published geological map indicates Oxford Clay cropping out and more survey work is clearly necessary before this problem can be resolved.

The possible course of the pre-Glacial Ouse beneath Fenland must be largely speculative. Drift sequences over 40 m thick have been proved at Wisbech (site investigation boreholes), Long Sutton (e.g. 145/10 and 11), Fosdyke (144/2) and Boston. At this last locality a borehole (128/5) in the town centre proved 58 m of drift, mostly Chalky/Jurassic till (Whitaker and Jukes-Brown, 1899, pp. 113-115), resting on Upper Jurassic clay. The northerly continuation of this valley may lie beneath the western edge of The Wash beneath an area where the water is too shallow for seismic profiling. The present-day course of the Gt Ouse is artificial below Earith and is almost entirely cut in solid deposits. The natural post-Glacial outfall of the river, which ran northwards from Earith via Manea to Wisbech, is also largely cut in solid deposits. The pre-Glacial course of the river probably occupied a narrow valley, cutting through the Corallian escarpment to the north of Huntingdon, that was later blocked by Chalky/Jurassic till.

In the offshore area, the presence of two major glacially-filled valleys was proved by the seismic work. The first, referred to here as the Old South valley, is interpreted as a south-westerly-draining tributary; the second, as the major river (here called the Wash River) that breached the Chalk escarpment and carried the combined waters of all the Fenland rivers in pre-Glacial times (Figure 17). A short, glacially-filled tributary of the Wash River lies beneath the Ants sandbank.

Infilling deposits of the valleys

The borehole evidence from the feasibility study provides few data concerning the shapes of the glacially-filled valleys in the Stage 1 area or the overall nature of their fills. The core samples from both the Babingley and the Nar valleys were almost wholly in uniform Chalky/Jurassic till. In the case of the Nar valley, this was overlain almost everywhere by water-laid till and varved clay. Varved clay was present in only a few of the boreholes in the Babingley valley and the till there was generally more stony than in the Nar valley. Details ofthe Glacial sequences proved in the boreholes are given in Appendix A.

A general appreciation of the lithologies of the Glacial deposits of the feasibility study area can be obtained from a consideration of the Glacial history and deposits of the surrounding area.

The Chalky/Jurassic till of Fenland is everywhere characteristically composed of stiff slightly sandy clay with fine and medium gravel-sized erratics of chalk, flint, Jurassic limestone and cementstone and a few farther-travelled materials: rare cobbles and boulders of flint, limestone and sandstone also occur. The lowest part of the till is commonly rich in locally derived materials. On the Upper Jurassic and Lower Cretaceous outcrops in the feasibility study area dark-grey clays, derived from the Upper Jurassic and containing Jurassic cementstone and Lower Cretaceous erratics, are overlain by paler, more calcareous clays rich in chalk and flint erratics. Evans (1975) has suggested that this lithological difference indicates a readvance of an upper (chalky) till across a stagnating lower till. In many sections, however, there is no sharp junction between the two lithologies and it seems likely that the lower till merely represents a basal layer of slow-moving ice.

Erratic blocks of Upper Jurassic clay, several metres thick, were proved in Boreholes 13 and 40. Blocks of densely pyrite- and calcite-cemented sandstone, up to 2 m across, derived from the basal bed of the Sandringham Sands, have been recorded in all the large exposures of Chalky/Jurassic till dug in recent years in the King's Lynn area. Such blocks can be seen at the present time at Leziate sand pits [TF 675 195] and were formerly visible at Hardwick borrow pit [TF 638 173]. Similar blocks in the 1965 King's Lynn Bypass excavations [TF 661 217] were removed with explosives.

In the Nar and Babingley valleys, the varved clay, although generally occurring in the upper part of the Glacial sequence, is present at several levels. It probably occurs as lenticular deposits that formed in small ephemeral lakes.

Thick sequences of Glacial sand and gravel were not proved in any of the feasibility study boreholes, although such deposits occur in large quantities in both the Babingley and Nar valleys (upstream of the Stage 1 area) where they are commercially worked. Gravelly sands were proved beneath till in the buried valley of the Ouse near Huntingdon (Horton, 1970, fig. 7) and the possibility that similar gravels are present should not be overlooked in any future site investigation in the present area.

By analogy with the valley shapes proved by the seismic profiles in the offshore area, one might expect the shapes of the glacially-filled valleys in the inland area to be partly controlled by the cementstone bands cropping out in their sides. The boreholes in the inland area are too widely spaced to enable valley shapes to be determined but a disproportionately large number of them proved Glacial deposits resting on a cementstone or other hard band, thus suggesting that the harder bands form distinct topographical features beneath the drift of the inland area, as they do in the offshore area.

In the offshore area, the deep glacially-filled valley in the central Wash appears to have been cut in two stages, resulting in a valley about 60 m deep with a steep-sided notch cut in its floor extending down for at least another 20 m. One might expect such a notch to be infilled with either till of different lithology from that of the main valley, or with sandy or gravelly deposits. No similar valley shape was suggested by any of the inland boreholes but detailed exploration of a particular route would be necessary before such a possibility could be excluded.

Rockhead contour map

A possible form for the rockhead surface in the Stage 1 area, assuming a pre-Glacial valley system to be present, is given in Figure 18. This is illustrated by a series of contours drawn to fit the limited borehole data available. It should be recognised, however, that the true rockhead surface will have a much more complex shape. Comparison of the topography seen in the offshore seismic sections with that of the land area on the eastern side of the Fens, suggests that the general shape of the surface shown in Figure 18 is probably correct but, in addition to the two main valleys, a number of short tributary valleys and scour hollows are probably also present; these valleys are likely to follow the north-north-east to south-south-west trend of the offshore valleys. Any future site investigation for a possible tunnel route in the area will need to look for such valleys that may have gone undetected in the present broad survey. In the offshore area, lying within the plateau of solid deposits which stretches from the Old South valley to the Norfolk coast, there are a number of pockets of till which rest on a rockhead surface at 20 to 40 m below OD. These features appear to be glacial scour hollows infilled with Chalky/Jurassic till. Similar features may occur on the land area within the −20 metre contour plateau shown in Figure 18.

Summary of Pleistocene history

The sequence of Pleistocene deposits in the feasibility study area and their correlation with the sequences in adjacent areas are summarised in Table 3. The evidence on which this sequence is based is briefly discussed below. No attempt has been made to relate this sequence to the standard Pleistocene stages proposed by the Quaternary Era Sub-Committee of the Geological Society (Mitchell and others, 1973). This committee has proposed a division of the Pleistocene on the basis of climatic cycles in which each cold (glacial) phase and each warm (interglacial) phase has been allocated a stage name. This use of the term 'stage' has been proposed as the most satisfactory alternative available in the absence in Britain of sufficient palaeontological evidence in the Pleistocene deposits to enable them to be grouped into faunal zones and stages. The proposed system of subdivision suffers from the limitation that individual stages cannot be uniquely defined since any particular stage may include a variety of deposits that are similar in lithology and fauna to deposits of other stages. The success of the proposed scheme therefore depends largely on the recognition of field evidence in which the relationship of glacial and interglacial deposits can be determined and on the Sub-Committee's deduction that this field evidence indicates the presence of three glacial phases (Anglian, Wolstonian and Devensian stages) and two interglacial phases (Hoxnian and Ipswichian stages) in Britain. Recent work on the isotope ratios of oxygen in the air bubbles trapped in the ice in the Greenland icecap (Dansgaard and others, 1969) and in calcium carbonate shells from deep-sea foraminiferal oozes (Shackleton and Opdyke, 1973) suggests that the Pleistocene Epoch was characterised by many climatic fluctuations with cold phases of various lengths. Thus, each glacial phase, although representing a long predominantly cold period, may have within it short warmer periods

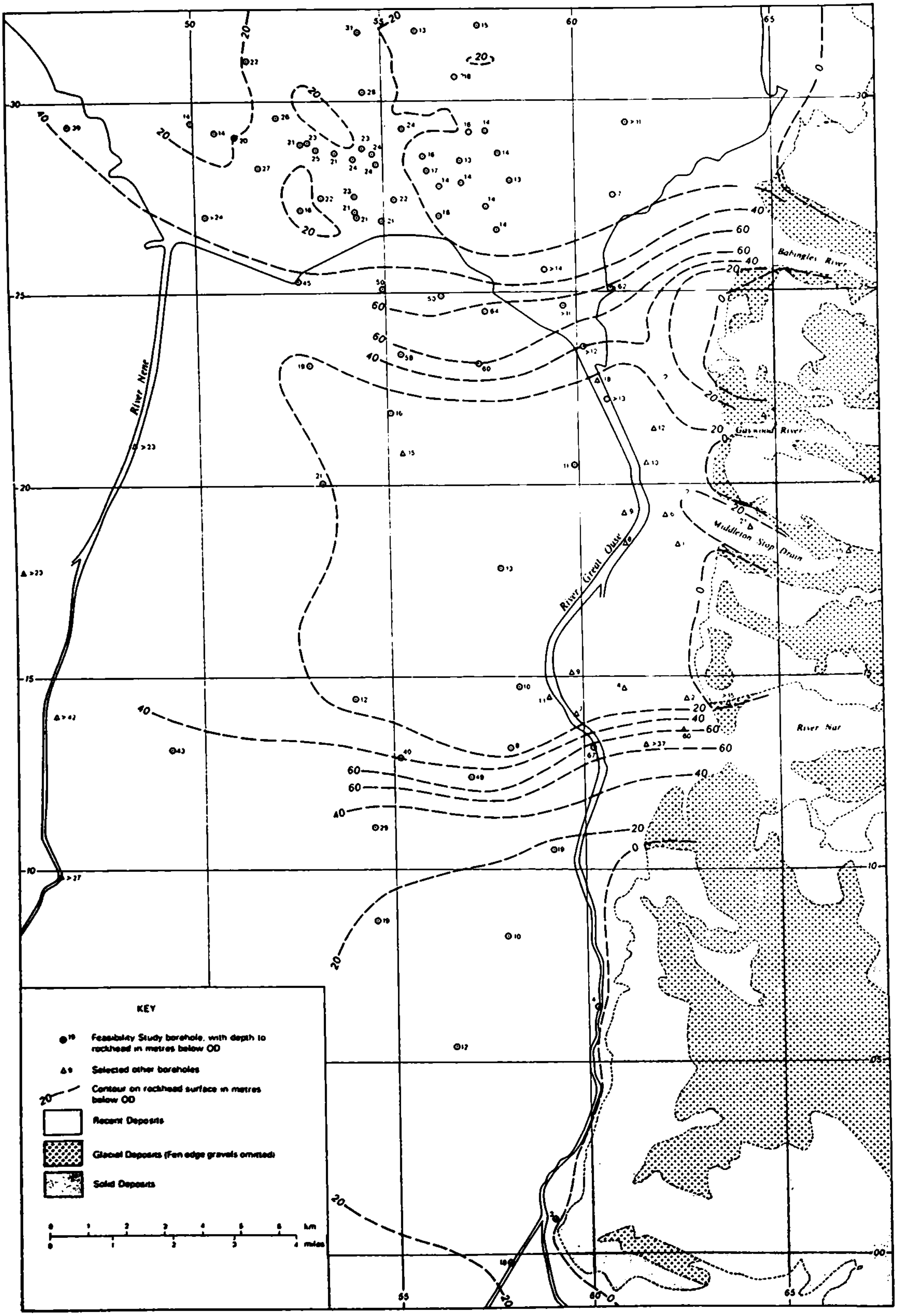

Figure 18 Rockhead contour map

Table 3 Correlation of the Pleistocene sequences of the Feasibility Study area and adjacent areas

Deposits			Approximate age in years before present	Presumed sea level relative to present	Erosional features in feasibility study area
Feasibility Study area	Southern Fenland	Humberside and Lincolnshire			
Solifluction deposits	Solifluction deposits	Solifluction deposits	10 000 to ~15 000	Rising from −100 to −30 m	Formation of meltwater valleys
Hunstanton till and associated sand and gravel	'Fen-edge gravels' including Terrace 1 of rivers Gt Ouse and Cam; Wretton Terrace of R. Wissey	Drab, Purple and Hessle tills and associated sand and gravel	~15 000 to ~46 000	−100 m 'Fen-edge gravels' graded to levels of postulated glacial lake	? Formation of Fenland 'islands'
Hunstanton raised beach; ?upper part of Tottenhill Gravels	? March Gravels	Sewerby raised beach	> 46 000	+3 to +5 m	Formation of Hunstanton buried cliff
Lower part of Tottenhill Gravels	Higher terraces of rivers Cam and Ouse	? Basement till of Bridlington		Lower than present	Extensive erosion of earlier Pleistocene deposits
Nar Valley Clay	? Salt marsh clay at March			Rising from −8.5 to +30 m	
Nar Valley Freshwater Beds	Higher terraces of Rivers Cam and Ouse			Rising from −20 to −8.5 m	
Varved clays passing down into Chalky/Jurassic till with associated sand and gravel deposits	Chalky/Jurassic till with associated sand and gravel deposits	Chalky/Jurassic till with associated sand and gravel deposits		−100 m	Modification of fluvial valleys; formation of scour hollows and tunnel valleys
Pre-Glacial weathering products				Falling from 0 to −100 m	Pre-Glacial valley system

(interstadials) and the interglacial periods may similarly contain short glacial periods. The recognition of the Geological Society stages therefore requires not only a knowledge of the depositional environment and stratigraphical relationships of any particular deposit, but also an assessment of whether that deposit represents a long or a short period of time. The terms 'long' and 'short' have not been defined but the Devensian Glacial Stage is believed to have lasted about 72 000 years and to contain interstadials lasting from a few thousand to 10 000+ years.

Because of the laterally-impersistent nature of glacial and interglacial deposits, the type localities for each of the proposed Geological Society stages are of necessity geographically isolated from one another and expose only fragments of the succession. The full sequence of stages is therefore based on assumed correlations between the type localities. The Hoxnian Stage, for example, is defined in terms of widely separated localities in East Anglia and the Midlands and its status as either an interglacial or an interstadial period is difficult to ascertain. The type locality of the Anglian (glacial) Stage at Corton, Suffolk, contains both glacial (till) and fluviatile (sand) deposits whose relationship to the overlying Hoxnian (interglacial) Stage (type locality Hoxne, Suffolk, about 43 km from Corton) is based on the assumed correlation that the youngest till at Corton is the same age as the till that underlies the 'interglacial' deposits at Hoxne. The deposits of the type locality of the Wolstonian (glacial) Stage at Wolston, Warwickshire, cannot be directly related to those at Hoxne but are thought to be correlatives of glacial deposits in the Birmingham area that overlie deposits containing warm pollen floras similar to those from Hoxne. What length of time does the Hoxnian Stage therefore represent?

The Ipswichian (interglacial) Stage is even less well documented than the Hoxnian. The type locality at Bobbitshole, Suffolk, is geographically isolated from the type localities of both the underlying Wolstonian and the overlying Devensian glacial stages and the deposits at Bobbitshole are underlain and overlain by gravels of uncertain age. It has been suggested (Bristow and Cox, 1973) that the Hoxnian and Ipswichian 'interglacials' are either the same age or merely two interstadials within a single glacial episode.

It is not surprising, therefore, that the Geological Society scheme has led to difficulties of correlation; the situation has become exacerbated by the fashionable tendency to allocate all Pleistocene deposits to one or other of the stages within the scheme even where the stratigraphical evidence is insufficient to justify such correlation. In the present work these terms have not been used and an attempt has been made to differentiate between those stratigraphical relationships which can be demonstrated and those which are based on the presumed equivalence of geographically separated deposits.

The oldest glacial deposits in the feasibility study area are the Chalky/Jurassic till (Chalky Boulder Clay of some authors) and associated sand and gravel deposits. These deposits infill a topography cut into the solid rocks and are made up almost entirely of Upper Jurassic and Cretaceous materials derived from Lincolnshire and Norfolk. The relationship of the till to the sand and gravel is complex. On the north side of the Nar valley at Blackborough End [TF 675 144] gravels are banked against a cliff cut in Sandringham Sands and appear to be part of a lateral moraine which underlies the main mass of the valley till. In the central part of the valley at Wormegay [TF 681 128] similar gravels form a ridge surrounded by till. Elsewhere glacial gravels of apparently similar age occur beneath (e.g. at Leziate [TF 677 192]) and on top of (e.g. in the Babingley valley [TF 703 254]) the till.

The Chalky/Jurassic till of west Norfolk now occurs as dissected remnants of what may originally have been an almost continuous deposit. Thick till sequences are confined to the glacially-filled valleys with thin patches of till occurring on the interfluves and on some valley sides. The till in the valley sequences generally becomes less stony and better sorted in its upper part and, in the case of the valleys of the Babingley, Middleton Stop Drain and Nar, becomes interbedded with varved clay before finally passing up into varved clay. A gas pipeline trench in the Middleton Stop Drain valley [TF 650 174] to [TF 668 178] showed that varved clay in the central part of the valley passed laterally, via water-sorted almost stoneless till, into heterogeneous Chalky/Jurassic till in the valley side. When traced away from the valley floor towards the interfluve the stones in this till become coarser and the till generally more heterogeneous.

The relationship of the varved clay to the Nar Valley Beds is not yet clear but it seems likely that the two deposits are conformable. Shell-and-auger boreholes drilled by IGS in the Nar valley near Setchey [TF 6458 1394] and [TF 6377 1435] proved fine-grained grey silty sands and silts (basal part of the Nar Valley Freshwater Beds) resting on grey silts with widely spaced laminae of reddish-brown clay (highest part of the varved clay sequence) which passed down into varved clay. The varved clay was probably deposited in a series of small, ice-dammed lakes during the retreat phase of the glaciation that produced the Chalky/Jurassic till. The Nar Valley Freshwater Beds, from which Stevens (1960) obtained a flora indicative of an ameliorating climate, may therefore represent the last stages of that glaciation and the early stages of the subsequent interglacial stage.

The Nar Valley Clay consists of finely laminated marine clays, silts and silty clays and has been proved at outcrop (Stevens, 1960) and in boreholes to overlie the Nar Valley Freshwater Beds. In the lower part of the Nar Valley the base of the marine clay in the IGS boreholes at Setchey and at Tottenhill gravel pits [TF 633 115] is marked by a shell bed composed almost entirely of large oysters which rests disconformably on freshwater peat. The age of both the peat and the oyster bed have been shown by radiocarbon dating (samples IGS C14 129 and IGS C14 222) to be greater than 46 000 years. In the central part of the Nar valley near Setchey the junction of the marine and freshwater sequences is at about −8.5 m OD. Traced towards the valley sides the junction rises to about +4 m OD at Tottenhill gravel pits and −2.0 m OD at Setchey village. The junction rises eastwards as it is traced up the valley and is at more than +6 m OD in the valley side at Horse Fen, West Bilney [TF 692 142] (Stevens 1960, p. 295) and at about +13 m OD at East Winch [TF 705 116] (Young *in* Institute of Geological Sciences, 1972, p. 23).

The Nar Valley Clay has yielded a rich fauna of bivalves (*see* Whitaker and others, 1893, pp. 84–85 for details) that indicate a brackish-marine environment comparable to that of the present-day Wash. The clay was clearly deposited in a rising sea that transgressed eastwards across the Nar Valley Freshwater Beds and older Pleistocene deposits. Rose (1835-6) recorded exposures of undoubted shelly Nar Valley Clay at heights up to 24 m above OD in the Narford area, which suggests a minimum sea level at about +30 m AOD for the maximum extent of the transgression if later isostatic or other differential land movement is assumed to be absent. Sparsely stony clays mapped as Nar Valley Clay by Whitaker and others (1893, p. 89) in the Ashwicken area [TF 698 188] at heights greater than +30 m OD have been re-interpreted by the present author as water-sorted till.

Stevens (1960, p. 295) and Baden-Powell and West (1960, p. 79) have described sections at Blackborough End gravel pits [TF 684 145] in which gravels of presumed glacial origin overlay the Nar Valley beds. Whether these gravels represent the main mass of the Blackborough End Gravels, part of the Tottenhill Gravels (*see* below) or soliflucted material derived from the Blackborough End Gravels is unclear, as the sections are no longer visible.

At Tottenhill gravel pit at the mouth of the Nar valley the Nar Valley Freshwater Beds and Clay are overlain by a thick sequence of flint gravels which are here termed the Tottenhill Gravels. Boreholes in the Nar valley show that this extensive spread of gravel continues upstream, beneath the Holocene deposits of the central part of the valley. The relationship of the Tottenhill Gravels to the gravels at Blackborough End and Wormegay (both of which are presumed to be glacial and associated with the Chalky/Jurassic till) is not known.

At Tottenhill the gravels can be divided into two parts. The lower part (up to 5 m thick), consists of coarse, poorly sorted, mostly angular gravels and is characterised by cross-bedding, which dips steeply (20 to 25°) to the south-east, and by frost-wedge and cryoturbation structures; it contains pebbles of woody and reedy peat, soft brown clay, varved clay and Jurassic erratics, all presumed to have been derived from nearby outcrops of Nar Valley Beds and Glacial deposits. The upper part (about 3.5 m thick) is characterised by regular planar cross bedding. The junction of the two units is a well defined, slightly irregular surface, in part calcreted, along which the upper gravel truncates cryoturbation and bedding structures in the lower gravels. The Tottenhill Gravel appears to form part of an almost continuous narrow strip of gravel which runs from Hardwick [TF 631 182] to Wimbotsham [TF 608 058] and which forms an eastern limit to the Fenland Holocene deposits.

A gas pipeline trench at West Winch [TF 631 167] showed 3.5 m of cross-bedded, well rounded flint gravel banked against a low cliff of Chalky/Jurassic till. At Stowbridge [TF 614 074] about 3 m of similar flint gravel rests on Kimmeridge Clay. The upper surfaces of the gravels at West Winch (about 7.6 m OD) and Stowbridge (about 6.7 m OD) are at similar heights. The base of the gravels at West Winch (about 4.0 m estimated) and Stowbridge (about 3.7 m) are at similar levels to the base of the upper gravels at Tottenhill (about 5.0 m).

Whitaker and others (1893, p. 91) interpreted this long strip of gravel as a terrace deposit marking the east bank of a forerunner of the River Gt Ouse. However, there is no evidence that the Gt Ouse, or indeed any other Fenland river, followed a course along the eastern edge of Fenland before its diversion there in Roman times, and it is difficult to envisage a river without a western bank. Whitaker (in Whitaker and Jukes-Browne, 1899, p. 92) later suggested that similar patches of gravel near King's Lynn might have a marine origin comparable with that of the Hunstanton raised beach (*see* below).

The Lower Tottenhill Gravels, by virtue of their included frost structures, clearly indicate a cold phase younger than the interglacial Nar Valley Clay.

The strip of gravels outcropping between King's Lynn and Stowbridge, together with Upper Tottenhill Gravel appear from their field relationships to be a marine (or possibly lacustrine) beach deposit. In southern Fenland, around March, shelly gravels at a similar height (the March Gravels) have been interpreted as an interglacial beach deposit.

There is no direct evidence by which the age of the Tottenhill Gravels can be determined or their relationship to the distinctive reddish-brown till of the Hunstanton area deduced. Nor can the relationship of the Chalky/Jurassic till to the Hunstanton till be directly demonstrated at the present time.

The Hunstanton till is characteristically a dull reddish-brown sandy clay, derived largely from Triassic marls, containing chalk and flint erratics together with a large percentage of Bunter pebbles, Carboniferous sandstones and coals, schistose and gneissic metamorphic rocks and a variety of igneous rocks. Among the more easily identifiable igneous rocks are Whin Sill dolerite from northern England and rhomb-porphyry from Norway. The Hunstanton till is everywhere thin (probably less than 10 metres) on the land area in west Norfolk. At Hunstanton and Old Hunstanton it overlies well-rounded chalk and flint gravels which appear to be a former beach deposit at the foot of an old cliff cut in Chalk, Red Chalk and Carstone. At some localities (e.g. Old Hunstanton [TF 681 425]) the upper part of the beach deposit is interbedded with frost-shattered chalk debris. At Hunstanton [TF 671 406] the beach deposit contains layers of shelly sand with a fauna of marine gastropods and bivalves (Whitaker and Jukes-Browne, 1899, p. 90) interbedded with well-rounded gravels composed largely of far-travelled erratics. The molluscan fauna can be matched with that of the present-day Wash or North Sea and this fauna combined with the height of the gravels (maximum about +8 m OD), suggests deposition in a climate and at a sea-level similar to that of the present-day.

In the Holderness peninsula in Humberside (Jukes-Browne, 1885) a series of tills (the Purple, Drab and Hessle), lithologically similar to the Hunstanton till, overlie a beach deposit and chalk cliff comparable to that at Hunstanton. At Sewerby [TA 199 686], Humberside, Lamplugh (1888) described the beach as composed of shingle rich in far-travelled erratics (many the same as occur in the Hunstanton beach) together with a molluscan fauna, that can also be matched with that from Hunstanton, and vertebrate bones. The molluscan fauna is not diagnostic of age but it does suggest a similar climatic origin for both the Sewerby and Hunstanton beaches. The vertebrates from Sewerby include warm-climate forms of the elephant, hippopotamus and rhinoceros (Boylan, 1967), indicative of an interglacial rather than an interstadial phase (Catt and Penny 1966, p. 386). Catt and Penny (1966, p. 387) have also recorded an older till, the Basement Till, beneath the raised beach at Sewerby and it is from this material that far-travelled erratics in the beach deposit are presumed to have been derived. If this interpretation is correct, then, by analogy, one might expect to find an older till, lithologically similar to the Hunstanton till, in the offshore area close to the north Norfolk coast. It has been suggested (Catt and Penny, 1966, pp. 403–404) that the Basement Till of Holderness is equivalent to part of the Chalky/Jurassic till of Norfolk.

It seems more probable however that the Sewerby and Hunstanton raised beaches represent a warm phase within a single glaciation and that this glaciation is separated from that which deposited the Chalky/Jurassic till of the feasibility study area by the Nar Valley Beds interglacial.

Organic fresh-water silts at Dimlington [TA 391 217], Lincolnshire, which lie between the Basement and Drab tills, have been radiocarbon-dated as about 18 500 years old (Penny and others, 1969) supporting the suggestion by Straw (1960) that the Hunstanton till represents the maximum extent of the last glaciation in East Anglia.

Returning to the Tottenhill Gravels, these can now be tentatively correlated with the Hunstanton succession as an early Hunstanton glaciation (the lower part of the gravels) followed by a warmer phase (the upper part of the gravels).

Throughout west Norfolk the youngest Pleistocene deposits are cryoturbated solifluction deposits; these are present over large areas of the district and are commonly associated with periglacial features such as stone stripes and polygons.

RECENT DEPOSITS

The Recent deposits of the feasibility study area have not been studied in detail since their engineering properties are generally so poor that access shafts and other works that might pass through them would be likely to require the use of special soft-ground techniques such as freezing (*see* p. 49).

The stratigraphy of the Recent sediments of Fenland is laterally variable and complicated (*see* Skertchly, 1877, for regional details). The history of the area over the past 10 000 years is one of repeated transgression and regression with, at any given level, zones of peat passing seawards first into reedy clays and then into salt marsh, intertidal and finally offshore deposits. Superimposed on these zones is a complex pattern of migrating tidal creeks and freshwater streams.

In that part of the feasibility study area examined in detail for Stage 1, and in the adjacent areas surveyed as part of 1 to 50 000 Geological Sheets 145 (King's Lynn) and 159 (Wisbech), the Recent deposits can be divided into five broad units, based on three transgressions and two regressions (Figure 19). The younger units crop out on Sheets 145 and 159 and are here named the Terrington Beds, Nordelph Peat and Barroway Drove Beds after areas in Norfolk where they are well displayed. Other minor transgressions and regressions occur at several levels within the sequence over restricted parts of the area, notably within the Barroway Drove Beds.

The Terrington Beds include the present-day salt marsh deposits of Terrington Marsh and adjacent marshes, together with similar deposits inland (the 'marshland'* area) which have been reclaimed during and since Roman times. The Terrington Beds rest disconformably on the Nordelph Peat over much of the 'marshland'; the maximum extent of the transgression that produced this disconformity has been dated at some point between 1300 and 300 BC (Salway, 1970, p. 8) on the basis of Roman pottery (hence the term 'Romano-British silt' of some authors). In more northerly areas the Terrington Beds rest on intertidal deposits that pass laterally landward into the Nordelph Peat (Figure 19).

The Terrington Beds consist of finely interlaminated, dull, slightly reddish-brown clays and pale-brown silts. Most of their original bedding structures have been destroyed by plant roots to give a silty clay much favoured by fruit, root crop and bulb growers. Within these clays there is a well developed pattern of tidal creeks infilled with silt and very fine-grained micaceous sand. In the southern part of the 'marshland' these infilled creek and river courses stand above the surrounding peat lands as sinuous ridges or roddons. The same features are present throughout the 'marshland' but, in the absence of the height contrast caused by differential compaction and wastage of the peat, are more subdued.

The Nordelph Peat ('Upper' Peat of some authors) underlies the Terrington Beds in the southern and eastern part of the Stage 1 area and crops out to the south of the Terrington Beds outcrop to form the peaty soils of the 'fenland'. Over much of the feasibility study area the Nordelph Peat is composed largely of reed stems and rhizomes and only in those areas close to the edge of Fenland (where it is underlain by Pleistocene or older deposits) does it contain appreciable quantities of wood. Radiocarbon dating has shown the Nordelph Peat to be generally between 4000 and 2000 years old in the 'marshland' area; these dates represent the maximum regression of the peat and the arrival of the Terrington Beds transgression respectively. Over much of the 'fenland' area peat continued to be formed until the reclamation works of the 17th to 19th centuries; it continues to form in a few small areas.

