

AN ENGINEERING GEOLOGY DATA BASE FOR URBAN RENEWAL

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ABSTRACT

Following a degeneration of many urban areas in recent decades, Government formed various Development Corporations with new powers to stimulate urban renewal. The London Docklands Development Corporation (LDDC) was one of the first. The thesis describes a role for engineering geology as a central function in urban renewal by developing the idea of data collation into a coordinated procedure to allow a continuing increase in experience and knowledge of the area.

The process of 'urbanization' is described, together with the legislative history to the Development Corporations.

Methods of geotechnical data storage and presentation are reviewed and considered within the needs of the LDDC. A system based on the use of microcomputer has been developed and is described. This requires only minimal staff and resource commitment. It provides for the transfer of data on floppy diskette and may be searched through a number of enquiry modules to extract and process the data.

A reappraisal of the geology and hydrogeology has been undertaken. This concludes that there is no evidence for the Greenwich Fault, the dominant structural feature being a northwards plunging syncline, the Greenwich Syncline. A depositional model developed for the Woolwich and Reading Beds indicates a number of transgressions and shows the area to be at the transition between marine and lagoonal facies separated by a series of migrating sand bars. The Thames Gravels correlate with work in the Middle and Lower Thames Valley and a further erosion level has been identified represented by the Silvertown Gravel. Groundwater levels are shown to be rising and are modelled to show their sensitivity to the urban setting.

An assessment of the engineering parameters of the Formations has been made. This shows a variation in the Woolwich and Reading Beds that correlates with the proposed depositional setting, that the London Clay conforms to the expected regional variations and that the Thanet Sand is a locked sand. The nature and problems of made ground are described.

A number of examples illustrate the engineering geological problems experienced during the process of urban renewal in the Docklands.

The approach described is considered to be applicable to other areas.

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CHAPTER ONE : INTRODUCTION

Over recent decades there has been a general degeneration within a number of the major urban areas of Great Britain. This has often been associated with a changing commercial base whereby a loss of traditional activities has left large areas devoid of stimulus. The reasons for the change are complex and not clearly understood. However, the Inner City Research Programme at Cambridge University has suggested that one factor is the actual physical constraints that are inherent in the established urban environment. The size and style of buildings, the layouts of roads and the capacity of its infrastructure impose a constraint on the necessary further expansion of business activity (Fothergill et al 1985).

In recent years increasing social and political pressures for the redevelopment of the rundown urban areas has become an accepted political aim so that Government policies currently favour urban renewal rather than earlier commitments to decentralisation.

Within the existing urban environment the changing trend in land use has resulted in extensive former industrial and commercial districts becoming available for redevelopment. Where a specific activity, such as may be generated by a single large employer, the presence of mining or a port, formed the reason for the very existence of the urban area itself it is very unlikely that if this activity is lost that it would be replaced by another of a similar scale. The trend of degeneration then becomes progressive as the secondary and tertiary activities lose their local market and customer base.

The Docklands area of London lies to the east of the City of London along both banks of the River Thames from the Tower of London to Beckton (fig. 1). It experienced a period of social and economic decline during the 1960's and 1970's and in 1981 the London Docklands Development Corporation (LDDC) was created by Government to provide

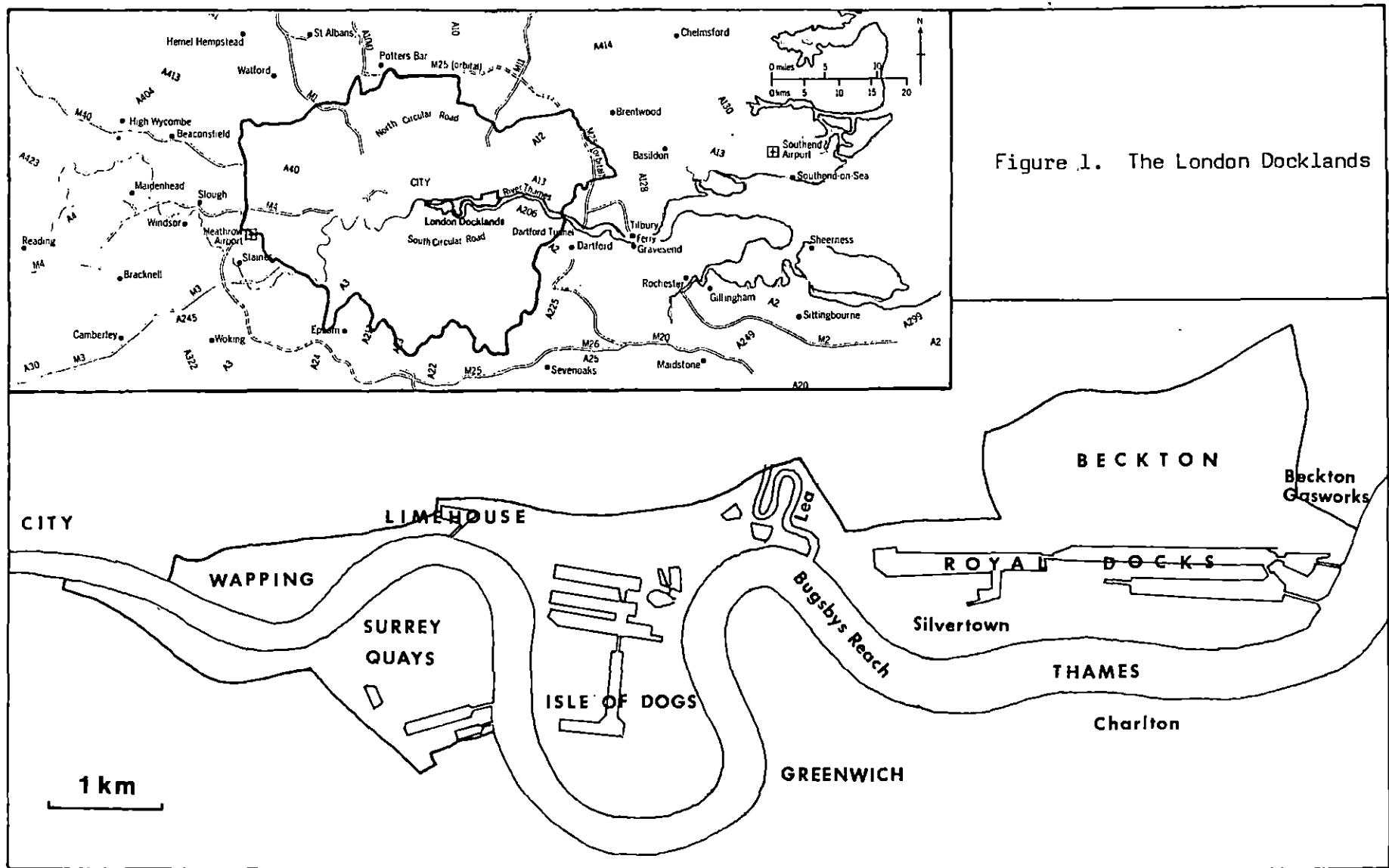


Figure 1. The London Docklands

the necessary impetus for the systematic regeneration of the area and provides a case study of a programme of urban renewal. By being one of the first two Development Corporations set up in Great Britain it has provided a precedent and an opportunity for lessons to be learnt.

The adoption of a systematic approach by the LDDC to the underlying problems has produced an overall optimization of cost benefits that has resulted in a new self generating land use pattern for the area. The engineering geological consideration associated with such a programme of renewal cannot be underestimated and can be broadly related to three factors;-

- The problems of natural setting
- The problems of the existing urban character
- The adequate interfacing of the technical factors with the political and economic pressures driving the renewal programme

The interaction of these factors ensures a role for engineering geology in the primary function of the process of urban renewal. In some areas this role may seem more obvious than in others. For example the value of engineering geology in areas blighted by former mine workings is quite clear. However, the requirements for urban renewal means that this is also true of those areas where the basic geological hazard is not so clearly evident.

The underlying philosophy to urban renewal on which the Development Corporations were founded regarded private enterprise as an essential ingredient to the success of the programme. One of the initial problems of the LDDC was therefore to attract the private sector to the area. At the time it was widely considered that the ground conditions would require expensive foundation solutions. The costs, when balanced against the land values at the time and the potential returns on investment, was one of the major disincentives to such commitment from the private sector. The problem has been tackled with a two pronged approach by the LDDC. Initially, it sought to

ensure that discussions were not based on perceived ideas of the ground conditions and undertook a phase of data collection and assimilation both to establish a true understanding of the engineering geology of the area and to make this available, without charge, to potential developers. Secondly, it carried out an improvement and replacement of the infrastructure in the area. From the outset the LDDC also accepted that significant practical and financial advantages were to be had by ensuring that geotechnical and geological data was collected through in-house procedures.

This thesis describes work undertaken since 1981 while the writer has been retained by the LDDC as a soils consultant. Until 1985 this was in association with Professor J L Knill, who also acted as advisor to the thesis. The work described was devised and instigated by the writer to provide for the effective input of engineering geology to the urban renewal of the Docklands area. It must be emphasised that political pressures on the LDDC meant that there was no lead-in time to develop and test their effectiveness. The approach was necessarily produced in response to the requirement for an immediate and commercially viable solution. It has resulted in the development of a new geotechnical information system using microcomputer technology. In addition a detailed knowledge base of the engineering geology of the area has been a consequence.

It was clear that a large amount of data would be collected during the renewal process. In order to maximise the benefits the approach included a commitment to retain the information for posterity. It will therefore be available as future development occurs within the area, even after the disbanding of the LDDC. It was also recognized that the computer system will be particularly suitable for use of the data for other academic and scientific purposes to increase the basic understanding of the archaeology, historical geology and engineering geology of the Docklands area and the London Basin in general.

CHAPTER TWO : URBANIZATION AND THE RENEWAL PROCESS

2.1 Introduction

Urbanization is the development of permanent habitation often drawn together to form settlements to the mutual benefit of all those in the settlement. Although settlements may be categorised in a number of ways perhaps according to size or status, such distinctions are largely arbitrary for in reality there is a "settlement continuum" in which the categories merge one with the other (Daniel and Hopkinson 1979). Urbanization is often used as a barometer of social and economic status of a community although in fact it is an abstract concept which may best be considered as a relative condition to a background rural setting. It is the natural sociological progression of human settlement which culminates in the concept of the 'city'.

Human occupation in Britain has probably been continuous since the end of the last Ice Age about 10-12000 yrs BP. About 8000 yrs BP there is good evidence that England, at least, was occupied by a technologically aware people (Taylor 1983). Urbanization developed in the wake of the agricultural revolution of the Neolithic period (6300-4500 BC) (Hudson 1976, Short 1984). In the late Bronze Age a structured society developed around a reliable and economically viable base brought about by a developed hierarchy of authority sustained by trade. By the time of the Domesday Survey in 1086 it is likely that most of the settlements of pre-industrial Britain had been established (Daniel and Hopkinson 1979).

During the sixteenth, seventeenth and eighteenth centuries the influence of trade and commerce brought growth to many cities in Britain. The merchant class had been a strong influence within the continent throughout the Dark Ages but Britain had remained isolated from this. Only following the adventuring of the Elizabethan age and

the formation of its colonies did the importance of trade and finance establish itself. Thus although London and Bristol had been cultural backwaters through the Dark Ages by the seventeenth and eighteenth centuries they had become world cities and major trading ports (Hudson 1976, Short 1984).

2.2 The Effect of the Industrial Revolution on Urban Character

The economic activity that characterises the Industrial Revolution throughout the nineteenth century involved a great concentration of people and capital on a scale not previously experienced. The concentration of manufacturing and industrial production to maximise profit gave birth to the factory system and a need to locate in areas of power and raw materials. The growth rate of these urban areas was staggering and so was the necessary supply of labour to sustain the industrial activity. Between 1801 and 1891 the population of England and Wales grew from 9 to 29 million and the percentage living in towns grew from 17% to nearly 50%. In 1801 70% of the country lived in communities with a population less than 2500, but by 1851 40% lived in cities with populations greater than 100,000. Major cities grew from small hamlets or were newly sited in previous rural settings to take advantage of the accessibility of power or raw materials. Over this same period London grew from a population of 865,000 to 6.5 million. The population of Manchester and Birmingham increased 10 times and Middlesborough increased from 40 in 1829 to 100,000 by 1900. The social deprivation that resulted from this period is extensively documented both by contemporary writers and modern social historians (Brigg 1963, Burke 1975, Dyos and Wolff 1977, Engles 1973, Morrison 1897). From 1831 to 1841 the death rate in the five largest British cities increased by 50% (Short 1984).

The style and character of urbanization resulting from the Industrial Revolution differed significantly from all previous periods (Hudson 1976, Short 1984). The factory system, which was an integral part of

the industrial explosion of the nineteenth century, was labour intensive and required a large workforce easily to hand. As the individual manufacturing areas spread and coalesced the conditions and squalor that developed produced a dangerous and unwholesome urban environment which resulted in a social and political reaction.

During the succeeding period developments in transportation and communications allowed this reaction to be mobilised. The basic requirement of the workforce and their place of work to be very close became less severe. This heralded the beginning of post-industrial urban sprawl of the twentieth century.

2.3 The Social and Political Factors leading to the Process of Urban Renewal

The Barlow Commission had been set up in 1937 on the Distribution of the Industrial Population. This reported in 1940 and recommended that further suburban growth of the major urban agglomerations should be restricted, that controls should be placed on the location of new industry and that an effective system of town and country planning should be implemented. A Ministry of Town and Country Planning was set up in 1943 and by then the concept of new towns as an answer to urban sprawl was accepted. In 1945 the Reith Committee was set up to consider:

"The general questions of the establishment, development, organisation and administration that will arise in the promotion of New Towns in furtherance of a policy of planned decentralization from congested urban areas; and in accordance therewith to suggest guiding principles on which such towns should be established and developed as self-contained and balanced communities for work and living."

The recommendations of the Reith Committee were embodied in the New

Towns Act of 1946. By 1970 28 New Towns were either in existence or under construction in addition to the controlled urban growth under the Town Development Act of 1952. By 1970 1 in 60 of the county's population lived in a New Town. As a consequence during the 1950's and 60's there was a general loss of central city population. In some areas the old housing stock was replaced with new high rise and multi-level maisonette developments. These were based on a systemized modular form of construction and had the dual purpose of improving public sector spending as well improving housing standards and producing an overall lower density accommodation.

During the 1970's and 80's changes also occurred in the role of the rural town. During this time their former decline has been reversed, largely spearheaded by the technological revolution. In consequence, small towns have established themselves as economic growth points. At the same time Britain's largest cities have lost manufacturing jobs at a much faster rate than the country as a whole. The reasons for this urban-rural contrast is complex but can in part be attributed to the older commercial building stock of the city areas becoming too restrictive to continued business growth.

The policies of decentralization implemented after the Reith Report and the failure of the housing policies of the 50's and 60's have both played a part in causing the subsequent decay within the existing inner city areas. This included an old and inadequate infrastructure, bad physical conditions for the populace, limited job opportunities and a concentration of the lower income groups and those with social difficulties. In 1977 the Government published a White Paper to redirect their main policies and programmes in favour of the inner cities. The aim was to develop a more unified approach to the problems by considering various economic, environmental as well as social projects. This Urban Programme was implemented under various Acts which gave a number of inner city authorities special powers and access to grants to direct to the policy to secure economic regeneration, including assistance to firms in their areas,

to improve the physical environment and ensure that local services and amenities were geared to the particular social needs of the local communities.

The Government realised that the problems could not be overcome by the public sector alone and that it was vital to involve the private sector. In particular the lending and investing policies of the major financial institutions was felt to be of prime importance to the inner city. In July 1981 Michael Heseltine, then the Secretary of State paid a visit to Merseyside and requested that the Chairman or Chief Executive of 26 financial Institutions should accompany him to see the conditions there. Between 1981 and 1982 each of the Institutions provided a manager to advise the Secretary of State and to work with departmental civil servants to develop new approaches to secure urban regeneration. Four main policy areas were, development, small businesses, housing and employment.

In the main the initiatives were accommodated by changes in the existing public sector structures, but in some areas the scale of the problem was considered sufficient that a more radical approach was required. This resulted in the establishment of Urban Development Corporations and Enterprise Zones.

In two major areas of redundant dockland, close to the heart of London and Merseyside the scale of the problems of regeneration was beyond the capacity of the existing local government structure. In 1981 the Merseyside Development Corporation (MDC) and the London Docklands Development Corporation (LDDC) were set up under the provisions of the Local Government Planning and Land Act of 1980 with the objective of regenerating these areas and with the powers to achieve this. The two Corporations were structured on the new town development corporations. Their principal directive was the reclamation and servicing of sites for industrial, commercial and housing development together with the wider considerations of providing necessary infrastructure and public amenities.

2.4 Engineering geology in the process of urban renewal

The pace and concentration of development required of the new Development Corporations by Government together with the past history and existing character of the area was expected to generate engineering geological problems. These would not necessarily be unique to the process of urban renewal, as they would result from a legacy of the underlying natural setting and the effects of the more recent industrial past. However, many of the areas in which the degeneration has occurred are associated with suspect ground. For example, this may include the presence of mine workings, the presence of fill and the redundant structures of a past activity.

The Development Corporations gave an opportunity to exercise a regional approach to the role of engineering geological. The Docklands offered a large coherent area which was controlled by a single client to which a single set of standards could be applied. As the redevelopment of virtually the entire area was expected within a ten year period it has been possible to devise new techniques and procedures to coordinate this approach. This contrasts markedly with the usual piecemeal approach where development of any given area may occur over many decades prompted often by a variety of clients or pressures. This is typified by consideration of sites only in relation to the window of an individual project or development. This piecemeal approach has been the case not only in the private sector, where sites are often unrelated and therefore viewed individually, but also in the public sector even though bodies, such local authorities, may have definable boundaries.

The construction of the New Towns has provided perhaps the closest analogy to the Development Corporations and offered the first modern opportunity for engineering geology to develop as a viable factor within the developing discipline of town planning and development.

Other than for a few exceptions, such as Telford New Town, Milton Keynes and to some extent Peterborough, the engineering geology has largely only been connected with the particular problems of individual sites. Even in the exceptions this has been extended only as far as collating the site details. Although some efforts to resolve these into thematic maps has been made, notably by the British Geological Survey, there appears to have been no real coordination to develop the potential benefits. The cartographic based procedures used by the Survey and independently by the Tyne and Wear Databank developed at Newcastle University are discussed more fully in Chapter Four and shown to be a serious limitation to the flexible use of the data, particularly as required for urban renewal.

The Docklands example and the procedures described in this thesis extend the role of engineering geology in a town planning setting. There is particular value in the control and means of data collection being viewed as a central function rather than the usual situation where it is devolved for action by independent commissioned professionals such as the consulting engineers. This ensures that a set of standards are maintained which makes storage and further use of the data more possible. The basic idea of collation of the data is also extended in the thesis to positively encourage its re-use for activities other than for which it was commissioned. In particular the systematic evaluation of the data to establish an engineering geological model for the area allows a iterative process to be maintained which produces an increase in the total knowledge base which can be drawn on and used in further projects and developments.

The primary aim of the urban renewal programme in the Docklands has been the stimulation of private sector development. This has required the implementation of extensive engineering schemes to ensure an adequate infrastructure to service the new developments and allow them to function. The scale and character of the problems in the area have also changed over the lifetime of the LDDC. It is necessary to appreciate that when it first came into being there was

no precedent by which to prejudge its probable success. Initial development proposals were relatively modest while a major concern was to increase and improve the local housing stock. The natural geomorphological and geological setting of the area together with the presence of significant thicknesses of made ground required that deep foundations should be used even for low rise buildings and units in traditional construction. Although consideration was given to the use of high level foundations the practicality of minimising any concern over their behaviour and the need to work within an established local authority building control procedure meant that these were not used

One of the first engineering geological problems in the Docklands was to establish the potential variation in the ground conditions which might affect the possible foundation solutions. This was important because these formed an integral part of the economic viability of the private sector interest in the area. It was necessary therefore to develop a procedure to provide actual data in the potential areas of interest. This was done by the systematic collection of existing geological and geotechnical data. Mapping of the area by the British Geological Survey was originally carried out in the middle nineteenth century and revised during the early part of the twentieth century following a re-survey for the six inch to one mile County Series. The four sheets of the current 'one inch' series which cover the area are based on the County Series mapping. Geotechnical data was obtained from existing site investigation boreholes. However, the age and character of the former development in the area meant that much of the information was relatively old with little penetrating to any great depth. Also the system of build and foundation styles which had been used in the docks meant that little quantified data had been included in the investigations. Some notable exceptions did exist, such as the site investigation for the east London Jubilee Line extension. In practice, this collation was aggravated and delayed by the refusal of the adjacent local and statutory authorities to acknowledge the existence of the LDDC.

In order to provide immediate and reliable data for the area annual period contracts for site investigation have been let by the LDDC each year since 1982. The development and maintenance of these was carried out under the responsibility of the writer who later split these into separate contracts to cover geotechnical aspects and chemical and environmental aspects. They were initially used to provide rapid information on known areas of interest but in the later years have been used increasingly for specific construction projects. The use of the term contracts for any work carried out for the LDDC whether directly or indirectly through one of the consulting engineers commissioned for specific projects has been a particularly important feature of the approach to the engineering geology.

The LDDC has carried out some 2800 boreholes at an average cost of £325,000 per year over that time using the geotechnical contract. The vast majority of these have been based on light cable percussive techniques, commonly referred to as 'shell and auger'. In the main these have been taken to a depth of 15m below ground level or to prove 3m of 'solid geology' although there has been a gradual increase in the average depth of the boreholes as the scale of the development attracted to the area has increased. For an average borehole depth of 15m this indicates an approximate cost for each investigation of about £62 per metre bored.

The contract for chemical and environmental investigation was set up as a specific facility because of the potential problems associated the former industrial character of the area. It is believed that this was the first time that such a term contract has been let. Although a requirement to undertake chemical testing may be found incorporated in various other term contracts for site investigation it was believed by the writer that the tendering procedures current in the industry did not provide a reliable access to the necessary chemical and environmental expertise to ensure that these were used effectively or that the most meaningful interpretations would be

achieved. Therefore the separate term contract was opened only to specialist firms able to offer the necessary in-house facilities and expertise to provide the required service.

The chemical and environmental term contractor was required by specification to interface with the geotechnical term contractor. Although the main part of the chemical and environmental investigation was based on machine dug trial pits inspected by the contractor any deeper samples, or the installation of methane monitoring standpipes were provided by the geotechnical contractor. The chemical and environmental contract has operated as a separate contract for five years and valued at about £75000 per year and covered some 111 projects or sites.

These costs for site investigation can be compared to a spend on projects by the LDDC which has increased from an initial £30 million in 1982/83 to £329 million in 1989/90 and during this period has attracted nearly £7000 million of private investment.

By ensuring that the data collected during the various investigations was integrated a regional interpretation and understanding of the engineering geology of the area could be carried out. This overview approach was believed by the writer to provide a particularly valuable benefit to the renewal programme for as the majority of the final development areas were actually unknown and the scale of the eventual development uncertain it was felt that this would offer the maximum return on the information collected.

The use of the term contracts and the systematic collection of any available information meant that a large amount of data was going to be collected in a relatively short space of time. The LDDC had been set up to work only with a limited staff and had no provision for librarians or archivists. In addition it was known that the offices would move to a number of different buildings in due course. These constraints posed particular problems for the effective storage and

retrieval of the data once collected. This was further aggravated by the need to have the data in a useful and readily available form to allow both its continuing evaluation by the writer and to make it available to professional third party enquiries. Chapter Four gives a detailed consideration of the options that were available. These were assessed both on their individual merits within the constraints imposed by the particular situation. It was concluded that the need to provide a working system in a restricted time scale without imposing staff or physical storage commitments could only be serviced by a computer based system as described in Chapter Five.

2.5 Examples of the engineering geological problems

2.5.1 Introduction

Two examples are cited here to demonstrate the engineering geological problems which the writer feels are particularly characteristic of the renewal setting. These are a direct result of, or greatly exacerbated by the urban setting of the area and the requirements for its regeneration. They provide illustrations of the particular and often large scale problems which influence renewal of an area which was formerly dominated by a single industry or land use. The first example shows how the presence of a redundant dock system has a marked influence on the design and construction of a new infrastructure. The second example demonstrates the problems associated with the legacy of contaminated ground and how these need to be fully adequately treated before the more sensitive land uses which follow the renewal process can be instigated. A further example is given in Chapter Eight of a site investigation which was carried out for forensic purposes. The investigation was prompted by a Clause 12 claim situation. The existence of the computer database enabled the instant retrieval of all available information and rapid processing of further data as it was collected.

2.5.2 Albion Dock, Southwark

The Albion Dock formed part of the Surrey Commercial Docks. They docks had been mainly constructed in the latter part of the nineteenth century and were taken over by the Port of London Authority (PLA) by Act of Parliament in 1908 but went into decline and ceased operations in 1960's. Following closure the docks began to be infilled by the PLA. This commenced in 1967 and continued to 1981 (fig. 73b). It was intended by the PLA that the infill would comprise largely natural materials with a restriction on 'inflammable, vegetable or noxious material. It was also intended 'not to have a high silt or clay content'. The material was intended to be placed by end-tipping so displacing the silts which had collected naturally at the bottom of the dock (Gahir et al 1987). In fact the control was largely left to the contractors. At peak periods 2300 cubic metres of material were handled per day and eye-witness accounts suggest that considerable amounts of indiscriminate fly-tipping took place (Thomson & Aldridge 1983). In 1976 the area came into the ownership of the London Borough of Southwark. They carried out a programme of ground improvement of a number of the infilled docks to remove the self-weight consolidation of the infill material. This consisted of dynamic consolidation with vibroreplacement in areas of structural sensitivity (Thomson and Aldridge 1983). The areas were then developed with housing and industrial units following the construction of roads and services.

In 1981 the remaining parts of the Surrey Docks were passed to the LDDC and became known as the Surrey Quays. It had been planned by the PLA and the London Borough of Southwark to dewater the Albion Dock and place the fill in layers with controlled compaction. However, a failure of the dockwall occurred during the dewatering and consequently end-tipping took place near the dockwalls with controlled compaction being carried out in the central areas.

A principle point of concern during development proposals was the potential for differential compressibility between the infilled dock and the former wharf areas. In addition this was expected to be aggravated by the residual self-weight consolidation of the dock infill. The situation was further complicated by the presence of the dockwalls themselves which existed as a vertical contact between the two soils and an incompressible line at the point of change. The planning and development considerations were not able to take account of the former positions of the docks in the layout proposals. It was therefore essential to establish the properties of the dock fill material and evaluate the residual self-weight consolidation that could be expected.

It is difficult to determine the engineering characteristics of such infill material with any great certainty from standard site investigation procedures because of its inherent variability. Therefore in order to assess its mass behaviour skip loading tests were carried out following the procedure described by Charles and Driscoll (1981). In order to increase the depth of influence of the tests the test configuration included eight loaded skips stacked two high (Gahir et al 1987). Elastic settlements under loads of about 30 kN m^{-2} were found to be about 5 to 10 mm. Consolidation settlements were observed up to 10mm over a two week period although this was still continuing when the tests were terminated. The tests indicated coefficients of volume compressibility of 0.1 to $0.3 \text{ m}^2 \text{ MN}^{-1}$ which compared to laboratory determinations on undisturbed borehole samples of 0.1 to $1.1 \text{ m}^2 \text{ MN}^{-1}$.

If the self-weight consolidation was based on primary consolidation of the clay matrix of the material (BRE 1983) then conventional consolidation theory can be used to provide a measure of its magnitude and rate of occurrence. Analysis showed that the residual self-weight consolidation in docks which had been backfilled in 1972 and 1974 would be in the range of 0 to 10mm with a maximum of 30mm. This was considered capable of being accommodated in normal design.

The filling of the Albion Dock had been only completed in late 1980 and the residual self-weight consolidation was estimated at 60 to 120mm which would occur over a period of 10 to 15 yrs.

The residual self-weight consolidation of the Albion Dock was considered likely to have an adverse effect on the serviceability of the infrastructure. It was therefore necessary to reduce or eliminate this to an acceptable level. This could be done by a variety of techniques, namely;-

1. excavation and replacement in a controlled manner,
2. dynamic compaction,
3. vibro-replacement, or
4. surcharging

Excavation was dismissed because of the time constraints and the possibility of further failure of the dockwalls. Although dynamic compaction had been used elsewhere in the Surrey Docks the high fines content of the fill meant that excess pore pressures developed during compaction would take some time to dissipate such that the period necessary for adequate treatment was assessed to be too long. Vibro-replacement had also been used elsewhere and was considered to be a viable technique except that the presence of obstructions in the fill might influence the effective development of the stone columns. The existence of a large stockpile of fill material in the area determined that surcharge loading was the most cost effective option to treat the Albion Dock fill material.

There was sufficient material to cover the area with a 3m high surcharge embankment. Removal of the material was to be based on monitoring the rate of settlement of the dock fill. Two road corridors across the dock were treated with vibro-replacement as insufficient time was judged to be available before construction of the roads was required.

The surcharge was monitored with magnetic probe extensometers, settlement plates, hydraulic settlement cells and pneumatic piezometers. Large settlements were recorded immediately and continued at a reducing rate for some months. The surcharge was eventually removed after a period of eight months when a maximum of 160mm of movement had occurred.

Back analysis of the behaviour of the embankment gave consolidation characteristics for the dockfill and showed good agreement with those determined from the skip tests

2.5.3 The Beckton Gasworks

The former Beckton Gasworks lay in the east of the area. It produced gas from 1870 and finally ceased operation in 1968. It had a large chemical by-products works situated adjacent to the main production area while the area south west of the works area acted as a marshalling area for the storage of coal and coke. It has also accumulated large amounts of waste materials from disposal from the works. Development plans for this storage and disposal area required it to be made available for housing. A succession of investigations showed that heavy contamination is present over much of the area although the degree and distribution varies considerably. The contamination derives directly from the waste and by-products of the gas production. Total and free cyanides are commonly high and are due to the waste product known as spent oxide which is produced when iron oxide is used to purify the gas and remove hydrogen sulphide, hydrogen cyanide, ammonia, organic sulphur and tarry compounds. Various liquors and tarry products are associated with high levels of phenol and other toluene extractable matter. Sulphide, sulphate and less commonly the heavy metals are also found in elevated concentrations. Surface water ponding on the area has also been shown to be highly acidic and contaminated with oil-tar material.

The waste products are present on the site to a depths which range up to four metres. Many of the substances identified are both toxic and carcinogenic even at very low concentrations. In addition many of the contaminants are also corrosive and therefore damaging to construction materials.

The LDDC became involved in the purchase of the site through a compulsory purchase order. This went to public inquiry at which it argued that the area should be developed for housing and that the contaminated nature required a total and managed approach to the treatment of the area as a whole. It was argued that this would optimise the resources available and lead to a better control of the attendant operations than would otherwise be possible if the total area was developed on a piecemeal basis.

Consideration of the whole site would also allow a greater flexibility of approach to its reclamation. The methods broadly fall into three categories;-

1. removal
2. cover
3. treat

The level of contamination classifies the material as special waste under the Control of Pollution Act 1974. Consideration needs to be given to the large volumes involved which could make its removal and disposal impractical. Not only would the haulage costs by specialist contractors be very high, but it would be necessary to move a large number of lorries carrying the material through existing congested residential areas. In addition the tips licensed to accept such material have only a finite capacity and their willingness to accept such large volumes would need to be confirmed. There is also a problem of assessing the depth of material to be removed. On average there is some three metres of made ground but as the underlying natural soils are also contaminated it will be necessary to carry out

further remedial measures on the remaining soils once the overlying material has been removed.

Protection from the contaminated material can be provided by a cover to the site. This has the advantage that no material needs to be removed. the nature of the the cover is somewhat dependent on the final use of the site. For sensitive uses, such as housing, this must provide not only an adequate physical barrier to the material, it must also provide a suitable depth of growing material in the vegetated areas. In order to prevent a recontamination of the cover material consideration must also be given to the potential for upward migration. This can occur as a result of the water soluble phases and other liquid contaminants moving upward by capillary action. Also by the physical reworking of the material by fauna. Liquid and solid phases of various contaminants are also able to be mobilized and brought up from depth by vegetation. This last point provides a particular concern because although the cover may provide a physical barrier to the material where garden areas are expected the scheme must also prevent the accumulation in vegetables which are grown for consumption.

Treatment of the material could be carried out by a variety of techniques including;-

1. physical (solvent leaching, flotation etc)
2. chemical (oxidation, hydrolysis, neutralization etc)
3. thermal (direct heating, steam stripping etc)
4. microbial (selected microorganisms, vegetation etc)
5. stabilization/solidification (cement or resin based systems)

The methods of treatment vary according to the contaminants such that no single approach would seem to be suitable for the whole area. Some of the methods require to be carried out off-site and therefore face many of the problems of removal as discussed above. Some of the

most interesting systems come under heading 4. It is argued that by the use of selected microorganisms and vegetation the contaminants can be removed from the soils by natural processes. The systems were initially developed for sewage waste and their extension into the treatment of other materials is relatively new. Because the system is based on a natural process it can take many years to complete. One system described to the LDDC was estimated could take up to 20 years to complete. It also catered only with the water soluble contaminants and would therefore not leave a totally clean material at the end.

The major factor in these proposals is in fact the time required to achieve the results. If the area is required to be developed during the course of the treatment the short term measures would need to be as great as those otherwise required without the long term benefits of the microbial treatment. Therefore no benefits would be gained.

It was concluded that the only viable approach to the reclamation of the area could be based a system of cover to provide a physical barrier. in view of the degree of contamination it was felt that the barrier should consist of 1.0 to 1.5m of clean imported material. As the area is to be used for housing this would allow a sufficient depth of soil to provide moisture retention in the drier summer months, it will also provide an additional safety measure on the depth necessary for adequate root development. It would also provide an adequate thickness of physical separation of the occupants and the contaminated ground and could reasonably be expected to provide a sufficient depth able to accommodate normal gardening activities and the play requirements of children.

In order to ensure that the long term recontamination of the barrier material is prevented there would need to be an additional barrier between the contaminated material and the clean soil. This should be incapable of sustaining a capillary rise and should prevent the burrowing of animals and other soil fauna. Such a barrier is usually

made up of a coarse granular material. Its long term efficiency would need to be assured by the design of a suitable filter sequence to prevent clogging by the ingress of the adjacent soils. This is traditionally carried out by a progression of layers of granular material with a designed and controlled grading. More recently geotextiles have been used as a substitute for the filter sequence but some care would have to be exercised to ensure its long term durability in the environment produced by the contaminants.

Without the use of geotextiles, the capillary break together with a necessary filter zone could require a depth of at least 0.5m and be made up of at least three separate layers. To be effective it is also necessary that it is constructed above any groundwater table. Certain restrictions must apply where such preventative means are adopted. The ground cannot be lowered at any stage, for example to produce a sunken garden, as this would reduce the thickness of clean material. Any activities which would damage or disrupt the capillary break and filter zone should similarly be prevented.

CHAPTER THREE - THE PHYSICAL SETTING OF THE LONDON DOCKLANDS

3.1 Regional Geology

3.1.1 Structural Setting

London's docklands lie on the flood plain of the River Thames within the geological province known as the London Basin. The basin is formed by an open synclinal fold in Cretaceous and younger rocks with an overall east west trending axis which plunges gently towards the east. It has a geomorphological expression defined by the Chalk downlands of the Chilterns and the North Downs to the north and south respectively, and in the west by the Marlborough Downs where the two limbs of the syncline converge. The London Basin forms one of a family of such structural features which dominate the geology of southern and southeast England and extend across into northwest Europe (fig. 2). They are typified by depositional basins which contain estuarine and marine deposits of Tertiary Age resting unconformably on the Chalk of Upper Cretaceous Age.

The major features in this structural suite have amplitudes in excess of 1500m. Although they have classically been considered to be largely influenced by compressive forces from the south it has also been argued that the structural elements have occurred over a much greater geological time scale (Wooldridge 1923, 1926, Wooldridge and Linton 1955). More recently the controls on the form and historical activity of the structures has been recognized to stem equally from deeper seated crustal extension associated with the spreading Atlantic and downwarping of the North Sea Basin as well as the simple compressive forces and that this activity has been present throughout the whole of the Palaeogene (Anderton et al 1979, Jones 1980).

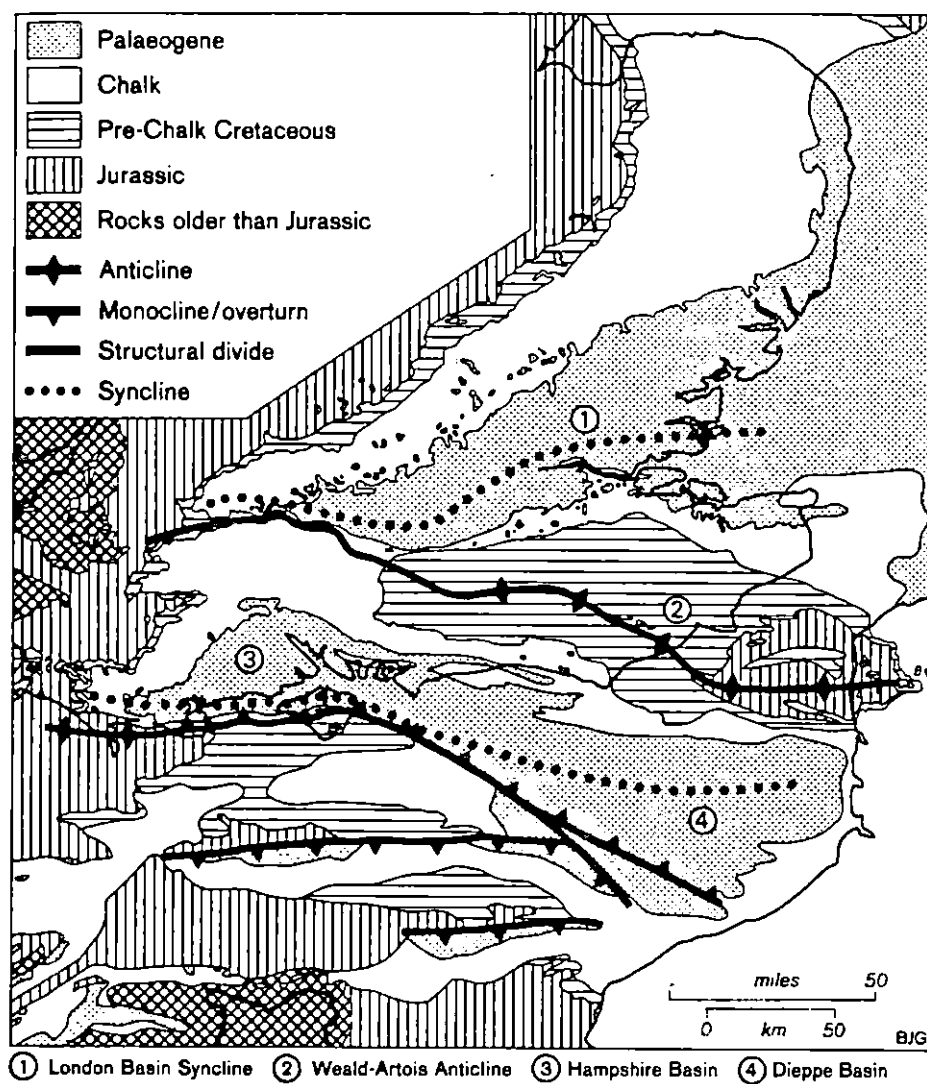


Figure 2 Geology and major structures in southeast England (after Jones 1981)

Although the overall structural axis of the London Basin is approximately east west it is also crossed by three families of smaller structural feature which have north south, northeast southwest and, a less well developed northwest southeast trends (Wooldridge 1923, 1926; Wooldridge and Linton 1955; Jones 1980, 1981). The main structural axis is locally orientated to nearly southwest northeast through the London area (fig. 3). In transverse section the basin is asymmetrical with dips on its northern limb usually about 2 degrees and those on the southern limb somewhat steeper at about 4 degrees (fig. 4). However, dips do vary locally and in places steepen to 30 degrees.

Deep boreholes across southern England have shown that the Mesozoic cover rocks to the Palaeozoic basement are much thinner northwards of a line which approximates to the course of the River Thames. Wooldridge (1923) argued that the relatively thin cover of the softer Mesozoic rocks have not been able to fold independently of the Palaeozoic basement rocks under the influence of the northwards compression. Consequently, they have flexed or faulted in sympathy with renewed movements on pre-existing structural trends in the basement. With varying degrees of success these trends have been shown to be evident in the younger Formations of the London Basin. The Docklands lie in a region where the disposition of the principal stratigraphic units is controlled by an east west anticlinal structure on the southern limb of the London Basin. This is referred to by Wooldridge (1926) as the Lower Thames Valley Anticline which he suggests is a continuation of a trend also recognized in the Purfleet Anticline which follows a Hercynian fold trend in the basement rocks. He also postulates that continued activity of this feature accounts for a thinning in the Thanet Sands and that the structural trend can be traced westwards through Bristol into South Wales.

The outcrop of the solid deposits in the London Basin is modified by a series of faults with a marked northeast southwest Caledonoid trend. One in particular, the Greenwich Fault, has been

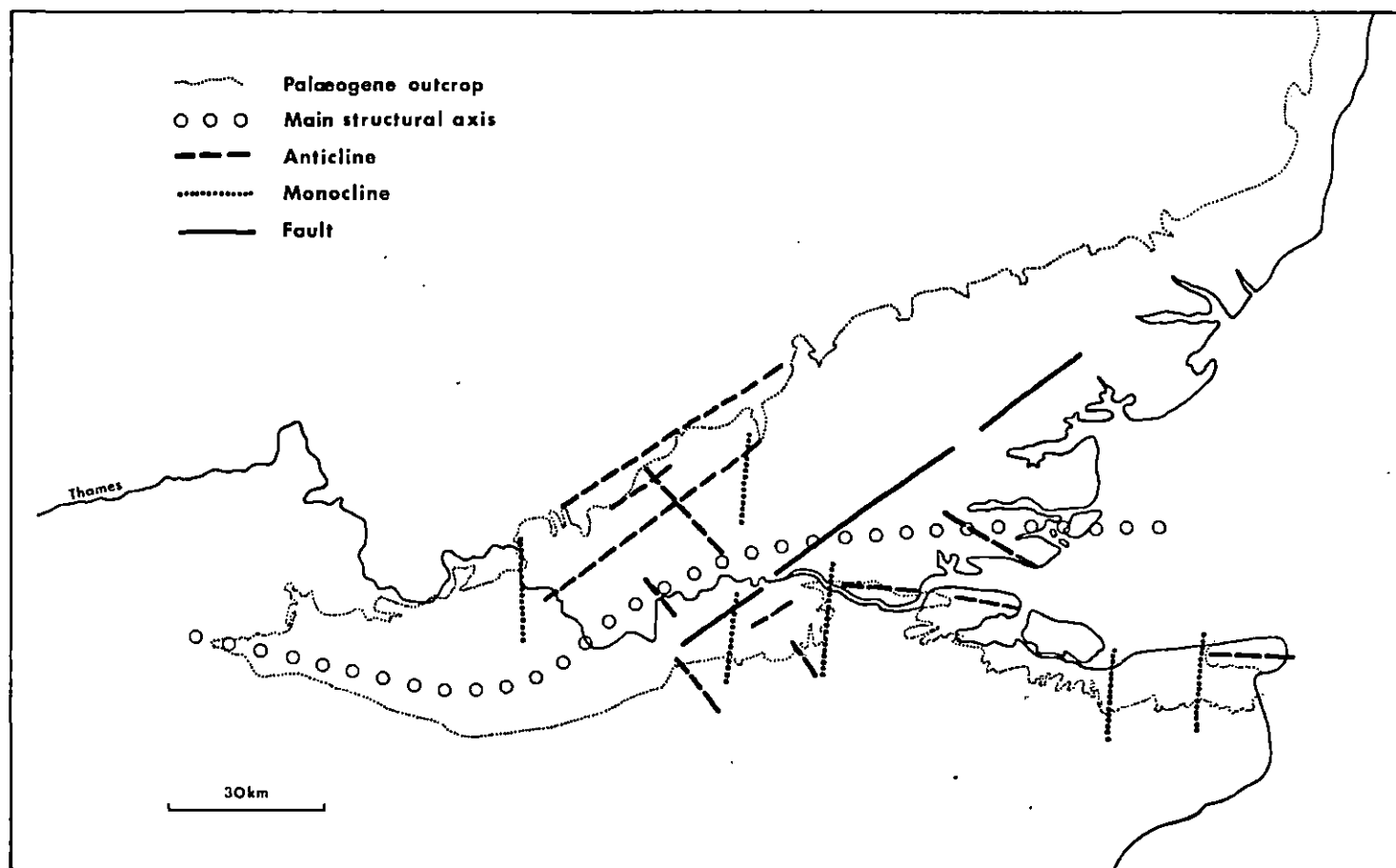


Figure 3. Structural types and trends traditionally shown to be present in the London Basin
(Based on Jones 1981; Wooldridge 1923; Wooldridge & Linton 1955)

Note that the trends and distribution given by Wooldridge and Wooldridge & Linton are schematic and do not necessarily imply the presence of continuous features

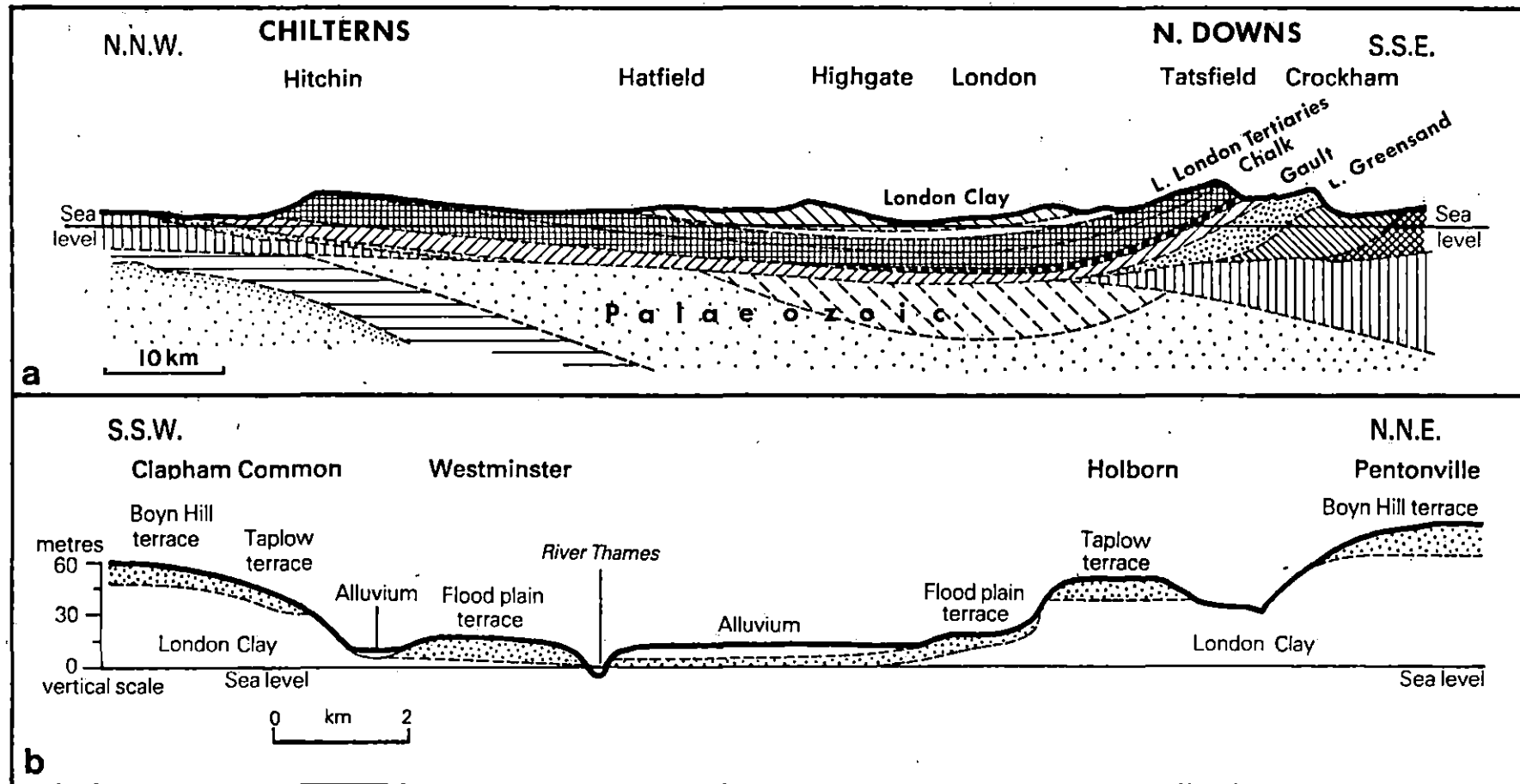


Figure 4. Generalized section across the London Basin showing,
 a) the structure and distribution of the principal geological units, and
 b) the relationship of the terrace gravels in the lower levels of the Thames Valley

traditionally mapped to traverse the Docklands area following a trend which may extend to Colchester where an earthquake experienced in 1884, has been suggested, may be a notable example of the continuing activity along these structural trends (Allsop and Smith 1988; Bristow 1985; Wooldridge 1926; Wooldridge and Linton 1955).

A Malvernian north south trend has also been argued to be picked out by a series of monoclines in the London basin. Wooldridge (1926) provides a lengthy argument for their presence. He shows one of these monoclinal features to be coincident with the valley of the middle River Lea. This is shown to have an easterly throw and to extend towards the Docklands area and is argued to have a possible structural relationship with a similar feature, but with an opposite throw, which runs through Croydon. In view of the implication of this work on the structural aspects of the Docklands area a closer review was given to Wooldridge's arguments. Without wishing to criticise the value of the fundamental aspects of his basic model, it was found that these structural aspects which appeared to most directly affect the Docklands area were based largely on indirect evidence, postulation and a loose analogy with the South Wales Coalfield. This thesis has been able to define the structural geology of the area with more certainty and changes the emphasis from faulting to folding.

3.1.2 Historical setting

The Gault Clay forms the basal bed of the London Basin (Table 1). It is a persistent deposit of marine clay laid down at the end of the Lower Cretaceous. It resulted from a deepening of the sea in the area and a reduced supply of terrestrial material as the earlier tectonic activity of the Jurassic and Lower Cretaceous came to a close. During the Upper Cretaceous the sources of terrestrial material were further eliminated by the major westward transgression which occurred across the north European Craton. The principal

ERA	PERIOD		EPOCH	FORMATION	AGE (Ma)	
Cainozoic	Quaternary		Holocene		0.01	
			Pleistocene		1.8	
	Tertiary	Neogene	Pliocene		5.0	
			Miocene		22.5	
		Palaeogene	Oligocene		37.5	
			Eocene	Headon Beds Barton beds Bracklesham Beds Bagshot Beds London Clay	53.5	
			Palaeocene	Blackheath Beds Woolwich and Reading Beds Thanet Sand	65.0	
			Upper Cretaceous		Upper Chalk Middle Chalk Lower Chalk	93.0
			Lower Cretaceous		Upper Greensand/Gault Lower Greensand Wealden Beds	135.0
Jurassic						

Table 1. Geological deposits of southeast England
(Based on Anderton 1979 and Jones 1981)

source of sediment became the skeletal material of pelagic fauna which gave rise to the characteristic thick pure carbonate Chalk of the Upper Cretaceous.

Following deposition of the Chalk, tectonic movements resulted in a broad scale uplift and tilting to the east. This caused a cessation of Chalk deposition in southern England which then lay on the north western margin of a shallow marine gulf which opened out towards the present North Sea Basin. Repeated oscillations in the position of the coastline occurred throughout the ensuing Tertiary Period (fig. 5) brought about by further intermittent tectonic activity. This resulted in a sequence of deposits characterized by cyclic alternations of clays, sands and gravels with a general regional coarsening towards the west as the sediments grade from predominantly marine through estuarine to fluvial in origin. The earliest of these transgressions occurred in the Palaeocene about 60 million years ago (60 Ma) and deposited the Thanet Sand. This was followed by the Woolwich and Reading Beds transgression also during the Palaeocene but about 5 million years later. Following this a more extensive marine incursion occurred in the Eocene between about 53 and 49 Ma when up to 200m of typical deep water mudrocks called the London Clay were deposited in a probable water depth of 160-360m (Davis and Elliot 1957).

Following deposition of the London Clay renewed structural movements resulted in extensive erosion of its upper levels. Tectonic activity associated with the later phases of the Alpine Orogeny enhanced and deepened a number of the basins of northwest Europe and caused further marine transgressions giving rise to a cyclic sequence of deposits of Upper Tertiary Age. In the London Basin, besides a few isolated patches capping the North Downs and the Chilterns, these younger beds have been totally removed by subsequent erosion leaving the London Clay as the youngest material of significant extent.

During the Pleistocene the last geological event of major influence in the London area occurred. During this period north west Europe was subjected to a series of relatively rapid climatic fluctuations which produced a number of glacial periods with intervening warmer

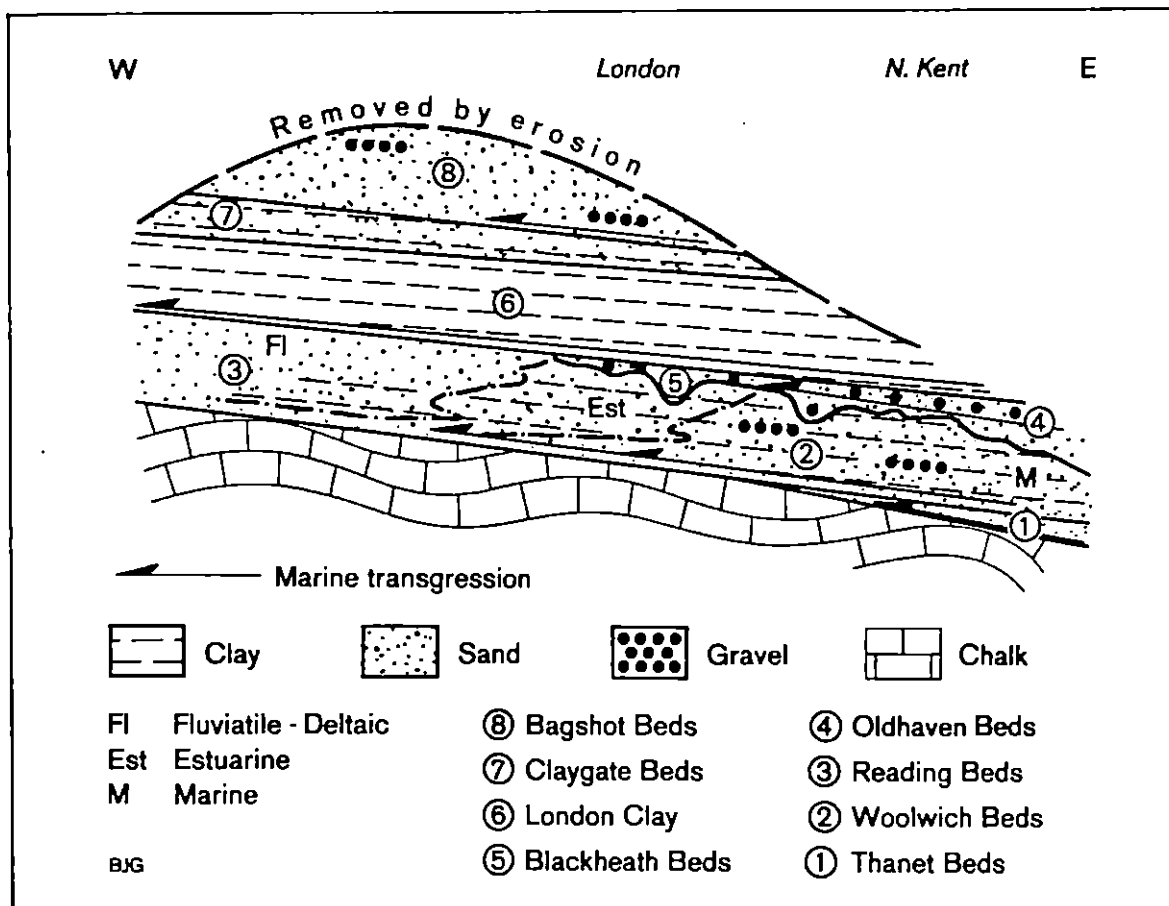


Figure 5. Diagrammatic representation of the Palaeogene succession of the London Basin

(after Jones 1981, based on Curry 1965)

inter-glacials. An important aspect of the glacial period was the incorporation of large proportions of the Earth's available water into continental ice sheets with a resulting lowering of sea level. The intermittent decay of the glacial ice produced fast flowing meltwater streams. This was associated with flooding and changes in drainage courses as ice dammed lakes were formed and released. At the same time vast quantities of frost and ice comminuted rock became available to enhance the erosive power of the meltwaters. Tundra conditions reduced the natural vegetation cover allowing easier erosion. Deposits of loess, boulder clay and fluvio-glacial sands and gravels developed while the periglacial conditions coupled possibly with local snow packs created instability of slopes on angles much lower than is possible in temperate conditions (Howland 1989a). The freeze-thaw action and the growth of ground ice also produced a deep mechanical weathering which later allowed increased water percolation and increased weathering at greater depths.

The glacial periods occurred as a number of episodic events over the last few million years. Although, to some extent, the products and effects of one stage have been largely removed by subsequent stages the overall sequence of glacial periods as had a profound effect on the local geology and engineering properties of the near surface materials in the London area.

The River Thames flows along the length of the London Basin. It is a product of the more recent geological past and is discordant with the structure of the London Basin (fig. 3). It flows across the structure entering on its northern limb at Goring and continues variously across the dip to eventually intersect the southern limb at Dartford. The course of the Thames has been displaced progressively southward by ice-dams during the Pleistocene. At various times it has flowed to a reduced sea level while its discharge was often swollen by meltwaters. Under such circumstances it was able to erode rapidly to levels controlled by the lower sea levels. As the relative sea level rose at the end of each glacial period its

abundant detritus was deposited as gravelly alluvium in braided stream deposits over wide flat flood plains. These gravels are referred to collectively as the Thames Gravels and are found extensively along the present course of the river.

Since the Pleistocene a steady rise in sea level and a reduced discharge in the river has allowed deposition of silts and clays over the lower tracts of the Thames Gravels. Referred to generally as alluvium these cohesive materials, together with subordinate and sometimes extensive peats, have been accumulating throughout the Recent up to modern times. In historical times the natural depositional sequence of the area has been interrupted by the effects of man associated with the growth of London as an urban area.

3.2 Lithostratigraphic description of the principal geological units

3.2.1 Gault Clay and Upper Greensand

The Gault Clay forms the lowest of the Formations of the London Basin. It was laid down at the close of the Lower Cretaceous as a marine clay. It is characteristically blue grey in colour, often fissured, with few fossils. It was classically considered to be overlain by the coarser Upper Greensand, although it is possible that the coarser material is a facies variation of the clays which represent a change from deep to shallow water (Sherlock 1960). A palaeontological distinction does exist which divides the combined sequence into the Upper and Lower Gault suggesting an unconformity is present between the two. Together the two divisions are about 50 metres in thickness.

3.2.2 Chalk

The Chalk overlies, and for the most part, grades imperceptibly from the Gault. It represents a virtually continuous pelagic sedimentation throughout the whole of the Upper Cretaceous which lasted for a period of nearly 30 million years. The Chalk reaches a maximum thickness in Britain of 550m in the Isle of Wight but increases to nearly 2000m elsewhere in Europe (Hancock 1975; Jones 1981). In south east England this thinned to some 400m due to the influence of the London-Brabant Massif which, although by then relatively denuded, had been a dominant feature of the Mesozoic palaeogeography (Anderton et al 1979; Wooldridge and Linton 1955). Continued activity, perhaps on an underlying Charnoid axis present in the Palaeozoic basement, caused a later differential uplift on an approximate northwest southeast axis called the London Ridge by Wooldridge and Linton (1955). This produced a possible 200m of erosion of the Chalk across the area of the present London Basin (Curry 1965) which can be demonstrated by the macro-fossil zonation of the present erosion level (fig. 6). The necessary uplift to cause such erosion must necessarily predate the development of the London Basin synclinal axis (Jones 1981).

The Chalk can be conveniently divided into the Lower, Middle and Upper Chalk based on its lithostratigraphic variation. This can be divided further on biostratigraphic considerations but the actual zonation is dependent on the fossil assemblage used (Hancock 1975).

Chalk is characterized by a whiteness and purity and although the Lower Chalk does contain a significant clay content the calcareous content gradually increases through the succession so that in the Middle and Upper Chalk it forms generally less than one percent of the make-up. The calcium carbonate is predominantly a low-magnesium calcite and is unusual for limestones in that the bulk of the sediment was deposited in this form and has not been derived from diagenesis of aragonite or high-magnesium calcite, as is more

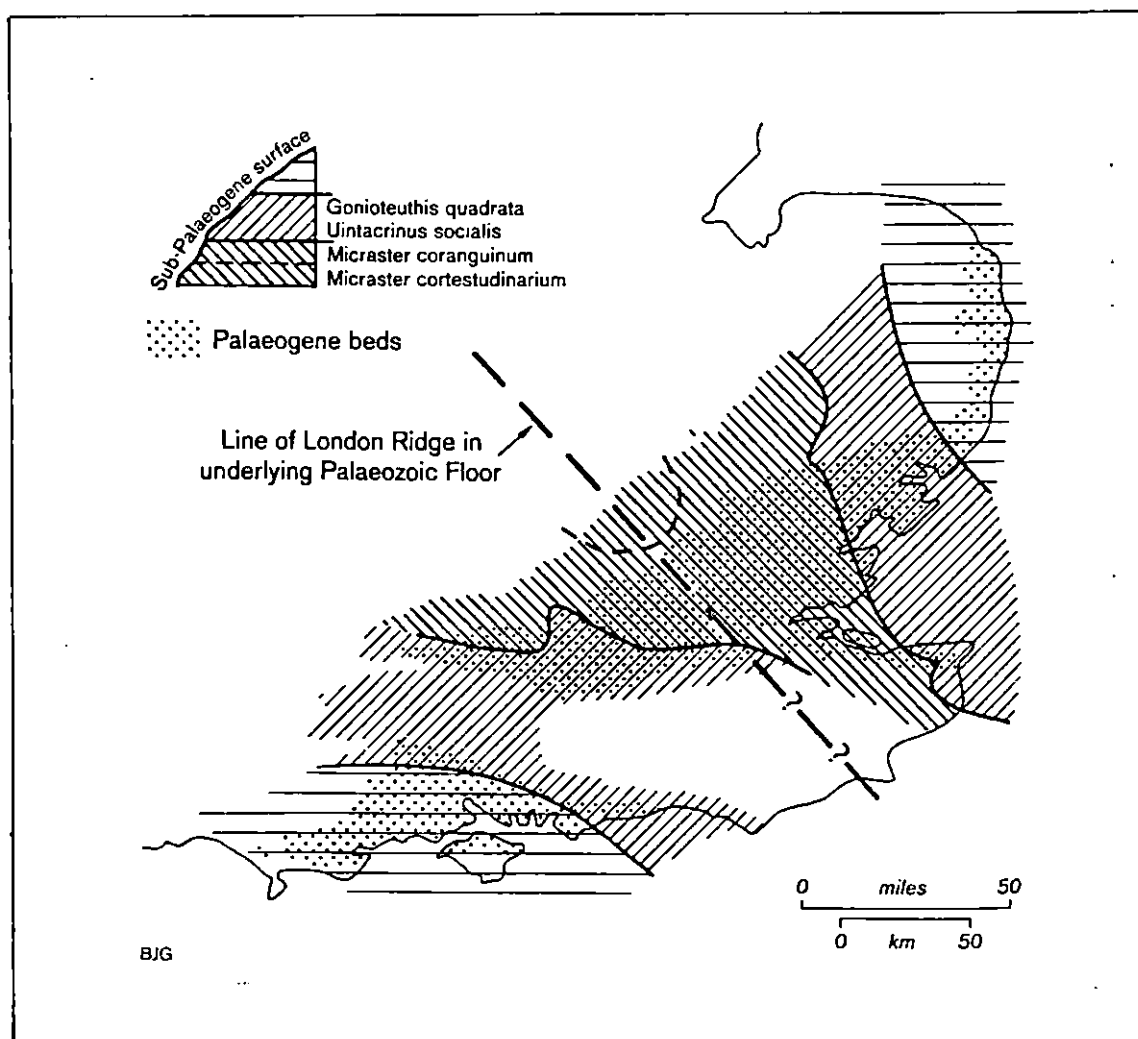


Figure 6. The distribution of the Upper Chalk zones below the Palaeogene in southeast England

(after Jones 1981, based on Curry 1965)

Note the apparent coincidence of the suggested anticlinal form in the Chalk and the position of the London Ridge postulated by Wooldridge and Linton (1955)

commonly the case. The calcite particles of the sediment are made up by a proportion of microfossil material, chiefly from foraminifera, but in the main are composed of coccoliths the external plates derived from the disintegration of planktonic algae (Hancock 1975; Sherlock 1960).

Sedimentary structure is evident within the Chalk on both a macro and micro scale, even though the material is typically considered to be massive or massively bedded. Hancock (1975) describes a number of features which he relates to the regional depositional setting some of which are confused by or related to, the presence of trace fossil structures. Of most interest in the Chalk are the presence of hard grounds. These are a result of penecontemporaneous diagenesis which produced local hardening of the Chalk. This is found on a scale ranging from centimetres to metres but at each hardground horizon the effect fades with depth. Their formation probably represents a break in deposition as they are often associated with the presence of Chalk pebbles, encrustations, phosphatisation or glauconisation. Although a few have been given specific names, for example the Chalk Rock and Top Rock, they are considerably more common than this would suggest. The more important hard grounds may be traced over very large distances while others may be relatively impersistent and extend laterally for perhaps only a few hundred metres. As they formed during breaks in sedimentation it means that they are associated with deposition in the more shallow regions of the Chalk sea, particularly over massifs at times of reduced sea level.

A characteristic feature of the Middle and Upper Chalk is the presence of flint. This consists of micron sized randomly arranged crystals of chert, a cryptocrystalline silica. It is found as tabular or nodular concretions which generally follow bedding, although they can cut across the structure along vertical or oblique discontinuities. The flint is a secondary product probably derived from the mobilization of siliceous material from biogenic sources such as sponge spicules. That it was formed after the deposition of

the Chalk is suggested by the absence of flint pebbles in the Chalk itself, but it must have formed before deposition in the Tertiary where such pebbles are found.

3.2.3 Thanet Sand

The Thanet Sand is the youngest of the Tertiary materials being deposited at the beginning of the Palaeocene about 60 Ma. It oversteps the Chalk from east to west. When fresh it is characteristically green in colour due to the presence of glauconite but on exposure weathers to a pale yellow brown. It is fairly homogeneous over most of its thickness comprising a fine grained quartz sand. It is poorly graded with a marked uniformity about the fine or fine to medium sand sized fraction. This study has shown that in the Docklands area it shows a developing silt content and a slight fining of the whole with depth. Minor fractions of clay are found and occasional thin clay laminae are present. Its basal layer contains dark green rounded flint pebbles in a silty clay matrix. This is referred to as the Bullhead Bed. In fact the layer is variously developed, in places little clay is present and elsewhere cobbles as well as gravel size material is present. The Formation represents a shelf sand laid down within a shallow marine environment. Regionally it thickens significantly towards the east and contains deep water shaley clays at depth. Even so it can show considerable variation in thickness on the smaller scale and is known to thin locally to a metre or so from a more usual 10 metres in parts of the London Basin (Thurrell 1989).

The Bullhead Bed is considered to represent the lag from the storm beach of the transgressing Thanetian Sea. The contained gravels are very well rounded with a coating of glauconite. As Curry (1965) has indicated that the unconformity with the underlying Chalk represents a time span of at least 15 million years and the erosion of perhaps 150 metres of Chalk in south east England it is possible to speculate

that much of the gravel is not necessarily derived from flint eroded directly from the Chalk during the transgression but from some earlier derived sediment. The lack of any residual surface weathered cortex to the gravels which is present on modern flint gravels which have been derived fairly directly from the Chalk does support this contention. However, this can not be taken as conclusive proof as the loss of the cortex may be related to secondary processes in the intervening period.