In the older reclaimed parts of Fenland peat wastage due to oxidation, bacterial action and erosion has revealed the underlying Barroway Drove Beds. In the Barroway Drove area of Norfolk, and elsewhere throughout Fenland, these beds consist of very soft, wet, interlaminated clays and silts which are commonly referred to as 'Buttery Clay' on account of their almost thixotropic properties. They differ from the Terrington Beds only in their colour (shades of grey) and the presence of numerous water-filled, peat root-holes (from the overlying Nordelph Peat). The bulk of the Barroway Drove Beds is probably a salt marsh deposit; the presence of fine lamination and burrows at certain levels suggests that they also include upper tidal flat deposits. Thin peat beds have also been recorded locally (e.g. Edmunds *in* Godwin and Godwin, 1933) within the Barroway Drove Beds, indicating that the sequence of transgressions and regressions within the area is more complex than is yet understood. Tidal creeks infilled with silt and very fine-grained sand occur throughout the Barroway Drove Beds and some of these are floored by gravelly channel lag deposits. The patterns made by these creeks (as seen in aerial photographs) in the Barroway Drove and Stowbridge areas suggest that more than one phase of creek development is present.

Over most of the feasibility study area the Barroway Drove Beds disconformably overlie peat (the 'Lower' peat of some authors) which in turn rests on a thin gravelly sand of complex origin. The peat does not crop out since it is everywhere overstepped by either the Barroway Drove Beds or the Nordelph Peat. Radiocarbon dates suggest that it is about 5000 to 6000 years old.

This peat has a greater extent than the Nordelph Peat in northern Fenland and the offshore area. Peat was recorded at the base of the Recent deposits in Borehole WY 152 in the intertidal area. In several other boreholes (e.g. WY 220, 501 and 513) the upper surface of the Glacial deposits was weathered and penetrated by peat roots, indicating the former extent of this bed.

The underlying gravel is presumed to be early Holocene in age, but it may be markedly diachronous and in part late Pleistocene. It usually consists of blackened flints set in a sand matrix, being shelly in the tidal channels but barren elsewhere. In places it is clearly a marine lag deposit derived from glacial deposits; elsewhere it appears to be either a sheetwash deposit (head) or a freshwater channel deposit. Its apparently ubiquitous nature as a thin sheet beneath the Recent deposits of Fenland is problematical. It may have originated in a variety of ways and been re-worked in late Pleistocene times during periods of high meltwater run-off and, in some areas, subsequently by tidal creeks.

The thickness of the Recent deposits varies considerably; they fill a buried topography that is in part related to the original pre-Glacial drainage system. They appear to be thicker along the axis of the presumed pre-Glacial valley of the Babingley River, (up to 26 m thick in Boreholes 2, 30 and 40) and along the course of the drift-filled valley running through Wisbech (up to 30 m thick). Some of the boreholes within these valleys, however, record much thinner Recent deposits, suggesting that the Recent deposits fill valleys which are narrower than the underlying drift-

* The terms 'marshland' and 'fenland' are used here to mean the clay lands and the peat lands respectively. The Norfolk part of the clay lands is formally known as Marshland, the equivalent area in Lincolnshire being called Holland.

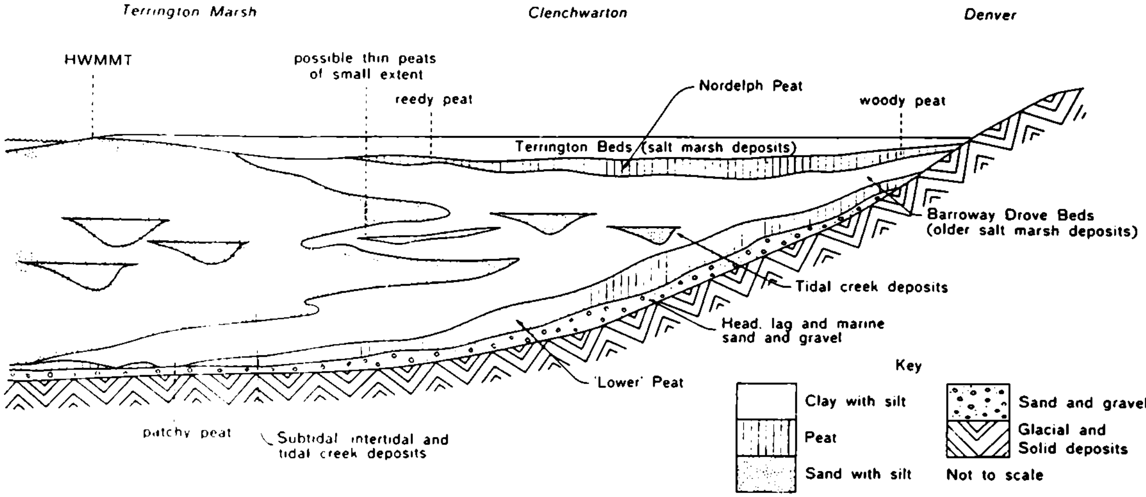

Figure 19 Generalised section through the Recent deposits of Fenland and the southern part of The Wash

filled valleys. No abnormal thickness of Recent deposits was recorded along the line of the presumed pre-Glacial valley of the River Nar.

No sample of Recent deposits was taken in any of the inland cored boreholes. The disturbed and undisturbed samples from five shell-and-auger boreholes (Boreholes 1A, 2, 8, 12, and 14), put down to examine the Recent deposits at the sites of possible structures, are briefly classified in Appendix A.

GEOPHYSICAL LOGGING TECHNIQUES

Several geophysical logs were run in the Denver Sluice (Bh. 1), West Walton Highway (Bh. 3C), Gedney Drove End (Bh. 4C) and North Wootton (Bh. 23) boreholes by the Resources Division of the Central Water Planning Unit to provide standard traces for the whole of the Upper Jurassic clay sequence within the feasibility study area. These logs were correlated with the borehole cores to try to establish a simple technique which could be used at short notice on site to determine, in conjunction with a rapid visual inspection of the borehole cores, the positions of the main stratigraphical marker beds in any particular borehole within a few hours of completion of the borehole. Rapid and reliable interpretation of the borehole sequences was essential in planning the efficient use of the four drilling rigs on site. A secondary aim was to establish detailed correlations between the geophysical logs to supplement the palaeontological evidence from the cores in areas where the palaeontology was difficult to interpret or was absent (e.g. core losses, sparsely fossiliferous beds).

The various geophysical techniques used are discussed below. Total gamma-ray and resistivity logging offer the best prospects of success for establishing detailed correlations within argillaceous formations such as the Upper Jurassic clays. In practice the total gamma-ray log was found to be the more useful site investigation technique in the feasibility study area, where it gave more distinctive signatures than the resistivity log and had the added advantages that it could be used above the water-table and in lined or cased boreholes.

Total gamma-ray logging

The total gamma-ray log measures the natural radioactivity of rocks, the gamma radiation being emitted almost entirely by the radioactive isotope of potassium (^{40}K) and by radioelements in the uranium and thorium decay series (Anon., 1966). In sedimentary rocks these radioactive isotopes are usually concentrated in the argillaceous formations.

In sediments such as the Upper Jurassic clays, which are lithologically uniform over very wide areas, one might expect these radioelements to act as sensitive indicators of change in sediment source or in general conditions of depositional environment. The use of a combination of sedimentary rhythms and gamma logging can enable detailed correlations to be made over large distances in the Upper Kimmeridge Clay (Gallois, 1973). The work for the feasibility study has shown that the Lower Kimmeridge Clay, and to a lesser extent the Ampthill Clay and the West Walton Beds, respond to the same techniques.

Equipment: In gamma-ray logging a detector is drawn up the borehole to provide a continuous record of the radioactivities of the formations present. Two types of gamma-ray detector were used in the present work, a Gearhart-Owen Geiger-Müller counter with an external diameter of 1 11/16 in (43 mm) and an active length of 18 in (0.46 m), and a Widco Portalogger scintillation counter with an external diameter of 1 in (25 mm) and an active length of 4 in (0.10 m). In the Geiger-Müller counter voltage pulses produced by the passage of the gamma-rays through a very-low-pressure ionised tube are presented as a continuous graph or signature. In the scintillation counter similar voltage pulses are produced by the photoelectric amplification of scintillations caused by gamma-rays passing through a selenium iodide crystal. The voltage pulses are averaged over equal time intervals, known as the 'time constant', in order to minimise the effect of the intrinsically erratic nature of the gamma-ray emission. To reduce spurious readings caused by the erratic nature of the count, it is usually advantageous to choose as long a time constant as possible. This has to be offset against the logging speed, excessively long time constants necessitating excessively slow speeds. The fastest satisfactory logging speed is that at which the active part of the counter moves through its own length in one time constant. In formations such as the Upper Jurassic clays which are relatively uniform in lithology, which have a relatively narrow range of low gamma counts, and in which the more distinctively gamma 'low' or gamma 'high' beds are often only a few centimetres thick, excessive logging speeds cause the counts from these distinctive beds to be averaged with those of adjacent beds within a single time constant interval, thus destroying much of the detail that could be present in the gamma signature. A combination of fast logging and a long time constant can result in the upward displacement on the gamma log of the true positions of formation boundaries (Kokesh, 1951). This error, however, is unimportant in the present work because the more serious problem of loss of detail appears at much slower logging speeds.

Ideally the maximum logging speed should take into account the thickness of the marker beds to be detected. For a time constant of t seconds, an active probe length of d metres and a minimum bed thickness of x metres the maximum logging speed in horizontal strata will be $(d + x)/t$ metres per second. In the present work (in which the strata can be everywhere assumed to be horizontal) the thinnest distinctive bed was about 50 mm thick. With the Widco Portalogger (active length 0.10 m) a time constant of 5 seconds was generally used, giving a maximum logging speed of 0.03 m per second (108 m per hour). In practice a logging speed of about 60 m per hour was used. Steady speeds slower than this are difficult to achieve due to operator boredom; it is clear from the above that an unsteady logging speed can produce spurious variations in the gamma trace.

For a borehole 60 m deep (about the average for the site), setting up and dismantling the equipment required about one hour, logging time about one hour, and travel to and from the site, waiting for drillers, etc., 1 to 2 hours. In addition, cleaning and maintenance of the equipment averaged about ½ hour per borehole visit. The time that could be saved by using higher logging speeds is therefore small in comparison to the time taken for the logging procedure as a whole and its detrimental effect on the results would be disproportionately large.

For the Geiger-Müller counter (active length 0.46 m), a time constant of 4 seconds was used, giving a maximum logging speed of 480 m per hour. This equipment was mounted in a forward-control Landrover and operated through an electric winch at a steady logging speed of 240 m per hour. Although more sensitive and less prone to operator error than the Widco, this equipment had certain disadvantages. It forms part of an integrated geophysical logging unit and it was not economically practicable either to have the equipment on permanent standby for the feasibility study or for it to make repeated journeys from Reading at very short notice. For most site investigation work the lower sensitivity of the Widco would be more than offset by its availability and portability.

Calibration and errors: No attempt has been made in the present work either accurately to measure the radioactivities of the various formations encountered or to calibrate the individual gamma logs in relation to one another. Absolute quantitative measurements of gamma-ray activities in boreholes are notoriously difficult to carry out. Not only are such measurements affected by variations in the gamma-ray absorption properties of the formation, in borehole diameter, mud density and the geometry of the beds in the boreholes, but also by minor changes in the circuitry of the equipment. These drift effects can be overcome to some extent by calibration of the equipment against a standard source at the beginning and end of each borehole run. Corrections can also be made for borehole diameter if the hole is in good condition, but, if caving or squeezing are suspected, a caliper log must be run.

For stratigraphical purposes, such as that carried out for the present work, it is usually only necessary to be able to make qualitative comparisons between the gamma-ray signatures. Variations in the diameters of the boreholes (but not large variations within a given borehole) and in the sensitivities of the equipment can largely be ignored.

In stiff uniform clays, such as the Upper Jurassic clays, little caving or squeezing occurs during drilling or even when standing, providing the borehole is protected by a thick drilling mud. The most likely error that could have occurred in the present work would have been to confuse the low counts of a cavity with those of a cementstone. With continuously cored boreholes this danger is unlikely to arise, but care would be needed in interpretation where core recoveries were poor or where only a limited number of samples was taken. A caliper log was run in Borehole 23, which had an abnormally erratic drilling history, and the amount of caving was shown to be too small to markedly affect the gamma log.

Normal bentonite mud has a negligible gamma count: natural mud generated from the Upper Jurassic clays during the drilling process uniformly enhances the background count and would only produce errors if it were allowed to settle over a long period and become layered. All the present boreholes were logged immediately after drilling and mud circulation had ceased.

The maximum borehole diameter in Upper Jurassic clay suitable for gamma logging with the Widco equipment, due to absorption losses in the air or mud-filled space between the probe and the rock source, is about 0.3 m. Casing has a proportionately greater effect on signal loss as the borehole diameter increases and the background count becomes a progressively larger part of the total count. Most of the present boreholes were logged at diameters of 0.18 m or less and were unlined in the Upper Jurassic clays.

A statistical check was made near the bottom of most of the boreholes to ensure that the variations observed in the traces were a true reflection of variations in the gamma-ray emissions of the various strata. The simplest method of checking the validity of any particular section of trace is to repreat that section. The repeated trace should at no point vary from the original by more than the amount of the statistical variation in the background count.

Results: Annotated copies of the gamma-ray logs showing the main lithological marker beds are filed at IGS, together with detailed lithological logs drawn at the same scale.

The general gamma-ray emission features of the formations examined in the feasibility study are discussed below.

1. Lias: mudstones and faintly bituminous

mudstones with gamma counts comparable to those of the Kimmeridge Clay. These beds were encountered only in Borehole 1 (Denver Sluice) where they are separated from the Upper Jurassic clays by the water-bearing Middle Jurassic. They are of no interest to the present work and were not gamma logged. Lithological and gamma-ray evidence from other areas suggests that they would be amenable to the same correlation techniques based on gamma logging as have been used here for the Kimmeridge Clay, should later stages of the water storage scheme require this stratigraphical level to be examined.

2. Middle Jurassic and Kellaways Beds: mostly limestones and sands with low gamma counts. These beds lie below the level of interest for Stage 1 and probably form a natural lower limit for tunnelling for later stages. They were penetrated only in Borehole 1. The sharp rise in gamma count at their junction with the overlying Oxford Clay may prove to be a useful marker during any future exploration of the Stage 2, 3 and 4 areas.

3. Oxford Clay: soft mudstones and bituminous mudstones passing up into calcareous mudstones. The Oxford Clay was not examined in detail for Stage 1, but might become important if Stage 2 were to draw water from the Wisbech area. The lower part of the formation was penetrated only in Borehole 1, where the lithologies and gamma counts were similar to those of the Kimmeridge Clay. Marker beds such as the *lamberti* Limestone and the *acutistriatum* Band, both of which would be likely to have an important effect on tunnelling, could provide the framework for detailed correlations based on gamma logging.

The upper part of the formation, mostly calcareous mudstones with few geophysical marker beds, was penetrated and logged in boreholes 1 and 3C. Correlations could be made at this level, but only with difficulty.

4. West Walton Beds: mostly silty and very silty mudstones and calcareous mudstones which show small scale lateral variations within the Stage 1 area. Gamma counts are generally lower here than in either the underlying Oxford Clay or the overlying Ampthill Clay. Despite the lateral variations in lithology the signatures for the West Walton Beds in Boreholes 1, 3C and 4A are broadly similar, the junction with the Ampthill Clay giving a distinctive trace in all three boreholes. Over distances shorter than those examined here gamma-ray logging is likely to be useful for detailed correlation and might in closely-spaced boreholes enable individual cementstone horizons to be identified.

5. Ampthill Clay: soft mudstones and calcareous mudstones with some silty mudstone and rare bituminous bands. The Ampthill Clay exhibits a higher range of gamma counts than does the Upper Oxford Clay or the West Walton Beds and gives rise to distinctive signatures which can be broadly correlated throughout the feasibility study area. Detailed correlations can usually be made only over short distances due to the minor lateral variations in lithology that occur within the formation.

Distinctive parts of the gamma signatures that reflect widespread lithological features include the sharp fall in count at the base of the Ampthill Clay, high counts of the plant-rich mudstones in Bed 5, low counts of the pale calcareous Bed 17, high counts of the bituminous Bed 22, high counts (probably due to secondary uranium enrichment) caused by phosphatisation and phosphatic nodules at minor erosion surfaces at the base of Beds 30, 33, 36 and 37 and the low counts of the silty calcareous Bed 40.

Broad correlations can be made over relatively large distances in the Ampthill Clay, but for detailed correlation more sampling control is required than would be necessary to obtain the same degree of detail over the same distances in the Kimmeridge Clay. Impersistent horizons, such as some of the shelly cementstones and oyster plasters recorded in the Ampthill Clay, can have a marked effect on the gamma traces.

6. Kimmeridge Clay: soft mudstones and calcareous mudstones with prominent thin silty beds and bituminous (oil shale) beds at a number of levels. The greater range of lithological types in the Kimmeridge Clay, together with their lateral persistence, is reflected in the gamma-ray signatures.

The range of counts is high in comparison with those of the other Upper Jurassic clay formations and detailed correlations can be made over large distances. A good example of this occurs in the lowest part of the Kimmeridge Clay where a series of minor erosion surfaces, which are probably persistent from The Wash to Dorset, give rise to rhythmic influxes of new sediment and fauna accompanied by phosphatisation and phosphatic nodules. These rhythms are reflected in the gamma traces by three peaks, at the base of the Kimmeridge Clay, the base of Bed 5 and the base of Bed 8, which mark the erosion surfaces. They are particularly clear in Borehole 24 (from 50 to 60 m), Borehole 31 (from 63 to 73 m) and Borehole 32 (from 64 to 74 m) where each peak is separated by a marked trough caused by pale calcareous beds.

Similar strong signatures occur in the higher parts of the Lower Kimmeridge Clay and in the Upper Kimmeridge Clay where the high counts of the oil shales are in marked contrast to the low counts of the pale calcareous beds and cementstones. A detailed account of the relationship of sedimentary rhythms and lithologies to gamma counts in the Upper Kimmeridge Clay of the Wash area has been given elsewhere (Gallois, 1973). The present work has shown that these results apply equally well to the whole of the Kimmeridge Clay of the feasibility study area.

Although the radioactivities of the Upper Jurassic clays have not been measured in the present work, the lithological similarities between the Kimmeridge Clay of the Wash area and that of the Institute's Warlingham Borehole in Surrey suggest that the counts are comparable with those of Warlingham where Burley (1971, p. 116 and pl. V) recorded radiation levels of around 5.5μg Ra. equiv./ton.

7. Lower Cretaceous: mostly sands and clayey sands. The erosion surface and phosphatic nodule bed at the base of the Sandringham Sands gives rise to a very distinctive gamma peak in Borehole 23 (the only borehole to sample this level in the present work) and in IGS boreholes in Norfolk and The Wash. The low counts of the overlying loose sands (Roxham Beds) are often accentuated by caving, thereby making this peak even more distinctive. A second peak commonly occurs within the sands, marking the level of phosphatic debris in the Basal Cretaceous Nodule Bed. Higher levels within the Lower Cretaceous have not been considered in the present work but the variable nature of the Lower Cretaceous sequences of the area suggests that gamma-ray correlations will not be possible except over very short distances (e.g. *see* Wingfield and others,

1978, fig. 10, showing gamma-ray logs of boreholes IGS 72/77 and 72/78).

8. Glacial deposits: till (boulder clay) with subordinate beds of varved clay and water-laid till. Gamma counts in the till vary considerably in response to its constituents: chalk-rich till generally gives rise to low counts and Kimmeridge Clay-rich till to high counts. In almost all cases, however, counts in the till are lower than in the Kimmeridge Clay and, except where the junction is particularly disturbed, the two can be readily separated in the gamma-ray signatures. The junction of till with the Ampthill Clay can be more difficult to determine since the more calcareous parts of the Ampthill Clay give counts similar to those of the till. The sequence of till on West Walton Beds or Oxford Clay was not encountered in any of the present boreholes but such sequences could be difficult to interpret since the counts in the till are commonly higher than those in the solid formation. In such cases one would have to rely on the overall nature of the gamma signature; the till, because of its poorly stratified nature, gives a characteristically uniform signature (i.e. one with a count range only slightly greater than the statistical variation).

Varved clay varies in its counts: examples occur in the gamma-ray traces in which counts are much higher than those of the surrounding till, and in other cases lower than, or of similar magnitude to, those of the till. Higher counts appear to be more common but it would be impossible to tell the difference between varved clay, Kimmeridge Clay-rich till or a large erratic of Upper Jurassic clay within the till, from the gamma logs alone. Water-laid and water-sorted tills generally give slightly lower counts than the average Chalky/Jurassic till, but they are not distinctive in the gamma logs. No thick bed of sand and gravel was encountered within the Glacial deposits in the present work (other than as core losses described as sand and gravel by the drillers) but such beds would be expected to produce low gamma counts, in many cases accentuated by caving.

9. Recent Deposits: variable sequences including clay, silt, sand, gravel and peat. None of the Recent deposits was sampled in the boreholes that were gamma-logged but it is possible to make some general comments on the basis of the drillers' logs and a knowledge of the local stratigraphy.

With the exception of silt and clay (the Terrington and Barroway Drove beds), all the Recent sediments of Fenland and the Wash area have very low gamma counts which differ from one another by less than the statistical variation in the background count. Beds of peat and sand and gravel can be identified in the gamma trace with difficulty, only where they occur between beds of clay or silt. With more sophisiticated logging equipment, accompanied by a sampling programme, it might be possible to make detailed correlations in the coarser parts of the Recent sediment sequences on the basis of gamma logging.

The very low gamma counts of the Recent sediments do serve one useful function; they contrast markedly with the counts in the solid rocks and the rockhead surface can therefore usually be accurately positioned in those areas where Glacial deposits are absent (e.g. Boreholes 38 and 39). Where the Recent sediments are argillaceous, even this boundary can be difficult to determine from the gamma-ray log alone (e.g. Borehole 33). However, gamma logging combined with a minimum number of disturbed samples (e.g. taken from the rock bit) would remove this problem.

Conclusions: Total gamma-ray logging can provide a quick, inexpensive method of stratigraphical correlation which can be of considerable use on site for determining depth to rockhead, thickness of Drift deposits, major formation boundaries etc., thereby enabling the drilling programme to be more efficiently planned. It also provides a useful check on depth or labelling errors made on site.

Once calibrated against core samples, as in the present work, correlations can be made within the Upper Jurassic clays over an area greater than that of the feasibility study on the basis of the gamma-ray logs alone. Detailed correlations of the sort likely to be necessary in a site investigation for a tunnel route could be made, particularly in the Kimmeridge Clay, by using the gamma-ray logs in conjunction with a minimum of sampling. Rather more sampling would be required for a detailed investigation of the Ampthill Clay, but this would still be less than would be required without the aid of gamma-ray logging.

Gamma-ray logging is not particularly useful in Glacial deposits, other than to determine the position of the contact with the solid deposits. The usefulness of gamma logging in the Recent deposits was not explored in the present work but the indications are that some correlations could be made, particularly in the more argillaceous sediments.

All the gamma logging referred to in this report is *total* gamma-ray logging. Equipment is available which is capable of differentiating gamma-rays of differing wavelengths (e.g. uranium sources can be differentiated from thorium sources) and such equipment might in the future lead to more sophisticated correlations.

Resistivity and other methods

Few geophysical borehole logging methods are suitable for site investigation use in shallow, small diameter (<130 mm) boreholes in the Upper Jurassic clays. Methods which might be expected to yield information on the *in situ* density of the rock—e.g. sonic logging and formation-density (gamma-gamma) logging—are not usually readily available on site. Furthermore, they are greatly affected by variations in the borehole diameter and in soft, friable rocks such as the Upper Jurassic clays caving is nearly always present. It should be possible to distinguish oil shales (low density) and cementstones (high density) from the bulk of the mudstones in the Upper Jurassic using sonic and formation-density logs. This has not yet been done successfully because of the irregular profiles of the boreholes logged. Density tools may become more readily available in the future and, in suitable boreholes, might be useful for correlation purposes. By comparing the sonic and formation-density logs it might also become possible to comment on the overall state of fracturing of the rock, since the sonic log is likely to be more affected by fracturing than the formation-density log.

Neutron and neutron-gamma logs are also considerably influenced by variations in borehole diameter and are not useful site tools at the present time. Both methods detect variations in moisture content and can provide traces in which the very calcareous mudstones can be distinguished.

The spontaneous-potential (SP) log, which is used in the oil industry primarily to detect the positions of permeable formations, has not been found to be a useful site investigation tool in the Upper Jurassic clays.

The only borehole log which currently compares in usefulness with the total gamma-ray log for the present type of work is the electrical or resistivity log. In site investigations such as the feasibility study, where detailed correlations were required, the most useful resistivity techniques have been found to be the 'short normal' and the 'single electrode' methods. Both gave comparable qualitative results: for quantitative results (these are rarely required) the 'focussed electric' method replaces the 'short normal'. For site investigation purposes the 'single electrode' method is probably the most useful since it has the advantages of being simple and quick to use and is incorporated into most portable logging equipment (e.g. the Widco Portalogger). Resistivity methods can readily be used to distinguish clay-mineral-rich mudstones (low resistivities) from calcium-carbonate-rich mudstones (high resistivities) and cementstones (very high resistivities). They can provide the basis for detailed correlation, especially if used in conjunction with the gamma-ray log. Resistivity logging has two disadvantages; it can only be used below the water-table and it cannot be used in the cased part of the borehole. These limitations were not usually a problem in the feasibility study area since the water-table is everywhere close to ground level. However, every borehole had to be cased in the soft and loose Recent Deposits and no resistivity log could be made at this level.

ENGINEERING PROPERTIES

UPPER JURASSIC CLAYS

Although the Upper Jurassic clays have a broad outcrop in eastern England and have provided the founding materials for numerous structures and earthworks, little systematic work has been done on their engineering properties.

Most existing site investigation data is of little value for detailed analysis or comparative work because the tested samples are commonly lacking in stratigraphical information. In many cases it is impossible to assess whether a particular tested sample was Upper Jurassic clay *in situ*, an Upper Jurassic clay erratic incorporated in till or simply Upper Jurassic clay-rich till. Detailed lithological descriptions are usually absent and weathering features are rarely described. Stratigraphical levels, where given, are usually described as 'Oxford Clay' or 'Kimmeridge Clay', the former often including the West Walton Beds or Ampthill Clay.

The aim of the present work has been to try to relate the stratigraphy, the lithologies and bulk chemistry of the Upper Jurassic clays to their engineering properties. With the limited amount of soil test data available only broad generalisations can be made at the present time but it is hoped that these results will provide a framework for future work.

The following lithological types (excluding cementstones) can be readily distinguished by eye in Upper Jurassic clay cores and might be expected to differ significantly in their engineering properties:

1. Oil shale, barren, non-fissile;
2. Oil shale, shelly, fissile;
3. Clay, smooth, dark-grey, barren, unbedded (straight fracture);
4. Clay, smooth, medium-grey, barren, unbedded (curved fracture);
5. Clay, smooth, pale-grey, barren, unbedded (tending to sub-conchoidal fracture);
6. Clay, smooth, dark-grey, barren, fissile;
7. Clay, dark-grey, shelly, fissile;
8. Clay, medium grey, tough, shelly, burrow-mottled (irregular fracture);
9. Clay, medium grey, silty, shelly with shells leached in part (irregular fracture).

Other minor variants occur such as interburrowed mixtures of the above, weakly calcite-cemented patches (quasi-cementstones), shell plasters, phosphatic nodule beds etc., but the above list covers all the lithologies that occur in beds of sufficient thickness to be of interest for tunnelling purposes. With careful sampling and testing, it should be possible to determine the engineering properties of each of the above lithologies in their unweathered state. The variations in their properties with depth and degree of weathering could then be studied and realistic predictions made about their likely behaviour at a variety of depths and in various engineering situations. At present the data are sufficient to indicate only that these lithologies are unlikely to be equally suitable at any given depth as a tunnelling medium and that the most suitable lithology for tunnelling purposes will vary with depth.

Bulk chemistry

Forty-two samples (many of them taken from the residues of the soil-tested samples) were chemically analysed. They were selected to be representative of the full range of lithologies in the Upper Jurassic clays of the Stage 1 area and are probably representative of the full feasibility study area. The bulk chemistry of these materials can be represented in terms of three main constituents, clay minerals, calcium carbonate and kerogen (Figure 20). Appreciable amounts of quartz are present throughout; pyrite and small amounts of dolomite, apatite and feldspar are also present at certain levels (*see* Appendix C for details of analyses).

Many of the samples analysed contain small crystals of gypsum: these grow either in the core during the drying out process or *in situ* in the zone of chemical weathering.

The constituent minerals of the Upper Jurassic clays are derived from three main sources. The clay minerals, quartz and feldspar are clastic materials derived from land areas. The calcium carbonate occurs both as microscopic shells and shell debris, and as precipitated mud. Most of the calcium carbonate in the shells is now in the form of calcite, having inverted from aragonite. The kerogen is largely derived from chitinous microfossils. The pyrite, which usually occurs as a replacement of calcite shells and burrowfills, was probably precipitated shortly after the deposition of the sediment. Apatite and small amounts of other phosphatic material are probably derived from vertebrate fossils.

The bulk chemistry and lithologies listed above can be shown to be simply related. The dark-grey clays are characterised by calcium carbonate contents of less than 15 per cent (except where shelly) and by generally high total clay and quartz contents. The pale-grey clays are characterised by calcium carbonate contents of over 30 per cent, some reaching more than 50 per cent and passing into the range of the weak cementstones. Total clay and quartz contents are generally lower than in the dark-grey clays.