The Thanet Sand outcrops over a limited area of southeast England. Although this may represent the original size of its area of deposition it may also indicate that later further uplift occurred with subsequent erosion of the deposits. Certainly Wooldridge (1926) has postulated that relative thicknesses of the deposit across the London Basin are due to such continuing movements. More recent work on the differences in heavy mineral contents between the Thanet Sand and the basal beds of the overlying and unconformable Woolwich and Reading Beds confirm this view (Morton 1982). This indicates a marked difference in source area for the two materials. In addition the surface characteristics of the heavy mineral assemblages in the upper levels of the Thanet Sand are probably due to etching and partial dissolution by acidic groundwaters. The influence of such acidic groundwater on a marine sandstone clearly requires the necessity of a post depositional phase of subaerial erosion. It seems likely therefore that the unconformity accounts for a period of emergence and subaerial erosion of the Thanet Sands before the major transgression at the beginning of the Woolwich and Reading Beds and not merely a surface of marine planation. It is also probable that the original area of deposition of the Thanet Sand was greater than that of its present outcrop. Morton (1982) suggests that the source area for the heavy minerals in the Thanet Sand was the Scottish Highlands and therefore a marine environment must have extended to the north and west of the present London Basin which allowed the movement of the material by longshore drift.

The whole sequence of Thanet Sand formation is coloured with a greenish tinge due to the presence of the mineral glauconite. This is a complex hydrated silicate of iron and potassium generally believed to be derived from the breakdown of ferromagnesian minerals, particularly biotite, under conditions of fairly slow sedimentation in marine conditions. It is easily oxidised and results in colour change to browns and yellows in the weathered material.

3.2.4 Woolwich and Reading Beds

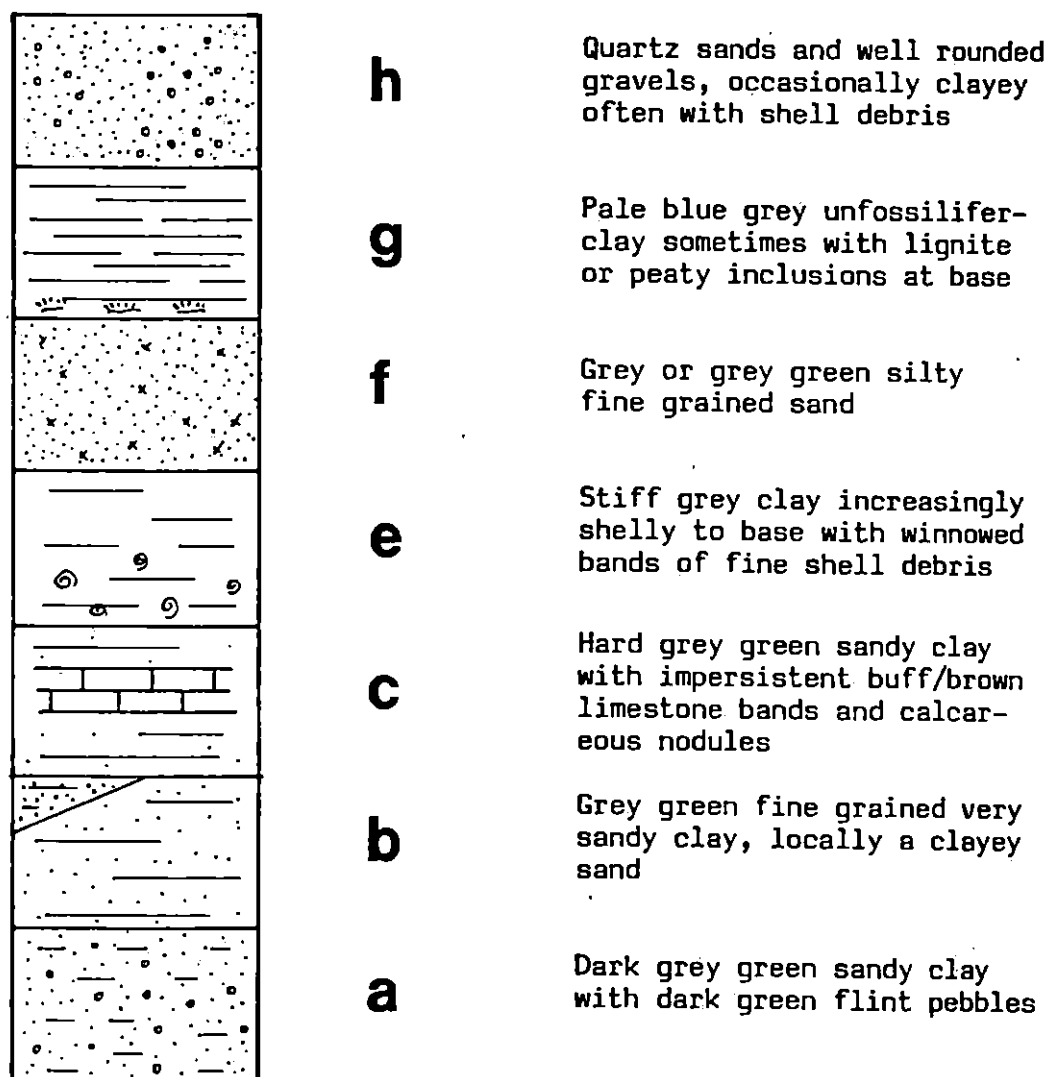
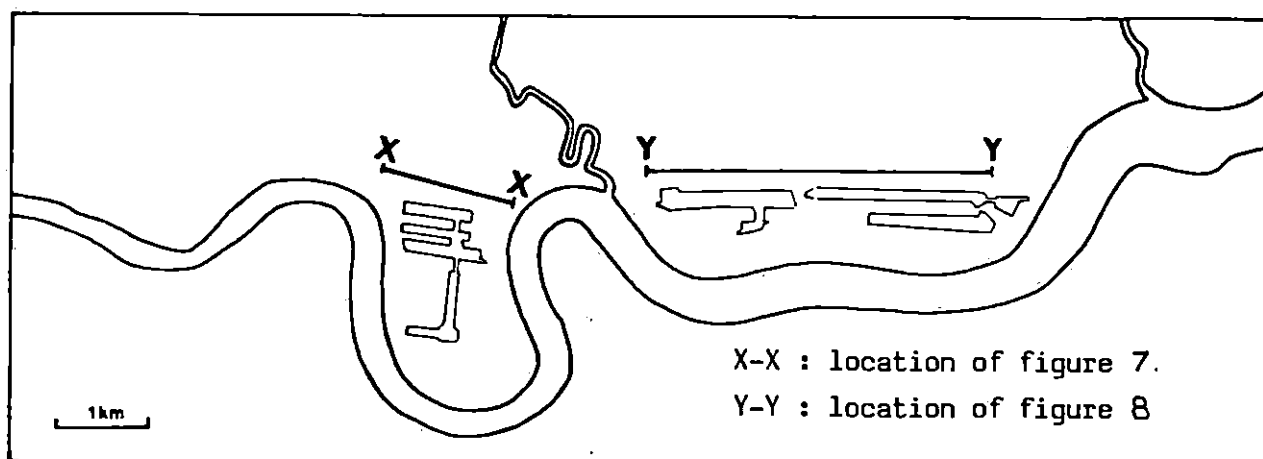
The Woolwich and Reading Beds rest unconformably on the Thanet Sand and overstep them to the west to lie directly on the Chalk. They are a much more varied sequence than the Thanet Sand and a recent correlation of data across the London Basin by Ellison (1983) extending the earlier work of Hester (1965) has suggested six main lithofacies. Ellison suggests that the distribution indicates an oscillating coastline with an off-shore sand barrier with open sea to the east and a tidal inlet complex to the west on the landward side. This study has been able to apply this model to the Docklands area and shows that the area straddles the transition between the marine and lagoonal environments. Seven lithofacies are identified for the area which are broadly correlated with those of Ellison. The thesis has developed a model which indicates that the Formation represents a number of distinct transgressions.

To the east of the Docklands area in north Kent and south east Essex the Formation is represented by littoral sands. These have broad sedimentary characteristics with the Thanet Sand indicating a similar transgressive environment (Prestwich 1852, 1854) while mineralogical similarities in the immediate basal layers does suggest a degree of local reworking (Morton 1982). Occasional developments of ferruginous sands within the Formation perhaps result from erosion of the main sand bar following periods of exposure during regressive periods (Ellison 1983). To the east of the Docklands area the

Formation is dominated by shallow lagoonal clays with estuarine and brackish characteristics. During emergence of the barrier bar shelly clays were laid down in the lagoonal environment containing a varied amount of brackish water fauna. The isolation from the sea allowed the development of occasional beds of freshwater limestone. In the upper part of this sequence the clays also take on a mottled character which has been interpreted to be marsh deposits. These are complicated locally by a laminated sand which may represent a wash over deposit into the lagoonal setting.

This study has been able to refine Ellison's general model for the Woolwich and Reading Beds in the docklands area. Figures 7 and 8 show an east west section through the Formation in the area which show seven distinct facies. These are identified by an alphabetical sequence. The basal bed (a) is a sandy clay with a varying gravel content which in places dominates the grading. This is typically a dark grey green and the gravels are well rounded, dark green or black in colour. The bed varies in thickness, but is usually less than a metre and often much less. It is very persistent across the outcrop of the Formation and has certain similarities to the Bullhead Bed at the base of the Thanet Sand.

The upper contact of Bed 'a' is often less marked than the upper surface of the Bullhead Bed and can grade into the overlying Bed 'b' or there may be further bands of 'a' type material within Bed 'b'. Bed 'b' is a persistent clayey sand often described as a loam by geologists. However, in engineering terms the cohesive content can be sufficient to classify it as a clay even though its grain size is dominated by a fine to medium sand size fraction. It does contain some localized gravel, and this becomes increasingly common towards the west, noticeably from the Lea confluence. It is usually green or green grey in colour and appears to have very little sedimentological structure, although some clay partings and lenses have been noted in cored samples. The fines content can often be detected to decrease upwards through Bed 'b'. It is commonly about two to four metres in



KEY TO FIGURES 7 AND 8. SHOWING THE LOCATION OF THE SECTIONS AND THE FACIES UNITS OF THE WOOLWICH AND READING BEDS CORRELATED ON THE SECTIONS

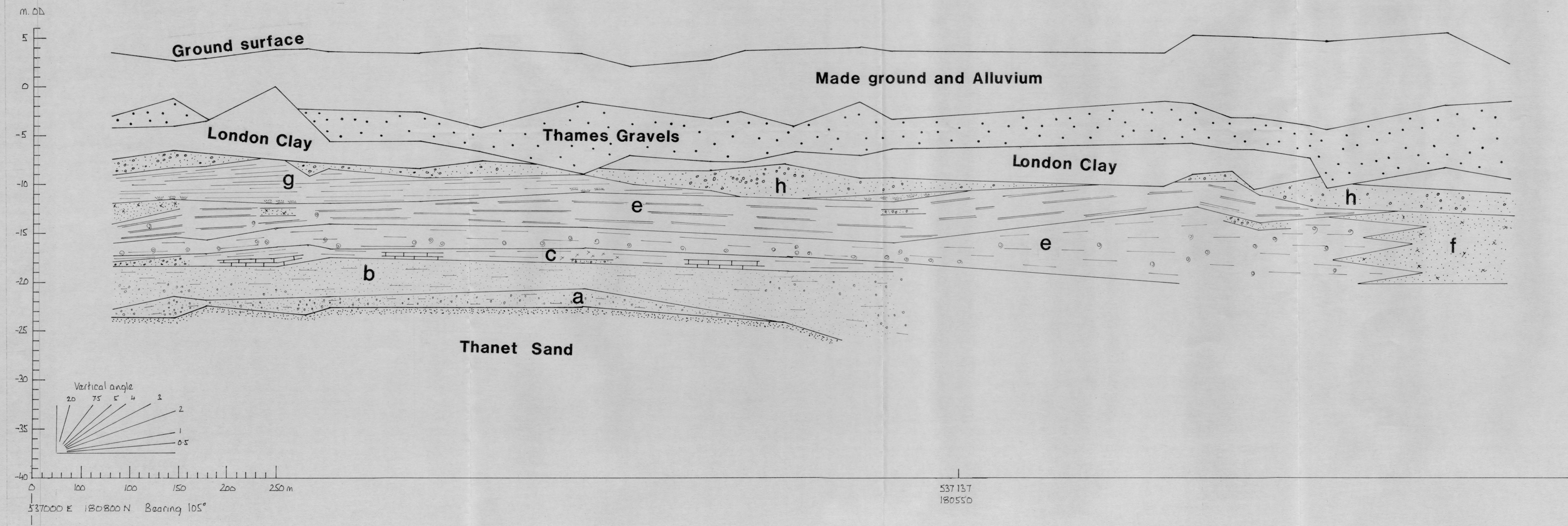


Figure 7. Section showing the principal facies of the Woolwich and Reading Beds to the west of the Greenwich Syncline

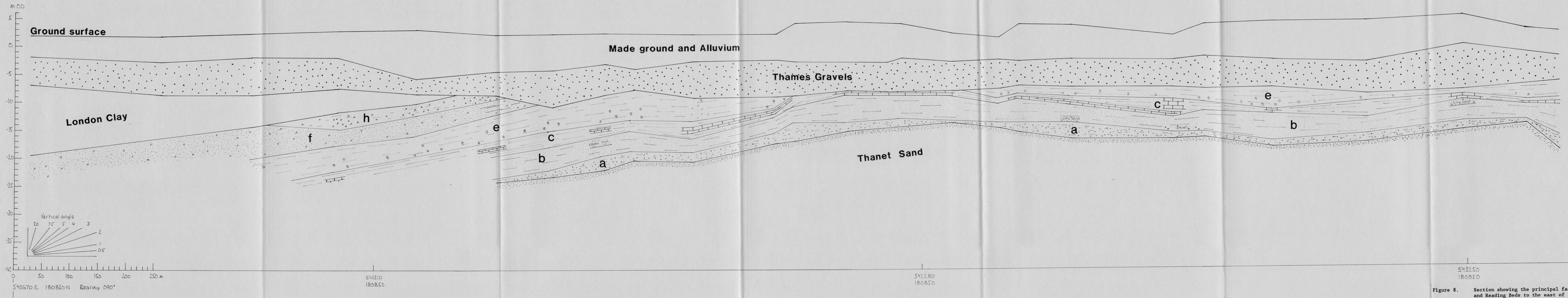


Figure 8. Section showing the principal facies of the Woolwich and Reading Beds to the east of the Greenwich Syncline

thickness, but can thicken locally above the local norm. There is some evidence that this thickening is associated with a reduction in thickness of the underlying Thanet Sands. Together with Bed 'a' this appears to correlate to Ellison's Glauconitic Sand as well as the Bottom Bed of the British Geological Survey (BGS).

Above Bed 'b' is a distinct horizon of grey green clay. This is associated with buff or pale cream limestone. The limestone is often found as a single band or occasionally two bands may be present. It varies somewhat in thickness and although it has been recorded as being a metre or so it is more commonly only a fraction of this. Limestone has been known in the area for some time by the BGS who regard it as a freshwater deposit and refer to it as the 'Paludina Limestone' (Hester 1965; Sherlock 1960). It is often found as, or described as, a band but can also appear as nodules or concretions. Where the limestone is more persistent it appears to reduce in hardness with depth and can be very rubbly or poorly developed in its lower parts. Specimens of the limestone are often weathered with a coloured tinge to fractures while voids and open fissures can be found suggesting partial resolution has occurred. The horizon is associated with sand units towards the west, while elsewhere both the sand and limestone are absent. Ellison defines a bed called the 'shelly clays' into which he groups the limestones. Although some shell is present in the clays of Bed 'c', as recognized here, these appear to be distinct from a more shelly Bed 'e' above.

Bed 'd' is not used presently as it was reserved for a correlation which assumed that the limestone was present as a single horizon. However, this has proved not to be the case as it has been recognized that the individual limestone horizons are impersistent. However, they are associated with and confined to a more extensive band of clay and together are termed Bed 'c'.

Ellison's 'Shelly Clays' are recognized here as Bed 'e'. He describes these as the "characteristic lithology of the Woolwich Beds" being a grey clay with both intact and broken mollusca shell material. These sediments were deposited in a brackish to marine environment and contain minor sand and silt laminae and partings. Although Ellison includes the limestones in his 'Shelly Clays' unit, here Bed 'c', which contains the limestone is considered to be separate from the thicker Bed 'e'. There is a distinct colour change to a more uniform grey in Bed 'e'. It is also characterized by the presence of shell material which is usually found in bands. The shells are generally broken, and where the valves are whole they are separated and associated from other fragmented material. The beds of shelly material often contain very little other material and must represent winnowed horizons. Overall there is an increase in shell content and the frequency of the shell bands with depth through the bed. The upper part of the bed is usually unfossiliferous and is characterized by the presence of partings and laminations of silt and occasionally fine sand.

Bed 'f' is a return to a more granular sequence it overlies Bed 'e' across the eastern part of the area but may partly replace it in the central section as shown on figure 7 and 8. However the evidence is limited here and the precise relationship is uncertain. Nonetheless, it does not extend into the west of the area and therefore must be, at least in part, contemporaneous with Bed 'e'. Ellison refers to this as part of the Glauconitic Sands. They are a similar greenish grey in colour to the lower Bed 'b' but they are a much cleaner material being a silty fine to medium sand without the slight clay content.

In the west the upper laminated section of Bed 'e' is more prominent and a number of bands of silty fine to medium sand are also present. In the west its upper contact is also marked by an organic horizon which is described as peaty inclusions or as lignite. This is overlain by a light blue grey unfossiliferous referred to as Bed 'g'.

The final unit in the sequence is Bed 'h' which is a series of quartz sands and well rounded flint gravels, sometimes with a clay content and often containing shell debris. It can be locally cemented to a conglomerate and lies irregularly on the various facies of the Woolwich and Reading Beds. They appear to correlate with the Blackheath Beds which to the east of the Docklands area are found to be up to 12 metres in thickness and locally fill erosional troughs cut well into the underlying materials.

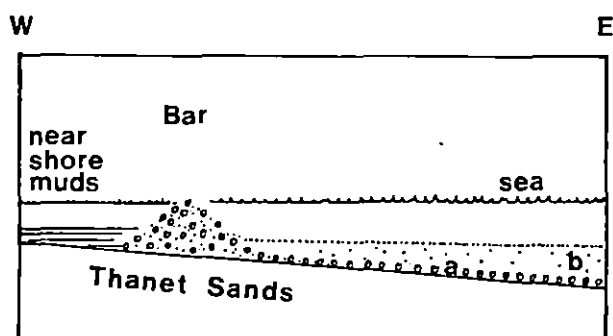
It is not always possible to develop a true depositional model with data from only a small part of the basin as the small scale variations may mask the larger regional trends and may therefore lead to incorrect assumptions. However, the data can be compared to Ellison's model as a starting point. It is evident that a number of Ellison's facies are not present in the Docklands area. In particular his Mottled Clay which characterizes the fluviatile Reading Beds is missing indicating that the depositional setting is probably a marine or brackish environment. The Woolwich and Reading Beds therefore represent a sequence of deposits laid at the margin of a more extensive marine environment which extended to the east across the present North Sea. Marine currents were strong enough to develop a longshore drift which brought heavy minerals into the area with a Scottish Highlands provenance (Morton 1982) and developed a linear shoreline with bars and beaches running parallel to the coast. These are characterized by a lateral transition from a fluviatile coastal plain, lagoonal and tidal flat complex, barrier island and offshore marine shelf environment (Selley 1985). The Docklands appears to lie at about the transition point from the inshore lagoon and tidal flat complex and the offshore marine sequence.

The change in heavy mineral assemblage between the Thanet Sand and the Woolwich and Reading Beds suggests that a significant unconformity is present between the two rather than just a depositional hiatus. Similarly because the provenance has changed

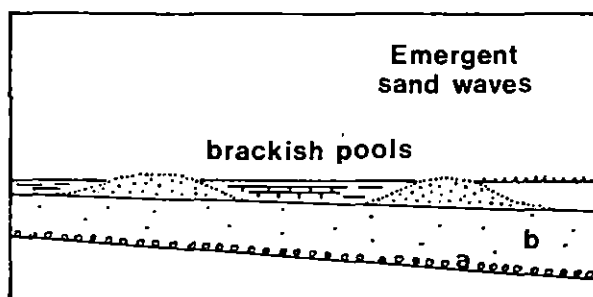
from a southerly to a northerly source area the basin hydraulics which generate the marine currents must also have undergone a marked change. It is not unreasonable to conclude that the Thanet Sand have undergone emergence. This is of course supported by Morton's contention that the heavy minerals in the Thanet Sand has experienced acidic etching in a terrestrial environment. This would also account for the apparent lack of marginal deposits in the Thanet Sand which could have been lost to erosion during the period of emergence. The consequence is that the basal units of the Woolwich and Reading Beds represent a major marine transgression (fig. 9).

The following model has been developed from the study to account for the facies variation present in the Docklands area. Bed 'a' is a residual gravel lag from a storm bar. That this can be identified at the base of much of the Formation suggests that the transgression was a result of a further gradual tilting of the landmass to the east. The overlying Bed 'b' therefore represents a littoral shelf sand and has similarities to the Thanet Sand. Indeed the grading envelopes of both are very comparable indicating that they were deposited in similar environments and energy regimes. The presence of further gravels within Bed 'b' suggests either that the general climate was more unsettled with storms as a more common event than during the Thanet Sand time or that the Woolwich and Reading transgression occurred at a slower rate so that minor fluctuations in the bar position have been preserved.

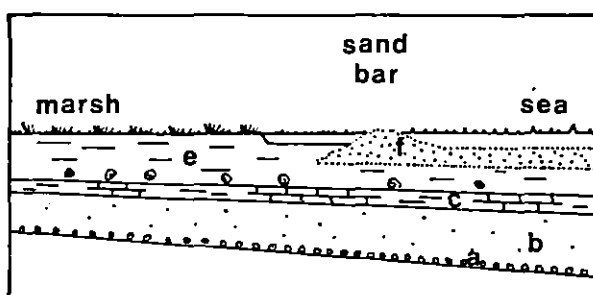
Following deposition of Bed 'b' a fairly shallow water must have developed to allow the accumulation of the limestone and its associated clay. However, there are also some sands within this unit. Ellison shows his 'Shelly Clays' to be restricted to a thin north south band and assigns them to a brackish environment. Within this context the limestone and clays may have been laid down in brackish pools contained by sand bars. Such a setting could account for the form of the limestone which is often progressively poorly developed with depth. Similarly it would account for the varying thicknesses and further bands of limestone. It is possible that a

**STAGE 1: TRANSGRESSION**

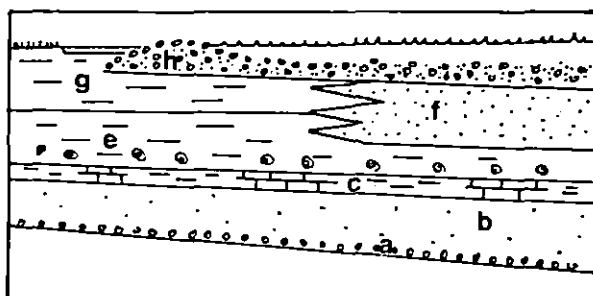
During submergence of the Thanet Sands a migrating storm bar left a bottom lag (a) which may incorporate some near shore muds was succeeded by a marine shelf sand (b)

**STAGE 2: REGRESSION**

The development of linear sand bars parallel to the coast caused brackish pools following a minor regression. Limestone and some clays were deposited. Residual sand from the sand bars was also incorporated (c)

**STAGE 3: TRANSGRESSION**

Brackish clays were laid down following as the water deepened. These were shelly with tidal currents producing winnowed bands of shell debris (e). Further shelly sands (f) were deposited in the east behind a migrating sand bar

**STAGE 4: TRANSGRESSION**

Following emergence of the brackish claysand development of a marsh condition further deepening of the water caused deposition of light blue clay (g) in an estuarine or lagoonal setting. Continued deepening allowed the migration of a shelly sandy gravel (h)

Figure 9. The suggested depositional model for the Woolwich and Reading Beds facies present in the Docklands

slight regression caused emergence of sand waves or offshore bars with the development of a series of brackish pools between. At times the limestones may have been broken up by currents and even weathered during periods of further local emergence.

Later deepening of the brackish environment would account for the more extensive fossiliferous clays of Bed 'e'. As this is also part of Ellison's 'Shelly Clays' which he shows to have a limited outcrop this may have been contained behind a barrier complex lying to the east of the Docklands area. Although brackish, the environment was probably less stagnant than that evident for Bed 'c' times. The clay was probably derived from the landmass to the west and redistributed by currents within the lagoonal setting. Tidal channels crossing the complex would have caused the local accumulation and winnowing of shell debris. The development of a finer laminated structure, the loss of shell bands and less fossiliferous nature of the bed in its higher parts suggests the development of a tidal flat environment in its later stages. A number of sand bodies in this bed can therefore be interpreted as infilled tidal channels or perhaps wash-over deposits. The organic deposits recorded at the upper level of this bed may be remnants of algae mats which developed on the surface of the tidal flat, or if complete emergence occurred the development a marsh or vegetated surface.

It can be seen that a further significant transgression brought the shelf sands of Bed 'f' in from the west. However, this did not encroach further west than the Isle of Dogs in the Docklands area. Although this is found overlying the clays of Bed 'e' in the east (fig. 8) a lateral facies change between the two is seen on figure 7 which supports the concept of the development of a brackish lagoon and tidal complex behind a barrier. Continuing deepening of the water allowed the deposition of the light blue clays of Bed 'g' behind the barrier.

A final transgression of the area appears to have resulted in the sands and gravels of Bed 'h' which represent the development of a more substantial barrier island complex which may be related to the Blackheath Beds which are more fully developed to the south and east.

3.2.5 London Clay

Following deposition of the Woolwich and Reading Beds a period of stabilization and possible emergence was followed by a major transgression associated with a deepening of the North Sea basin. This developed a deep water marine environment across south east England which resulted in the deposition of the London Clay. This is a typical marine clay deposited in water depths of 160 to 360m.

Over its greater part the London Clay is a dark grey or purplish grey fissured clay with varying proportions of silt and sand. The sand content increases generally towards the west suggesting the source area lay in that direction. The middle beds become less sandy but this increases again in the upper beds. It is generally inferred from this that the transgression extended further south and westward during Middle London Clay times perhaps opening a connection between the North Sea Basin and the Tethyeen Basin in the south. At its greatest extent a continuous sea covered much of southern England and northwest Europe (Curry 1965; Davis and Elliot 1957; Williams 1971).

The London Clay has a significant stratigraphic thickness but is remarkably uniform in lithology and effectively homogeneous for much of this thickness. This is in part due to the distal environment of deposition but is also aided by an intense bioturbation during deposition although Curry (1965) notes that the lowest 15m or so in the London area are particularly unfossiliferous and attributes this to unfavourable bottom conditions.

Historically three broad divisions have been identified in the London Clay by most workers (Burnett and Fookes 1974). More recent studies of the micropalaeontological and sedimentological aspects by Williams (1971) has confirmed a threefold division and established further subzones within these. The divisions can be attributed to further tectonic activity varying the water depth and rate of sediment supply, but because of the depth of water in the London Clay basin at the time these had a more subdued effect on its character.

Regionally the London Clay grades upwards into a series of more sandy facies which indicate the onset of further transgressive and regressive depositional regimes which continued to the end of the Tertiary Period.

3.2.6 Thames Gravels

Thames Gravels is a general term given to a series of superficial deposits composed of quartz sands and flint gravels found extensively along the tract of the flood plain and lowest slopes of the Thames Valley (fig. 10). In fact the deposit forms a series of terraces laid down during the Pleistocene in response to fluctuating sea levels and climatic conditions. In decreasing age these are classically described as the Boyn Hill, Taplow and Flood Plain Terraces following the work of Bromehead (1912) and as modified and used by the BGS (fig. 4). More recent work on the lower terraces has shown a greater complexity in the deposits and is developing a lithostratigraphic nomenclature based on local associations (Bridgland 1988, Gibbard 1985) as shown on table 2. Mapping by the BGS shows the Flood Plain Terrace to be the largest in present extent in the Docklands area, having eroded through and destroyed any of the earlier and higher terraces. Although this has been divided into the Lower and Upper Flood Plain Terrace (Berry 1979) the revised nomenclature of later workers working variously in areas to the east and west of the Docklands redefines these as the Mucking Gravel and

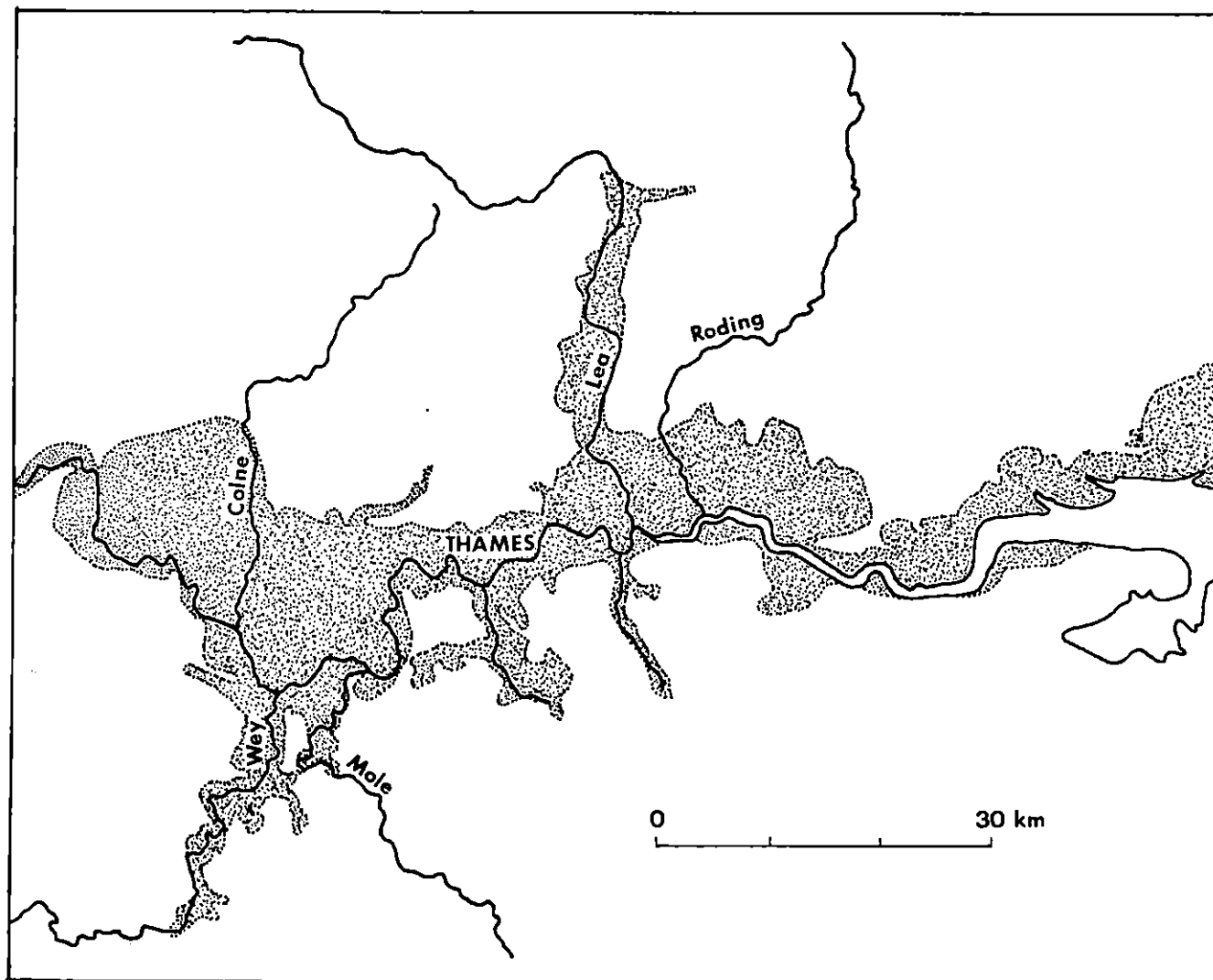


Figure 10. The distribution of the Thames Gravels of the middle and lower Thames and its principal tributaries

The distribution of the gravel is taken from BGS 1:625000 South Sheet First Edition (Quaternary) which shows it to be part covered by younger alluvium

Classic Useage	Middle Thames	Docklands	Lower Thames	Stage	Climate
Alluvium	Alluvium	Alluvium	Alluvium	Flandrian	Temperate
Brickearth	Langley Silt Cmplx	not present	-	L Devensian	?
-)	-	Silvertown Gr.	-	Devensian ?	Glacial
Low Fl Pln Gr.)	Shepperton Gr.	Shepperton Gr.	-	Devensian	Glacial
Upp Fl Pln Gr.	Kempton Pk Gr.	Kempton Pk. Gr.	E. Tilb. Mrsh Gr.	Devensian	Glacial
Brickearth	Langley Silt Cmplx	not present	-	Devensian	?
	Trafalgar Sq Dp.	-	-	Ipswichian	Temperate
Taplow Gravel	Taplow Gravel	not present	Mucking Gravel	Wolstonian	Glacial
Taplow Gravel	Lynch Hill Gr.	not present	Corbetts Tey Gr.	Wolstonian	Glacial
Boyn Hill Gr.	Boyn Hill Gr.	not present	Orsett Heath Gr.	Wolstonian	Glacial

Table 2 Summary of the correlation of the Thames Gravels in the docklands with adjacent areas
(in part after Bridgland 1988 and Gibbard 1985)

the East Tilbury Marsh Gravel/Kempton Park Gravel. In the lower Thames Valley Bridgland (1988) describes the East Tilbury Marsh Gravel to lie largely below the present alluvium of the flood plain with its upper surface rising somewhat above Ordnance Datum at the Lea confluence, that is above the flood plain alluvium. This suggests it to be the only terrace found in the area of the Docklands and so supersedes the Flood Plain Gravels of the BGS. This can be correlated with the Kempton Park Gravel in the middle Thames Valley which is shown by Gibbard (1985) to have a further gravel unit, termed the Shepperton Gravel, present below. This study has been able to extend the correlation between the two areas to the east and west and has confirmed the correlation between the Kempton Park Gravel and East Tilbury Marsh Gravel. It has shown that the lower Shepperton Gravel extends as far east as the Docklands area, and may therefore extend further into the lower Thames Valley area. It has also postulated a still lower terrace which has been termed the Silvertown Gravel which at present appears to have no counterpart in the middle or lower Thames (fig. 11).

The Thames Gravels are composed mainly of worn subangular and subrounded flint with a small proportion of other derived material. The flint gravel is usually well graded from fine to coarse grained and contained in a matrix of medium to coarse grained sand. Although it has not been possible to observe any sections of the gravels in the Docklands area it is possible to extrapolate from those described by Gibbard from equivalent units from the middle Thames valley. From these it can be expected that the gravels are massive or crudely horizontally bedded. Individual units within the main terrace body may be persistent but they usually have erosional bases and are often channelled into the beds beneath. Broad shallow channels filled with cross bedded sands and gravels can be present. These range up to 15m wide and 1.5m deep, but can be on a much smaller. There is a tendency for an upward fining sequence to be present in these channel fills but the sequence is often incomplete due to truncation by further gravel units above. Fine grained sediments are relatively

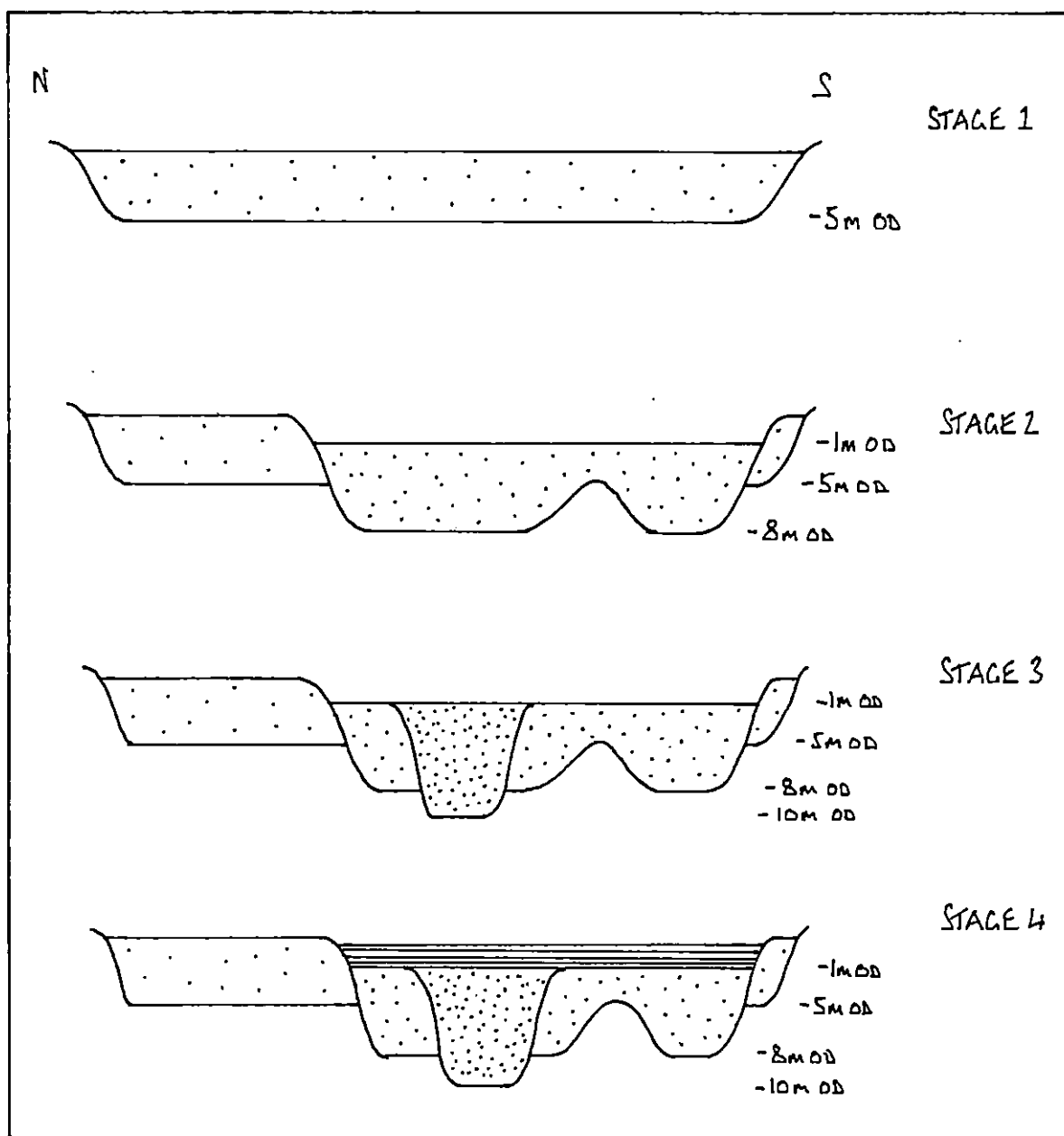


Figure 11. The suggested depositional sequence for the Thames Gravels in the Docklands area

- Stage 1: Deposition of the Kempton Park Gravel/East Tilbury Marsh Gravel following erosion to -5m OD.
- Stage 2: Erosion to -8m OD across the area of the present flood plain leaving some residual high spots and subsequent deposition of the Shepperton Gravel to -1m OD
- Stage 3: Further erosion to -10m OD within the Shepperton Gravel and deposition of the Silvertown Gravel to -1m OD
- Stage 4: Deposition of the present river alluvium above the Shepperton and Silvertown Gravels within the terrace of the Kempton Park/East Tilbury Marsh Gravel

rare but local accumulations of silty clay, clayey silts and some organic deposits can be found often as fill deposits to channels and other hollows.

Gibbard concludes but the grading and morphology of the units indicates that they were laid down in a braided stream environment as described by Miall (1977). Cold climate indicators, such as cryoturbation and ice wedge casts and the remains of an arctic fauna have been recorded in association with the lower terraces indicating that they were laid down under periglacial conditions during the Devensian. It is probable that they were deposited by meltwater controlled flood discharge. Evidence from the Blackwater Valley of Berkshire by Clarke and Dixon (1981) indicates a palaeohydrology during deposition of the gravels with a bank full discharge some 30 to 60 times that of the present river flows.

The terraces all show an overall downhill gradient from the west to the east following the long profile of the river at the time of their deposition. For the lower gravels in the central London area this gradient is about 0.6m per kilometre (Mather et al 1970). However the exact thickness and elevation varies considerably on the small scale. Although the lower contact with the underlying solid geology is relatively planar, albeit with some undulation, there are localized but significant deepenings which extend to depths of 20m or more below the normal erosion level. These have been related to the effects of scour at the confluence of the main channel and its tributaries by Berry (1979) and later to the growth of ground ice structures such as pingoes by Hutchinson (1980). This study has not been able to draw positive conclusions about these features. However the detailed contouring of the base of the gravels in the area suggests that they may be more common than previously considered. Also that they occur at varying scales. All of the features identified appear to be closed with no evidence of an outlet. The large elongate feature adjacent to the present confluence of the Lea which has been previously identified by Berry appears to be the most

non-circular of the mapped features. No evidence was found of disruption of the underlying solid deposits as described by Berry.

3.2.7 Alluvium

The final retreat of the last ice sheets about 10,000 yrs ago marked a significant change in the climate and geomorphology of the area. The abundant meltwater discharge that was previously available disappeared with the ice. Additionally, the sea level, and with it the base level of the rivers, began to rise. As a consequence the hydrology and form of the rivers changed to a single dominant stream course. The sea level has risen by over 100m in the last 14,000 yrs with perhaps 45m of this occurring during the last 10,000 yrs (Devoy 1977, 1979). The effect of the reduced discharge and flow rates was the deposition of fine sediment as alluvial silts and clays occasionally with subordinate and sometimes extensive peats.

The gradual rise in sea level is still occurring in the Thames estuary, currently at a rate of about 300mm per century (Horner 1977). Associated deposition of the alluvium has continued up to modern times and historically forms a wide tract of marshland running through the city of London and widening out downstream to the east where it merges into the tidal flats of the Thames estuary proper. In its natural setting the river formed a wider shallower channel than it does today with a shelving bank. Archaeological evidence suggests that in central and east London the river was anything up to five times as wide as its present channel and had a tidal range which was not as great as it is today (Hobley 1986).

As the general sea level rose through the post glacial period deposition kept pace and the marsh would have been dissected by creeks and riverlets. At times the area was inundated by flood water. Horner (1977) lists a number of contemporary reports of major floodings going back to the eleventh century. At other times it seems equally likely that the marsh would have become more

established as the water level dropped or vegetation stabilized the muds and caused it to rise above the water level by the continued accumulation of vegetable debris and overspill deposits. The character of the river sediments is such that significant distinctions within the alluvium due to these changes are not readily evident without a detailed investigation of their mechanical parameters and fabric. Skempton (1953) carried out a study of the alluvial deposits of the Thames at Tilbury and Shellhaven and has produced results which indicates such a variation to be present. However, it is not easy to transfer the inference of these variations directly into the London area as the deposits at these localities are much thicker and show a greater influence from their estuarine setting.

The major unit of distinction within the alluvium in the east London area is a significant and persistent peat horizon contained above and sometimes below by silty clay which otherwise typifies the alluvium. It seems likely that this developed during a more stable sea level when the vegetation debris had time to develop to substantial thicknesses and was later buried by a later inundation as the overall rise in sea level continued.

3.2.8 Made ground and the influence of man

Rising above the marshland at the edges of the alluvial tract would have been shelving banks of gravels and locally these would have been dissected by the former braided stream channels to form low islands. It is probable that the islands were more common towards the west due to the overall rise in the levels of the terrace gravels in that direction. Such features formed the important bridging point which influenced the original siting of London by the Romans and were also used by the Saxons as settlement sites in Southwark and on the north bank of the Thames in the vicinity of the present Strand (Biddle 1984; Hobley 1986). Another such gravel tract at Ratcliffe may have

been an important staging point on the bank of the main river and it is interesting that the modern road called the Highway runs directly from the area of the Tower of London to Ratcliffe and is associated with numerous finds of Roman artifacts. In the area of the Docklands and further downstream gravel islands did not rise above the alluvium other than perhaps in prehistoric times, therefore the main centres of population were sited further away from the main river where the higher gravel terraces rose above the alluvial tract of the widening flood plain.

Construction of a quayside along the river began in the first century AD by the Romans. Although the later Saxons, who succeeded the Romans, required a shelving strandline to beach their boats by about 1000 AD changing styles of their boats also prompted the use and construction of such quays. A consequence of a steadily rising river level, the need to provide increasingly deeper drafts for boats moored at the quayside and the pressure for more dockside wharfage meant that the quayside progressed steadily into the river. Although archaeological evidence for this has only been found in central London, this may in part reflect the areas that such investigation has been undertaken. Nonetheless, finds of Roman and later material in Newham suggest that settlements may have also existed in the Docklands area.

By the Middle Ages ship building had begun along the river front in Wapping. This was probably associated with other commercial activity. The move eastwards was prompted by the presence of the London Bridge built by Peter de Colechurch which with its nineteen narrow arches formed a physical barrier to all but the smallest craft. Although evidence for most of the early development is scanty records remain for a few. For example, in 1661 a small fitting out dock of 1.5 acres with gates to retain water was built at Blackwall and was the first wet dock in London. The more ambitious Howland Great Wet Dock was constructed at Rotherhithe in 1703 (Greeves 1980).

The development of the principal docks that followed over the next three centuries is well documented by Greeves (1980) and Pudney (1975). By the turn of the twentieth century docks were found on both sides of the Thames from the Tower through to Beckton (fig. 12). The last to be opened was Quebec Dock in 1926 in Southwark. Although further improvements of the existing docks continued into the post war years by that time the general prosperity of the docks had declined. In 1967 docks began to be closed and a number were infilled to make way for new development (Gahir et al 1987; Thomson and Aldridge 1983).

Throughout the history of the area secondary and tertiary commercial activities grew up alongside the docks themselves. These used the raw materials brought in by the ships, provided the services and goods necessary to maintain the industry or were just attracted to the developing industrial character of the area. Consequently heavy industry and processes requiring large amounts of land or plants and factories which produced noxious materials were sited in the area.

Along the river front, by modern times, quays and wharfs were present on both banks of the river with few exceptions. These too had pushed further into the river as had their historical precedents and as such the original sloping foreshore of the river became covered by a wedge of made ground. This made ground immediately along the river frontage is often found to be at a greater height than the ground immediately behind largely due to the need to provide deeper wharfage for ships as well as some protection from high tides. Nonetheless, the entire Docklands area is now covered by made ground to a varying degree except perhaps for the Beckton area immediately to the north of the Royal Albert dock which until recently has remained undeveloped. Elsewhere, successive development, the need to provide deeper docks or higher wharves, or indeed just the need to dispose of spoil whether excavated from the docks or produced by some industrial process has covered much of the area with made ground.

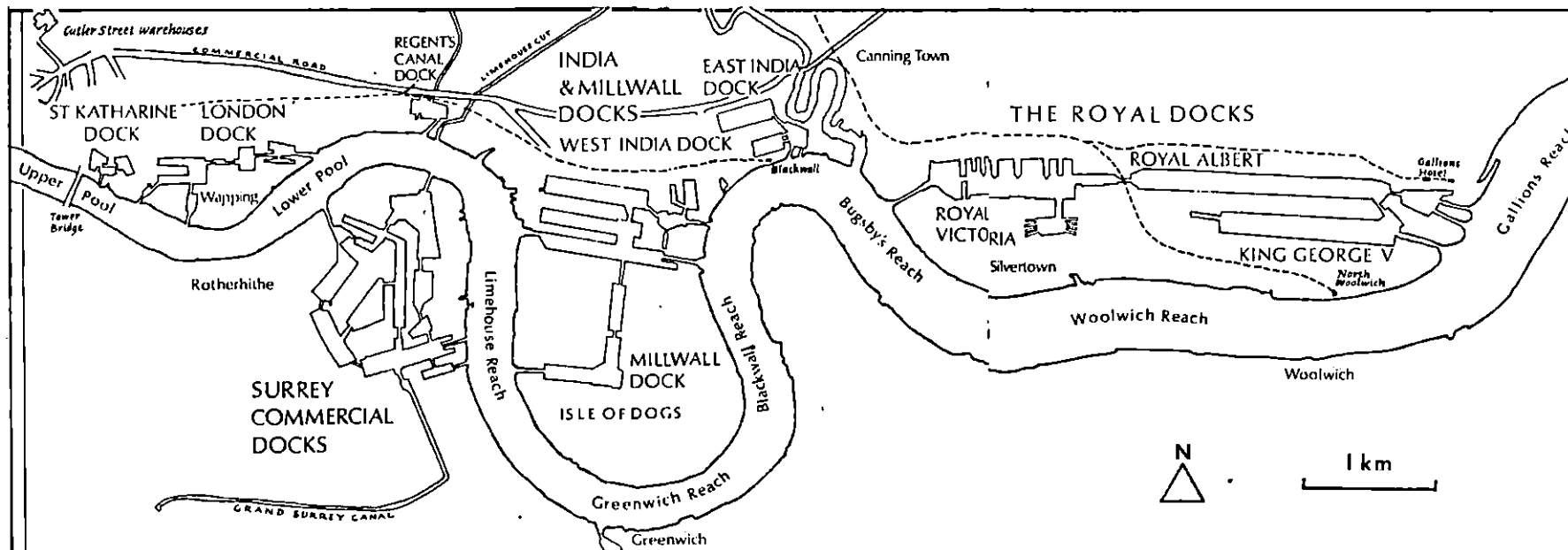


Figure 12. The London dock system at its greatest extent in the 1930's
(from Pudney 1975)

Because of the very varied history and source of the made ground few generalizations can be made regarding its character and condition. Adjacent to the docks it is predominantly made up of the dredgings and excavated material during the construction process. Commonly in the upper levels an increasing proportion of demolition rubble is encountered reflecting the continued redevelopment of the area and the extensive damage caused in the area during the Second World War. Elsewhere the made ground is strongly influenced by local industry. In particular the Beckton Gas Works in Newham has produced vast quantities of waste product which has been spread over adjacent land. Similar waste or spoil has been generated and disposed of locally and depending on the nature of the material it can now provide significant health hazards for the area. More recently plans to infill docks has resulted in relatively new and thick accumulations of made ground. Docks have been infilled in the area throughout the historical past, but the more recent major infillings of the Surrey Commercial Docks and London Docks have been of an unprecedented scale. Where these docks have been infilled as part of a construction programme only inert materials were intended to be included. However, it seems possible the large amounts of domestic refuse may also have become included in some docks (Gahir et al 1987).

In addition to the character and make up of the made ground itself the previous development of the area means that substantial buried structures may be found. These may be small features such as walls or more major structures such as pier foundations or dock walls.

The randomness of made ground and the overall lack of control to its character and distribution makes prediction for any one site very difficult.

3.3 The distribution of the principal geological units

The availability of some 3500 borehole records from civil engineering projects in the Docklands area has allowed a detailed consideration of the distribution of the principal geological units to be undertaken in this study. This shows some variation with that mapped by the British Geological Survey (BGS) which is covered by four sheets, No. 256 (North London) at a scale of 1:63630 and No.'s 257 (Romford), 270 (South London) and 271 (Dartford) at a scale of 1:50000. The geological detail shown on these maps was originally surveyed during the middle of the nineteenth century. It was revised during the early part of the twentieth century following a re-survey at a scale of six inches to the mile and has had only minor amendments since that time. Figure 13 shows the distribution of the solid deposits mapped by the BGS which can be compared with that based on the data presently available, as shown on figure 14.

Nonetheless, the present work has identified a broad overall agreement with the BGS mapping apart from two significant differences which markedly affect the understanding of the geology and hence the engineering geology of the area. These are the absence of the Greenwich Fault and a modification to the mapped outcrop of the Thanet Sand.

Perhaps the most important of these two differences is that there has proved to be no evidence for the Greenwich Fault or any other structural dislocation in the area. This affects not only the geology along the previously postulated route of the fault but also the structural implications for the region in general which otherwise follow from the presence of such features.

The Greenwich Fault has been traditionally shown to truncate the Thanet Sand outcrop where it crosses the Albert and King George V Docks to produce a faulted contact with the Woolwich and Reading Beds

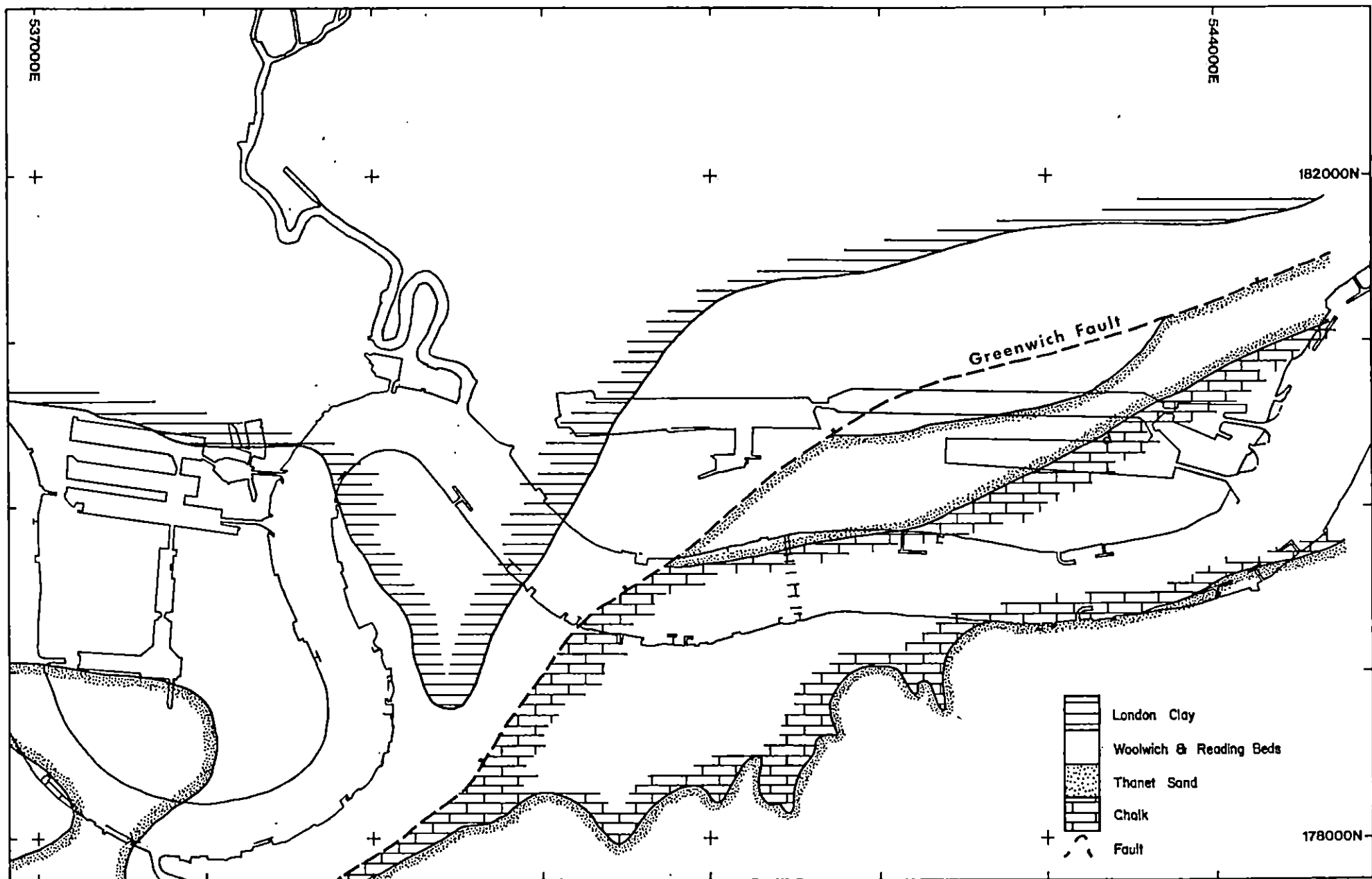


Figure 13. The solid geology as mapped for the area by the British Geological Survey

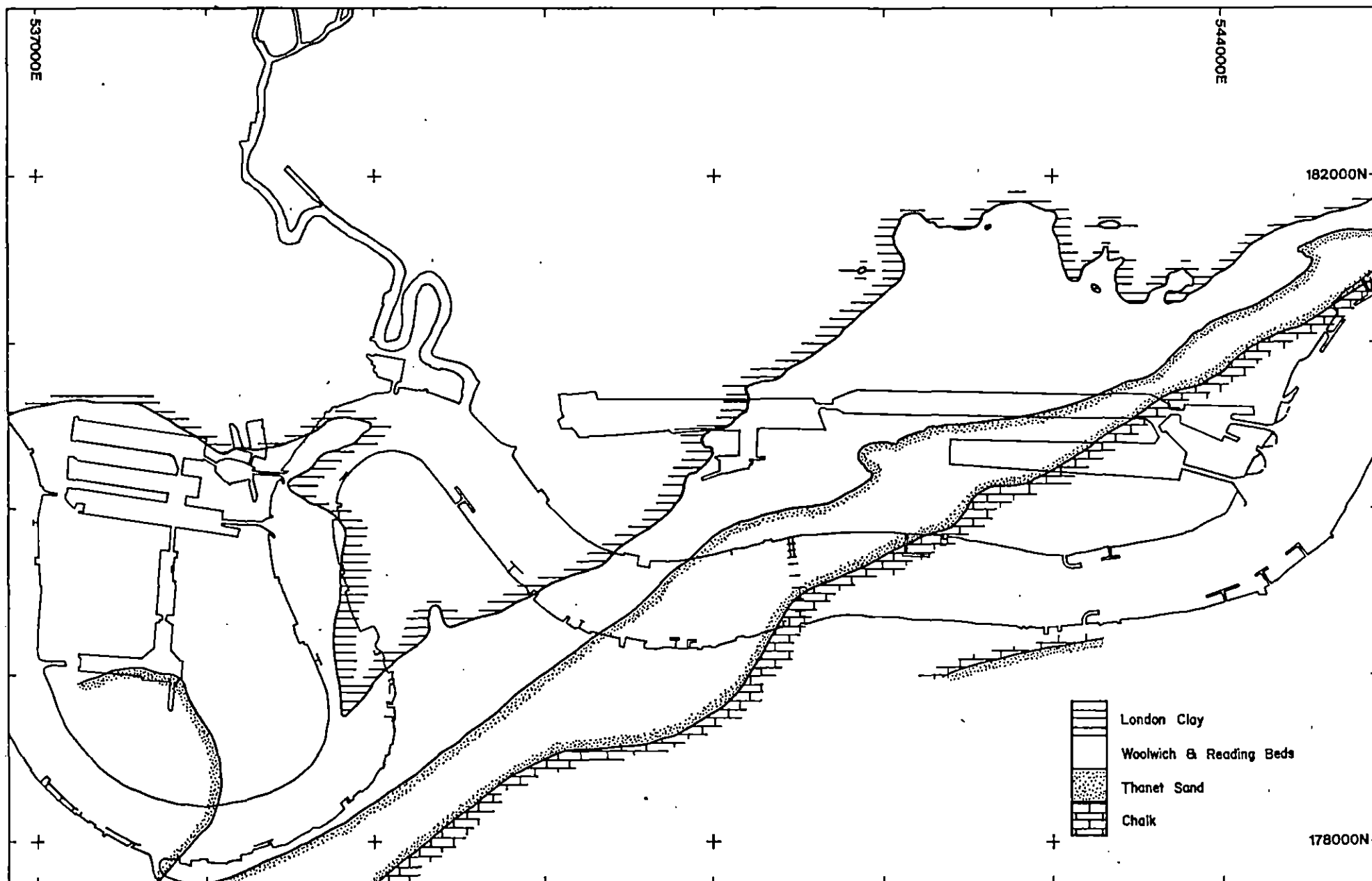


Figure 14. A revised solid geology subcrop for the Docklands after the present study

(fig. 13). Further to the southeast the Chalk is mapped thrown against the Woolwich and Reading Beds which indicates that there must be a minimum vertical displacement of 15m, if this is taken as being about the thickness of the Thanet Sand. This creates a problem without the fault as it would then be necessary to postulate the absence of the Thanet Sand. However, all the relevant boreholes used in this study show the Thanet Sand to be present below the Woolwich and Reading Beds consistently throughout the area which corroborates the general stratigraphy understood for the Palaeogene (Curry et al 1978). The Thanet Sand is also mapped by the BGS to be present in the high ground which forms the southern steepened valley slope of the Thames stretching from Greenwich Park to Charlton. Although no work has been undertaken for the LDDC south of the Thames in this area a review of the boreholes held by the BGS indicates that in fact the Thanet Sand is present and so eliminates the need for a fault to account for its absence. The outcrop of the Thanet Sand is therefore re-mapped to extend further to the southwest to cross the Thames immediately west of the Thames Barrier site and to extend into Greenwich (fig. 14).

The dominant structural feature in the area is a synclinal feature mapped by the BGS and more closely defined here and termed the Greenwich Syncline. It crosses the area with a northnortheast to southsouthwest trend from Greenwich Naval College plunging northwards to cross the mouth of the Lea at about its confluence with the Thames (fig. 15). The syncline is encroached by the Deptford Pericline centred to the southwest of the Isle of Dogs and which may be the cause of the westerly turn of the mapped nose of the fold. The axis of the fold is also curvilinear to the north and no available detail exists with which to postulate an extension further to the north.

A number of east west cross sections show the form of the Greenwich Syncline to be an open curvilinear relatively slight fold at its northern end but to tighten and develop a cusped form towards the south (fig. 16). Its flanks open out with a relatively planar

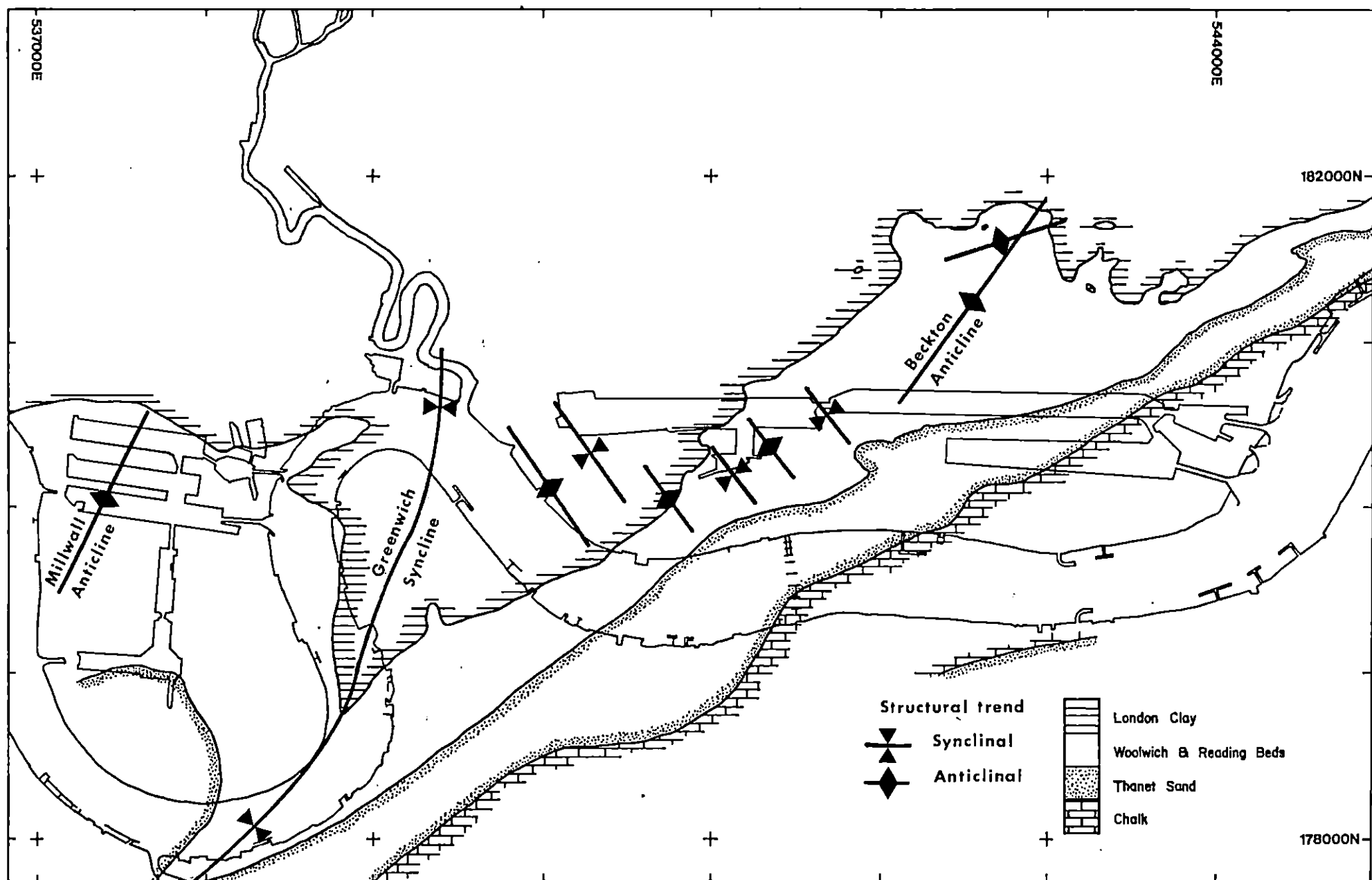


Figure 15. The principal structural elements identified in the Docklands from the present study

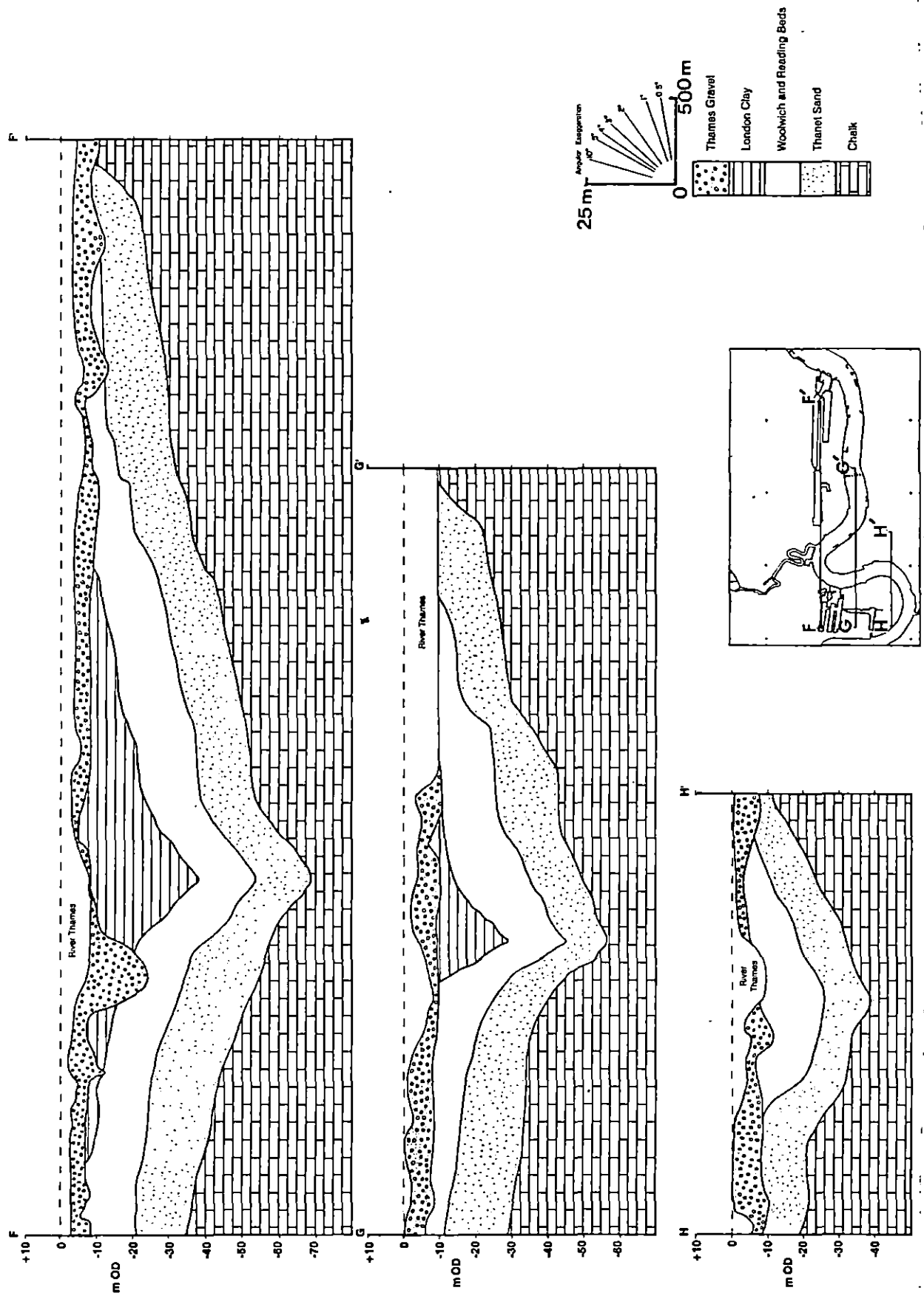


Figure 16. Three east west sections showing the principal geological units of the solid geology

form. However, there is some evidence for some minor folding with a complementary northwest southeast trend, particularly on the east flank, which are otherwise relatively constant in dip and strike. In general the eastern flank dips at about 2 degrees with a northeast southwest strike and the western at about 0.5 degrees. Although there are no complementary features of a similar scale to the Greenwich Syncline in the mapped area, low amplitude anticlinal features are evident to both the east and the west and are termed the Beckton Anticline and the Millwall Anticline respectively. Both the Beckton and Millwall Anticlines are confused by the smaller scale features on the flank of the Greenwich Syncline and it is felt that they both require further definition as more data is collected. The Beckton Anticline appears also to be affected by an east west axis which has produced a small periclinal structure within it. The larger Deptford Pericline, south west of the Isle of Dogs, must similarly have axes with north south and east west components, but on the available data these cannot be refined further.

The deep geology of Essex into which the Docklands encroach has recently been considered by Allsop and Smith (1988). They suggest that the dominating structures in the basement have an east west trend. Therefore, while the correlation between the basement structure and the east west trend in the cover rocks first suggested by Wooldridge (1923) is supported there is no comparable sympathy with the Greenwich Syncline. However, they conclude that the deep geology is complex and it may be that the relevant features are presently masked by the scarcity of data.

The age of any fold can be determined only by indirect evidence using the relationships of other strata and features. The sections across the Greenwich Syncline indicate that both the Thanet Sand and the Woolwich and Reading Beds maintain a uniform thickness across the fold. This suggests that the folding has taken place since their deposition, perhaps in response to some deep seated movement in the basement rocks of the area. As the relationship between sympathetic

folding in the cover rocks to deep movements is complex the form of the resulting structures to underlying stress directions is similarly speculative. However, if it is assumed that the fold axis is normal to the principal stress directions then a major compressive force acting in a northwest southeast direction can be invoked. This of course suggests its formation was related to the Alpine orogenic phase.

Figures 17, 18 and 19 show the contours at the base of the London Clay, the Woolwich and Reading Beds and the Thanet Sand respectively using the site investigation borehole data held by the LDDC and supplemented by boreholes from the BGS. It is evident that fewer deeper boreholes will exist than shallow ones and that interpretation at deeper levels will therefore be based on fewer data points. The contouring procedure has assumed that a linear relationship exists between adjacent data points. This means that the closer the points the more representative will be the contouring of the small scale fluctuations on the actual surface, while the further apart the data points such local fluctuations will be smoothed out. Wherever boreholes penetrate the full sequence it has been found that the Woolwich and Reading Beds and the Thanet Sand have a fairly constant thickness. It has therefore been possible to supplement the model of the lower surfaces by reference to the more certain higher surfaces.

In addition to the overall tectonic influence on the contoured surfaces there is also a small scale undulation which is evident in areas where a sufficient density of data exists. Much of this high order undulation is interpreted to be depositional rather than tectonic in origin as, in the Woolwich and Reading Beds in particular, variations in the thickness of the basal facies can be correlated with these undulations.

It is worth noting that it is necessary to view all borehole data with some care, particularly where this is derived from cable

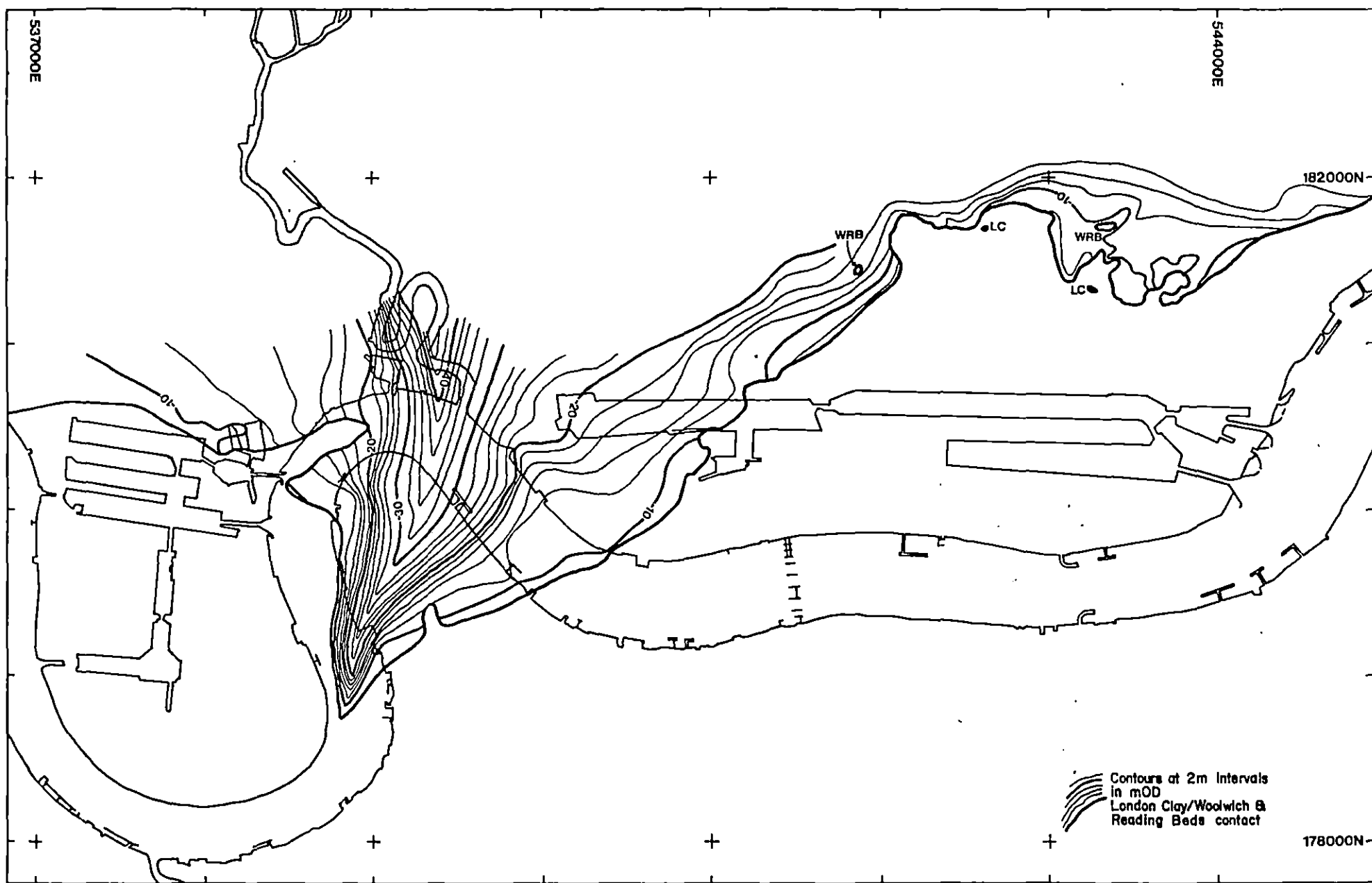


Figure 17. Contours in metres O.D. on the base of the London Clay (1:10000 copy is in the rear pocket)

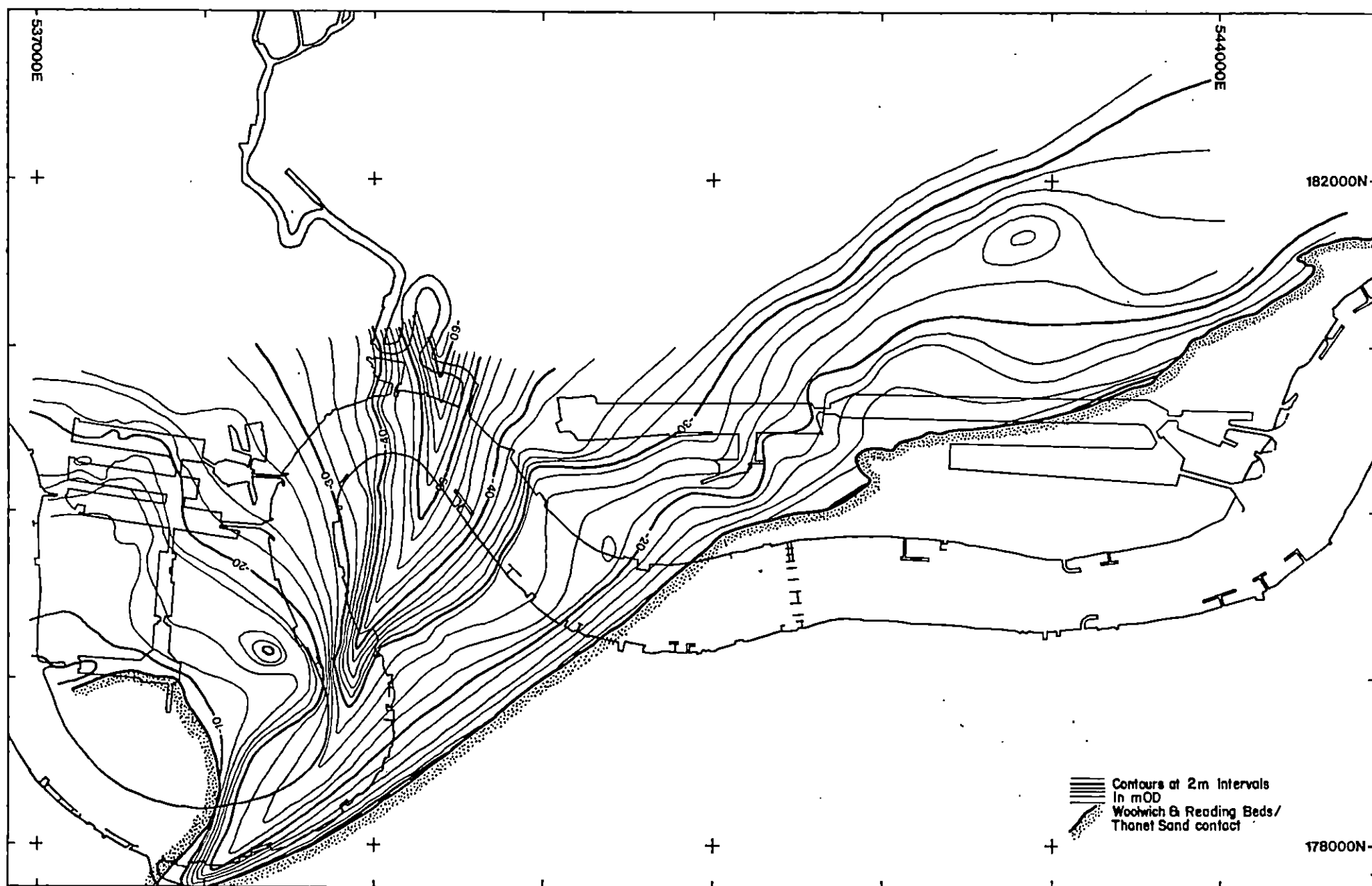


Figure 18. Contours in metres O.D. on the base of the Woolwich and Reading Beds (1:10000 copy is in the rear pocket)

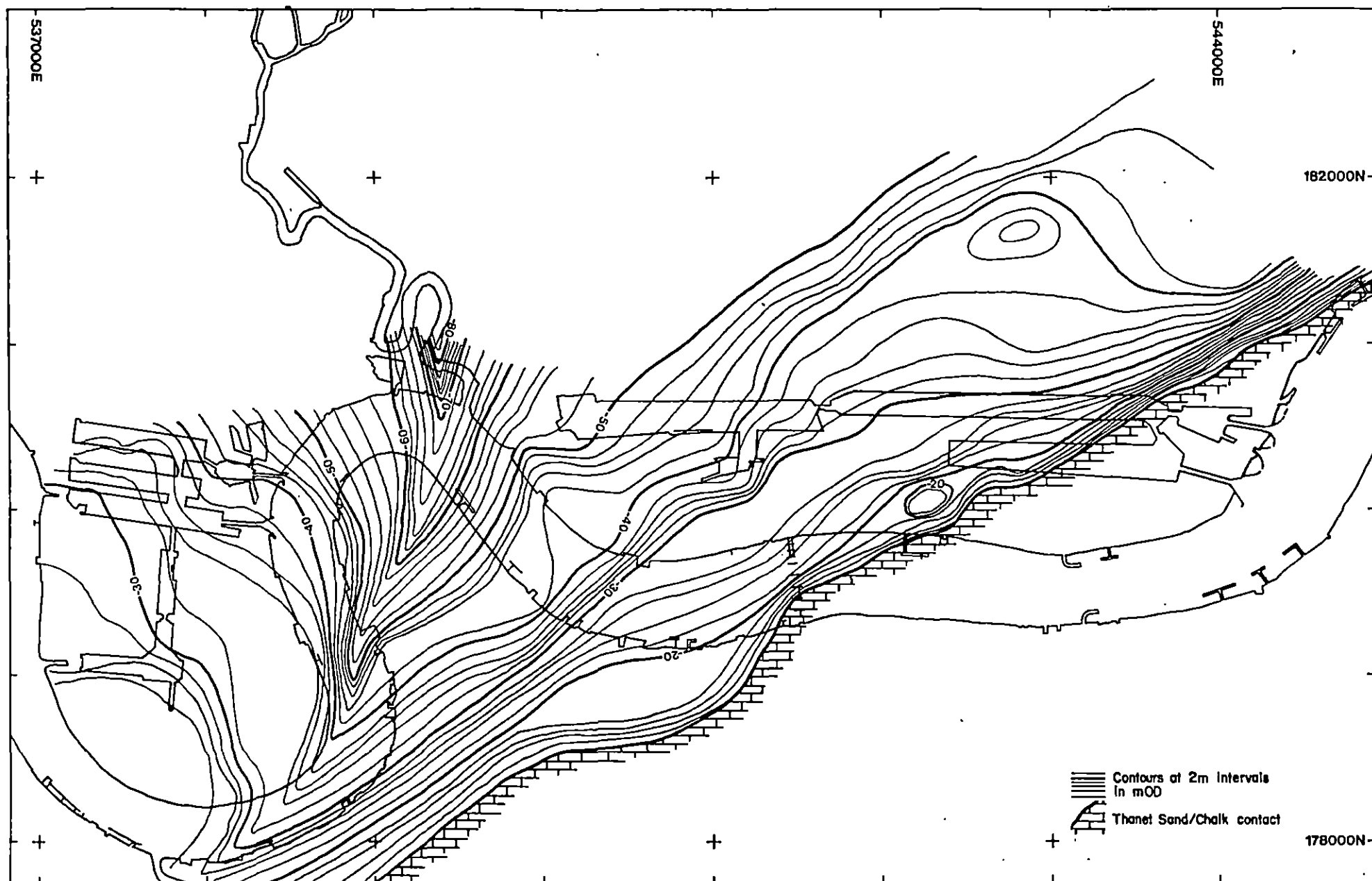
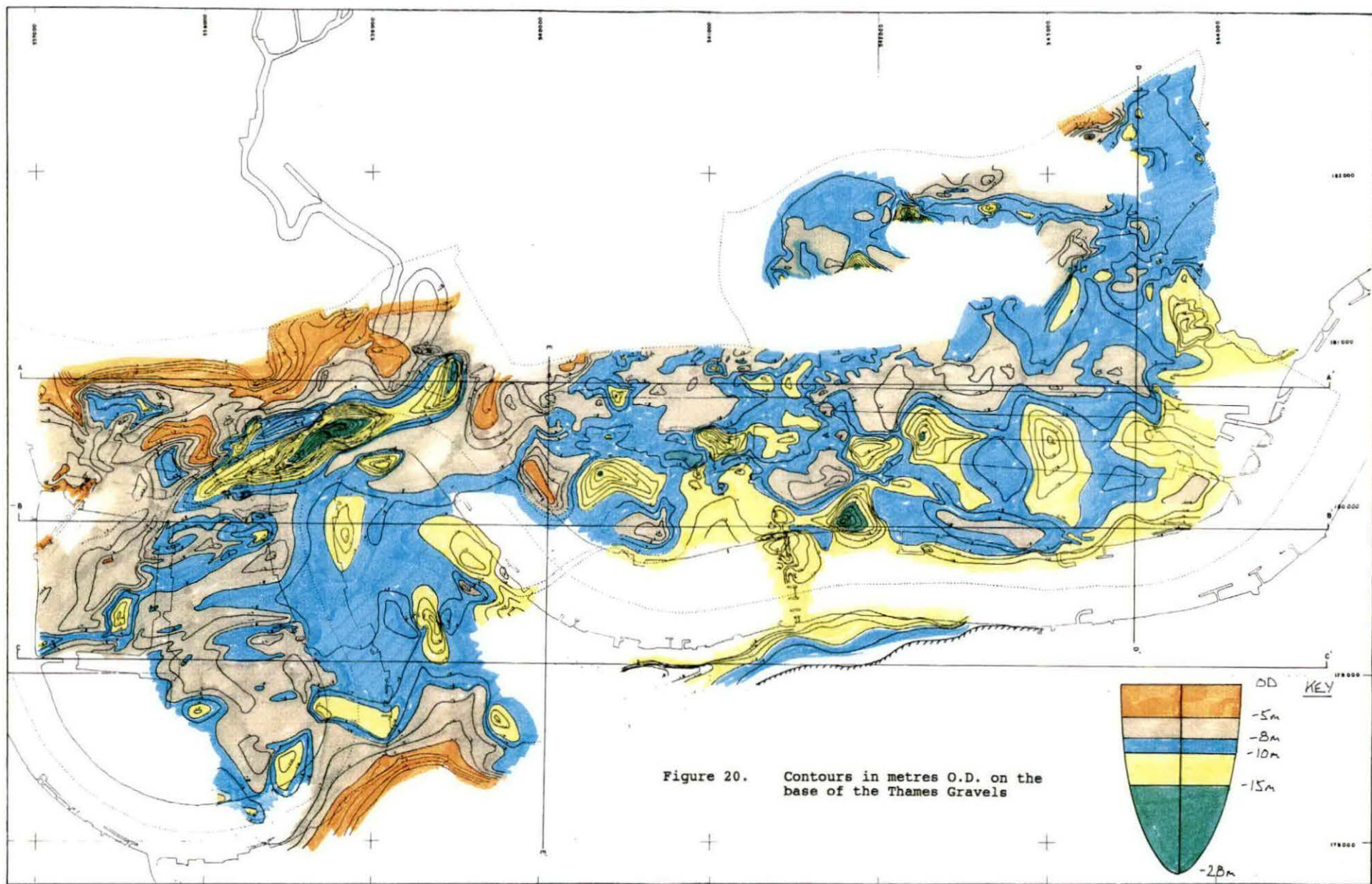


Figure 19. Contours in metres O.D. on the base of the Thanet Sand (1:10000 copy is in the rear pocket)

percussive techniques as traditionally used in civil engineering site investigation. This is for two reasons. Firstly there is a loss of detail because of the inevitable mixing of the more granular soils which is a result of the standard sampling procedures. This is compounded by the selective sampling which is normally at a routine frequency or even occasionally at the whim of the driller. Secondly there is the uncertain reliability of the depth measurements. This is often most noticeable over the lower levels of deeper boreholes and may be due to accumulating errors within the measurement technique or may even be deliberate. Examples of this have been found where the lower few metres of a borehole have not been bored once a 'persistent' strata has been reached and the sample depths are falsified on material obtained from higher up the borehole. This comes to light when the 'persistency' of the strata has been misjudged by the driller.

It has been shown that the solid geology in the Docklands is overlain by superficial materials which can be separated conveniently into the Thames Gravels and the Alluvium. The Alluvium covers much of the area of study and defines the present flood plain of the river. The Thames Gravels rise above the Alluvium to the North of the area with a lesser tract on the south side flanking Greenwich Hill.

Contours of the base of the Thames Gravels are shown on figure 20. It must be realised that the Gravels do not necessarily represent a single depositional event. Although the base of the Gravels at any spot is the lowest to which erosion has occurred, a braided stream environment in which the Gravels were deposited is such that the process of erosion and aggregation is episodic. The situation is further aggravated by fluctuations in both the base level and the stream discharge rates which have a marked influence of the erosion energy. In addition other processes peculiar to the cold climate of the time may well have affected the distribution and character of the gravel, the most important of which would be the role of ground ice.



The most noticeable feature of the base of the gravels is the absence of any definite channels and the presence of numerous closed hollows. Berry (1979) has described various hollows in the middle Thames area. This work has shown that not only are they extremely common in the Docklands, but that they vary significantly in scale and extent.

Colour has been used on figure 20 to help identify more readily the main features of the surface. It can be seen that the modern flood plain is also defined roughly by the base gravel contour at an elevation of about -5m OD. However, there are a number of residual high spots present within the flood plain area. It seems therefore that an early erosion level of about -5m OD existed and that this was wider than the present flood plain. It has been argued earlier that this corresponds to the East Tilbury Marshes Gravel of Bridgland (1988) and the Kempton Park Gravel of Gibbard (1985). Subsequently, it can then be seen that across the area of the present flood plain further erosion occurred to about -10m OD.

However, within this surface a number of large plateau areas are present at around -5 to -8m OD. This suggests that reduction to the lower level occurred in two phases (fig. 11). Interestingly, it can be seen that across the Isle of Dogs there is a virtual barrier of the higher ground with very little evidence of significant breaching. This may in part be related to the gradual dip of the terraces towards the east.

Alternatively, there may be an increase in the general level of erosion resulting from an increase in the discharge rate of the main channel from waters from the Ravensbrook or perhaps more likely the Lea. The base of the Gravels along the Thames itself is about -7m OD in Limehouse Reach to the west of the Isle of Dogs and at about -10m OD from Bubbys Reach and it seems unlikely that it is generally present much below -12m OD throughout the rest of the area. This sudden increase in depth is perhaps more likely to be related to an increase in discharge rate rather than the overall dip of the terrace.

The gravels are only found below an elevation of -10m OD where they occur in discrete hollows. The available information indicates that these are roughly circular or elliptical in shape, although this might be somewhat

influenced by distribution of the data points. However there is no evidence to suggest that any of these have an exit. Berry (1979) concludes that they are scour features perhaps aggravated by the growth of ground ice and this, or possibly the influence of stress relief, has allowed an interpreted diapiric rise of the underlying solid geology at some of the hollows. The idea of the role of ground ice was further developed by Hutchinson (1980) who suggested that the features were initiated as pingoes although possibly modified by later fluvial erosion. The greater number of hollows in the study area show that they are not obviously related to the distribution of the underlying solid geology as was assumed by Hutchinson. However, neither are they related to channels as was concluded by Berry. It seems that the origin of the features has become less clear rather than more obvious from the present information.

The upper surface of the Thames Gravels shows a similar variable pattern (fig. 21) although the relief in the surface is not as great as across the base. Depressions are still evident in the surface the most marked of which is in the north Beckton area. This is the only clear example of coincidence between a depression in the upper and lower surfaces and gives the strongest candidate for the likelihood of a post-depositional collapse structure following local ice growth. There is clear evidence of a channel with a base at about -5m OD running across Silvertown which is separated from the present river course by a tract of higher ground. In contrast significant areas of gravels above Ordnance Datum are found across the Isle of Dogs which suggests that here the present course of the Thames has been persistent during most of the Recent Period.

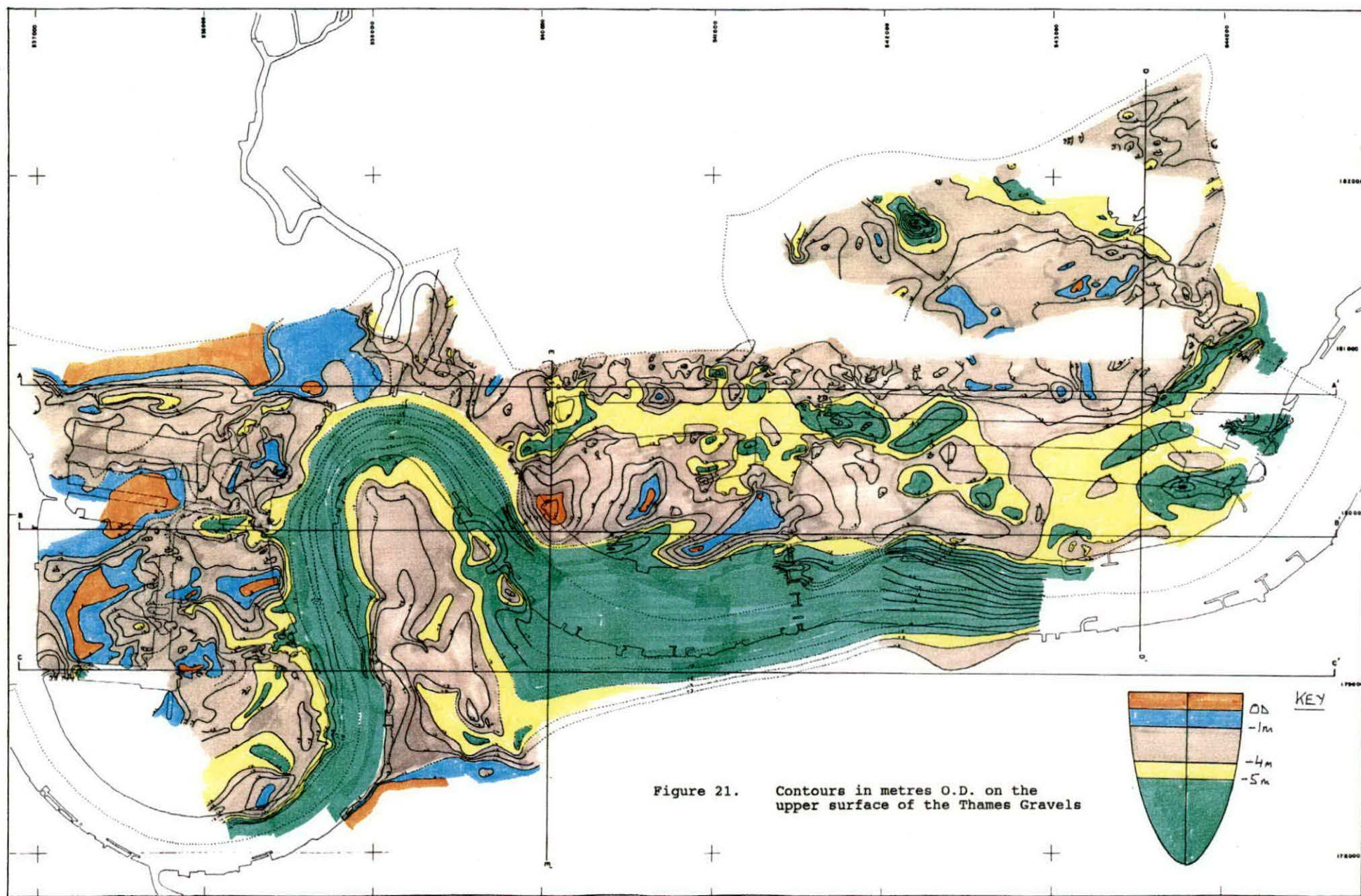
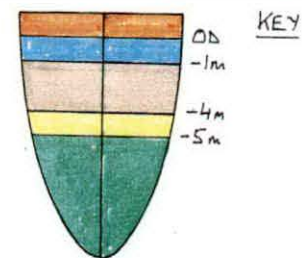


Figure 21. Contours in metres O.D. on the upper surface of the Thames Gravels



CHAPTER FOUR : A REVIEW OF THE COLLECTION, STORAGE AND PRESENTATION FOR RE-USE OF GEOTECHNICAL DATA AS PERTINENT TO THE DOCKLANDS

4.1. Introduction

The extent of the degeneration in London's docklands at the time of the formation of the LDDC was reflected in the land prices throughout the area. In order to tackle the situation and reverse the trend it was necessary to encourage development interest from the private sector. Although a number of socio-economic factors had been argued to have contributed to the existing state of affairs (Ward 1983) one of the practical reasons for a lack of interest seemed to be that the ground conditions were widely accepted to be poor and would therefore require extensive substructure costs for even low rise development. At the time the private sector was generally unwilling to invest in the site investigation necessary to even assess sites as the overall land values meant that the potential return on development was insufficient to justify the necessary foundation works. In order to overcome this reluctance, the LDDC decided to market the area with site investigation details so that discussions with potential developers could advance with realistic considerations given to the ground costs.

Shortly after its inception the LDDC began to collect site investigation and other ground data for the area. This was to be made available to all interested parties so providing a significant amount of data both on a regional scale and at a site specific level. Three sources were employed to generate this data;-

- Existing ground information, in the form of site investigation reports, was amassed from local authorities and other public bodies in the area.
- An overall appraisal of the geotechnics of the area was carried out (Knill and Howland 1982) following an extensive literature survey.

- A systematic programme of data collection was implemented through its own term contracts for site investigation.

The accumulation of data required a consideration of two important aspects. On the one hand there was the basic need to retain the data and to be able to retrieve it efficiently from some library, store or depository. While on the other there was the need to be able to re-use that data for projects and considerations other than for which it had been first collected. Although the two aspects may be viewed separately there is inevitably an interaction between which means that the one cannot be considered completely in isolation of the other.

4.2 The character of the data and the requirements of a storage system

The information collected from site investigations takes the form of borehole records and associated laboratory data. This is usually supported by an interpretive report provided by the organisation which carried out the investigation. These interpretive reports, although of interest, tend to be specific in their consideration having usually been commissioned for particular projects. The detail contained in the interpretation therefore cannot easily be used for other projects even where these may be located on the same site. However, this is not so of the borehole and laboratory data. This is factual in character, forming merely a record of the vertical variation of the material types on the one hand and a quantified assessment of their behavioural characteristics using standardised laboratory techniques on the other.

Traditionally site investigations for civil engineering purposes are carried out piecemeal, on a site by site basis by different interested parties. As the ground at any one location will rarely

change with time without some outside influence, the raw factual data may also be used for successive development considerations at any one site. In addition, as the distribution of natural materials is not controlled by artificial site boundaries, with care the data can be used to extrapolate to other areas outside. A unified approach to data storage provides the most efficient access to it at any later time. A further advantage is that the data itself can be used to provide a regional study, allowing trends and patterns to be determined which may not be evident from the studies of individual sites. Therefore, the value of the whole is greater than the sum of the parts.

It was evident that from a practical point of view there would be substantial problems associated with the basic storage of the volume of material being collected by the LDDC, let alone its cataloguing and re-use. The collected information was primarily intended to form a library available to all interested parties as part of the general stimulus to development of the area. It was essential therefore that a system was devised which should have certain attributes:-

- It should ensure ready access to the stored information,
- it should be capable of revision on a regular basis as more information is collected, and
- due to the working procedures of the LDDC it was also expected not to involve excessive staff commitments.

It was anticipated that by the time the LDDC had completed its intended programme of investigation under its term contracts and had collected together any additional data available on the area it would have amassed a data bank of many thousands of boreholes. Therefore it also seemed essential that any system developed for storage and retrieval should not become redundant with time. Indeed it should form a worthy legacy to be handed on by the LDDC to aid and stimulate subsequent generations of development in the Docklands, even after the LDDC itself ceased to exist as a body.

4.3 Methods of data storage and their suitability

The principal requirement for the storage of the basic data can be undertaken in a number of ways. It can be based on;-

- traditional paper records in the form of the original reports,
- microfilm or microfiche copies of the original data, or
- computer storage methods.

Each of these have advantages and disadvantages which are summarized on Table 3.

Traditional forms of paper archive were not felt to be viable within the working environment of the LDDC. This would require a long term storage commitment and the necessary provision of a librarian to control and index the material if it was to remain usable and intact from loss. This was clearly incompatible with the LDDC's restricted staffing policy and the fact that office facilities were only taken on short term leases. In addition the limited life of the LDDC might easily result in the eventual total loss of the information. The practical difficulties of traditional library systems had also been recognized by the British Geological Survey (Lawson et al 1975) and had prompted a number of studies of alternative systems for their own data.

The use of microfilm and microfiche have the advantage over traditional library systems in that only a small amount of storage room is required. A further very practical advantage is that additional copies can be easily made if material in the system is damaged or lost.

The data contained in geotechnical reports are usually presented in discrete sections. When used as working documents it is necessary to be able to continually refer to and cross reference the information on more than one page from one or possibly a number of reports. This

STORAGE SYSTEM	ADVANTAGES	DISADVANTAGES
Paper archive	- Traditional reports can be stored in original format - General familiarity with the system	- Large storage commitment - Usually centralised - Needs efficient and reliable indexing - Trained staff required to administer the system - Material may be on loan when required - Working copies need to be made for long term reference - Material can be lost or damaged - Material deteriorates with time
Microfilm/ microfiche	- Small storage commitment - Style of original format retained - Rapid perusal of large amounts of data possible by experienced user - May be held at many locations	- Needs efficient and reliable indexing - Trained staff required to administer system - Intermediate hard copies needed to allow comparative perusal of data
Computer	- Small storage commitment - May be held at many locations - Data can be processed by machine	- Data not necessarily in original format

Table 3. A comparison of the main storage and retrieval systems for geotechnical data :

can not be easily carried out with microfilm or microfiche systems without the need to make intermediate paper copies of the information. It was concluded therefore that this would impose a serious limitation to the efficient use of the stored data. In addition, as neither microfilm nor microfiche systems provide more than a condensed form of traditional library, they would not eliminate the need for a librarian and an efficient index. Indeed, without the provision of a librarian and index the casual enquirer would very likely end up ignorant of the presence of the information contained in the system.

The data derived from borehole records and laboratory test results provides the variation of a number of discrete parameters each recorded against depth as a common reference. They are therefore of a form which is inherently suited to simple tabulation. This is one of the basic structures used by computers for the storage of information. The use of a suitable database as a vehicle for the storage of the basic data would satisfy the requirements for the basic storage of the data. In addition it was argued that such a system would lend itself readily to the needs for data presentation and re-use as its datafiles could be interrogated and manipulated at some later stage by any number of output programs.

The perceived advantage of computerized approach was that as the output programs would be separate from the database they could be developed at a later time as needs dictate. In this way the raw geotechnical data could be stored from very early on in the development of the total system. Importantly, as the data could be stored in its complete and original form it also eliminated many of the problems and limitations of a number of other devised systems for storage and presentation which require varying levels of interpretation or simplification of the basic data.

4.4 Engineering geological maps and plans as a method of data presentation

The presentation of spatially distributed data in a readily usable form has been traditionally based on cartographic techniques and has been considered and used at various times as an aid to planners, architects, engineers and geologists both for specific projects and as a more general appraisal for larger areas or regions. The use of such plans fits naturally into the working practices of these disciplines and has perhaps fostered a measure of interaction between them. Indeed, the basic tool of the earth scientist is the ability to map and represent three dimensional relationships on to a two dimensional format.

It has long been recognized that there is a fundamental relationship between surface landform, the underlying geology and the processes which have acted at that locality. This morphogenetic relationship is widely used in remote sensing and terrain evaluation and is also relevant to the production of engineering geological maps.

The relationship between geology, soil profile, climate and landform has similarly been used in soil science where it is termed a catena (Ollier 1976, 1977). Since the factors which influence the soil profile, that is the mineralogy and grading, will also affect the geotechnical properties, it seems logical that materials with similar engineering characteristics will be found in similar landforms in areas which have the same geology and which have been affected by the same climatic processes. For example Kolb and Shockley (1957) demonstrated the genetic relationship between material type, its mode of formation and geotechnical properties for the alluvial soils in the Mississippi Valley. However, where environmental changes have occurred over geological time the relationships are likely to be complicated. Since the response to change at any one locality is not instantaneous but time related, the resulting relationships may, in fact, be very variable, particularly if the environmental changes occur on a frequency greater than the time period required to develop

a stable profile. In north west Europe and other regions where significant climatic variations have occurred during the Quaternary this effect is likely to be particularly marked and may be at least one of the causes why in a study area in Northamptonshire Knott et al (1980) found that the relationship between geomorphological unit alone and geotechnical properties was indeterminate.

The general concept of engineering geological maps, on which the information shown is concentrated on those aspects of the ground most pertinent to civil engineering considerations, has developed naturally from the basic mapping techniques of the geologist and other earth scientists. In Britain much of the information contained on these maps is fundamentally geological in character supplemented by some geomorphological detail (Anon 1972, Dearman 1987a, Dearman and Fookes 1974). However, the use of such maps is not commonplace in Britain. Perhaps noteworthy, is the fact that the relevant section in the most recent British Standards Institution code of practice for site investigation, (BS5930) includes only geological detail in its suggested symbols. Although the Site Investigation Manual produced by CIRIA, the Construction Industry Research and Information Association (Weltman and Head 1983) does indicate a somewhat broader range of factors to be considered it is still far from exhaustive. Both in fact fall short of the coverage suggested by The Commission on Engineering Geological Mapping set up by the International Association of Engineering Geology in an attempt to standardize international production of such maps (Anon 1981).

In truth, the character of the content of any engineering geological plans and maps will have an emphasis on local problems such as climatic conditions, hydrology, slope stability or other local hazards. Nonetheless, they have been used with advantage as an aid to specific projects particularly in the search for construction materials and for hazard zonation on corridor projects, and in particular where detailed studies of slope stability have been necessary (Brunsden et al 1975a, 1975b, Clarke and Johnson 1975,

Falkowski and Lozinska-Stepien 1979, Hansen 1984, Howland 1979, Newbery and Subramanian 1977, NIRRR 1971).

Less easily represented on this type of mapping is the efficient inclusion of quantified information. At a small scale the maps are most suited to broad or generalized studies. Therefore it is possible to include summarized data on the ground without jeopardising its worth to the intended or possible uses. At the large scale generalizations of the condition and engineering parameters of, for example a particular soil type must limit its use. It is even arguable whether the most pertinent parameters for any one project would necessarily be chosen to be included in general purpose maps without a detailed foreknowledge of the project in hand.

4.5 The role of engineering geological plans and maps in Great Britain

In their review of engineering geological maps Dearman and Fookes (1974) recognized that there has been a general lack of their development in the United Kingdom. They suggest that this is, in fact, due to the wealth of available basic geological map cover. However, this seems to be somewhat contradictory to the amount of site investigation being carried out, the extent of the published literature regarding engineering geological mapping, or indeed the general discussion within the industry for the need for enhanced mapping procedures. In reality the use of such maps in an engineering setting is very limited unless they have been designed around the specific needs of that project and, most importantly, that there is sufficient lead-in time for them to be produced. In addition, in urban environments the difficulties of the basic mapping is aggravated by the nature of the built-up area itself. Any morphogenetic relationships present may be masked by the buildings, if indeed the land surfaces of the present day are actually those which occurred naturally in the area.

This situation is in some contrast to a greater use of such maps in many parts of Europe, particularly eastern Europe and Russia (Lozinska-Stepian 1979, Ronai 1979, Melnikov 1979), although similar work has been undertaken at Toulouse in France (Vidal-Font 1979) and in Spain (Abad Fernandez et al 1979, Lopez Prado and Pena Pinto 1979). Perhaps the only comparable situation in Britain has been the study undertaken by the British Geological Survey for the Milton Keynes New Town (Cratchley and Denness 1972).

In conclusion, it is felt that the most likely reason for the lack of development of engineering geological maps and plans in Great Britain is that, in the general case, they are inappropriate to civil engineering practice as it currently operates and, perhaps the techniques are not suited to the nature of the landscape itself.

4.6 Some previous attempts at the systematic storage and presentation of geotechnical data

The systematic storage and presentation of geological and geotechnical data is not new. William Smith produced the first geological maps in Great Britain at the turn of the nineteenth century. In fact, these were produced as an aid to the canal engineers of the time to predict the ground conditions and find suitable construction materials. Although they are generally referred to as the first true geological maps, perhaps they would be better described as the first engineering geological maps. The work begun by Smith was continued from 1832 by the Geological Survey which was set up to produce geological maps of the whole country. The work of the Survey, now the British Geological Survey (BGS), has continued since. They have collected water well records going back to the nineteenth century. More recently, these have been supplemented by additional boreholes, largely put down for civil engineering site investigation purposes to form a collection of over half a million

records. These are used by the BGS to continue their basic geological appraisal of the country. Although it is possible for the public to gain access to much of the information held by the BGS, the effects of scale often caused by the low density of available information severely disadvantage its local use for engineering purposes.

A number of more recent sheets produced by the BGS have included some geotechnical data on the principal soil types or made reference to features which may have engineering relevance. They have also produced a number of specific engineering geological maps such as those for Belfast (Bazley 1971), the upper Forth Estuary (Gostelow and Browne 1986) and south east Essex (Cratchley et al 1979).

A lengthy project to include quantified data of an adequate level for general purpose enquiries has been carried out at Newcastle University for the Tyne and Wear Databank (Dearman et al 1979; Strachan & Dearman 1982; Scott 1976). This attempted to categorize the ground conditions within 100 metre square areas by abstracting data from available reports. It was found that the production of the map required a considerable amount of time for input and evaluation of data. Like all such approaches where a single map or series of maps is the principal form of data presentation the product is correct only as far as the latest information contained on it and useful only as far as the actual data detailed and the scale and resolution of the map is relevant to any individual project. It was finally concluded that actual ground conditions even within this relatively small basic mapping unit were too variable for the approach to have general application (Dearman and Strachan 1983, Dearman 1987b).

Using the concept of land facet mapping, more common in terrain evaluation techniques, the Geotechnical Control Office in Hong Kong has developed a technique of mapping which includes multiple overlays (GCO 1987). This overcomes some of the problems of the Tyne and Wear

Databank in that it allows a greater degree of selective weighting of the necessary parameters to the project in hand.

The use of computers for the storage of borehole and related data has been considered at various times by the BGS where the practical difficulties of maintaining traditional library systems had been appreciated and prompted various studies to consider the use of computers (Cratchley et al 1979, Gill 1975, Gover et al 1971, Harvey 1973, Henderson and Laxton 1986, Lawson et al 1975, Reekie et al 1979; Rhind 1973, Rhind et al 1971). However, they also appreciated the limitations of the traditional cartographic forms of data presentation (Rhind 1973) and realized that such systems would need to allow selective retrieval of the stored data to be of benefit to later users.

This ability to control the way that stored data is referenced is a feature of the Scottish Land Borehole Database. This is a pilot study by the BGS of ten square kilometres of Glasgow to provide a computer database of available borehole information (Henderson and Laxton 1986, McMillan et al 1984). Its purpose was to provide a ready aid for the assessment of lithological distribution in the area to serve further pure and applied scientific studies, such as sand and gravel resource surveys (Shaw and Aitken 1983) or the production of the Environmental Geology Maps for Glasgow (Forsyth et al 1985). Geotechnical data was not included in the database. Geotechnical data was included in the production of the South East Essex Geological and Geotechnical Survey by the BGS. However, it was concluded that the type of databank would not be justified for the recording of general site investigation data throughout the country (Cratchley et al 1979).

In contrast a similar approach has been followed in Czechoslovakia where there is an increasing demand for improved interpretation and prediction in regional studies (Matula 1979). There, a national computerized Engineering Geological Databank has been set up. The

system is continually updated by reports and borehole records which by law are required to conform to a standardized format and terminology. The databank is then accessed by a series of output programs which can provide the data in various tabulated, analytical or graphical forms depending on the needs of the user. Similar systems have also been described for databanks in Canada (Morin 1979), Italy (Montanari and Previatello 1979) and France (Buisson et al 1979).

In South Africa the concept has been applied specifically to the problem of road construction. The National Databank for Roads was set up in 1971 to collate and make available the data collected during separate road projects (Clauss and Vail 1975, NIRR 1971). Using the relevance of the land facet mapping to the particular climatic and geological conditions of the country (Kantey 1971, Weinert 1968, 1974) a standard approach to materials investigation was developed (NITRR 1978) based on a structured format and terminology which then allowed storage and later retrieval of the data.

In Great Britain there has been a reluctance to establish a unified approach to data collection with the aim of developing a similar databank. Although the BGS have collected a considerable number of borehole records and indeed the relevant legislation of England and Wales (Anon 1926, 1973) and their counterparts in Scotland and Northern Ireland (Anon 1946, 1959) require certain borings to be supplied to the BGS there has been no attempt to standardize their format or terminology. Although site investigation boreholes and related reports maintain a general similarity of style based on various codes of practice and working party reports (Anon 1972, Anon 1981) there is as yet no legislative requirement that they should be followed.

The use of computers as a means of manipulation as well as storage of borehole data have been described by various workers (for example;

Astle 1985; Day 1983, Day et al 1983, 1987; Raper and Wainwright 1987; Rosenbaum 1987; Rosenbaum & Warren 1986; Wainwright et al 1985; Wood et al 1982, 1983). However, the only assessment in Britain of the possibility of a structured national databank has been undertaken by the Construction Industry Research and Information Association (CIRIA) which undertook a feasibility study of the formation of a National Registry of Ground Investigation Reports (Tuckwell and Sadgrove 1977). It considered specifically the storage of the wealth of borehole data which exists for civil engineering purposes and how to make them more readily available to other interested parties. Following the recommendations of the Working Party that a National Registry should be set up an underlying reluctance from the industry led to the matter being taken no further.

4.7 The suitability of geotechnical data to storage by computer based systems

Although the CIRIA working party on a registry of ground investigation reports dealt specifically with a national requirement it is worth considering the various conclusions arrived at as similar factors would affect any further attempt at the systematic storage of geotechnical data in Britain.

CIRIA felt that if such a depository of data was to be established the user would prefer to have the actual information made available rather than be supplied only with a list of addresses from which the reports could later be obtained. It is clear perhaps that if only the source of such information was supplied it would take the user extra time to contact those sources before the information was supplied. Such a system would also impose an additional practical difficulty, for in order to work the third party holder of the information itself has to be set-up for and be receptive to the rapid retrieval of the information from its own archives. Taking a practical viewpoint many of these third party sources are likely to

be commercial organisations. It must be expected that these would have a variable willingness to cooperate with the request or indeed at times may not be in a position to be able to cooperate. An additional factor for consideration is that over recent years a number of companies that would be expected to hold such information have ceased to trade, presumably such an occurrence would result in the loss of much material from the total system. It seems therefore that a system which only indicates the source of material could result in a very variable success in obtaining any relevant information, particularly where the material is retained by third parties.

The point was also made that engineers are particularly interested in seeing the source material so that they can assess its quality and therefore its value. It is unlikely that précis's or abbreviated versions of the data would therefore be widely acceptable.

CLRIA concluded that microfilming of the records was a better method than the use of computers as they were concerned that the extraction of data from the report for computer storage would "require judgment, introduce scope for errors and be too costly". The actual storage and retrieval of the microfilmed information would then be carried out by manual filing. However, since they reported there has been a significant advance of computer technology. The conclusions were therefore made at a time when the scale of computer capability was very different to that available today. This is not to say that computers can necessarily do any more now than then, just that the access to that capability is now more readily achieved. Nonetheless, the fundamentals of the arguments put forward by the Working Party are still open to dispute. For example, they were concerned that judgment would be necessary to achieve computer storage of the data. The need to apply judgment during input occurs for one of two reasons.

- Firstly, if the storage vehicle or the input method are inflexible it may be necessary to restyle the data to allow its storage.
- Secondly, limitations of the system may require some selection of the total data to be stored.

Both of these situations would indeed require an element of judgment, but both can be eliminated by the use of a high level database language. As CIRIA accept, the user would prefer to have the full and complete information as contained in the original report. It is essential, if this is to be achieved, that the original information is therefore not précised or abbreviated either by choice at the input stage or by limitations within the system. The aim should merely be to accept and be able to subsequently output the complete and original information. Consequently, if all the information is to be stored it is only necessary to transcribe the original data. This eliminates any need for judgment at input and therefore the associated scope for errors. The ease and efficiency with which the transcription of the information can be achieved can also be controlled by the quality and format of the input programs used.

Clearly, no matter how well contrived the input program may be if the information is to be keyed in at a conventional keyboard it would not be possible to eliminate all transcription errors. This does however presuppose the use of a conventional keyboard. It is possible for information to be read from the printed page directly by the computer although there are some restrictions due to the quality and style of the characters which can be read. Alternatively it is now common practice for laboratory tests to use data loggers. Where this is the case it is possible to transfer the laboratory data directly from the logger to the central store.

It has been recognised by a number of commercial practices that the production of borehole records by microcomputer has significant advantages in time and efficiency (Chaplow 1986, Finn and Eldred 1987, Howland 1986, Howland and Podolski 1985). Such procedures can

be developed to allow the routine and logical aspects of the borehole format to be carried out and produced by the computer. For example the header information on each borehole sheet can be abstracted each time from a single job file. Likewise the automatic generation of such parameters as sample numbers and elevation is easily achieved. As the information can be sorted, ordered and printed to any scale by the computer the method of input of the raw data can be relatively simple and in any convenient order (Howland and Podolski 1985).

The logical extension is to consider the production of the borehole record by the computer, and its use as a database as complementary. This would then provide particular advantages to the speed with which new information can be passed into the database. More importantly, it maximises the accuracy between the stored data and the source material as the input of the one and the production of the other are achieved by the same keyboard. Although some use has been made of automatic transfer of data from the field (McMillan 1985, McMillan et al 1984, Ward & Damtaro 1989), traditionally a borehole record is produced by an engineer using a drillers record and his own descriptions of the samples. As the engineer is intimately involved with the job an importance is attached to the job which in most cases produces an accurate and reliable borehole record. The actual production of the borehole record from the field sheets is usually completed by a typist, for obvious reasons. This naturally needs to be checked for errors. Again because of the importance of the boreholes to the project this is generally done by the engineer. Therefore, errors are likely to be rare in the original borehole record because of the importance of the checking and the close involvement of the engineer. However, this is not the case when such boreholes are later transcribed for entry into a storage system. This is likely to be done with only a limited involvement of an engineer. The numbers of boreholes being handled produces an anonymity which reduces the level of checking of each record. It is therefore necessary to involve further in-built validation facilities such as the double entry of all data and an automatic alarm whenever there is a discrepancy.

These problems can be eliminated if datafiles created by a computerized borehole record system are then used to transfer the information to the database. The problems of re-typing the data would be eliminated so that any errors in the database would only be those related to the original borehole production. Their validity would be as good as the original checking by the author of the records.

Transcription errors can only occur where there is a manual input of information, typically through a keyboard. The absolute elimination of all sources of transcription errors can be easily achieved where the information is derived from a single source, such as a term contract, for a client who has the facility to instruct the method of data presentation. The necessary level of cooperation from the contractor is easily achieved by including it into the contract documentation.

4.8 The approach adopted in the London Docklands

As part of its strategy for the regeneration of the Docklands the LDDC felt that it was necessary to foster a geotechnical understanding of the area and to control the overall collection of further data in the area. In this way it was argued that the understanding and appreciation of the area would be cumulative and that this could be passed on to third parties as and when they became involved in the area so reducing the need to "reinvent the wheel". However, it was also decided that at no time would project specific information be offered without the direct involvement of the individual design engineer in its collection.

The general lack of development in the area over the preceding decades meant that reliable modern data was very limited.

Nonetheless, an overview of the geotechnical aspects of the area was produced immediately (Knill and Howland 1982). This provided a summary of a literature review and gave a detailed summary of the geology, the hydrogeology and a geotechnical appraisal of the soil types present and their lithological associations. Additional influences on the development of the area were also described. A number of maps and long sections showing the distribution, contours and thickness of the principal soil units were included. Use of the document gave an immediate insight into the conditions of the area for those unfamiliar with it.

As outlined in the introduction to the Chapter the two main points of concern were, to produce a simple but reliable storage facility for the mass of data that was expected to be collected, and secondly the need to be able to process and assimilate that data into project specific considerations.

Following a review of the options it was decided that the raw data should be stored on computer. It was also expected that if the storage system was carefully designed the data could be retrieved in a far more interactive and selective manner than would be the case if the computer was used merely as an electronic filing cabinet. It was necessary therefore that a system was set up which did not corrupt or limit data by the need to interpret or modify it. This went hand in hand with the acceptance of the conclusion of CIRIA (Tuckwell and Sadgrove 1977) that unless data in its complete and original format was provided to third parties it would be largely disregarded.

It was decided that the use of engineering geological maps, per se, would not be followed even though, on first consideration, they seem to fit ideally into the rationale of the redevelopment of a large but defined area. This was for two main reasons. Firstly, there was the fundamental consideration that such maps provide only a distillation of the available data and not the original records. It is therefore impossible to be certain of the reliability of any generalized

statement of condition or uniformity within any mapped zone. Therefore, it would still be necessary to allow for the storage and ready extraction of the original raw data. Secondly, the pressures behind the LDDC to begin the redevelopment without delay left no time for such plans to be produced. It was also difficult to assess which areas would have development pressure at any one time so that the problem could not have been relieved, for example, by limiting the size of the areas of consideration.

It should also be noted that the scale and character of the development in the Docklands has changed dramatically even during its limited existence. Maps produced for a projected level of development in the early period of the LDDC would have seriously underestimated the scale which is now taking place. They would have provided data with an emphasis towards low rise development and concentrated on the pertinent factors and would have seriously underestimated the needs of the current scale of development.

The pace of development was such that geotechnical data was required immediately by individual projects. In addition, the character of the overall development has been far more evolutionary than was the case in the New Town areas where the concept of the town plan was rigorously structured and programmed with a greater lead-in time to actual construction. It was therefore concluded that although the value of engineering geological plans and maps was conceptually valid, in the context of urban renewal of the style undertaken in the Docklands the production of preconceived maps was not possible other than for background use.

In order therefore to provide a means to provide the level of flexibility that would enable plans to be produced only when and as relevant it was necessary to provide a greater interaction between the storage system and the retrieval and presentation of the data than might otherwise be the case such that the plans would be a product of the system rather than the system itself.

CHAPTER FIVE : GEODASY: THE GEOTECHNICAL DATA STORAGE SYSTEM DEVELOPED FOR THE LONDON DOCKLANDS

5.1 Hardware

Having examined the requirements for a computer-based storage and retrieval system it became clear that one could be developed equally well on a mainframe, a mini-computer or a micro-computer. Recent trends in computer advances are such that the distinctions between the capabilities of these three traditional categories is less exact than it once was. The main differences being now conceptual rather than actual. In essence a mainframe is able to execute a number of programs at any one time from a number of independent users. The size and power capacity in a mainframe is suited for it to serve as a central coordinator to separate and usually remote systems.

Mini-computers are also able to execute a number of programs at any one time. They are particularly capable of expansion to reflect the growing or changing requirements of the organisation they serve. Capital costs are often less than those of the mainframe and they are therefore suitable to single site users. Both mainframe and mini-computers do have a finite limit to the rate of work that they accept. This often results in the delays experienced at individual terminals by users, for although the operational speed of the computer is very fast delays can develop due to the stacking of the enquiries within the system.

Micro-computers have traditionally been stand-alone machines serving only one user at a time but recent developments allow them also to act as terminals to mini-computers or mainframes. The capability of passing information from the micro-computer to the central processor of the mini-computer or the mainframe has led to the inevitable independent networking of micro-computers with each other. Networking allows the transference of information between separate

machines and the capability for one machine to use data stored on another. Such advances are meeting with varied success, but the greatest advance in micro-computer technology is the phenomenal increase in their storage capacity and the speed at which they work. This has fostered a number of advances in database technology for micro-computer systems and opened up uses for them which would until recently have been restricted to the mini-computer or mainframe.

The solution proposed by the writer for the storage and retrieval of the borehole and laboratory data held by the LDDC was to develop a system to run on a microcomputer. The standard for the industry over recent years has been that system developed by IBM. This has resulted in a degree of uniformity within the industry which hitherto was missing. Whereas previously independent manufacturers had produced micro-computers which were worthy of note, the uniqueness that was built into them restricted the development of support hardware or software. With the advent of IBM into the micro-computer market their system has been adopted by other manufacturers. This has resulted in the availability of a large number of machines with a compatible format so that the independent producers of peripheral hardware and support software have been able to justify the development costs involved in the production of better and more powerful products.

A further advantage of the use of micro-computers is the degree of autonomy they provide from the centralised system. This was assessed to be of benefit to the LDDC for a number of important reasons:

- The independence, so achieved, isolates the large storage commitment for the data from the central system and therefore any likely interference with other demands on space from other users.
- It allows a number of specific hardware peripherals, such as specialized printers and plotters, to be supported locally to the machine.

- Perhaps most importantly, the envisaged procedure for the use of the system whereby random and ad hoc enquiries can be readily addressed lends itself most readily to a stand alone system.

An IBM compatible microcomputer was assessed as the most viable base for the proposed system. At the same time the use of this standard, with appropriate software, ensured that later communication with the existing LDDC Prime minicomputer would be possible, if required.

5.2 Software

The software required for the perceived GEOTECHNICAL DATA SYSTEM (GEODASY) comprises two elements. On the outside there is the application software which is that part with which the user interacts. This is constructed from the development software which are often commercial computer languages and utilities and which provides the fundamental tools and building blocks for the application software.

It was envisaged that GEODASY would consist of a number of related computer programs whose total purpose would be threefold:

- firstly to create a suitable database to contain all the geotechnical data from work carried out within the LDDC area.
- secondly to enable both skilled and unskilled personnel to add to the database as a routine procedure.
- thirdly to enable a wide range of users to interrogate the database and to output required information in a number of different ways.

Each of the programs within GEODASY, although separate within their own right would interface with each other through a menu driven format. In addition they would interact with each other following

automatic and otherwise unseen routines activated by the use of GEODASY. Figure 22 shows the relationship of the main elements within GEODASY and the manner in which they interact.

The user is aware only of the facilities offered by GEODASY at their interface. Its principal attributes are shown on figure 23. However, it is important to realise that the modular character of the system allows these to be modified or further facets to be added at any time.

The principal development software for the database element was REVELATION a high level relational database utility which was assessed as particularly suited to the style of the information to be stored. The advantages and features of relational databases in general has been described by Henderson and Laxton (1986) in connection with the Scottish Land Survey Computer Database developed by the BGS. The principal feature of all these is the manner in which the data is stored which enables both rapid and very selective retrieval of that data. Although the majority have their own general enquiry language and some quite sophisticated report generators which can be programmed to provide a selection of available searches through the data, access to the data can also be achieved through standard file transfer methods. In this way the data can be manipulated, analysed and output in either printed or graphical format by any enquiry program written in a wide variety of possible languages.

5.3 The data to be stored

The nature of the information is such that it can be conveniently divided into header information and general remarks; and depth details. The header information contains the entries which are discrete for each borehole record and therefore require only a single

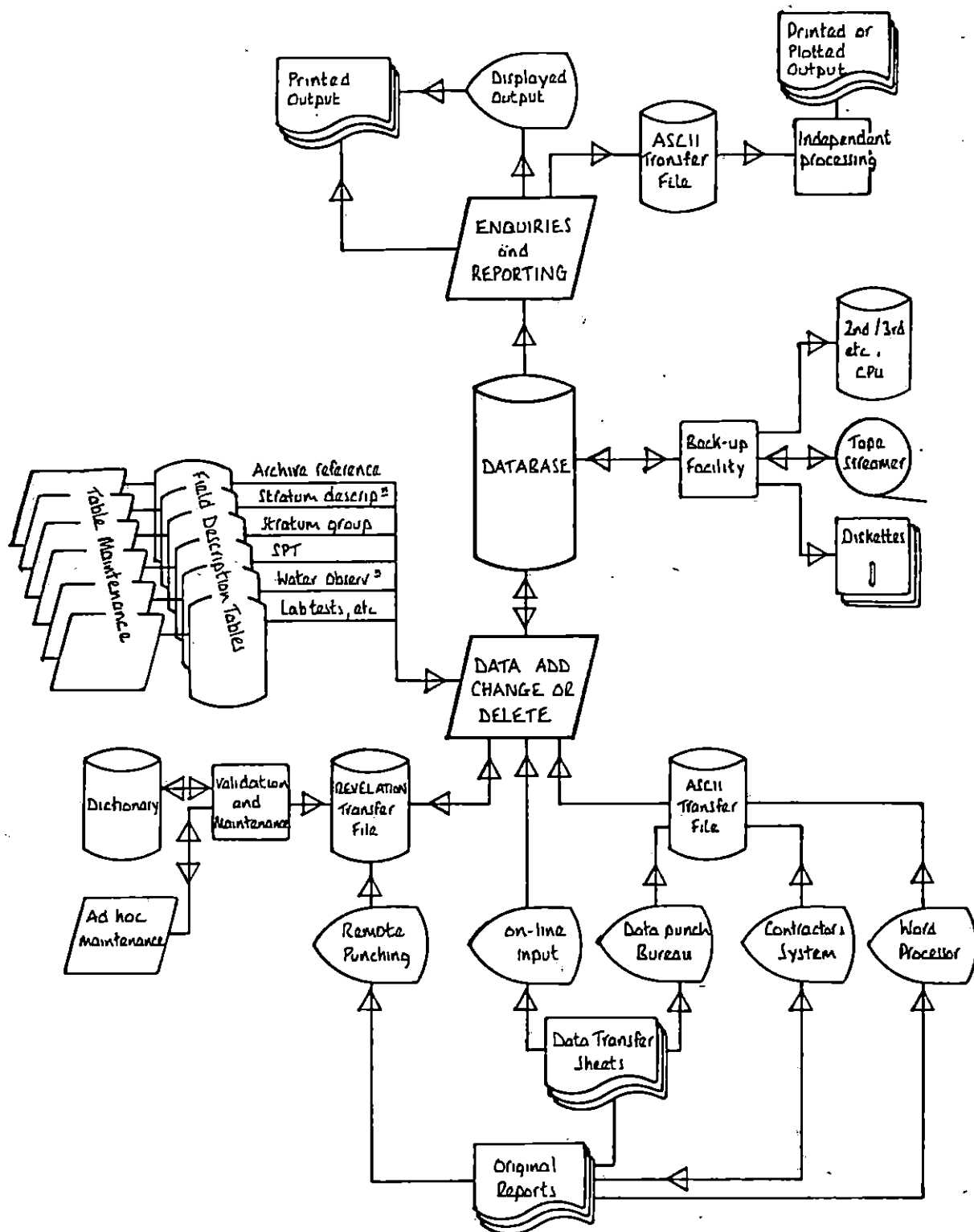


Figure 22 Flow diagram showing the relationship of the main elements within GEODASY and the manner in which they interact

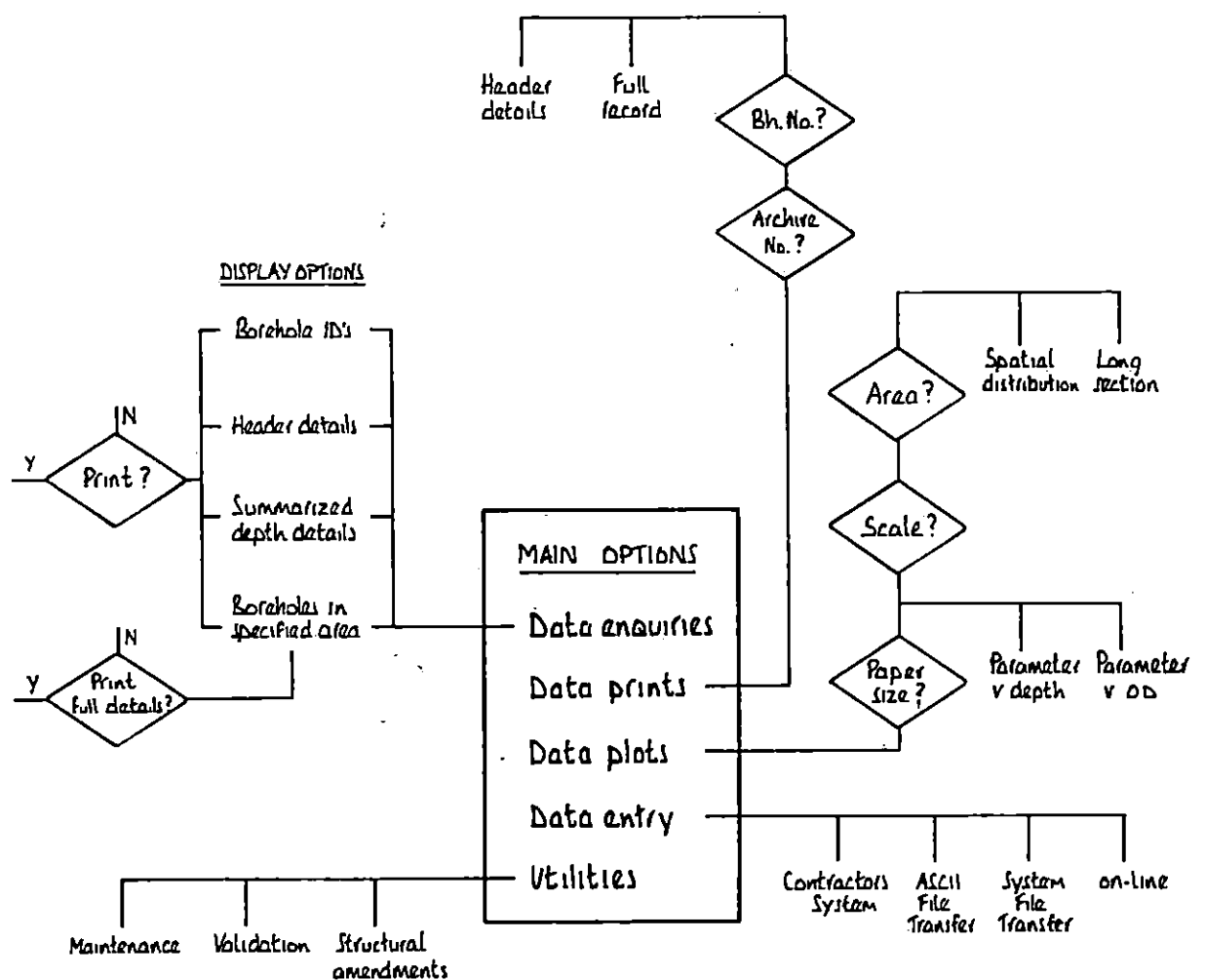


Figure 23 Schematic diagram showing the principal features of GEODASY which interface with the user. For a more detailed view of each of the retrieval options refer to flow diagrams shown in figures 25, 31 and 33.

entry per record regardless of depth or complexity of the record. It comprises;-

- **Archive Reference:** A four figure sequential number which identifies the report containing the data. Use of a dictionary relationship allows the Report name to be related to this and reported in any enquiry.
- **Report Name:** The full report name and author. However this is related to the archive reference as a dictionary item. It is therefore not stored specifically with each record but is available to be extracted and used in any report requirements.
- **Borehole Number:** As given in the original report.
- **Grid Reference:** The Docklands area is contained approximately within TQ 532177, TQ 532183, TQ 546183 and TQ 546177. At the scale of the drawings available grid references are required for each borehole to be reported to twelve figures to give an accuracy of 1.0m
- **Date Bored:** As given on the original borehole record.
- **Depth of the Borehole:** This is useful where only partial information is held by a database as it provides the most useful single piece of general information to suggest the value or otherwise to any particular enquiry.
- **Ground Elevation:** The ground elevation is important to provide the control on the position of the borehole in the third dimension. It is also used to calculate the reduced level for all other entries referenced against depth.
- **Instrumentation and additional testing:** The depth at which standpipes, piezometers, insitu vane tests and more detailed permeability tests are stated.
- **Refer to report for:** Any additional details contained in the original report are indicated here.