The medium-grey clays, as one might expect, have calcium carbonate contents in the range 15 per cent to

Table 4 Engineering properties of the solid deposits

Formation	Borehole No.	Sample depth	Natural moisture content	Bulk density	Atterberg Limits PL	Atterberg Limits LL	Atterberg Limits PI	Unconfined compressive strength
		m	%	Mg/m³				kN/m²
Kimmeridge Clay	1	13.06*	29	1.93	30	71	41	122
	1	16.81	24	—	38	75	37	—
	1	23.14	21	2.01	24	50	26	185
	1	34.38	21	2.02	33	61	28	320
	1	45.61	24	2.04	28	57	29	320
	1A	22.00	25	1.91	—	—	—	271
	2A	72.58	22	2.04	32	74	42	245
	8	14.15*	30	1.86	—	—	—	57
	10	22.69	27	1.91	28	62	34	175
	12	12.20*	34	1.83	—	—	—	72
	17	19.25	28	2.02	21	59	38	170
	24	50.43	21	2.10	30	70	40	325
	25	30.17	27	1.97	29	79	50	126
	25	37.20	26	1.90	32	70	38	600
	25	47.14	23	1.86	31	71	40	220
	26	23.59	28	1.97	30	76	46	118
	26	35.14	23	2.08	26	66	40	370
	26	43.01	27	2.12	27	63	36	180
	28	14.20	28	1.91	36	77	41	119
	28	21.38	20	2.13	33	74	41	180
	28	30.90	23	2.08	23	47	24	175
	35	13.49	23	1.92	31	78	47	97
	35	17.97	27	1.92	34	83	49	215
	35	24.70	24	2.17	31	62	31	350
	35	30.00	25	1.88	19	37	18	910
	39	22.37*	24	2.03	33	70	37	72
	39	32.79	25	2.03	31	74	43	175
	39	39.38	19	2.09	26	60	34	550
Ampthill Clay	1	56.29	26	2.07	31	72	41	195
	1	67.02	23	2.08	28	62	34	340
	1	78.38	21	2.10	24	57	33	395
	2A	84.97	23	2.08	—	—	—	425
	3C	52.16	21	2.07	29	68	39	232
	3C	61.02	28	—	35	70	35	—
	3C	64.75	24	1.97	36	91	55	775
	4A	53.95	22	2.05	36	74	38	415
	4A	62.78	23	2.07	—	—	—	145
	4A	71.82	18	2.14	23	65	42	1010
	4A	78.40	21	2.04	20	45	25	425
	13	54.30	23	1.92	31	70	39	385
	13	67.75	24	2.02	30	68	38	225
	24	58.61	20	2.10	27	67	40	435
	24	67.80	21	2.09	34	71	37	400
	27	21.70	24	2.10	27	65	38	115
	27	28.68	15	2.27	23	51	28	535
	27	35.92	24	2.05	31	70	39	135
	36	42.78	21	2.14	24	59	35	140
	36	52.54	24	2.10	29	77	48	190
	36	55.65	25	2.02	29	73	44	131
	36	65.39	30	2.05	30	71	41	185
	37	37.30	21	2.10	25	57	32	285
	37	45.32	26	2.11	28	65	37	130
West Walton Beds	1	88.50	22	2.10	27	73	45	965
	1	92.71	21	2.10	31	78	47	720
	3C	69.79	14	2.20	14	41	27	805
	3C	76.91	15	2.20	24	47	23	865
	4A	97.23	17	2.13	32	49	27	890
Oxford Clay	1	104.62	15	2.07	25	52	27	905
	1	118.56	17	1.89	24	48	24	945
	1	136.20	14	2.16	21	50	29	835
	3C	89.39	18	2.16	—	—	—	635
	3C	97.88	15	2.22	23	53	30	1640

*probably affected by weathering
— not measured

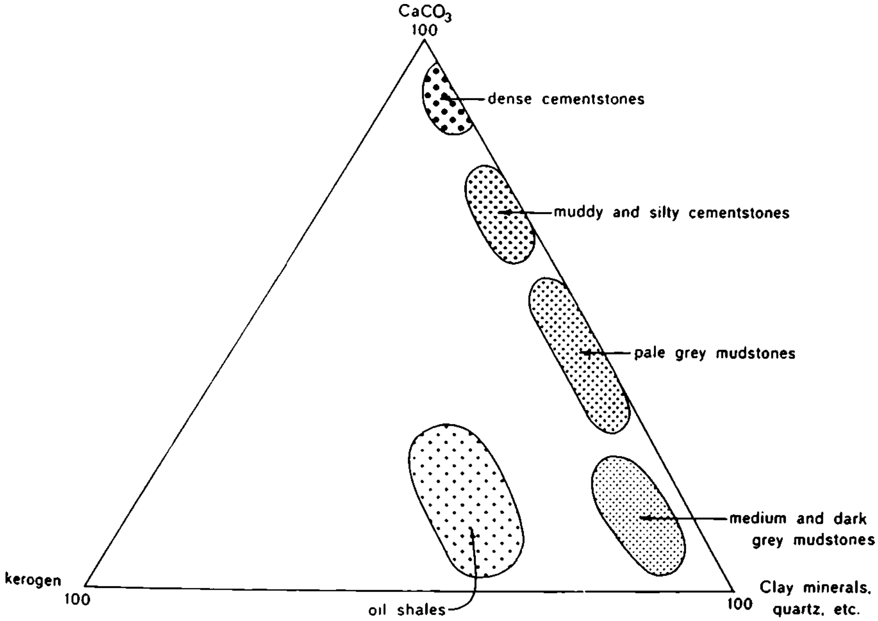

Figure 20 Diagrammatic representation of the bulk chemistry of the more common Upper Jurassic clay lithologies

30 per cent, intermediate between those of the dark and the pale clays. This close correlation between colour and calcium carbonate content suggests that materials, such as finely disseminated plant debris, which are commonly quoted as being the cause of the dark-grey colour of many clays, are not important as colouring agents in the Upper Jurassic clays.

The clay mineral content of the clays has been examined by Messrs G. E. Strong and R. J. Merriman of the Petrographical Department of IGS, using X-ray diffraction analysis (Appendix C). They report that in all the tested samples the dominant clay mineral is clay-mica, probably mostly illite, with kaolinite and chlorite present in subsidiary amounts. Three cementstone and pale-grey clay samples contain small quantities of the expandable clay mineral smectite. There is therefore no evidence from the present work to indicate that any of the Upper Jurassic clay lithologies contain expandable clay minerals in sufficient quantities to adversely affect their use as a tunnelling medium.

Calcimeter analyses were carried out on a number of samples, mostly cementstones. These samples appear to continue the pattern described above in which dark-grey clays pass into pale-grey clays with increase in calcium carbonate content. The weakest cementstones, those that tend to occur as tabular masses or doggers within the pale-grey clays, generally have carbonate contents in the range 60 per cent to 70 per cent. Dense splintery cementstones, cut by calcite veins and septarian cracks, have carbonate contents over 80 per cent.

In addition to the above analyses five samples were analysed by the Laboratory of the Government Chemist for their kerogen content (*see also* section on Hydrocarbons below). Four of these samples were chosen as representative of the full range of oil-shale lithologies and the fifth as a typical non-bituminous clay for comparison. The oil shales have kerogen contents ranging from 9 per cent to over 40 per cent, and the normal clay has 3 per cent. This suggests that the most distinctive lithological features of the oil shale—its brown colour and lightness in weight—can be caused by relatively small kerogen contents.

Engineering properties

Fifty samples of waxed core were selected by the consulting engineers for soil testing by Wimpey Laboratories Ltd. The debris from these samples was retained for examination and description so that an assessment could be made of how representative the selection had been, both lithologically and stratigraphically. As a result of the examination of the debris a further 20 core samples were tested to enable a more comprehensive analysis of the results to be made. The results are summarised in Tables 4 and 8. Twenty-two of the soil-tested samples were chemically analysed (Appendix C). Descriptions of the 70 tested samples are given by Gallois (1974, App. D).

The purpose of these descriptions was accurately to locate the stratigraphical levels of the samples and to describe them in the same lithological terms as the remainder of the cores. The tested samples are only a very small part of the total core and this descriptive process is necessary for the soil test results to be applied to the cores as a whole.

An attempt was also made to assess whether or not the failure seen (or likely to be present) in the tested samples was 'representative' of the lithology tested. That is to say, whether or not such features as joints, shell material or bedding significantly affected the apparent shear strength of the particular sample. Such an attempt might at first sight appear to be an illogical procedure because the features concerned are all of natural origin, are present in the ground, and would affect the suitability of the clays as a tunnelling medium. However, with such a small number of tested

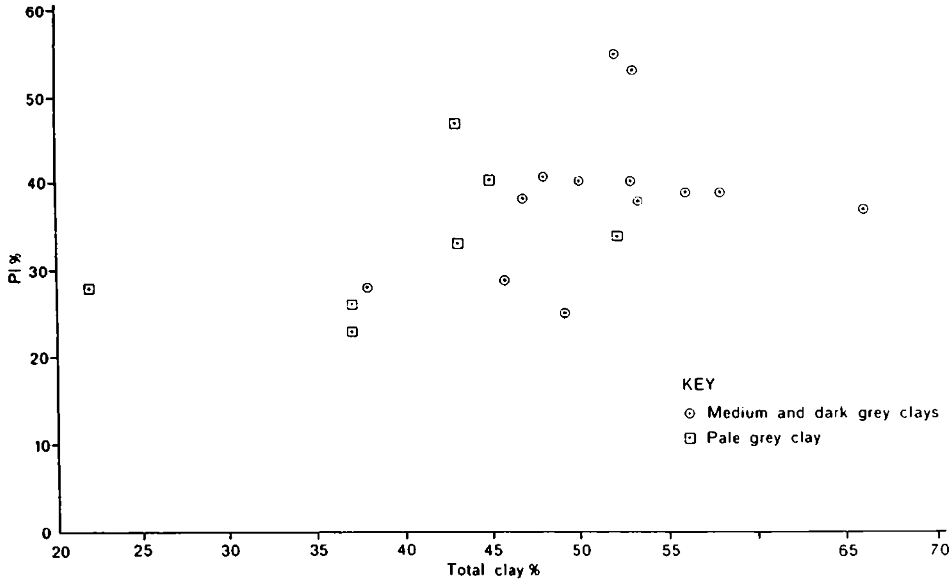

Figure 21 Relationship of plasticity index to total clay content

samples, the primary aim of any analysis of the data must be to try to relate the soil test results to the broader lithological features within the Upper Jurassic clays. A further aim must be to attempt to assess what effect secondary features such as jointing and bedding might have on the properties of the soil mass. Such an assessment can be made only by comparing the test results of samples of identical lithology and stratigraphical horizon, some with and some without these secondary features. In the present work materials suitable for such comparison were rare. Furthermore, it is difficult to compare shear strength results from samples tested at differing cell pressures since it cannot be assumed that the angle of shearing resistance is unaffected by these secondary features.

All the tested samples were horizontally bedded and were tested with the principal stress normal to the bedding. Under such circumstances bedding plane discontinuities are not usually thought to influence the shear strength significantly. In a number of samples in which bedding was well developed, the failure surface developed as a series of small steps linked by short lengths of bedding.

Atterberg limit tests, in which the material is reworked and its fabric and much of its lithological character are destroyed, might be expected to yield results related largely to the mineralogy of the clay. In the Upper Jurassic clays, one would expect the dominant clay mineral, illite, to impart plasticity to the soil and the quartz, calcite and most of the accessory minerals to lower that plasticity.

All the soil-tested samples that were chemically analysed fall in the range of inactive and normally active soils (Figure 21), the majority being normally active (Acitivity range 0.75 to 1.25). Montmorillonite (smectite) is an important constituent of the clay mineral assemblage only in some of the cementstones and very calcareous clays where its effect on plasticity is offset by the high percentage of calcite.

The strength/moisture content relationship of the tested samples shows a clear stratigraphical separation into two groups of differing properties; one characterised by the Ampthill and Kimmeridge clays and the other by the Oxford Clay and West Walton Beds (Figure 22). Comparison of these data with published results for other Jurassic clays shows that the properties proved here for the Ampthill and Kimmeridge clays compare closely with those proved elsewhere for the Lias (Chandler, 1972) and the Oxford Clay (Parry, 1972). In all three materials, undrained shear strengths rise from below 100 kN/m^2 to about 400 kN/m^2 as moisture content falls from about 30 per cent to 18 per cent.

The higher strengths of the Oxford Clay and West Walton Beds of the feasibility study may not therefore be a stratigraphically related feature. General consideration of their tectonic and glacial histories suggests that all the Jurassic clays of the east Midlands have had comparable consolidation histories. In the feasibility study area, the Upper Jurassic clays were probably once overlain by over 1000 m of Cretaceous and possible Tertiary sediments; the maximum thickness of overburden on the Lias or the Oxford Clay in the east Midlands probably nowhere differs from this by more than about 10 per cent. Estimates of the thickness of ice that covered the area during the maximum extent of the Pleistocene glaciation vary considerably. It is unlikely, however, to have been greater than 1000 m and the original consolidation pressure would not have been exceeded.

The most likely explanation for the anomalous Oxford Clay and West Walton Beds results is that they are related to the present depth of burial and limit of mechanical weathering. Examination of the jointing in the deepest boreholes drilled for the feasibility study has shown that the frequency of joints falls sharply at depths below 80 to 85 m (*see* pp. 50–51 for details). The Oxford Clay and West Walton Beds samples tested in

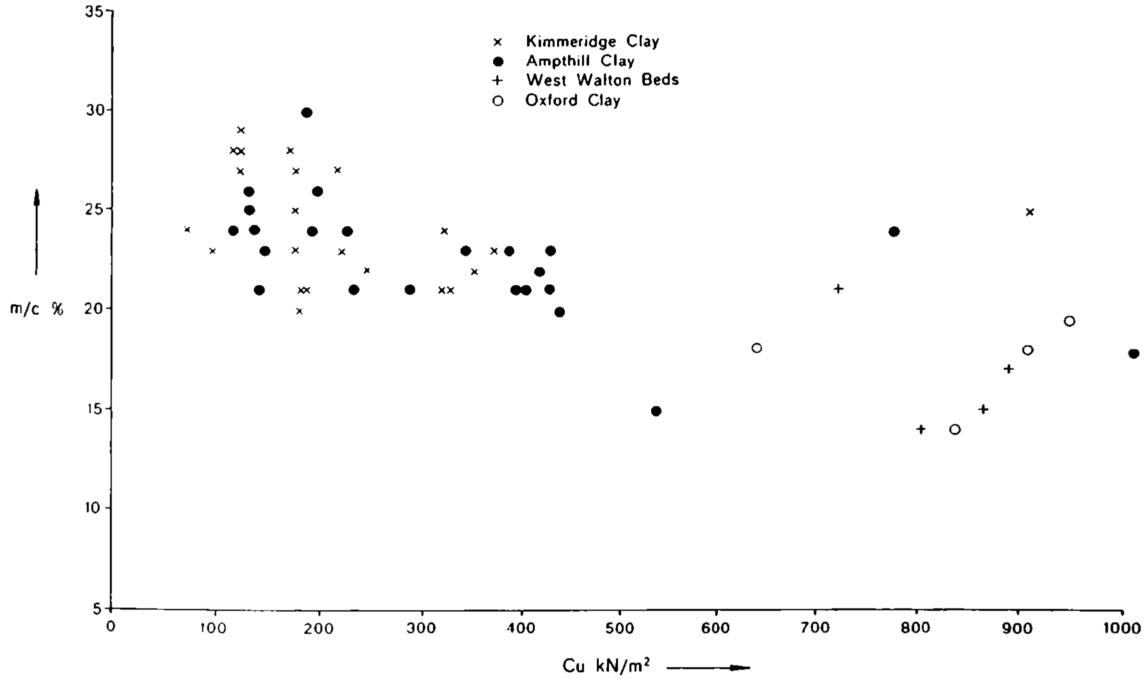

Figure 22 Moisture content/strength data

the present work came from depth close to or below this apparently critical depth; most of the Ampthill Clay and Kimmeridge Clay samples came from shallow depths. This explanation is supported by the general increase in shear strength with depth of burial in the tested samples (Figure 23).

The results of the present work show no discernible difference between the strengths of the Ampthill Clay and the Kimmeridge Clay samples or between those of pale, medium and dark grey clay. This seems surprising in view of the range of lithologies that can be recognised in the cores. However, it may be that at most depths shallower than about 80 m, secondary features caused by mechanical weathering reduce the strength of the material to only 10 per cent to 40 per cent of its unweathered (maximum) strength and it is this latter strength that is directly related to lithology.

A number of lithologies can be shown to have significantly different properties from the bulk of the clays. Samples of oil shale and bituminous clay from the Kimmeridge Clay had high strengths when tested normal to the bedding. These lithologies are generally fissile and one would expect much lower values if they were tested parallel to the bedding. Several samples of shelly clay had low moisture contents and low strengths. Few samples of silty clay were tested, but these generally had low moisture contents and high strengths.

Hard bands, hydrocarbons

The Upper Jurassic clays contain a number of harder bands which might significantly affect the rate of tunnelling with a soft ground shield. The more important of these are discussed below.

Limestones: One of the prime aims of the stratigraphical work for the inland site investigation has been to identify the levels at which persistent limestones occur and impersistent limestones are likely to occur. In the past, the term cementstone has been used to describe many of the calcareous bands in the Upper Jurassic clays: for simplicity this use is continued here.

The following six types of limestone have been identified in the present study:

1. Muddy limestone—the most common type of cementstone in the Upper Jurassic clays and the most important for tunnelling purposes.
2. Silty limestone—the second most important type of cementstone; prominent bands occur in all the Upper Jurassic formations and are particularly common in the West Walton Beds.
3. Bituminous limestones—restricted to two bands in the Kimmeridge Clay.
4. Septarian nodules—occur at many levels, generally widely-spaced and probably not very important for tunnelling purposes.
5. Shelly limestones—occur at only a few levels (mostly in the Ampthill Clay) and may locally be important for tunnelling purposes.
6. Coccolith limestone—restricted in the present area to thin, soft bands close to the junction with the Sandringham Sands, and therefore unlikely to be of interest for tunnelling purposes.

The stratigraphical distribution of limestones recorded in the cored boreholes in the Upper Jurassic clays (excluding those in the Oxford Clay for which there are insufficient data) is summarised in Table 5. However, it should be noted that the reliability of the

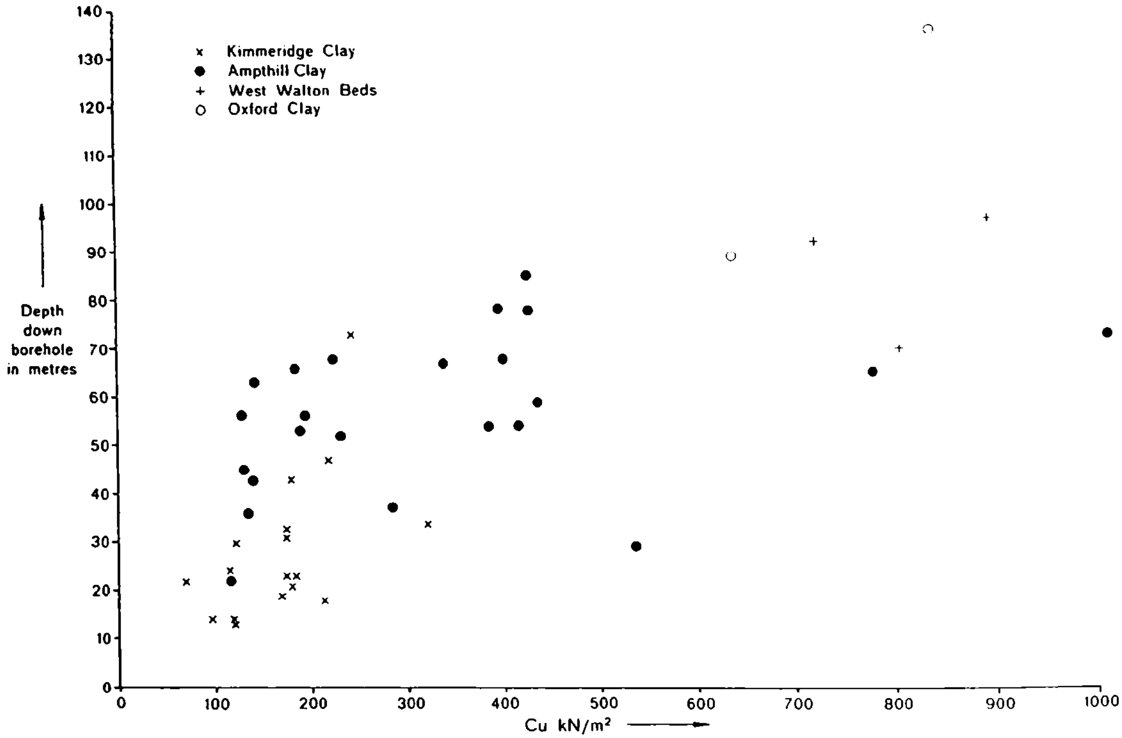

Figure 23 Relationship of sample strength to sample depth

information is uneven because some stratigraphical horizons were cored as many as twelve times, whereas others were cored only twice. Widely spaced doggers are likely to have been missed where they occur at stratigraphical horizons which were sampled only a few times.

The continuous tabular cemented bed at the base of the Sandringham Sands is included in Table 5 for completeness because it forms an important seismic reflector which marks the top of the Upper Jurassic clays. The limestones which formed persistent reflectors in the offshore seismic work are thought to be continuous tabular beds or layers of closely-spaced doggers. These are numbered in accordance with the geological interpretations of the sparker traverses. Horizons below TA have not been included since, without supporting borehole evidence, they cannot be identified with certainty. The lowest stratigraphical level reached in the offshore cored boreholes was Bed 40 of the Ampthill Clay (in Borehole 513 B).

Thirty-four limestone horizons have been identified in the West Walton Beds, Ampthill Clay and Kimmeridge Clay. Nine of these are in the West Walton Beds and can be considered as a single unit. Fifteen of the remaining 25 were recorded as single occurrences (mostly widely-spaced doggers), and ten are likely to be important for tunnelling purposes. To these ten can be added three of the single occurrences (KC Beds 8, 17 and 24) and locally cemented shell beds in the Ampthill Clay (not included in Table 5, but see below).

The important horizons can be divided into muddy limestones (8 horizons), silty limestones (4 horizons), bituminous limestone (1 horizon) and shelly limestones (2 or more horizons). Several of the single occurrences are probably septarian nodules. In cored boreholes, it is often difficult to be certain of the nature of the limestone since some of the larger muddy limestone doggers contain densely cemented patches with septarian cracks lined with calcite crystals.

Details of the lithologies and distributions of the main types of limestone are given below:

(i) Muddy limestones (cementstones) may occur either as continuous tabular beds or as closely-spaced flattened ovoids (doggers) following a bedding plane. They are usually moderately densely cemented (up to 70 per cent calcium carbonate content) and always occur in association with pale calcareous clays (up to 55 per cent calcium carbonate content): their stratigraphical positions have been closely defined in the present work. Evidence from the offshore sparker profiles and correlations based on total gamma-ray logging in Norfolk and Lincolnshire indicate that this type of limestone is laterally persistent and maintains its stratigraphical level over very large areas.

Little can be said from the borehole evidence alone about the size, shape and spacing of the cementstone doggers at any particular level. Seismic reflectors K1, K3, K4, TA and Bed 17 of the Ampthill Clay (all muddy cementstones) were recorded in the boreholes almost every time the relevant stratigraphical horizon was penetrated, suggesting that each of these bands is a tabular bed or very closely spaced doggers.

The only exposures of cementstone in Norfolk at present occur in the banks of the Flood Relief Channel at Downham Bridge [TF 601 003], and near Fordham [TL 607 996]. The following section was recorded at Downham Bridge.

Table 5 Distribution of limestones in the Upper Jurassic clays

Stratigraphical horizon	No. of times stratigraphical level penetrated in boreholes	Total no. of limestones recorded	Maximum no. of limestones in any one borehole	Seismic reflector	Probable lithology
Base of Sandringham Sands•	6	6	1	TK	Calcareous sandstone
KC Bed 44•	6	6	1	K1	Muddy
KC Bed 40	5	1	1		Septarian
KC Bed 37•	2	2	1	K2	Bituminous
KC Bed 34	4	1	1		Bituminous
KC Bed 30•	3	3	2	K3	Muddy
KC Bed 24•	9	1	1	K3A	Silty
KC Bed 23	9	1	1		Septarian
KC Bed 18•	10	8	2	K4	Muddy
KC Bed 17•	10	1	1		Silty
KC Bed 15•	10	3	1	K4A	Silty
KC Bed 13	9	1	1		Septarian
KC Bed 8•	12	1	1	K4B	Silty
KC Bed 7	12	1	1		Septarian
KC Bed 4	11	3	1		Muddy
KC Bed 1	12	1	1		Muddy
AC Bed 41•	9	4	2	} TA	Muddy
AC Bed 40•	10	21	4		Muddy and silty
AC Bed 38•	10	3	1		Muddy
AC Bed 36•	11	2	1		Muddy and shelly
AC Bed 33	9	1	1		Shelly
AC Bed 17•	9	3	1		Muddy
AC Bed 15	4	1	1		Muddy
AC Bed 12•	4	1	1		Muddy
AC Bed 10	4	1	1		Muddy
WWB Bed 16•	3	1	1		Muddy and silty
WWB Bed 15•	3	1	1		Muddy and silty
WWB Bed 13•	3	2	2		Muddy and silty
WWB Bed 12•	3	1	1		Muddy and silty
WWB Bed 10•	3	4	2		Muddy and silty
WWB Bed 8•	3	1	1		Muddy and silty
WWB Bed 5•	3	1	1		Muddy and silty
WWB Bed 4•	3	1	1		Muddy and silty
WWB Bed 1•	3	1	1		Muddy and silty

AC Ampthill Clay
KC Kimmeridge Clay
WWB West Walton Beds
Souce of data: feasibility study cored boreholes (1972) and IGS cored boreholes 71/65, 71/66; Skegness, Hunstanton, Gayton and Marham
•Beds likely to be important for tunnelling purposes

	Thickness m
Clay, pale grey, uniform, almost barren, softened and weathered; discontinuous line of cementstone doggers 1.0 m above base	1.40
Clay, dark grey, shelly, fissile	0.05
Oil shale, fissile, deeply weathered	0.03
Clay, dark grey, shelly, alternating with thick beds of oil shale with pyritised *Saccocoma*, deeply weathered, poorly exposed	*about* 1.00

The presence of *Saccocoma* in the oil shales immediately below the cementstone horizon clearly indicates that the latter is the *hudlestoni* Zone bed (K1) of Table 5. The cementstone horizon is continuously exposed for some 200 m northwards from the bridge and the doggers can be seen to vary considerably in their horizontal spacing.

They occupy rather less than half the total length of the outcrop—the spacing here is probably wider than that in the Marham to Skegness area where all six boreholes that penetrated this level proved tabular beds of cementstone. Most of the doggers at Downham are flattened ovoids (when small) or tabular masses with rounded edges (when large). Almost all the doggers, whether large of small, appear to be 0.30 to 0.35 m thick. The maximum visible length of dogger at Downham is 2.05 m; the maximum visible width (measured into the bank) is about 0.8 m. Doggers of a similar size and at the same stratigraphical level are present at Fordham but are more widely spaced than at Downham Bridge; it seems likely that the density of spacing increases northwards into the feasibility study area.

Cementstones K3 and K4 (KC Beds 30 and 18 respectively) are also likely to be persistent throughout the feasibility study area and to consist of closely-spaced doggers or, locally, continuous tabular beds. Both horizons contain more than one cementstone level but for practical purposes these levels are sufficiently close together to be regarded as a single thick bed.

The only other muddy cementstone horizon likely to be important in the Lower Kimmeridge Clay is that in Bed 4. The three records of this cementstone occur in adjacent boreholes (Boreholes 29, 30 and 31) in the northern part of the Stage 1 area and it may be that this band is developed only in that area and northwards beneath The Wash.

The highest part of the Ampthill Clay is particularly rich in cementstones. Those of Beds 38, 40 and 41 can be regarded as a single thick bed, locally over 8 m thick, with at least seven cementstone horizons. This unit is similar in lithology to the West Walton Beds and is likely to be the most difficult tunnelling horizon in the Ampthill Clay. Most of the cementstones at this level are muddy, but some, like those of the West Walton Beds, are silty and gritty-textured due to the presence of shell debris.

Muddy cementstones that are likely to be persistent throughout the feasibility study area also occur in Bed 17 of the Ampthill Clay.

(ii) Silty limestones occur at four horizons in the Lower Kimmeridge Clay (Beds 8, 15, 17 and 24) and in the West Walton Beds. They are typically silty, shelly bEds in which part of the shell material has been leached and reprecipitated as a patchy calcite cement. In some cases, small discrete septaria are formed, but more commonly the cement occurs irregularly over wide areas. Although the degree of cementation in this lithology is not usually high, the combination of a slower tunnelling rate and a slightly more permeable bed (with low moisture content) could produce excessive amounts of dust.

(iii) Bituminous limestones were recorded at two horizons, one in the Upper and one in the Lower Kimmeridge Clay. Both are essentially calcareously cemented oil shales which have been formed in a similar manner to the silty limestones. The Upper Kimmeridge Clay occurrence (reflector K2) is almost certainly a very persistent horizon and may be continuous from The Wash to Dorset. It has been penetrated in two boreholes (Borehole 23 and IGS 71/65) adjacent to the feasibility study area and was encountered in a sewerage tunnel beneath the Gt Ouse, north of King's Lynn [TF 604 227]. At this last locality, the bed was mostly densely cemented and tabular, but in places passed into uncemented oil shale and shelly clay. The Lower Kimmeridge Clay horizon (Bed 34) has been recorded only at Denver Sluice (Borehole 1).

(iv) Septarian nodules have been recorded only as single occurrences; they are listed in Table 5. Many of those cored had curved surfaces or were only partly projected into the core, suggesting that they are generally small in relation to the borehole diameter. It seems likely that they are mostly less than 0.3 m across and rounded in form. Although very densely cemented, and hence strong, many contain septarian cracks which are only partially infilled. As a result, these can be readily broken into small pieces by a sharp hammer blow. Unless they are particularly large or particularly closely spaced, it seems unlikely that septarian nodules would cause much difficulty to a tunnelling shield.

(v) Shelly limestones (cemented shell coquinas) were recorded at several levels in the Ampthill and Kimmeridge clays but they appear to be of restricted lateral extent. Each example recorded consists of a mass of shell material secondarily cemented by calcite. In the Lower Kimmeridge Clay, *Nanogyra*-rich horizons in Bed 30 are locally weakly cemented; in the Ampthill Clay, the serpulid-rich Bed 34 is locally densely cemented and shelly concretions occur around large oysters in Bed 28.

Finally, it should be noted that in the Ampthill Clay (particularly in the lower part of the formation which was penetrated by only four boreholes) there are beds of pale clay in which no limestone was recorded (Beds 3, 7 and 19) and beds in which only one limestone horizon was recorded (Beds 10, 12 and 15). These beds are of similar lithology to levels in the Kimmeridge Clay which contain persistent horizons of muddy limestone.

Pyrite: Pyrite (FeS_2) is common throughout the Upper Jurassic clays, occurring mostly as coatings and infillings of fossils and burrows. Less commonly, it occurs in thin impersistent tabular beds or as part of the cementing matrix of a cementstone or silty mudstone. The thickest band of pyrite recorded in the present boreholes is about 20 mm thick, but slabs up to 0.1 m thick occur in the Kimmeridge Clay spoil from the Flood Relief Channel between Downham Market and Stowbridge.

It is not possible from the borehole information to detect any consistent stratigraphical pattern for the distribution of these tabular pyrite bands. Pyritised burrowfills are generally more common in the Ampthill Clay and the West Walton Beds (where they can constitute up to 10 per cent of the total rock by volume), whilst tabular beds or lenses occur more frequently in the Kimmeridge Clay.

All the pyrite nodules encountered in the boreholes were small, and the tabular beds were well jointed. They are unlikely to cause difficulties in tunnelling, other than excessive tooth wear (pyrite has a hardness of 6 to 6½ on Moh's scale). Thicker, partially pyritised beds, such as cementstones TK and K2 are dealt with above. Other partially pyritised beds include dinosaur bones (*see* below), fragments of wood and phosphatic nodule beds close to the Ampthill Clay/Kimmeridge Clay junction, which may locally by pyrite-cemented.

On exposure to the atmosphere, much of the pyrite in the cores becomes oxidised to sulphites and sulphates which, in the presence of moisture, react with the calcareous fossils to produce 'pyrite mould' overgrowths, thereby destroying much of the stratigraphical information in the cores. This oxidation process is considerably inhibited if the cores are allowed to dry quickly under warm, well-ventilated conditions.

Groundwater in the Upper Jurassic clays is likely to be sulphate-rich. Analyses from site investigation reports in the King's Lynn area show SO_3 concentrations of up to 100 parts per 100 000; however, much of this is derived from the Lower Cretaceous, the Glacial deposits or the Recent deposits, all of which contain pyrite.

Dinosaurs: Although it might seem unlikely that reptiles that have been extinct for over 60 million years could hold up progress in a modern tunnel, the possibility cannot be completely dismissed. Fragments of densely phosphatised bone material were cored in the Kimmeridge Clay and in the Ampthill Clay. The first sample was pyrite-cemented, the second calcite-cemented. A small plesiosaur (about 2 m long) was found in the Kimmeridge Clay near Fordham during excavation of the Cut Off Channel (R. G. Thurrell, personal communication); ichthyosaur bones were found in the Flood Relief Channel at Downham Market and Stowbridge (*Eastern Daily Press*, 28/7/58) and loose icthyosaur and plesiosaur vertebrae are relatively common in the spoil from both channels. Woodward (*in* Whitaker and others, 1893, p. 8) noted that saurian bones were not uncommon in the Kimmeridge Clay in the former brickyard [TF 603 029] adjacent to Downham Bridge.

Although, from the limited amount of evidence available, no comment can be made on the stratigraphical distribution of these remains, it is known that clusters of such bones commonly occur on a single bedding plane. The remains are usually disarticulated and would readily be broken up by a tunnelling shield. Where pyrite- or calcite-cemented, they would probably represent the same local degree of inconvenience as the thicker pyrite bands.

Hydrocarbons: During and shortly after the First World War, the Kimmeridge Clay between King's Lynn and Denver was extensively explored as a possible source of oil. Bituminous shale had long been worked as a coal substitute in small quantities at Kimmeridge, Dorset, and oil seepages from other Kimmeridge Clay outcrops, including that at Hilgay in south-west Norfolk, prompted suggestions that the formation might yield hydrocarbons in commerical quantities.

These suggestions received considerable stimulus from a paper on the Norfolk oil shales by Forbes-Leslie (1917a) with the direct result that over fifty cored or partially cored boreholes were drilled in Norfolk between about 1918 and 1923. Some of these boreholes are within the Stage 1 area. Few of them are geologically well documented since they were drilled before the introduction of compulsory notification in 1926. However, information from Forbes-Leslie's paper, the published and unpublished work of the late J. Pringle and C. H. Dinham, and specimens held at IGS indicate that the most prominent horizon of bituminous shales lies at the junction of the *wheatleyensis* and *hudlestoni* zones of the Upper Kimmeridge Clay (KC Bed 42). This is the horizon of the Blackstone in Dorset and the Smith's Series of Forbes-Leslie (1917a, p. 17) in Norfolk. Another prominent group of oil shales has been proved by the present work at the junction of the *eudoxus* and *autissiodorensis* zones (KC Bed 32) and lesser concentrations occur in the *elegans* Zone and the lower part of the *eudoxus* Zone. The group of seams in Bed 32 may correspond with Forbes-Leslie's Puny Drain Series (1917a, p. 17), although his lithological descriptions and thicknesses are so inaccurate that the relationship must remain tentative. The former opencast working and mine at Setchey, Norfolk, worked the *wheatleyensis/hudlestoni* seams and the *elegans* seams, respectively.

Although explored in detail in Dorset and Norfolk, the Kimmeridge Clay has not aroused wide commercial interest. Very small quantities of oil were produced from the shallow mine and opencast working at Setchey from about 1918 to 1936. The oil was used in medicinal soaps under the trade name Icthyol (ichthyosaur oil) to combat skin fungus in the tropics.

Published analyses of both the Dorset (Strahan, 1920) and the Norfolk (Forbes-Leslie, 1917a) oil shales are very similar, the shales in both cases yielding 40 to 50 gallons of oil/ton of dry shale. Despite this apparent richness, attempts at commerical exploitation have failed, probably because of the high sulphur content of the oil and the thinness of seams.

Forbes-Leslie (1917a, pp. 16–17) recorded at least three 1.8-m thick oil shale seams in the Kimmeridge Clay in Norfolk, two of which yielded 50 or more gallons of oil/ton. Up to 75 per cent of this oil was described as free oil filling cavities in the shale (Forbes-Leslie, 1917b, p. 181), the remainder being yielded by the pyrolysis of kerogen. In his earlier account Forbes-Leslie (1917a) describes yellow sandstone with bitumen on the bedding planes (p. 16) and oil-covered water rushing into the workings (p. 18).

Whilst parts of Forbes-Leslie's account were undoubtedly exaggerated, the similarity of his Norfolk oil shale analyses to the later, well authenticated, Dorset analyses made for the Mineral Resources Development Department in 1917–18 (recorded by Strahan, 1920, pp. 25–26) suggested that the shales warranted further study. His record of 1.8-m thick seams with high oil yields was probably based on the extrapolation of results from small samples. The thickest oil shale recorded in the present work was a 0.6-m thick seam in the *hudlestoni* Zone of the Upper Kimmeridge Clay in Borehole IGS 71/65 (Gallois and Cox, 1974). This seam and the underlying group of oil shales in the *wheatleyensis* Zone could, if taken together, be mistaken for a single bed of oil shale more than 1.8 m thick. In Boreholes IGS 71/65 and IGS 71/66 and in the IGS North Wootton, Hunstanton, Gayton and

Table 6 Analyses of some Kimmeridge Clay lithologies from the North Wootton Borehole (Bh. 23)

Depth down borehole	IGS Petrol. Dept./LGC Lab. No.	Loss on drying at 100°C	Ash (600°C)	Kerogen content		Oil yield* on distillation to 450°C		Sulphur content in oil	Lithology
m		% w/w	% w/w	%	%	% w/w	U.S.gal/ short ton†	% w/w	
36.10	2491	5.07	49.7	42.6	40.7‡	25.6	61.3	7.5	Oil shale, shelly
64.00	2492	5.08	61.1	30.9	30.5‡	16.9	40.5	5.7	Oil shale, shelly
45.70	2493	4.85	79.4	10.2	10.2‡	2.4	5.8	6.0	Oil shale, barren
75.80	2494	3.14	88.4	3.4	3.3‡	0.2	0.5	Not tested	Mudstone, medium grey, silty
76.10	2495	5.93	79.7	9.4	9.5‡	6.0	14.4	4.3	Oil shale, shelly

* S.G. of oil assumed to be 1.00
† Of dry shale
‡ Duplicate analyses

Marham boreholes, these oil shale beds were separated by shelly clays and oil yields from the group as a whole would be considerably less than that recorded by Forbes-Leslie.

No free oil was recorded in any of the boreholes, although most of the oil shales, and some of the intervening clays, gave off a strong bituminous smell when freshly broken. Like the Dorset Blackstone, some of the oil shale was combustible and burned with a sooty yellow flame on ignition with a Bunsen burner. No sandstone was seen in the Kimmeridge Clay in any of the present boreholes and Forbes-Leslie may have mistaken a silty-textured cementstone (e.g. cementstone K2 which lies between two of the more prominent groups of oil shale) as the sandstone which separated his Smith's and Puny Drain series of oil shales.

Four samples of oil shale and one of non-bituminous clay, all from Borehole 23 (North Wootton), were submitted to the Laboratory of the Government Chemist for kerogen analysis. The four oil shale samples were chosen as representative of the range of oil shale lithologies; the non-bituminous sample was chosen as typical of the remaining lithologies. In addition to the kerogen analyses, an attempt was made to assess whether hydrocarbon gases might be released from the oil shales at relatively low temperatures in sufficient quantities to give rise to potentially explosive or poisonous atmospheres.

The results of the analyses, carried out by Mr D. M. Green of the Laboratory of the Government Chemist, for kerogen content and oil yield are summarised in Table 6. Details of the methods used are given elsewhere (Green *in* Gallois, 1978).

Samples of the coarsely ground shale (15–60 mesh) were equilibrated in sealed containers at room temperature and the headspace gas analysed for hydrocarbons by gas-liquid chromatography. One sample (Lab. No. 2493) was heated to various temperatures and the analysis of the headspace gas repeated (Table 7).

Table 7 Generation of hydrocarbon gases at differing temperatures from oil shale

Temperature	Relative yield of methane	Gases identified
°C	ppm	
60	1	Methane
100	5	Methane, ethylene, ethane and propylene
150	19	Methane, ethylene, ethane, propylene and propane
200	67	As for 150°C
250	433	As above, plus C_4 hydrocarbons
300	1707	As above, plus C_5 and C_6 hydrocarbons

All samples showed the presence of a small quantity of methane in the headspace gas at ambient temperature—approximately a few parts per million by volume. Furthermore the evolution of hydrocarbon gases at relatively low temperatures was established, the quantity increasing with increasing temperature. All these gases are flammable and, although the concentrations were low, e.g. approximately 50 parts per million of methane in the headspace gas at 150°C, the total of hydrocarbon gases was two or three times this value. It is difficult to relate a laboratory test to practice but the results indicate that flammable hydrocarbon gases could be evolved from the shales and, in a confined space might accumulate and constitute a hazard. It was also recorded that hydrogen and hydrogen sulphide were evolved when the shale was heated and a preliminary experiment (Lab. no 2491) showed that hydrogen sulphide was evolved at approximately 200°C. The presence of hydrogen was not tested.

Two points should be noted in connection with the above report. Firstly, the tested samples were analysed several months after the drilling had been completed and the samples had completely dried out. Any free hydrocarbon gases would therefore be likely to have escaped before analysis. Secondly, the sample examined for the effect of temperature on the evolution of gases (Lab. No. 2493) had an oil yield less than 10 per cent that of the richest sample analysed (Lab. No. 2491).

Thick oil shale seems yielding the quantities of oil quoted by Forbes-Leslie (1917a) might prove a hazardous tunnelling medium, particularly if a soft ground shield were used. Hydrocarbon vapours might be released in sufficient quantities to give rise to potentially explosive or poisonous atmospheres either continually by the grinding action of the shield teeth on the shale or intermittently due to pressure release at the tunnel face between working shifts.

Within the area studied in detail, thick oil shale seams are confined to two main levels and two subsidiary levels in the Kimmeridge Clay. They are absent from the Ampthill Clay (with one very minor exception), West Walton Beds and the Upper Oxford Clay. Thin bituminous bands occur in the Lower Oxford Clay, but these are likely to be less rich than the Kimmeridge Clay occurrences and are deeper than 150 m beneath most of the Stage 1 area.

If the Kimmeridge Clay is to be used as a tunnelling medium some attempt must be made at site investigation stage to ascertain the likely behaviour of the oil shales in the tunnels.

Hydrocarbons of presumed natural origin have also been recorded from the Recent deposits of the area. Natural gas of a methane type was encountered during piling operations at 5–11 Chapel Street, King's Lynn [TF 6183 2023] on 23 October 1967 (West Norfolk District Council files). The amounts of gas were said to be considerable, leaking from around the pile as well as up the pile hole. The gas caught fire and part of the surrounding area had to be sealed off. The gas was said to come from a depth of about 6 m, from the approximate level of a thin peat bed. Lesser amounts of the gas were subsequently encountered in a number of pile holes at the same site.

GLACIAL DEPOSITS

The Glacial deposits of the feasibility study area can be divided into three distinctive lithological types: till, varved clay and sand and gravel, each of which is relatively constant in its engineering properties. The engineering problems that are involved in dealing with the Glacial deposits do not arise from the properties of the materials themselves but from the difficulties of predicting how these three lithologies are related in space to one another and to the solid geology.

Throughout Fenland, the constituents of the Chalky/Jurassic till are remarkable uniform. Apart from scattered erratic boulders of Jurassic cementstone

Table 8 Engineering properties of the drift deposits

Formation	Borehole No.	Sample depth	Natural moisture content	Dry density	Bulk density	Atterberg Limits PL	LL	PI	Unconfined compressive strength
		m	%	Mg/m³	Mg/m³				kN/m²
Barroway Drove Beds	1A	3.40	42	1.24	1.76	—	—	—	—
	1A	5.32	50	1.16	1.74	—	—	—	12
	8	2.26	27	1.53	1.95	—	—	—	—
	8	6.50	40	1.36	1.90	—	—	—	14
	12	3.20	45	1.22	1.77	—	—	—	10
	14	5.53	73	0.91	1.57	—	—	—	24
Varved Clay	1A	13.00	23	1.67	2.05	—	—	—	90
	3C	38.60	23	—	2.01	24	49	25	131
	14	11.53	24	1.64	2.04	—	—	—	66
Till (Boulder Clay)	1A	9.0	19	1.78	2.12	20	41	21	128
	1A	18.0	16	1.40	1.62	18	49	31	167
	2	22.3	15	1.91	2.20	—	—	—	206
	2	36.0	16	1.87	2.16	16	30	14	131
	2	43.5	15	1.91	2.19	15	33	18	257
	2A	54.52	21	—	2.13	24	54	30	340
	2A	62.80	18	—	2.15	19	38	19	190
	3C	26.10	18	—	2.14	24	44	20	205
	4A	29.23	15	—	2.21	18	40	22	470
	4A	41.28	16	—	2.21	16	32	16	325
	14	20.78	14	1.96	2.24	18	40	22	297
	14	21.70	24	1.61	1.99	15	29	14	169
	24	29.04	12	—	2.31	15	29	14	495
	24	43.13	15	—	2.06	19	39	20	215
	36	32.79	18	—	2.15	22	48	26	220
	37	24.97	18	—	2.18	20	41	21	225
Water-laid till	14	13.40	21	1.71	2.08	18	35	17	87

— not measured

and Lower Cretaceous sandstone, the till encountered in the inland boreholes was almost everywhere made up of coarse sand- to medium gravel-sized erratics (usually over 90 per cent chalk, with flints and other Cretaceous and Jurassic materials making up the remainder) set in a stiff, slightly sandy clay matrix. This uniformity is reflected in the soil test results.

Natural moisture contents in the till are generally less than 20 per cent, commonly in the range 15 per cent to 18 per cent (Table 8). Dry densities are mostly 1.7 to 2.0 Mg/m³ and shear strengths in the range stiff to hard (mean C_u 252 kN/m²; $\phi = 0$). The softness of the chalk erratics and the comparative rarity and small size of the flints suggest that much of the till would provide a tunnelling medium that differed little from the Ampthill Clay or Kimmeridge Clay.

In the field, varved clay is usually described as soft to firm, parting readily along the silt laminae. Only three varved clay samples were tested in the present work: these results, together with other results from Fenland and in the published literature (*see* Metcalf and Townsend, 1961, for summary) confirm that varved clay usually has a higher moisture content, lower shear strength and higher coefficient of compressibility than till. During tunnelling the problem of water transfer from the silt laminae to the clay laminae in varved clay might be difficult to overcome and the sensitivity of the clay fraction may therefore have a disproportionately large effect on the engineering properties of the material as a whole.

No glacial sand and gravel was cored in the present work. Exposures of this material in quarries in the area adjacent to that of the feasibility study area show lithologies ranging from fine sand to small boulders. The material is everywhere very permeable and is sufficiently loose to be worked by dragline or mechanical shovel.

RECENT DEPOSITS

The engineering properties of the Recent deposits of Fenland vary considerably, both laterally and vertically, reflecting the variable nature of their lithologies and modes of deposition. The Recent deposits are normally-consolidated sediments, although local leaching and chemical effects can give rise to apparently overconsolidated properties.

In the inland area, where almost all borehole sections contain at least some peat or clay, the Recent deposits are generally poor founding materials. Few soil tests were carried out on these deposits in the present work and the general notes below are based largely on data from a variety of site-investigation sources in the area. In choosing these data, consideration has been given to the degree of confidence with which particular horizons could be identified.

No sample of Terrington Beds was tested in the present work. Typically, they are soft, dull reddish brown, slightly silty to silty clays with the silt concentrated in laminae. Locally the silt may be replaced by very fine-grained sand. The Terrington Beds form a thin surface layer over much of the 'marshland' (Figure 19) and samples taken for soil testing are commonly contaminated by modern worm and plant action and have been affected by atmospheric

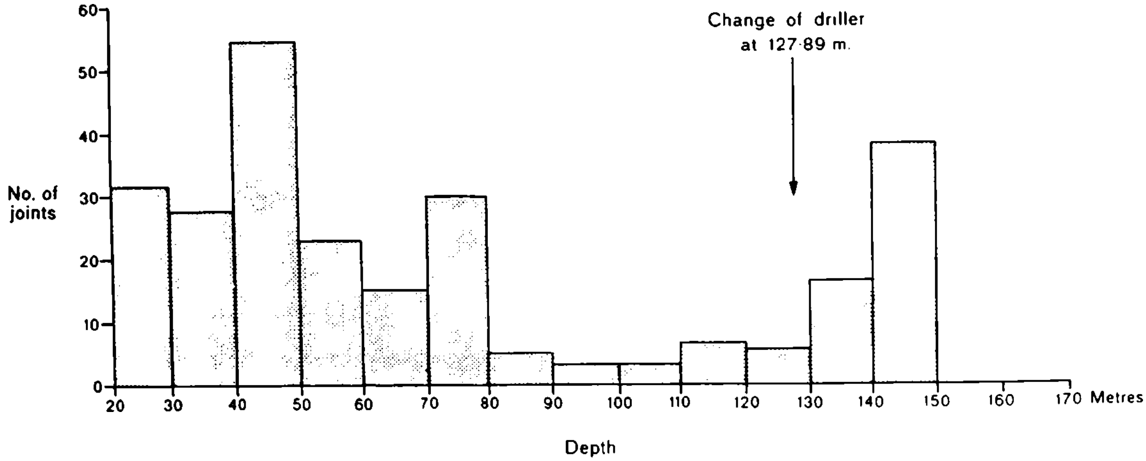

Figure 24 Histogram showing distribution of observed joints with depth in Bh. 23 (North Wootton)

oxidation. Natural moisture contents vary in relation to the efficiency of the local artificial drainage system and to seasonal conditions, but are generally in the range 10 per cent to 40 per cent. Dry densities are mostly between 1.3 and 1.6 Mg/m³. Triaxial compression test results vary considerably in response to small amounts of contaminants such as peat or gravel: C_u (quick undrained) is usually less than 40 kN/m².

The Nordelph Peat and the 'Lower' Peat vary in texture from woody to fibrous depending on the area in which they were deposited and their distance from higher ground. Dry densities and natural moisture contents vary from place to place in relation to the compaction and drainage histories of the area. One sample of Nordelph Peat was tested in the present work.

Natural moisture contents in the Nordelph Peat are generally high, between 40 per cent and 90 per cent, with records of over 500 per cent occurring in the King's Lynn area. Dry densities are usually less than 1.3 Mg/m³. Values for C_u vary with the texture of the peat but are rarely more than 20 kN/m² for the fibrous peats. The properties of some samples of Nordelph Peat from King's Lynn have been discussed by Skempton and Petley (1970).

Soil-test data for the 'Lower' Peat are rare, but its moisture content is generally lower and its shear strength higher than that of the Nordelph Peat as a result of its greater consolidation.

The Barroway Drove Beds are typically very soft, slightly silty, or finely sandy, clays riddled in their upper part with water-filled peaty root-holes that extend down from the lower surface of the Nordelph Peat. Local lenses of peat and sandy tidal creek deposits occur within the Barroway Drove Beds, but none was proved in the present work.

Several samples of typical Barroway Drove Beds were tested. Natural moisture contents generally vary from about 25 per cent to 50 per cent, with records of over 80 per cent, where large numbers of root-holes are present. Dry densities are usually similar to those of the Terrington Beds but shear strengths are much lower (C_u rarely more than 20 kN/m²), because of the organic content and high moisture content.

The engineering properties of the marine, intertidal and tidal creek sands and the gravelly lag deposits have not been examined in the inland area. They have been the subject of extensive testing in the offshore area where they form the founding material beneath the possible reservoir sites.

FEATURES AFFECTING THE SOIL MASS

Within the feasibility study area, a number of natural features are present which may affect the suitability of the Upper Jurassic clays as a tunnelling medium; most of these act to reduce the bulk strength. Such features include mechanical discontinuities (joints, shears, faults), folds and weathering (including glacial and periglacial effects).

Mechanical discontinuities

A confusing number of terms is currently available to describe the mechanical discontinuities that can be observed in almost all soil or rock masses. In this account, the term joint is used to describe mechanical discontinuities having small (less than 2 m) displacements. In the present work, the joints are mostly planar or slightly curved and can be small (cf. the fissures of 'stiff fissured clay') or large (cutting across several lithological units). Displacements are commonly accompanied by slickensided surfaces ('shears' of some authors). Bedding-plane joints are mechanical discontinuities that approximately follow a bedding plane, usually at the interface of two slightly differing lithologies. The term fault is used here for mechanical discontinuities with displacements of more than 2 m.

A realistic assessment of the effect discontinuities may have on the engineering behaviour of a soil or rock mass can rarely be made from boreholes alone. In the case of the feasibility study, where the boreholes are widely spaced and designed to explore a number of different stratigraphical levels, the data from the boreholes can at best indicate only the general pattern of discontinuities at the specific points at which the boreholes were drilled. Measurements of RQD (Deere and others, 1967) and similar parameters in cores of

Table 9 Distribution and dip of observed joints in the North Wootton Borehole

Depth down borehole	Bedding	0° to 15°	15° to 30°	30° to 45°	45° to 60°	60° to 75°	75° to 90°	Vertical	Total
m									
20 to 30	15	3	-		-			14	32
30 to 40	13	6	1	-	1	-	-	6	27
40 to 50	34	3	2	1	1	-	1	12	54
50 to 60	11	5	-	-	-	-	1	6	23
60 to 70	10	1		-	-	2	-	2	15
70 to 80	25	3	-	-	-	-	-	2	30
80 to 90	-	4	1	-	-	-	-	-	5
90 to 100	1	1	1	-	-	-	-	-	3
100 to 110	2	-	-	-	-	-	-	1	3
110 to 120	3	2	-	-	-	-	1	-	6
120 to 130	4	-	-	-	1	-	-	-	5
130 to 140	8	6	1	-	-		1	-	16
140 to 150	15	10	3	3	5	-	2	-	38
150 to 160	-	-	-	-	-	-	-	-	0
160 to 170				-	-	-	-	-	0
Total	141	44	9	4	8	2	6	43	257

fractured soil are usually misleading since it is almost always impossible to differentiate between natural fractures that are open in the ground and those that are opened by the effects of de-stressing and the drilling process.

However, for tunnelling purposes, the state of natural fracturing in the cores, including the fractures which can be opened up by drying out the core and tapping it with a hammer, may provide a useful guide to the mass behaviour of the material when subjected to the mechanical action of a shield.

An analysis of the distribution of the joints observed in the cores of Borehole 23 (North Wootton) is given in Figure 24 and Table 9. Borehole cores do not of course provide a statistically representative picture of the spacing of the joints in a rock mass. In vertical boreholes, such as those of the present study, the bias is strongly in favour of low-angle joints and against steeply dipping joints. Nevertheless, it can be seen from Table 9 that the observed jointing shows a strongly bimodal distribution with over 70 per cent of the joints being either perceptibly horizontal (bedding-plane joints) or vertical. Within the 0° to 15° group, almost all the joints were within the 0° to 10° range, with over 60 per cent in the 0° to 5° range. Thus over 80 per cent of all the observed joints fell within the ranges 0° to 5° or 85° to 90°. Many of the vertical joints terminated against bedding plane joints and it is clear even from the limited results available that the Upper Jurassic clays are cut by a closely-spaced network of near-vertical and near-horizontal joints. Over 94 per cent of the bedding joints were accompanied by slickensiding or by polished surfaces of presumed natural origin (as distinct from those of drilling origin) and at least 90 per cent of the 0° to 15° group of joints were similarly affected.

Slickensiding was rare within all other groups and no slickensided vertical joint was seen, even though many of the vertical joints showed displacements, some as much as 0.1 m.

Joint measurements made in other feasibility study boreholes show a similar strong bimodal distribution (Table 10), but the total number of joints recorded in any one borehole was too small to warrant detailed analysis. Each borehole must be regarded as a single source of information which may have been subject to local tectonic influence, and the results cannot be used in a cumulative manner.

Two other trends are apparent from the North Wootton results. Firstly, the number of joints recorded decreases markedly below 80 m depth (Figure 24), rises from 130 m to 150 m and then falls to zero below 150 m. The distribution down to 80 m is thought to be a genuine reflection of the state of the discontinuities in the ground, with only very tight joints present below about 80 m. The secondary peak at 130 m to 150 m corresponds with a change of driller and a series of rig breakdowns. It serves to illustrate the difficulty of reaching reliable conclusions in this type of analysis.

Examination of the frequency of joints in Boreholes 1, 3C and 4A, the deepest drilled, suggests that 80 m to 90 m may be a critical depth below which joints are rare or absent (Table 10).

Table 10 Dip of joints in the Denver, West Walton Highway and Gedney Drove End boreholes

Borehole no.	Dip of joint			Total	Depth below which joints become rare (<5 per 10 m)
	0° to 5°	85° to 90°	others		
					m
1*	42	90	27	159	88
3C	12	12	6	30	90
4A	22	29	9	60	85

*Upper Jurassic clays only

The second apparent trend is the relationship of joint-spacing to lithology. The relationship cannot be conclusively demonstrated in any one borehole but the results from a number of boreholes indicate that the dark grey smooth clays (e.g. Bed 16 of the Lower Kimmeridge Clay) are always more closely-jointed than the tougher shelly (e.g. KC Bed 30) or silty clays (e.g. KC Bed 15).

The geological structure in the feasibility study and surrounding areas is extremely simple and faults with displacements greater than about 20 m are unknown. Only four faults were recorded in the land area survey of the Lower Cretaceous rocks between Hunstanton and the River Nar: these were at North Wootton (10 m throw), at Pott Row (estimated maximum 20 m throw), at King's Lynn (10 m throw) and at Blackborough End (10 m throw). No fault was recorded by the 19th century geological survey of the remaining outcrop of the Lower Cretaceous rocks between the River Nar and Southery. The only other faults that have been recorded in West Norfolk are in the Lower Chalk near Hockwold (10 m throw), in the Middle Chalk at Mundford (10 m throw) (Ward and others, 1969) and in the Gault of the Ely Ouse tunnel scheme (about 12 m throw) (Samuels, 1975). It should be noted, however, that faults with throws of less than 10 m are unlikely to be detected by field surveys in west Norfolk except where exposures or stratigraphical control are exceptionally good.

Most of southern Britain experienced earth movements in late Jurassic times and it could be argued that faulting and folding in the Upper Jurassic clays are likely to be more intense than in the Cretaceous rocks. The gentle nature of the overstep of the Sandringham Sands across the Kimmeridge Clay (Gallois, 1973, fig. 4b) indicates that this late Jurassic folding was minimal in the feasibility study area. This conclusion is confirmed by the offshore seismic work which shows small faults and folds to be as common in the Lower Cretaceous rocks as in the Upper Jurassic clays.