The depth details are that information referenced to depth and for which multiple entries will exist to the final depth of the borehole. They can be summarized as follows;-

Firstly from the borehole record:

- **Stratum Description:** This is the full and complete description for each stratum given on the original borehole record. It is referenced to the depth at the base of the stratum and as necessary the elevation is calculated by the system from the ground elevation provided in the header details.
- **Stratum Group:** As no mnemonics, codes or structure is required in the stratum description in order to provide for the free format descriptions it is necessary to include a separate stratum group code as an identifier to normalize the stratum and which can be used in later correlation and interpretation of data by the system. The stratum group code structure is a three part classification of each stratum as detailed in Table 4.
- **Water Observations:** Water observations in the boreholes consist of a level at which it is encountered, the strike level; the level to which a strike may rise under subartesian pressures, the rise level; and a standing level which is measured after any ad hoc break in the boring as for instance after an overnight stop. These are identified by the characters S, SR and ST respectively. Subsequent more detailed observations from instrumentation read over extended periods can be included in the system as a subset of the principal data.
- **Standard Penetration Test:** The determined "N" value extrapolated as necessary where only partial penetration is recorded.
- **Permeability Test:** Reported on $m \text{ sec}^{-1}$,

and then from the laboratory results:

GENERIC GROUP	STRATUM GROUP	FACIES OR SUBGROUP DESCRIPTION
Made Ground	A 1 A 2 A 3	Cohesive Granular Solid, e.g. concrete
Alluvium	B 1 B 2 B 3 B 4 B 5 B 6	Firm clay, $C_u > 40$ kPa Soft clay, $C_u < 40$ kPa Silt Peat Very organic peaty clay or silt Granular
Thames Gravels	C 1 C 2 C 3 C 4 C 5	Loose sand or gravelly sand, $N < 10$ Dense sand or gravelly sand, $N > 10$ Loose gravel or sandy gravel, $N < 10$ Dense gravel or sandy gravel, $N > 10$ Cohesive unit
Chalk	D 1 D 2 D 3	Transported or residual Chalk, $N < 10$ Weathered Chalk, $N = 10-25$ Intact Chalk, $N > 25$
Thanet Sand	D 4 a D 4 b D 4 c	Bullhead Bed, pebbly sandy clay at base Silty sand forming bulk of the unit Zone of bioturbation at upper contact
Woolwich and Reading Beds	D 5 a D 5 b D 5 c D 5 e D 5 f D 5 g D 5 h	Bottom Bed, pebbly sandy clay Clayey sands and sandy clays Mottled clays and sands with impersistent limestone bands Stiff grey shelly clays Silty fine sands Stiff fissured unfossiliferous clays Sands and gravels, often shelly
London Clay	D 6	Stiff fissured clay

Table 4. Stratum group classification used in GEODASY

- Bulk Density: Reported in kN m^{-3} .
- Natural Moisture Content: Reported in percent.
- Apparent Undrained Cohesion: Reported in kN m^{-2} the result is generally expected to be provided by unconsolidated undrained triaxial compression tests on undisturbed samples.
- Apparent Undrained Angle of Friction: Reported in degrees an apparent friction angle may be measured during unconsolidated undrained triaxial tests on certain materials.
- Liquid Limit and Plasticity Index: Reported in percent.
- Coefficient of Volume Compressibility M_v : Reported in $\text{m}^2 \text{MN}^{-1}$ for a 100 kN m^{-2} stress increase over the effective overburden pressure at the sample depth.
- Grading Details: The grading curve is defined as the D10, D60 and D85 points reported in mm. For more critical studies the full grading curve may be digitized and held as a subset of the original data.
- Additional Tests: A reference to any additional testing the results of which may be obtained from the original report.

5.4 Use of GEODASY

5.4.1 Data Input

The usefulness of GEODASY relies upon the presence of data. The most functional system imaginable is of little use without it. In preparation of the development of the system the data from a large number of boreholes and associated laboratory results had been collected in a form suitable for easy entry into a database. This form, called data transfer sheets (fig. 24) comprised a simple tabulation of the data from the borehole record and laboratory sheets so that a keyboard operator would be able to input all the information without referring to different sections of the report. The transfer sheets also had the advantage that they normalized the style of the data and eliminated the vagaries of individual reporting formats. Although a large part of the backlog of data required

DATA TRANSFERENCE TO COMPUTER STORAGE		Bh. No. V.68		SHEET 3 OF 4	
GRID 541678...m.E.	DATE 1/1/85	DEPTH 25 m.	ELEVATION 5.19 m.O.D.	BORE CLASSIFICATION	
REFERENCE 189457...m.N.	BORED 2/1/85				
REPORT...ROYAL VICTORIA DOCK (SOUTH SIDE)				ARCHIVE REFERENCE	
REFERENCE BY SOILS ENGINEERING LTD.				C/83095	

BORING TECHNIQUE: Shell & Auger..... DIAMETER..... 150 mm..... PIEZOMETER AT..... 16.0m..... STANDPIPE AT.....
 PERMEABILITY TESTS AT..... 16.0m..... VANE TESTS AT..... REFER TO REPORT FOR Organic Content

DESCRIPTION	Legend	C. Group	Sub-Group	Depth (m)	Level m.O.D.	Water Observations	S.P.T.	Bulk Density Mg/m ³	Moisture Content %	C _u kN/m ²	φ _u Degrees	Liquid Limit %	Plasticity Index %	m _v m ³ /MN	Grading			Permeability m/sec.	Additional Tests
															D ₁₀ %	D ₆₀ %	D ₈₅ %		
Medium dense to dense grey brown V. sandy Gravel.	C	C4		12.00	-6.81										85	17	28		
				12.15	-6.96		30												
				13.00	-7.81										51	7.8	85		
				13.15	-7.96		42												
Hard grey, green, white, V. sandy silty clay, more sandy at depth.	D	DS		13.7	-8.51				18						-	17	32	CH	
				13.9	-8.61														
				14.45	-9.26		40												
				14.80	-9.61				16						-	17	27	CH	
Dense grey green, clayey silty Sand.	D	DS		15.50	-10.31		2.54	12	321	0	29	15	0.33	-	2	29	CH		
				16.00	-10.81				13						-	21	28	CH	
				16.8	-11.61														
				17.15	-11.96		42												
	D	DS		17.50	-12.31				18						-	13	175	CH	

Figure 24. Example of a typical data transfer sheet
 (reduced from an original A3 size)

transfer sheets to be drawn up as a separate exercise, for any new work a requirement to complete the sheets was included in the LDDC's term contract for geotechnical site investigation. As it was intended that the system should include the complete data and not impose any restrictions relatively few rules were necessary to allow the successful completion of these sheets other than the order in which the data was tabulated and the addition of a stratum group code (Table 4).

Once GEODASY had been developed the services of a commercial punching bureau was used to input the existing data held on the transfer sheets. The accuracy of the input from the sheets was ensured by double punching, that is the data is keyed twice, each time by different operators, and a comparison made of the two entries. However, as was recognized this could not eliminate errors on the transfer sheets themselves. Therefore extensive checking of the database has been necessary as a consequence.

In order to further improve the accuracy of the data the term contract later included a requirement to supply the data on computer diskette for direct input into the database. An input program, called the Contractors System, was supplied by the LDDC as part of the contract. This provides a number of entry screens which are modified for each contractor to suit his operating methods. At this stage the input is subject to a number of validation rules and error traps, however each of these can be manually overridden to maximise the free format of data. The system also provides a simple tabulated output allowing the contractor to carry out a manual check allowing any corrections to be made before the disk is submitted.

The data disk from the Contractors System is loaded automatically into GEODASY via a menu option where it undergoes a series of further validation checks and indexing. In this way the on-going maintenance of the database with information from the term contract is ensured with a minimum of effort by the LDDC.

A further means of data entry exists to input ad hoc reports obtained from investigations carried out in the area by third parties but which have been submitted to the LDDC for information. This is somewhat similar to the Contractors System in that the information is keyed in against a series of screen masks. To accommodate the variation in reporting styles a greater flexibility is provided in the layout of the screen masks. Similarly, if typing facilities are temporarily unavailable or become limited it may be useful to pass only partial data to GEODASY. For example, if the coordinates and reference of any new borehole are stored immediately subsequent enquiries would at least be aware of the existence of a borehole. Appropriate notes are included at output for any boreholes with only partial data on the system which are then removed as the complete data is included.

5.4.2 Data output

5.4.2.1 Introduction

An overriding requirement for GEODASY was a simplicity of use so that it could be searched by even a casual user with a minimum of instruction. It therefore incorporates a number of standard enquiry and print options which are summarized on figure 23. These are activated by menu driven procedures enabling the system to be used by personnel with no previous computer experience or knowledge. They do not represent either a limit or the full extent of the type and character of searches that are open to the system but merely those which are most generally required. For more sophisticated or detailed enquiries it is often more effective to isolate the relevant data into a separate datafile and perform searches using the REVELATION enquiry language.

Probably the most important attribute of the borehole data is its

grid reference which uniquely identifies its geographical position. Most enquirers would want to access the data by area to find, for example, any previous investigations that had been carried out in their area of interest. Therefore, the original report, per se, becomes of less concern other than as the vehicle which supplied the data. GEODASY references the reports as a sequential archive number. As it is inevitable that a hard copy of each report will be stored this also provides a practical advantage for their storage which is similarly done by the archive number and not by area, client, contractor or some other attribute. Filing cabinets are consequentially systematically filled.

Output from GEODASY takes one of three forms. These are;

- Data Enquiries; where hard copies are not generally required
- Data Prints; where hard copies are required
- Data Plots; where a greater emphasis on data selection and presentation is required.

Figure 25 shows a flow diagram for the Data Enquiries option. One of each of four options is chosen from a menu of the form given in figure 26. This is the standard format for all GEODASY menus. The screen displays the available choices which are made either by keying its number or highlighting the appropriate line by the cursor controls. A one line description of the choice is given at the base of the screen which is updated as each is considered. The choice is then activated by pressing the return key.

5.4.2.2 Data Enquiries option

The Data Enquiries option is schematically summarized on figure 25. The available choices are;

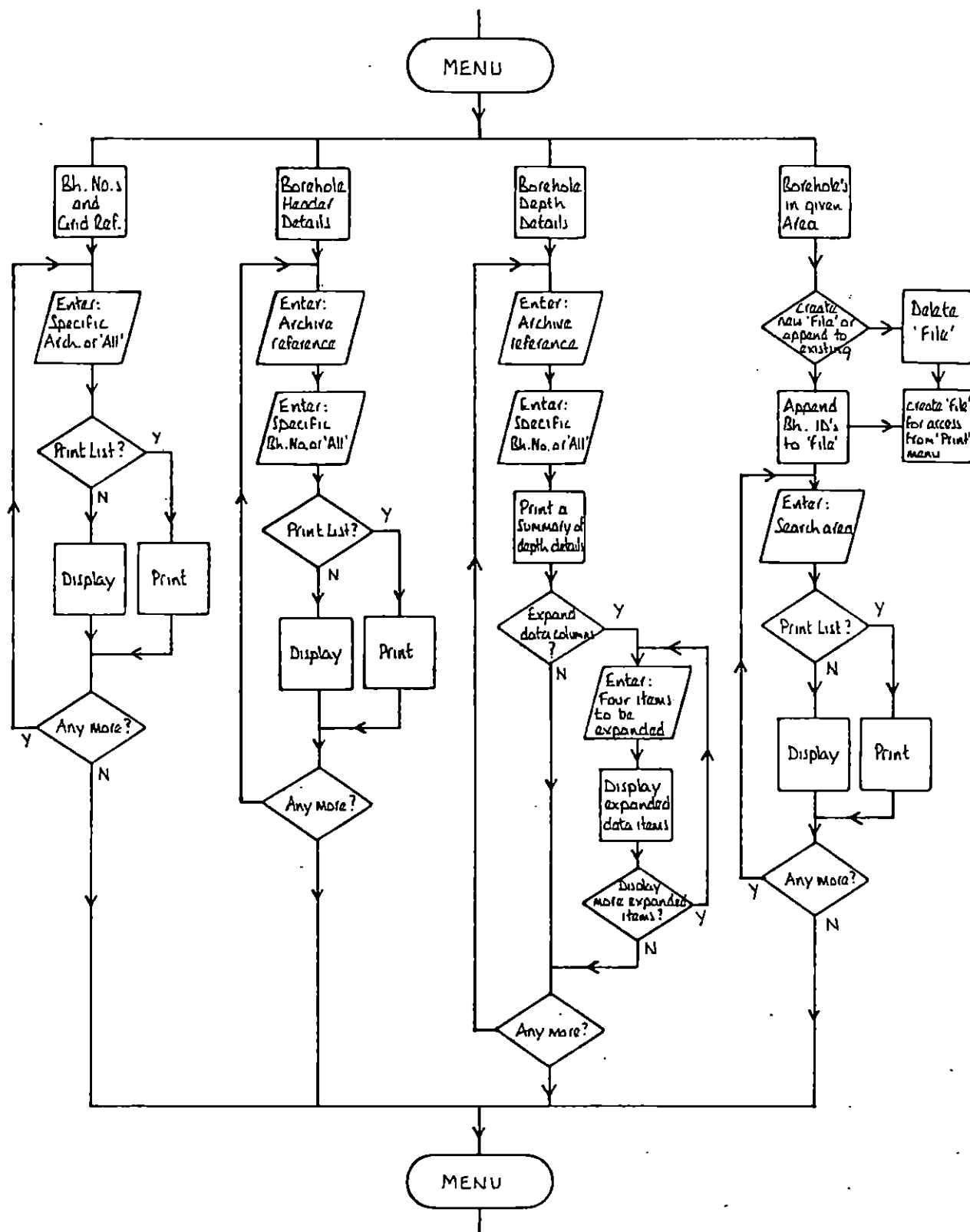


Figure 25.

Flow diagram detailing the options and procedures for retrieving data through the Data Enquiries menu option

```

#####
GEODASY - DATA ENQUIRIES                                SYSPROG
21:13:13  22 MAY 1989

1. DISPLAY BOREHOLES WITH SAME ARCHIVE REF
2. DISPLAY BOREHOLE HEADER DATA
3. DISPLAY DEPTH DETAILS
4. DISPLAY BOREHOLES WITHIN A GIVEN AREA
5. DISPLAY PARTICLE SIZE DISTRIBUTION LISTING
6. EASYLIST THE DATABASE

USE THIS TO VIEW ALL BOREHOLE I.D.'S FOR ONE REPORT
Press RETURN to run Menu Option  F5 to go BACK to previous Menu

```

Figure 26.

Screen mask for the GEODASY 'Data enquiries' main menu. This shows the style of all GEODASY menus. Current date and time are displayed together with the selection options available. These can be accessed by typing the adjacent number or highlighting the appropriate line with the cursor control. The bottom of the mask shows a one line explanation of each option. This is updated each time the selection procedure is changed. Two additional prompts providing general detail on how to run the menu option or return to the previous menu are always provided at the base of the mask

1. **Display borehole with same archive reference:** This will list the borehole numbers together with their grid references from a specified archive reference as shown on figure 27, or alternatively for all the reports on the database.
2. **Display borehole header data:** This will display the header data for a given archive reference either for a specific borehole or for all the boreholes in that archive as shown on figure 28.
3. **Display borehole depth details:** This will display the borehole and laboratory data for either a specified borehole or all the boreholes from a given archive as shown on figure 29. The laboratory data is summarized in that an indication of the existence of a test result is given by an asterix in the appropriate column. At the end of each borehole displayed the option is given to expand four of the columns to provide the actual test values as shown on figure 30.
4. **Display boreholes within a given area:** To avoid the need to know the presence of a borehole or even a report within an area of interest this allows for a search area to be defined and a list produced showing the archive number, borehole number and grid reference for any records contained within it. Figure 25 shows that an option is available to create a file of those boreholes which can be called in later from the Data Print options to have the full borehole details printed out.

Reference to the flow diagram through the Data Enquiries options (fig. 25) shows that print options are available at the relevant stages should a hard copy list be required. Alternatively a hard copy can be made of the information contained on the screen at any one time for later reference.

LIST OF BOREHOLES WITH ARCHIVE REFERENCE NUMBER 1033 PAGE: 1

ARCH REF	BH NO	GRID REF
1033	1	543258-179809
1033	10	543475-179918
1033	11	543586-179948
1033	12	543668-179988
1033	13	543537-179892
1033	14	543617-179905
1033	2	543201-179861
1033	3	543089-179893
1033	4	543076-179844
1033	5	543146-179862
1033	6	543059-179773
1033	7	543149-179788
1033	8	543346-179853
1033	9	543400-179897
1033	TP1	543056-179778
END OF LIST		

Figure 27 Example output of the 'Borehole number and grid reference' enquiry option shown on figure 25

DISPLAY OF BOREHOLE GENERAL INFORMATION FOR BORE REFERENCE: 1033*1

ARCHIVE REFERENCE	:1033
BOREHOLE NUMBER	:1
GRID REFERENCE	:543258-179809
DATE BORED	(from):16/09/86
	(to) :19/09/86
DEPTH(M.)	: 40
ELEVATION(M.O.D.)	:3.51
BORE CLASSN.	:
REPORT REFERENCE	:NORTH WOOLWICH PUMPING STATIONAND RISING MAIN
BORING TECHNIQUE	:SHELL & AUGER
BOREHOLE DIA.(mm)	: 150
- AT DEPTH OF(M.)	:
PIEZOMETER AT	: 16
STANDPIPE AT	:
PERMEABILITY TEST AT	: 17
VANE TESTS AT	:
REFER TO REPORT FOR	:CH

Figure 28 Example output of the 'Borehole header details' enquiry option shown on Figure 25

DETAILS OF BOREHOLE NO:1 ON REPORT NO:1033 21:15:51 22 MAY 1989 PAGE 1

* INDICATES A VALUE IS PRESENT IN THIS COLUMN-IT CAN BE VIEWED LATER

DESCRIPTION.....	SG	DEPTH	V	O	P	D	O	U	R	L	I	V	1	6	8	H	T
		0	*														
Loose mixtures of grey brown clay,sand,gravel,etc.(MADE GROUND)	A1	.7	*														
		1.15	*		*												
		1.7	*														
Loose mixtures of grey brown clay,sand,gravel,etc.(MADE GROUND)	A1	1.9	*														
		2.1	*			*	*	*		*	*	*					*
Soft grey & black mottled silty CLAY	B2	2.5	*														
		2.8	*														*
		3	*			*	*	*		*	*	*					*
Firm grey & brown mottled	B1	4	*														

Press <E> to continue?

Figure 29.

Example output of the 'Borehole depth details' enquiry option shown in figure 25. The asterisks indicate the and type of test available. A rolling option is given to expand any four of these to show the actual results as shown in figure 30 a and b

PLEASE INDICATE ANY 4 OF THE FOLLOWING ITEM NUMBERS TO BE DISPLAYED:

- | | |
|-----------------------|------------------------|
| 1- Level m O.D. | 9- Plasticity Index % |
| 2- Water Observations | 10- Mv m3/MN |
| 3- S.P.T. Values | 11- Grading D10 mm |
| 4- Bulk Density Mg/m3 | 12- Grading D60 mm |
| 5- Moisture Content% | 13- Grading D85 mm |
| 6- Cu kN/m3 | 14- Permeability m/sec |
| 7- Phi U Degrees | 15- Additional tests |
| 8- Liquid Limit % | |

CHOICE 1

?1

CHOICE 2

?2

CHOICE 3

?3

CHOICE 4

?6

Press <E> to continue?

(a)

DETAILS OF BOREHOLE NO:1 ON REPORT NO:1033 21:16:25 22 MAY 1989 PAGE 7

DESCRIPTION..... SG DEPTH Level m Water S.P.T. Cu

		0	3.51		
Loose mixtures of grey brown	A1	.7	2.81		
clay,sand,gravel,etc.(MADE					
GROUND)					
		1.15	2.36		9
		1.7	1.81		
Loose mixtures of grey brown	A1	1.9	1.61		
clay,sand,gravel,etc.(MADE					
GROUND)					
		2.1	1.41		33
Soft grey & black mottled	B2	2.5	1.01		
silty CLAY					
		2.8	.71		
		3	.51		72
Firm grey & brown mottled	B1	4	-.49		

(b)

Press <E> to continue?

Figure 30.

Example output of the continuation screen masks for the 'Borehole depth details' enquiry from that shown in figure 25. when the actual test results indicated by the asterisks are required. Four items to be expanded are chosen from screen mask (a) and displayed as shown in screen mask (b).

5.4.2.3 Data Print options

The Data Print options is schematically summarized on figure 31. The available choices are:

1. **Borehole Header Details:** This will provide a direct printout of the borehole header details as shown in figure 28 for the selected archive or all the archives.
2. **Borehole depth details:** This prints a tabulated listing of the borehole and laboratory information. The flow diagram (fig. 31) shows that it is possible to select the records in a number of ways:
 - The temporary file created under the Data Enquiries option to search for boreholes in given area can be accessed directly,
 - a list of ad hoc archive references and boreholes numbers can be established, or
 - a list of boreholes numbers from an individual specified archive.

The printout provides the complete details held on the database tabulating both strata descriptions and laboratory records against depth as shown on figure 32.

3. **List of archive number, boreholes and status:** This is automatically generated by GEODASY each time it is called for. It lists the archive reference and by calling in a dictionary item shows the actual report name. It calculates the number of boreholes in each archive and indicates which boreholes have partial or all details missing. This provides a rapid means of checking that all boreholes have been entered from each report and that archives which may have originally had only partial data entered have later been completed.

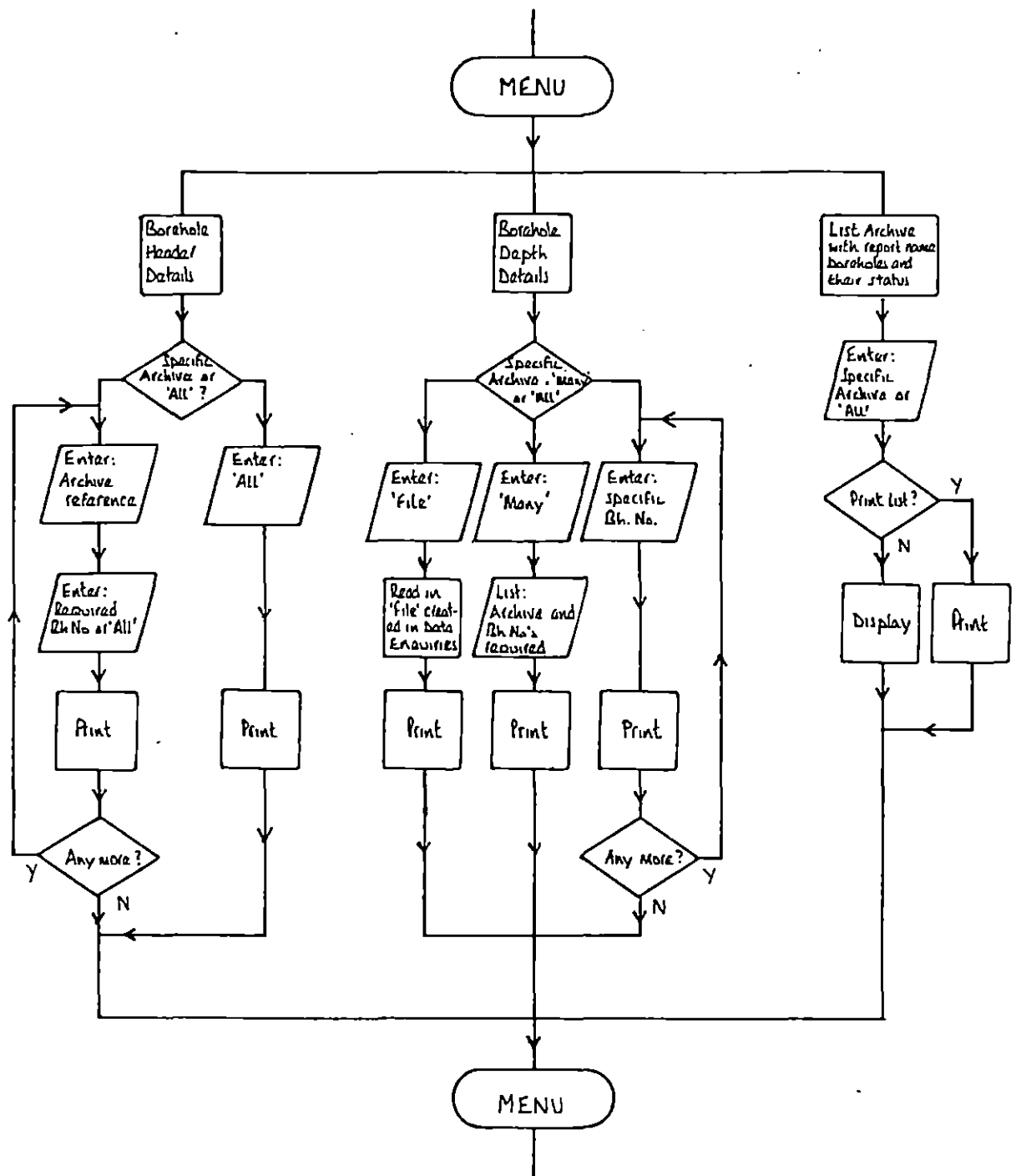


Figure 31.

Flow diagram detailing the options and procedures for retrieving data through the Data Prints menu option

DETAILS OF BOREHOLE NO:SD1 ON REPORT NO:4008

(C) THE LDDC BOREHOLE DATABASE SYSTEM

12:26:14 23 MAY 1989

ARCHIVE REFERENCE :4008
 BOREHOLE NUMBER :SD1
 GRID REFERENCE :535709-180155
 DATE BORED (from):22/06/83
 (to):27/06/83
 DEPTH(M.) :25.45
 ELEVATION(M.O.D.) :+5.60
 BORE CLASSH :
 REPORT REFERENCE :HOUSING AREA 2 SURREY DOCKS
 BORING TECHNIQUE :CABLE PERCUSSION
 BOREHOLE DIA.(cm) :200 & 150 - AT DEPTH OF(M.) :
 PIEZOMETER AT : STANDPIPE AT :11.00 PERMEABILITY TEST AT : VANE TESTS AT :
 REFER TO REPORT FOR :1 CHEMICAL TEST RESULTS

Description.....	SG	Depth	Water Obs.	SPT Values	Bulk Density	Moist. Cont.	Cu kN/m2	PHI(U) degree	Liqu. Limit	Plast. Index	Nv m2/KN	Grading D10	D60	D85	Perm. n/sec	Addit. tests
Probably firm to stiff brown sandy silty gravelly CLAY containing masonry rubble including concrete and metal - Made Ground	A1	0.00														
		0.00														
		1.00		17												
		2.00				14			27	13			0.053	0.36		
		3.00			1.9929	24	15		53	33						
		3.10	ST													
		4.00				24										
		5.00	SP		2.2192	14							0.4	14		
		6.00		16												
		7.00		15												
As above	A1	7.10														
		8.00		7												
		9.00		29												
		10.40														
Very dense, brown sandy GRAVEL and gravelly SAND	C4	10.40														
		10.50		66								0.41	15	28		
		11.50										0.54	17	31		
		11.59		93												
		12.20														
Stiff grey silty CLAY containing fragments with a layer of greenish grey silty CLAY between 14.3 and 15.25 (MOOLWICH and READING BEDS)	D5B	12.20														
		12.50			1.9817	25.1					0.11					
		14.00			2.0265	25.9	95				0.11					
		15.00			2.0051	22	71									
		17.00														
Very stiff, green silty sandy slightly gravelly CLAY to very dense green slightly clayey gravelly SAND	D5A	17.00														
		17.50		129												
		18.50		76	2.1203	15			36	20						
		19.50														
		19.80														
Very dense, green slightly clayey silty SAND (MOOLWICH AND READING BEDS)	D4B	19.80														
		21.00		100												
		22.50			2.0499	21			33	16		0.022	0.33	0.43		
		24.00		76												
		25.45		81												
- End of Borehole -		25.45														

Figure 32. Example output of the 'Borehole depth details' print option shown on figure 31

5.4.4 Data plots

The Data Plots option is schematically summarized on figure 33 and provides the following options:

1. **Plot all boreholes on database at 1:50000 scale:** As shown on figure 34 all boreholes are plotted out by grid reference to a 1:50000 scale.
2. **Plot spatial distribution:** This allows data to be plotted for any given search area. The available hardware dictates the choice of plot size. The scale is presently restricted to a choice of 1:1250 or 1:2500 as being the most appropriate to the area but could readily be varied. Either the boreholes can be plotted with an indicator giving the archive number and borehole number (fig 35) or various parameters can be chosen. At present the boreholes can be plotted to show;
 - their identification as archive reference and borehole number,
 - the thickness of an individual strata identified by a stratum group
 - the top or bottom of a strata group as depth below ground level or reduced elevation.

For easy reference a print of the boreholes and plotted details is also given with each plot. Although the program will seek to plot each identifier or detail in a space, where the boreholes are particularly densely packed such that some overwriting is unavoidable this additional list is very useful.

3. **Plot a parameter against depth, elevation or time:** This will plot any parameter on the database which is referenced to depth, such as standard penetration test results or laboratory results, against depth or elevation as chosen. Where extensive water observations are available these can also be plotted over any chosen time period. Reference to figure 33 shows that the

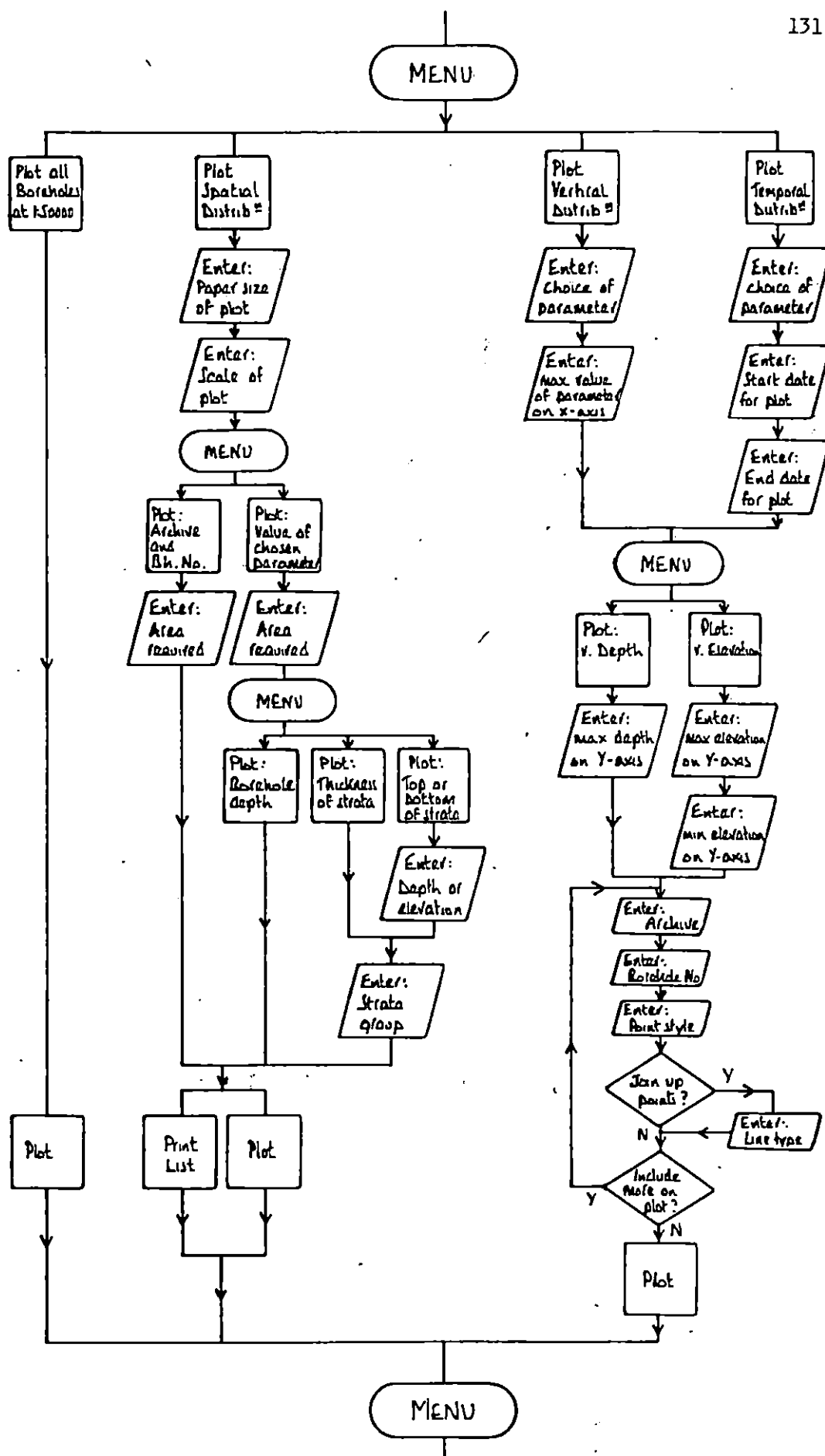
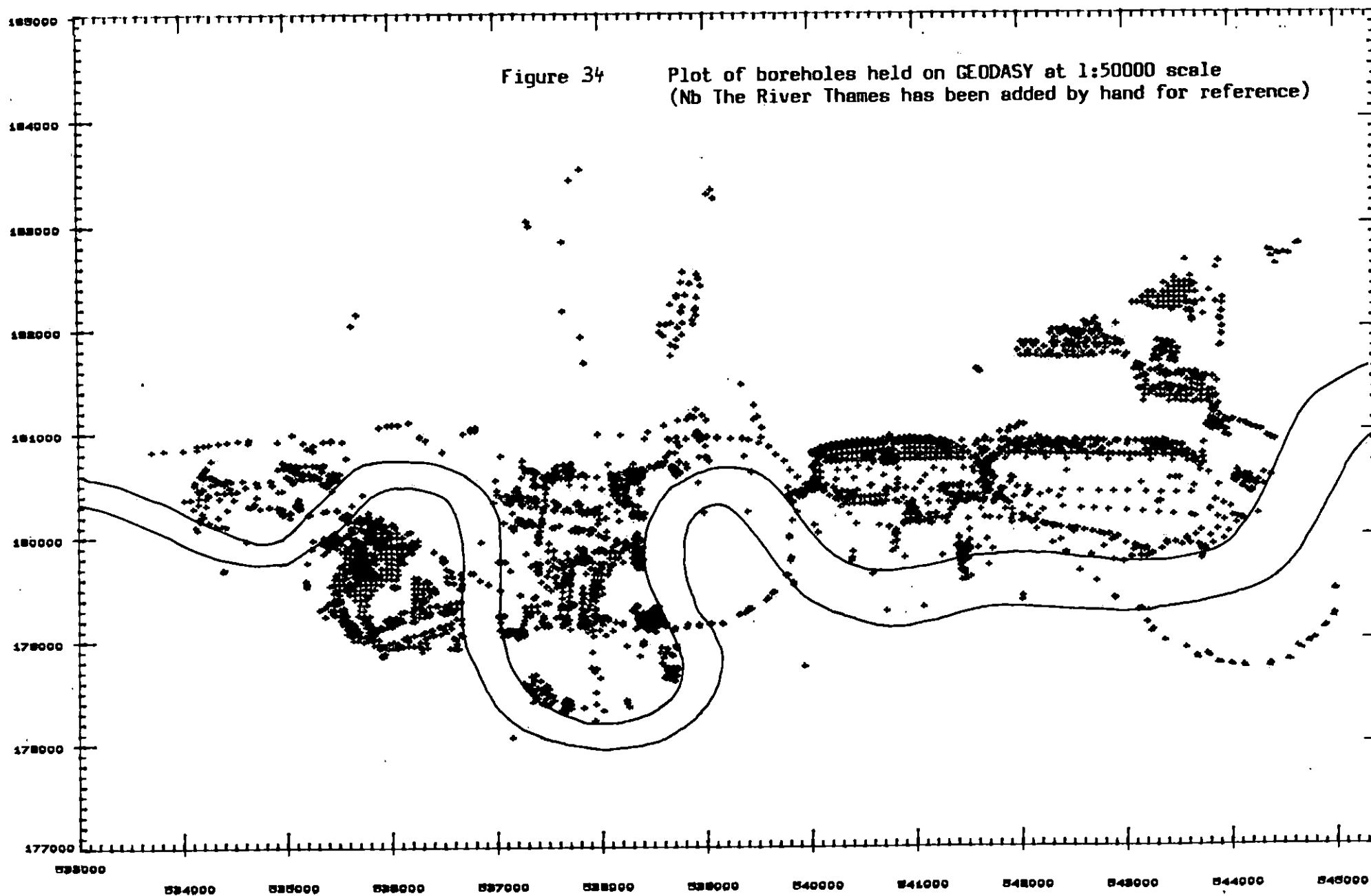


Figure 33.

Flow diagram detailing the options and procedures for retrieving data through the Data Plots menu option

Figure 34

Plot of boreholes held on GEODASY at 1:50000 scale
(Nb The River Thames has been added by hand for reference)



style of the data point is selectable with 16 choices together with the option to join the points up or not with one of 8 line types. As further boreholes can be selectively added to the same plot and each can be shown with the same or different point and line style it provides a ready means to demonstrate the variation of a given set of data against a background compilation of other data. As such the facility is particularly useful for rapid comparisons of large data sets.

5.4.5 Additional search facilities

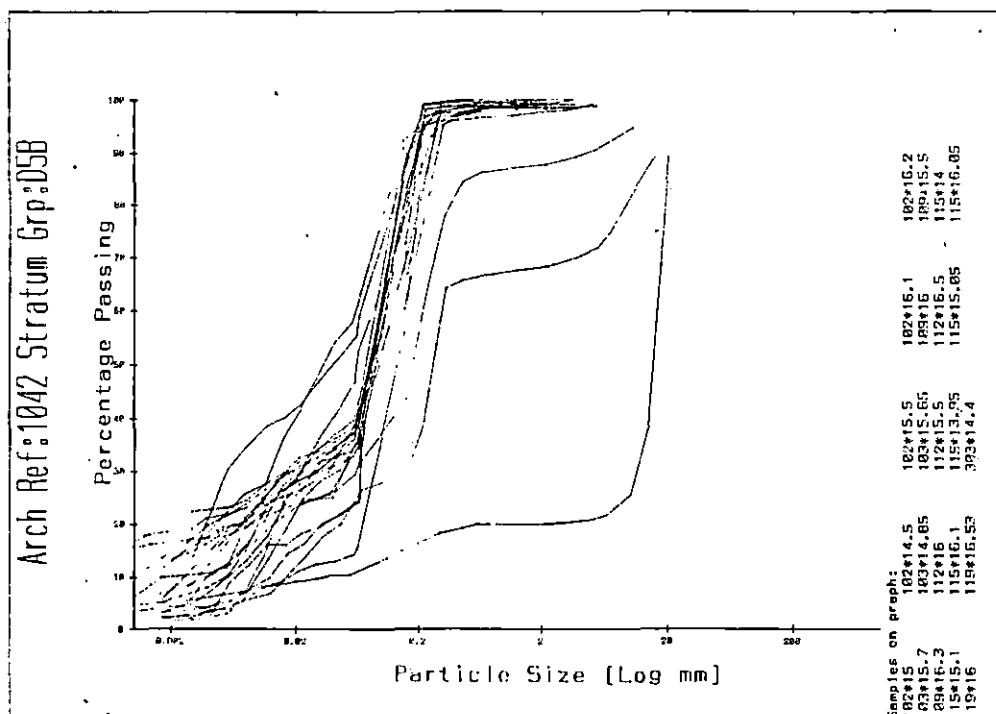
As described above the extent of the search facilities contained on the menu options do not represent the limit of the those available. In fact a far greater selection and manipulation can be carried out within the computer. For example data could be selected on strata type rather than archive and borehole number. Figure 36 gives the grading details for the facies classifications in the Woolwich and Reading Beds and provides a summary of the means and standard deviations for each group. However, such enquiries are not considered to be sufficiently general purpose that they are included on the main menu options but they are available for use as required.

Particle Size Dist. Details for Arch Ref . 15:05:38 13 MAR 1988. Page: 1.

Borehole Number	Sample Depth	Stratum Group	Grading Details			
			D10	D60	D85	D60/D10
102	14.000	D5A	.0013	.1042	.2111	80.15
102	15.000	D5B	.0006	.0960	.1469	160.00
102	14.100	D5A	.0006	.0964	.1587	160.67
102	14.500	D5B	.0006	.0869	.1349	144.83
102	15.500	D5B	.0008	.1049	.1963	131.13
102	16.100	D5B	.0057	.1497	.2557	26.26
102	16.200	D5B	.0343	16.2342	19.4369	473.30
102	17.200	D5A	.0092	.2058	.3102	22.37
102	17.500	D5A	.0762	.2125	.2806	2.79
102	18.100	D4B	.0742	.2060	.2840	2.78
102	18.500	D4B	.0874	.2178	.2804	2.49
102	19.100	D4B	.0697	.2141	.2843	3.07
102	19.750	D4B	.0746	.2107	.2792	2.82
102	21.600	D4B	.0631	.1615	.2505	2.56
102	22.100	D4B	.0692	.1478	.2442	2.14
102	22.600	D4B	.0685	.1435	.2373	2.09
102	23.100	D4B	.0693	.1469	.2343	2.12
102	21.680	D4B	.0667	.1549	.2431	2.32

Press <E> to continue?

(a)



(b)

Particle Size Dist. Details for Arch Ref 1042. 16:23:32 18 JAN 1988. Page: 7.

Grp/Av/SD	D10	D60	D85	D60/D10
Average	.0149	.2195	1.0058	196.1925
S. Dev.	.1911	3.6976	14.3114	4969.2549
B4A Average	.0006	.0905	.1486	150.83
S. Dev.	0	0	0	0
B6A Average	.3868	12.4707	27.6878	32.46
S. Dev.	.0445	.0223	7.2297	3.7901
C1A Average	.0179	.3582	2.1474	20.01
S. Dev.	0	0	0	0
C3A Average	3.6798	19.5803	34.9314	5.9
S. Dev.	2.6672	4.2765	2.5256	3.211
C4A Average	.9595	11.9705	22.6539	18.6815
S. Dev.	6.791	23.8348	37.0404	66.4141
D4B Average	.0734	.1865	.2396	3.1989
S. Dev.	.1332	.2652	.3533	34.8219
D4C Average	.0767	.181	.2161	2.36
S. Dev.	0	0	0	0
D5A Average	.0253	2.0817	5.9624	100.5415
S. Dev.	.1213	19.6709	48.9569	2366.1912
D5B Average	.0062	.8187	1.5475	72.7761
S. Dev.	.0371	15.7639	21.7061	460.1014
D5C Average	.0033	1.5261	3.0676	1104.7569
S. Dev.	.0183	11.9683	23.5667	11534.0737

(c)

Figure 36

Example output using ad hoc enquiry features of GEODASY
This lists the principal grading characteristics of part of the Woolwich and Reading Beds. In this case the values of D10, D60 and D85 shown in (a) have been interpolated digitized input of the original grading curve. This can be re-output selectively as shown in (b) or statistical analysis carried as shown in (c).

CHAPTER SIX : THE ENGINEERING CHARACTERISTICS OF THE PRINCIPAL STRATIGRAPHIC UNITS

6.1 General

The stratigraphy of the London Basin is based largely on lithological changes which can be used to define the main Formations present. Conveniently these are also chronologically distinct on a broad time scale although facies variation within each Formation, particularly the Woolwich and Reading Beds, may be diachronous. Within practical limitations the engineering characteristics of any material are governed by its lithology and its stress history. The stress history will influence the mechanical character by altering its moisture content and the characteristics of its constituent particles. While at high stress levels the mineralogy of the material will also be affected. The stress history of the Formations of the London Basin has been relatively uniform. In consequence, and since each of the Formations has a relatively persistent lithology, there is a corresponding regularity of engineering characteristics in each.

The main influence on the condition of the materials in southern England has in fact been in the recent past. As all the solid geological Formations are overconsolidated and are therefore out of phase with near surface temperature and pressure conditions, they will have a tendency to weather on exposure or following removal of overburden. This process will extend to some depth, reducing in intensity, until a balance is achieved between the material and stress condition. This weathering has been enhanced by the climatic changes during the Pleistocene which allowed the effects to extend to greater depths than might otherwise have been the case.

The following Chapter summarizes the available information on each of the main formations. Much of this has been processed through the

computer database for easy manipulation. A more detailed consideration of this facility and the benefits to further scientific study is given in Chapter Eight.

6.2 Upper Chalk

The Upper Chalk has a relatively uniform lithology comprising virtually pure calcium carbonate rarely falling below 95% of the whole. It is interspersed by siliceous inclusions in the form of flint bands, although the silica content of the remaining mass is less, and often very much less than 1.0%. The carbonate is mainly in the form of calcite which has a specific gravity of 2.715 (Hancock 1975).

Chalk is extremely frost susceptible and the effects of freeze-thaw action during the Pleistocene was to cause a mechanical break-down. The size of the reduced block size often increases with depth as the effects became less marked. At the most intense levels this breakdown can have disaggregated the particulate bonds of the Chalk reducing it to a softened mass with the characteristics of a silt. This is commonly referred to as 'Putty Chalk' and can be found in association with the intact material either as an infilling to discontinuities or as a matrix to a disordered mass. Two distinct phases to the weathering of Chalk can be appreciated. The disruption of the material into smaller blocks will affect its bulk properties often increasing its permeability and causing it to behave as a granular material. The further disaggregation to 'Putty Chalk' is associated with a release of pore water. In these circumstances the material will behave with a closer affinity to a cohesive material. Its shear strength will be controlled by its moisture content and its permeability will be reduced as the discontinuities are lost so that it can experience undrained loading. Under certain circumstances Chalk should be regarded as sensitive.

In an unweathered state Chalk is able to stand to significant heights at steep angles, as is evidenced by the famous cliffs of Dover and many Chalk workings. Failure of such slopes can occur through wedge failure or toppling failure and although some failure of intact material may be involved the stability of any situation will be largely controlled by the overall geometry and disposition of the discontinuities. With time a surface ravelling of the slope will occur due to frost shattering. Under temperate conditions this will be fairly mild and will give rise to a scree and in time, if that scree is not removed as would occur along a sea cliff, a stable situation will develop. During the cold phases of the Pleistocene the shattering occurred to a much greater depth and the development of the Putty Chalk produced a mantle which then became susceptible to solifluction and other low angled slope processes. These are often associated with an increase in moisture content of the transported material. This will occur not only through the release of pore water from the Chalk but by the entrainment of water into the material during the hillslope process. Transported Chalk may therefore become a weaker material than would be the case if weathering occurred only in situ.

The weathered Chalk can also be transported and deposited by water action. In this case the Putty Chalk is largely removed and the broken Chalk will act as a conventional granular bedload leaving a sand or gravel sized deposit of Chalk clasts.

A classification of the condition of Chalk was devised during an investigation for a proton accelerator site on Middle Chalk at Mundford in Norfolk (Ward et al 1968). The results were later compared with two sites on Upper Chalk at Northfleet, Kent and Hampshire by Wakeling (1970) who proposed a correlation between the weathering grade and SPT blow count. This classification has become widely used even though the original work was very cautious about its general applicability. In most cases the grade is based only on SPT values with little if any assessment of the mass characteristics.

The unreliability of the relationship between Chalk grade and SPT has been further emphasised by Dennehy (1975) and Hobbs and Healy (1979).

In the Docklands no evidence for the presence of solifluction deposits has been found in the Chalk although they have been found elsewhere in the Thames valley. This absence is in part because of the limited area in which the Chalk has been exposed in outcrop in the recent geological past, and therefore accessible to the appropriate processes, but also because any weathered material will have been readily removed by the later fluvial action which preceded deposition of the Thames Gravels which now cover the outcrop in the area. Nonetheless, Fookes and Martin (1978) found that the frost shattering could be detected in the Chalk on the southern side of the Thames Barrier. The presence of soliflucted Chalk and the other effects of ice action can not be totally discounted as a possibility.

Various workers have established a broad relationship between the stratigraphy of the Chalk and its engineering properties (Carter and Mallard, 1974; Bell, 1977; Higginbottom, 1965). In essence these suggest that the engineering parameters of the Chalk vary with its age as a consequence of the greater preconsolidation experienced by the older Chalk. The Chalk in the Docklands lies in the Micraster Coranguinum zone of the Upper Chalk and is therefore relatively young within the sequence. A water well borehole in the Beckton Gasworks put down in 1909 penetrated the full Cretaceous sequence and proved 197.2m of Chalk. Carter and Millard show that voids ratio can be correlated to the height above the base of the Chalk (figure 37). Using this a voids ratio e , of 0.82 can be expected for the Chalk in the docklands area. Voids ratio can be readily correlated with porosity n , through the relationship,

$$e = \frac{n}{1 - n}$$

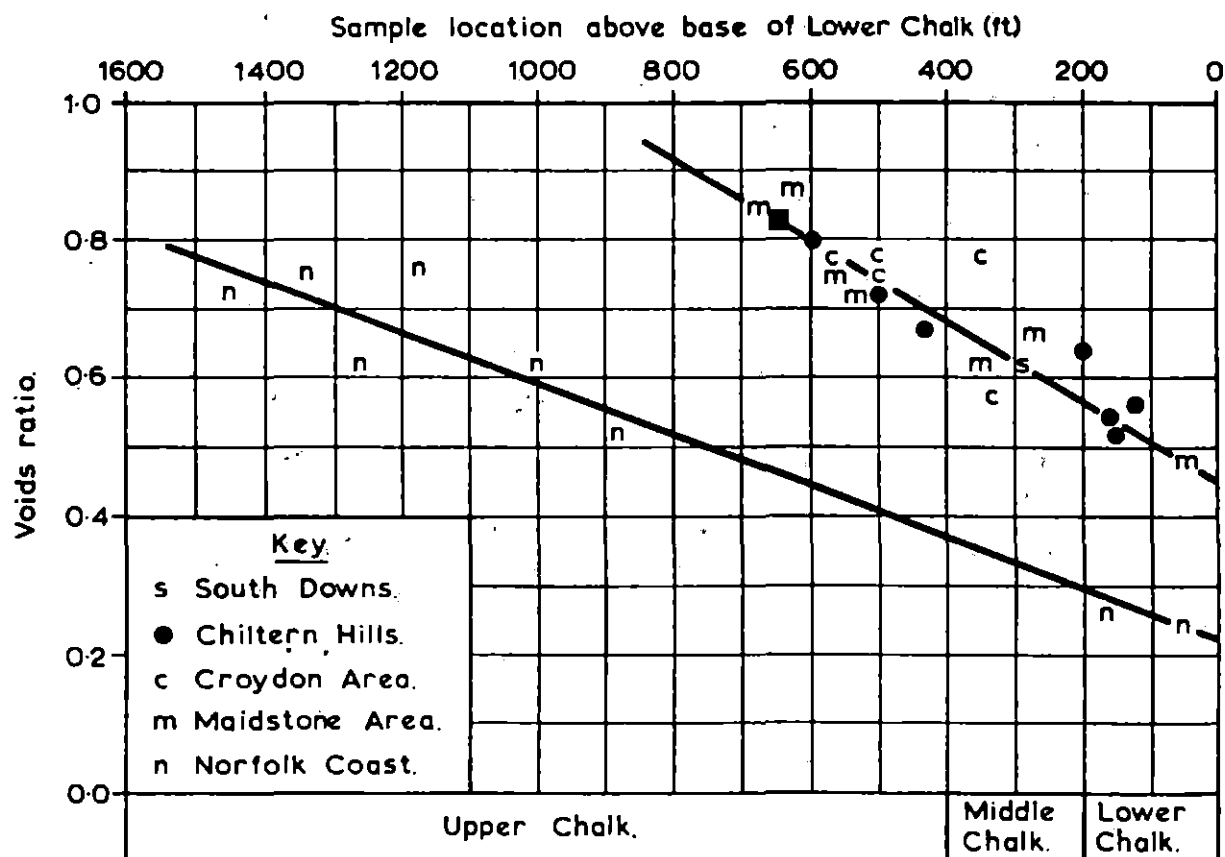


Figure 37.

Relationship between voids ratio and height above the base of the Lower Chalk (after Carter and Millard 1974)

The average porosity measured in the Jubilee Line investigation (Wimpey, 1978) was 44% which equates to a voids ratio of 0.79. Hancock (1975) gave an average porosity of 0.42% for the white Chalk facies of southern England which gives a voids ratio of 0.72. Allowing for the wider coverage of the Hancock data this suggests that a general value of 0.80 may be adopted in the Docklands area.

Voids ratio can also be related to moisture content m , by:-

$$e = m \times G$$

Thus for the range of voids ratio calculated from the reported porosity values from the Jubilee Line investigation a range in moisture content from 20 to 31% could be expected. This compares well to the actual range measured of 19.3 to 33% and also to the range of 15 to 36% measured at the Thames Barrier site. The average of 29 and 28% from each of these sites correlates well with a determined value of 30% for a voids ratio of 0.80.

Since dry bulk density is also intimately related to voids ratio a similar range in value has also been reported. Bell (1977) reports the dry unit weight for the Upper Chalk from Kent to range from 1.35 to 1.64 Mg m^{-3} . This compares to a range of 1.23 to 1.68 Mg m^{-3} (average 1.57 Mg m^{-3}) at the Thames Barrier (Fookes and Martin 1978). The Jubilee Line investigation (Wimpey 1978) report the natural bulk unit weight to range from 1.82 to 2.18 Mg m^{-3} with an average of 1.97 Mg m^{-3} . By using the relationship between voids ratio and density, a voids ratio of 0.80 gives a dry and wet bulk density 1.51 Mg m^{-3} and 1.96 Mg m^{-3} respectively, both of which compare very well to those measured in the investigations.

The strength of Chalk can be considered in a number of ways. The intact material has an inherent strength which may be considered in both the undrained and drained state, but because the moisture content of the material can vary over such a large range and the interparticulate bonds are susceptible to break down the measured

strengths themselves should be expected to reflect this variability. In addition the discontinuous nature of the material en mass means that the behaviour of the material may in fact be controlled by the mass characteristics.

The undrained shear strength was measured in the Jubilee Line investigation and was found to vary from 47 to 549 kN m^{-2} with an average of 210 kN m^{-2} . The drained shear strength was determined at the Thames Barrier site and was found to have a negligible effective cohesion and a drained angle of shearing resistance of 40 degrees. It can be argued that in fact a significant effective cohesion should be anticipated because on the basis of the steep sided slopes present in Chalk quarries (Fookes and Martin 1979). The test results from the Canary Wharf site reported by Wimpey (1985) showed a cohesion value of 80 kN m^{-2} which reduced to zero in the residual condition.

The unconfined compressive strength of the Chalk falls into the moderately weak class of the rock strength classification of the Geological Society (Anon 1970). However Bell (1981) reports that the measured strength is significantly reduced when the Chalk is saturated and reports a reduction of 70% in samples of Upper Chalk from Kent.

Poisons ratio has been found to be a fairly consistent at about 0.25 while the modulus of elasticity is very sensitive to its weathering state and has a very large reported range, from 120 to 9600 MN m^{-2} (see also figure 38). Ward et al (1968) also showed that the Chalk was non-elastic and would undergo creep prior to failure. The bearing stress which caused yield varied from less than 200 kN m^{-2} for the remoulded Chalk to over 1000 kN m^{-2} for the unweathered intact material. Nonetheless, the Chalk does exhibit elastic behaviour at stresses lower than the yield point and for even soft low grade Chalk bearing stresses have been demonstrated to give acceptable settlements (Burland et al 1974).

For most engineering purposes the results of the standard penetration test may be used to assess the character of the Chalk. Although it has been argued that they show only a poor relationship to weathering grade, it is possible to separate the results from this classification. Dixon and Carter (1960) proposed a simple three part grouping for the Chalk which has since been adopted by the CIRIA working party report on piling in Chalk (Hobbs and Healy 1979).

The standard penetration test is a useful method of assessing the broad characteristics of the Chalk. Although the test is influenced by a number of factors the relationship with any one factor is loose, therefore it has the advantage of practicality and simplicity and is of particular use where good sections or samples of the material are not possible.

The permeability of the Chalk, together with the other principal Formations, has been measured with great care on an investigation carried out by the LDDC in the Royal Docks to assess the ground conditions around a Herrenknecht tunnelling machine which became stuck during a drive (Soil Mechanics 1988). This gave values of 6 and $8 \times 10^{-8} \text{ m sec}^{-1}$ based on falling head tests in piezometers. This compares with a range of 1×10^{-6} to $5 \times 10^{-5} \text{ m sec}^{-1}$ from the Thames Barrier investigation and 1.5×10^{-8} to $6.4 \times 10^{-4} \text{ m sec}^{-1}$ from the Jubilee Line. Although the results show a wide scatter, this may be because the permeability of Chalk will be controlled by its discontinuity pattern rather than the permeability of the intact material itself.

6.3 Thanet Sand

The Thanet Sand is a poorly graded silty fine or fine to medium grained sand. The grains are almost entirely quartz with a small percentage of quartzite, flint, feldspar, chlorite and a very few heavy minerals. Clay minerals and iron hydroxides form occasional

coatings to some grains although their presence is rare. The grains are mainly angular to subangular and equant in form, or slightly tabular. Very occasional subrounded and rare well rounded grains are present. The surfaces of the grains are mainly clear but some frosting exists, mainly on the more rounded medium grains. The heavy minerals have been shown to consist of a basal sequence of epidote-garnet-hornblende assemblage which grades up the sequence to a zircon-tourmaline-rutile assemblage. The heavy minerals are unstable in sediments and their surfaces are characteristically etched so destroying the original grain morphology (Morton 1982).

To enable ready comparison of differing samples the grading envelope of any particulate material can be defined in terms of the particle size below which certain percentages of the whole material fall. The main reference points are usually taken as the 10, 60 and 85% values and the associated particle size referred to as the D10, D60 and D85 values respectively. The D10 value is also called the effective size as it is the finest material in any soil which often defines it's engineering behaviour. Similarly a measure of the overall grading, that is the uniformity of the particle size, can be given by the ratio of D60 to D10 which is called the uniformity coefficient.

Although the Thanet Sand Formation is commonly considered to be relatively uniform, when considered in detail it appears that it can be separated into two distinct units (fig. 39). On average the whole Formation is about 16 metres in thickness in the Docklands area. The upper part shows a gradual but perceptible fining with depth. This is more marked in the coarse fraction such that the uniformity coefficient shows a corresponding slight reduction. From about five metres above the base the fines content increases markedly and the Formation becomes increasingly silty and eventually clayey over the basal layers. Interestingly, the coarse fraction, as defined by the D60 and D85 values, shows a continuation of the trend established in the higher levels. Consequently, the uniformity coefficient rises significantly over the basal five metres.

The Bullhead Bed, which forms the basal deposit of the Thanet Sand Formation, is usually between 0.25 and 0.5m in thickness and is noticeably more clayey than the main body of the unit. It is also characterized by a content of well rounded dark green or black flint gravel which can range up to cobble size.

Figure 39 shows the variation in D10, D60, D85 and the Uniformity Coefficient above the base of the Formation. Only two boreholes have been plotted because there is also variation between individual boreholes in the absolute grading size which would mask the trend in each if further data was added. The boreholes are from a detailed study of the Thanet Sand which has been carried out in the Connaught Road area of the Royal Docks by the Corporation (Soil Mechanics 1988). This shows the main part of the material, above the lowest five metres, to have an average D10, D60 and D85 of 0.074, 0.181 and 0.230mm respectively. This compares to 0.004, 0.089 and 0.126mm in the lower five metres. The average uniformity coefficient being 2.5 for the upper and 56 for the lower material. An investigation carried out in the Limehouse area to the west (Soils Engineering 1988) shows the Thanet Sand to be slightly more coarse at any stratigraphic level, but that the decrease in overall grain size is still evident. In the Limehouse area, the value of D10 over the lower five metres does not show the very marked increase in fines content. However, this may be due to the fact that the results were obtained only from mechanical sieve analyses and did not determine the fines content more closely by hydrometer method as in the Connaught Road investigation.

The possibility of an overall but slight fining in the Thanet Sand in an easterly direction across the docklands area was also reported from the Jubilee Line investigation (Wimpey 1978).

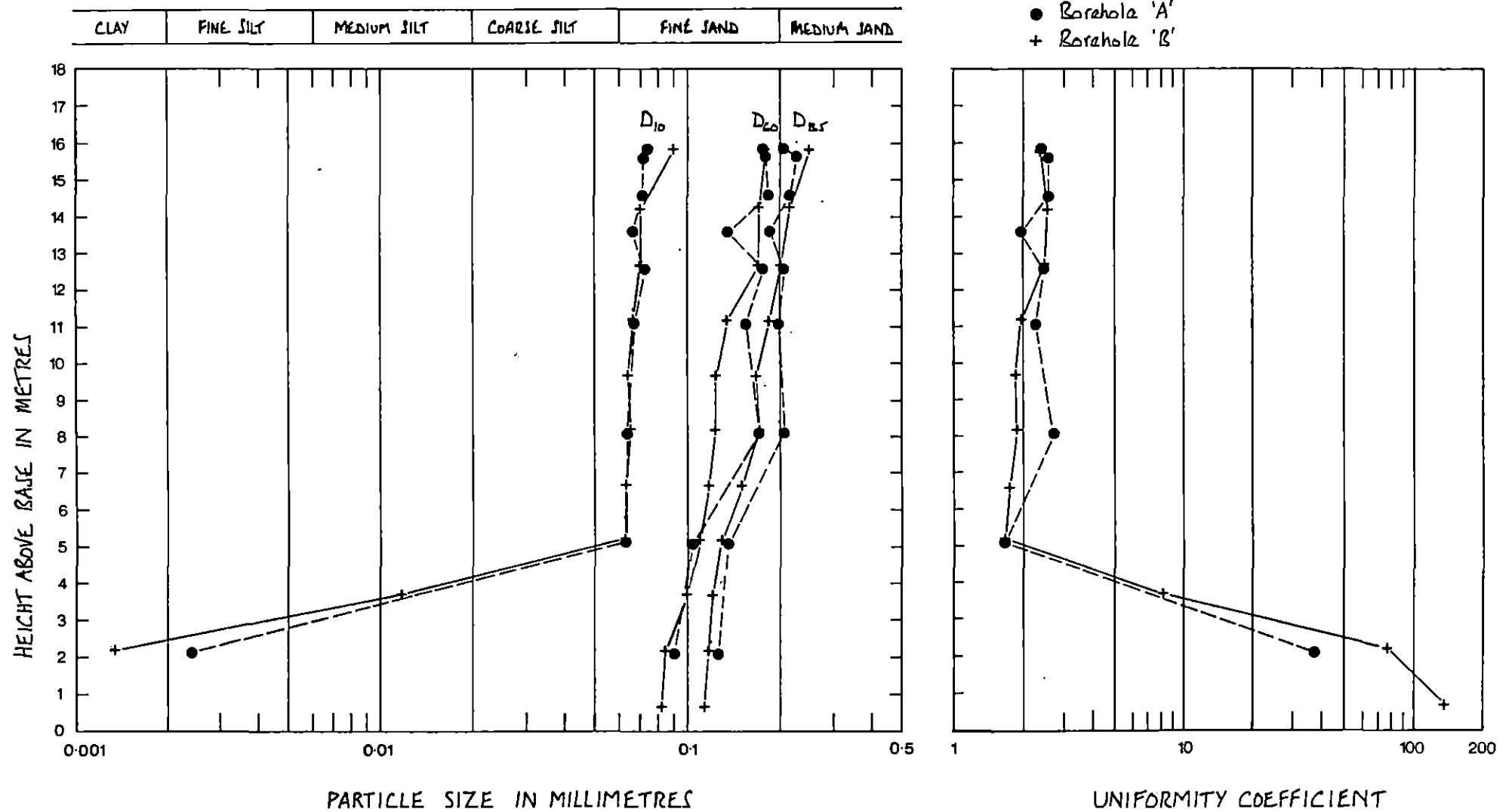


Figure 39 Variation in D₁₀, D₆₀, D₈₅ and Uniformity Coefficient (D₆₀/D₁₀) in the Thanet Sand plotted against metres above the base of the Formation from two boreholes in the Royal Docks area

As assessed by the standard penetration test the Thanet Sand has blow counts usually in excess of 60 and very often the test cannot be completed before refusal is reached. Fookes and Martin (1979) report that a reduction in blow count in the upper few metres indicates weathering or disturbance of the Formation below the Thames Gravels and that this disturbance is increased below the River in the area of the Thames Barrier. However, no evidence of this has been found elsewhere in the Docklands area.

The Formation is heavily overconsolidated due to the removal of substantial thicknesses of later Tertiary materials. The evidence suggests that it represents an example of "locked sand", as defined by Dusseault and Morgenstern (1979). This is a sand material in which a mechanical intergrowth of its particulate grains has occurred giving a state of packing which is greater than could be achieved in the laboratory from a disaggregated sample without producing grain disintegration. This mechanical locking means that a degree of apparent cohesion is developed in such materials (Barton et al 1986; Barton & Palmer 1989). This is true of the Thanet Sand for where it outcrops at surface or is found in excavation it can stand at steep angles and can, with care, be cut into discrete and manageable blocks. It is sometimes reported to be locally cemented to a weak sandstone but this may be a confusion with the characteristic behaviour of a locked sand. Photomicrographs have been taken of a number of undisturbed samples (Soil Mechanics 1988). These show the grains to be fairly angular but with a very high intimacy along the contacts between adjacent grains with a large percentage of straight and some convexo-concave contacts. Such contacts are described by Dusseault and Morgenstern (1979) as indicative of locked sands.

The close state of packing produces a dilatant behaviour in the material during shear. A number of consolidated drained shear box tests carried out on undisturbed samples gave an internal friction which was consistent at 42 degrees. Although regression analyses through the sample points gives a slight cohesion intercept, for practical purposes this can be regarded as zero. This compares with

a range of 34 to 43 degrees for recompacted samples carried out during the Thames Barrier investigation by Fookes and Martin (1979) from which no cohesion might be expected, but is in some contradiction to results reported from the Canary Wharf site in the Isle of Dogs in which a cohesion of 25 kN m^{-2} found.

Laboratory determinations of the minimum and maximum dry bulk densities appear to be more consistent. Average values of 1.34 and 1.65 Mg m^{-3} respectively were found in the Royal Docks area and 1.26 and 1.54 Mg m^{-3} from the Thames Barrier. This agreement should be regarded as more fortuitous than real as the results are very sensitive to testing technique (Head 1980). Differences in test procedure possibly accounts for lower values obtained during the Jubilee Line investigation. A natural dry bulk density was also determined by Fookes and Martin from a sample of Thanet Sand obtained at Maryon Park in Woolwich. This gave a value of 1.76 Mg m^{-3} which compares with 1.79 Mg m^{-3} obtained on insitu material from the Royal Docks. Both compare very well with the value of 1.77 Mg m^{-3} which can be calculated for a voids ratio of 0.52 and a specific gravity of 2.69 .

Fookes and Martin note that the natural density from the Maryon Park sample was greater than the maximum achieved laboratory value and suggest that this was due to a possible variation in grading, or possible cementing in the sample or even to differing states of overconsolidation. In fact it seems probable that this is merely a function of the locked sand phenomenon in which case the material from Maryon Park need not be considered to be different in condition to that on the north side of the river.

The dilatant behaviour of the sand will also influence the results obtained from standard penetration tests as the induced negative pore pressure which develops under dynamic undrained loading will produce a significant element of strain hardening to the material. This will increase the resistance to penetration in the same way that wet sand

on the beach will not give to a hard stamp of a foot but will allow the foot to sink into it if it is gently "wiggled". For this reason the actual results obtained from the standard penetration tests should be viewed with some caution and any correlation of variation in the character of the Thanet Sand with the blow count is unlikely to be practical.

The permeability of Thanet Sand has been found to be typically in the range of 10^{-6} m sec⁻¹. Although a fairly wide range in results has been reported the results from in situ tests appear to be very sensitive to technique. A suite of laboratory tests devised to determine the permeability of the undisturbed samples and to compare this to recompacted material in fact produced very similar results (fig. 40). This perhaps suggests that the permeability of the Thanet Sand is controlled only by its grading and is not influenced by sedimentary structure. This also adds further support to the absence of cement in the material since its presence would have reduced the permeability of the undisturbed material against the recompacted material in which the cement would have been broken down. The lack of any carbonate cement in the Thanet was confirmed by the results from a Collins calcimeter which showed an average calcium carbonate content in 14 samples to be 0.012%.

An important engineering characteristic of any uncemented granular material is that it is susceptible to disruption by seepage pressures generated as water flows through soil. These seepage forces are controlled by the hydraulic gradient which at some critical condition will overcome the weight of the soil and will be able to move its constituent grains. This is commonly experienced as a quicksand where the seepage force acts upwards, or, as running sand into an excavation. The critical hydraulic gradient can be related to voids ratio according to the formula;-

$$H_c = \frac{G - 1}{1 + e}$$

	<u>PERMEABILITY OF UNDISTURBED SAMPLE</u>		<u>PERMEABILITY OF SAMPLES COMPACTED TO BS 1377 TEST 12</u>		<u>PERMEABILITY OF SAMPLES COMPACTED TO MAXIMUM LABORATORY DENSITY</u>	
	Borehole 407 Sample 36	Borehole 407 Sample 40	Borehole 407 Sample 36	Borehole 407 Sample 40	Borehole 407 Sample 36	Borehole 407 Sample 40
Bulk Density (tonne/m ³)	2.09	2.15	1.93	1.97	2.08	2.09
Moisture content (%)	22	23	26	24	23	23
Permeability, 2 m head						
after 0 hr (m/sec)	2.07×10^{-6}	2.81×10^{-6}	2.28×10^{-6}	3.07×10^{-6}	2.13×10^{-6}	2.95×10^{-6}
$\frac{1}{2}$ hr (m/sec)	2.04×10^{-6}	2.77×10^{-6}	2.27×10^{-6}	3.00×10^{-6}	2.12×10^{-6}	2.92×10^{-6}
2 hr (m/sec)	2.02×10^{-6}	2.72×10^{-6}	2.23×10^{-6}	2.99×10^{-6}	2.10×10^{-6}	2.92×10^{-6}
Permeability, 5 m head						
after 0 hr (m/sec)	1.49×10^{-6}	1.85×10^{-6}	1.77×10^{-6}	1.97×10^{-6}	1.53×10^{-6}	1.89×10^{-6}
$\frac{1}{2}$ hr (m/sec)	1.45×10^{-6}	1.82×10^{-6}	1.81×10^{-6}	1.96×10^{-6}	1.51×10^{-6}	1.89×10^{-6}
2 hr (m/sec)	1.47×10^{-6}	1.85×10^{-6}	1.80×10^{-6}	1.94×10^{-6}	1.50×10^{-6}	1.87×10^{-6}

Figure 40 Laboratory determinations of permeability on undisturbed and recompacted samples of Thanet Sand

Thus, for a voids ratio of 0.52, H_c is 1.11.