The boreholes drilled for the present work are too far apart to indicate whether any faulting is present between them. However, the general absence of faulting in the exposed Cretaceous rocks of the land area and the scarcity of faulting in the Upper Jurassic clays in the seismic sections suggest that the clays beneath the feasibility study area are not extensively faulted.

The combined evidence suggests that faults with displacements of more than 20 m are likely to be very rare and those with displacements of more than 10 m rare. Faults with displacements of less than 10 m may be relatively common. Such faulting could produce two effects of importance to tunnelling. Firstly, the intensity of jointing might be increased in the vicinity of the fault. At depth, this effect could pass unnoticed, but near the surface, or close to the junction with the Lower Cretaceous rocks, the more intensely jointed ground might have been softened by groundwater movement. Secondly, the fault might throw a cementstone or other hard band into the tunnel line.

The spacing of boreholes drilled at a possible site investigation stage is unlikely to be such that faults with throws of less than 10 m would be detected, even though the Upper Jurassic clays can be divided stratigraphically into beds mostly 2 to 3 m in thickness. It would be advisable, therefore, if tunnelling were eventually to be carried out, to sample the tunnel face at frequent intervals in order to monitor the position of the tunnel in relation to the stratigraphy. This procedure would not only give some warning of the approach of small faults but would enable a new course to be determined if the tunnel passed through a fault into particularly difficult ground.

Folds

The simple geological structure of the area is also reflected in the style of folding (e.g. Figure 6). Dips of more than 1° are rare and folds in the Upper Jurassic clays and the Lower Cretaceous rocks can only be interpolated from regional changes of dip. In the offshore area, the seismic traverses have proved a similar pattern of very broad gentle folds. Although this folding is related to the formation of the discontinuities described above, none of the folds is likely by itself to have greatly affected the bulk properties of the Upper Jurassic clays or their engineering behaviour.

Weathering

For engineering purposes, the weathering of the Upper Jurassic clays can be regarded as being governed by two types of process, one chemical and one mechanical.

Chemical weathering is readily recognisable in the cores by colour changes from unweathered greys to weathered yellowish browns and by general elimination of the mudstone fabric in which bedding and fossil burrows, trails and shells are destroyed. These changes reflect oxidation processes in which sulphides (e.g. pyrite) are converted to sulphites and sulphates and ferrous minerals to ferric hydroxides. Weathered Upper Jurassic clays generally have higher natural moisture contents and lower shear strengths than their parent materials.

Modern chemical weathering (the processes by which groundwater-leaching and oxidation cause the fabric of the clays to be destroyed) rarely extends down below 3 to 5 m in the present area. Glacial or pre-Glacial chemical weathering was observed in a number of the borehole cores. This effect was usually limited to a layer 1 to 2 m thick and it is possible that much of the pre-Glacial weathered zone has been incorporated in the Glacial deposits. A small amount of leaching also occurs in the clays for 1 to 2 m below the junction with the Sandringham Sands.

Mechanical weathering (the process by which the discontinuities in the soil or rock mass are opened) takes place in two principal ways, one due to frost action, the other due to de-stressing. Present day frost action has no effect on the Upper Jurassic clays in the feasibility study area, protected as they are by a thick layer of Recent deposits. However, Jurassic clays were exposed when the area experienced a periglacial climate and the permafrost layer may have extended down to depths of 100 m. Frost action could therefore have affected the clays down to this depth, and this may account for the apparent increase in the frequency of joints at depths shallower than 80 m to 90 m.

It is impossible to assess from the borehole cores which part of the fracturing has been opened by permafrost action, erosional de-stressing (e.g. adjacent to river valleys) and the drilling process. Lengths of very broken core, possibly indicating open discontinuities *in situ*, were noticeably more common in the first 30 m of drilling where the Upper Jurassic clays cropped out at the surface or beneath the Recent deposits, and in the first 20 m where they were overlain by Glacial deposits.

The degree of erosional de-stressing, in response to the lowering of overburden pressure caused by erosion, is likely to have been relatively uniform throughout an area of low relief such as that of the feasibility study.

Discontinuities are therefore likely to be significantly more open only near the steeper parts of the pre-Glacial valleys.

For tunnelling purposes, a limited amount of mechanical weathering is likely to have the advantageous effect of producing a clean, easily transportable spoil when worked with a shield. More intense mechanical weathering may result in overbreaks, but even here the fallen debris is likely to consist of joint-bounded fragments of an easily transportable size.

A more detailed analysis of the discontinuities within the Upper Jurassic clays at a site investigation stage might provide much information about their likely behaviour and their effect on specific problems such as tunnelling rate, size of spoil and tunnel overbreak. Research into the unloading behaviour of discontinuities in the Oxford Clay in the brick pits of the Peterborough area has been carried out by the Building Research Establishment (Moore, 1972). This and similar work could be of specific interest to later stages of the feasibility study, and of general interest to Stage 1. A general appreciation of mechanical discontinuity patterns within the Upper Jurassic clays might be gained from an examination of available exposures such as those at Warboys Brick Pit (Upper Oxford Clay) and Kimmeridge Bay (Lower and Upper Kimmeridge Clay).

Pre-Glacial weathering effects, other than the mechanical weathering referred to above and a small amount of cryoturbation, were not seen in any of the cores. Large-scale features such as cambering and valley-bulging appear to be absent from both the onshore and offshore areas, and it seems likely that a covering of Glacial deposits protected much of the area from these effects. However, the Upper Jurassic clays are lithologically very susceptible to valley-bulging and any future site investigation should bear in mind the possible occurrence of this phenomenon in narrow belts running along the pre-Glacial valleys. In borehole cores, such disturbances are generally indicated by broken ground, unusual dips and displacements of stratigraphical marker beds. In a single borehole, a valley-bulge might be mistaken for a fault. Extensively broken and softened ground caused by a valley-bulge can be water-bearing and may extend down for more than 30 m.

OLD BOREHOLES AND SHAFTS

Several of the oil shale exploration boreholes referred to above in the section on hydrocarbons lie within the Stage 1 area along the western margin of Fenland between Setch and Denver. All the known boreholes in this area were drilled by English Oilfields Ltd between about 1918 and 1923. Several other oil exploration syndicates were operating in west Norfolk during the same period and other boreholes may have been drilled, of which no record has been kept.

The records of the known boreholes vary considerably in quality; the sites of those in the area of present interest are not known precisely. Borehole diameters are not known in most cases but samples of core range in diameter from 25 mm to over 150 mm. Some of the well documented boreholes penetrated the full thickness of the Kimmeridge Clay and one reached the Lias. It is likely that few of these boreholes have been adequately sealed by modern standards. If left open they will probably have sealed themselves. Some may have been imperfectly backfilled with permeable material.

Water boreholes and wells are rare in Fenland because of the thick, impermeable nature of the underlying Upper Jurassic clays. However, where boreholes occur they were commonly continued until forced to stop by mechanical problems or lack of money and are therefore deep. An unusually deep dry well [145/23], consisting of a shaft and borehole, was reputedly dug at King's Lynn [TF 617 205] in 1812 to 207.3 m. It is likely to have been backfilled with domestic rubbish. Details of other water wells and boreholes are held by the Hydrogeological Department of the IGS.

The only other boreholes known to have been drilled within the feasibility study area are those for site investigation purposes. The majority of these have been sunk for road, river or bridge works and rarely penetrate more than a short distance into the solid or glacial deposits that are used as the founding material. Details of many site investigation boreholes are filed in the Records Department of the IGS. Such boreholes are not notifiable and these records are therefore incomplete.

LOCAL DETAILS OF THE GEOLOGY

The inland site investigation examined in detail the geology of the area under which tunnel routes might lie for a Stage 1 reservoir in the region of Breast Sand and a freshwater source on the River Great Ouse between Denver and King's Lynn (Figure 1). The stratigraphy and glacial history of a much larger area, embracing all four possible reservoir stages, was examined in general terms.

DENVER TO ALTERNATIVE STAGE 1 SITES

The freshwater source for the four alternative Stage 1 sites was assumed to be the River Great Ouse between Denver and King's Lynn. Most of the area was examined in detail, the more important exceptions being the areas beneath the Alternative 1 (Bull Dog Sand) reservoir and beneath the western part of the Alternative 4 (Wingland) reservoir.

Much of the area of interest for tunnel routes is common to all four alternative sites. The geology of this area is summarised in a series of figures showing structure and rockhead contours and isopachytes for some of the more important horizons within the Upper Jurassic clays. Geological sections can be plotted for any possible tunnel line within the area examined in detail by combining the data from these figures. Three examples of geological sections are given (Figure 26): these are intended for descriptive purposes only. A more accurate section (Figure 27) along one of these lines shows the degree of detail that is likely to be required for a comparative assessment of alternative tunnel routes.

Detailed sections can be plotted by following the procedure set out below:

1. Plot rockhead surface (Figure 18);
2. Plot the bases of the Kimmeridge Clay (Figure 6), Ampthill Clay (Figure 5) and West Walton Beds (Figure 3);
3. Plot the base of Bed 40 of the Ampthill Clay by subtracting the thicknesses of Beds 40 to 42 (Figure 9) from the base of the Kimmeridge Clay.

Individual limestone bands within the Ampthill Clay and the Kimmeridge Clay (*see* Table 5 for details) can then be fitted into the section by projecting data

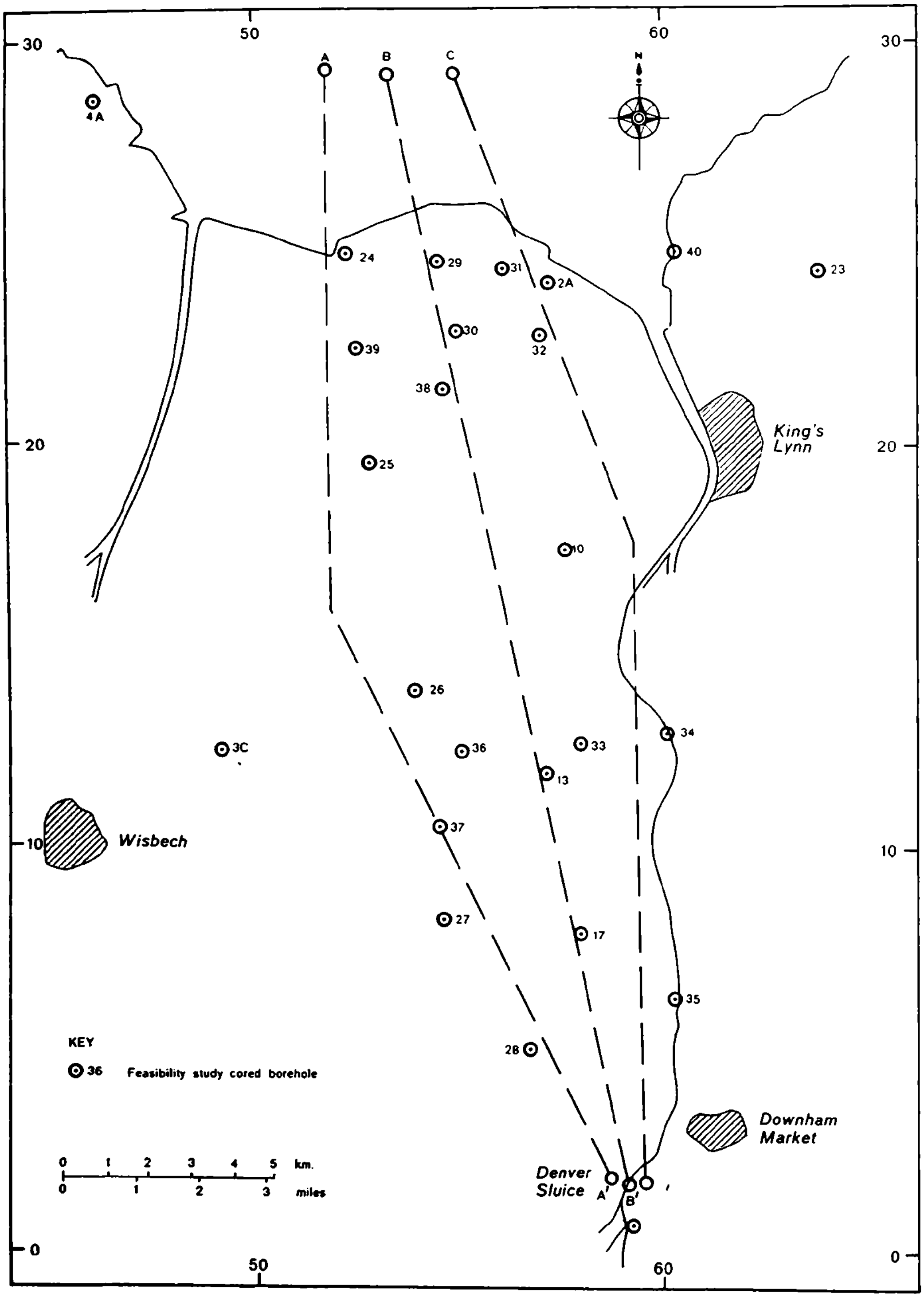

Figure 25 Site map showing lines of sections in Figures 26 and 27

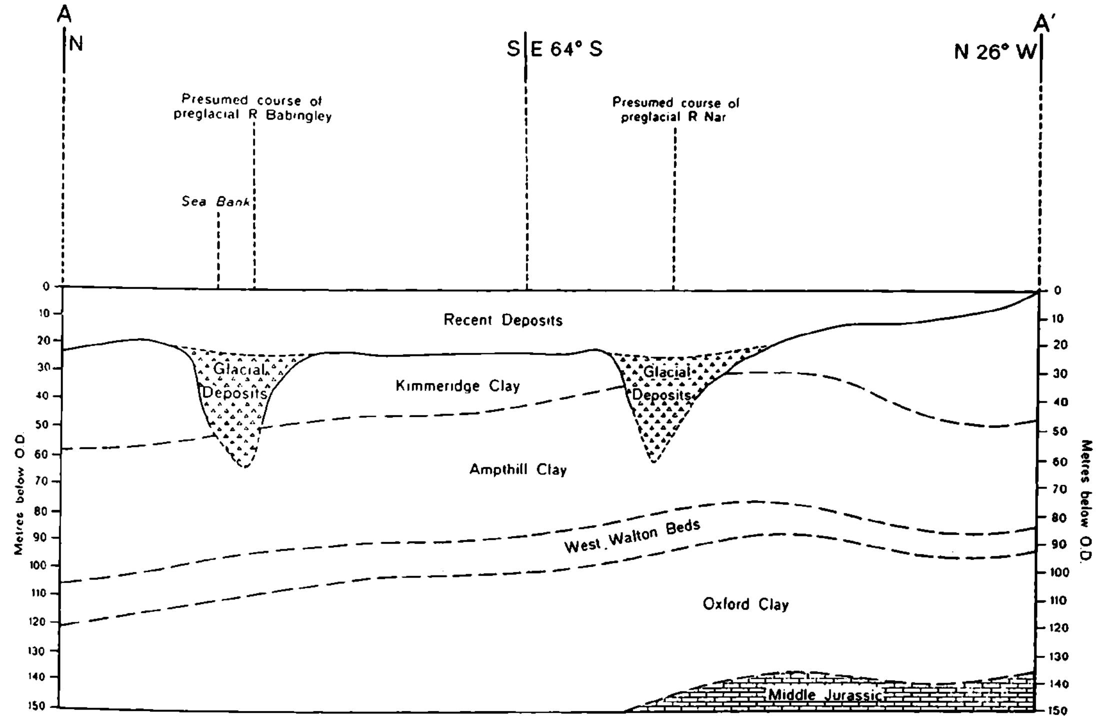

Figure 26A Geological sketch section along line AA′ on Figure 25

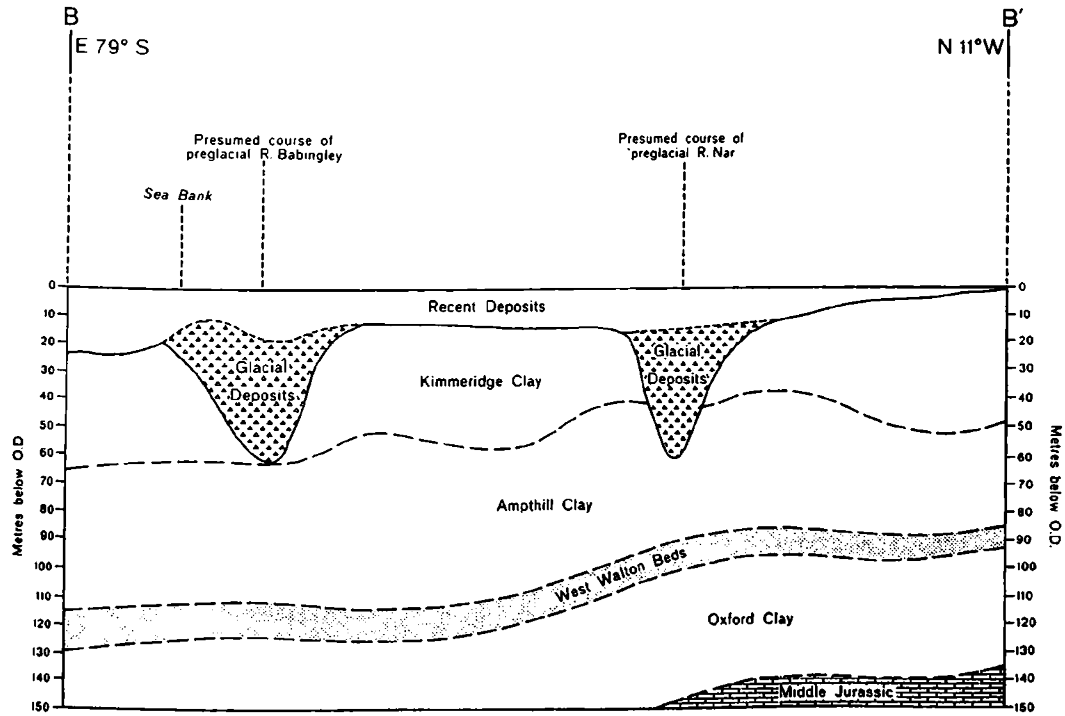

Figure 26B Geological sketch section along line BB′ on Figure 25

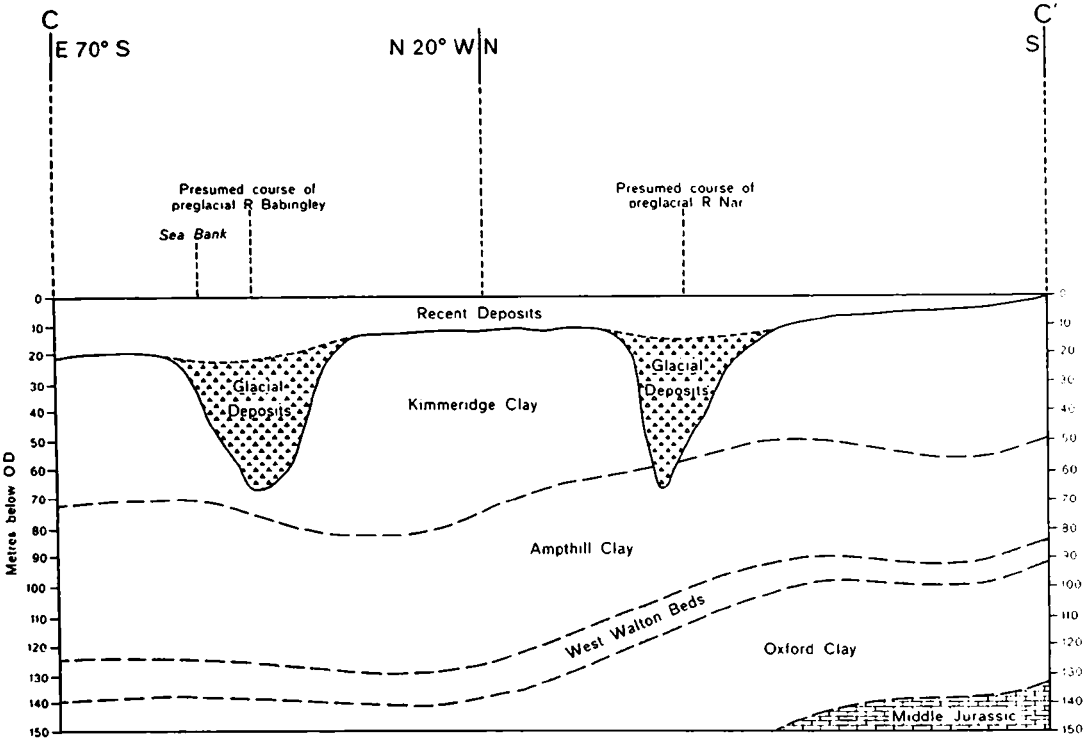

Figure 26C Geological sketch section along line CC′ on Figure 25

from boreholes (Appendix A) adjacent to the line of section. Where no borehole is particularly close to the section, approximations can be made by combining the data from several boreholes: allowance must of course be made for the positions of the section and the boreholes in relation to the local dip and to the regional variations in the thicknesses of the beds.

It can be seen from the rockhead contour map (Figure 18) that the Stage 1 area is underlain by Upper Jurassic clays (almost all Kimmeridge Clay) mostly at depths of less than 20 m except where the deep glacially-filled valleys of the rivers Babingley and Nar cross the area from east to west, separating the possible reservoir sites from the freshwater source at Denver.

It is likely that within this area the top of the West Walton Beds forms the lowest limit at which soft ground tunnelling might easily be carried out. The base of the Sandringham Sands, lying to the east of the area, forms the upper limit.

In the far western part of the Stage 1 area, the top of the West Walton Beds probably intersects the pre-Glacial valley of the River Nar, and any tunnel routes which sought to avoid the Glacial deposits of the valley would need to pass through the West Walton Beds and into the Oxford Clay.

Eastwards (Figure 26 A to C), the regional dip carries the West Walton Beds below the level of the buried valley and a route in the Ampthill Clay could avoid both the West Walton Beds and the Glacial deposits. Further east still, beyond the area examined in detail, routes beneath the buried valley would be possible in the Kimmeridge Clay.

Similarly, several choices of stratigraphical level would be available within the Upper Jurassic clays that could avoid the Glacial deposits in the glacially-filled Babingley valley. Apart from individual stone bands, the only bed likely to cause difficulties within either the Ampthill Clay or the Kimmeridge Clay in this area would be Bed 40 of the Ampthill Clay.

From the evidence available, the shapes of the two buried valleys can only by estimated. The glacially-filled Nar valley appears to be asymmetrical in cross section with a steeper, relatively straight, northern side that could indicate some degree of tectonic control. Comparison with the offshore seismic sections suggests that the valley is likely to be much broader where it crosses the Upper Jurassic clays than where its sides are cut in Lower Cretaceous rocks.

The same is true of the Babingley valley which is no more than 1.5 km wide at Castle Rising where it crosses the Cretaceous outcrop, whereas in the Terrington Marsh area, where it crosses the Upper Jurassic clays, the borehole evidence suggests that it has broadened to 2 to 3 km in width.

There is no evidence from the land area boreholes to suggest that these valleys are deeper where they are narrower. If the Glacial deposits are to be avoided then routes lying on the eastern edge of the area examined in detail would be easier to explore and might involve less difficulty than more westerly routes. The possibility of passing under the glacially-filled Nar valley beneath the Lower Cretaceous escarpment in the Setchey-Tottenhill area, east of the area examined in detail, should therefore be considered.

Much of the till that fills these valleys is lithologically uniform and would provide a suitable tunnelling medium. It does, however, contain scattered large erratic stones up to 2 m across and may contain, or

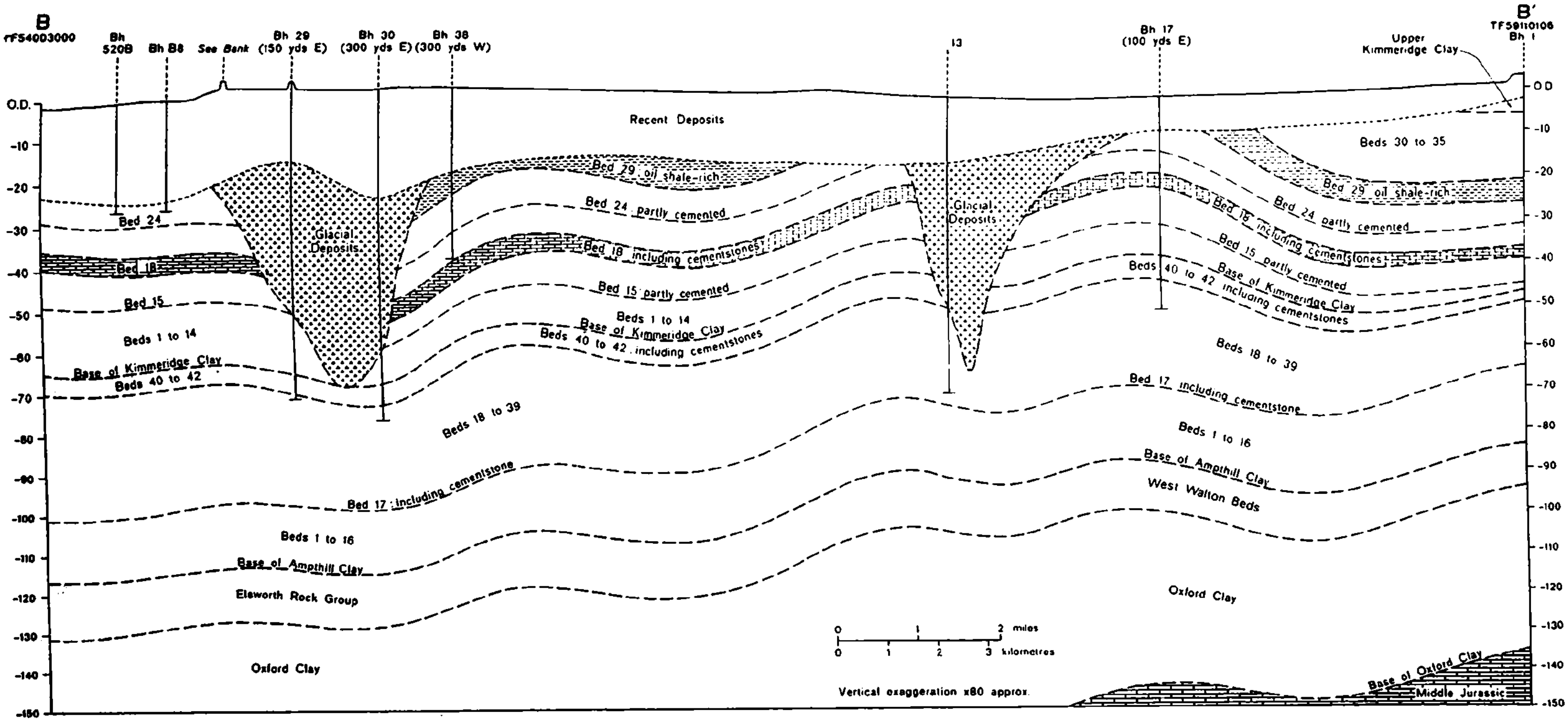

Figure 27 Geological section between Terrington Marsh and Denver Sluice (along line BB′ on Figure 25)

be floored by, pockets and lenses of water-logged flint gravel. The central parts of these valleys are also characterised by lenses and beds of varved clay of significantly lower strength than the till. It may be advisable, therefore, to examine tunnel routes within the till, aiming to avoid the gravels and the varved clay. In this case easterly routes, taking advantage of the more closely defined nature of the valleys, are likely to be preferable for ease of site investigation but are more likely to encounter deposits of glacial sand and gravel.

Alternative 1 (Bull Dog Sand):
Little is known about the detailed geology of the Bull Dog Sand area. The shallowness of the sea and the presence of flint gravels in the Recent deposits in this area resulted in poor seismic records which revealed little of the solid and glacial geology. Only two boreholes have been drilled in the area. The first of these, Wimpey 1503, showed Kimmeridge Clay at shallow depth; the second, Wimpey 1509, ended in till. It is possible either that the course of the pre-Glacial Babingley River was similar to that of the medieval river which crossed this area or that a glacially-filled tributary of the Babingley runs beneath the area. Further exploration would be necessary to resolve this.

Assuming the area to be entirely underlain by solid deposits at a relatively shallow depth, then the evidence from the adjacent land and offshore areas indicates that the junction of the Kimmeridge Clay and the Sandringham Sands runs across the northern tip of the area. The remaining part of the area is underlain by Lower and Upper Kimmeridge Clay dipping very gently east to north-eastwards. Any tunnel route from the reservoir to Denver would have to cross the glacially-filled Babingley valley in an area where its depth is presumed, from Borehole 40, to be at least 70 m and its shape is unknown.

Alternatives 2 and 3 (West Stones and Breast Sand)
All possible tunnel routes from these two alternative sites to Denver lie within the area examined in detail. The geology of the land area is summarised in the various contour diagrams and in the stratigraphical interpretations of the boreholes. Tunnelling could be carried out in the Ampthill Clay or the Kimmeridge Clay and possibly also in the till.

A large number of boreholes and soundings have been made in the areas of the possible reservoir sites. The contractors' reports (Anon., 1972; Anon., 1973b) indicate that Kimmeridge Clay is probably everywhere present at depths of less than 30 m.

Alternative 4 (Wingland)
Routes from the eastern end of this alternative site to Denver lie within the area examined in detail and are covered above. The northern parts of direct routes from the western end of the area to Denver lie in unexplored ground which is likely to be complicated by thick Glacial deposits. The westerly continuation of the glacially-filled Babingley valley probably crosses this area as a very broad structure and more information would be needed before any critical comparison of possible tunnel routes could be made.

The south-western part of the possible reservoir site is probably underlain by Glacial deposits lying near the edge of this valley. The remainder is underlain by Lower Kimmeridge Clay with the base of the Kimmeridge Clay possibly subcropping beneath the drift in the south-western corner of the site. Tunnel routes could be restricted to the Ampthill Clay or the Kimmeridge Clay for most of their lengths but, depending on the shape of the buried valley, they might need to pass through the till or down through the West Walton Beds to the Oxford Clay. Direct routes from this alternative site to Denver also cross the glacially-filled Nar Valley in an area where it is likely to be broad and poorly defined.

WISBECH TO STAGE 2
The general pattern of glacially-filled valleys beneath the Fens (Figure 17) suggests that possible tunnel routes from Wisbech to Stage 2 might be among the most difficult to explore in the whole of the feasibility study area.

The two routes indicated in Figure 1 start at Wisbech in an area where thick (25 m to 38 m) Recent deposits overlie varved clay and till of unknown thickness. These latter deposits seem likely to be filling a major valley which runs northwards towards Long Sutton (*see* Figure 17). If this is the case then the glacially-filled Nar valley probably joins this larger valley somewhere between Wisbech and West Walton, an area crossed by the tunnel routes. Farther north the routes cross the glacially-filled Babingley valley in an area where it is poorly known.

Most of the effort in any site investigation along these routes would therefore need to be aimed at defining the shape of the rockhead surface and at considering the suitability of the Glacial deposits as a tunnelling medium. If the Glacial deposits proved unsuitable, the southern parts of both routes would probably need to lie within the Oxford Clay. Care would be needed to determine accurately the position of the base of the Oxford Clay to avoid possible water problems close to the junction with the Kellaways Beds and the Middle Jurassic. Water in these latter formations may be present under artesian head and could give rise to hydraulic fracturing in the beds lying between the aquifer and any possible tunnel in the Lower Oxford Clay.

The northern parts of routes below the Glacial deposits would be in Ampthill and Lower Kimmeridge clays. The stratigraphy, lithology and engineering properties of both formations are likely to be similar to that described elsewhere in this report.

FOSDYKE TO STAGE 3 AND BOSTON TO STAGE 4
Both reservoir areas overlie Lower Kimmeridge Clay, except where glacially-filled valleys have cut down into the underlying formations. One such major valley (over 50 m deep) has been shown by the offshore seismic work to run beneath Old South, at the junction of reservoirs 3 and 4, and there is borehole evidence to indicate the presence of a similar glacially-filled valley in the Boston area (*see* Figure 17).

The problems likely to be encountered in any site investigation for Stages 3 and 4 are therefore similar to those of Stage 2, with the possible advantage in the case of Boston to Stage 4, that the tunnel route probably crosses the glacially-filled valleys at high angles. The Fosdyke to Stage 3 route however may run obliquely across the Old South valley or may even follow a continuation of the Babingley valley.

Tunnel routes would be possible in the Ampthill or Oxford clays for both stages if the Glacial deposits were to prove unsuitable. Care would again be needed if the lower part of the Oxford Clay were to be utilised. Part of any site investigation for Stages 2, 3 and 4 should be designed to examine groundwater conditions in the Kellaways Beds and the Middle Jurassic (which in the western part of the Stage 3 and 4 areas includes the Lincolnshire Limestone aquifer).

The lithologies and engineering properties of the Upper Jurassic clays are likely to be similar in the Stage 3 and 4 areas to those of the Stage 1 area.

POSSIBLE FUTURE SITE INVESTIGATION

SUGGESTED FIELD PROCEDURES

The method by which a desk study comparison can be made of all possible tunnel routes within the Stage 1 area is described on p. 53. Once a particular tunnel line (or lines) has been chosen, further site investigation should be designed to provide the following information along the proposed route:

1. Shape of the sub-Recent surface;
2. Shape of the sub-Pleistocene surface;
3. Lithologies of the Glacial deposits, their lateral extent and relationship to one another;
4. Positions of the main marker beds in the Upper Jurassic clays;
5. Presence of any major folds or faults;
6. Engineering properties of all possible tunnelling horizons.

The shape of the sub-Recent and sub-Pleistocene surfaces could be explored most economically with percussion boreholes and limited sampling. Detailed correlations are unlikely to be required within the Recent deposits, since sites of structures will require individual investigation. Macdowell (1971) has described a resistivity method for determing the position of the sub-Recent surface beneath the Fens near Earith, Cambridgshire. Similar geoelectrical methods could probably be economically employed to supplement the borehole programme in the exploration of the shape of the sub-Recent surface in the feasibility study area. It is unlikely that the sub-Pleistocene surface can reliably be detected using this method because the lithologies of the till and the Upper Jurassic clays are not markedly dissimilar.

Seismic methods have been used in the offshore area to plot the sub-Recent and sub-Pleistocene surfaces. Research currently in progress on the use of small craft and sparker sources to carry out continuous seismic profiling in shallow natural and artificial waterways may assist future site investigation. The sparker survey of the tidal reaches of the River Gt Ouse, carried out by the Institute's Marine Geophysics Unit for the feasibility study, has shown that such techniques, combined with a borehole programme, can provide valuable information about the position of the rockhead surface. Tidal rivers such as the Nene, Welland and Witham could be surveyed using the same equipment. With improvements in design, particularly regarding weight and resolution, many of the larger freshwater drains, such as the Middle Level Main Drain, could be similarly surveyed. Sparker surveys of this type could provide information which could not be gained from boreholes alone or which could be obtained only at great expense. Land seismic methods might be suitable for determining the sub-Recent and sub-Pleistocene surfaces in areas of particular interest but their cost is likely to make them unsuitable for general use.

The stratigraphy of the Glacial deposits can be satisfactorily explored only by means of closely-spaced boreholes. Geophysical borehole logging methods are unlikely to prove useful either for detecting the complex lithological variations that are likely to occur in the Glacial deposits or for making correlations between these deposits in boreholes.

The positions of the main marker beds in the Upper Jurassic clays could be most satisfactorily explored using a combination of continuously cored boreholes, boreholes with limited sampling and total gamma-ray and resistivity logging. The stratigraphy of most of the Upper Jurassic of the feasibility study area is now known in detail. In the later stages of the scheme, further stratigraphical work would be required on the Oxford Clay if this formation were to be extensively used as a tunnelling medium. The stratigraphy of the West Walton Beds, Ampthill Clay and Kimmeridge Clay is sufficiently well known from the present work for horizons within these formations to be identified with confidence from only limited sampling. Assuming the tunnel route to lie within the solid deposits it would be unnecessary, in the area examined in detail, for all site investigation boreholes to be drilled to the level of the tunnel invert. Over most of the area and at most stratigraphical horizons, about 15 metres penetration into the solid deposits would provide the information required, irrespective of the depth of the tunnel. A large number of relatively shallow boreholes could be drilled along the proposed tunnel route. These would provide, at the same cost, more information about the sub-Recent surface, the sub-Pleistocene surface, possible folding and faulting and ground conditions at the tunnel level, than would a smaller number of boreholes drilled to the tunnel level.

It would probably be possible to deduce the presence of major folds or faults from a general consideration of the borehole data; the larger the number of boreholes along the tunnel route, the greater would be the accuracy in determining the geological structure and the greater the chances of detecting small-scale structures such as valley-bulges.

In addition to the undisturbed sample testing carried out for the feasibility study, consideration should also be given to more elaborate testing such as plate tests and tests on block samples during any future site investigation. Muir Wood (1975) has drawn attention to the importance of accurately determining Young's modulus and Poisson's ratio when designing tunnels in elastic ground. The difficulty of extracting representative samples, from which these and other parameters can be determined, using conventional borehole sampling techniques has been demonstrated by Samuels (1975) for the Gault clay, an overconsolidated clay with properties similar to those of the Upper Jurassic clays.

McKinlay and others (1974) have suggested that tills require a careful and generous sampling programme to compensate for the scatter of test results that is likely to be obtained. The investigation of possible varved clay or glacial sand and gravel along a proposed tunnel route would require special attention.

CONCLUSIONS

STRATIGRAPHY

1. The feasibility study area is underlain by a complex sequence of sediments of Jurassic–Cretaceous, Pleistocene and Recent age (p.3).
2. The Upper Jurassic sediments are almost wholly clays: the Oxford Clay, West Walton Beds, Ampthill Clay and Kimmeridge Clay (p. 6). Stratigraphical levels within these clays can be precisely defined using the fauna and lithology. The Kimmeridge Clay is the easiest formation to subdivide stratigraphically because of its greater range of lithologies and richer fauna (p. 10).
3. The Lower Cretaceous sediments consist mainly of loose sands, the Sandringham Sands (p.21).
4. The Pleistocene (Glacial) deposits are lithologically complex (p. 22); they probably infill a pre-Glacial land surface which, in buried valleys, locally extends down to 70 to 100 m below OD (p. 27).
5. The Recent deposits, up to 30 m thick, infill a topography of lower relief than that of the sub-Pleistocene surface; (p. 33–34).
6. Geophysical borehole logging techniques, particularly total gamma-ray logging, can be used for rapid stratigraphical correlation purposes and can supplement the data from the borehole cores where the latter are incomplete (p. 38).

ENGINEERING PROPERTIES

1. The bulk chemistry and lithologies of the Upper Jurassic clay can be broadly related (p. 39). The engineering properties of the soil-tested samples of Upper Jurassic clay cannot be related in detail to their lithologies. Tested samples from the Oxford Clay and the West Walton Beds were appreciably stronger than those from the Ampthill Clay and the Kimmeridge Clay; these results may be related to a lower limit of mechanical weathering at 80 to 90 m below OD (p. 43).
2. Much of the Upper Jurassic clays would probably provide a suitable medium for soft-ground tunnelling. However, they contain a number of harder bands, the most important of which are limestones (p. 43). Kerogen-rich clays, capable of producing hydrocarbon vapours at relatively low temperatures, occur in the Kimmeridge Clay (p. 48).
3. Much of the Glacial deposits is composed of till which is likely to be comparable to the Ampthill Clay and the Kimmeridge Clay as a tunnelling medium. Other lithologies, less suitable for tunnelling, such as sand and gravel and varved clay, are also present (pp. 48–49). Erratic boulders occur in the till.
4. The Recent deposits are mostly soft and very soft, and are unlikely to be a suitable medium for tunnelling (pp. 49–50).
5. The Upper Jurassic clays appear to be mechanically weathered down to about 80 to 90 m below present ground level. At depths greater than this, irrespective of stratigraphical horizon, the clays may be significantly stiffer (pp. 50–51).
6. The geological structure of the feasibility study area is simple: no major fold or fault has been recorded in either the offshore or the inland area. Small faults and very broad gentle folds have been recorded; these are unlikely to have any major influence on the tunnelling properties of the clays (p. 52).
7. Pre-Glacial weathering effects (e.g. valley-bulging) have not been recorded in the present study. They might be present, however, particularly in the central parts of the glacially-filled valleys (p. 53).

LOCAL DETAILS OF THE GEOLOGY

1. The data needed for a comparison of all possible tunnel lines to depths of 150 m, in the area examined in detail, are summarised in a series of contour and isopachyte diagrams (p. 56).
2. Further drilling would be needed before the areas beneath the Bull Dog Sand alternative (p. 58) and the western part of the Wingland alternative (p. 58) could be assessed in similar detail.
3. The general geology of Stages 2, 3 and 4 is similar to that of Stage 1, with glacially-filled valleys cut into Upper Jurassic clays. The stratigraphy and engineering properties of these clays are likely to be similar to those of the Stage 1 area. Parts of the later stages might need to use the Lower Oxford Clay as a tunnelling medium. Care would then be needed to avoid water problems and possible hydraulic fracturing close to the junction with the Kellaways Beds and the Middle Jurassic (p. 58).

POSSIBLE FUTURE SITE INVESTIGATION

1. The shapes of the sub-Recent and sub-Pleistocene surfaces could best be explored using boreholes. Geoelectrical methods and water-borne seismic profiling could also be employed to supplement the borehole programme in certain areas (p. 59).
2. The stratigraphy of the Glacial deposits could only be explored satisfactorily by means of closely-spaced boreholes (p. 59).
3. The stratigraphy of the Upper Jurassic clays could be explored most economically by means of boreholes combined with total gamma-ray logging; other logging techniques might also prove useful. If tunnelling were carried out in the Upper Jurassic clays it would not be necessary for all boreholes to be drilled to the tunnel level or for continuous cores to be taken (p. 59). Because the stratigraphy of the Kimmeridge Clay is known in greater detail, it could more easily be explored than the Ampthill Clay or the West Walton Beds.
4. The presence of folds and faults could be deduced only from a general consideration of the borehole data (p. 52). If a tunnel were dug, it would be advisable to monitor its course stratigraphically by taking frequent samples from the cutting face. Any small fold or fault encountered could then be noted and appropriate action taken.

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APPENDIX A

Details of Feasibility Study boreholes referred to in the text

Thirty cored boreholes and forty-two shell-and-auger boreholes were drilled in connection with the feasibility study. Twenty-five cored boreholes were drilled by Foraky Ltd in the inland area, one by Wimpey Ltd in the intertidal area and four by the Wimpey drilling ship m.v. *Whitethorn* in deep water in the central part of The Wash under the direction of the Continental Shelf Unit South of IGS. All the cored boreholes are described below.

Details of the shell-and-auger boreholes (including sites, sampling procedures and drillers' logs) are given in the contractors reports (Anon., 1972a by Soil Mechanics Ltd; Anon. 1972b by Foraky Ltd; and Anon., 1973 by Wimpey Ltd). Only the shell and auger boreholes in the inland area (drilled by Foraky Ltd) and those in the offshore area which penetrated glacial deposits (drilled by Wimpey Ltd) are described below. The lithological descriptions given for the sequences in these boreholes are based on limited sampling: the thicknesses allocated to the formations are therefore taken from the drillers' logs.

CORED BOREHOLES

Borehole 1: Denver Sluice [TF 5911 0106] Ground level: +3.60 m OD
Drilled by Foraky. 'Rock bitted' to 8.00 m; cored to 171.10 m. *See* Figure 28 for details of succession.

Borehole 2A: Ongar Hill [TF 5767 2444] Ground level: +3.89 m OD
Drilled by Foraky. Shell and auger (Borehole 2) to 52.00 m; cored to 88.20 m.

	Thickness m	*Depth* m
Recent deposits (see Borehole 2 for details)	21.15	21.15
Glacial deposits: Chalky/Jurassic till with thin beds of varved clay and waterlaid till; Kimmeridge Clay-rich in lower part	46.82	67.97
Kimmeridge Clay: Beds 1 to 13 inclusive	c13.5	c81.5
Ampthill Clay: Beds 36 and 40 separated by core losses	c6.7	88.20
Final depth		88.20

Borehole 3C: West Walton Highway [TF 4913 1316] Ground level: +1.58 m OD
Drilled by Foraky. 'Rock bitted' to 20.73 m; cored to 99.40 m. *See* Figure 28 for details of succession.

Borehole 4A: Gedney Drove End [TF 4665 2939] Ground level: +3.72 m OD
Drilled by Foraky. 'Rock bitted' to 20.13 m; cored to 100.44 m. *See* Figure 28 for details of succession.

Borehole 10 and 10A: Tilney All Saints [TF 5791 1779] Ground level: +2.41 m.
Drilled by Foraky. 'Rock bitted' to 9.00 m; cored to 50.15 m.

	Thickness m	*Depth* m
Recent deposits; clay, silt and fine-grained sand with thin peat beds; flint gravel at base	c15.0	c15.0
Kimmeridge Clay: Beds 18 to 30 inclusive	c35.15	50.15
Final depth		50.15

Borehole 13: Lordsbridge [TF 5704 1244] Ground level: +0.31 m OD
Drilled by Foraky. 'Rock bitted' to 16.00 m; cored to 70.00 m.

	Thickness m	*Depth* m
Recent deposits: clay, silt and fine-grained sand with thin peat beds	c16.0	c16.0
Glacial deposits: Chalky/Jurassic till with thin beds of varved clay, sand and gravel and waterlaid till	c33.6	49.58
Ampthill Clay: Beds 19 to 39 inclusive	20.42	70.00
Final depth		70.00

Borehole 17: Hook Drain [TF 5721 0827] Ground level −1.21 m OD
Drilled by Foraky. 'Rock bitted' to 8.59 m; cored to 49.78 m. *See* Figure 28 for details of succession.

Borehole 23: North Wootton [TF 6439 2457] Ground level +9.26 m OD
Drilled by Foraky. 'Rock bitted' to 5.38 m; cored to 170.34 m. *See* Figure 28 for details of succession.

Borehole 24: Walkers Marsh [TF 5268 2530] Ground level +2.12 m OD
Drilled by Foraky. 'Rock bitted' to 14.90 m; cored to 69.18 m. *See* Figure 28 for details of succession.

Borehole 25: Emorsgate [TF 5321 2006] Ground level +2.54 m OD
Drilled by Foraky. 'Rock bitted' to 23.00 m; cored to 49.52 m.

	Thickness m	*Depth* m
Recent deposits: clay and fine-grained sand with flint gravel at base	c23.6	c23.6
Kimmeridge Clay: Beds 6 to 18 inclusive	c25.9	49.52
Final depth		49.52

Borehole 26: Terrington St John [TF 5401 1435] Ground level: +2.21 m OD
Drilled by Foraky. 'Rock bitted' to 20.02 m; cored to 45.00 m.

	Thickness m	*Depth* m
Recent deposits: clay and fine-grained sand with flint gravel at base	c12.5	c12.5
Kimmeridge Clay: Beds 1 to 18 inclusive	c31.6	44.10
Ampthill Clay: Beds 41 and 42	0.90	45.00
Final depth		45.00

Borehole 27: Marshland St James [TF 5449 0875] Ground level: −0.96 m OD
Drilled by Foraky. 'Rock bitted' to 18.70 m; cored to 40.12 m.

	Thickness m	*Depth* m
Recent and Glacial deposits: clay and fine-grained sand (Recent deposits) on Chalky/Jurassic till and laminated clay	c18.0	c18.0
Kimmeridge Clay: Bed 1+, deeply weathered	c2.2	c20.2
Ampthill Clay: Beds 30 to 41 inclusive	c19.9	40.12

Borehole 28: Old Podike Bank [TF 5657 0536] Ground level: −1.40 m OD
Drilled by Foraky. 'Rock bitted' to 12.16 m; cored to 34.20 m.

	Thickness m	*Depth* m
Recent deposits: clay with thin peat beds	c11.0	c11.0
Kimmeridge Clay: Beds 16 to 29 inclusive	c23.2	34.20
Final depth		34.20

Borehole 29: Symington Farm [TF 5499 2507] Ground level: +4.85 m OD
Drilled by Foraky. 'Rock bitted' to 20.68 m; cored to 75.20 m.

	Thickness	Depth
	m	m
Recent deposits: silt and fine-grained sand	c19.3	c19.3
Glacial deposits: Chalky/Jurassic till	c35.8	55.13
Kimmeridge Clay: Beds 1 to 12 inclusive	c14.1	c69.2
Ampthill Clay: Beds 40 and 41	c6.0	75.20
Final depth		75.20

Borehole 30: Balaclava Farm [TF 5549 2339] Ground level: +3.40 m OD
Drilled by Foraky. 'Rock bitted' to 30.00 m; cored to 80.36 m.

	Thickness	Depth
	m	m
Recent deposits: silt and fine-grained sand	c26.2	c26.2
Glacial deposits: Chalky/Jurassic till with pockets of chalk and flint gravel	c35.3	c61.5
Kimmeridge Clay: Beds 1 to 12 inclusive	c8.5	69.95
Ampthill Clay: Beds 33 to 42 inclusive	10.41	80.36
Final depth		80.36

Borehole 31: Admirals Farm [TF 5651 2486] Ground level: +4.14 m OD
Drilled by Foraky. 'Rock bitted' to 23.71 m; cored to 71.70 m.

	Thickness	Depth
	m	m
Recent deposits: clay, silt and fine-grained sand with thin peat bed	c22.0	c22.0
Glacial deposits: Chalky/Jurassic till with thin beds of varved clay and gravelly sand	c32.0	54.00
Kimmeridge Clay: Beds 2 to 16 inclusive	17.70	71.70
Final depth		71.70

Borehole 32: Pierrepont Farm [TF 5748 2322] Ground level: +3.50 m OD
Drilled by Foraky. 'Rock bitted' to 18.28 m; cored to 83.10 m.

	Thickness	Depth
	m	m
Recent deposits: mostly fine-grained sand	c20.5	c20.5
Glacial deposits: Chalky/Jurassic till, very gravelly in part	c43.3	63.81
Kimmeridge Clay: Beds 1 to 16 inclusive	18.99	82.80
Ampthill Clay: Bed 42	0.30	83.10
Final depth		83.10

Borehole 33: The Grange [TF 5807 1329] Ground level: +1.32 m OD
Drilled by Foraky. 'Rock bitted' to 10.00 m; cored to 30.00 m.

	Thickness	Depth
	m	m
Recent deposits: clay with thin peat beds	c9.5	c9.5
Kimmeridge Clay: Beds 18 to 25 inclusive	c20.5	30.00
Final depth		30.00

Borehole 34: Wiggenhall St Peter [TF 6030 1319] Ground level: +2.86 m OD
Drilled by Foraky. 'Rock bitted' to 14.10 m; cored to 90.31 m.
See Figure 28 for details of succession.

Borehole 35: Stowbridge [TF 6022 0640] Ground level: +1.48 m OD
Drilled by Foraky. 'Rock bitted' to 5.66 m; cored to 49.47 m.
See Figure 28 for details of succession.

Borehole 36: Spice Chase [TF 5513 1292] Ground level: +2.47 m OD
Drilled by Foraky. 'Rock bitted' 20.29 m; cored to 66.90 m.

	Thickness	Depth
	m	m
Recent deposits: mostly clay	c11.2	c11.2
Glacial deposits: Chalky/Jurassic till	c31.6	42.78
Ampthill Clay: Beds 17 to 40 inclusive	24.12	66.90
Final depth		66.90

Borehole 37: Tilney Fen Side [TF 5445 1106] Ground level: -0.25 m OD
Drilled by Foraky. 'Rock bitted' to 11.10 m; cored to 49.30 m.

	Thickness	Depth
	m	m
Recent deposits: clay and fine-grained sand	c11.0	c11.0
Glacial deposits: mostly varved clay to c18 m on Chalky/Jurassic till	17.9	28.92
Ampthill Clay: Beds 26 to 41	10.38	49.30
Final depth		49.30

Borehole 38: Racecourse Road [TF 5510 2194] Ground level: +3.49 m OD
Drilled by Foraky. 'Rock bitted' to 21.08 m; cored to 39.45 m.

	Thickness	Depth
	m	m
Recent deposits: silt and fine-grained sand	c20.7	c20.7
Kimmeridge Clay: Beds 19 to 28 inclusive	c18.8	39.45
Final depth		39.45

Borehole 39: New Common Marsh Farm [TF 5299 2308] Ground level: +1.57 m OD
Drilled by Foraky. 'Rock bitted' to 20.77 m; cored to 39.75 m.

	Thickness	Depth
	m	m
Recent deposits: silt and fine-grained sand	c19.4	c19.4
Kimmeridge Clay: Beds 14 to 19 inclusive	c20.4	39.75
Final depth		39.75

Borehole 40: Vinegar Middle [TF 6092 2505] Ground level: +3.20 m OD
Drilled by Foraky. 'Rock bitted' to 12.68 m; cored to 84.26 m.

	Thickness	Depth
	m	m
Recent deposits: clay, silt and fine-grained sand	c10.7	c10.7
Glacial deposits: Chalky/Jurassic till with thin beds of varved clay and waterlaid till	c54.3	64.96
Kimmeridge Clay: Beds 12 to 19 inclusive	19.30	84.26
Final depth		84.26

Borehole 513: Daseley's Sand [TF 5591 3189] Ground level (Sea bed): -1.20 m OD
Drilled by Wimpey. 'Rock bitted' to 13.20 m; cored to 80.02 m.
See Figure 28 for details of succession.

Borehole IGS 71/65 (in Lynn Deeps) [TF 5850 4676]
Borehole datum: sea bed. Water depth: 30.0 to 33.5 m (tidal).
Drilled by m.v. *Whitethorn.*
Rock bitted to 11.50 m; cored to 43.00 m.
See Gallois and Cox, 1974, pp. 23–28 for details of succession.

Borehole IGS 71/66 (off Sunk Sand) [TF 6117 4475]
Borehole datum: sea bed. Water depth: 19.0 to 22.0 (tidal).
Drilled by m.v. *Whitethorn.*
'Rock bitted' to 15.00 m; cored to 45.00 m.
See Gallois and Cox, 1974, pp. 17–23 for details of succession.

Borehole IGS 72/77 A & B (near The Well) [TF 6313 4835]
Borehole datum: sea bed. Water depth: 27.0 to 31.4 (tidal).
Drilled by m.v. *Whitethorn*.
Borehole A: 'rock bitted' to 6.00 m; cored to 10.50 m.
Borehole B: 'rock bitted' to 9.00 m; cored to 53.20 m.
See Gallois and Morter (*in* Wingfield and others, 1978, Appendix A) for details of succession.

Borehole IGS 72/78 (near The Well) [TF 6494 4972]
Borehole datum: sea bed. Water depth: 16.0 to 20.2 m (tidal).
Drilled by m.v. *Whitethorn*.
'Rock bitted' to 4.00 m; cored to 56.15 m.
See Gallois and Morter (*in* Wingfield and others, 1978, Appendix A) for details of succession.

SHELL-AND-AUGER BOREHOLES

Borehole 1A: Salter's Lode [TL 5784 9976] Ground level: +3.74 m OD
Drilled by Foraky. Bulk, disturbed and U4 samples.

	Thickness m	*Depth* m
Made ground: dredged silty sand	c1.0	c1.0
Recent deposits		
Terrington Beds: interlaminated, micaceous silt and dull red-brown silty clay	c0.70	1.70
Nordelph Peat: soft reedy peat	1.70	3.40
Barroway Drove Beds: very soft pale grey clay riddled with peat rootlets	c4.6	c7.0
Glacial deposits		
Chalky/Jurassic till: stony grey clay with chalk and flint pebbles and locally derived Jurassic and Cretaceous pebbles; varved clay from c10.5 to c15.0 m	c14.9	21.90
Lower Kimmeridge Clay	1.10	23.00
Final depth		23.00

Borehole 2: Ongar Hill [TF 5767 2444] Ground level: +3.89 m OD
Drilled by Foraky. Bulk, disturbed and U4 samples.

	Thickness m	*Depth* m
Topsoil: organic silt	0.40	0.40
Recent deposits		
Terrington Beds passing down into intertidal flat and tidal creek deposits: fine- and very fine-grained sand and silty sand with rare disarticulated *Tellina*, *Cerastoderma* and small oyster shells	16.56	16.96
Subtidal deposit: shelly gravelly sand with small blackened flints and common fragments of *Mytilus*, *Cerastoderma*, *Ostrea* and *Tellina*	c1.0	c18.0
?Lag deposit: gravelly sand, clayey in part, with blackened flints and many other stones derived from local glacial deposits; small shell chips scattered throughout	c3.2	21.15
Glacial deposits		
Chalky/Jurassic till: stiff grey clay with chalk and flint stones, locally rich in derived Sandringham Sands; varved clay from c49.7 to 52.00 m	30.85	52.00
Final depth		52.00

Borehole 8: Clenchwarton [TF 5988 2048] Ground level: +2.11 m OD
Drilled by Foraky. Bulk, disturbed and U4 samples.