In boreholes and other excavations the effect of this is to cause 'boiling' in the base. In boreholes the effect can be to disrupt the soils and nullify any further insitu test results and possibly influence the grading of the soils. In excavations such failure of the base can be catastrophic and may cause failure of the entire excavation, while again the disruption of the soils below may seriously influence their characteristics and affect the validity of any assumptions previously used in design. This has indeed happened in a number of excavations in the Docklands.

A programme of tests to monitor the behaviour of the Thanet Sand to this effect was carried out in a number of boreholes in the Royal Docks and in the laboratory. These showed that the base of a borehole became very indistinct and rose up the borehole when the water level was dropped by less than a metre below the local standing water level. In the laboratory a number of undisturbed samples were subjected to a slight back pressure applied at the base of the specimen in a triaxial cell. The samples were noted to swell slightly as the pressure differential across the specimens increased above 3 kN m^{-2} and at about 7 kN m^{-2} the specimens failed by disruption of the upper surface. The samples were about 93mm in length suggesting that the specimens began to fail at a hydraulic gradient of 3.2 and failed catastrophically at a hydraulic gradient of 7.5. The difference between this and the calculated critical hydraulic gradient cannot be definitely explained but is possibly related to the boundary conditions developed in the test sample. It does however confirm the susceptibility of the material to low pore pressure differentials.

In order to determine whether the material was susceptible to vibration two triaxial tests were carried out under conditions of dynamic loading. Undisturbed samples were saturated under an applied

back pressure and consolidated anisotropically to give ratios of σ_h'/σ_v' of 0.33 and 3.0 for the two tests. A series of tests were then applied to each specimen by applying a cyclic deviator stress of different magnitudes and frequency levels to determine any sensitivity to each variable. 1000 cycles were applied, although for two tests this was increased to 10,000 cycles. The load applied, the axial and radial deformations were monitored. The results are summarized on figure 41 from which it can be concluded that the samples were not very susceptible to vibration. A small negative pore pressure was induced at the smaller fluctuations in deviator stress. However, this was eliminated by increasing the frequency. In contrast, small positive pore pressures were found to be present after the higher magnitudes of fluctuation in the deviator stress.

The cyclic loading test monitored the radial and axial deformation under strain. This was done with the axial load as the principal stress axis on one sample and with the horizontal axis as the principal stress axis on the second test. The ratio of deformation defines the Poissons ratio and gave 0.055 and 0.031 respectively.

6.4 Woolwich and Reading Beds

There is greater variation in the lithology of the Woolwich and Reading Beds (WRB) than in the preceding Thanet Sand. This variation exists both laterally and vertically and ranges from clean granular materials to heavy clays with occasional rock bands interspersed amongst them. It has been shown in Chapter Three that the Formation can be divided into a seven part classification in the area based on a broad lithostratigraphy.

It has been stated above that generalizations can be made for engineering properties of the principal Formations of the area. However, while this is true of the more uniform Formations, because

TEST A

Initial bulk density = 2.04 Mg/m^3
 Initial dry density = 1.71 Mg/m^3

B value = 0.93

Sample consolidated $\sigma_v = 650 \text{ kN/m}^2$, $\sigma_h = 450 \text{ kN/m}^2$, back pressure = 350 kN/m^2

Sub test	Data files	$\Delta(\sigma_v - \sigma_h)$ kN/m^2 (nominal)	No of cycles	Frequency Hz	Approx axial deformation amplitude	Increase in axial deformation during test	Increase in pore water pressure during test (kN/m^2)
1	1,2,3	+ 5	1000	1	-	0.107mm	-3
2	4,5,6	+ 12.5	1000	1	0.05mm	0.013mm	-5
3	7	+ 12.5	1000	10	0.01mm	0.006mm	0
4	8,9,10	+ 25	1000	1	0.08mm	0.054mm	+2
5	11,12,13	+ 37.5	1000	1	0.11mm	0.174mm	+7
6	14,15,16	+ 50	1000	1	0.15mm	0.294mm	+9

TEST B

Initial bulk density = 2.02 Mg/m^3
 Initial dry density = 1.64 Mg/m^3
 B value = 0.96

Sample consolidated $\sigma_v = 450 \text{ kN/m}^2$, $\sigma_h = 650 \text{ kN/m}^2$, back pressure = 350 kN/m^2

Sub test	Data files	$\Delta(\sigma_v - \sigma_h)$ kN/m^2 (nominal)	No of cycles	Frequency Hz	Approx axial deformation amplitude	Increase in axial deformation during test	Increase in pore water pressure during test (kN/m^2)
1	1,2,3	+6	1000	1	-	-	-
2	4,5,6	+ 15	1000	1	-	-	+3
3	7	+ 12.5	1000	10	Unsatisfactory loading pulse. Data not presented.		
4	8	+ 12.5	1000	25			
5	9,10,11	+ 32.5	1000	1	0.005mm	0.005mm	+17.5
6	12	+ 17.5	1000	10	-	-	-
7	13,14,15	+ 15	10000	10	0.005mm	-	+6

Notes

- 1 Sample may not have been fully saturated during the test which would explain in part the low porewater pressure response during the cyclic loading.
- 2 Undrained cyclic loading carried out with the sample being allowed to consolidate anisotropically between each sub test.
- 3 Axial deformations measured over a base length of 50mm.
- 4 - = no response.

Figure 41 Summary of cyclic loading triaxial tests on Thanet Sand

Parameter	Range	Reported Values Standard Deviation or majority	Ave	Source	Remarks
Grading (mm)					
a. >5m above the base	D ₁₀ D ₆₀ D ₈₅ D ₆₀ /D ₁₀	0.042 - 0.157 0.011 - 0.325 0.142 - 0.401 1.66 - 3.94	0.014 0.034 0.045 0.44	0.074 0.181 0.230 2.48	)) 3)))
b. Base to 5m above base	D ₁₀ D ₆₀ D ₈₅ D ₆₀ /D ₁₀	0.001 - 0.121 0.083 - 0.100 0.123 - 0.134 8.22 - 137.67	0.005 0.008 0.005 55.99	0.004 0.089 0.126 65.13	)) 3)))
					Royal Docks; based on 77 results see also fig 39
Specific gravity	2.68 - 2.70 2.45 - 2.72	0.008 2.55 - 2.70	2.69 2.65 2.65	3 1 2	Royal Docks; based on 4 results Jubilee line Specific gravity for quartz
Carbonate content (%)	0 - 0.140	0.014	0.012	3	determined by a Collins calcimeter and assumed that all CO ₂ was derived from CaCO ₃
Voids ratio			0.52		Calculated for a porosity of 0.34
Porosity	0.30 - 0.37	0.03	0.34	3	Royal Docks; based on 4 results
Bulk density (Mg/m ³)					
a. Natural samples					
i) wet density	2.07 - 2.18	0.04	2.12	3	Royal Docks; based on 6 samples, moist cont=20.0%
ii) dry density	1.70 - 1.87	0.07	1.79 1.76 1.77	3 2	Royal Docks; base on 4 samples Undisturbed sample from Maryon Park, Woolwich Calculated from e = 0.52 and G = 2.69
b. Recompact samples					
i) max density: wet	1.99 - 2.04	0.02	2.02		Royal Docks; based on 4 samples, moist cont=22.8%
ii) max density: dry	1.62 - 1.69	0.03	1.65		Royal Docks; based on 4 samples
iii) min density: dry	1.49 - 1.96 1.33 - 1.35 1.04 - 1.24	0.01	1.34	1 1	Jubilee line Royal Docks; based on 4 samples Jubilee line
Moisture content (%)	8 - 31 29 - 37	3.2	22.7	1	Royal Docks; based on 95 samples Thames Barrier site
Drained shear strength (c' = kN/m ² ; β' = degrees)			c' = 0 β' = 42 c' = 25 β' = 36 cr' = 0 βr' = 33	3 5	Royal Docks: based on manual best-fit line, regression analysis gives c' = -2.1 to 11.7 kPa Canary Wharf: Isle of Dogs) peak) residual
Modulus of elasticity (MN/m ²)	19.3 - 189.0			1	Jubilee line
Poissons ratio a) vertical b) horizontal			0.055 0.031		) Based on cyclic loading tests on undisturbed) material in triaxial load cell
Permeability (m/sec)	1.5x10 ⁻⁶ - 2.8x10 ⁻⁶ 1.0x10 ⁻⁶ - 1.0x10 ⁻⁴ 3.0x10 ⁻⁹ - 2.0x10 ⁻⁶ 1.0x10 ⁻⁶ - 5.0x10 ⁻⁵ 5.0x10 ⁻⁷ - 5.0x10 ⁻⁶			3)) 1 4	Royal Docks; lab. value on undisturbed samples falling head test in boreholes falling head test in piezometers Jubilee line Thames Barrier site

Source: 1 - Wimpey 1978; 2 - Mason & Berry 1968; 3 - Soil Mechanics 1988; 4 - Fookes & Martin 1978; 5 - Wimpey 1985

Table 6. Geotechnical data sheet for the Thanet Sand

these vary on a scale which is greater than the particular area of interest, for Woolwich and Reading Beds this supposition breaks down as the variation within the units of the Formation occurs over the area of the Docklands and therefore becomes significant.

Nonetheless, the particular depositional environment which typifies the Woolwich and Reading Beds means that many of the units constitute c- ϕ materials. As such even though there may be a complex lithostratigraphic variation in the Formation the distinctions in engineering behaviour between the various units becomes less distinct.

A broad grouping of the soil types can therefore be established by comparing their index properties. In this way the Formation can be divided into three main units; an upper mix of sands and clay, a middle section of heavy shelly clays and a lower section of sands and clays. The upper and lower sections rarely consist of significant thicknesses of pure sand or clay and are dominated by various sandy clays and clayey sands. If sufficient clay is present to give a soil a plasticity, and hence a cohesive engineering behaviour, then it should be described as a clay (Norbury et al 1986). However, this contradicts the philosophy of BS5930 which suggests that the main and secondary descriptor of a soil should be based on grading. It is clear therefore that correlation and grouping governed by strata description alone may be misleading, particularly where those strata descriptions are taken from varying sources.

However, because traditional site investigation practise varies the choice of sampling and testing to the broad category of soil present the availability of index data is governed by a real or perceived grouping of the soils during the investigation. Therefore, this can limit the number and range of tests that are available for comparison from investigation to investigation.

By taking the data from a number of selected investigations across the area the necessary comparisons can be made which can then be used to assess other data as available.

Although it was originally devised for cohesionless soils, the standard penetration test (SPT) is now also used in cohesive soils. However, the factors which affect the penetration resistance are different in each type so that results cannot be correlated between a sand and a clay. This restriction will become less severe where the grading, and hence behaviour, of any soil straddles the clay:sand boundary and develops a $c-\phi$ characteristic.

Figures 42 and 43 show the SPT results from the clay and sand facies within the Woolwich and Reading Beds plotted against metres below the upper contact. Most noticeable is a wide scatter of results on both plots. However, there is an underlying grouping which can be correlated to individual investigations. This may be due to:-

1. differences in the geological condition of the Formation,
2. differences in the engineering character of the material,
3. differences in technique used by the contractor at each site.

It can be seen that the blow counts from the Limehouse Link investigation (Soils Engineering 1988) for both sands and clays show a slight increase over the initial five metres from about 40 to 70 and from there are fairly consistent with depth at about 70.

Although the results for the sands are supported in the upper levels by results from the north side of the Royal Victoria Dock (Soils Engineering 1985a) those to the south of the dock are a factor of 2 to 4 times greater (Soils Engineering 1987a). In contrast results from the lower five metres from the Limehouse area are higher than from the Royal Docks and Gaslands area (Soils Engineering 1987b).

Table 7 shows the grading details of the basal lithostratigraphic subgroups in the Woolwich and Reading Beds for the Limehouse area and

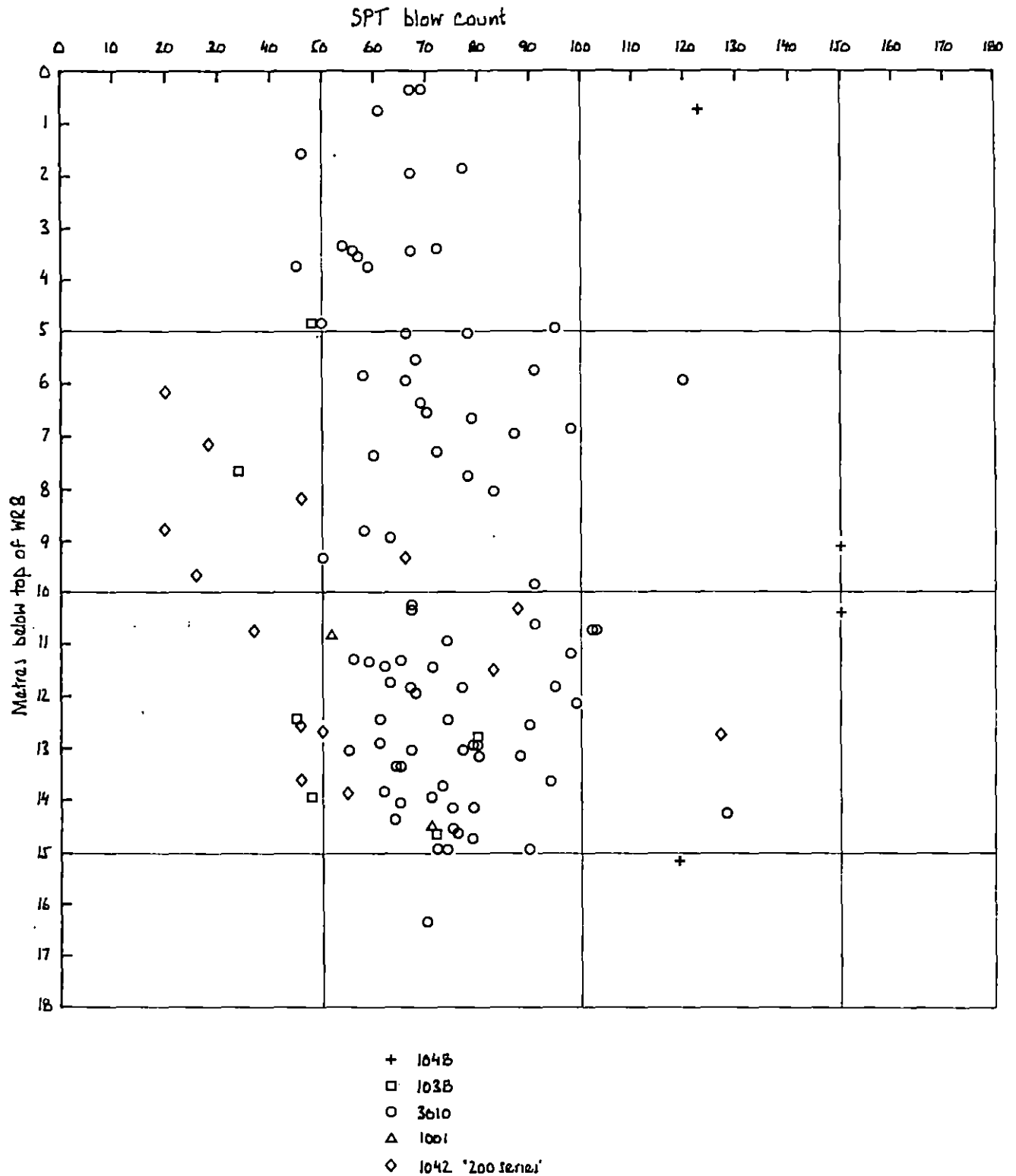


Figure 42.

SPT blow count from the clay facies of the Woolwich and Reading Beds against metres below the stratigraphic top of the Formation (see figure 44 for the position of the various sites)

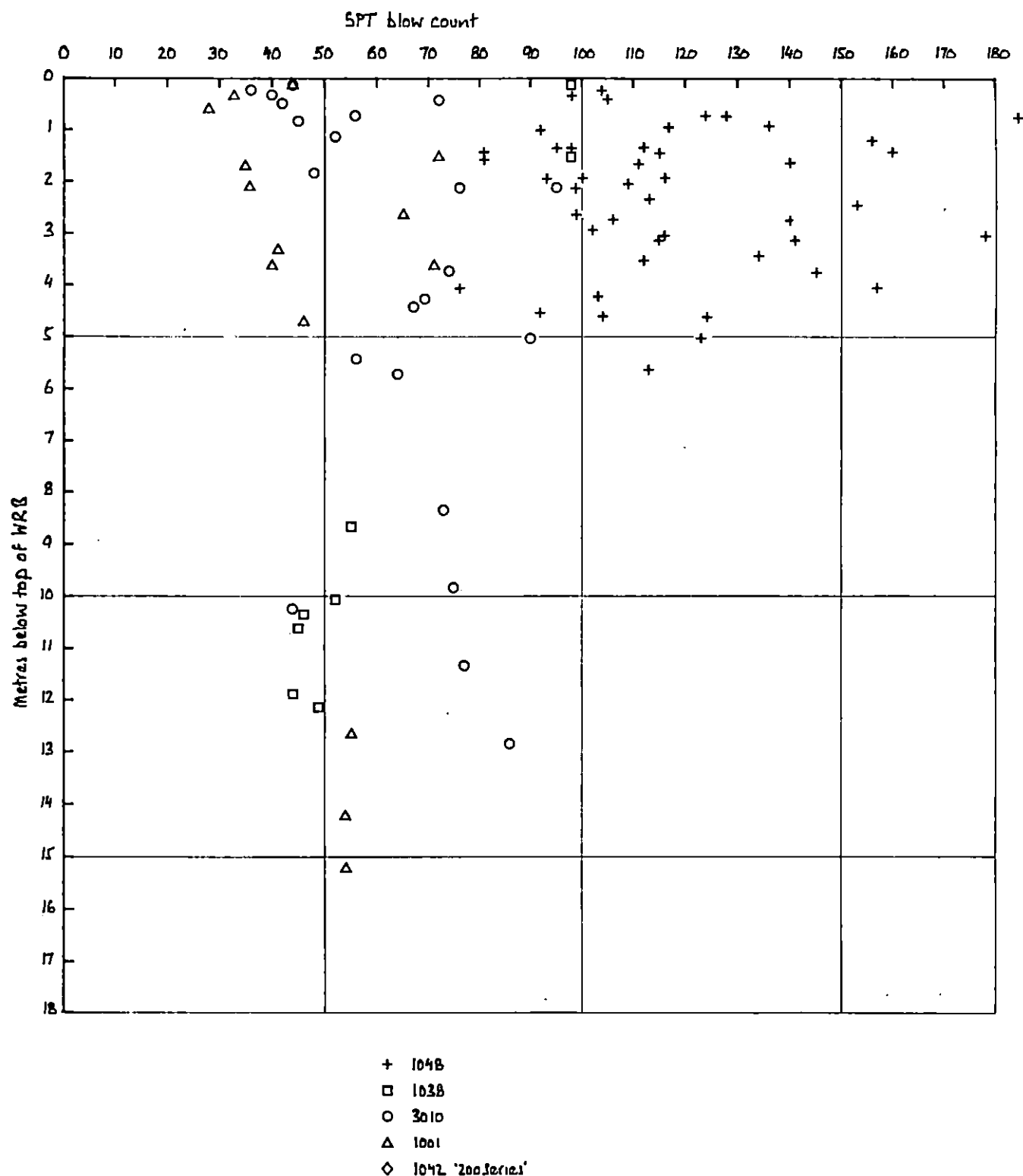


Figure 43.

SPT blow count from the sand facies of the Woolwich and Reading Beds against metres below the stratigraphic top of the Formation (see figure 44 for the position of the various sites)

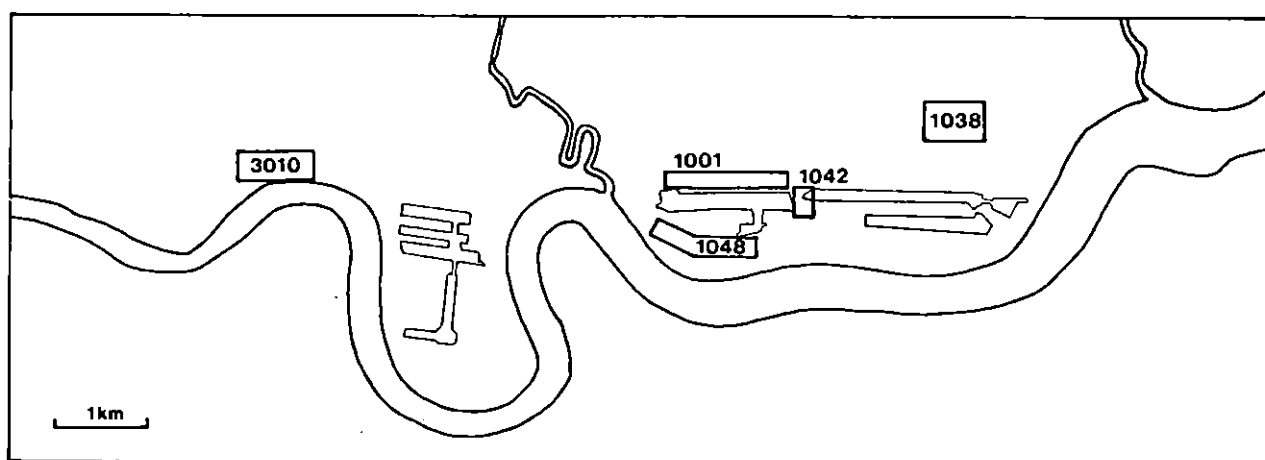


Figure 44. Distribution of various sites in a number of figures

L I M E H O U S E				R O Y A L D O C K S		
	F a c i e s			F a c i e s		
	a	b	c	a	b	c
D10						
ave.	0.0454	0.0279	0.0317	0.0271	0.0162	0.0035
min.	0.0008	0.0006	0.0006	0.0006	0.0006	0.0006
max.	0.2254	0.1997	0.4260	0.0762	0.0697	0.0239
D60						
ave.	3.7213	5.5593	3.1489	1.9986	0.5036	0.8429
min.	0.2220	0.0291	0.0028	0.0964	0.0462	0.0151
max.	14.3182	24.7867	17.0977	14.4783	16.2342	10.9584
D85						
ave.	14.0286	11.2554	6.5560	5.7123	0.9289	1.8235
min.	6.2007	0.0973	0.01075	0.1587	0.1214	0.0605
max.	27.0442	30.3303	39.1932	39.6163	19.4369	19.6906
D60/D10						
ave.	360.2	319.4	255.3	191.4	513.2	599.5
min.	4.64	7.62	4.67	2.55	1.68	9.33
max.	2864.3	2788.1	1360.1	2129.2	473.3	12176.0

Table 7. A comparison of the grading characteristics of the lower facies of the Woolwich and Reading Beds

south of the Royal Victoria Dock. In Limehouse little difference is seen in subgroups a, b and c which make up the lower five metres or so. At the Royal Docks the differences between subgroups a, b and c are slightly more marked but what is most noticeable is that the lower five metres in the Royal Docks have a finer overall grading.

Results of standard penetration tests from the lower five metres, as shown on figures 42 and 43, can be seen to be lower in the Royal Docks and Gaslands area of east Beckton than in Limehouse. It seems unlikely that there is any major difference in the geological aspects of the sites, such as former depth of burial, which might influence the engineering characteristic. The difference in the blow counts can therefore be attributed to the variation in grading. Although the presence of the greater proportion of coarse fraction in the Limehouse area is unlikely to increase the frictional resistance in the soil itself, it is likely that a greater energy will be required to displace the larger volumes of material as the test is completed. A support to this contention can be seen in the results from the Gaslands area which although in general have been shown to have lower blow counts associated with the finer grading, two individual results of 80 and 72 are comparable to the results from the Limehouse area. However, these are from tests taken within the Bottom Bed of the Woolwich and Reading Beds which has an inherent coarse content and is closer in character to the material from the lower five metres in the Limehouse area.

The upper five metres show a marked difference between the results from south of the Royal Docks area as typified by (Soils Engineering 1988) and the remainder of the data. The argument that this is due to a differing grading does not apply, and at this stage the differences cannot be accounted for.

The sand facies of the upper and lower sections of the Woolwich and Reading Beds bear some similarities to the Thanet Sand. They are also in a dense condition although in contrast to the Thanet Sand

the full penetration is usually readily achieved during the test giving blow counts which are very much less than for the Thanet Sand. The sands in the Woolwich and Reading Beds have a wider grading, often being clayey and extend further into the medium and coarse grained sand size. In the basal levels the clayey facies only vary from the sand facies in that the clay content is sufficient to impart a plasticity. It is the clay of the middle section which are more characteristic of the heavy clays of the London Basin.

The clay of the middle section are heavily overconsolidated often with a slight shaley texture. It often has a well developed fissuring, although this can be masked by a sedimentary structure. It is often fossiliferous with shell material varying in proportion from rare to an uncemented thickness of winnowed shell debris. The overall content of shell material usually increases with depth. The clay is usually dark grey or purple grey, although it will weather to brown and in those facies which have undergone probable pedogenesis may have a mottled character. It has a high plasticity and will therefore weather and soften in exposure. Undrained shear strengths are variable and influenced by structure but will give values typically 100 to 300 kN m^{-2} but may increase to 800 kN m^{-2} where the facies become more shaley.

The dominant sedimentary structure of the Woolwich and Reading Beds will control the permeability of the material and allows very much greater horizontal than vertical permeability.

The limestone bands within the Woolwich and Reading Beds were laid down in a freshwater environment and have been reported to be up to a metre in thickness and in a hard and massive condition. A number of attempts to sample and even to core the material in the Docklands has been largely unsuccessful. It appears to be a poorly developed band, often being very rubbly or disaggregated. In places partial solution is evident. Although direct determinations of the rock strength have not been carried out, visual assessments of obtained samples

suggest strengths in the range weak to moderately strong of BS5930 (Anon 1981). The limestone has been encountered by one tunnel drive in the Royal Docks and although the site investigation suggested this to be locally over a metre in thickness and in a moderately strong condition (CJA 1988) it was successfully tunnelled through with a full face tunnel boring machine operating in earth balance pressure mode. It seems that the influence of the limestone on engineering works is, at least locally, dictated by its overall condition and character rather than the strength of small samples which may be unrepresentative of the mass.

6.5 London Clay

A detailed study of the relationship between the regional geology and engineering properties of the London Clay across its entire outcrop in southern England has been carried out by Burnett and Fookes (1974). In this the lithology, bed thickness, structural contours, palaeontological and sedimentological zones of Williams (1971) were related to the detailed mineralogy of the clay. They concluded that grading of the London Clay had a close relationship to its engineering index properties. Since a number of other engineering parameters are intimately related to the index properties of clays it meant that a correlation was possible between grading and fairly wide range of basic engineering characteristics. In essence, it was found that as the clay content decreased then the behaviour was increasingly influenced by the silt and sand sized fraction, which in the London Clay is dominated by quartz.

It is felt that this conclusion can be explained by the relative strength of the surface forces on the differing size particles. Those on the larger silt and sand fraction are much weaker than those of the clay fraction. This, together with the closed crystal lattice of the quartz produces a very different bonding structure to that of the clay minerals. In fact, in clays, it is this bonding structure which controls many of their basic engineering properties.

Burnett and Fookes based their study on the stratigraphic model of Williams (1971) which showed three megacyclothems in the London Clay termed the Lower, Middle and Upper Divisions. If the engineering properties are dependent on grading the stratigraphic model can be extended to provide a prediction of the range and distribution of those properties. The exact grading variation associated with this type of rhythmic deposition depends on the actual depositional setting at any locality, which in essence means how far away it was from the shore-line and how dramatic was the change in relative sea-level.

Burnett and Fookes work indicates that the Middle and Lower Divisions should be present in the Docklands, although this of course is a maximum as the Formation is missing completely over much of the area.

The mineralogy of the London Clay broadly corresponds to a grading in which the silt and sand fraction are increasingly dominated by quartz and the clay fraction by the clay minerals (fig. 45). Nonetheless, the clay fraction accounts for some 60 to 80% of the whole, although there is a slight decrease in this with depth in the Lower Zone.

Based on the regional trends given by Burnett and Fookes the liquid limit (LL) should be about 80% with a plasticity index (PI) of 48% in the Docklands. As might be expected tests carried out in the area show a wide range to be present (Table 8). However, since the London Clay is truncated across the area it can be expected that any suite of results will be weighted towards the basal range. As both the liquid limit and plasticity index will decrease as the silt and sand fraction increases and as the silt and sand content increases towards the base, the trend should be reflected in the Atterberg limits. By plotting the liquid limit and plasticity index for two sites from the west and east of the area (fig 46) it can be seen that although the expected decrease with depth is present in the west

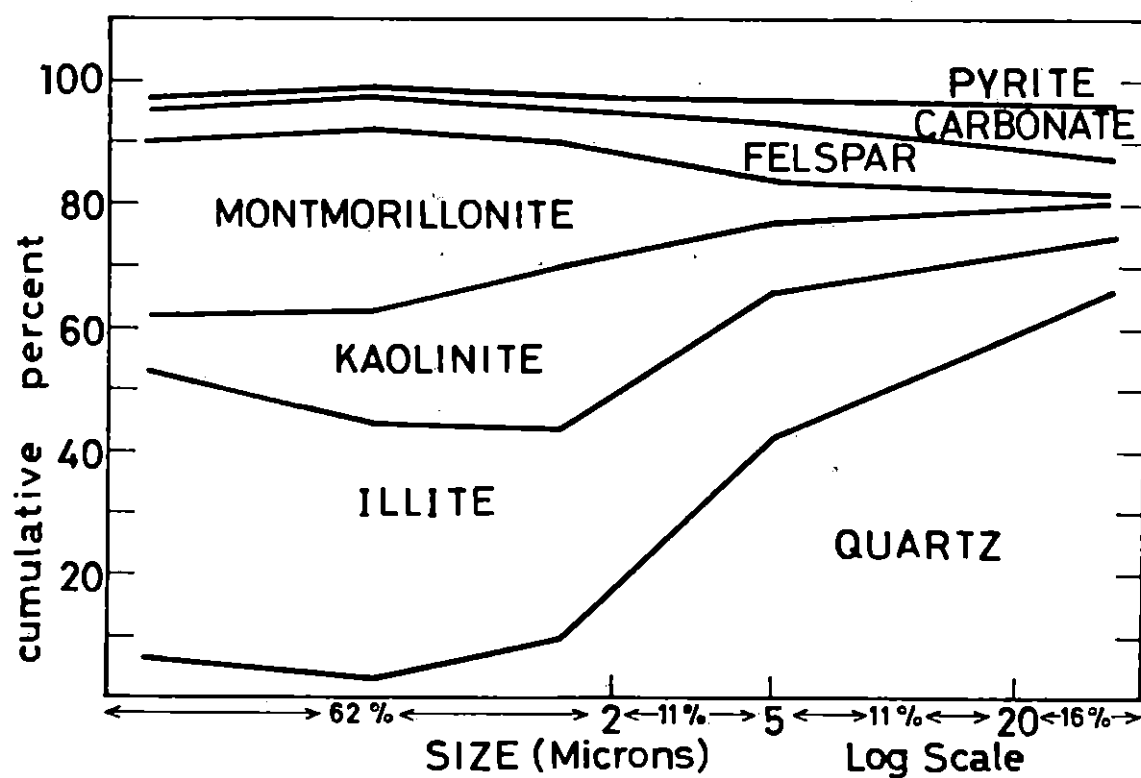


Figure 45. Mineral distribution by particle size within a single sample of London Clay

(after Burnett and Fookes 1974)

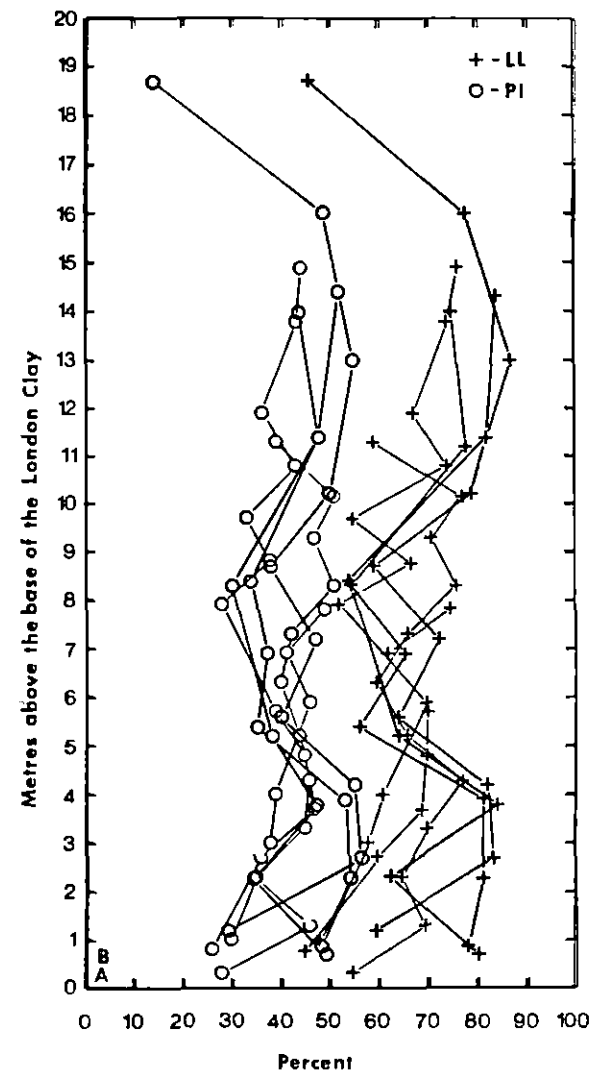
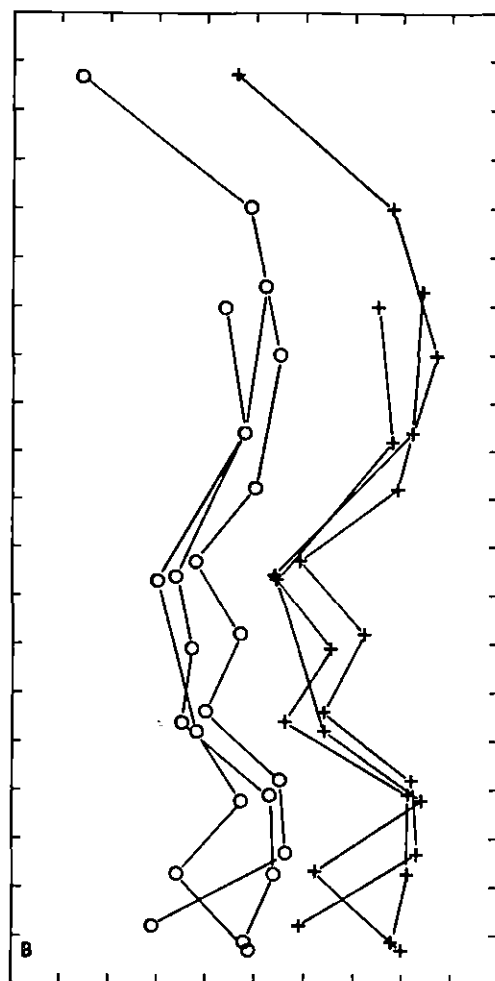
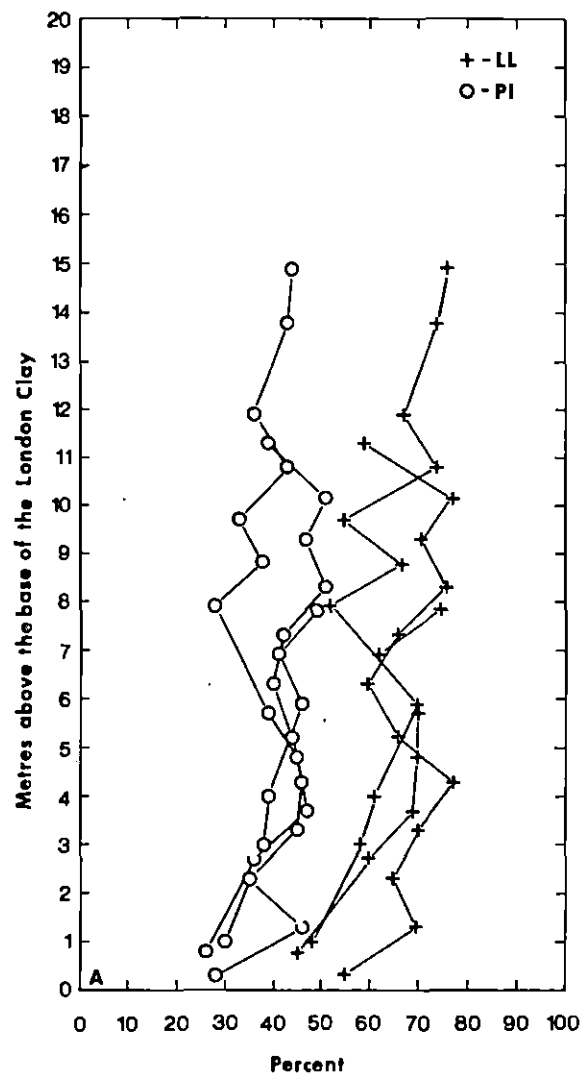


Figure 46 Liquid limit (LL) and plasticity index (PI) for the London Clay plotted against metres above its stratigraphic base for two sites; A - in the west (3010 on fig. 44, and B - in the east (1038)

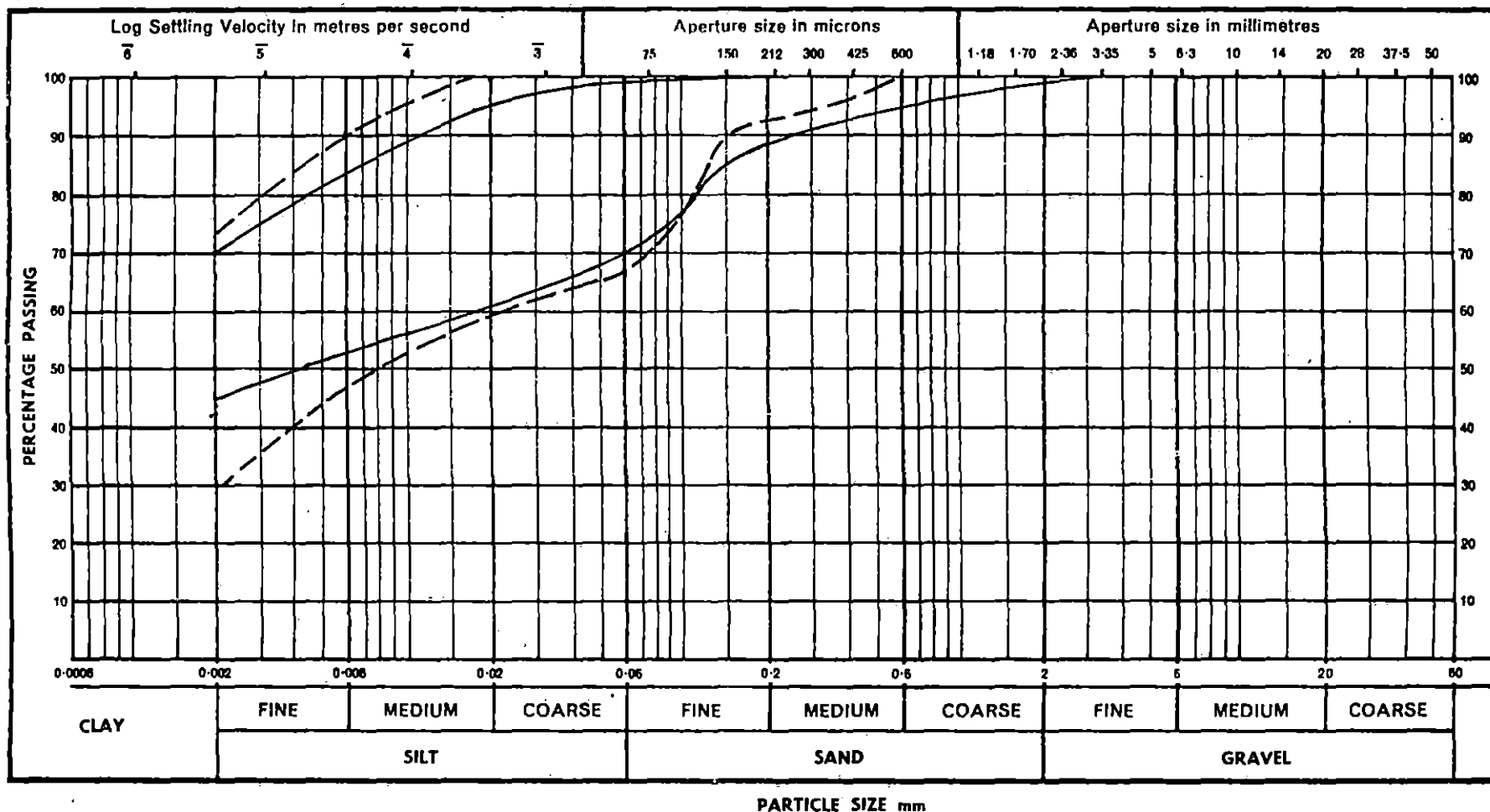


Figure 47 Grading envelope for the London Clay
 ————— Jubilee Line investigation (Wimpey 1977), based on 14 samples
 - - - - - Limehouse area (Soils Engineering 1988), based on 68 samples

Parameter	Reported Values Range	Majority or standard deviation	Ave	Source	Remarks
Mineralogy					
montmorillonite	25 - 30			)	Based on regional trend of the London Clay
illite	25 - 30			) 1	
kaolinite	10 - 15			)	
SiO ₂	20 - 25			)	
Specific gravity			2.70 2.69	2 1	Based on mineralogy
Bulk density (Mg/m ³)	natural:wet 1.96 - 2.19 1.96 - 2.20	0.21 0.08	1.99 2.04	3 4	Royal Victoria Dock; based on 30 samples Limehouse; based on 9 samples
	natural:dry 1.48 - 1.89 1.52 - 1.88	0.19 0.11	1.51 1.62 1.66	1 3 4	Based on a regional study of the London Clay Royal Victoria Dock; based on 30 samples Limehouse; based on 9 samples
Moisture content (%)	17 - 32 11 - 34	6.9 15 - 35	21.2	3 4	Royal Victoria Dock; based on 39 samples Limehouse area; see also fig 6.10
Liquid Limit (%) (see also fig 6.10)	28 - 84 54 - 90	16.7	80 66.4	1 3 5	Based on a regional study of the London Clay Royal Victoria Dock; based on 24 samples Jubilee Line.
Plasticity Index (%) (see also fig 6.10)	5 - 57 33 - 63	13.5	48 37.3	1 3 5	Based on a regional study of the London Clay Royal Victoria Dock; based on 24 samples Jubilee Line.
Particle size distribution (%)					
a. clay <0.002mm	45 - 70			)	Jubilee Line. See also fig 47
b. silt 0.002 - 0.06mm	25 - 29			)	
c. sand:fine 0.06 - 0.2mm	1 - 18			) 5	
d. : med 0.2 - 0.6mm	0 - 7			)	
e. : coarse >0.6mm	0 - 5			)	
Undrained shear strength (kN/m ²)	25 - 258 30 - 260	47.3	153.6 cu = 25+10z cu = f ₁ × N	3 4 6	Royal Victoria Dock; based on 34 samples Limehouse area; design curve for increase in strength with depth, z below top of LC As correlated with SPI blow count N and where f ₁ varies from 4.5 to 5.0 for a PI of 40-60% and reduces to 5.5 for a PI of 25%
Drained shear strength (c' = kN/m ² ; φ' = degrees)			c' = 14) φ' = 29)	4	Limehouse area
Modulus of elasticity (MN/m ²)	a. drained, E'		= 30 + 5z = 0.55 × N = 0.65 × cu	4 6	Limehouse area, where z is depth below top of LC As correlated with SPI blow count assumed
Poissons ratio			0.1	6	assumed
Compressibility (kN/m ²)			= 1/(440×N) = 1/(100×cu)	6 6	As correlated with SPI blow count, N By implication from a correlation with blow count

Source: 1 - Burnett and Fookes 1974; 2 - Mason & Berry 1968; 3 - Soils Engineering 1985; 4 - Soils Engineering 1988
5 - Wimpey 1985; 6 - Stroud & Butler 1975

Table 8. Geotechnical data sheet for the London Clay

of the area this is not the case in the east. In the east the decrease appears to be most marked in a zone between five and nine metres above the base of the London Clay. Also the plot suggests that the east is, overall, somewhat more plastic than the area to the west. What is also interesting is the strong parallelism between the liquid limit and the plasticity index from any individual borehole.

Burnett and Fookes suggest the dry density of the London Clay in the Docklands to be about 1.51 Mg m^{-3} and give evidence to show that as the sand content increases so does the dry density. Tests results actually show a somewhat, greater dry density at about 1.65 Mg m^{-3} (Table 8). There is also an indication that the results from the east are greater by about 3% than those in the west. This, together with the reduction in plasticity postulated above, may reflect a greater quartz content towards the west and would be in keeping with the source area of the Formation being towards the west.

Although an attempt to provide a regional trend for the undrained shear strength was attempted by Burnett and Fookes they correctly recognized that it is not a true index property and that the absolute value will be influenced on the local scale by a variety of factors. Skempton (1957) showed that the undrained shear strength of a clay soil to increase in direct proportion to its depth of burial as the contained pore water is squeezed out as consolidation takes place under its own self-weight. Where very high consolidation pressures exist and the material is geologically old then its strength will also be affected by the orientation of the particles, by physical and chemical bonds which develop in the adsorbed layers around the clay particles and lastly by intergranular cements due to the precipitation or re-crystallization of a variety of minerals. Skempton (1970) suggests that the London Clay has been consolidated by a load of 3400 kN m^{-2} or about 340m of overburden which has since been substantially removed by erosion. Assuming the relationship developed by Skempton (1957) between plasticity index and the rate of increase in undrained shear strength, the strength following

consolidation under 340m of sediment can be expected to be 885 kN m². This is a rate of increase of approximately 25 kN m² per 10m of burial. Therefore if the strength increase is irreversible once the overburden is removed there would be only a nominal change in strength in clay over the depths of interest for most engineering schemes. However, this is not found to be the case and plots of undrained shear strength against depth for most overconsolidated clays usually show a more marked rate of increase in shear strength, particularly in the upper levels. In the initial few metres it will often drop to strengths of 30 to 50 kN m². This is largely because at the former depths of burial of the London Clay, many of the changes to which it was subjected are, to some extent, reversible. The modifying influence following weathering of the London Clay occurs from its erosion level and although most marked in the upper ten or twenty metres can affect the strengths to considerable depth. The undrained shear strength must, therefore, be considered as independent of stratigraphic position. The actual scatter of strength results from any investigation is usually so great however, that the appropriate design line is somewhat arbitrary and may be influenced by the design approach for which it is assessed. Gibb (1988) have assessed a relationship for the undrained shear strength, c_u in the Limehouse area based on laboratory test results. They give two plots for data within and data from outside the Limehouse Basin. The "best-fit" line through both sets show similar gradients for the increase in strength with depth but have a different intercept due to the truncation of the London Clay in the Basin area as it was excavated in historical times.

As the shear strength is governed largely by the weathering profile and overrides any correlation with stratigraphic position in the London Clay, for the general case the shear strength c_u at any depth z may be taken as:-

$$c_u = 25 + 10z \text{ kN m}^{-2}$$

Stroud and Butler (1975) have shown that the shear strength can also be correlated with the blow count N , from the standard penetration test where;

$$c_u = f_1 \times N \text{ kN m}^{-2}$$

They demonstrates that f_1 varies with plasticity index and that for London Clay with a plasticity index of 40 to 60% it is in the range of 4.5 to 5.0 and increases to 5.5 for a plasticity of 25%.

6.6 Thames Gravels

Thames Gravels is a collective name for the major tract of Pleistocene gravels which characterize the middle and lower Thames Valley. Although they have a complex sedimentary history, comprise more than one depositional event and form a number of terrace structures, they are usually considered to have sufficient consistency to make detailed separation unnecessary for most engineering purposes.

It has been described in Chapter Three that the Thames Gravels are marked by a distinct basal contact which forms a major overstepping unconformity with the various units of the solid geology. The basal surface is relatively planar across the valley and on a regional scale dips gently to the east. However, it undulates considerably in detail and although distinctive erosion channels are not present a number of closed hollows and mounds do exist.

In contrast the upper surface is somewhat more diffuse. It is usually shown on borehole records to have an equally marked junction with the overlying alluvium but on inspection of open sections appears to fine rapidly upwards to a sand such that there is a gradational contact between the gravels and the alluvium. There may also be a general coarsening downwards in the gravels which is most

marked over the basal levels by a reduction in the fines content. However, the depositional history is sufficiently complex that this generalization is subject to considerable variation.

The gravels are made up predominantly of siliceous materials comprising flints from the Chalk and cherts and some quartzites from older rocks. Some limestone is found and this appears to be concentrated in bands, most noticeably, but not always found along the basal contact. The siliceous material is usually subangular to subrounded in shape but can range from angular to well rounded. In contrast the limestone, which although softer than the siliceous material, is usually subangular and often tabular in shape. Very occasionally the gravels are found to be cemented with an iron oxide.

Although there is likely to be a significant segregation and sedimentological structure in the gravels the sampling process used during borehole investigations for civil engineering purposes destroys this on all but a coarse scale. Grading analyses of such samples show a well graded material which characteristically ranges from fine sand to coarse gravel and occasionally up to cobble size (fig. 48). Only rarely is any clay found in the gravels and when it is it is usually as a distinct band or lens.

The condition of the gravels is most readily assessed by the standard penetration test which shows a wide range of results. The results are generally found to be in the medium dense range but locally decrease to loose or even very loose (fig. 49). A generalized blow count of perhaps 20 can be adopted for much of the area which indicates a drained friction angle ϕ' of 33 degrees following the relationship of Peck et al (1967). However, there is variation in the condition of the gravels. Although the higher blow counts may be influenced by the presence of cobbles, some areas show consistently lower blow counts such that the generalized blow count should be decreased to 15 with a reduction in friction angle to 32 degrees. Locally the blow counts can reduce to less than 10 indicating a very loose condition.

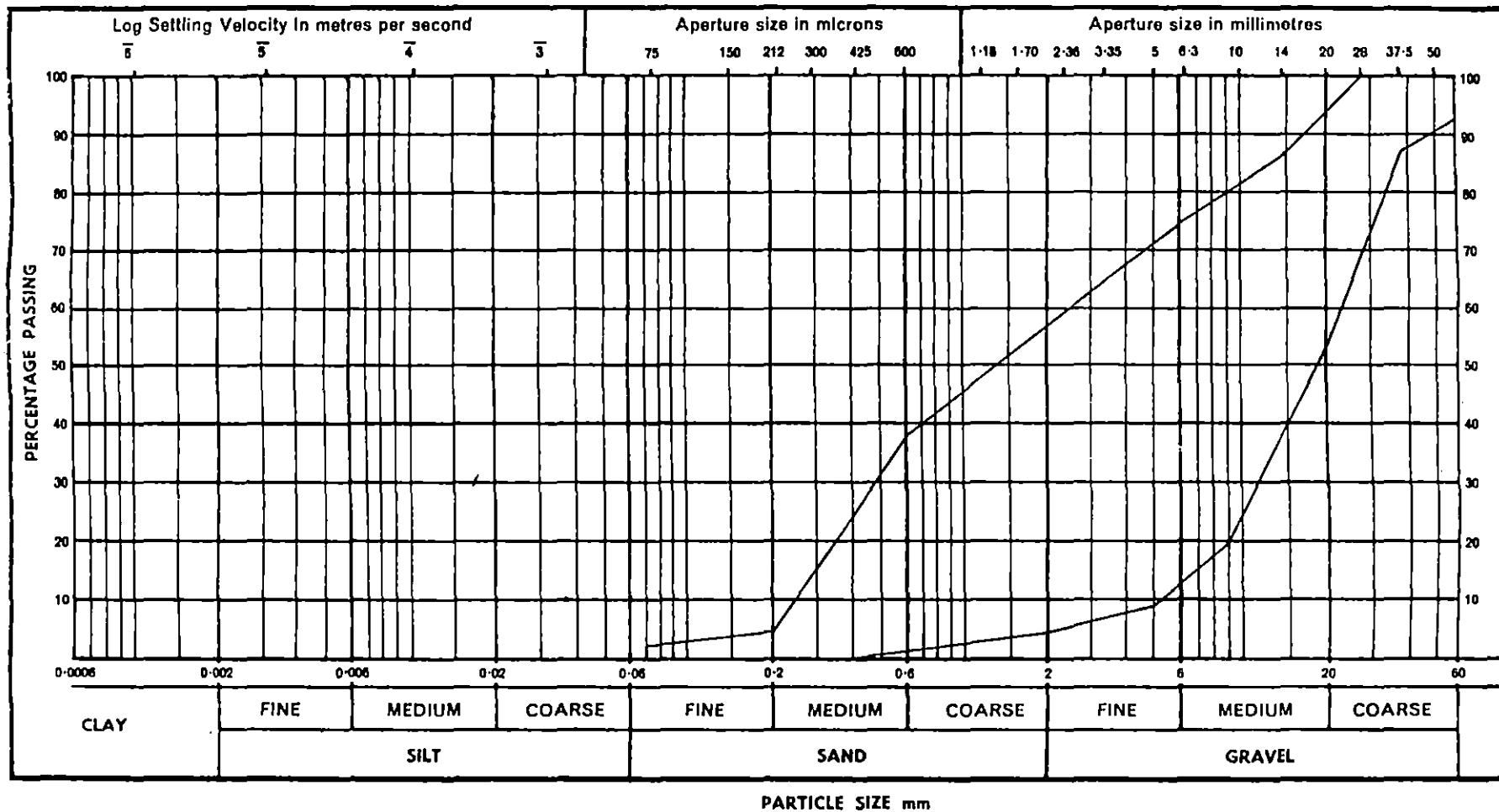


Figure 48. Grading envelope for the Thames Gravels

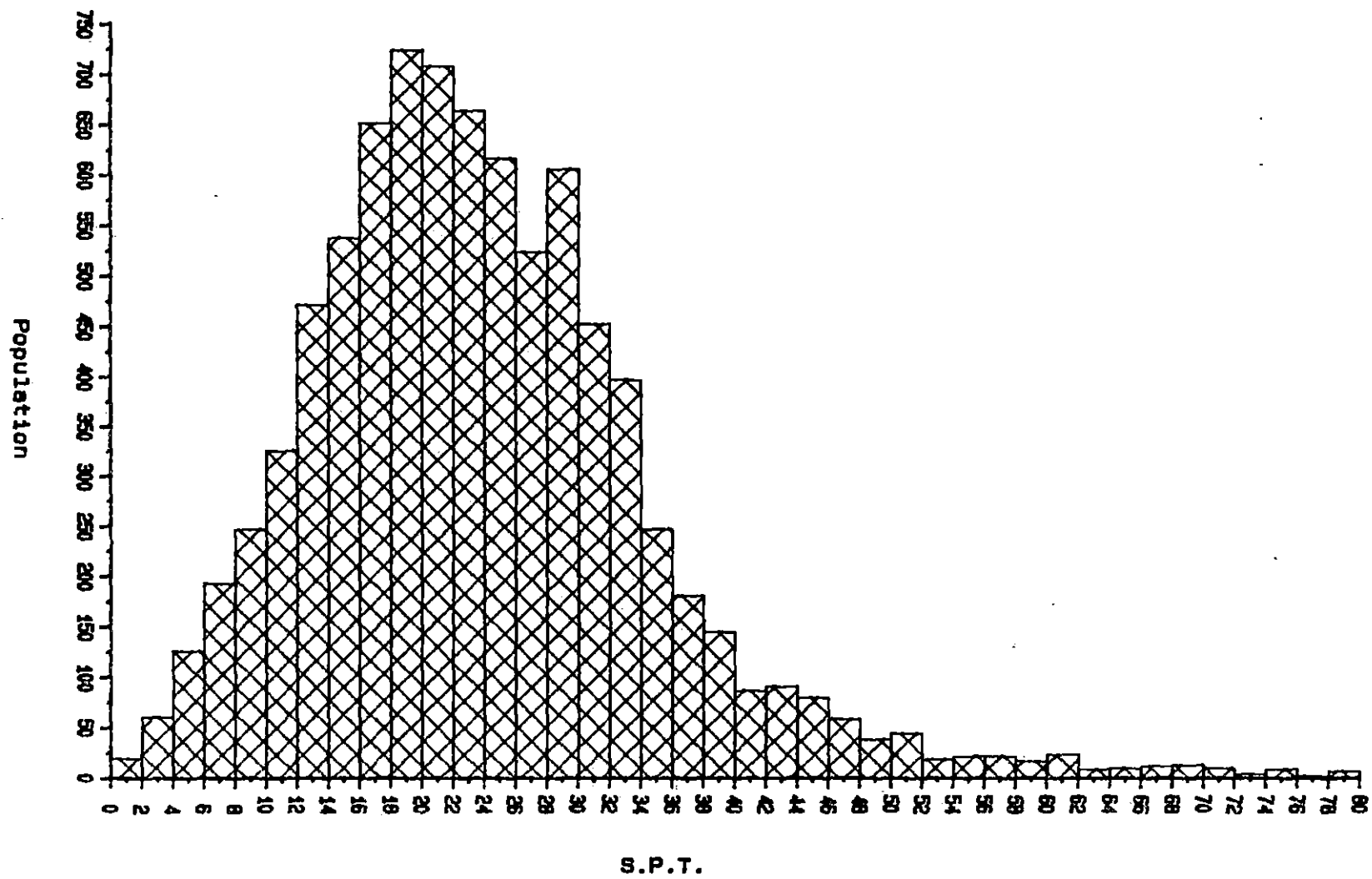


Figure 49 SPT blow count 'N' for the Thames Gravels from the total docklands area

The permeability of the gravels is controlled by the precise grading and sedimentological structure of the gravels. The relationship developed by Hazen (1894) between the effective grain size (D_{10}) and the permeability suggests a value of $2.5 \times 10^{-3} \text{ m sec}^{-1}$ if D_{10} is 0.5mm. The results of in situ tests often show a significant range with the most reliable results tending to confirm the Hazen relationship and suggesting values of 10^{-3} to $10^{-4} \text{ m sec}^{-1}$.

6.7 Alluvium

The alluvium can be divided conveniently into two principal divisions, a distinctive group of peats and a more varied group of clays and silty clays with a varying organic content and often with contained peaty inclusions. The present condition and distribution of the alluvium has been affected greatly by the development of the area. In places it has been surcharged by the placement of considerable thicknesses of made ground. Elsewhere, it has been partly or completely excavated. During this study it was only in the Beckton area that the alluvium approached its natural condition. However, this area has now been largely developed with housing estates.

The alluvial clays are generally in a soft to firm condition and have been described locally to be in a stiff condition, indicating that some desiccation has taken place. However, the liquidity index is usually greater than zero indicating that the natural moisture content is greater than its plastic limit and therefore consistent with a soft consistency. The undrained shear strength is seen to lie mainly in the range 10 to 45 kN m^{-2} , but with the major part of that falling between 15 and 30 kN m^{-2} (fig. 50). Natural moisture contents range from 20 to 80% with an average of about 50% (fig 51). Interestingly, there appears to be no correlation between undrained

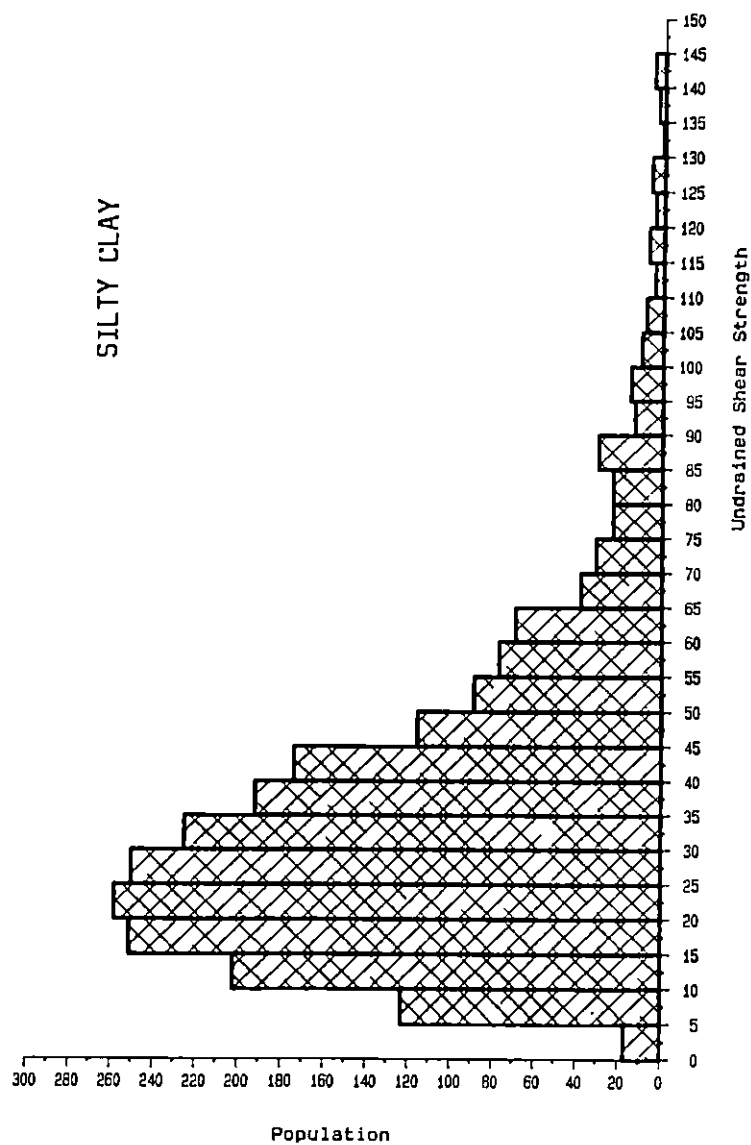
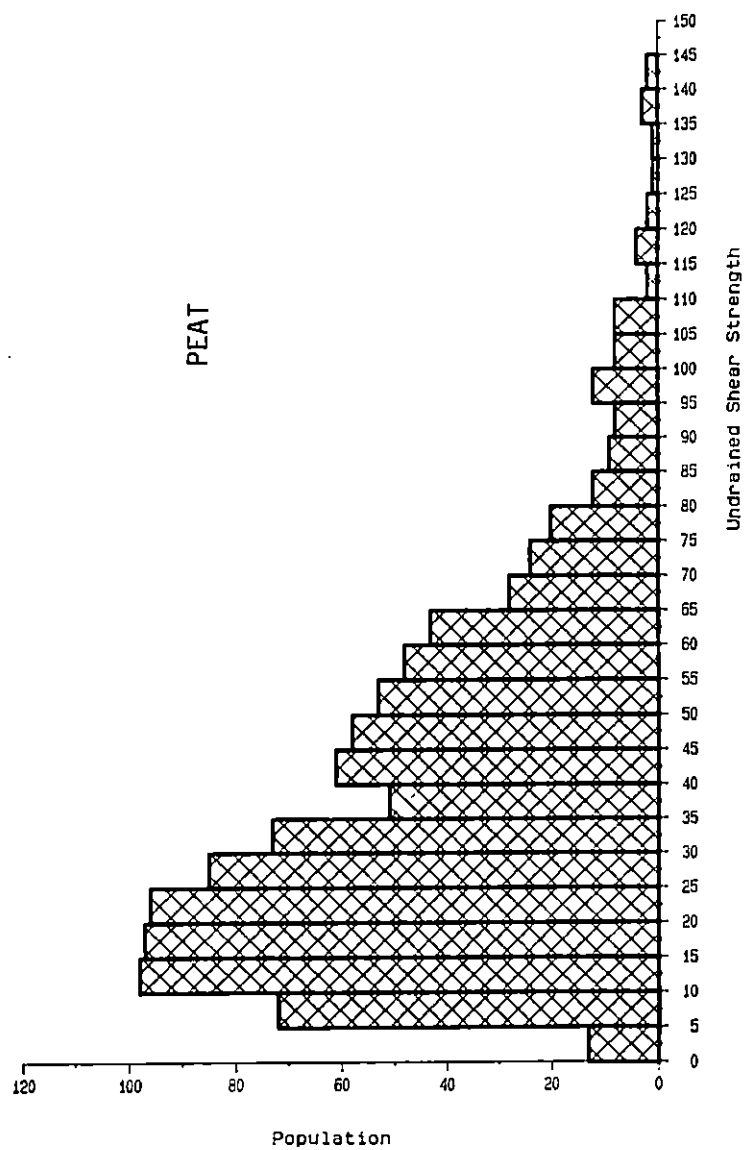


Figure 50.
Undrained shear strength for the alluvium
from the total docklands area for the
peat and silty clay facies

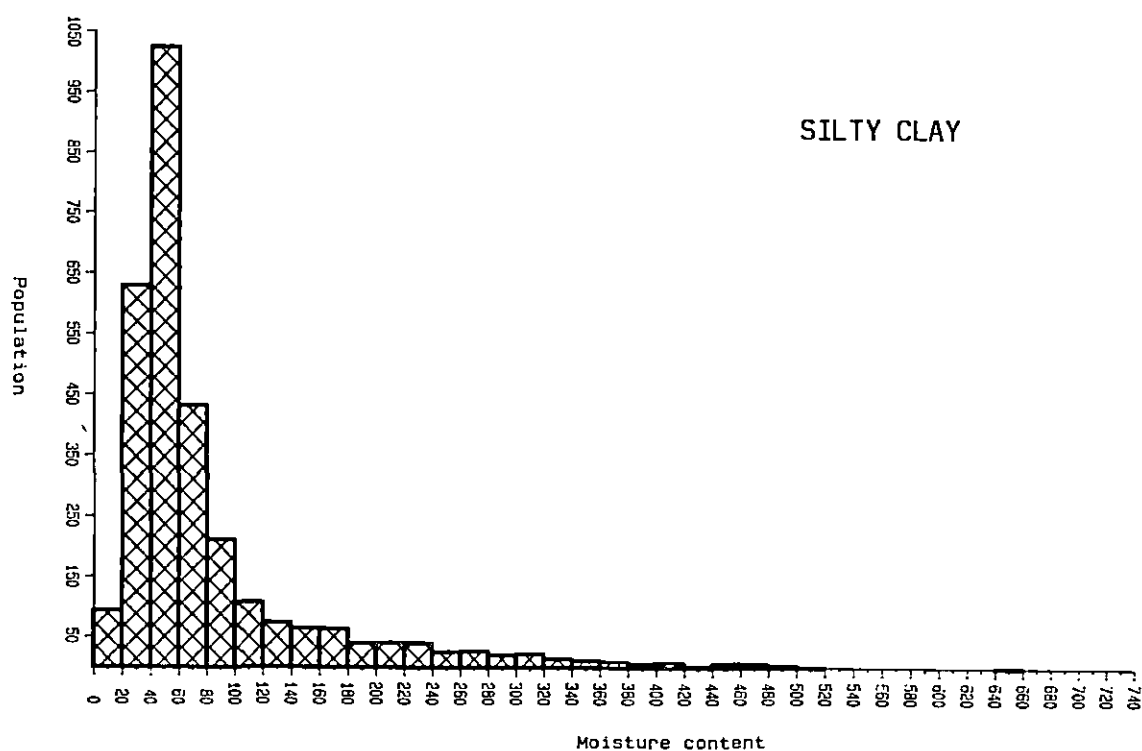
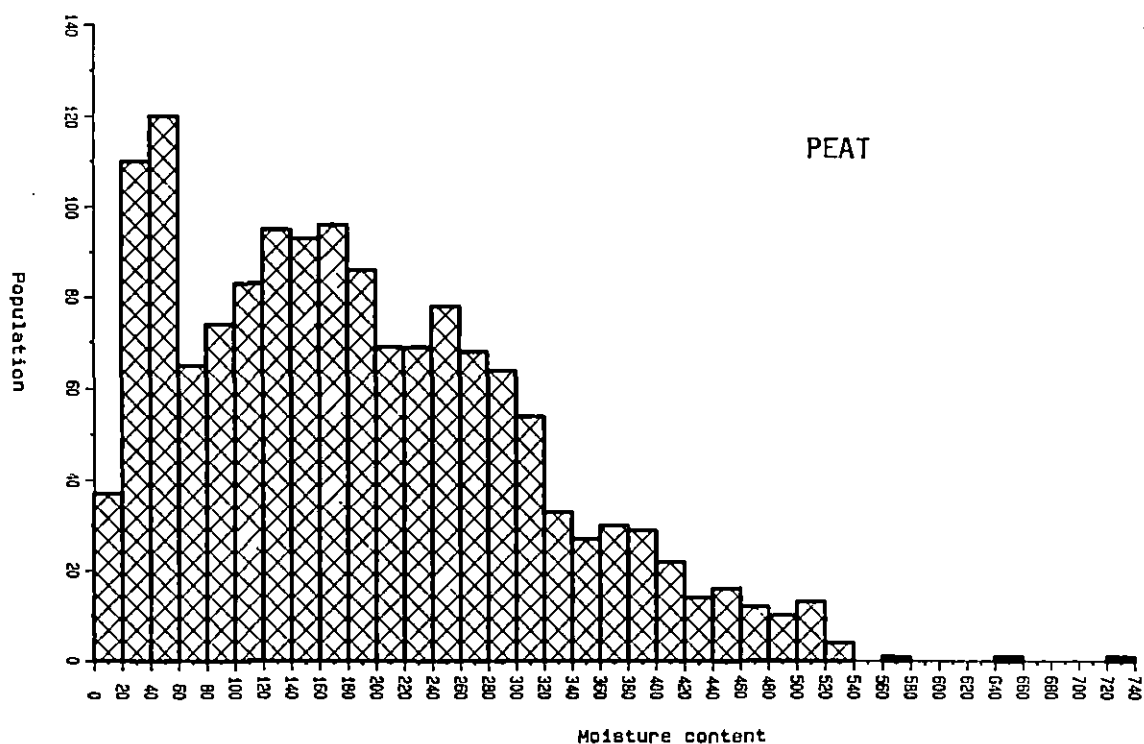


Figure 51.