	Thickness m	*Depth* m
Recent deposits		
Terrington Beds: dull reddish brown slightly silty clay	1.30	1.30
Nordelph Peat: soft reedy peat	0.10	1.40
Barroway Drove Beds: very soft pale grey clay riddled with peat rootlets	2.28	3.68
Barroway Drove Beds: intertidal flat or tidal creek deposits; very fine-grained sand and silt with fragments of thin-shelled bivalves and bivalve spat	2.32	6.00
Barroway Drove Beds: soft pale grey clay as above; silty in part with *Scrobicularia* common at some levels	5.20	11.20
?Lag deposit: clayey sand with scattered shells resting on flinty sand	c1.8	c13.0
Lower Kimmeridge Clay	c1.6	14.61
Final depth		14.61

Borehole 12: Smeeth Lode [TF 5838 1472] Ground level: +1.07 m OD
Drilled by Foraky. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Terrington Beds: soft grey clay with many *Hydrobia* at base	1.20	1.20
Nordelph Peat: soft reedy peat	1.06	2.26
Barroway Drove Beds: very soft pale grey clay riddled with peat rootlets; becoming silty in lowest part	5.24	7.50
Channel lag deposit: clayey gravelly sand with many tiny pebbles of Kimmeridge Clay; passing down into shell bed composed of *Cerastoderma*, *Mytilus*, *Tellina* and other bivalves set in a gravelly sand matrix	1.00	8.50
'Lower' Peat: soft reedy peat mixed with peat-riddled soft clay (?base of Barroway Drove Beds)	0.40	8.90
Lower Kimmeridge Clay	3.76	12.66
Final depth		12.66

Borehole 14: Wiggenhall Sidings [TF 5911 1041] Ground level: +2.82 m OD
Drilled by Foraky. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Made ground: railway embankment made of redeposited Terrington Beds	2.60	2.60
Terrington Beds: dull reddish brown clay and silt	1.62	4.22
Nordelph Peat: soft reedy peat	0.31	4.53
Barroway Drove Beds: very soft pale grey clay riddled with peat rootlets	c4.3	c8.9
'Lower' Peat: soft reedy peat	c0.1	8.99
Lag deposit: gravelly sand with blackened flints	c1.5	c10.5
Glacial deposits		
Varved clay and Chalky/Jurassic till interbedded to 13.4 m, then till to base of deposit	c11.7	22.16
Kimmeridge Clay	0.84	23.00
Final depth		23.00

Borehole WY 208: (near Hull Sand) [TF 5545 2921]
Ground level (sea bed): -0.40 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine-grained sand and silty sand with scattered shells	13.20	13.20
Glacial deposits		
Hunstanton till: dull orange-brown sandy clay with small chalk and other erratic stones	4.30	17.50
Sand and gravel (driller's log)	4.80	22.30
?Till or interglacial deposit: grey sandy clay with traces of organic matter (driller's log)	1.70	24.00
Kimmeridge Clay	1.00	25.00
Final depth		25.00

Borehole WY 220 (near old barrier wall) [TF 5729 2916]
Ground level (sea bed): -1.80 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand and silty sand with scattered shells	8.50	8.50
Glacial deposits		
Hunstanton till: dull orange-brown and red-brown slightly sandy clay with small chalk and red marl (?Keuper) pebbles common; rarer coal, igneous rock and flint pebbles together with streaks of grey Chalky/Jurassic till: deeply weathered upper surface with traces of peat roots	2.80	11.30
Sand and gravel (driller's log)	2.80	14.10
Lower Kimmeridge Clay	2.10	16.30
Final depth		16.30

Borehole WY 501 (on Breast Sand) [TF 5322 2704] Ground level (sea bed): +1.30 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine-,medium- and coarse-grained sands, shelly in part	16.00	16.00
Glacial deposits		
Varved clay: pale grey and brownish grey clay and silty clay; deeply weathered and penetrated by peat roots	1.50	17.50
Kimmeridge Clay	1.45	18.95
Final depth		18.95

Borehole WY 503 (near River Nene outfall) [TF 4998 2712]
Ground level (sea bed): +1.80 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand	14.70	14.70
Sand and gravel with shell fragments (driller's log)	2.05	16.75
Glacial deposits		
Chalky/Jurassic till: grey slightly sandy clay with scattered chalk, flint and Jurassic erratic pebbles	7.45	24.20
Final depth		24.20

Borehole WY 509 (on Hull Sand) [TF 5445 3033] Ground level (sea bed): -0.90 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand	13.40	13.40
Sand and gravel	2.50	15.90
Glacial deposits		
Varved clay: interlaminated dull red-brown clay and fine-grained sand	1.10	17.00
Sand with thick beds of sand and gravel (driller's log)	10.20	27.20
Kimmeridge Clay: deeply weathered	0.05	27.25
Final depth		27.25

Borehole WY 510 (near Daseley's Sand) [TF 5698 3055]
Ground level (sea bed): -0.30 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand	8.65	8.65
Glacial deposits		
Hunstanton till: mottled grey and dull red-brown slightly sandy clay with chalk, flint, Triassic and other erratic stones	6.55	15.20
Varved clay: dull red-brown clay with partings of brown silt; tiny stones widely spaced throughout	c1.8	c17.0
?Kimmeridge Clay or interglacial deposit		
Soft grey and brownish grey clay with scattered leached bivalve fragments	c1.0	18.00
Final depth		18.00

Borehole WY 513 (on Daseley's Sand) [TF 5591 3189]
Ground level: -1.20 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand	10.50	10.50
Glacial deposits		
Hunstanton till: dark red-brown and brownish grey sandy clay with tiny chalk, flint, Triassic and far-travelled erratics; weathered and penetrated by peat roots	1.50	12.00
Lower Kimmeridge Clay: *see* Daseley's Sand cored borehole for details of Jurassic succession	1.00	13.00
Final depth		13.00

Borehole WY 514 (on Daseley's Sand] [TF 5579 3194]
Ground level (sea bed): -3.50 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	*Depth* m
Recent deposits		
Fine- and medium-grained sand	5.10	5.10
Gravel and sand with shell fragments	0.90	6.00
Glacial deposits		
Chalky/Jurassic till: dark grey sandy clay with chalk and flint erratics	5.50	11.50
Lower Kimmeridge Clay	0.45	11.95
Final depth		11.95

Borehole WY 1001 (in River Gt Ouse) [TF 5944 2527]
Ground level (river bed): +1.50 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	Depth m
Recent deposits		
Fine- and medium-grained sand	11.40	11.40
Brown peaty clay (driller's log)	0.20	11.60
Sand and gravel	0.90	12.50
Glacial deposits		
Chalky/Jurassic till: pale brownish grey clay with chalk and flint erratics	2.50	15.00
Final depth		15.00

Borehole WY 1002 (in River Gt Ouse) [TF 5979 2431]
Ground level (river bed): -1.80 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	Depth m
Recent deposits		
Fine- and medium-grained sand and silty sand	6.70	6.70
Glacial deposits		
Varved clay: interlaminated very pale grey silt and pale grey clay with scattered small chalk and flint pebbles	2.80	9.50
Final depth		9.50

Borehole WY 1003 (in River Gt Ouse) [TF 6011 2360]
Ground level (river bed): -2.10 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	Depth m
Recent deposits		
Fine- and medium-grained sand; gravelly below 5.30 m	8.10	8.10
Glacial deposits		
Chalky/Jurassic till: grey and brownish grey sandy clay with chalk and flint erratics	1.90	10.00
Final depth		10.00

Borehole WY 1004 (in River Gt Ouse) [TF 6069 2220]
Ground level (river bed): -2.60 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	Depth m
Recent deposits		
Fine- and medium-grained sand	3.10	3.10
Glacial deposits		
Till: deeply weathered dull red-brown and grey clay with chalk erratics (?Hunstanton till) passing down into dark grey clay with chalk and flint erratics (Chalky/Jurassic till)	7.35	10.45
Final depth		10.45

Borehole WY 1509 (near Bulldog Sand) [TF 6131 2947]
Ground level (sea bed): +1.50 m OD
Drilled by Wimpey. Bulk, disturbed and U4 samples

	Thickness m	Depth m
Recent deposits		
Fine- and medium-grained sand and silty sand with scattered shells	7.50	7.50
Sand and gravel	1.35	8.85
Glacial deposits		
Hunstanton till: dull red-brown sandy clay with streaks of grey clay and with chalk, flint and Triassic erratics	c1.1	c11.0
Chalky/Jurassic till: dark grey clay with chalk and Kimmeridge Clay erratics	c1.5	12.45
Final depth		12.45

APPENDIX B

Description of the standard stratigraphical sequences of the Upper Kimmeridge Clay, Ampthill Clay and West Walton Beds

Beris M. Cox and R. W. Gallois

The feasibility study and associated IGS cored boreholes have provided the opportunity for a detailed study of the lithological and faunal sequences of the West Walton Beds, Ampthill Clay and Kimmeridge Clay. The detailed stratigraphy of these formations was previously unknown in this area due to lack of exposure. The present work has shown that all three formations contain lithological and faunal characters which, taken together, can be traced throughout an area much larger than that of the feasibility study; the sequences have therefore proved to be of considerable use in the study of Upper Jurassic stratigraphy throughout eastern England.

A bed-by-bed description of the standard stratigraphical sequence for the Lower Kimmeridge Clay has been given elsewhere (Gallois and Cox, 1976). Similar descriptions for the Upper Kimmeridge Clay (*see* Figure 13), Ampthill Clay (*see* Figure 7) and West Walton Beds are given below. Further discussion of the Ampthill Clay and West Walton Beds sequences of the feasibility study area and other parts of Fenland is given in Gallois and Cox (1977).

Upper Kimmeridge Clay

In the feasibility study area the highest part of the Kimmeridge Clay has been removed by erosion at the base of the Sandringham Sands and the upper part of the *Pectinatites (P.) pectinatus* Zone and the *Pavlovia* zones are missing. The following bed-by-bed description is based mainly on IGS Boreholes 71/65 and 71/66 (Gallois and Cox, 1974) and the North Wootton Borehole (Bh. 23). The beds are numbered consecutively (36 to 49) to follow those of the Lower Kimmeridge Clay (1 to 35) described elsewhere (Gallois and Cox, 1976).

Additional details have been taken from IGS boreholes at North Runcton and Donington on Bain (Gallois, 1978) and Skegness, Hunstanton, Gayton and Marham (Institute of Geological Sciences 1971; 1972). Thicknesses refer to the North Wootton Borehole (Beds 35 to 45) and the Donington on Bain Borehole (Beds 46 to 49). The fossil determinations are taken mainly from Gallois and Cox (1974) and Cope (1974).

Pectinatites (P.) pectinatus Zone

Bed 49: Oil shale, sparsely shelly with some *'Lucina'* plasters and three thin coccolith-rich bands; interbedded with dark grey, sparsely shelly mudstone 4.49 m

Bed 48: Cementstone, medium grey, muddy limestone with secondary calcite veins; barren 0.11 to 0.23 m lenticular

Bed 47: Mudstone, predominantly dark and medium grey with several thin interbeds of pale grey mudstone and, in upper part, oil shale; generally sparsely shelly with *'Lucina' miniscula* Blake, *Protocardia morinica* (de Loriol), *Discinisca latissima* (J. Sowerby) and *Lingula ovalis* J. Sowerby common at some levels; *Camptonectes* cf. *morini* (de Loriol), *Grammatodon, Modiolus autissiodorensis* (Cotteau), *Pleuromya, Oxytoma* and small oysters also present; fragments of finely ribbed perisphinctid ammonites including *Pectinatites (P.) eastlecottensis* (Salfeld); base taken at top of coccolith-rich band 4.33 m

Bed 46: Mudstone, dark and medium grey, thinly interbedded with fissile, shelly oil shales which include several thin bands of pale brownish grey coccolith-rich limestone; fauna as Bed 47 but with fish debris and faecal pellets common in the oil shales; *Pectinatites (P.) eastlecottensis* common throughout; rarer *P. (P.) cornutifer* (Buckman) and *P. (P.) pectinatus* (Phillips); base taken at base of shelly oil shale which marks the lower limit of *P. (P.) eastlecottensis* 0.35 m

Pectinatites (Arkellites) hudlestoni Zone

Bed 45: Mudstone, dark and medium grey with thin oil shale interbeds common in upper part; prominent pale grey band in middle part; sparsely shelly except in lower part; scattered *Dicroloma, Lingula, 'Lucina', Protocardia, Thracia* and small oysters; *Pectinatites*, including *P. (Virgatosphinctoides) encombensis* Cope, scattered throughout; colour change at base 4.70 m

Bed 44: Mudstone, pale and medium grey, highly calcareous; sparsely shelly with well preserved ammonites including *Pectinatites (Virgatosphinctoides) reisiformis* Cope and rarer *P. (Arkellites) hudlestoni* Cope, *P. (V.) donovani* Cope and, in the lower part, *P. (V.) pseudoscruposus* (Spath); epizoic oysters common and other bivalves including *Pleuromya; Dentalium* and fish fragments; persistent tabular cementstone band near base of bed; pyritised pins; base marked by sharp colour change with evidence of minor erosion in some Norfolk sections 6.35 m

Bed 43: Mudstone, medium and dark grey; sparsely shelly with fragments of bivalves including oysters, fish debris, *Dicroloma* and ammonites including *Pectinatites (V.) pseudoscruposus, P. (V.) reisiformis* and *P. (V.) wheatleyensis* (Neaverson); base taken at top of oil shale seam 0.35 m

Bed 42: Oil shale, fissile, shelly, foraminifera-spotted, with plasters of *'Lucina'* and fragmentary ammonites including *Pectinatites (V.) grandis* (Neaverson), *P. (V.) pseudoscruposus, P. (V.) reisiformis* (highest part only) and *P. (V.) wheatleyensis;* pyritised radial plates of *Saccocoma* common at some levels in upper part of bed; interbeds of dark and medium grey, sparsely fossiliferous mudstone occur throughout; *'Lucina'*, small oysters and *Dentalium* locally common; *Protocardia, Opis, Chemnitzia, Dicroloma; Discinisca, Lingula* and fish fragments also present; the junction of the *hudlestoni* and *wheatleyensis* zones falls within this bed; base of bed taken at base of oil shale seam 3.63 m

Pectinatites (Virgatosphinctoides) wheatleyensis Zone

Bed 41: Mudstone, dark grey, smooth textured with pyrite 'halos'; sparsely shelly with bivalves including *Astarte* and well preserved ammonites including *Pectinatites (V.) grandis, P. (V.) pseudoscruposus, P. (V.) wheatleyensis* and *P. (V.) woodwardi* (Neaverson), some with epizoic oysters and some with partial infilling of cream-coloured phosphate; rare wood fragments and rhynchonellids; colour change at base 2.97 m

Bed 40: Mudstone, pale grey in upper part becoming medium and dark grey, brownish grey and silty textured with depth, with some burrowfills of oil shale; sparsely shelly in part with *Lingula, 'Lucina' miniscula, Modiolus autissiodorensis, Nanogyra virgula* (Defrance), *Protocardia morinica* and ammonites including *Pectinatites (V.) grandis, P. (V.) pseudoscruposus* and *P. (V.) wheatleyensis;* base taken at top of thin oil shale seam 1.58 m

Bed 39: Oil shale, brownish grey, shelly with *'Lucina'* plasters, *Modiolus, Protocardia, Thracia* and oysters; passing down into pale grey and brownish grey, smooth textured mudstone; colour change at base 0.92 m

Bed 38: Mudstone, medium and dark grey, sooty textured in part with much comminuted plant debris; foraminifera-spotted in part; sparsely shelly with *Grammatodon, Protocardia*, oysters, *Discinisca, Lingula* and fragments of *Pectinatites* including *P. (Virgatosphinctoides) sp.;* rare thin interbeds of oil shale; bed crowded with *Nanogyra virgula* locally present near base 2.35 m

Pectinatites (Virgatosphinctoides) scitulus Zone

Bed 37 Oil shale with interbeds of dark and medium grey mudstone; shelly in part with '*Lucina*' plasters and burrowfill concentrations of other bivalves including *Astarte* and *Protocardia*; rarer *Dentalium*, *Dicroloma*, *Discinisca* and *Pectinatites*; base taken at base of densely calcite-cemented oil shale 2.75 m

Pectinatites (Virgatosphinctoides) elegans Zone

Bed 36: Mudstone, dark, medium and pale grey interbedded and with thin interbeds of oil shale; shelly in part with *Astarte*, *Camptonectes*, *Inoceramus*, '*Lucina*', *Nanogyra virgula*, *Protocardia*, *Dicroloma* and *Pectinatites* including *P.* (*V.*) *elegans* Cope and *P.* (*Arkellites*) *primitivus* Cope; base taken at base of oil shale immediately above highest *Aulacostephanus* 3.35 m

Lower Kimmeridge Clay
(*see* Gallois and Cox, 1976, for details)

Ampthill Clay and West Walton Beds

The Ampthill Clay sequence is based mainly on the North Wootton (Bh. 23), West Walton Highway (Bh. 3C) and Gedney Drove End (Bh. 4A) boreholes. Additional details have been taken from boreholes 1, 2, 13, 17, 24, 26, 27, 29, 30, 34, 36, 37 and 513B. Information on the ranges of large ammonites and oysters, which are rarely preserved complete in the borehole cores (average core diameter 100 mm), is based on temporary exposures in southern Fenland. Thicknesses refer to Bh. 23 (Beds 2 to 42) and Bh. 3C (Bed 1).

The West Walton Beds sequence is based mainly on Borehole 3C. Additional details have been taken from boreholes 1 and 4A. Thicknesses refer to Bh. 3C.

Kimmeridge Clay (pars)
(*see* Gallois and Cox, 1976, for details)

Bed 1: Mudstone, strikingly interburrowed, pale and dark grey; sparsely shelly with *Entolium* and *Modiolus*. Minor but widespread erosion surface at base marked by burrowing and rare phosphatic nodules, with some bivalves and ammonites (including *Pictonia*) preserved in soft, pale brown phosphate 0.30 m

Ampthill Clay

?Amoeboceras regulare Zone

Bed 42: Mudstone, very pale grey, barren with burrowfill concentrations of pyrite knots and pins; passing down into pale grey, slightly silty mudstone with medium grey burrowfills; sparsely shelly with *Oxytoma* and small oysters; minor erosion surface at base marked by striking colour change with interburrowing and scattered cream-coloured phosphatic nodules 0.20 m

Bed 41: Mudstone, medium grey, smooth textured; moderately shelly with bivalves common, including *Anisocardia*, *Camptonectes*, *Oxytoma*, *Placunopsis*, *Protocardia*, *Thracia*, arcids and oysters; *Dicroloma*, rare serpulids, echinoid spines and brachiopods; *Ringsteadia* and partially pyritised perisphinctid nuclei common; burrowfills of shell debris common in upper part of bed; becoming slightly paler in lower part with rare cream-coloured phosphatic nodules and prominent pale bed including cementstone dogger with *Deltoideum delta* (Wm Smith) and common *Thracia*; lowest few centimetres darker than above with comminuted plant debris and many pyrite knots; striking lithological change at base with interburrowed junction 1.90 m

Bed 40: Mudstone, pale and medium grey, silty with irregular fracture; well developed chondritic mottling and other burrows occur throughout, a few partially phosphatised; cementstone bands and doggers at several levels; fauna dominated by oysters, many occurring as angular fragments in burrowfills and encrusted with *Bullapora*; *Chlamys*, *Ringsteadia*, perisphinctid nuclei, wood fragments and pyritised trails also present 2.00 m

weakly interburrowed junction with

Bed 39: Mudstone, pale and medium grey, smooth textured with rare cream-coloured phosphatic patches; shelly with *Camptonectes*, *Chlamys*, *Oxytoma*, oysters including *Nanogyra*, *Dicroloma*, serpulids and rare echinoid spines; partially pyritised perisphinctid nuclei and crushed *Ringsteadia?* 0.90 m

passing down into

Bed 38: Mudstone, pale grey, sparsely shelly with *D. delta*, *Oxytoma*, pectinids; partially pyritised perisphinctid nuclei and *Microbiplices*; pyritised trails 0.75 m

interburrowed junction with

Bed 37: Mudstone, medium grey, silty; intensely burrowed with small angular black phosphatic chips and oyster fragments, some with encrusting *Bullapora* and serpulids, scattered throughout; shelly in part with *D. delta*, *Oxytoma*, *Trigonia*, *Microbiplices* and belemnites; widespread erosion surface at base marked by phosphatic nodule bed and interburrowing 0.33 m

Amoeboceras regulare Zone

Bed 36: Mudstone, medium slightly greenish grey, smooth-textured; alternating sparsely shelly and shelly with shell debris plasters; belemnites and serpulids common with *Isognomon*, *Modiolus*, *Oxytoma*, *Pinna*, *Protocardia*, *Thracia*, thin shelled oysters, *Procerithium* and echinoids; partially pyritised perisphinctid nuclei and iridescent pyritised *Amoeboceras* including *A. freboldi* Spath; pyrite pins, knots and trails; widespread erosion surface at base marked by large oysters (*D. delta*), bored and rolled belemnites, black angular phosphatic pebbles and interburrowing 4.20 m

Bed 35: Mudstone, slightly greenish medium and pale grey; sparsely shelly with *D. delta*, *Pinna*, common *Thracia*, rare belemnites; *Amoeboceras* including *A. freboldi* 1.12 m

passing down into

Bed 34: Mudstone, medium grey, very shelly, packed with partially pyritised small gastropods and serpulids; rarer *Protocardia*, *Thracia* and crustacean fragments; rare *Amoeboceras* including *A. schulginae* Mesezhnikov 0.10 m

passing down into

Bed 33: Mudstone, slightly greenish medium to dark grey with several large cream-coloured partially phosphatised patches and local cementstones: sparsely shelly with *Astarte*, *Protocardia*, *Thracia depressa* J. Sowerby, *Amoeboceras freboldi* and *Perisphinctes*; widespread erosion surface at base marked by phosphatised oyster debris (including *D. delta*) and small angular phosphatic pebbles 0.48 m

Bed 32: Mudstone, medium slightly greenish grey; burrow-mottled with numerous pyritised trails; moderately shelly with *Amoeboceras* including *A. freboldi*, *Astarte*, *Protocardia* and small gastropods 0.28 m

passing down into

Bed 31: Mudstone, medium grey, silty, plant-speckled and with cream-coloured phosphatic patches; shelly with plasters of *Astarte*, *Protocardia*, *Camptonectes* and other bivalves; *Amoeboceras*, small gastropods and rare serpulids also present 0.20 m

passing down into

Bed 30: Mudstone, medium slightly greenish grey, smooth textured; sparsely shelly with *Amoeboceras* including *A.* cf. *freboldi* and *A. pectinatum* Mesezhnikov, belemnites, *Protocardia*, oysters and small gastropods; widespread minor erosion surface at base marked by oyster chips, rolled belemnites, small angular black phosphatic pebbles and, locally, by numerous *Modiolus* preserved in solid cream-coloured phosphate 0.25 m

Bed 29: Mudstone, medium slightly greenish grey; sparsely shelly but with clusters of *Procerithium; Protocardia, Thracia*, small belemnites, serpulids, iridescent pyritised *Amoeboceras* including *A. freboldi* and phosphatised body chamber fragments; pyritised trails also present 0.25 m
irregular junction with
Bed 28: Cementstone, densely cemented and locally composed largely of shells; rich in *Camptonectes, D. delta* and other oysters, *Protocardia, Thracia* and small *Amoeboceras*; lenticular bed of very variable thickness up to 0.70 m
Bed 27: Mudstone, medium and dark grey, slightly silty, plant-speckled and sooty textured in part; oysters, including *D. delta*, relatively common; *Thracia*, scattered serpulids, iridescent *Amoeboceras* including *A. freboldi* and *A.* cf. *leucum* Spath, and pyritised trails also present 1.66 m
passing down into
Bed 26: Mudstone, medium grey, slightly silty; very pyrite-rich with trails, knots and other burrowfills all with prominent brown oxidation 'halos'; sparsely shelly with partially pyritised *Protocardia* common at some levels, *Thracia*, small belemnites, rare serpulids, *Amoeboceras* including *A.* cf. *leucum* 1.40 m
passing down into

Amoeboceras serratum Zone
Bed 25: Mudstone, medium and pale grey, slightly silty in part, mostly burrow-mottled; pyrite pins and trails abundant at some levels; sparsely shelly with nests of thick shelled nuculoids, common *Thracia, Anisocardia*, rare belemnites, iridescent *Amoeboceras* including *A.* cf. *freboldi* and *A. leucum*, and *Perisphinctes*; base taken at highest *Protocardia* plaster of bed below 1.20 m
Bed 24: Mudstone, faintly greenish and brownish grey; slightly silty, sooty textured and plant-rich in part; foraminifera-spotted in part; plasters and partial plasters of *Protocardia* at many levels; *Camptonectes* and belemnites; shell plaster at base 0.63 m
Bed 23: Mudstone, medium grey, silty in part and with thin brownish grey weakly bituminous beds; shelly at some levels with *Protocardia* common, *Thracia*, belemnites, small gastropods, serpulids, rare fish fragments and faecal pellets; thin silty, foraminifera-spotted bed at base with bivalves in 'ghost' preservation and much fish debris 0.82 m
passing down into
Bed 22: Mudstone, medium brownish grey, fissile, bituminous; shelly with *Protocardia* and other bivalves in plasters; *Amoeboceras serratum* (J. Sowerby), belemnites, small gastropods and abundant foraminifera; interburrowed junction with bed below 0.10 m
Bed 21: Mudstone, pale slightly greenish grey with darker burrowfills and rare cream-coloured phosphatic patches; shelly in part with *Pinna, Protocardia, Thracia*, oysters, serpulids, rare *Pentacrinus*, common *Perisphinctes* with *Amoeboceras*, all preserved as debris; pyrite pins and trails common; marked lithological change at base 0.64 m
Bed 20: Mudstone, medium grey, silty with much plant debris and rarer wood fragments; intensely burrow-mottled with many burrows pyrite-stained; thin beds of smoother, paler grey mudstone at several levels; sparsely shelly with *Camptonectes, Entolium, Pinna, Protocardia, Thracia;* huge oysters (*D. delta*) locally present; iridescent *Amoeboceras* including *A.* cf. *mansoni* Pringle and *A. serratum*, rarer perisphinctids 1.56 m
passing down into
Bed 19: Mudstone, medium to pale grey, slightly silty with rare cream-coloured phosphatic patches; shelly in part with burrowfill concentrations of partially pyritised *Procerithium*, serpulids, *Pinna* and *Amoeboceras* fragments, scattered small oysters including *Nanogyra, Camptonectes, Thracia, Trigonia, Lingula*, echinoid spines, *Amoeboceras* including *A.* cf. *freboldi* and *A. regulare* Spath, rarer *Perisphinctes;* shell plaster with ammonites and bivalves at base 0.81 m

Bed 18: Mudstone, medium to pale grey, smooth textured with cream-coloured phosphatic patches and some thin beds of foraminifera-spotted and sooty textured mudstone with plant debris; rare plasters of *Procerithium, Pinna* and *Camptonectes*, together with burrowfill concentrations of these as shell debris; sparsely shelly with *Camptonectes, Oxytoma, Protocardia*, serpulids, rare echinoid spines, *Amoeboceras* including *A.* cf. *serratum*, and pyritised trails; shell plaster at base 0.99 m
Bed 17: Mudstone, medium grey becoming pale grey with depth; smooth textured with silty burrowfills and wisps of shell debris; pyritised trails and burrowfills, some with oxidation 'halos', common at several levels; rare coffee-coloured phosphatic nodules; bed includes thin tabular siderite mudstone and thin lenticular shelly cementstone band; sparsely shelly with *Camptonectes, Grammatodon*, paired valves of *Myophorella, Oxytoma, Pinna, Thracia, Dicroloma*, echinoid spines and rare serpulids; pyritised ammonites including large *Perisphinctes* and *Amoeboceras* including *A.* cf. *glosense* (Bigot & Brasil), *A. nunningtonense* Wright and *A.* cf. *serratum*, probable minor but widespread erosion surface at base 4.10 m

Amoeboceras glosense Zone
Bed 16: Siderite mudstone, pale brown, dense, barren; irregular upper surface with shrinkage cracks, encrusting oysters and extensive boring and burrowing; lenticular bed apparently occurring as tabular masses up to 2 m across at outcrop; sharp lithological change at base up to 0.10 m
Bed 15: Mudstone, medium grey with pyrite pins and trails, some with oxidation 'halos'; cream-coloured phosphatic patches, some enclosing fauna, common in lower part; shelly with fauna dominated by small partially pyritised iridescent perisphinctid nuclei (*Decipia?*) and *Amoeboceras* including *A. ilovaiskii* (Sokolov) and *A.* cf. *transitorium* Spath, some concentrated in burrowfills; larger *Amoeboceras* including *A. glosense, A. nunningtonense* and *A.* cf. *transitorium; Entolium, Pleuromya, Thracia, Pentacrinus* columnals and rare serpulids also present; equivalent of the younger Long Stanton fauna of Torrens and Callomon (1968) 2.72 m
passing down into

Cardioceras tenuiserratum Zone, *C. blakei* Subzone
Bed 14: Mudstone, medium and pale grey, slightly silty, almost barren with pyrite knots and trails; rare cream-coloured phosphatic patches; becoming paler and more calcareous with depth and with incipient cementstone bands; *Camptonectes*, small oyster fragments, *Dicroloma* and perisphinctid fragments and inner whorls including *Decipia;* at outcrop fauna dominated by *Decipia spp.*, older Long Stanton fauna of Torrens and Callomon (1968) 1.22 m
passing down into
Bed 13: Mudstone, pale grey becoming medium grey with depth; gritty and with irregular fracture due to included shell debris; pyrite pins and trails; burrowfill concentrations and partial plasters of comminuted shells and small fossils including *Camptonectes*, oysters, *Dicroloma, Procerithium* and perisphinctid nuclei; large oysters including, at outcrop, serpulid-encrusted *Gryphaea dilatata* J. Sowerby, common in lower part of bed; interburrowed junction at base 0.75 m
Bed 12: Mudstone, pale and very pale grey, calcareous, passing locally into cementstone; smooth fracture tending to subconchoidal; very sparsely shelly with *Camptonectes, Pinna, Thracia*, small oysters, perisphinctid fragments, *Cardioceras sp. nov.* and pyritised trails; including, at outcrop, fossiliferous cementstone doggers rich in *Decipia* and allied forms; becoming medium grey with paler burrowfills in lower part 1.25 m
passing down into

Bed 11: Mudstone, medium and pale grey, slightly silty in part; sparsely shelly but with many large *Gryphaea*, some smaller oysters, *Entolium*, *Grammatodon*, *Thracia*, *Dicroloma*, *Cardioceras sp. nov.*, perisphinctid fragments and pyrite pins and trails; base taken at lowest *Gryphaea* plaster 1.80 m

Bed 10: Mudstone, medium grey, gritty textured due to shell debris, passing down into pale grey mudstone with impersistent weak cementstone; shelly in upper part, becoming sparsely shelly with depth and including *Chlamys*, *Entolium*, *Myophorella*, *Oxytoma*, fragmentary and small oysters, some with encrusting *Bullapora*, rare *Lingula*, *Cardioceras sp. nov.*, perisphinctid fragments and pyrite pins and trails, *Dicroloma*, many with associated guilielmites structures, common in lower part 2.90 m

passing down into

Bed 9: Mudstone, medium grey, slightly silty with irregular fracture; foraminifera-spotted throughout; moderately shelly with *Thracia*, other bivalve debris, *Dicroloma*, *Cardioceras sp nov.* and perisphinctid fragments 0.15 m

passing down into

Bed 8: Mudstone, medium to dark grey, slightly silty; shelly in part with burrowfill concentrations of serpulids, *Dicroloma* with guilielmites structures and bivalve and ammonite debris; scattered perisphinctid fragments common; *Cardioceras kokeni* Boden and *C. sp. nov.* in plasters 0.45 m

passing down into

Bed 7: Mudstone, medium to pale grey, slightly silty with many small pyritised trails; irregular fracture due to scattered shell debris; generally sparsely shelly but with many serpulids; small oysters, *Entolium*, *Oxytoma*, *Dicroloma* with associated guilielmites structures, *Cardioceras kokeni* and *C. sp. nov.* also present 1.42 m

passing down into

Bed 6: Mudstone, medium grey, slightly silty but with smoother texture than bed above; shelly with crushed, small, thin shelled *Cardioceras* preserved in white calcite and often partially pyritised, including *Cardioceras blakei* Spath, *C. cawtonense* (Blake & Hudleston) and *C. sp. nov.*; scattered serpulids, bivalve debris and perisphinctid fragments 0.28 m

passing down into

Bed 5: Mudstone, medium grey with some slightly darker and paler bands; in part silty and with sooty texture, particularly in upper half of bed; rare plant-speckled and brownish grey faintly bituminous layers; rare cream-coloured phosphatic nodules; sparsely shelly in upper part but with small belemnites common; moderately shelly in lower part with *Grammatodon*, *Thracia*, *Dicroloma*, rare serpulids and crustacean fragments, and crushed small white *Cardioceras blakei*, *C. cawtonense*, *C. kokeni*, *C. maltonense* (Young and Bird), *C. tenuiserratum* (Oppel), *C.* (*Subvertebriceras*) *sp.* and *C. sp. nov.*, some with guilielmites structures; pyrite knots with oxidation 'halos' common in lower part of bed 3.10 m

passing down into

Cardioceras tenuiserratum Zone, *C. tenuiserratum* Subzone

Bed 4: Mudstone, medium grey, silty, plant-speckled; sparsely shelly with bivalve debris, *C. kokeni*, *C. maltonense*, *C. tenuiserratum*, rare small belemnites and wood fragments 0.80 m

passing down into

Bed 3: Mudstone, medium to pale grey, slightly silty to silty, burrow-mottled, finely plant-speckled in part; sparsely to very sparsely shelly with *Cardioceras tenuiserratum* very common at some levels in grey 'ghost' preservation; scattered bivalve debris including *Thracia*; *C. cawtonense*, *C. kokeni* and *C. maltonense* preserved partly as 'ghosts' and partly in white calcite 2.70 m

passing down into

Bed 2: Mudstone, medium and dark grey, slightly silty to silty, burrow-mottled and plant-speckled; foraminifera-spotted in part; moderately shelly with shells mostly in white or weakly iridescent calcite preservation; some shell debris concentrated in burrowfills; *Thracia*, *Cardioceras* aff. *blakei*, *C. cawtonense?*, *C. kokeni*, *C. maltonense*, *C. tenuiserratum* and rare belemnites 2.40 m

passing down into

Bed 1: Mudstone, medium grey, slightly silty becoming paler and more silty in lower part; silty burrowfills with plant specks and burrowfill shell concentrations common at some levels; moderately shelly with bivalves and ammonites preserved in white calcite, including *Grammatodon*, *Thracia*, *Cardioceras cawtonense*, *C. kokeni*, *C. maltonense*, *C. tenuiserratum*, *C.* (*Subvertebriceras*) *sp.* and rare belemnites; junction taken at the lowest white or iridescent calcitic fossils; these are coincident with a downward change to paler, more calcareous and more silty mudstone 3.15 m

WEST WALTON BEDS

Bed 16: Mudstone, medium to pale grey, silty; sparsely shelly with rare myid and pectinid bivalves, *Pinna*, *Cardioceras tenuiserratum* and large *Perisphinctes* all preserved as 'ghosts'; large serpulid-encrusted *Gryphaea* and small pyritised trails also present; locally containing small cementstone nodules 0.47 m

passing down with interburrowing into

Bed 15: Mudstone, medium to pale grey, silty, with intense chondritic mottling; passing down into pale and very pale grey, very calcareous, slightly silty mudstone and cementstone; very sparsely shelly with myid bivalves, small oyster fragments encrusted by *Bullapora*, *Lopha*, *Pinna* and pyritised trails 1.52 m

interburrowed junction with

Bed: 14 Mudstone, pale and medium grey, intensely interburrowed with smooth textured, pale grey mudstone and very gritty (shell debris), silty, medium grey mudstone; very irregular fracture; shelly with much broken bivalve debris, mostly oysters; *Lopha*, *Pholadomya* and pyritised ammonite 'ghosts', including *Cardioceras tenuiserratum* and *Perisphinctes*, also present 0.36 m

interburrowed junction with

Bed 13: Mudstone, medium and pale grey, slightly silty to silty, passing locally into cementstone; very sparsely shelly with *Gryphaea* encrusted by *Bullapora*, rare pectinid bivalves, *Oxytoma* and *Cardioceras tenuiserratum* 0.85 m

passing down into

Bed 12: Mudstone, medium and pale grey, very silty; shelly with large *Bullapora*-encrusted *Gryphaea*, *Chlamys* and partially pyritised *Cardioceras tenuiserratum* and *Perisphinctes* 0.12 m

interburrowed junction with

Bed 11: Mudstone, dark grey, silty, foraminifera-spotted and with much silt grade bivalve debris; moderately shelly with bivalves including *Chlamys*, *Grammatodon* and *Plagiostoma* in partially leached calcite preservation; partially pyritised ammonites including *Cardioceras schellwieni* Boden, *C. tenuiserratum* (common in burrow clusters) and *Perisphinctes*; echinoid debris, *Dentalium*, wood fragments and pyritised trails also present 0.53 m

interburrowed junction with

Cardioceras densiplicatum Zone, *C. maltonense* Subzone

Bed 10: Mudstone, medium to pale grey, slightly silty and silty; burrow-mottled throughout with chondritic mottling in upper part; shelly in part with calcitic and 'ghost' preservation bivalves including small oysters, *Gryphaea* (encrusted by serpulids and *Bullapora*), arcid bivalves, *Astarte*, common *Chlamys*, *Gresslya*, *Myophorella*, *Pholadomya* and *Pleuromya*; partially pyritised ammonites including *Cardioceras maltonense*, *C.* cf. *schellwieni*, *C.* cf. *wrighti* Arkell and *Perisphinctes*; rare belemnites, *Dicroloma*, serpulids and pyritised trails also present;

cementstone concretions formed around some *Gryphaea* 2.00 m
interburrowed junction with

Bed 9: Mudstone, medium grey becoming darker with depth, silty with much comminuted shell debris, burrow-mottled, locally intensely foraminifera-spotted, plant-speckled in part; shelly and very shelly with arcid bivalves, *Astarte, Chlamys*, encrusted and bored *Gryphaea, Oxytoma*, poorly preserved *Cardioceras* including *C. (Subvertebriceras) sp., Perisphinctes*, small belemnites and pyritised trails 0.50 m
interburrowed junction with

Bed 8 Mudstone, faintly greenish pale grey, slightly silty passing locally into cementstone; intensely burrow-mottled with darker, more silty, burrowfills; sparsely shelly with poorly preserved bivalves including small oysters, *Myophorella* and *Pinna;* partially pyritised *Cardioceras* fragments and rare echinoid fragments 0.60 m
interburrowed junction with

Cardioceras densiplicatum Zone, *C. vertebrale* Subzone

Bed 7: Mudstone, dark and medium grey interburrowed, silty with much comminuted shell and plant debris, foraminifera and disseminated pyrite in the matrix; burrow and chondritic mottling; shelly with partially leached and/or partially pyritised calcitic preservation including *Chlamys*, encrusted *Gryphaea* fragments, *Lopha, Myophorella* and common *Pinna*, some in growth position; *Cardioceras* common including *C. (Plasmatoceras) popilianense* Boden, *C. (Scoticardioceras)* cf. *excavatum* (J. Sowerby), *C. (S.)* cf. *expositum* (S.S. Buckman), *C. (S.)* cf. *serrigerum* (S.S. Buckman), *C. (Subvertebriceras)* cf. *densiplicatum* Boden; rare *Ochetoceras*, clusters of *Procerithium*, rare belemnites, common pyritised trails; oyster plaster at base 1.40 m

Bed 6: Mudstone, pale grey with darker burrowfills, slightly silty with some silt and foraminifera-rich burrowfills; sparsely shelly with oyster fragments, *Pinna, Cardioceras*, crustacean fragments, pyrite knots and trails 1.82 m
interburrowed junction with

Bed 5: Mudstone, medium to pale grey, with rare cementstone concretions; slightly silty to silty, faintly foraminifera-spotted and plant-speckled in part; tiny pyritised trails common; burrow-mottled in part; sparsely shelly but with burrowfill concentrations of shell debris including encrusted oysters, *Astarte, Chlamys, Myophorella, Pinna*, clusters of *Procerithium*, small belemnites (*Hibolites?*), serpulids and crustacean debris; *Cardioceras* including *C. (Subvertebriceras)* cf. *sowerbyi* Arkell, preserved as brown calcite films and pyritised nuclei 1.58 m
interburrowed junction with

Cardioceras cordatum Zone, *C. cordatum* Subzone

Bed 4: Mudstone, pale grey, smooth textured, very slightly silty, rare cementstone concretions; very sparsely shelly with *Cardioceras* including *C. (Plasmatoceras) sp;* brown oxidised pyritised trails common 0.40 m
interburrowed junction with

Bed 3: Mudstone, medium to dark grey, silty, plant-speckled in part especially towards base; burrow-mottled, faintly foraminifera-spotted; sparsely shelly with *Gryphaea, Procerithium* and *Cardioceras (C.)* cf. *cordatum* (J. Sowerby) 0.50 m
interburrowed junction with

Bed: 2 Mudstone, medium grey becoming darker with depth, silty, chondritic and burrow mottling in part with some burrowfill concentrations of silt, plant debris and foraminifera; passing locally into cementstone; sparsely shelly with *Cardioceras* including *C. (C.) ashtonense* Arkell and *C. (C.)* aff. *costicardia* S.S. Buckman, in calcitic preservation and as pyritised nuclei; rare *Euaspidoceras;* pyritised trails common together with irregular patches of pyrite film 1.05 m
interburrowed junction with

Cardioceras cordatum Zone, *C. costicardia* Subzone

Bed 1: Mudstone, medium to pale grey passing locally into cementstone; silty with much comminuted shell debris and foraminifera, faintly plant-speckled in part; sparsely shelly to shelly with *Cardioceras* including *C. (Subvertebriceras)* cf. *costellatum* S.S. Buckman and *C. (Scarburgiceras) sp.* in calcitic preservation and as pyritised nuclei; oysters and small belemnites common; strikingly interburrowed junction with burrowfills of foraminifera-rich silt extending down into bed below 0.36 m

UPPER OXFORD CLAY (pars)

Mudstone, pale grey, slightly silty, smooth-textured; brassy pyrite knots and trails common; sparsely shelly but with many well preserved crustacean fragments and numerous *Pinna* in pyritic preservation; rare oyster fragments, nuculoid bivalves, *Astarte, Dicroloma* and small belemnites (5 m +).

REFERENCES

See pp.60–62.

APPENDIX C

X-ray diffraction analyses of Upper Jurassic clay samples

R. J. Merriman and G. E. Strong

INTRODUCTION

Forty-two samples of Upper Jurassic clay were examined by X-ray diffraction analysis, to determine the respective percentages of clay minerals, calcium carbonate and quartz. For calcium carbonate determination, the X-ray method was complemented by calcimeter determination. Most of the samples were chosen from the debris of the soil-tested core samples; other samples were chosen to provide a representative selection of lithologies and stratigraphical horizons.

SAMPLE PREPARATION

In order to select representative portions of the samples for analysis, about 150 to 200 grammes of each sample was crushed to pass an 8-mesh BS seive, then the samples were dried at 60°C for two days prior to final crushing to pass a 100-mesh sieve. Portions from these powders were used for X-ray diffractometer analysis.

The calcite peaks on the X-ray charts were calibrated by determining the total acid-soluble calcium carbonate contents of six aragonite-free samples using a calcimeter (*see* Bascomb, 1961, for details). The calcium carbonate content of a seventh sample, containing a high proportionate of aragonite, was also determined using the calcimeter and the percentage calcite (obtained from the calibrated X-ray charts) subtracted from the total calcium carbonate content to determine the aragonite percentage.

CALCIMETER RESULTS

Sample nos.	$CaCO_3$
	%
GS 108/DX 917	8
GS 117/DX 926	20
GS 121/DX 930	40
GS 134/DX 938	69
GS 141/DX 944	90
GS 143/DX 946	73
GS 122/DX 951*	33

*Calcite 18%, aragonite 15%; remaining samples aragonite-free

Accuracy +5% to −1 per cent of figures expressed

X-RAY DIFFRACTION

X-ray examination was carried out with a diffractometer using the powdered sample back-packed into aluminium holders. The instrument was set to scan between 3° and 36°2θ, using nickel-filtered CuK$_\alpha$ radiation, 40 kV, 30 mA; slit system 1°, 0.1, 1°, at a speed of ½° 2θ/min.

The minerals detected in the course of the scan are listed in Table 11. The abundance of certain minerals is expressed as a percentage of the whole sample. Percentage quartz was estimated by measurement of the 4.26 Å and 3.34 Å peak heights, followed by reference to a plot of X-ray intensity data for known mixtures of quartz in montmorillonite. Calcite was determined by calibrating the X-ray intensity of the 3.04 Å peak against calcimeter results, using six aragonite-free samples that covered the range of calcite X-ray intensities.

The term 'total clay' in Table 11 refers to the total amount of phyllosilicate present in the sample, irrespective of grain size. Estimates of amounts were obtained by measurement of the non-basal reflection at 19.9° 2θ, after the method used by Schultz (1964). Because of variation in composition and degree of preferred orientation in the sample mount, no attempt has been made to quantify specific clay minerals. Instead, under the heading 'Clay minerals present', an estimate of the relative order of abundance is indicated. The dominant clay mineral present is a dioctahedral phyllosilicate possessing a 10 Å basal spacing. It forms perhaps as much as 50 per cent of some samples (e.g. GS 120 and 129). In most samples the 10 Å peak is broad and commonly asymmetric, descending steeply on the high-angle side, indicating the 'open' mica structure typical of illite. However, some 10 Å peaks possess a sharp apex (e.g. GS 113, 117 and 132), suggesting that a well-crystallised mica (?muscovite/sericite) is present in addition to illite.

Kaolinite is present in all but three of the limestone samples (GS 141, 143 and 147), possibly amounting to 12 per cent of the total in samples GS 124, 127 and 131. Chlorite, where present, is generally subordinate to kaolinite. An expanding clay mineral, probably a smectite, appears to be restricted to a few samples of limestone and very calcareous clay and accounts for no more than one or two per cent of the total clay mineral content.

Minor amounts of gypsum, pyrite, feldspar and aragonite are just detectable in many of the samples; a minimum of one or two per cent of these minerals can be detected by the present method. The high aragonite content in sample GS 122 (15 per cent) is thought to be due to the presence of abundant shell material.

Dolomite and apatite are identified tentatively in Table 11 since only the strongest reflections of their respective X-ray patterns appear to be present, and then only as low peaks. The dolomite peak at 30.96° 2θ is uncharacteristically broad in a number of samples (e.g. GS 108–117, 125, 132 and 133), due perhaps to very small crystal size or variation in iron content. This adds to the uncertainty of the identification. Dolomite is undoubtedly present in samples GS 126, 130, 146, reaching perhaps 6 per cent of the total in GS 130. The apatite peak at about 32° 2θ also tends to be broad, suggesting poorly-crystalline phosphate (collophane).

Very small amounts (<1 per cent) of accessory minerals would escape detection as their diffraction patterns tend to be swamped by the general background. Amorphous material, including kerogen, cannot be detected by X-ray diffraction.

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Bascomb, C. L. 1961. A calcimeter for routine use on soil samples. *Chem. & Ind.*, July–Dec., pp. 1826–1827.

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Table 11 X-ray diffraction analyses of Upper Jurassic sediments from the feasibility-study boreholes

IGS Sample No.	Depth	Bore-hole No.	X-ray Chart No. DX	Clay minerals present ‡	Total Clay	Quartz	Calcite	Other minerals detected	Lithology
	m				%	%	%		
GS 108*	13.06	1	917	Il, Ka, Ch	48	30	8	Gy, Py, Fs (j.d.), (?) Do	Mudstone, dark grey, sparsely shelly
GS 144	22.86	1	947	Il, Ka, Ch, Sm	19	3	71	Ar, Py	Quasi-cementstone, shelly
GS 109*	23.14	1	918	Il, Ka, Ch	37	10	32	Ar, Py, (?) Ap, (?) Do	Mudstone, medium and pale grey
GS 110*	34.38	1	919	Il, Ka, Ch	38	11	27	Gy, Ar, Py, (?) Do	Mudstone, dark grey, shelly, silty
GS 111*	45.61	1	920	Il, Ka, Ch	46	14	18	Gy, Ar, Py, (?) Do	Mudstone, dark grey, sparsely shelly
GS 107*	67.02	1	916	Il, Ka, Ch	52	12	22	Py	Mudstone, pale grey, barren
GS 106*	78.38	1	915	Il, Ka, Ch	43	14	19	Ar, Py, (?) Ap	Mudstone, medium grey, slightly silty
GS 143	91.95	1	946	Il, Ch, Sm	18	7	73	Py	Cementstone, barren
GS 105*	92.71	1	914	Il, Ch	43	16	28	Gy, Py	Mudstone, medium and pale grey, silty, tough
GS 112	99.80	1	921	Il, Ka, Ch	44	13	25	Py, Fs (j.d.), (?) Do	Mudstone, pale grey, barren
GS 142	117.70	1	945	Il, Ka, Ch	30	14	50	Gy	Mudstone, very pale, slightly silty

(continued)

Table 11 (continued)

IGS Sample No.	Depth	Bore-hole No.	X-ray Chart No. DX	Clay minerals present ‡	Total Clay	Quartz	Calcite	Other minerals detected	Lithology
	m				%	%	%		
GS 115•	52.16	3C	924	Il, Ka, Ch	58	13	17	Gy, Ar, Py, (?) Do	Mudstone, medium and pale grey
GS 116•	64.75	3C	925	Il, Ka, Ch	52	18	11	Gy, Ar, Py, (?) Do	Mudstone, very dark grey, sooty-textured
GS 114•	76.91	3C	923	Il, Ka, Ch	37	16	38	Gy, Py, (?) Do	Mudstone, pale grey, barren
GS 113•	89.39	3C	922	Il, Ka, Ch	47	13	26	Gy, Py, Fs (j.d.), (?) Do	Mudstone, pale grey, barren
GS 117	98.90	3C	926	Il, Ka, Ch	46	22	20	Py, (?) Do	Mudstone, medium grey, barren
GS 120•	53.95	4A	929	Il, Ka, Ch	53	18	-	Gy, Py	Mudstone, dark grey, sparsely shelly
GS 119•	62.78	4A	928	Il, Ka, Ch	59	13	10	Ar, Gy, Py, (?) Ap	Mudstone, medium grey, blocky
GS 118•	78.40	4A	927	Il, Ka, Ch	49	12	16	Ar, Gy, Py, (?) Ap	Mudstone, dark grey, sparsely shelly
GS 145	96.05	4A	948	Il, Ka, Ch	20	8	63	Py	Quasi-cementstone, silty, rare shells
GS 121	100.44	4A	930	Il, Ka, Ch	33	20	40	Py	Mudstone, medium grey, cemented, barren
GS 139	31.85	23	942	Il, Ka, Ch	23	7	54	Ar, Py	Mudstone, pale grey, barren, slightly silty
GS 122†	36.10	23	951	Il, Ka	20	9	18	Ar (15%), Gy	Oil shale, shelly
GS 124†	45.70	23	953	Il, Ka, Ch	46	20	-	Gy, Py, Fs	Oil shale, barren
GS 128	47.85	23	932	Il, Ka, Ch	18	9	66	Ar, Py	Cementstone, pyritic with oil shale patches
GS 123†	64.00	23	952	Il, Ka	27	12	20	Py, Gy, Ar	Oil shale, shelly
GS 125	68.20	23	931	Il, Ka, Ch	35	13	26	Ar, Py, (?) Do	Oil shale/mudstone, interburrowed, shelly
GS 137	69.15	23	941	Il, Ka, Ch	17	4	61	Ar, Py	Cementstone, muddy, shelly in part
GS 126†	75.80	23	954	Il, Ka, Ch	35	12	32	Gy (j.d.), Py, Ar, Do	Mudstone, medium grey, silty
GS 127†	76.10	23	955	Il, Ka	33	12	13	Py, Gy, Ar, (?) Do	Oil shale, barren, fissile
GS 140	98.30	23	943	Il, Ka, Ch, Sm	13	5	65	Ar	Cementstone, weakly cemented, slightly silty
GS 141	100.12	23	944	Il, Sm, Ch	7	2	90	-	Cementstone, densely cemented with calcite veining
GS 130•	58.61	24	934	Il, Ka, Ch	53	15	8	Gy, Py, (?) Ap, Do	Mudstone, medium grey, sparsely shelly
GS 129•	67.80	24	933	Il, Ka, Ch	66	17	4	Gy (j.d.), Py	Mudstone, dark greenish grey, almost barren
GS 131•	37.20	25	935	Il, Ka, Ch	47	14	-	Gy, Py	Mudstone, dark grey, fissile
GS 132•	47.14	25	936	Il, Ka, Ch	50	16	6	Gy, Ar, Py, (?) Ap, (?) Do	Mudstone, dark grey, sparsely shelly
GS 146	21.13	26	949	Il, Ka, Ch, Sm	25	8	47	Ar, Py, Do	Mudstone, pale grey, silty, almost barren
GS 133•	35.14	26	937	Il, Ka, Ch	45	12	18	Gy, Ar, Py, (?) Do	Mudstone, medium grey, sparsely shelly
GS 134•	28.68	27	938	Il, Ka, Ch	22	4	69	Gy	Quasi-cementstone
GS 135•	35.92	27	939	Il, Ka, Ch	56	17	6	Gy, Py, Fs (j.d.)	Mudstone, dark grey, blocky
GS 147	47.40	35	950	Il, Ch	10	<2	80	-	Cementstone, densely cemented
GS 136•	52.54	36	940	Il, Ka, Ch	53	21	-	Gy, Py, Fs (j.d.)	Mudstone, dark grey, sparsely shelly

Ap apatite
Ar aragonite
Ch chlorite
Do dolomite
Fs feldspar
Gy gypsum
Il illite
Ka kaolinite
Py pyrite
Sm smectite
(j.d.) just detectable
• soil-tested sample
† analysed for kerogen
‡ in decreasing order of abundance

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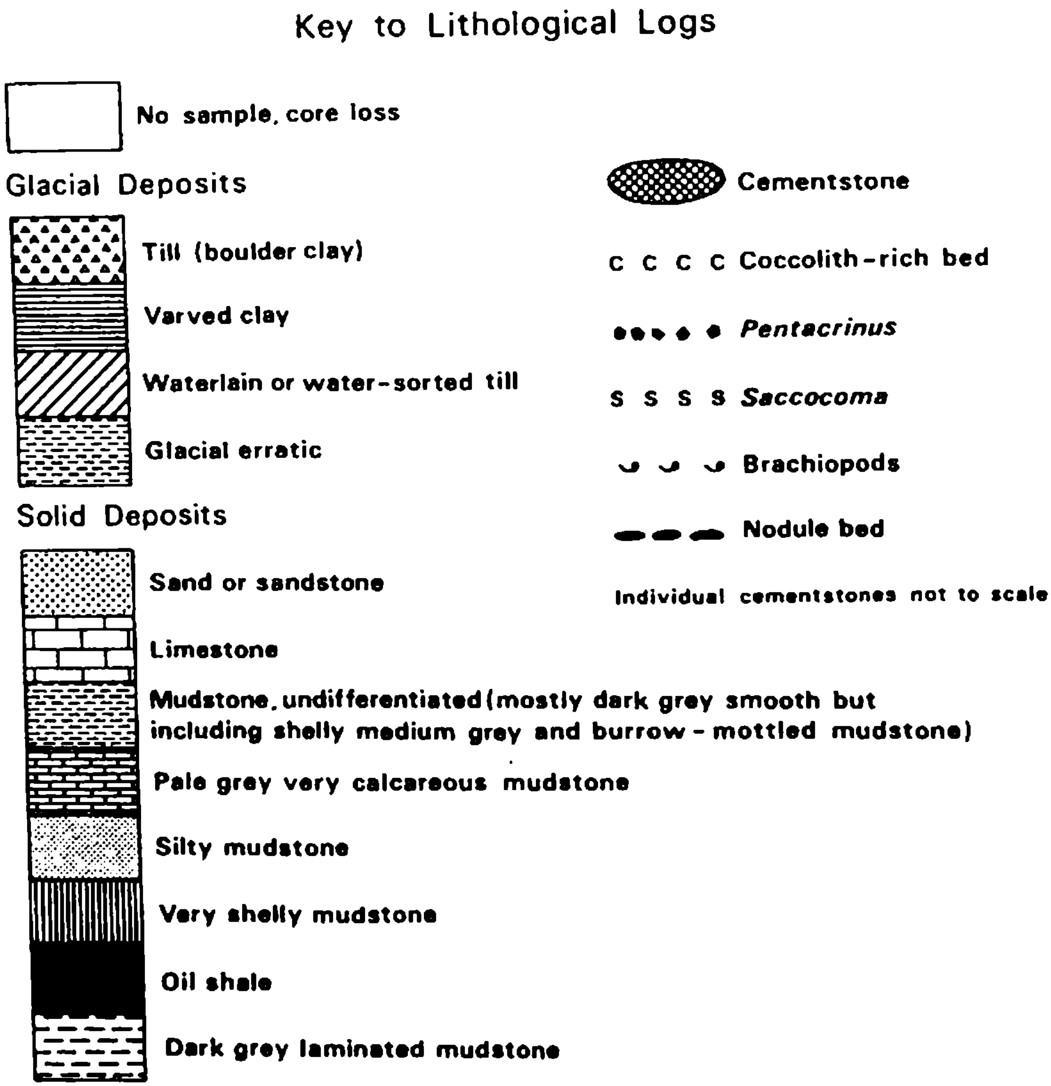

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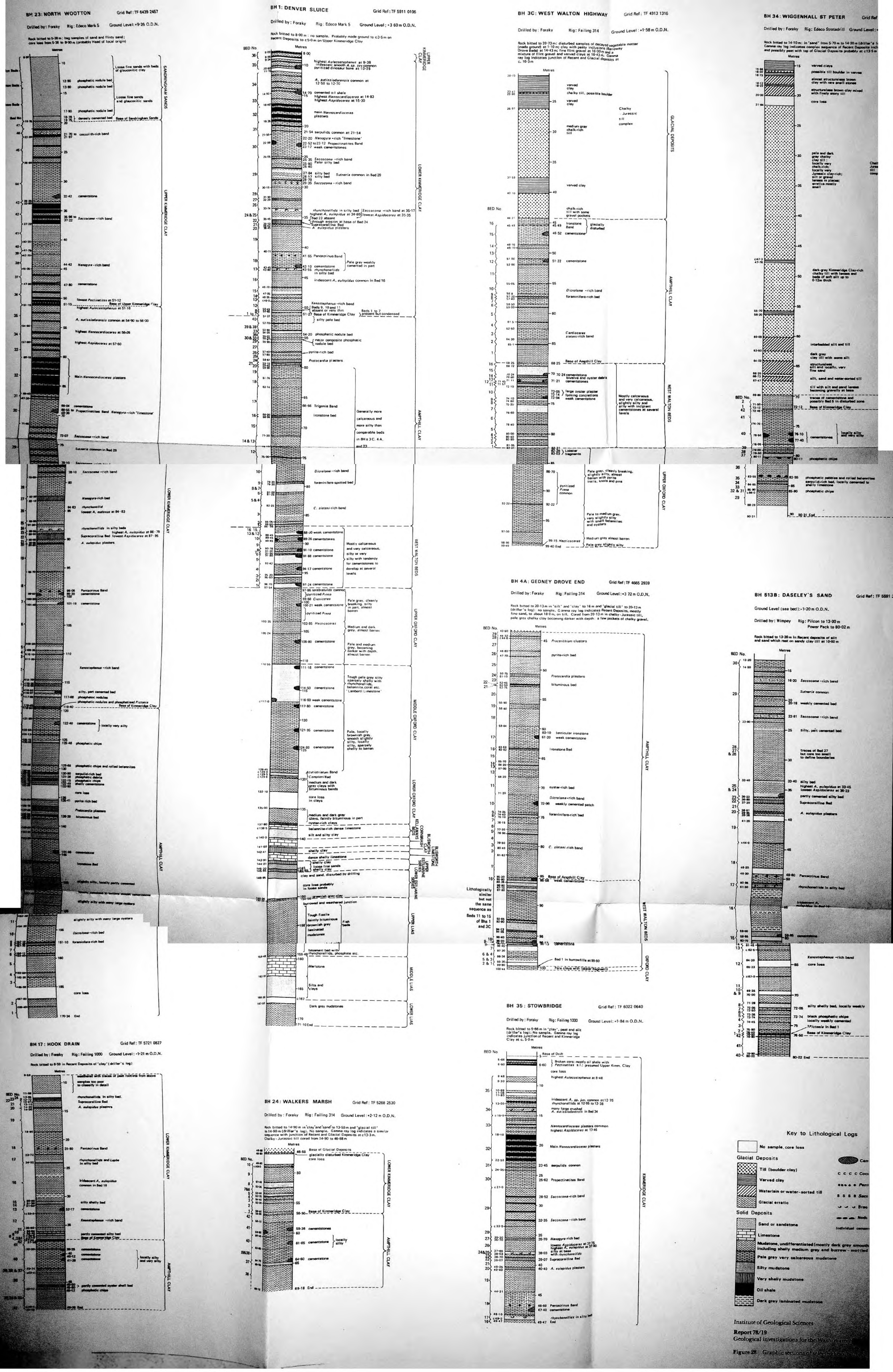
Figure 28 Graphic sections of selected Feasibility Study cored boreholes



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