Moisture content for the alluvium from
the total docklands area for the
peat and silty clay facies

shear strength and moisture content (fig. 52). Bulk density determinations (fig. 53) show a bimodal distribution across the ranges of 1.0 to 1.3 Mg m^{-3} and 1.6 to 1.8 Mg m^{-3} . These are expected to be due to the control of the clay or peat dominant material in the specimens and can be compared to the bulk density determinations of the peat which show the identical trend but with the opposite dominance (fig. 53). Moisture content is intimately related to the bulk density as shown on figure 54 through the relationship;

$$\gamma_b = \frac{W_s}{V} (1 + m)$$

Atterberg limit determinations generally fall around the 'A' line showing a wide range in plasticity from low to very high (fig. 55). The peats can be compared with the silty clays to show a striking similarity of trend and value as has been found to be the case by Hobbs (1986) working on a wide variety of British and foreign peats.

The undrained shear strength of the peats shows a somewhat greater range than the clays from 5 to 65 kN m^{-2} but with a slightly lower modal strength of 10 to 25 kN m^{-2} (fig. 50). This similarity is surprising when the moisture contents are compared (fig. 51). Although the overall range in results is the same the bimodal distribution and dominance of the high moisture contents is evident. It is clear that there is an overlapping suite of materials showing the moisture content characteristics of the silty clays while the peats proper are able to sustain moisture contents between 100 and 300% with a modal figure of about 150% . However, undrained shear strength is similarly unrelated to moisture content in the peats as well as the silty clays (fig. 52).

The bimodal character of the bulk density determinations supports the view that a suite of silty clay material is present in the peat data and vice versa (fig. 53).

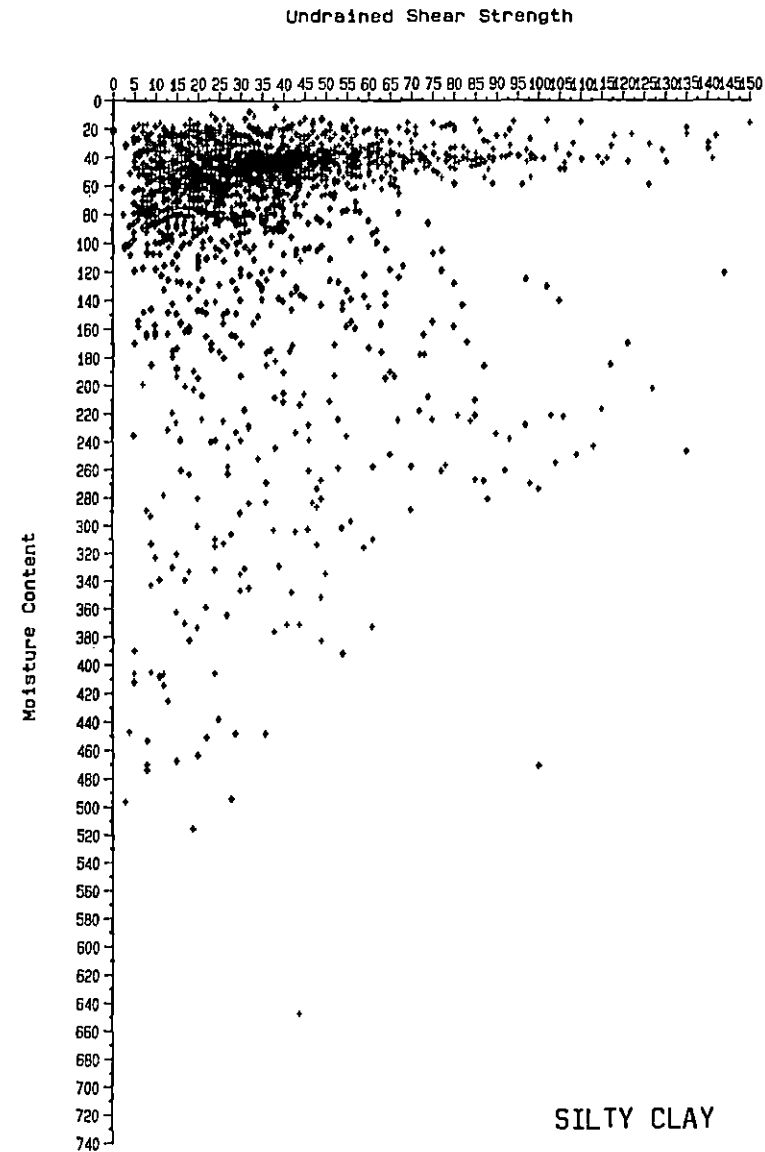
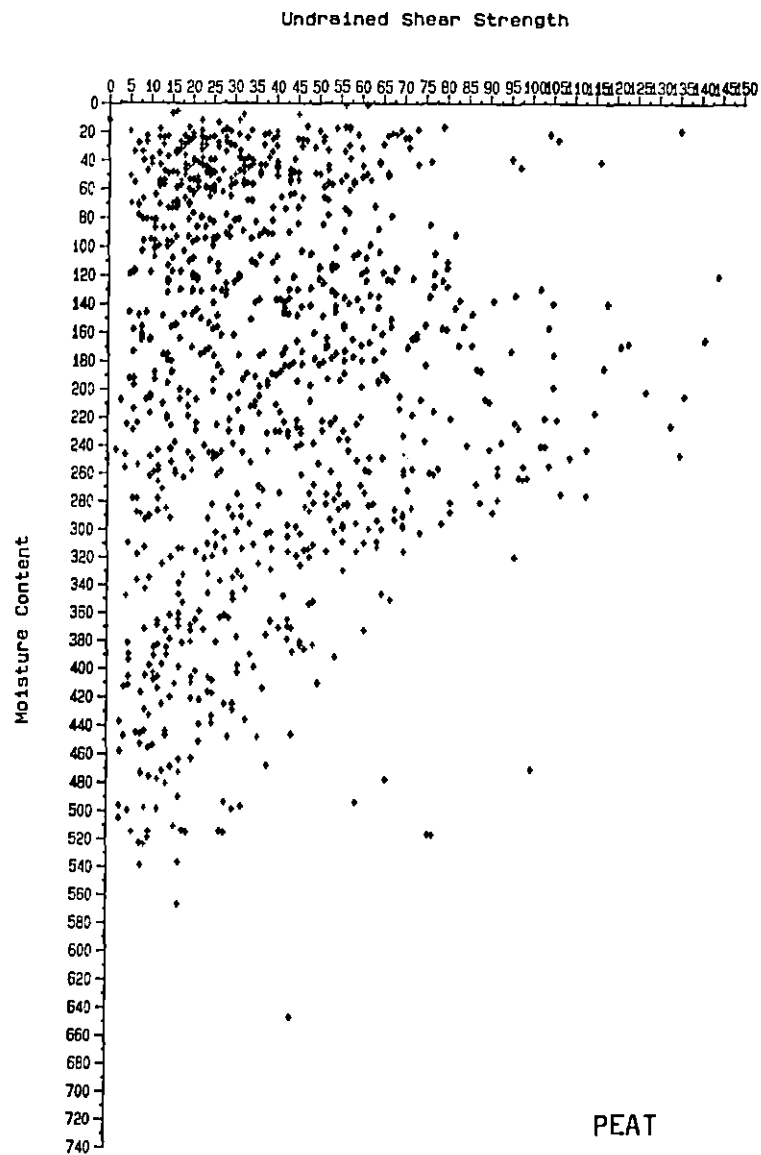


Figure 52.

Undrained shear strength versus moisture content for the alluvium for the total docklands area for the peat and silty clay facies

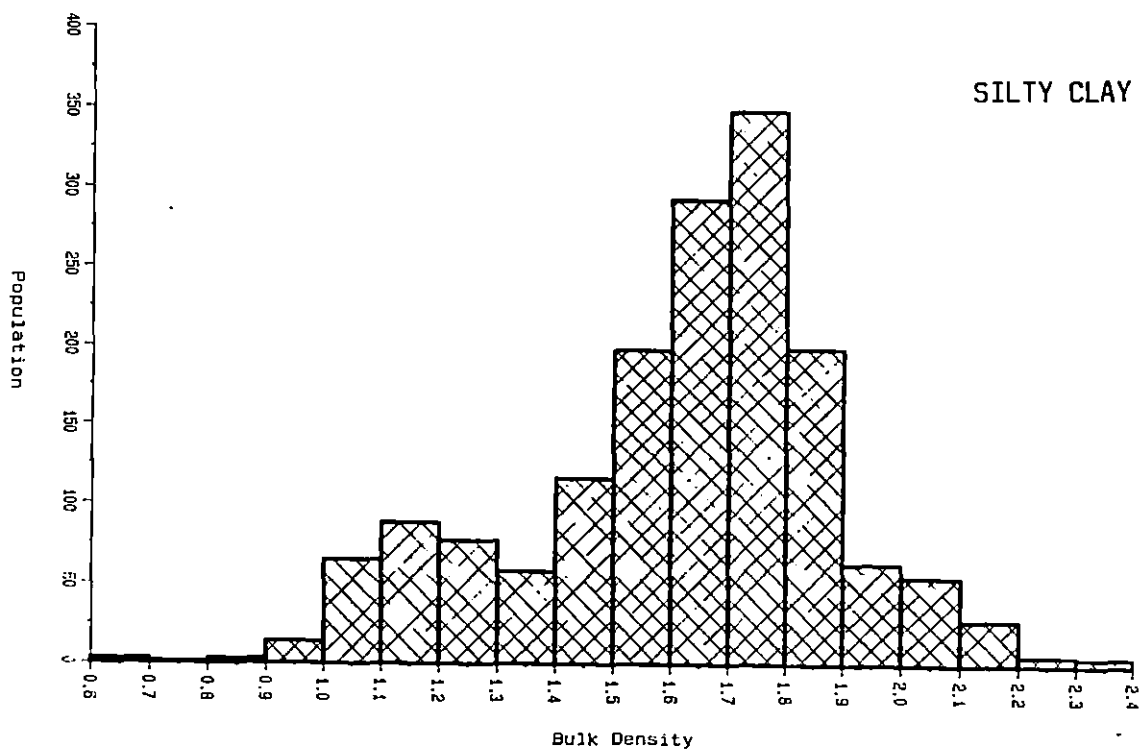
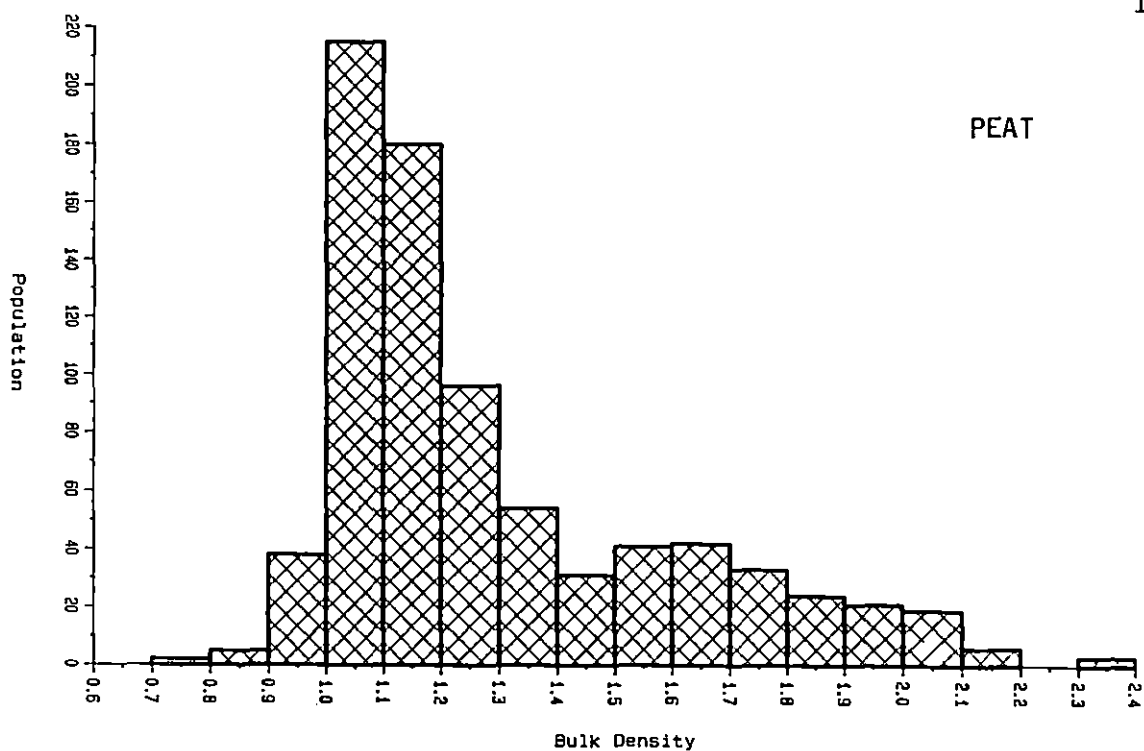


Figure 53. Bulk density for the alluvium from the total Docklands area for the peat and clay racies

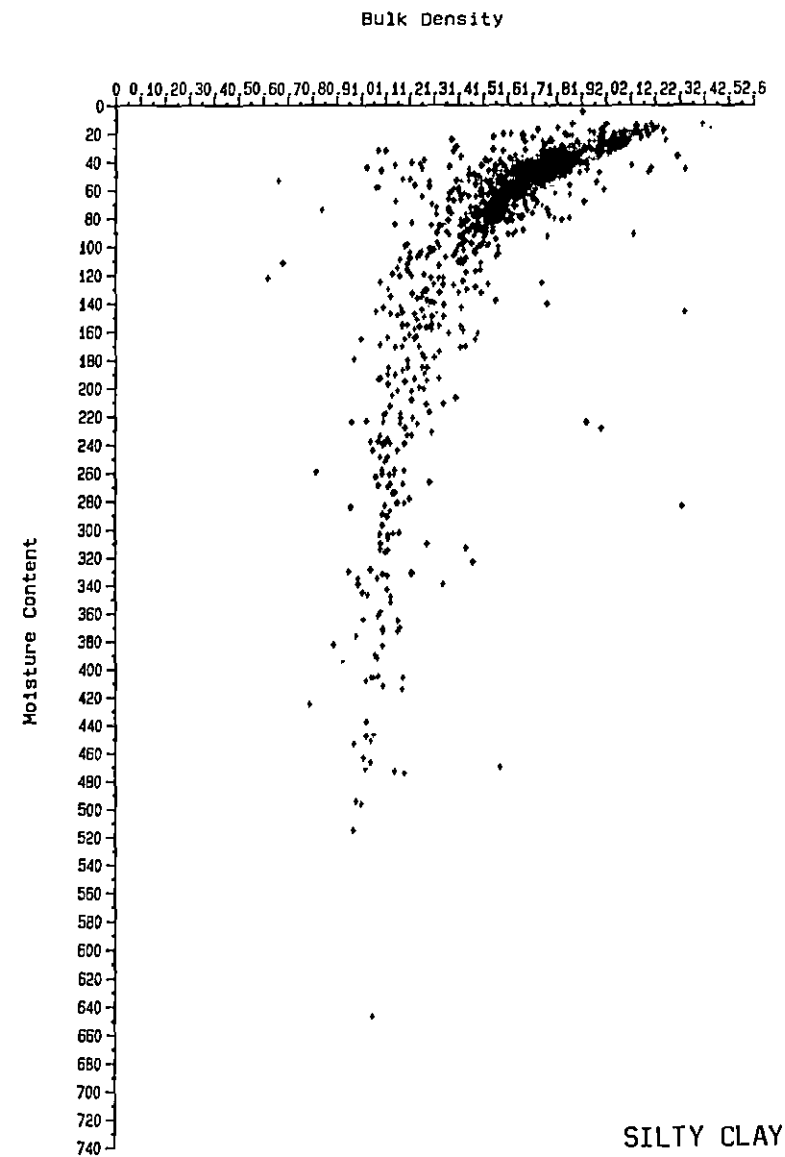
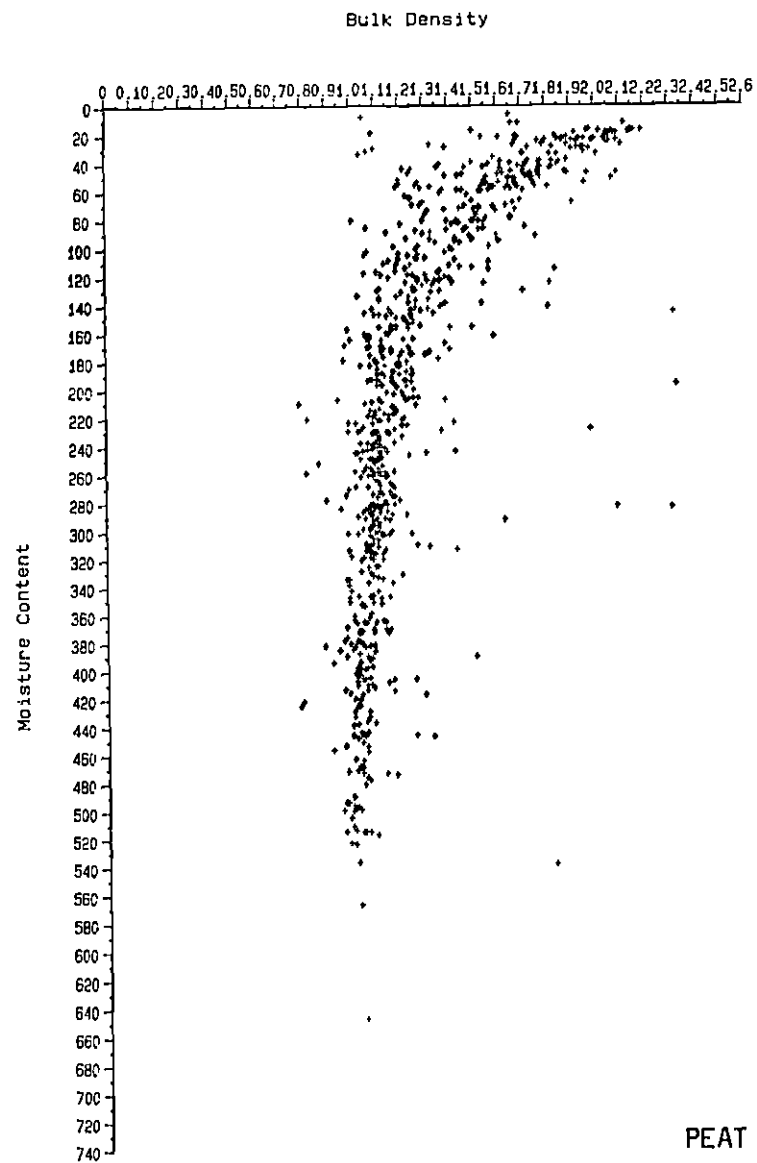


Figure 54.

Bulk density versus moisture content for the alluvium from the total docklands area for the peat and silty clay facies

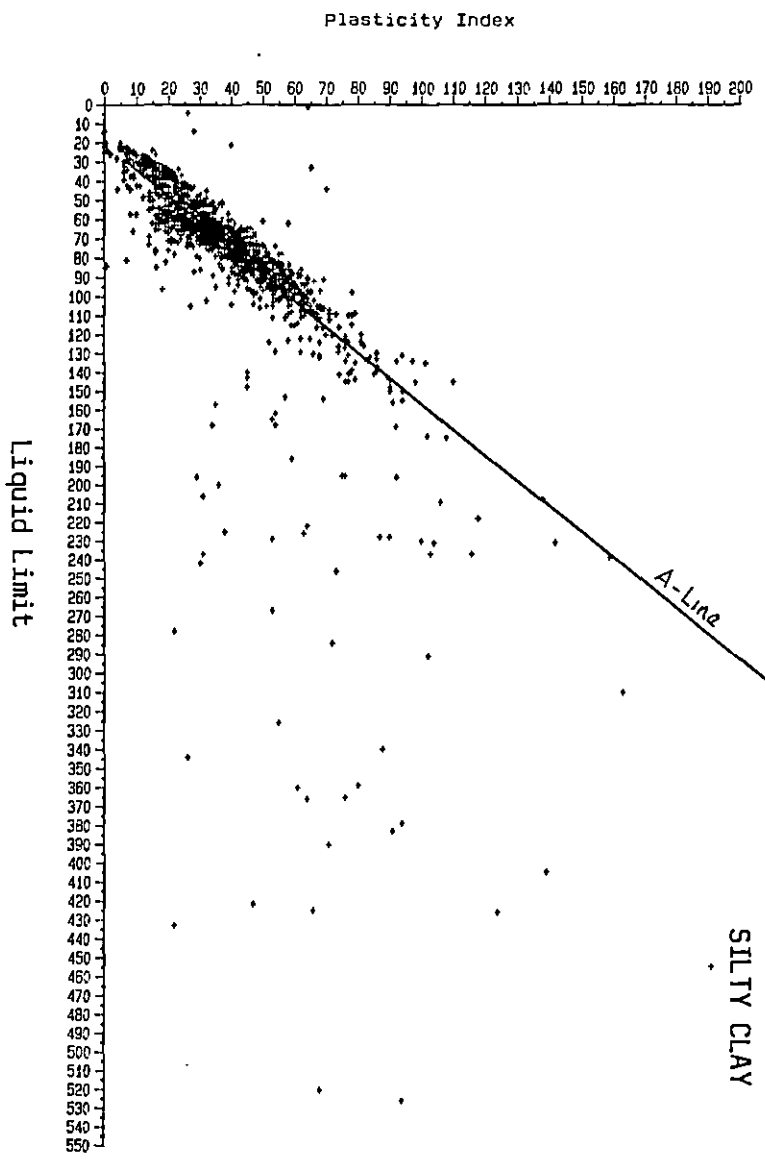
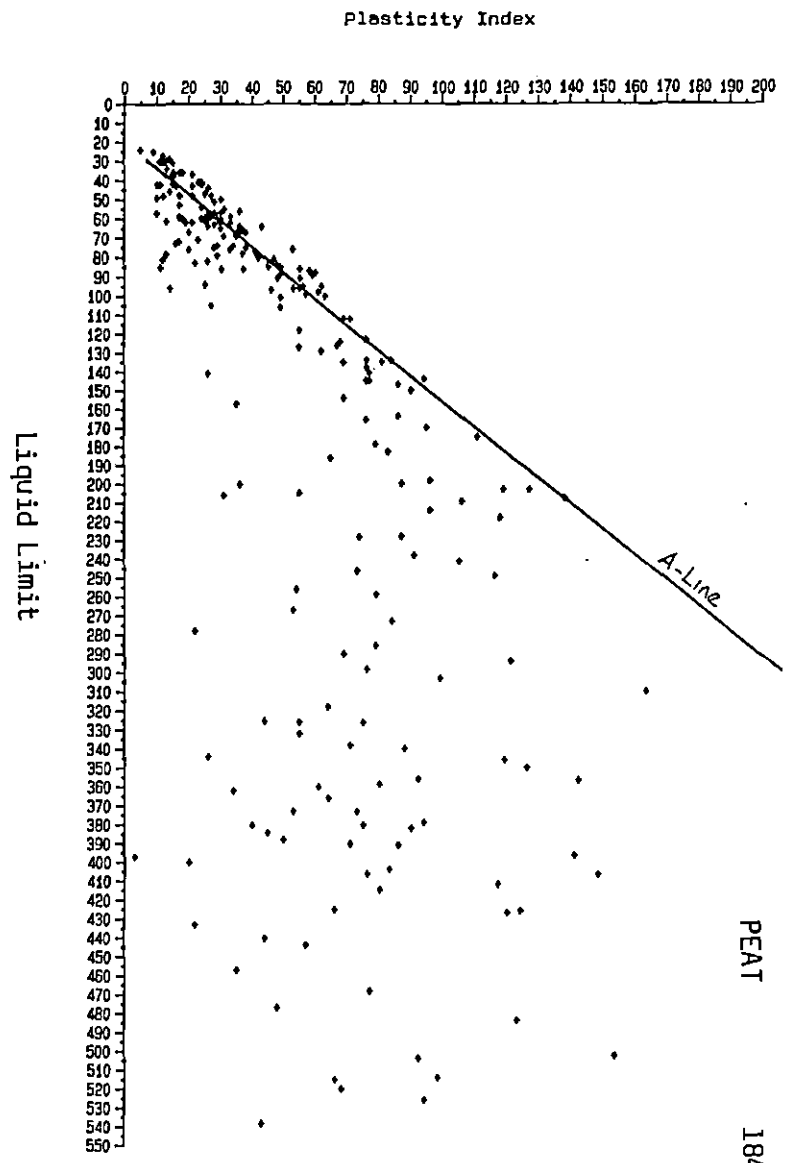


Figure 55. A-line plot for the aluvium from the total docklands area from the peat and silty clay facies



The distribution of the bulk density against moisture content is identical for the peats and the silty clays (fig. 54). However since this is also a function of the specific gravity of the solid particles this should clearly not be the case since the specific gravity of the inert clay minerals would be about twice that of the vegetable matter of the peat. It is probable that this has arisen because specific gravity has been assumed automatically in the testing laboratories to be 2.69, or thereabouts regardless of the character of the solid materials.

6.8 Made Ground

Made ground covers much of the area of the Docklands. It varies in thickness from less than a metre to more than ten metres but is most commonly between two and three metres. Over much of the area it comprises a diverse cover of sands, gravels and clays derived from the excavation of the docks together with demolition rubble and waste materials from the activities of former development. A number of docks and related structures have also been infilled to varying standards ranging from unregulated end tipping to controlled placement and compaction. Rarely have the substructures of former developments been removed so buried structures and services are also present.

The inherent character of made ground is such that it is the most randomly variable of the deposits in the area. Extrapolation between sample points, even on the small scale, should be made only with extreme caution. It should be expected to vary both in content and condition as well as in thickness. The presence of hard spots will aggravate the potential for differential behaviour under load while some of the more recently placed material is also likely to be experiencing self-weight consolidation for some time.

Although the content of the made ground can consist of granular materials on the one hand or clays on the other, it is most commonly described as having a wide grading. This suggests that it has undergone a fair degree of mixing during placement. Nonetheless, sections through the made ground only confirm its random nature often showing an uncontrolled variation of soil types and conditions.

Depending on whether it has a predominant cohesive or noncohesive nature the material condition is assessed by standard penetration tests or by triaxial compressive tests. A review of the reported SPT and undrained shear strength results for the total area shows that, as a generalization, the made ground can be expected to be in poor condition (fig. 56). The results of the standard penetration test classify it as in a loose or very loose condition with the majority of test results falling into the range of 2 to 10. Similarly the undrained shear strengths classify it mainly as a soft or very soft material with the majority of test results in the range 5 to 40 kN m⁻².

6.9 Chemical Pollution

6.9.1 Introduction

The previous use of much of the land within Docklands for industrial purposes means that it should be regarded as potentially contaminated by chemical pollution unless shown to be otherwise. The effects of industrial contamination are usually permanent or at least very long lived so that even where no evidence of the original cause of the contamination remains the problem can be sufficiently severe that there may be an immediate or long-term hazard to human health, to vegetation or construction materials.

Sites may be considered as polluted when the presence of toxic or other harmful products is sufficient to pose a threat to the health

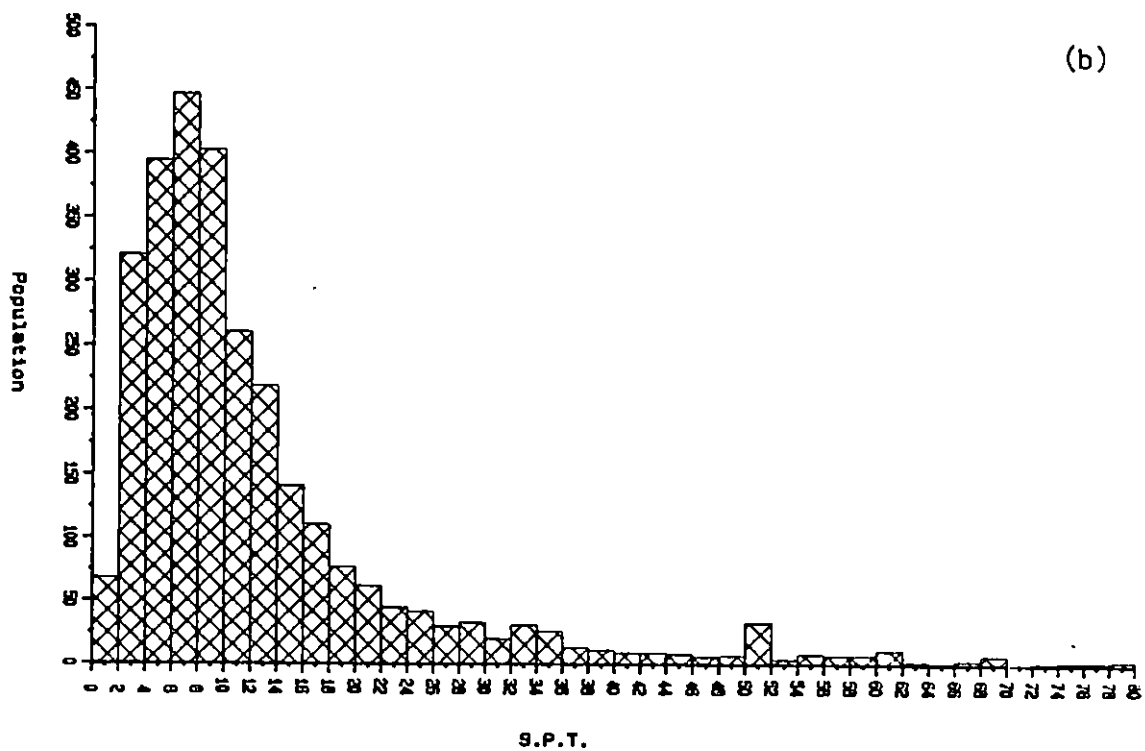
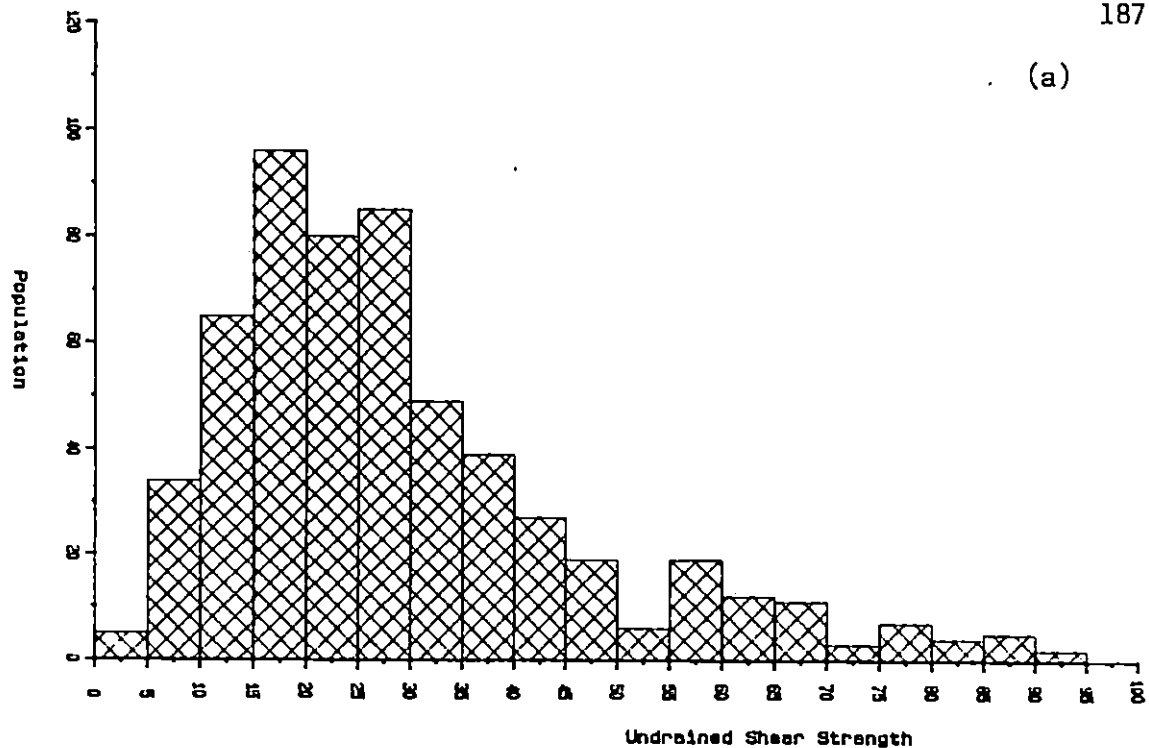


Figure 56. (a) undrained shear strength and
(b) SPT blow count 'N' for the made
ground from the total docklands area

of construction workers, end-users, or the public at large. This is extended to include a hazard to the healthy development of vegetation on the site or the likelihood that construction materials will be adversely affected.

The source of the contamination is invariably related to man's activities and can arise from a variety of causes. Spillage or leakage can often occur. This happens not only when tanks or storage vessels are broken, but can also develop from leachates or distillates from stockpiles of raw materials, from random spillages during the transport of liquids or solid materials, from airborne particles from dry stockpiles or chimney exhausts and by the legal or illegal disposal of waste or unwanted products. Very often the made ground within areas of intense industrial activity is derived from waste from its own processes.

6.9.2 Sources of contamination

The source of contamination can be varied but is generally related to man's activities. It can result from such activities carried out on the site or at some distance from it. The pollutants may originate from a variety of causes;-

- leakages or spillages:
 - from damaged plant and storage tanks
 - from leachates and distillates from stock piles of raw materials
 - during transport of materials
- airborne dust:
 - from dry stockpiles
 - chimney exhausts
 - from the burning of materials
- disposal of waste and by-products:
 - on-site
 - intentionally imported from a remote site for disposal

- unintentionally imported with
general fill
- illegally imported by 'fly-tipping'
- natural migration:
 - as a liquid or gaseous phase
 - in solution or suspension in
groundwater

The situation is further aggravated because in addition to the known on-site activities and the influence of other activities away from the site there is also the possibility of ad hoc contamination from illegal or non-documented activities.

Most of the industrial and manufacturing activities carried out in the Docklands over the past 100 years or so produced contaminated materials. Indeed, the attraction of such activities was largely because of its geographical setting. The low lying area had been unattractive to other urban developments and allowed the growth of processing and manufacturing plants requiring the easy transport of materials by water.

6.9.3 The assessment of chemical contamination

In order to assess the site for contamination it is necessary to analyse and determine the concentration of a number of a possible contaminants. The range of potential contaminants is clearly very large, but an appropriate suite can often be established from the findings of an initial archive study to establish the former use of the site and its neighbouring areas.

Although the toxicity of a wide range of chemical substances is known and various standards exist for safe levels in drinking water little comparable information is available for the acceptable levels in soils. A classification used by the former Greater London Council

can be used to indicate the ranges of contamination for various substances found in the London area (Kelly 1979), (table 9).

Reference to this provides a good qualitative assessment of the level of contamination but does not relate this to a measure of the harmful effects. Therefore, in order to consider the need for any remedial or preventative measures the results must also be compared to the tentative guideline figures produced by the Inter-departmental Committee on the Redevelopment of Contaminated Land (Anon 1987). These indicate trigger values for certain categories of end-use above which levels of contamination should be regarded as possibly needing treatment (table 10).

It is clear that there will be a significant uncertainty in the completeness of the background picture produced from an archive study because it is possible to overlook factors that may not be related to the recorded past activities at the site. In a full assessment it is therefore necessary to consider the potential or real presence of the following groups of materials:-

- Heavy metals
- Gasworks wastes
- Other industrial wastes
- Oils
- Pathogens and carcinogens
- Combustible and methanogenic materials
- Toxic and combustible or explosive gases
- Toxic corrosive and aggressive chemicals

6.9.4 Remedial and preventative measures

Any recommendations can only sensibly contain a consideration of the site with respect to the chemical and environmental hazards indicated by the results of the samples taken for analysis. Nonetheless, the inherent character of contaminated sites is such that random features

	Uncontam- inated	Slight contam- ination	Contam- inated	Heavy contam- ination	Unusually heavy contam- ation
pH (acid)	6-7	5-6	4-5	2-4	2
pH (alkali)	7-8	8-9	9-10	10-12	12
Arsenic	0-30	30-50	50-100	100-500	500
Cadmium	0-1	1-3	3-10	10-50	50
Chromium	0-100	100-200	200-500	500-2500	2500
Copper (avail)	0-100	100-200	200-500	500-2500	2500
Lead	0-500	500-1000	1000-2000	2000-1.0%	1.0%
Lead (avail)	0-200	200-500	500-1000	1000-5000	5000
Mercury	0-1	1-3	3-10	10-50	50
Nickel (avail)	0-20	20-50	50-200	200-1000	1000
Zinc (avail)	0-250	250-500	500-1000	1000-5000	5000
Sulphate	0-2000	2000-5000	5000-1.0%	1.0-5.0%	5.0%
Sulphide	0-10	10-20	20-100	100-500	500
Cyanide total	0-5	5-25	25-250	250-500	500
Phenol	0-2	2-5	5-50	50-250	250
Toluene extract	0-5000	5000-1.0%	1.0-5.0%	5.0-25.0%	25.0%

Results in mg/kg of air-dried soil, except pH

Table 9. Greater London Council Guidelines for contaminated soils
(after Kelly 1979)

Table 10. Tentative trigger concentrations for some selected contaminants

Contaminant	Planned use	Trigger concentration (mg/kg air dried soil)
<u>Contaminants which may pose hazards to health</u>		
Arsenic	Domestic gardens, allotments	10
	Parks, playing fields, open space	40
Cadmium	Domestic gardens, allotments	3
	Parks, playing fields, open space	15
Chromium (hexavalent)	All uses	25
Chromium (total)	Domestic gardens, allotments	600
	Parks, playing fields, open spaces	1000
Lead	Domestic gardens, allotments	500
	Parks, playing fields, open spaces	2000
Mercury	Domestic gardens, allotments	1
	Parks, playing fields, open spaces	20
Selenium	Domestic gardens, allotments	3
	Parks, playing fields, open spaces	6
<u>Contaminants which are phytotoxic but not normally hazardous to health</u>		
Boron (water soluble)	Any uses where plants are to be grown	3
Copper (available)	Any uses where plants are to be grown	50
Nickel (available)	Any uses where plants are to be grown	20
Zinc (available)	Any uses where plants are to be grown	130
<u>Contaminants associated with former coal carbonisation sites</u>		
Coal tar	Domestic gardens, amenity areas	200
	Public open space	500
	Industrial (no landscaping)	5000
Phenols	Domestic gardens and all uses	
	mains water services	5
	All other uses	100
Free cyanide	Domestic gardens, amenity areas,	
	open space	50
	Industrial (no landscaping)	500

Table 10. (cont.)

Contaminant	Planned use	Trigger concentration
Complex cyanides	Any uses where plants are to be grown	50
Thiocyanate	All uses	50
Sulphur	All uses	1000
Sulphide	All uses	250
Sulphate	Residential, commercial and industrial developments with no landscaping	1000
	All other uses including domestic gardens, open spaces and landscaped areas	200

This table is only applicable when used in accordance with the conditions and notes specified in the full ICRCCL publication.

not identified during the investigation may be present and may be encountered during subsequent site works. In this case modification may be required to the detail of the measures originally provided. In particular, site level changes will alter the relationship between the contaminated material and the ground level.

In a complete consideration of remedial and preventative measures it is necessary to assess the likely hazards to:-

- Site workers
- Final occupants
- The public at large
- Underground services, particularly water supplies, sewers and power cables
- Building materials including steel, concrete, plastics and bituminous materials
- Surface water and underground aquifers
- The general environment

The degree of treatment necessary for any site will be related to the sensitivity of the end-use. Areas of permanent hardcover such as paths, the area below buildings etc will prevent any long-term contact, particularly by eventual residents of the development. Treatment in these areas will therefore be governed by the consideration of short term exposure of construction workers. Where the level of contamination is sufficient site operations will need to ensure that dust is not caused, and if necessary damping of the soils with water prior to working should be adopted. Site workers in close proximity to the materials can be provided with face masks to prevent the inhalation of dust not otherwise eliminated. Barrier creams and coveralls will reduce the effects of skin irritants and although limited contact with the site may not be hazardous workers should be

provided with adequate washing and scrubbing facilities to minimise any intake of contaminated material through ingestion.

In order to provide a wider measure of protection, service trenches may be cut oversize and backfilled with clean material to eliminate future contact by later construction workers with the contaminated soils should re-excavation be required. Alternatively the statutory authorities, who may need to carry out much of this re-excavation, should be made aware of any potential hazard on the site.

In order to prevent any contact with contaminants by residents of housing developments, either directly or indirectly by the eating of plants and vegetables that have absorbed the contaminants, all open areas of the development should be treated.

In areas of domestic gardens or other areas where residents may plant vegetables for their regular consumption, an adequate depth of acceptable growing medium should be provided for cultivation. Depending on finished site levels this may require the removal and replacement of the contaminated soils, or the importation of clean material to act as a cover to it. Some opinion exists that in the long term clean material placed over contaminated soil will itself become contaminated by the upward migration of the water soluble fraction of the contaminants. Therefore it is often recommended that about 1.0m of clean material is provided from the final ground surface. The main area of such treatment may be restricted to the gardens, perhaps with a buffer zone around their outer boundary. Areas of permanent hardcover such as paths, the area of buildings etc may remain generally untreated as their presence will prevent any contact.

Areas of ornamental garden, amenity grass or other open ground that will not be used for the cultivation of edible plants need not be treated to the same degree as that proposed for the domestic garden areas. Care should however be exercised in the choice of permanent

vegetation since the contamination may be of a form which will affect its development.

In general, provided that approximately 150mm of good topsoil is provided to assist plant development, the bulk of clean imported material may be very low grade and may often be reject material for all other purposes. However where large vegetation such as trees are to be established it is prudent to excavate locally to a greater depth and replace with a greater depth of suitable growing material.

6.9.5 Methane

It should be anticipated that methane gas may be present within much of the Docklands. Methane and a number of other associated gases can be generated by the breakdown of the organic products within the naturally occurring peats and organic alluvial clays found extensively throughout the area. Methane can also be produced by the breakdown of refuse and other fill material if this contains organic debris.

Methane itself is not toxic, however hydrogen sulphide with which it is often associated can be, and at very low concentrations. However, methane will cause asphyxiation by the replacement or reaction with oxygen and has been the cause of a number of deaths in this way. Methane is also combustible and at low concentrations will form an explosive mixture in air.

6.9.6 Waste disposal

The responsibility for the assessment of the quality of waste materials lies with the relevant waste disposal authority within the terms of the Control of Pollution Act 1974. In the main no effective guidelines exist which allow assessment or detailed categorisation of

the material by others. At best materials are classified generally into four simple classes:-

- "Muck-away'
- Non-hazardous
- Hazardous
- Special Waste

Of these classes only Special Waste has any precise definition. This is related by Government legislation through the Control of Pollution Act 1974 to the concentration of contaminants which satisfy certain criteria of flammability, carcinogenicity, corrosivity or toxicity. The extreme caution necessary with such materials is such that they may be disposed of only at a limited number of licensed tips. This license is usually specific and valid only for closely defined contaminants and is granted by the waste disposal authority for the county in which the tip is located.

No similar precise definition is given in the legislation for hazardous material which can be defined only in abstract terms. This vagueness of definition together with the possible interaction of various substances means that assessment of the material is not easy and should be carried out only by the appropriate disposal authority.

All materials in the London area, whether hazardous or not, must be disposed of only at appropriately licensed tips. "Muck-away' a term which is given to exceptionally clean and inert material such as demolition debris or excavated clean natural ground can often be disposed of in general land-fill or used in other construction works. Non-hazardous, hazardous and special waste may all be contaminated, but the basis of their subsequent assessment is the likelihood that they may pollute the environment rather than their potential effect on users of the site. It must be recognized therefore that there is a distinction between contamination with respect to the potential effects on health, life and construction

materials at a site and hazardous with respect to removal of that material for waste disposal.

It is not necessarily the case that an authority will be prepared to accept the disposal of contaminated material even though it may have originated from within their own area. In London, a system was developed by the former Greater London Council which provides for a relatively rapid and efficient appraisal of material to be disposed of. Use of this system can provide significant benefits both in terms of time and ultimate expenditure.

The system requires that an adequate investigation be carried out to provide the raw analytical data to enable the assessment of the material to be made. Where possible background information regarding former land-use, processes undertaken, etc which are applicable to the site should be included. This data is then submitted for assessment by the relevant disposal authority who will circulate it to other authorities as necessary. Each will then provide a list of sites able to accept the material. These can then be compiled to produce a complete list of disposal sites licensed to handle and accept the waste indicated by the data.

The inclusion of the full listing or a pre-selection of available disposal sites into any tender documentation for construction requiring excavation and disposal should be considered. If included in an appropriate form, perhaps similar to that used for nominated subcontractors, and its use was a requirement of the Contract it could ensure the responsible and acceptable handling and disposal of materials. This would also mean that contractors would not need to 'cut-corners' following the temptation for under-pricing of the rates for handling excavated materials in competitive tender.

Of particular advantage would be the control that this could provide against 'fly-tipping'. As the disposal sites are licensed their use could be more rigorously enforced within the Contract. It would be a

simple matter to ensure a logging off-site of the material by lorry load and the logging in at the tip. By ensuring that no loads thus go astray considerable savings may be made in the costs which might otherwise arise from the subsequent clearing of other sites following fly-tipping. This saving could probably at least balance out the possible higher contract costs associated with the controlled handling of the waste from the site.

It should be understood that the capabilities of disposal sites are not permanent and that their situation with regard to the materials that they may accept often varies with time. They are therefore licensed only for the receipt of specific quantities and types of material and contaminant. Therefore in order to ensure that the listing of disposal sites is valid the assessment of the data by the disposal authority should be carried out sensibly close to the actual time of construction. In order to avoid unnecessary delays in situations where construction programmes can be uncertain it would alternatively be possible to have an initial appraisal carried out, and later an up-date of the assessment should excessive delays have occurred before construction begins.

CHAPTER SEVEN : HYDROGEOLOGY

7.1 General

The hydrogeology of the Docklands, unlike many elements of its engineering geology, is significantly variable on a time scale which is equivalent to the design life of many modern civil engineering works. Although in a natural state the hydrogeology has a stability which is a function of both the local and regional geology, this natural balance has been upset in the recent past by the influences of man. Nonetheless, there remains a basic intimacy between the various factors which control the hydrogeology. As will be shown, the hydrogeology of the area is in a state of transition. This Chapter therefore provides a discussion of the principles involved and illustrates them as appropriate, rather than attempting a quantification of the situation for a given moment in time.

Two principal aquifers have an influence on the Docklands. These are termed the upper and lower aquifers. The lower aquifer comprises the Chalk together with the overlying Thanet Sand and more sandy basal units of the Woolwich and Reading Beds, and the upper aquifer consists of the Thames Gravels. Over part of the area these are separated by an aquiclude which consists of the relatively impermeable London Clay or the cohesive units of the upper units of the Woolwich and Reading Beds so that the lower acts as a confined aquifer and the conditions in the two are unrelated. Locally the Thames Gravels lie directly on the beds of the lower aquifer such that it becomes unconfined and there is a resulting hydraulic continuity between the two.

In a natural state the groundwater contained in the lower aquifer is artesian, fed by recharge areas in the surrounding Chalk downlands. Therefore in the low parts of the London Basin occupied by central London and the Docklands there would be an overall upward flow of

groundwater from depth. This can be likened to the water in a U-tube finding its own level, such that, water added to one limb will flow around the base and up the second limb to egress at the top. Although in the natural situation some energy is lost in the passage through the ground, this source of water once provided a number of important features to the area.

Because of the original natural artesian pressure in the lower aquifer, where it was not covered by impermeable material the water was able to find a relatively easy path to the ground surface, appearing as springs feeding streams or riverlets, or would have discharged directly to the Thames. As the sensitivity of the groundwater flow, in the lower aquifer, to short term seasonal or climatic fluctuations is relatively low a supply of water to the Thames was ensured which was unaffected by seasonal drought. It also became a very important source of water for central London as its artesian head meant that wells could be sunk which, at least initially, did not require pumping to ensure a supply.

The general features of the hydrogeology of the Docklands and the relationship between the two aquifers is shown schematically on figure 57. This shows both the natural and present modified situation, the various aspects of which are discussed below.

7.2 Water abstraction from the lower aquifer

Prior to the late eighteenth century when development of the lower aquifer for water began in central London, its piezometric level was probably about +8.0m OD (Water Resources Board 1972). Consequently, in the Thanet Sand recharge would have been taking place from the lower aquifer to the upper aquifer and into the Thames where the two are in direct contact. Following exploitation of the lower aquifer by an increasing number of water wells the piezometric levels began to fall and a cone of depression developed across London (fig. 58).

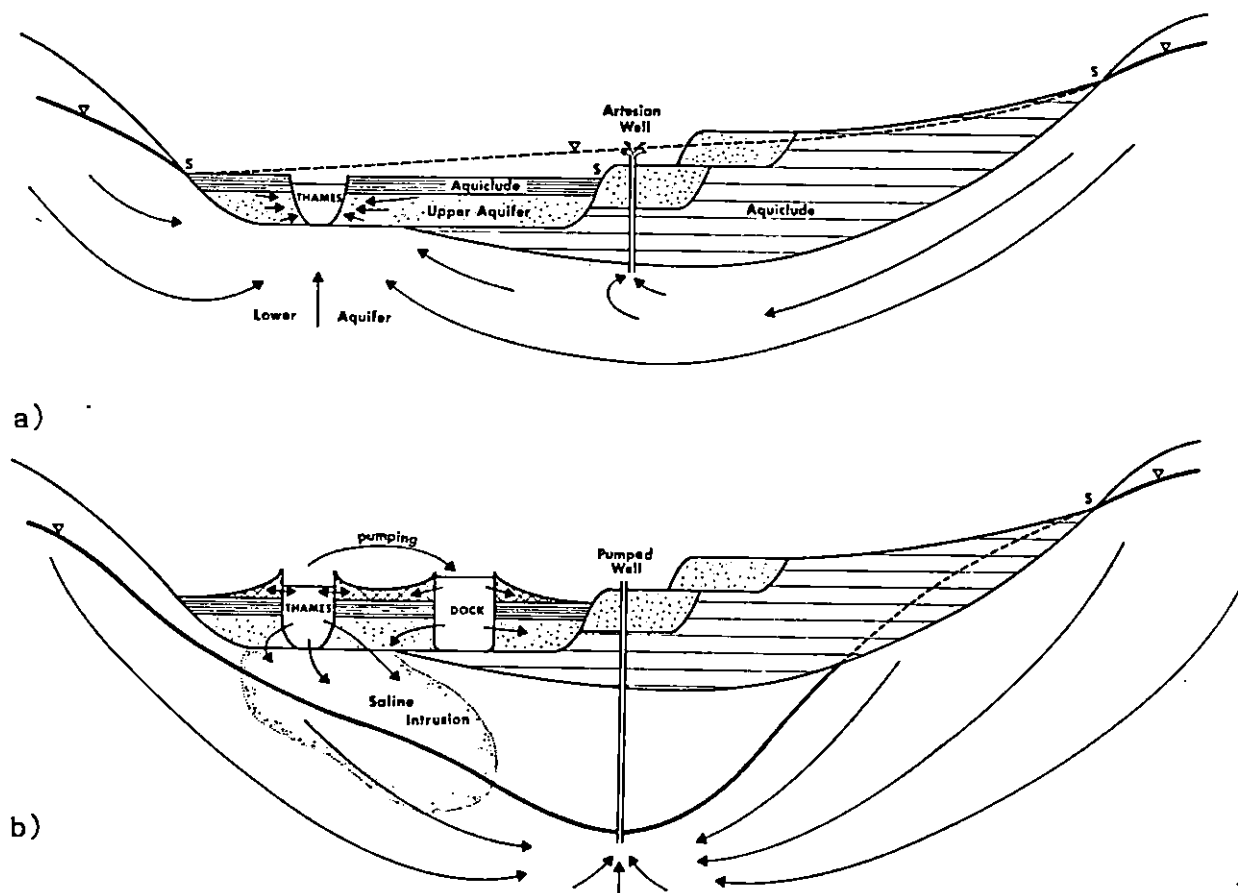


Figure 57

Diagrammatic representation of the principal hydrogeological aspects of the Docklands area of the London Basin, under a) natural conditions and, b) present conditions.

The lower aquifer comprises the Chalk, Thanet Sand and the more sandy units of the basal Woolwich and Reading Beds. The upper aquifer is the Thames Gravels. These are locally separated by an aquiclude comprising the cohesive units of the the upper Woolwich and Reading Beds together with the London Clay. The upper aquifer is contained by an aquiclude of alluvium. A number of potential spring points, which vary under the two conditions, are indicated by an 'S'.

Comparison of parts a) and b) show the reversal of flow direction in both aquifers below the Docklands and the resulting saline intrusion from the Thames. Also as abstraction from the wells has largely ceased in recent time the water table in the lower aquifer is again rising.

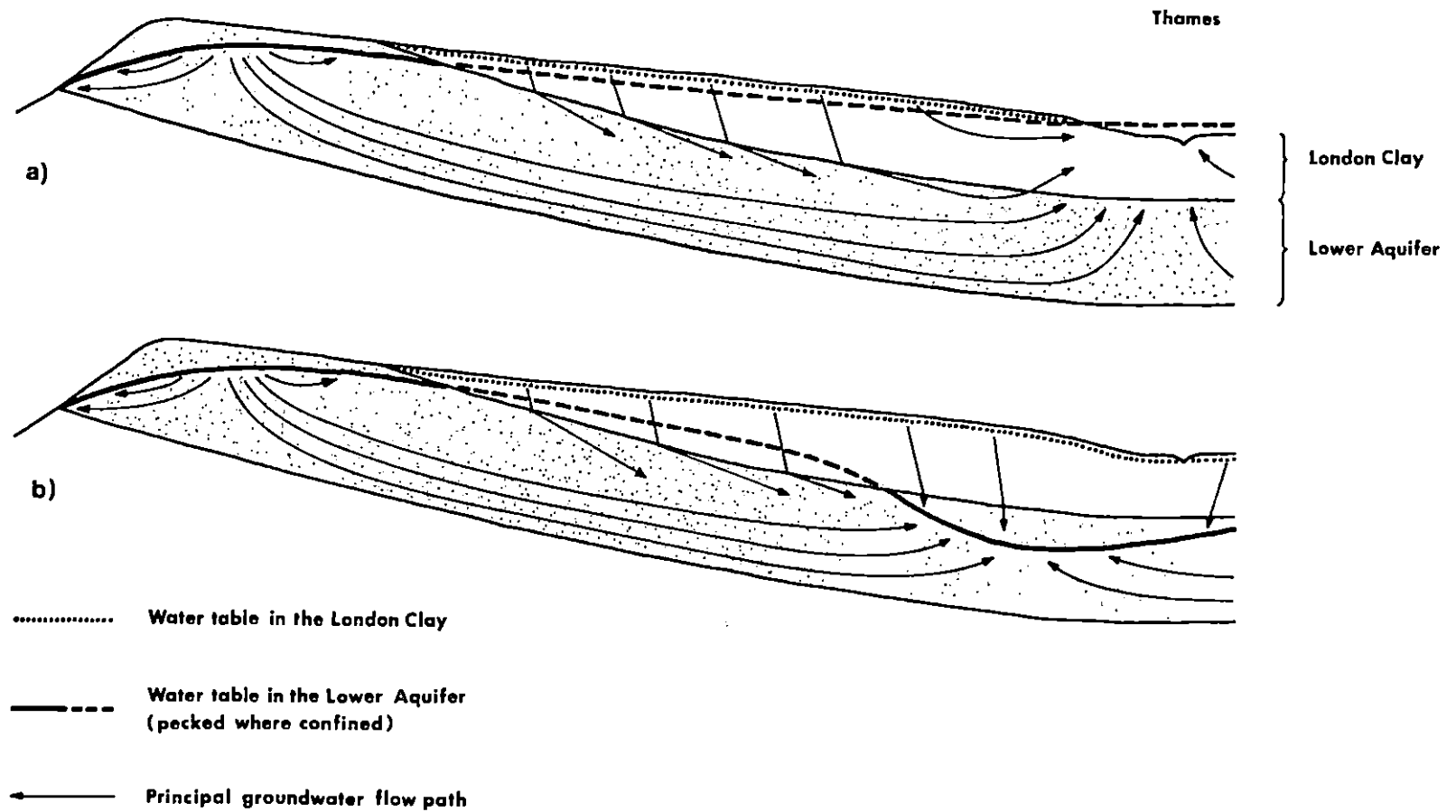


Figure 58.

Diagrammatic sections showing the groundwater flow patterns in the lower aquifer and overlying aquiclude under a) natural conditions and b) following modification by groundwater abstraction.

(after Water Resources Board 1972)

By about 1820 the water level in central London had fallen to about -6.0m OD and deepened further to -15.0m OD by 1850 (fig. 59 and 60). This represented a fall in water level in the aquifer of some 23m and was measurable from Enfield in the north to Morden in the south. The effects were also evident in south Essex where a fall in water level of over 15m occurred at Hornchurch.

Between 1850 and 1875 water levels continued to fall in central London at about 0.6m/yr deepening the cone to -30.0m OD. This continued well into the twentieth century, locally at rates up to 1.2m/yr due to an increasing demand from new industrial activity. By the second half of the twentieth century a major cone of depression had developed stretching from central London extending as far west as Southall and had deepened to over 85m (Water Resources Board 1972; Wilson & Grace 1943). A further feature existed north of Dagenham which extended to a depth of 60m.

Whereas the Thames had acted as a lower discharge boundary for the system the development of the cones of depression caused the flow of the groundwater in the aquifer to become divorced from the Thames (fig. 61).

By 1965 the piezometric surface in the lower aquifer fell across the area from Ordnance Datum south of the river at Woolwich to -8m on a line which crossed the Royal Docks and the southern Isle of Dogs. From there the cone deepened rapidly westwards to -60m through Wapping (fig. 62). Also a new cone of depression had developed in the Bow-Stratford area of the lower Lea Valley due to local abstraction somewhat deflecting the direction of flow in the lower aquifer below the Docklands towards the north.

Abstraction decreased during the 1940's following war damage in central London and a consequential reduced demand for the water. It picked up again in the post-war years to about 1957 but from then has shown a general decline. By the mid 1970's a significant reduction

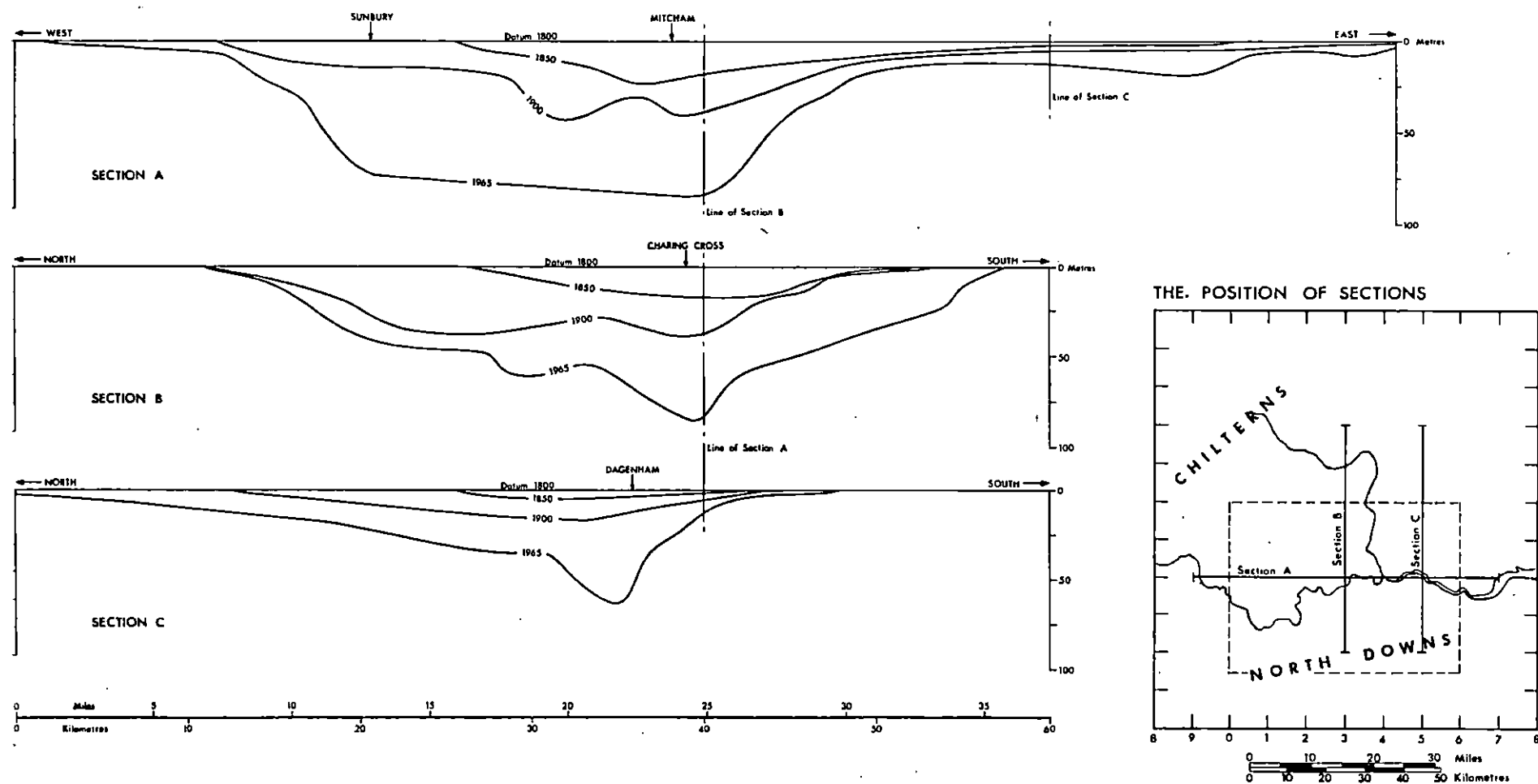


Figure 59.

Sections showing the progressive decline of the groundwater levels in the lower aquifer of the London Basin with time.

Note the inset map shows the positions of the sections lines and also the area of figure 60 .

(After Water Resources Board 1972)

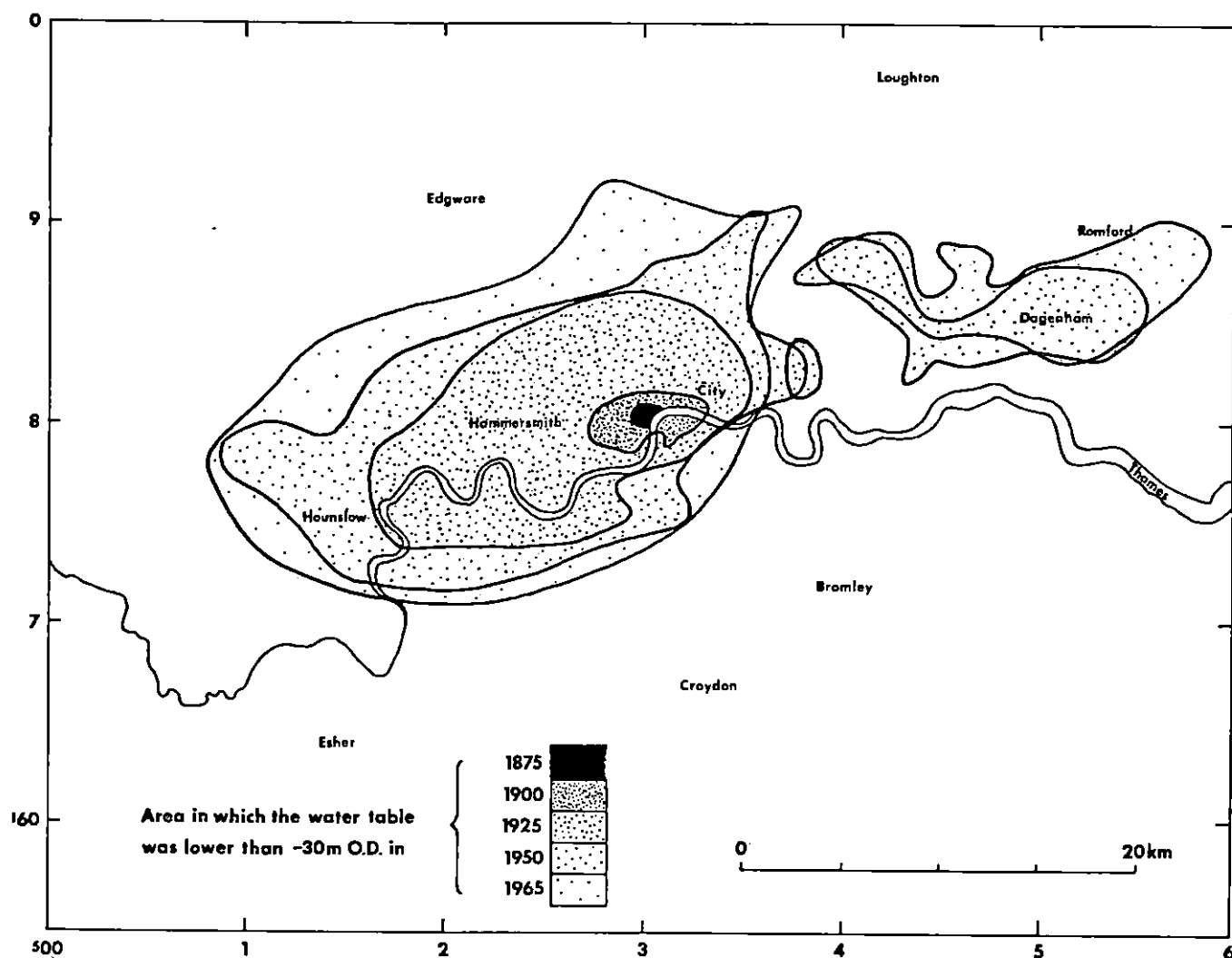


Figure 60.

Map showing the progressive decline in the groundwater table of the lower aquifer of the London Basin and the increasing size of the associated cone of depression.

(After Water Resources Board 1972)

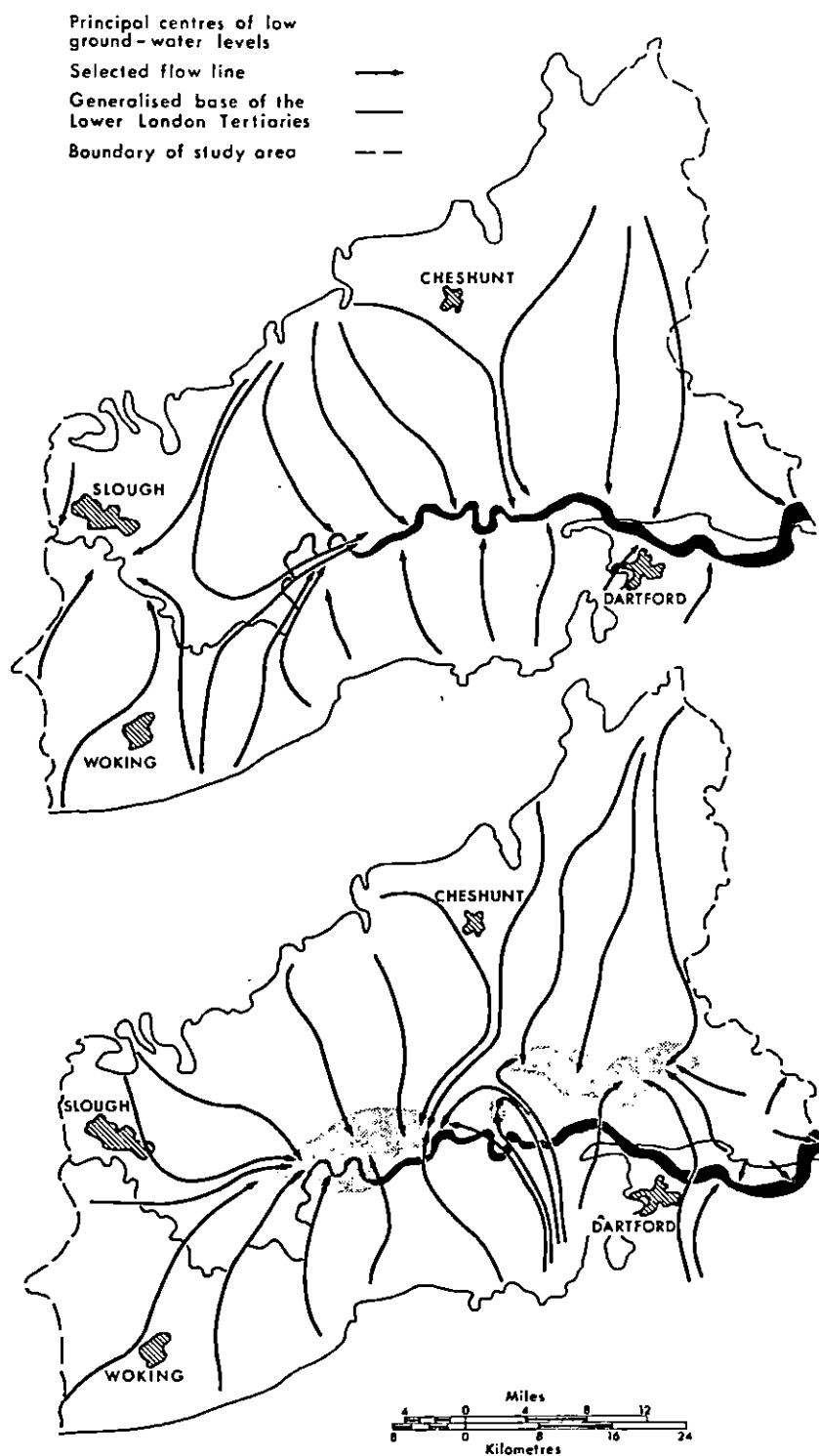


Figure 61.

Directions of regional groundwater flow in the lower aquifer, a) under natural conditions and, b) in 1965 when the flow was controlled by the developed cones of depression.

(After Water Resources Board 1972)

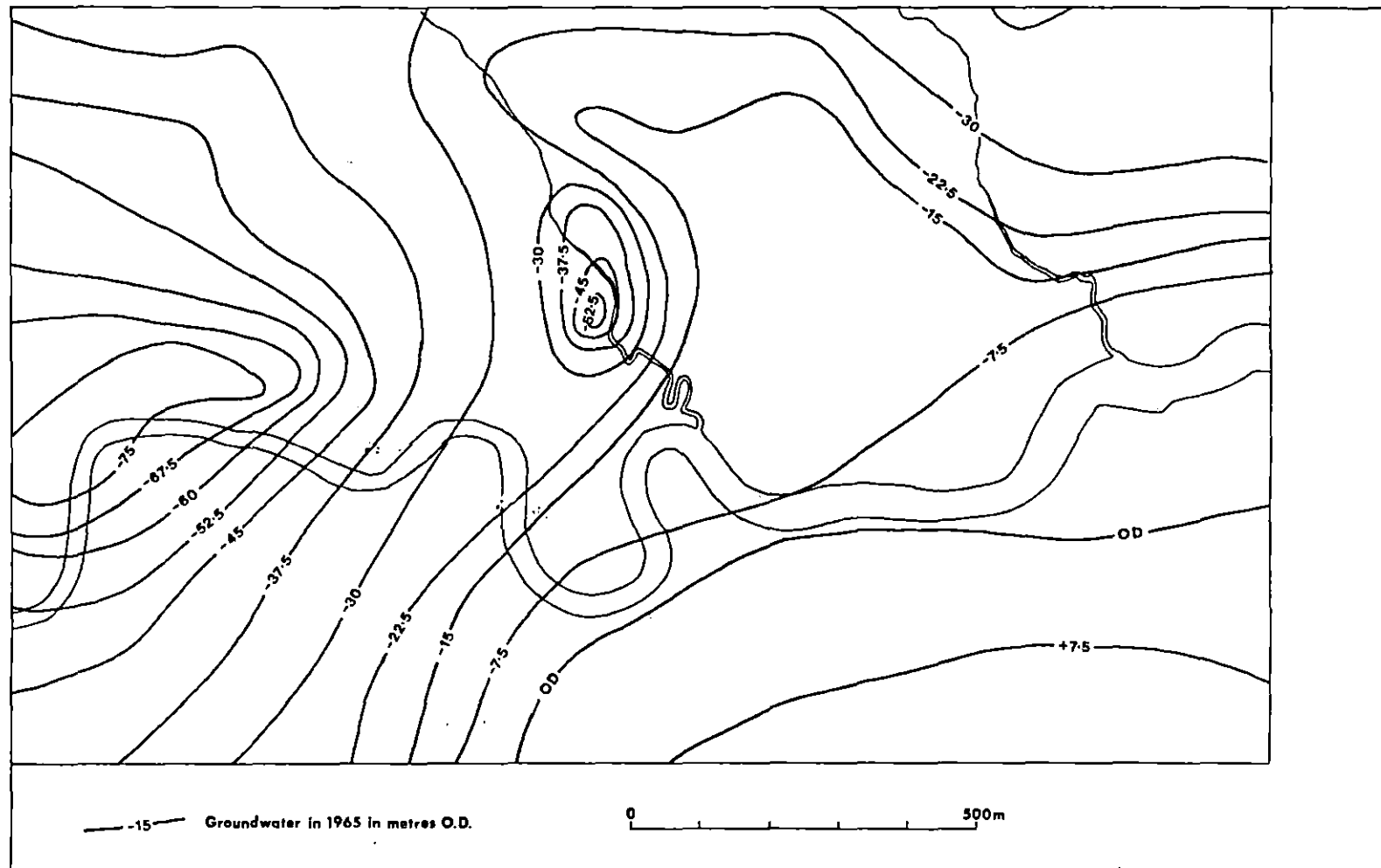


Figure 62.

Map showing contours of the groundwater level in the lower aquifer docklands area in 1965.

(After Water Resources Board 1972)

in groundwater abstraction had occurred, partly as a result of legislation, and partly because of the falling quality of the groundwater. This has resulted in a general rise in the groundwater level in the lower aquifer (Marsh and Davies 1983, Water Resources Board 1972). This study has established the presence of a reduced groundwater table in the lower aquifer across the Docklands and has detailed its partial return in recent decades. However, the situation is shown to be further complicated by the interaction with the docks which appear to be a major and persistent source of local recharge.

7.3 The hydraulic controls to the groundwater flow patterns

The effects of the changes in the aquifer have been to produce a marked variation, not only in flow directions of the groundwater but also in the pressure distributions which govern them. It is necessary to appreciate and understand these controls and the way that they can change in order that the relationship between any substantial engineering works and the groundwater can be evaluated.

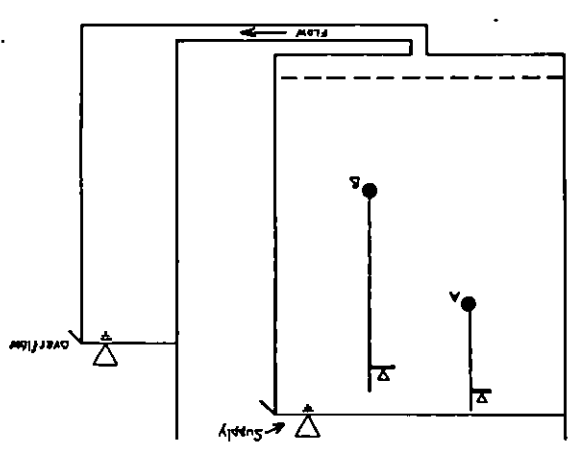
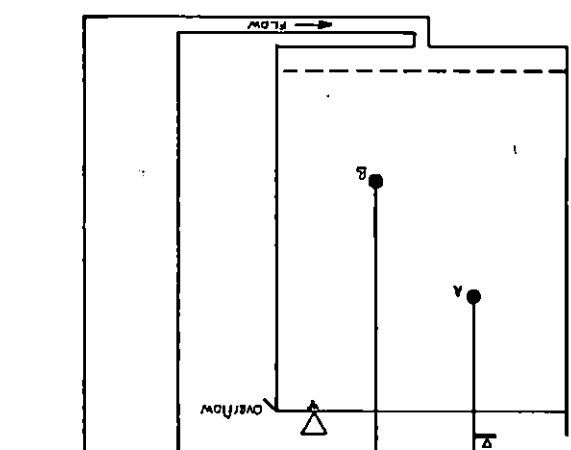
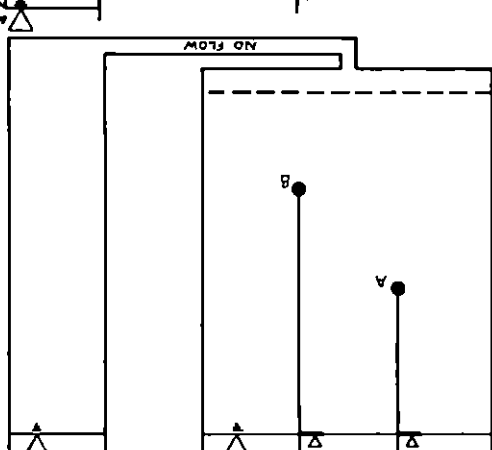
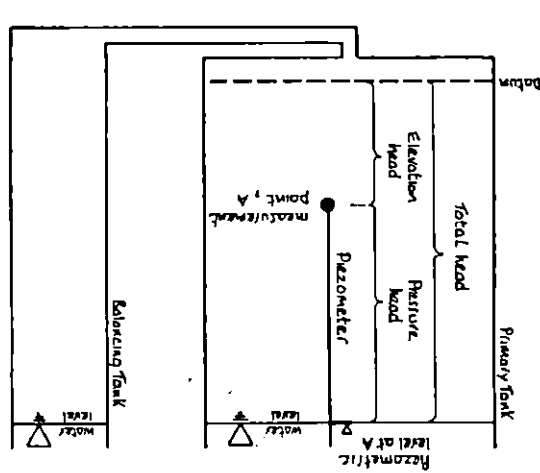
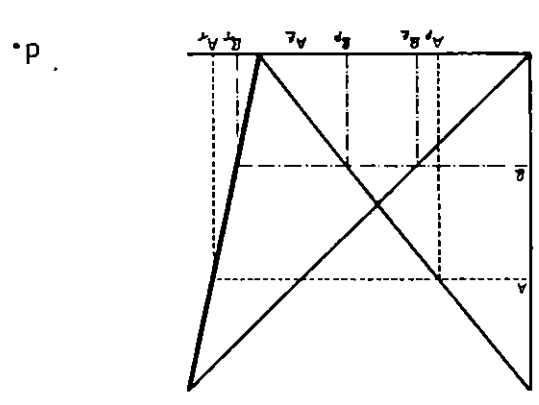
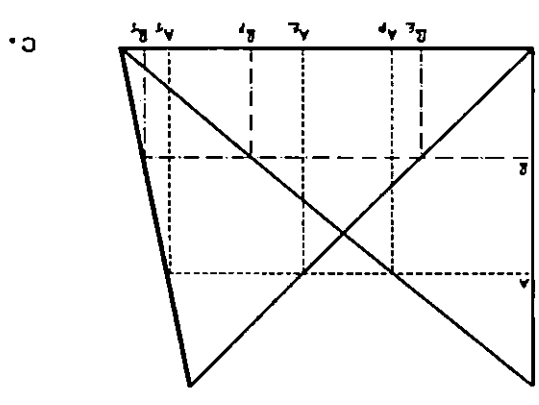
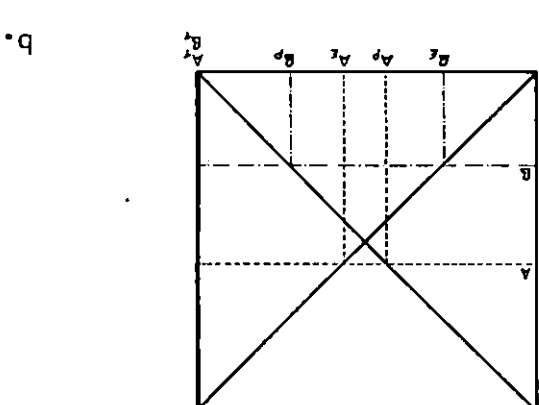
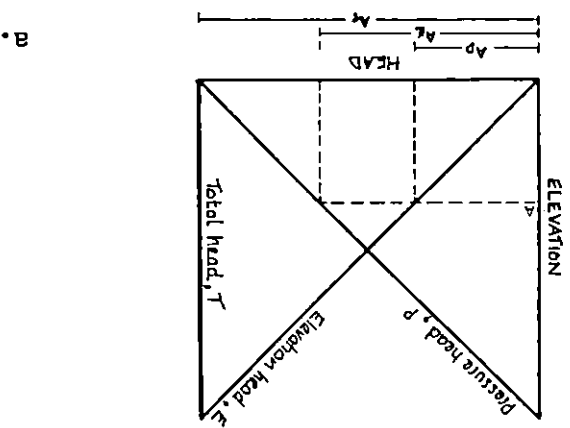
Cedergren (1967) shows that the groundwater level at any point can be conveniently resolved into components of pressure head, elevation head and total head. These are measured relative to an arbitrary datum and their relationship is that the total head is the sum of the pressure head and elevation head (fig. 63a). By developing the U-tube analogy for the lower aquifer its changing state can be modelled and explained in terms of an associated head diagram (fig. 63b-d).

Groundwater flow is controlled by a differential across the total head in which it occurs from a high to low state. In a hydrostatic situation the total head can be seen to be constant with depth, therefore no flow is taking place. A standpipe or piezometer installed anywhere below the groundwater table would record a free water level, or phreatic surface, at the same absolute height

Figure 63 (see over).

The head distribution and associated flow conditions in the Lower Aquifer of the London Basin shown by a simple physical model using water flow between two tanks and a pressure diagram showing the variation in pressure head, elevation head and total head.

- a) The general situation: The aquifer is modelled by two connected water tanks. The conditions in the aquifer in the London area are variously modelled by the situation in the primary tank. The principal elements of the pressure diagram show the relationship of the three components of head and how they relate to the readings from a piezometer which monitors the conditions at an arbitrary point.
- b) Hydrostatic situation: When the water levels in the primary and balancing tanks are equal piezometers installed at points A and B record a water level which is equivalent to the water level in the tank. Under these conditions there is a state of no-flow between the tanks. The pressure head distribution is controlled only by the weight of water. This increases linearly with depth in inverse proportion to the elevation head such that the total head is constant with depth.
- c) Upward flow: If there is an upward flow of water as would occur if the water level in the secondary tank were maintained at a higher level than the primary tank, a hydraulic gradient would develop such that there would be a higher energy potential at the lower of any two measurement points. The piezometric level recorded in the lower would be correspondingly higher than in the upper. The pressure head distribution reflects the increase due to the additional seepage force acting over the hydrostatic weight of water and is adjusted accordingly. The total head therefore increases with depth in keeping with the upward flow.
- d) Underdrainage: Where there is a downward flow of water from the primary to the balancing tank the seepage force acts against the hydrostatic weight of water such that the lower of two piezometers would record a piezometric level lower than that in the upper. The total head distribution therefore slopes to reflect the decreasing value with depth.



regardless of the depth of measurement (fig. 63b). In contrast, if an upward flow is occurring the total head would slope such that it would decrease with increasing elevation. As flow occurs from high to low total head and the elevation head remains constant the pressure head will increase proportionately with depth over that in the hydrostatic condition (fig. 63c). This will be noted in the standpipes in that the piezometric level at depth will assume a level above that indicated by an instrument at a shallower level. Similarly if a downward drainage is present the situation would be reversed (fig. 63d). Clearly the strength of the artesian pressure causing the upward seepage, or the underdrainage causing the downward seepage will be reflected in the degree to which the total head distribution is modified.

It can be seen from this that the difference between the operating total head and the hydrostatic total head increases with depth. This is because both the pressure head and elevation head of the upper surface of the groundwater table remain constant. That is, it remains at atmospheric pressure and does not fluctuate in position. Clearly if this is the case and if underdrainage or recharge both require that water is added to or subtracted from the system then the boundary conditions need to allow for lateral flow. The situation where water is added to or lost to the system by lateral flow, in fact, provides a closer model of the actual situation in the aquifer. However, it adds a further complication in that the total head distribution will vary laterally as well as vertically, such that the groundwater will have a component of both vertical and horizontal flow.

In order to accommodate this lateral variation in total head distribution and readily make sense of real data within a given area it is often helpful to plot the pressure head distribution and compare the scatter to a distribution that would occur if a hydrostatic or no-flow situation were present. This has advantages where real data is to be plotted since the hydraulic gradient, as

dictated by the total head distribution, must vary within the area in a way which is relative to the lateral distance from the apparent recharge or discharge point.

7.4 Groundwater controls in the upper aquifer

The water level throughout the original marshland of the area would have been at or near to ground surface and controlled by the level of the Thames. However, the underlying Thames Gravels would have contained groundwater derived from percolation from the higher gravel terraces together with recharge from the lower aquifer where the two were in hydraulic continuity. On the immediate flood plain of the river the gravels were confined by alluvium so that discharge would occur directly to the Thames or even as springs along the upper margin of the alluvium and may have been the source of a number of riverlets crossing the marsh.

The hydrogeology of the upper aquifer has also been affected by man in the recent past. The gravels have been further confined by the actions of man where they have been contained vertically by extensive tracts of made ground and laterally by the construction of the river walls (fig. 57b). Natural infiltration on the former recharge areas of the higher terraces has been intercepted by the impermeable surface of urban development and the construction of drains and sewers. The lost recharge from the lower aquifer has meant that the hydraulic gradient in the gravels has reversed and that underdrainage to the lower aquifer has resulted in the Thames becoming a recharge source for the upper aquifer. In consequence the piezometric levels in the upper aquifer and the character and quality of its water is now intimately related to that in the river, in contrast to the natural condition.

Tidal induced changes in groundwater level in the upper aquifer have been observed over varying distances from the river. The

transmission of such changes in river level is influenced by two factors;-

- the flow of groundwater through the river bed, and
- the propagation of pore pressure differentials away from the river

Several distinct settings can be postulated along the Thames through the Docklands which will control the immediate groundwater conditions in the upper aquifer.

1. areas where the upper aquifer is in direct hydraulic continuity with the river, and groundwater levels fluctuate according to river level.
2. areas where the gravels of the aquifer are blanketed by river muds reducing the hydraulic continuity between the two such that groundwater levels are stabilized around mean river level, and
3. areas where groundwater levels are significantly higher than mean river level; such areas are influenced by water level and seepages from the docks.

The cases 1. and 2. can be interchanged as natural or artificial changes to the river bed occur. For example, during the construction of the Thames Barrier observations were made of increases in tidal influences following dredging, indicating a greater ease of movement of water through the river bed (Foster & Cripps 1977).

7.5 Groundwater in the Made Ground

The confinement of the river between artificial banks over the last 1000 years or so has helped to increase its tidal range. This together with a slow but perceptible increase in relative sea level has resulted in much of the natural marshland now being below mean

river level. Consequently, much of the made ground contains groundwater which is recharged by the river. As the made ground generally lies above the natural alluvium, which itself acts as an aquiclude to the upper aquifer, its groundwater may often be perched. Adjacent to the river walls there is likely to be a tidal connection between the groundwater in the made ground and the river. The tidal response in such circumstances will depend largely on the character and condition of the walls.

The development of the docks has also had a marked influence on the local groundwater. Although their presence may have produced physical cut-offs to existing natural flow patterns, they also act as important areas of local recharge maintaining water levels in the surrounding ground above the natural balance level.

Other artificial influences on the local hydrogeology can also be produced by tunnels, basements, service runs etc all which are able to modify the local condition as they produce recharge, discharge or generally interrupt the groundwater flow.

7.6 Examples of groundwater levels in the Docklands and the controls to its pressure distribution

In order to consider the true pattern of groundwater flow it is necessary to have reliable observations. Even where monitoring instruments have been installed to the highest standard a number can always be expected to give anomalous or unreliable readings. This may be due to instrument or operator error, random outside influences, or may even be due to a real but not understood variation in the groundwater regime. Consequently, not only do such instruments need to be installed correctly but they also need to be read carefully, and read sufficiently regularly over a long enough period to establish the trends and fluctuations in the groundwater. Only then can anomalous readings be dismissed with some certainty and

the natural variations which occur over a diurnal, monthly or even annual period be smoothed out to allow comparison of data from differing sources.

A site investigation for the Jubilee Line east London extension was carried out across the Docklands in the late 1970's (Wimpey 1978). In this a number of water observations were made which can be used to determine the groundwater regime in the lower aquifer. Figure 64 shows a section along the western part of the investigation from Wapping across the Isle of Dogs and the Greenwich Peninsula. On this is shown the standpipes and piezometers installed and the elevation of the average piezometric level recorded in each of them. Those positioned in the lower aquifer were controlled by the groundwater regime present at the time. The distribution shows the strong influence of the cone of depression in central London, but by comparing the curve with the 1965 distribution shown on figure 62 it can be seen that the water table has risen by about seventeen metres, or 1.2 m/yr, in the intervening period, with a maximum below the Surrey Docks in Southwark. The drawing also shows that the soils above the piezometric surface of the lower aquifer should not necessarily be assumed to be dry. Piezometers in the London Clay show readings giving piezometric levels well above that of the lower aquifer. Also it is interesting to note that the elevation of the piezometric level reduces as the point of measurement approaches the lower aquifer. This clearly demonstrates that through drainage is occurring in the London Clay and that the pressure distribution is controlled by the underdrainage in the lower aquifer in the manner modelled in figure 63d and illustrated on figure 57b.

In 1983 a study was carried out in the former Surrey Commercial Docks by the LDDC in an area which lies just to the south of the line crossed by the Jubilee Line investigation. Only a limited number of instruments were installed below the Thames Gravels but these show a further increase in the level of the aquifer by an additional 10 metres in the west of the Surrey Docks area.

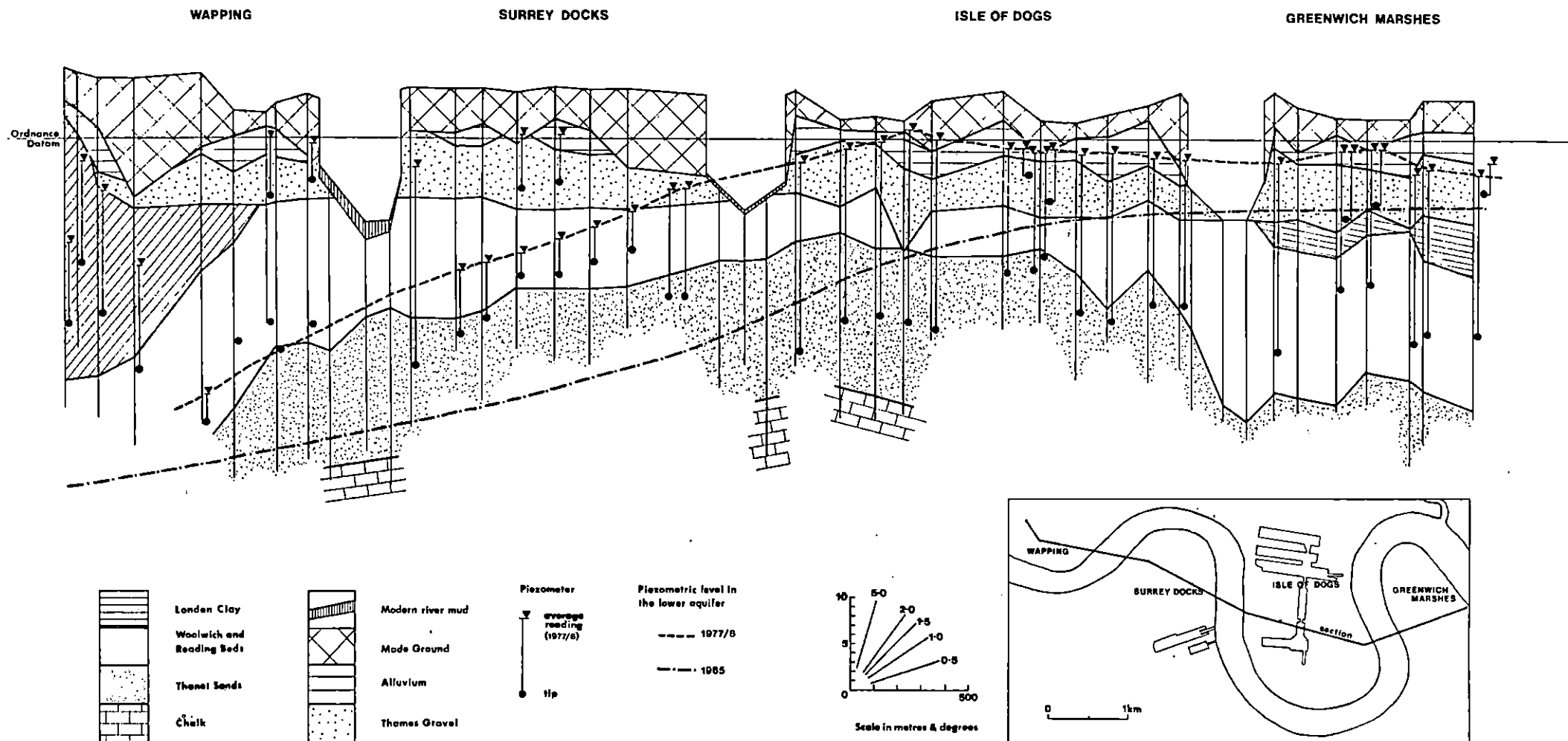


Figure 64.

Groundwater conditions on an east-west section through the western part of the docklands area. The geological section and 1977/8 piezometric details are taken from the Jubilee Line investigation (Wimpey 1978) and the 1965 detail from Water Resources Board (1972) as shown on figure 62

One borehole in the Surrey Docks study was installed with three instruments, one each in the Woolwich and Reading Beds, the Thanet Sand and the Chalk. As these offer a vertical section the complication of lateral variation in the total head distribution, as discussed above, is reduced. By plotting the values and determining the total head distribution the increasing imbalance in total head from the hydrostatic situation with depth is clearly seen. Similarly if a hydrostatic situation within the Chalk is assumed, a piezometric surface at about -6.0m OD is suggested. The apparent discrepancy with the piezometric surface which can be similarly established for the Thanet Sand is the result of the component of lateral flow which distorts the equipotential lines from the vertical. Consequently, a vertical section, as established by a suite of instruments installed in a single borehole, intercepts equipotentials of decreasing value, (fig. 65).

By presenting the data from the Jubilee Line investigation as pressure head against elevation and splitting it into a number of discrete areas the decreasing influence of the underdrainage in central London towards the east can be clearly seen (fig. 66). Area A shows readings from Wapping and the Surrey Docks (fig. 66a). The observations from instruments installed in the solid geology all fall below a line representing the hydrostatic condition from Ordnance Datum and although the water levels in the Thames Gravels indicate that this controls the groundwater regime in the upper aquifer, of which more will be discussed later, those from the lower aquifer clearly show the influence of underdrainage. As pointed out above, because of the lateral variation in the distribution of total head, further relationships between the points can not readily be determined. Similar plots for the areas to the east all show a closer relationship of the observations to the hydrostatic condition although as the depth increases, as might be expected, there is a tendency for the influence of underdrainage to be evident.

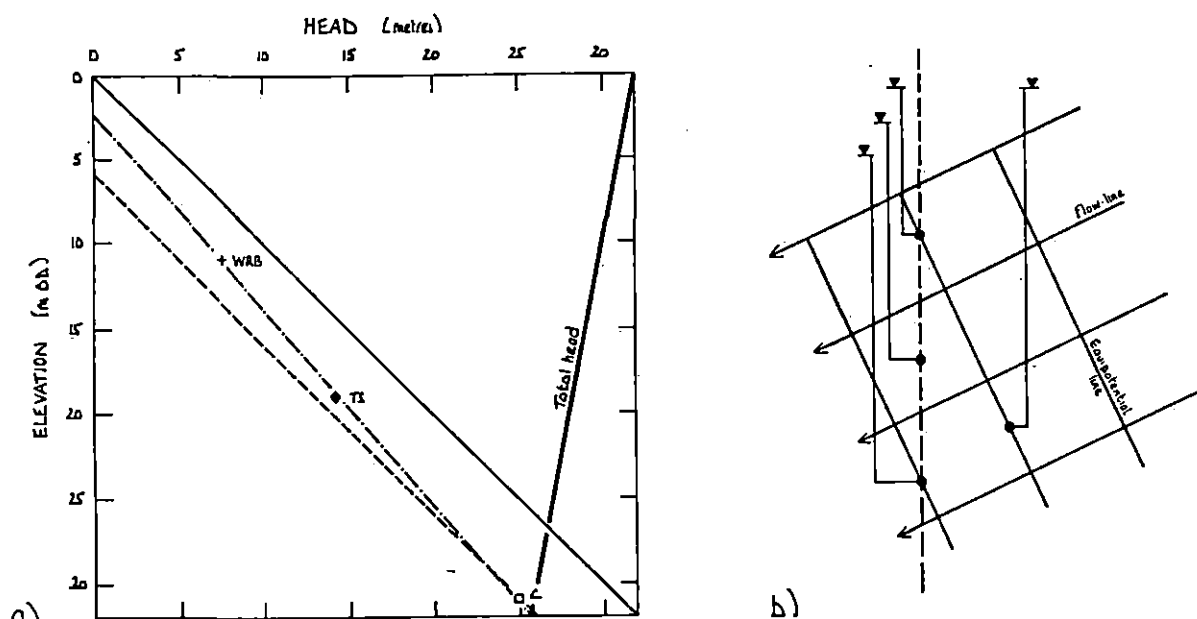


Figure 65.

Groundwater observations for three piezometers installed in the chalk (C), Thanet Sands (TS) and the Woolwich and Reading Beds (WRB) of the lower aquifer in a single borehole in the Surrey Docks area. a) shows a plot of pressure head against elevation. It can be seen that the observations fall below the hydrostatic condition from OD. Comparison with the diagrams given on figure 63 shows that a total head distribution indicates that flow is taking place in the aquifer. Figure 64 shows that a strong component of lateral flow is likely towards the cone of depression in central London. As the observations are from the lower aquifer the distribution can not be explained by simple underdrainage as in figure 63d. b) shows the groundwater flow diagrammatically as a portion of a flow net. In this the direction of flow and total head distribution is represented by the flow-lines and equipotential lines. It can be seen that a vertical section through the flow net, such as would be the case with a borehole, intercepts equipotential lines of decreasing magnitude with depth. Therefore the total head measured within a single borehole will also reduce with depth, as seen in a). For any two measurement levels the total head could only be the same if the two points were some distance apart, i.e. in two different boreholes.

Although the data is limited a similar return to the hydrostatic condition can be seen to be developing with time. Area B, which covers the Surrey Docks investigation of 1983 referred to above, is plotted as figure 66b and area H which covers the Limehouse Link investigation of 1987/88 as figure 66H. Although they both overlap somewhat with Area A the readings from the lower aquifer in each are much closer to the hydrostatic condition which corresponds to an increase in the level of the piezometric surface with time.

Figure 64 shows that a high existed in the piezometric surface of the lower aquifer in the Isle of Dogs in 1977. On the eastern side of the high there is apparent hydrostatic condition developed through the upper and lower aquifer as evidenced by a group of instruments recording a similar piezometric level at about -1.0m OD. This is maintained across the Greenwich Peninsular (fig. 66c). The piezometric high, at about +1.0m OD, in the centre of the Island may be associated with the presence of the Millwall Dock system and its artificially maintained level of about +4.0m OD. However, in itself this does not explain the development of high pressures within the lower aquifer. Reference to the geological structure on the same section line shows an anticlinal crest to be present in about the same area. The relatively thin cover of the remaining aquiclude has, coincidentally, been breached by a deepening of the Thames Gravels. It therefore seems likely that the localized hydraulic continuity between the two aquifers in this region driven by recharge from the dock system has allowed the increase in piezometric level to be propagated to depth. It can be postulated further that the local exceptional recharge of the lower aquifer below the Surrey Docks has been enhanced by this source.

Area D crosses the northern side of the Royal Docks and shows a strong correlation in both aquifers to a hydrostatic condition from about +0.5m OD (fig. 66e). This raised level in the aquifers compares with the situation in the Isle of Dogs and can probably be related to leakage from the adjacent dock system.

Area E crosses from the northern side of the Royal Docks across the Thames at Woolwich Reach and onto the south side of the river. The results available are difficult to interpret with certainty (fig. 66e). There appears to be a relation to the hydrostatic situation in the Chalk but this is not maintained in the Thanet Sand. It is noted that the majority of the instruments developed a wide range of readings with no strong average condition. It seems probable that the data is not sufficiently reliable to be certain that a stable situation has been monitored.

Area F shows a series of readings carried out in 1987 to 1988 in a very localized part of area E. These have the advantage that they were read very regularly over a period of almost a year. The exceptional control of the hydrostatic situation is clearly evident from the gravels through to the Chalk. The correlation of the results from the Thanet Sand and the Chalk support the contention that the data from area E should not be regarded as representative of the natural situation. Interestingly the data from area F can be used to show that there may be a strong annual fluctuation of about 0.5m with a low in the summers months and a high in the winter months (fig. 67). This appears to be related to a seasonal variation with no apparent time lag due to the infiltration times from the catchment areas of the Downs. If this is the case, the pressure variation caused by a changing local groundwater level on the Downs is being transmitted instantly through to the lower parts of the basin as a pressure change, rather than the hydraulic gradient increasing the flow of groundwater, which would be a much more sluggish response.

Area G, which lies south of the river, shows less uncertainty in the readings from those in area E and although taken in 1977 show good agreement with the readings from area F carried out in 1987/8. Figure 62 shows that the effects of the cone of depression in this area were relatively small in 1965 and it seems likely that since no

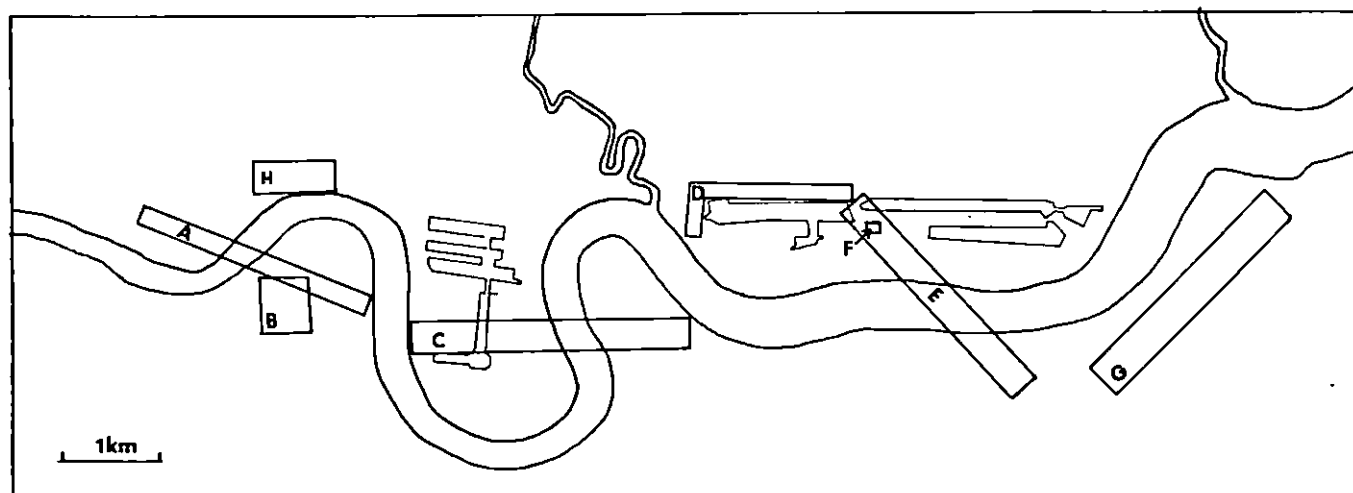


Figure 66.

Plots of pressure head against elevation for areas A to H as shown on the above key plan across the docklands.

Areas A, C-E and G : Based on the Jubilee Line investigation (Wimpey 1978) and relate to observations in 1977/8

Area B : Based on the investigation of the Surrey Docks for the LDDC (Groundworks 1984) and relate to observations in 1983.

Area F : Based on an investigation of a small area of the Royal Docks (Soil Mechanics 1988) and relate to observations in 1987/8

Area H : Based on an investigation for the Limehouse Link Road (Soils Engineering 1988) and relates to observations in 1987/8

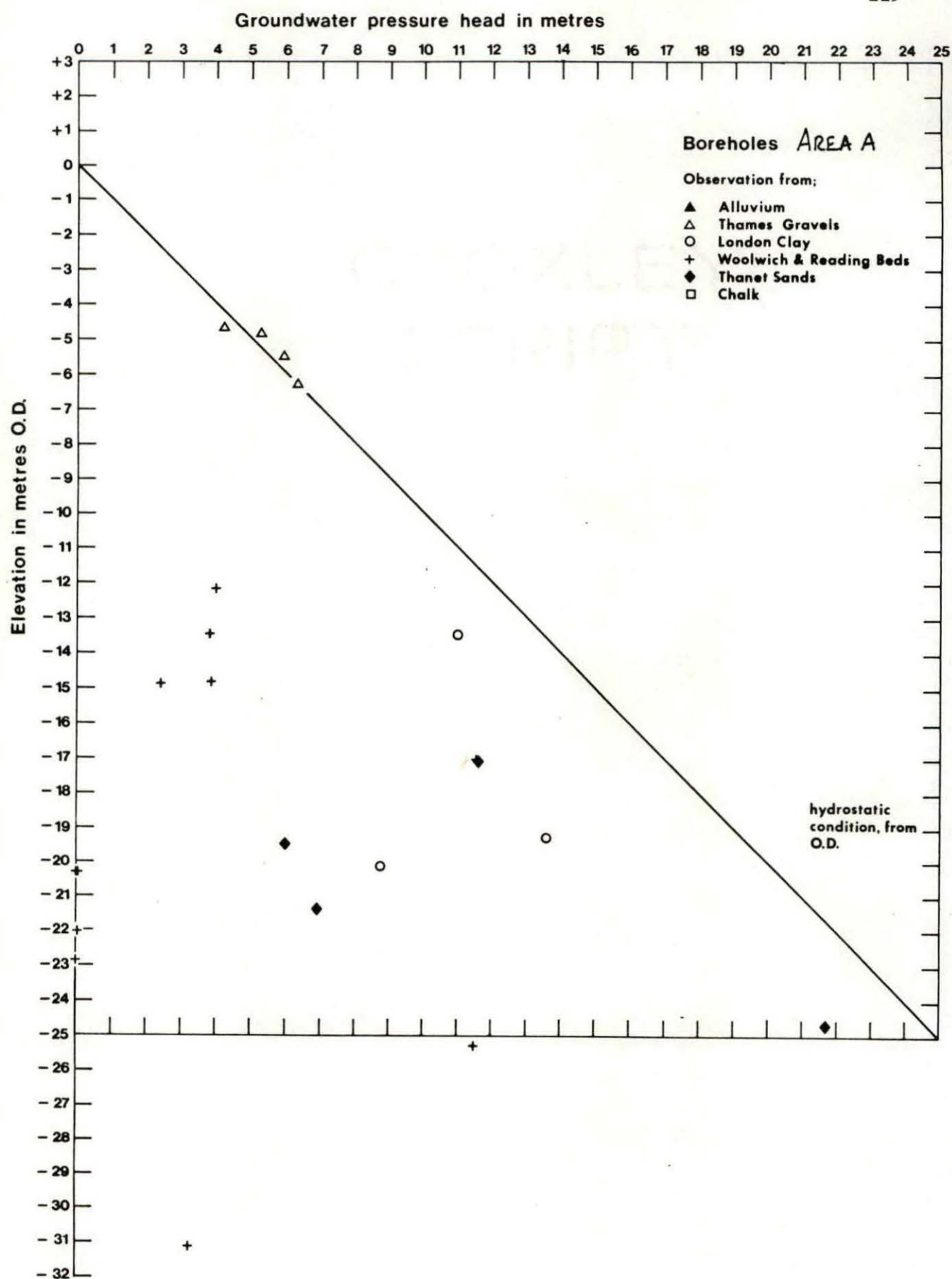


Figure 66a.

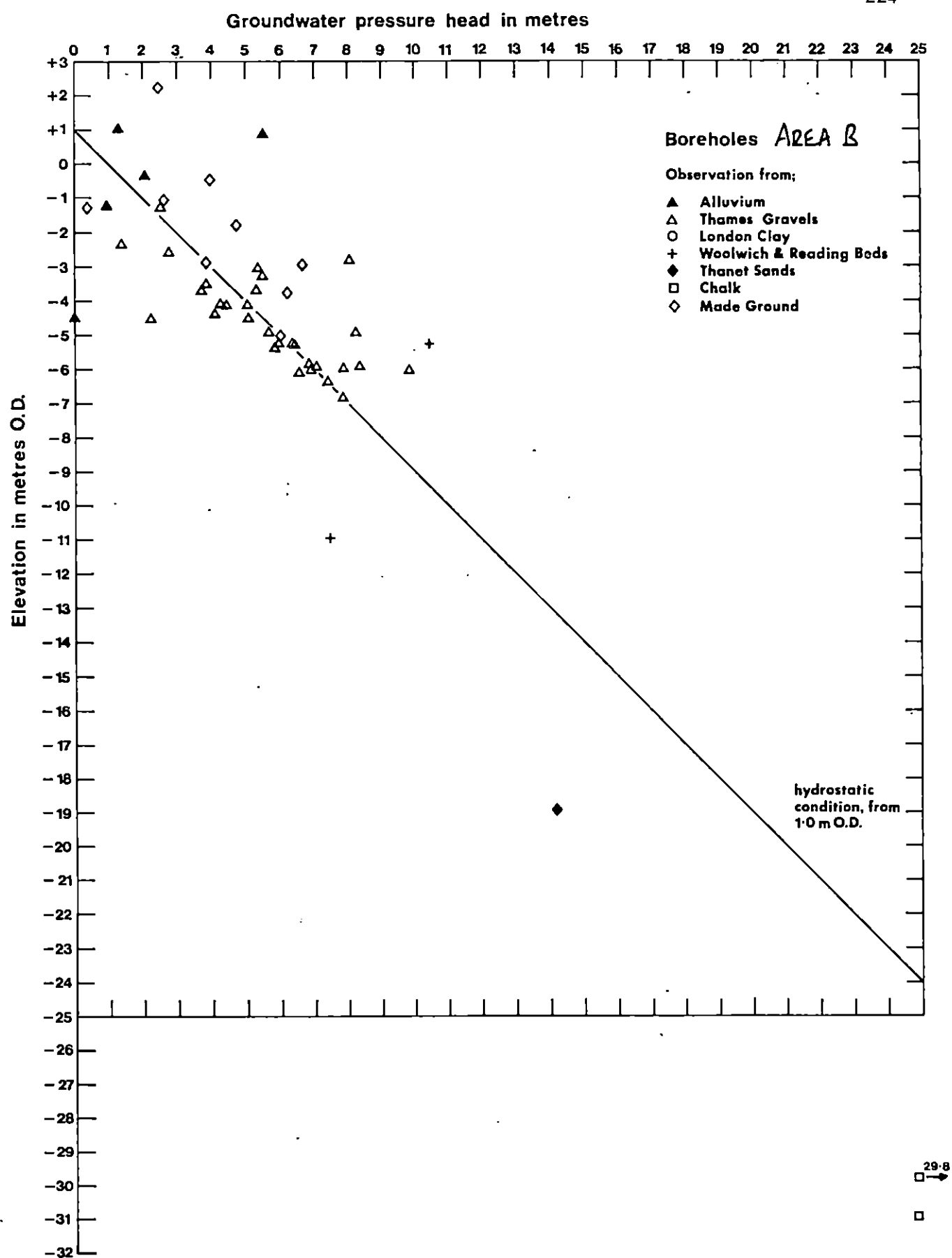


Figure 66b.

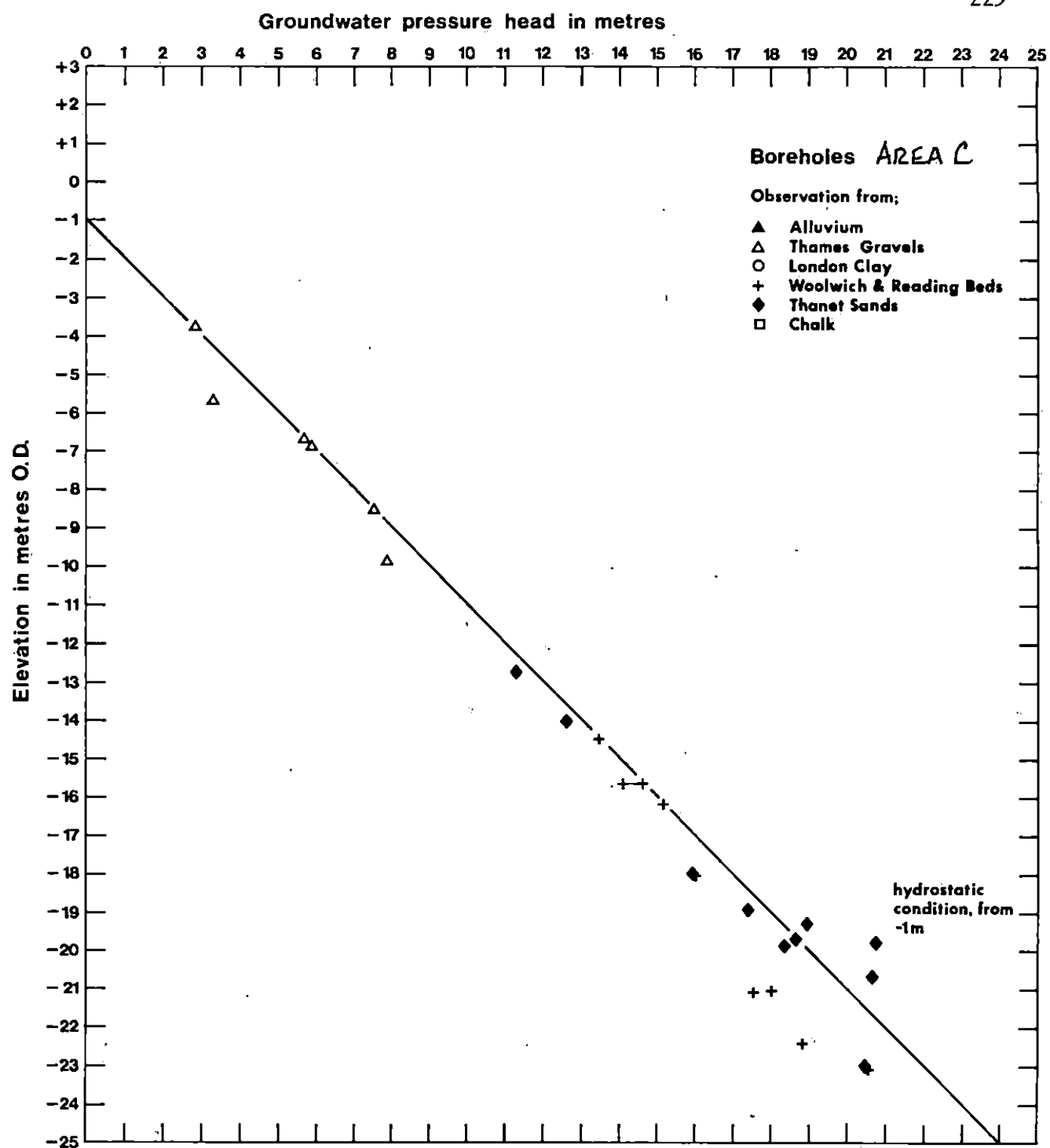


Figure 66c.

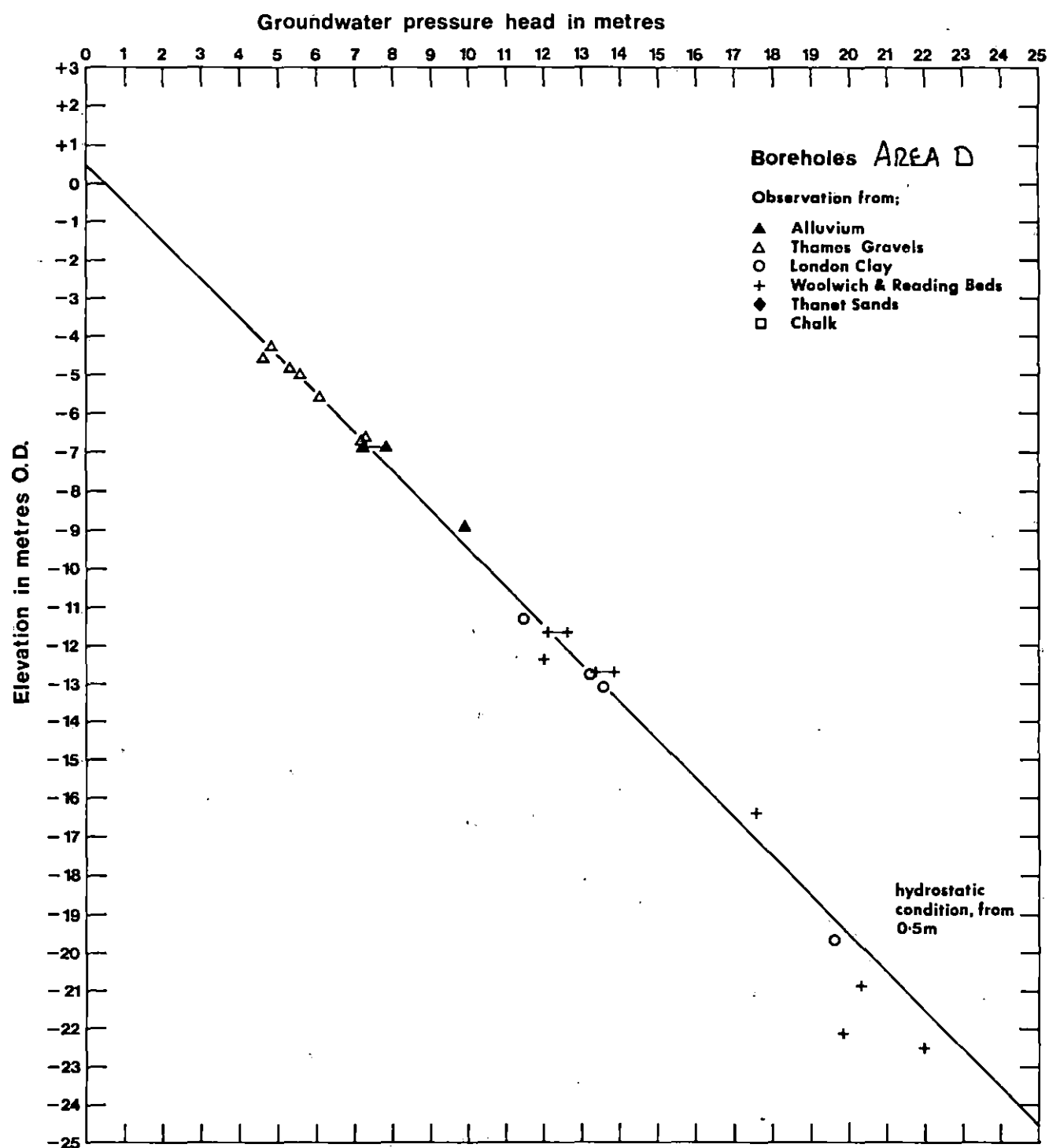


Figure 66d.

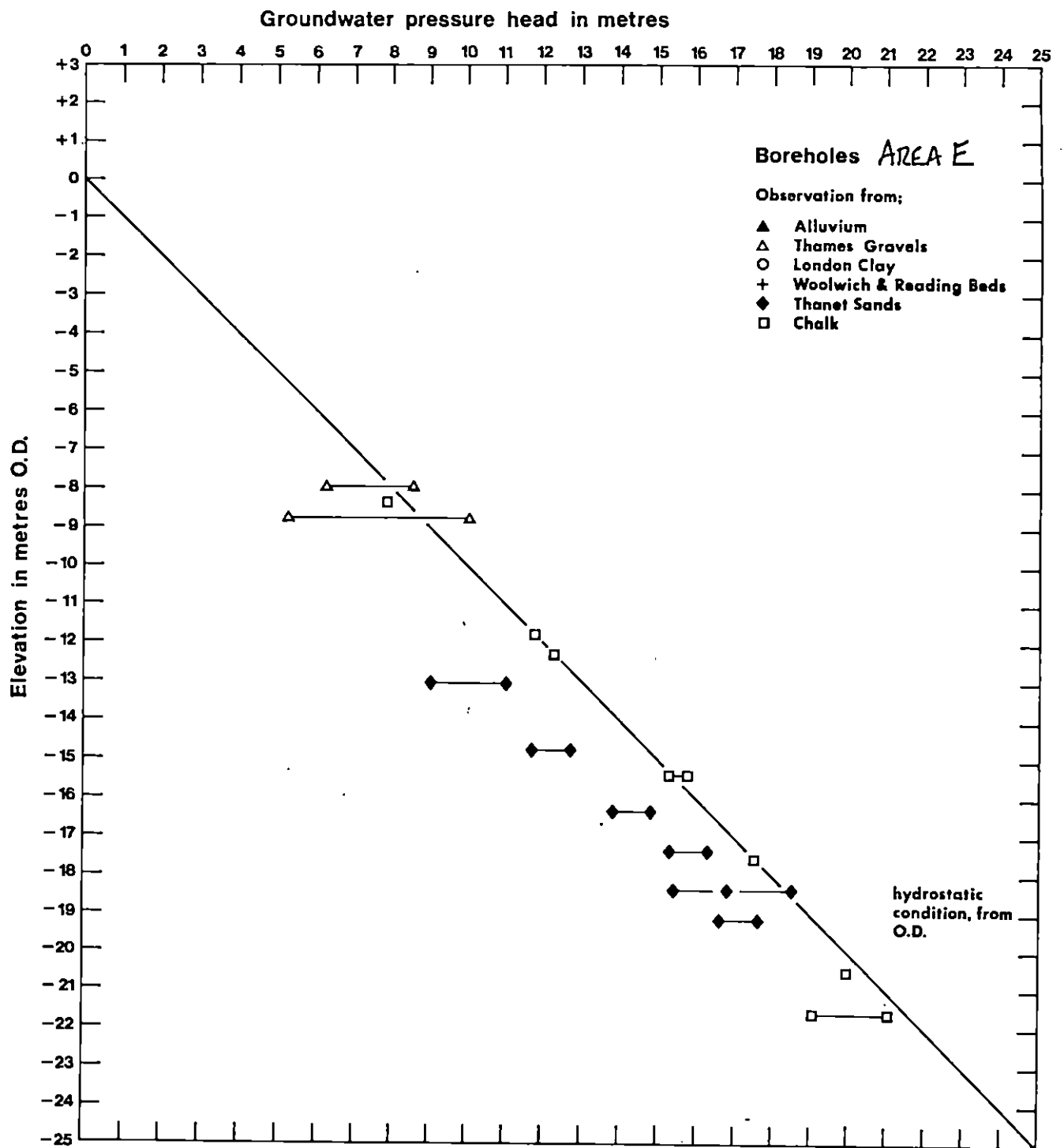


Figure 66e.

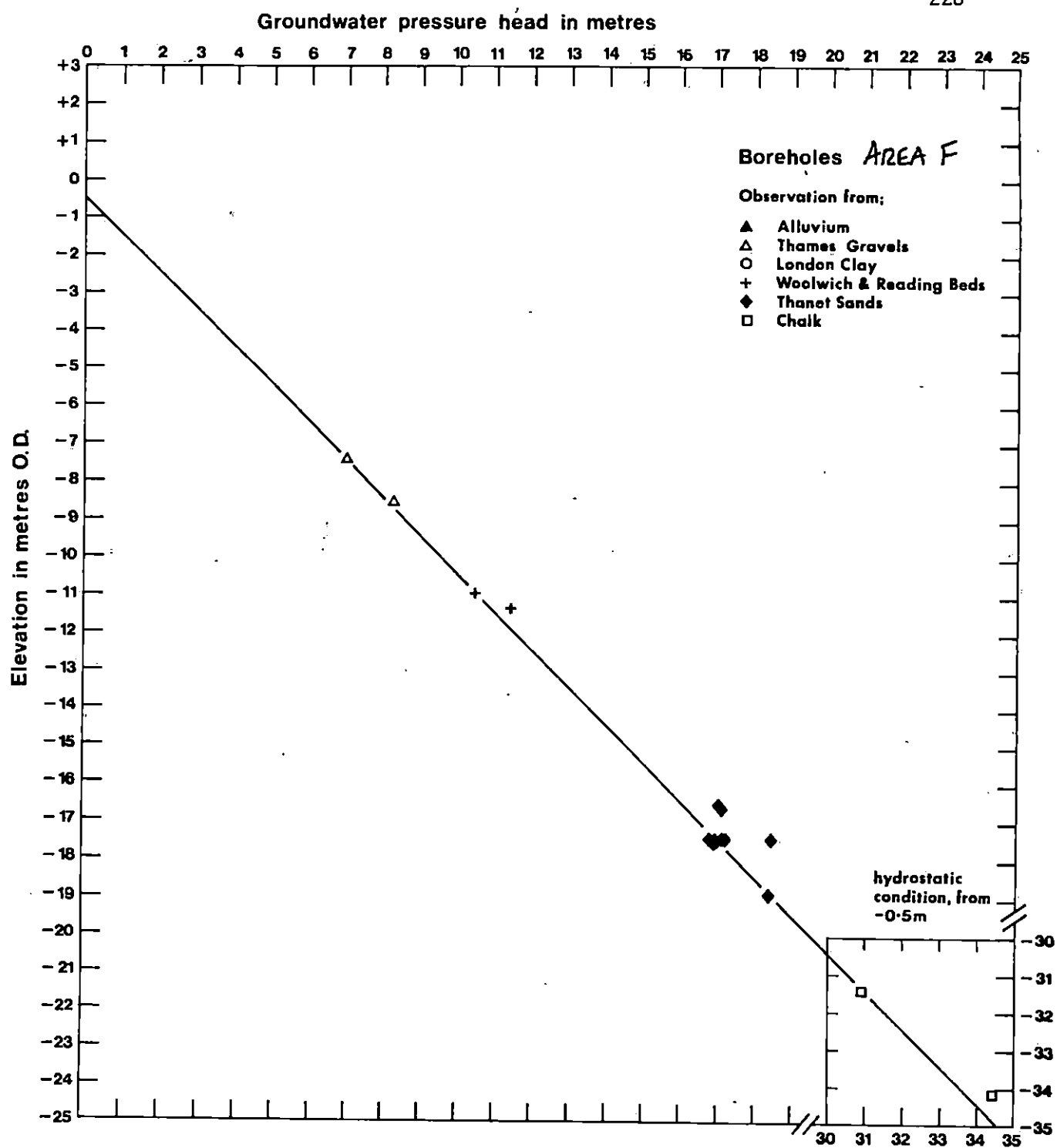


Figure 66f.

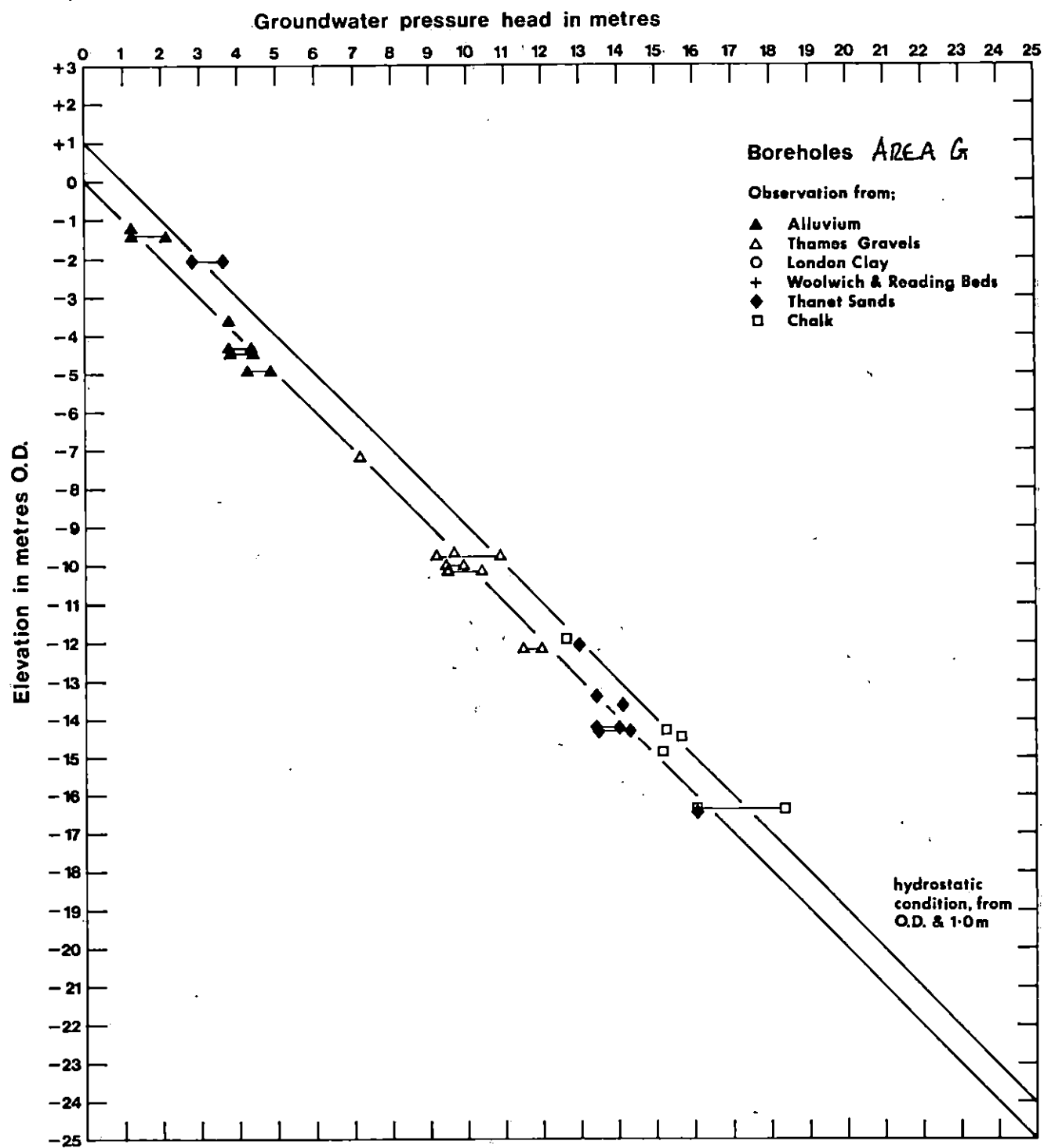


Figure 66g.

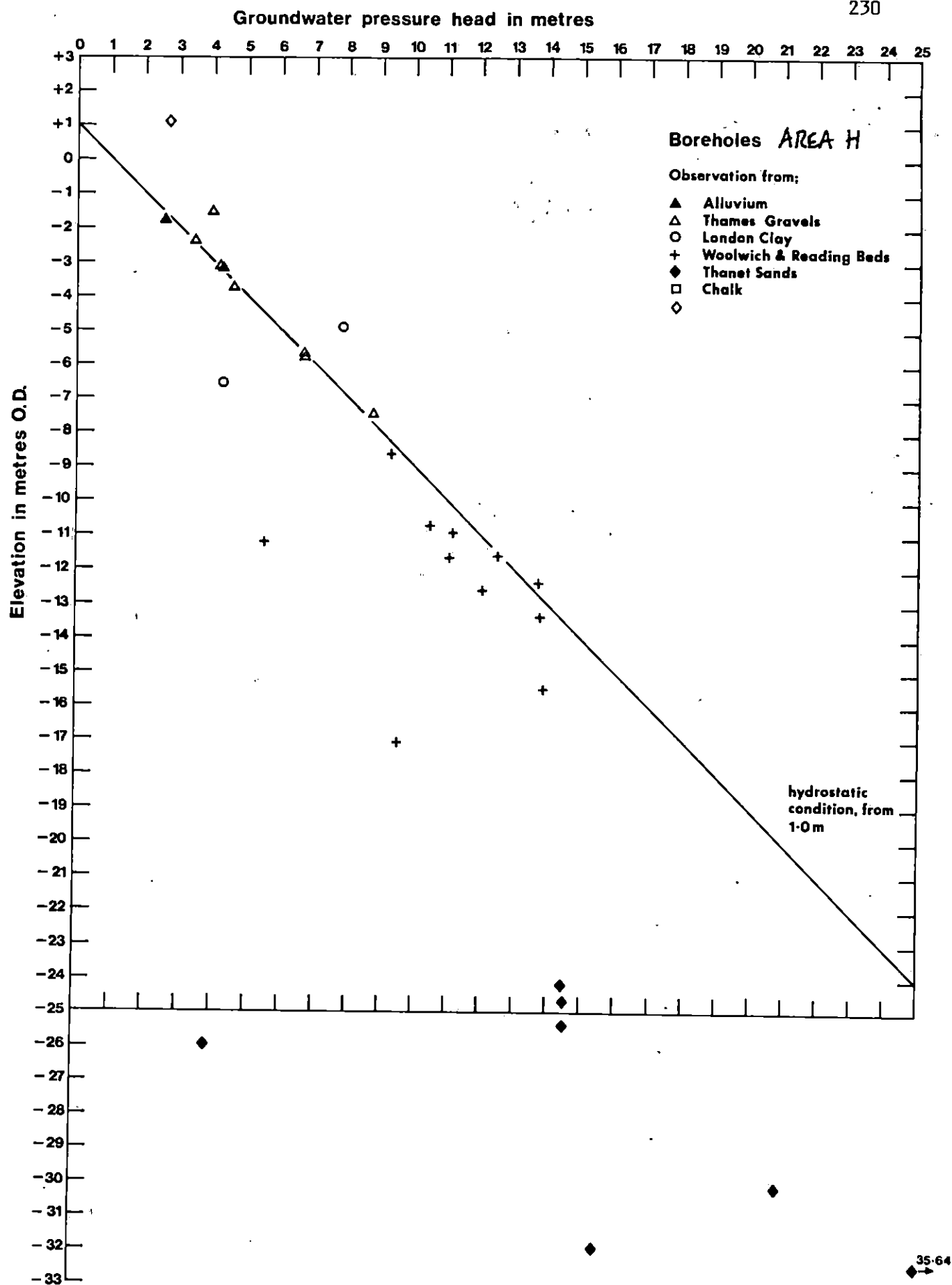


Figure 66h.

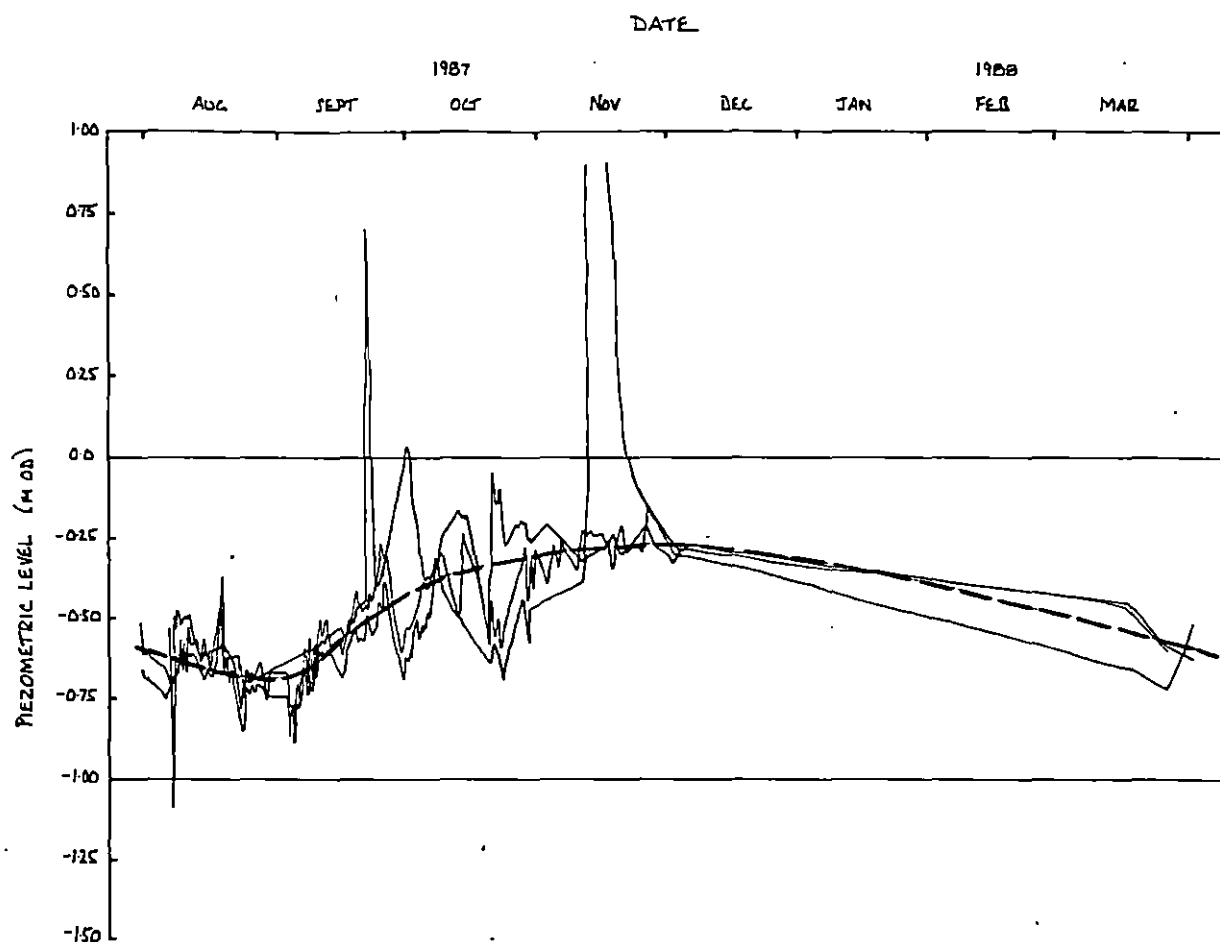


Figure 67.

Piezometric levels from piezometers installed in Area F of figure 66 showing an apparent annual fluctuation of some 0.5m. The composite plot shows measurements from two instruments in the Thanet Sands and one in the Thames Gravels.

change has occurred between 1977 and 1987/8 that a stable situation in this part of the aquifer has re-established itself.

7.7 Saline Intrusion

A consequence of the reduced groundwater levels in the lower aquifer has been the penetration of saline water from the Thames into the aquifer. Under natural conditions the groundwater flowed towards the Thames which acted as a discharge boundary for the aquifer. As the natural piezometric level was lowered the groundwater flow became independent of the Thames and flowed towards the developing cones of depression (fig. 61). The saline intrusion occurs along both sides of the Thames but is not symmetrical. In fact it extends some three to four kilometres on the north side but generally less than a kilometre on the south. This is largely due to the modifying effect of the principal groundwater flow in the aquifer (fig. 57b) but it may also be aggravated by the presence of the dock systems which exist mainly to the north of the river. All the groundwater in the lower aquifer in Docklands is within the 150 mg/l isochlor which is usually taken to define the boundary of the saline intrusion (Water Resources Board 1972). However, this does not necessarily define the full extent of the intrusion as concentrations below this may be a result of dilution by the natural groundwater.

7.8 Engineering significance

The hydrogeology of the region has been shown to be in a state of flux and is likely to change substantially over the next few decades. The consequences of the general rise in groundwater level have been described by Wilkinson (1984, 1985). He describes not only the consequences of new and increasing water flows into basements and tunnels but also the consequential increase in pore pressure and loss

of effective strength in the soils. Although, the potential flooding of basements and tunnels can be accommodated by pumping, the effects of a change in soil stress may be less easily overcome.

The increase in pore pressure will increase the lateral loads acting on basement walls and retaining structures. The associated decrease in effective shear strength will modify the behaviour of foundations, particularly those deep on piles. It will have the effect of reducing the factor of safety of the original design and could reduce it to below an acceptable margin. The reduced shear strength, perhaps in association with an increase in moisture content of the more cohesive soils, will also increase compressibility. Although, all the affected foundations will experience an increased settlement, where complex foundation solutions have been adopted for structures they are likely to be subjected to increased differential movements as the individual elements respond differently or at varying rates.

It is suggested here the problem is likely to be extended further in the Docklands for although the overall return of groundwater levels in the lower aquifer will affect deep structures and foundations as postulated by Wilkinson, since it acts as a recharge source to the upper aquifer it is likely that its water levels will also rise with an effect on more modest structures.

The situation will be further complicated by the development which takes place in the area. These will impose their local modifying influence on the groundwater patterns. Although, this is dependent on the nature and scale of the development it will add a confusion to the situation that will make reliable prediction less certain.

In summary, therefore, there is an interactive relationship between the redevelopment of the area and the groundwater regime. It is necessary that the renewal process takes due notice of this and that any design proposals are able to accommodate the final effect.

CHAPTER EIGHT : THE USE OF THE DATABASE IN URBAN RENEWAL AND ITS POTENTIAL AS A SCIENTIFIC TOOL

8.1 Introduction

Chapter Two proposed that a systematic approach to the understanding of the engineering geology of Docklands was of more benefit to the aims and requirements of the LDDC than would have been a series of otherwise unrelated project specific studies carried out on a piecemeal basis. The development and use of the GEODASY database has formed an integral part of this approach. The lack of development time and the pressure for immediate results meant that it was important that the techniques devised were able to be modified in order to respond to the needs of further situations. Similarly, the approach required an overall flexibility so that such modifications could be incorporated to the benefit of the system in general and future situations in particular.

A case history from the Royal Docks Drainage Scheme is given to illustrate the benefits to a specific situation from following the philosophy developed in this thesis. It shows the value of the overall understanding of the area in such situations and the ability to develop and test that understanding with the processing power of the database. This improves the understanding for later situations.

8.2 Royal Docks Drainage Scheme

8.2.1 Background

The redevelopment of the Royal Docks area has required the construction of a new main drainage system incorporating foul and surface water sewers (fig. 68). For the most part these have been constructed in tunnel with diameters of 1.8 to 2.1m at depths up to

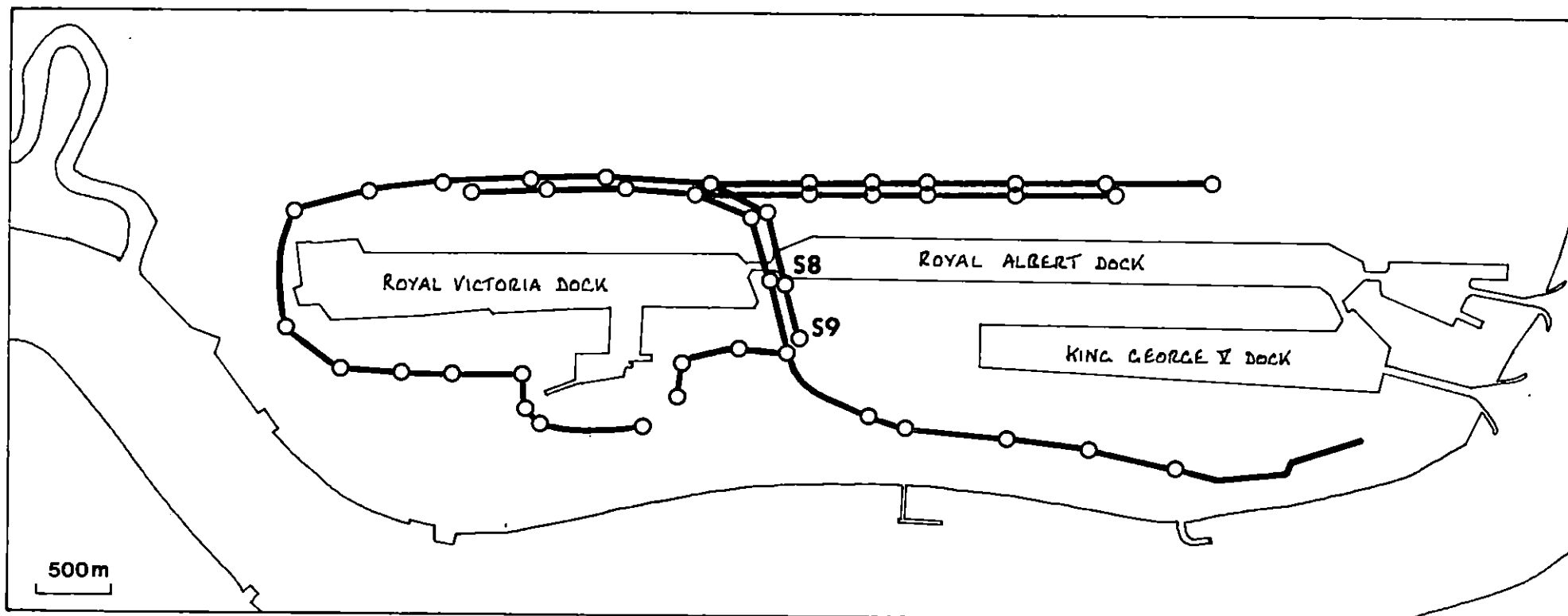


Figure 68. The Royal Docks Drainage Scheme

The failure of the tunnelling machine described in the thesis occurred while driving south from shaft S8 to shaft S9

17m. During the construction of one section which crossed from the north to the south of the docks the tunnelling machine experienced difficulties and had to be abandoned 50 metres from completion of the drive. The need to drive below the docks themselves and the concern that high water flows could be experienced had prompted the use of a slurry shield tunnel boring machine (TBM). A Herrenknecht Mixshield was adopted with the lining being installed by a pipe jacking technique.

Having successfully passed below the dock the TBM experienced a series of sudden settlements over a two day period that resulted in it being 370mm below the design vertical alignment. The resulting articulation in the following sections meant that the jacks were unable to achieve further advance. In effect the machine became stuck.

A detailed forensic investigation was carried out to determine the ground conditions in the vicinity of the machine under the control of a committee comprising the consulting engineer, the contractor and the writer for the LDDC. The agreed information was provided to each party for separate consideration of the cause of the situation. The investigation was aggravated because the machine had become stuck below the operating area of the new City Airport. It lay off the end of the runway immediately below an area of roadworks to provide a roundabout and road improvement to form the main entrance to the Airport. The area also formed the main marshalling area for the emergency services and during the course of the investigation the Airport was officially opened by Her Majesty the Queen. Therefore although the investigation was driven by the need to gather particular elements of information the ability to carry this out was controlled by a detailed logistics exercise which required a high degree of interfacing with other parties who themselves usually had no direct interest in the success of the operation.

8.2.2 Ground Conditions

The original site investigation for the scheme showed that the drive would encounter the Woolwich and Reading Beds along most of its length. A slight general dip of the beds towards the north meant that as the drive proceeded in a southerly direction progressively lower beds of the Formation would be present.

The contractor suggested that a reasonable interpretation of the original investigation showed that the contact between the Woolwich and Reading Beds and the underlying Thanet Sand was some two metres below the invert of the machine at its final position. This assumed a straight line interpolation between the two adjacent boreholes along the line of the tunnel. The subsequent detailed investigation showed there to be a coincidence between the contact of the Woolwich and Reading Beds and the Thanet Sand with the invert of the tunnel at the point of failure. The writer proposed that contour plans using the immediate regional data provided a better model of such trends. Contouring of the available boreholes in the area indeed suggested the base of the Woolwich and Reading Beds to be at about -14.5m OD. This was modified once the forensic investigation was complete to about -12.5m OD (fig 69). This also demonstrated that the contact between the two Formations was not planar but had a local undulation with an amplitude of about 0.5m. The final position of the head of the machine was the first point at which the Thanet Sand rose to the invert level on both sides of the tunnel line.

This aspect was further considered in view of the implication that this had on the claim situation. It was apparent on long sections that there was an apparent uncertainty in the basal beds (D5a and b) of the Woolwich and Reading Beds and although the higher limestone horizon (D5c) was fairly planar the contact with the Thanet Sand tended to undulate (fig 70a). A number of additional boreholes were positioned adjacent to two boreholes from the initial investigation. Comparison of these showed an apparent thickening of the lower

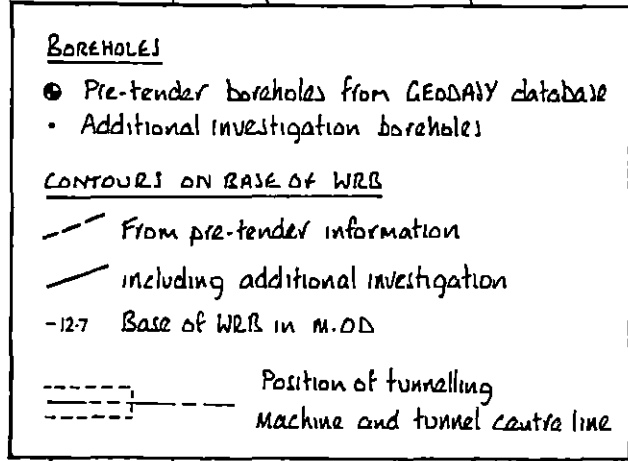
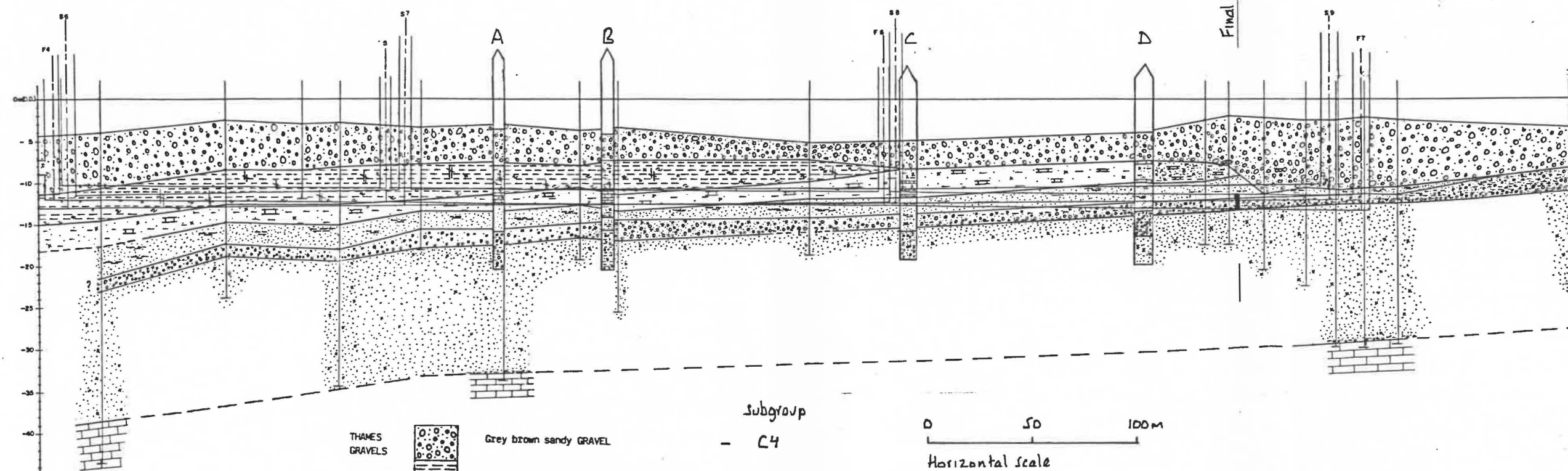
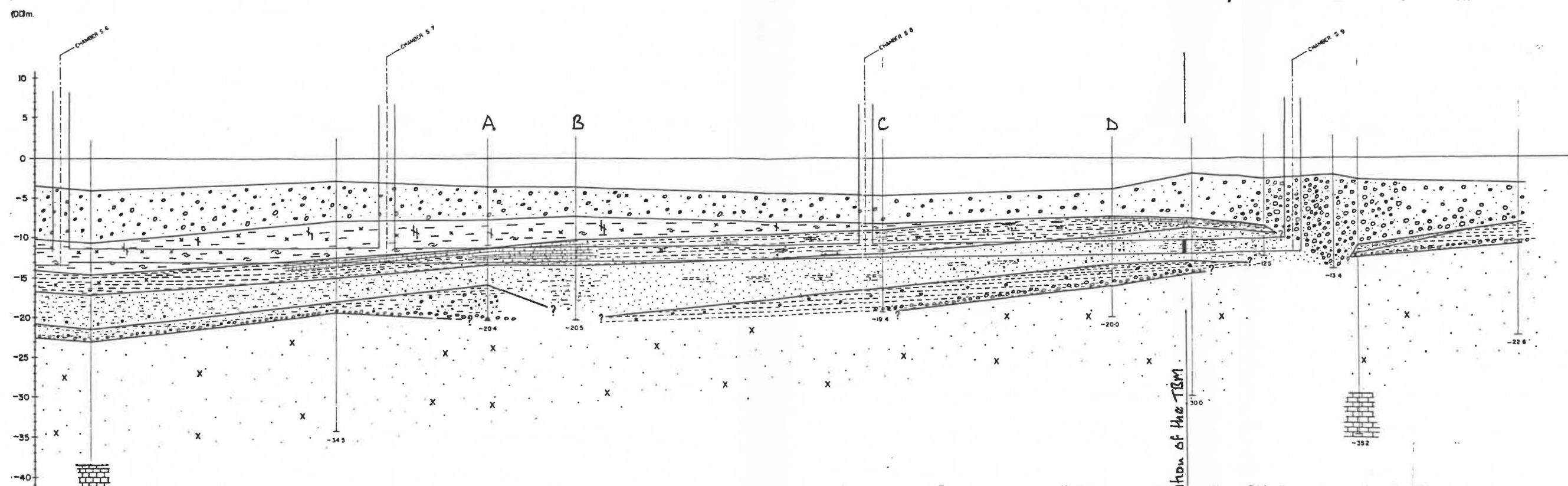


Figure 69. Contours on the base of the Woolwich and Reading Beds (WRB) based on information available before and after the tunnelling machine became stuck on the drive to shaft S9



		Subgroup
THAMES GRAVELS	Grey brown sandy GRAVEL	- C4
WOOLWICH	Stiff grey mottled fissured silty CLAY becoming very shelly with depth	- D5e
AND	Hard calcareous SILTSTONE/LIMESTONE with very stiff grey green white mottled sandy CLAY, with occ. shells and gravels	- D5z/c
READING BEDS	Clayey SANDS or/and sandy CLAYS	- D5b
	Green/dark grey sandy silty CLAY and fine SAND with abundant black rounded gravel	- D5a
THANET SAND	Very dense grey brown silty fine SAND	- D4 b/c
	Brown sandy CLAY with abundant pebbles	- D4a
CHALK	Rubby and blocky CHALK, locally weathered occasional flint throughout	- D3

Figure 70

The change in understanding of the of the base of the Woolwich and Reading Beds based on;

- pre-tender information
- further information from the additional investigation and the postulation that a number of original boreholes (A, B, C and D) were unreliable over their lower levels

strata in the original boreholes not present in the check boreholes. A further check on the original boreholes showed that those holes with the apparently thicker basal units were all bored by a single driller. The long section redrawn using the new data and without the information from those earlier holes shows a more persistent dip to the contact with the Thanet Sand which is sub-parallel to the strata in the higher beds (D5c) (fig 70b). It is postulated by the writer that the original boreholes had only been taken to a depth of 20m or so instead of the specified 25m and that the samples over the lower few metres were concocted from material from above. This resulted in the apparently lowered base of the Woolwich and Reading Beds as was initially interpreted from the boreholes available at tender stage.

8.2.3 Engineering characteristics

In Chapter Six the Thanet Sand have been shown to be a silty fine to medium grained sand with a overall distinctive uniformity in grading. It has been also been argued that the material can be regarded as being a 'locked sand'. A necessary characteristic of such material is that it has no effective cementation, that is it not bound together by any other means than the mechanical interlock of its constituent grains. As such the material can be very strong in an undisturbed state, and will even exhibit an apparent cohesion, however the lack of cementation means that the condition can be catastrophically and irreversibly disrupted.

In contrast to the Thanet Sand the lower levels of the Woolwich and Reading Beds in the area were found to show a much wider grading envelope (fig. 71). Perhaps the most relevant difference between the two being the greater percentage of fines in the Woolwich and Reading Beds. Indeed, although the major proportion of the grading lies within the sand fraction or coarser very often sufficient fines are present to give the material a measureable plasticity index. A marked cohesion is also similarly present in the Woolwich and Reading

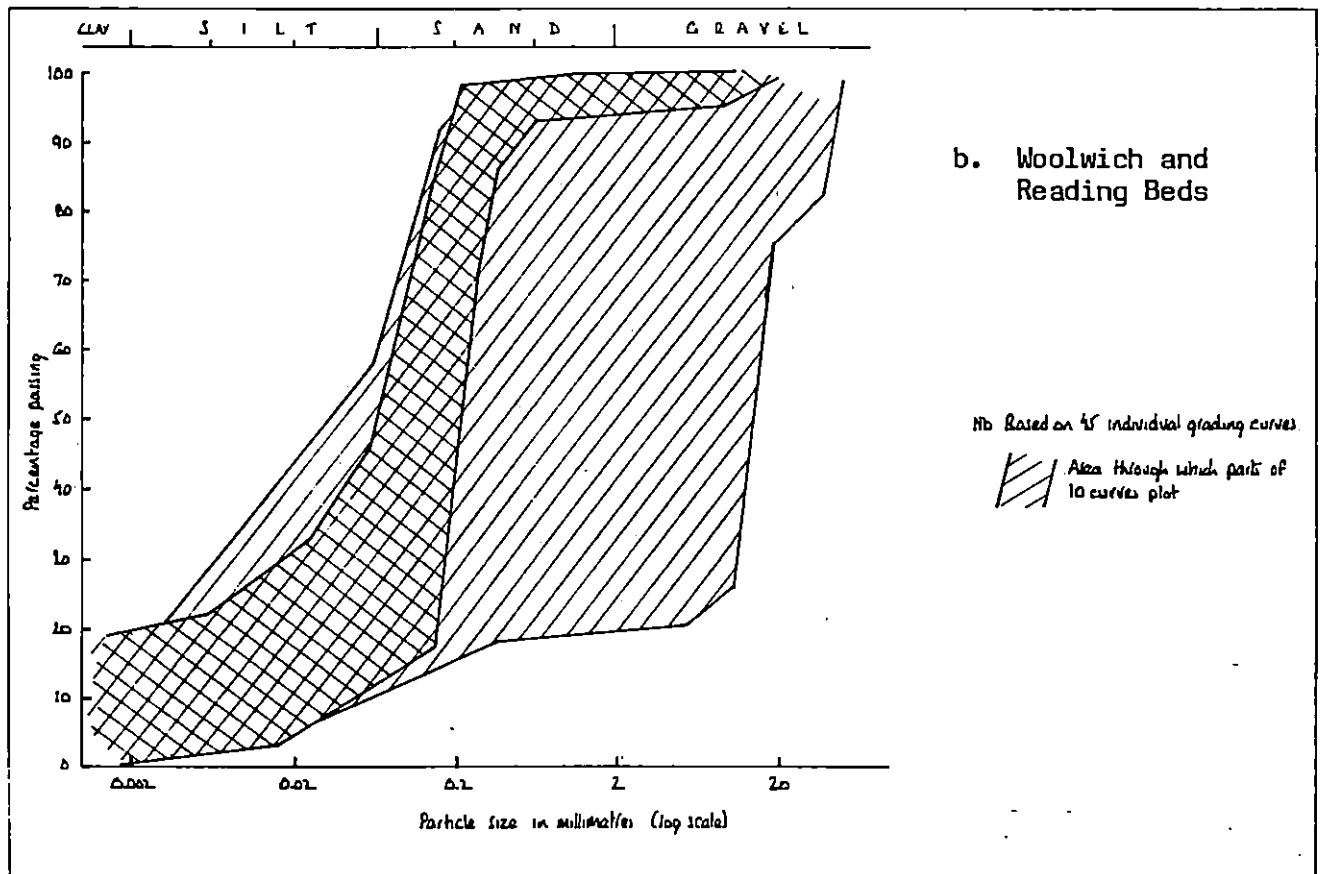
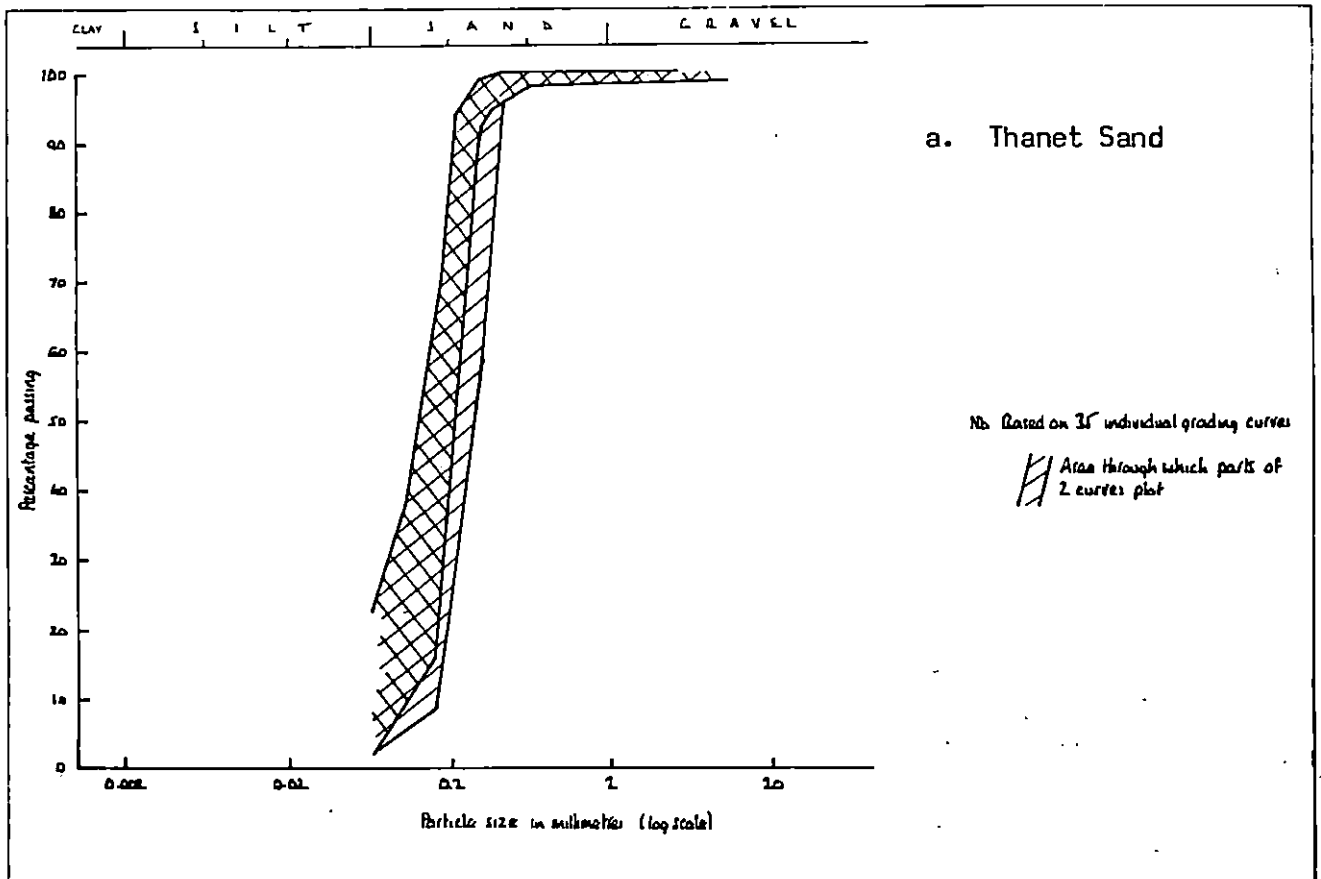


Figure 71

Grading envelopes for the Thanet Sand the lower facies of the Woolwich and Reading Beds (Bed b) in the vicinity of the tunnelling machine

Beds. However, as this is due to the fines present it may be regarded as more real than apparent. Standard penetration test results in the Woolwich and Reading Beds are characteristically lower than from the Thanet Sand. Often the test is not able to be completed in the Thanet Sand due to the high blow counts achieved, in contrast this is not the case in the Woolwich and Reading Beds. Nonetheless, the bulk density of the Woolwich and Reading Beds is comparable to, and can be greater, than that of the Thanet Sand. It seems that the locked condition is not present in the Woolwich and Reading Beds and that the clay content has precluded the development of grain intergrowth.

The variation in fines content is also reflected by a difference in the permeability of the two materials. A detailed assessment by in situ and laboratory measurement indicated a permeability for the Thanet Sand of $10^{-6} \text{ m sec}^{-1}$ compared to $10^{-8} \text{ m sec}^{-1}$ for the Woolwich and Reading Beds. As the Woolwich and Reading Beds has a greater variation in its grading and a better developed sedimentary structure it can also be expected to have a greater local variation than the Thanet Sand and a greater ratio of horizontal to vertical permeability.

8.2.4 Underlying Principles to the Mechanism of Failure

The mechanism which allowed the failure is believed to be understood by the writer and is demonstrated to have occurred because of the presence of the more permeable Thanet Sand below the less permeable Woolwich and Reading Beds. Nonetheless, failure in this situation was not inevitable but due to circumstances which resulted in a method of operation of the slurry shield at the time that the conditions were encountered.

The tunnel was constructed about 12 metres below the natural water table and would therefore act as a drain to which the groundwater

would flow. This flow upsets the hydrostatic situation of the groundwater and causes a change in the pore pressures acting around the tunnel. This change can be modelled conveniently by a flow net construction which can then be used to determine the total head condition around the tunnel (fig. 72). The flow net consists of flow lines and equipotential lines which intersect each other at right angles. The flow lines represent the drainage path that the groundwater would follow and the rules of construction require that an identical volume of flow is contained by any two adjacent flow-lines. It can quickly be seen from figure 72a that flow occurs fairly evenly around the tunnel and is not necessarily concentrated at the crown as perhaps might at first thought to be the case. The equipotential lines therefore represent lines of equal total head. As shown in Chapter Seven the total head distribution is the product of both the pressure head and the elevation head (fig. 73). Therefore, a piezometer placed to intercept a given equipotential will show a pressure head, measured as equivalent head of free groundwater, which would rise to the same level above a fixed datum, as shown by piezometers d, e and g on figure 72a. Flow nets also dictate that the difference in head between any two adjacent equipotential lines is constant. Therefore piezometers placed on the equipotential lines would show a uniform drop in the equivalent head of groundwater between that measured at the recharge boundary, in this case the base of the gravels, and the discharge boundary, in this case the tunnel invert. Referring again to figure 72a it can be seen that the distance over which this change in head occurs reduces towards the tunnel. This rate of change is the hydraulic gradient and can be seen to be greatest at the tunnel invert.

The rate and distribution of total head change around a tunnel can therefore be described by a flow net construction. Its form is dependent on the geometry of the situation and, in that it requires a steady state situation, also on time. Where the ground is uniform for large distances around the tunnel the flow net shows relatively gradual changes around the tunnel (fig. 72a).

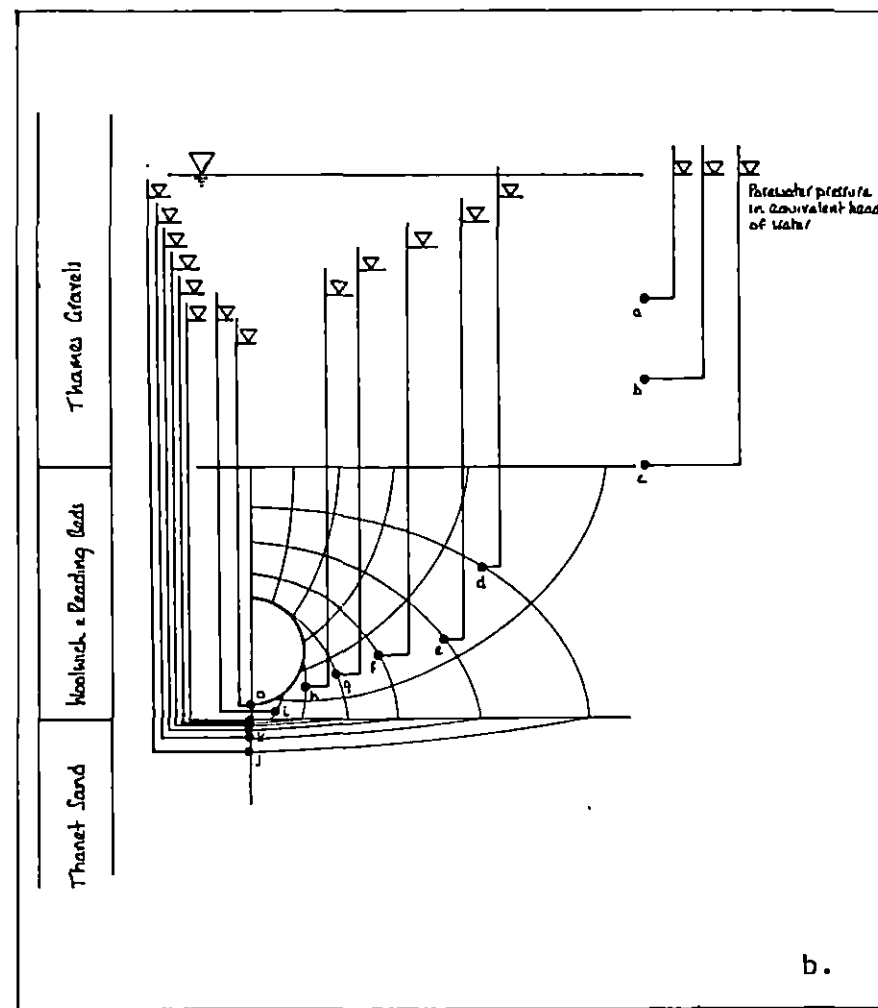
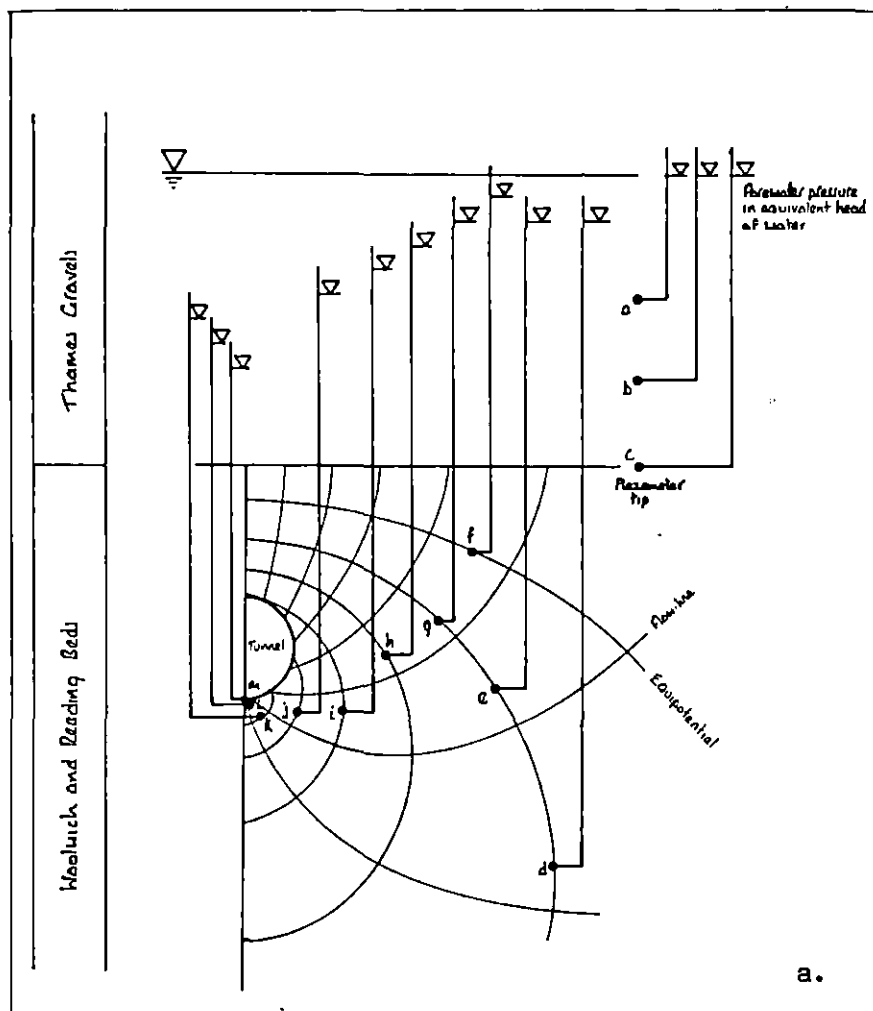
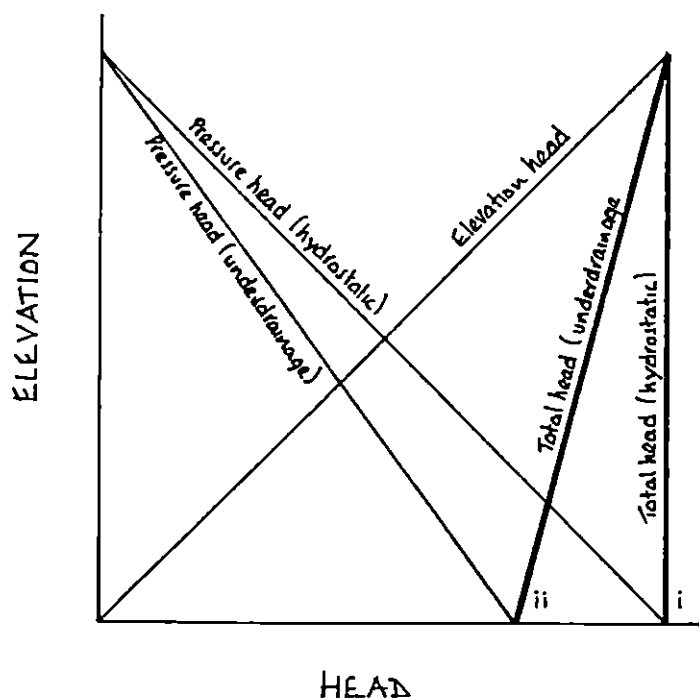


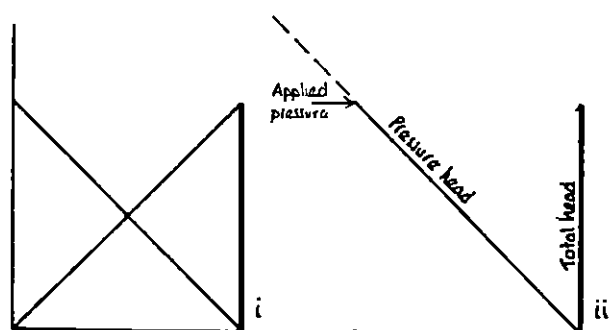
Figure 72. Generalized flow net construction for, a) when the Woolwich and Reading Beds are found to depth, and b) when the Thanet Sand is close to the invert

Note that uniformity and isotropy is assumed in each of the soil units. Pressure head is shown schematically at various points by a number of hypothetical piezometers, referenced a - o.



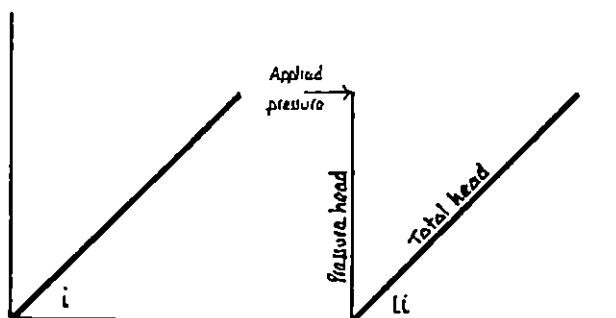
a) Groundwater

- i) for hydrostatic condition
- ii) for hydrodynamic condition caused by underdrainage



b) Slurry shield face support

- i) Unpressurized
- ii) Pressurized



c) Compressed air face support

- i) Unpressurized
- ii) Pressurized

Figure 73. Head distribution for groundwater and face support systems using a slurry shield and compressed air

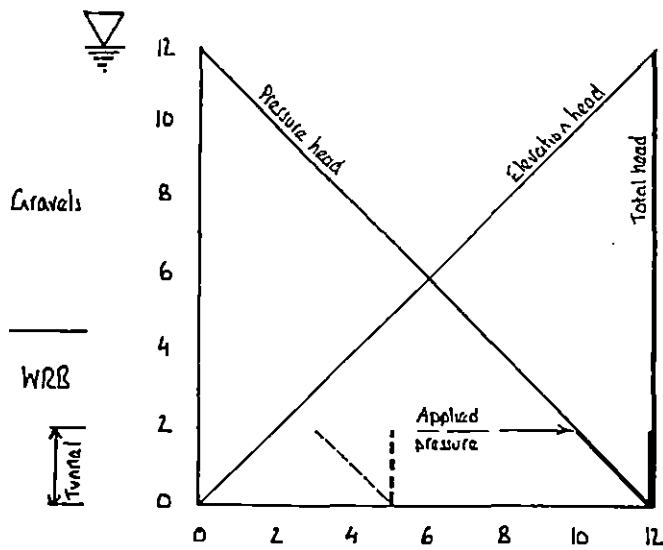
The magnitude of the pore pressure change represented by the flow net is a direct function of the difference between the total head acting at the recharge and discharge boundaries. As the total head at the recharge boundary can be shown to be constant the pore pressure changes are directly related to the operating tunnel pressures. This can again be illustrated by reference to figure 72. In the hydrostatic situation the increase in elevation head with depth is purely a function of depth such that a series of piezometer tips would show a rise of free groundwater to the level of the groundwater table regardless of the depth at which they were installed. The high permeability of the Thames Gravels will allow a greater recharge than could drain through the less permeable Woolwich and Reading Beds. The consequence will be that hydrostatic conditions would almost persist in the Thames Gravels even when drainage is occurring to the tunnel. That is piezometers such as a, b and c would indicate a pore pressure distribution measured in equivalent head of water which would rise to the natural groundwater table. The pore pressure in the less permeable Woolwich and Reading Beds reduces according to the flow net. The equipotential lines indicate a regular change in total head as illustrated by the piezometers d to m. Therefore it can be seen that as the tunnel pressure increases, so that the difference in total head between that and the recharge boundary is reduced the absolute pressure at each equipotential, as indicated by the rise in the water level in the standpipes, would increase. Eventually if the tunnel pressure was increased sufficiently the water levels in the standpipes would return to the free groundwater level in the gravels. This would indicate that no flow was occurring and that the groundwater had reverted to a hydrostatic condition.

Where the more permeable Thanet Sand is present within a close distance to the invert of the tunnel the flow net and head distribution is modified accordingly. It is seen in figure 72a that the groundwater over the lower section of the tunnel has a strong component of upward flow. If the soil has a greater permeability

with depth the groundwater will flow more readily through to replace that lost by drainage to the tunnel. The equipotential lines are therefore refracted at the boundary of the two materials (fig. 72b). By considering the effect of a series of piezometers it can be seen that the refraction of the equipotential lines in this way will maintain a higher total head in the more permeable material at any depth than if the less permeable strata only had been present.

The distribution of the pore pressures around the tunnel can be readily understood by resolving them into their component pressure head, elevation head and total head (fig. 73). In such a diagram head is measured relative to a datum and it is the total head distribution which determines the direction and amount of flow. Under hydrostatic conditions the pressure head and elevation head are summed to obtain a total head which is constant with depth and which shows that no flow is taking place, figure 73a. On the other hand if underdrainage is taking place in the groundwater the pressure head will be reduced. The elevation head will remain a constant so that the total head will reduce with depth indicating a downward flow in the groundwater.

The distribution of the pressure acting in the tunnel face support systems may be similarly represented (fig 73b and c). For example in a slurry shield system (fig 73b) the slurry operates as a fluid medium and its pressure, elevation and total head will have a similar form to the groundwater distribution. The slurry operates in a closed system so that it can be pressurized. This will have the effect of increasing the pressure head and moving the total head to the right. By combining the two concepts the relationship between the groundwater and the face support can be illustrated and appreciated. Figure 74a shows that in order to maintain hydrostatic conditions in the groundwater the face pressure would need to be increased until the total head in the slurry was equal to the total head in the groundwater. Figure 73 shows that the pressure necessary to achieve this is a function of the point of application. However

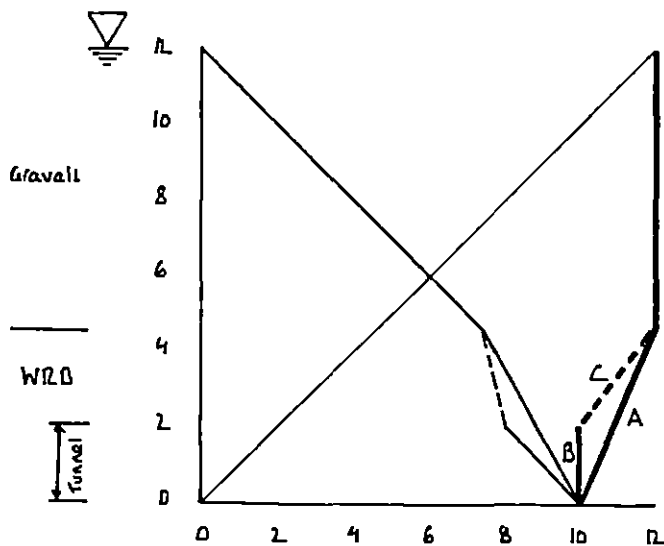


a) To maintain hydrostatic conditions

Pressure applied to the face system must be sufficient to move the total pressure in the face slurry to the hydrostatic groundwater condition

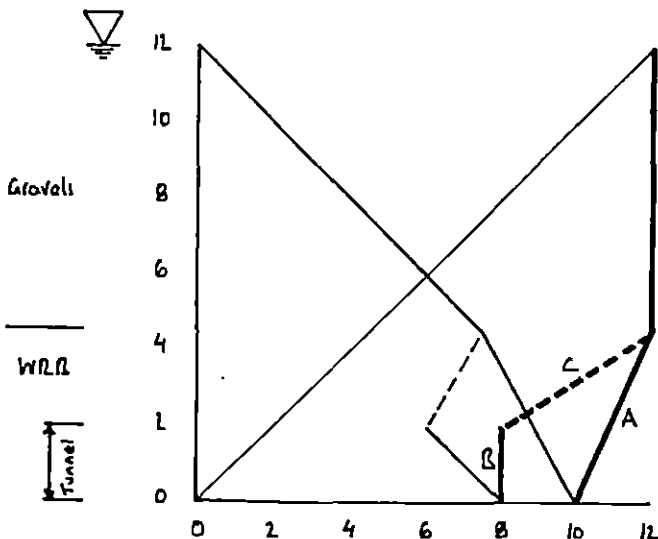
Nb The following diagrams show the total head in :-

- A - the surrounding ground
- B - the tunnel support system
- C - the interface between the two



b) To maintain 'no flow' with groundwater drainage to the tunnel system

As some drainage to the tunnel will occur (see text) the slurry pressure required to maintain 'no flow' at the face will be less than necessary to maintain the theoretical hydrostatic groundwater pressure

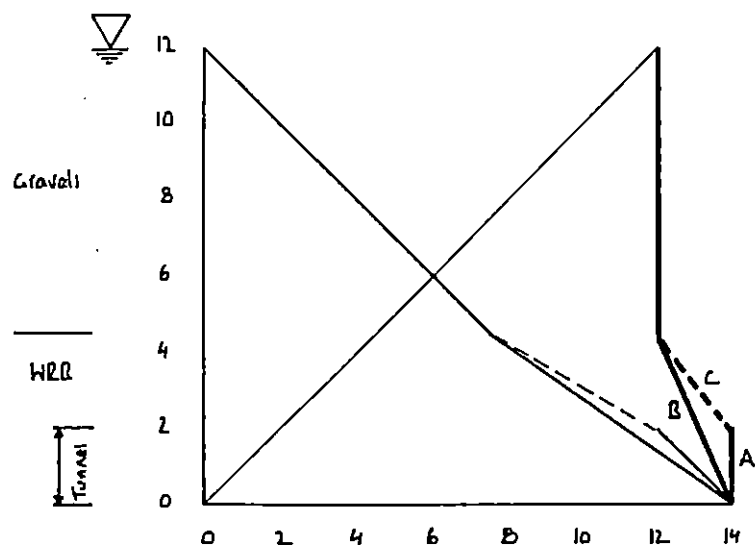


c) Rapid loss of face pressure

The pore pressures around the tunnel will respond only slowly to a rapid loss of pressure in the slurry. This will create an imbalance prompting increased drainage to the tunnel face

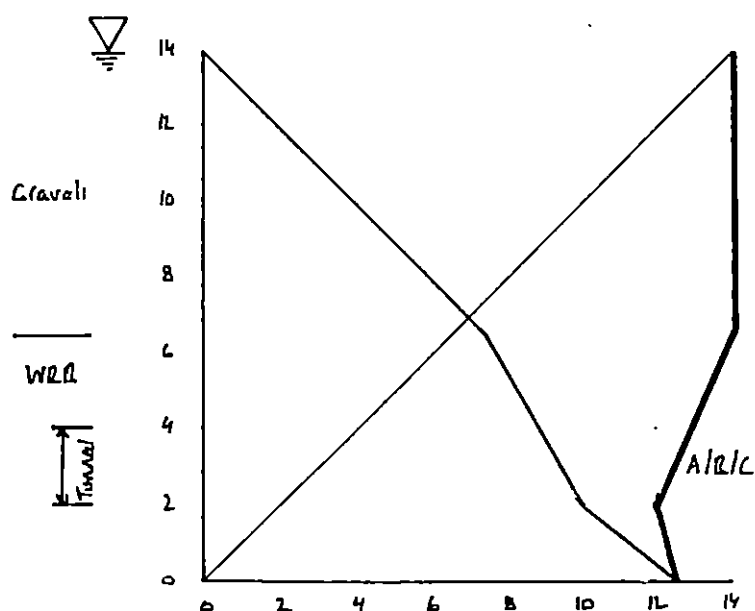
Figure 74. Idealized head distribution during slurry shield tunnelling

(continued over)

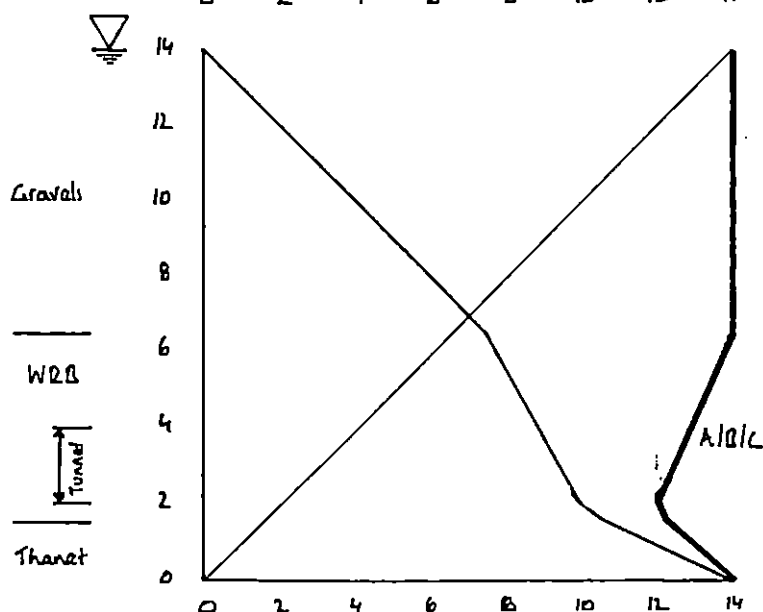


d) Maintaining the face pressure higher than hydrostatic groundwater pressure

Slurry pressures operating at levels higher than the groundwater pressures will increase the groundwater pressure immediately around the tunnel to a level greater than hydrostatic



e) 'No flow' situation with WRB for some distance below invert



f) 'No flow' situation with Thanet sand below invert

Nb: Datum level for head distribution is 2m lower than in a. to d.

Figure 74. (cont) Idealized head distribution during slurry shield tunnelling

it has been discussed above that the presence of the tunnel will act as a drain and that pore pressures around the tunnel will reduce as flow occurs towards it. The result is that a total head somewhat less than that equal to the hydrostatic condition of the groundwater would be theoretically required to establish a 'no-flow' situation to the tunnel face. Conversely if the face pressure is maintained at a level greater than the hydrostatic condition there will be a potential loss of slurry to the surrounding ground, figure 74d.

The similar schematic representation can be used to illustrate the difference between the influence of the Woolwich and Reading Beds at depth below the invert and the presence of the Thanet Sand within an influential distance of the invert. By reducing the datum point of the diagram to some level below the invert the component of upward flow shown by the flow net diagrams can be appreciated (fig. 74d and e). Figure 72 demonstrates that the pore pressures in the Thanet Sand would be greater for any given distance below the invert than would be the case for the Woolwich and Reading Beds. This is converted into a total head distribution to show the more rapid regain of total head in the groundwater below the invert (fig. 74d and e).

The principle concerns in the tunnelling procedure are the need to provide adequate stability to the face and the control of the absolute level of groundwater inflow balanced against the possibility of a blow-out. It can thus be seen from the above principles that the balance is sensitive to the ground conditions, the acting pressures around the tunnel and the type of machine, and in particular the way that face support is provided and the way that face pressures are maintained.

This therefore shows that as the permeability of the soil reduces so does its sensitivity to the balance pressure. At the two extremes, a clean sand would not remain stable at the face if the supporting pressure in the tunnel were not closely balanced to it. On the other

hand a clay could be excavated in free air even with the same head of water. In the middle range the materials will tend towards one extreme or the other. The less permeable Woolwich and Reading Beds can therefore be expected to be less sensitive to face pressure conditions than the Thanet Sand while the lower permeability will reduce the seepage forces in the soil and allow a lower balance pressure to operate at the face.

8.2.5 Mechanism of failure

Laboratory tests carried out on four samples of the Thanet Sand gave an average voids ratio e , of 0.50 equivalent to a porosity of 33%. The critical hydraulic gradient H_c , gives the seepage force which is able to move the constituent grains of the medium through which it is flowing, ie a quick sand situation would develop. For a voids ratio of 0.50 H_c is 1.13. For a hypothetical situation where the Thanet Sand is a nominal 100mm below the invert of the tunnel the differential pore pressure across this distance would need to be only 0.11m head of water. Figure 72b shows that seven equipotential lines would be present and therefore to develop a critical hydraulic gradient at the invert point the tunnel pressure would have to reduce by about 0.79m head of water (0.08 bar). In truth, analysis would show a similar relationship for the Woolwich and Reading Beds. The principal difference between the two materials is the higher flow rates within the Thanet Sand, without which the pore pressure would immediately drop and the hydraulic gradient would reduce to below the critical condition. In contrast the greater permeability of the Thanet Sand allows continued flow and therefore higher seepage forces and the retention of the higher hydraulic gradients. In addition the disruption caused to the fabric of the Thanet Sand at the critical hydraulic gradient would increase its porosity and lower the critical hydraulic gradient. At this point the conditions for hydraulic failure of the disrupted Thanet Sand would already be exceeded and the failure would be accelerated.

When the hydraulic failure occurs the Thanet Sand would behave as a quicksand, ie it would lose all shear strength and behave as a fluid. As the drainage conditions produce a net flow to the tunnel with a marked upward component at the invert the result would be for the Thanet Sand to flow into the machine where it would be removed by the tunnelling system itself to allow further inflows. The consequential loss of support at the base of the machine would result in a sudden drop of the head. Many of the events described at and around the time of the loss of the machine can be accommodated by this model.

For a similar failure to occur where the Thanet Sand is some greater distance below the Woolwich and Reading Beds it would be necessary for the pore pressures in the Thanet Sand to be great enough to hydrofracture the Woolwich and Reading Beds between the Thanet Sand and the tunnel invert. For this to occur a pressure situation would need to develop where the pore pressure would be in excess of the confining pressure in the ground by an amount greater than the tensile strength of the thickness of Woolwich and Reading Beds. Both the tensile strength and confining pressures operating around the machine are unknown. However if the influence of the machine on earth pressures is accepted to be only limited and the lateral confining pressure is taken as $0.3 \times$ vertical effective overburden pressure then about 5.0m excess pore pressure would be necessary to rupture a metre of Woolwich and Reading Beds. As such a pronounced pressure change cannot occur at the interface it is probable that rupture of the Woolwich and Reading Beds would not occur before it experienced hydraulic failure itself.

8.2.6 The role of the database

When the tunnel machine became stuck it prompted an obvious concern over the possible costs to the particular contract. However, it also

raised more far reaching questions on the viability of the tunnelling procedures in the Docklands. There was therefore some urgency for the cause of the situation to be identified.

The original site investigation for the scheme had been detailed and supervised by the appointed consulting engineer but had been carried out using the LDDC term contractor as it generally requires of its consultants. This meant that the information from the initial investigation was already in the GEODASY database. This allowed an immediate rapid retrieval of the pertinent records for the area which virtually eliminated the desk study time which would otherwise had to have been completed. The additional investigation was not carried out by the LDDC term contractor and the new contractor was not able to provide the information in an electronic format. In order to pass this information into the database as rapidly as possible a series of additional screen masks were produced which were identical in layout to the tables used by the contractor in his reports. The information was therefore typed into the database through a keyboard by clerical staff as it became available from the contractor. Initially this was kept on a separate database until the completion of the project to ensure that only finalised data was passed to the full system.

A number of developments were also added to the database to allow further comparison and enhanced presentation of the data. For example, it was possible that there may be a local variation in the character of the materials which may have been instrumental to the situation. Therefore the ability to plot depth profiles of selected parameters with differing permutations of borehole or strata groups was developed. This was also extended to include the records from a large number of standpipes and piezometers which were read during the course of the work.

In order to further investigate more subtle variations in grading it became useful to hold the full grading curve rather than just the D10, D60 and D85 values. These were input directly from the grading

curve provided by the contractor using a digitizing tablet and stored as a percentage passing each sieve size. From this the D10, D60 and D85 points could be interpolated for transfer either to the main database and or as output as required.

Regular progress meetings were held during the course of the additional investigation. Although, the data was collected under the common control of the three interested parties, for contractual reasons the interpretation and evaluation was carried out largely independently but with some interchange and cross referencing of ideas. The ability to process the data rapidly and make comparisons with the background situation allowed the writer to pursue or to limit various avenues and provide the required interim reports to the LDDC for decisions to be made at the project management meetings.

8.3 The further scientific and academic potential of GEODASY

The GEODASY database was developed as a tool to an applied discipline to work within a particular commercial environment. However, the flexibility that has been built into it has produced a system with a much greater potential. The writer was always aware that the ability to process large amounts of information would provide invaluable opportunities to answer questions of scientific interest as well as service the commercial needs. As stated in Chapter Four it was recognized at the outset that the vast amount of data that would be collected by the LDDC would probably be unique and should be passed on as a legacy rather than just becoming lost like so much before.

Much of the period covered by this thesis dealt with the development of the database and the input of information. This last aspect is perhaps one of the most crucial for the most sophisticated database in the world is of little value if it contains no data. The input systems are similarly fundamental if data is to be entered efficiently and quickly. Even so, it may take many years for

sufficient data to be entered to make facility truly useful and this overhead must be appreciated at the beginning of the exercise.

Chapter Four argued that it was a fundamental requirement that the data should be entered into the system completely and exactly as it was contained in the original report. Although this argument related to its engineering application it is equally true when the data is to be used for further academic purposes. For example, an original report may include Formation names within the strata descriptions. These are not changed in the database regardless of the interpreted subgroup to which the stratum belongs. Thus, the only interpretation applied to the data should be contained in additional data fields in this way. The subgroup identifier is integral to the way in which the true power of the database is exercised. However, it is also true that the very act of using it may change the model against which the subgroups are applied. It is therefore necessary, to be able to change the subgroups in the system without affecting the raw data itself and consequently the value of that data to other enquiries.

In the same way that the complete strata description is stored then so are any quantified and numerical data. These may include laboratory test results which are felt to be wrong or in some way unreliable. This opinion may be based on intuition, perhaps derived from previous experience of the material types and the area, or it may argued from first principles as perhaps could be the case for the minimum strength of a clay of given plasticity at any degree of overburden. However, it is the writer's belief that no matter how strong are the arguments such data must not be changed or deleted from the system. This is not only because the understanding which suggests its uncertainty may itself change, but because the precept can only apply to values which are not only wrong but which can be 'seen' to be wrong. Results which are similarly incorrect but which fall within an accepted range for the situation may not be so readily identified and may only be indicated by implication or some association with the other more obvious 'unreliable' data. In order

to weight or grade the data further fields should be used to flag the individual values, or the whole report. These may be used as search criteria for data selection to sort or sift the values to be used.

The writer believes that grading the data should be used only with caution and only when the enquirer is familiar with the data in its entirety. Such grading was not incorporated into the GEODASY system as it was intended to be open to ad hoc enquiries. Therefore any preselection of the data in this way would be against the principle of inclusion of complete and unabridged data as outlined. However, for more detailed and interactive enquiries, as would be the case in an academic exercise, the facility may be used with some advantage. For example, the ability to search the data by strata type has been achieved by re-indexing the data and holding this as a separate database. This was developed only as an in-house tool and is not available as a general purpose enquiry because the selection is based on the subgroup identifier, an interpreted field (see section 5.4.5).

When data is graded more positive relationships between parameters can be produced than when invalid data is included. More systematic and meaningful validation of the data is possible by applying statistical analysis rather than the more subjective assessment based on preconceived models. Extraction of selected parameters provides a data set to which any statistical function can be applied. Figure 36 showed the arithmetic mean and standard deviation applied to grading data from individual subgroups. This can be extended to give the range and sample population, the median and modal values, a measure of kurtosis or skewness and for presentation the data can be plotted as a histogram, as for example figure 49. Once the data sets are large enough that such assessments are statistically meaningful those values which fall outside of certain selectable criteria can be identified and extracted from the database and the accuracy of the original data considered more closely.

The character of the basic data is such that there is an underlying

intimacy between the various parameters. However, the variation of one may be derived from changes in more than one other parameter which themselves are otherwise largely unrelated to each other. For example the undrained shear strength may be related to depth from surface due to the presence of a weathering profile but may also be related to stratigraphic horizon. For example, it has been argued in the thesis that the influence of the weathering profile through the London Clay overrides any stratigraphic variation, at least in the local situation. Even when considering the London Clay on a regional scale Burnett and Fookes (1974) were unable to develop a trend for the undrained shear strength arguing that local factors offer too great an influence on the absolute value. The writer would suggest that of these the depth below ground surface may be one of the most influential and that if the data could be stored in the GEODASY database and processed statistically the relationships and trends may be identified.

In order to pursue such considerations it may be necessary to develop additional routines or use existing commercial software to provide the statistical analysis. However, the extraction of the data set is a matter of course and, as was explained in Chapter Four, it was proposed at the outset that the output and presentation programs should be considered as separate, being developed as and when required. However, where these are of a general purpose nature they can be added to the basic system as further menu options allowing the system to continue to evolve in response to the pressures on it. Those other routines which are more specific can be held in a library for when similar interactive evaluations are required.

It is anticipated that as more data is collected a number of basic questions can be further addressed in more detail than has been possible in this thesis. Although many of these may have an apparent academic overtone the implication of the answers on the practical engineering geology is believed by the writer to be sufficient that their solution forms part of the approach itself. For example, there

is still uncertainty over the form and origin of the depressions at the base of the Thames Gravels. What is their relationship to the underlying solid deposits? What influence did groundwater, as opposed to surface water, have on their formation? At what point in the deposition of the gravels were the depressions formed? Is there a difference between the gravels in the depressions and those outside? Similarly, a more detailed study of the lithological variation in the Woolwich and Reading Beds is expected to refine the depositional model developed in this thesis. It is anticipated that analysis of the variation in the mechanical parameters may provide a further differentiation of the facies so far identified on lithological and stratigraphical relationships alone.

It can be seen therefore that detailed interactive processing of the database, particularly with the use of appropriate statistical analysis is likely to provide further clues to the basic geological relationships present in the area. The thesis has shown that the structure in the Mesozoic cover rocks is dominated by open folding. Relatively little work has been done on this aspect although it is evident that the classical model for the area, which includes the Greenwich Fault, now needs to be substantially modified. The systematic use of the database might establish relationships between the mechanical or lithological variation in the facies present and the apparent stress trends. If, as postulated, the structural control exists within the basement rocks it is possible that the database may have significant implications on the understanding of the deeper geology of the region. Thus it can be seen that the value of the database extends beyond the spatial area of the Docklands or the timescale of its present phase of development. Even so, the benefits derived from any academic considerations will also improve the engineering geological understanding, the reason for its original implementation.

CHAPTER NINE : SUMMARY AND CONCLUSIONS

The present form and character of many urban areas in Great Britain is owed largely to a legacy of the Industrial Revolution. The pressures and controls which were active at that time are no longer valid or socially acceptable. More recently these areas have been unable to keep pace with the fundamental changes which have occurred within the industrial and manufacturing base of the country. Current Government policy to regenerate these areas has resulted in the need for a new approach to civil engineering development. For the regeneration to be successful, and therefore self-sustaining, it is necessary to provide sufficient impetus to the rate and scale of new development and population growth.

This thesis is formulated from the development of an approach to the collection, understanding and use of engineering geology which is sympathetic to the renewal process. The work has been carried out during the course of a consultancy appointment with the London Docklands Development Corporation.

Urban renewal is the most recent of a succession of philanthropic and legislative approaches to urbanization. A review of these shows it to be the descendant of these earlier concepts but that it varies significantly in the pace and pressure with which it is required to proceed. The thesis shows that the engineering geology of urban renewal must be concerned, not with the conditions of individual sites as is traditionally the case, but with the rate of collection and availability of information if it is to form a valid voice amongst the disciplines steering the renewal process.

A new approach to the collection and storage of basic geotechnical data has been devised specifically to be suited to the renewal process and is described in the thesis. This is based on the computerized storage and retrieval of data in the form of borehole

records and associated laboratory data. The GEOTECHNICAL DATA SYSTEM, or GEODASY, is based on low cost personal computers. Alternative methods of storage and retrieval were considered and are discussed. A number of previous descriptions of computer systems have been critically reviewed and have influenced the development of GEODASY accordingly. In particular the need for rapid updating of the system with new data, the need to ensure a minimum staff requirement and the need to eliminate all possible causes of data errors has resulted in the requirement that data is passed to the LDDC on computer diskette by its site investigation contractors. This, together with a developed interactive enquiry procedure, which has been devised specifically to allow non-computer specialists access to the data, has produced a system which is in daily operational use and which responds well to a commercial environment (Howland 1989b).

The study has had the benefit of approximately 4000 boreholes and associated laboratory data collected by the LDDC. These have been assimilated in a re-evaluation of the basic geology of the Docklands area from the Isle of Dogs to Beckton. This has drawn necessarily on the work of others working more generally in the London Basin. The geological succession for the area, as generally understood from the literature, has been confirmed but notable advances in the geological detail of the area have been found and are described.

A depositional model for the Woolwich and Reading Beds across the area has been developed and presented. Seven facies are identified and described. Lateral variation in these indicates that they were laid down in a linear siliclastic inshore marine environment. The Docklands area appears to be represented by a series of migrating bars separating the marine sands from lagoonal muds. It is recognized that the hypothesis is based only on lithological variation and would benefit from the addition of sedimentological and palaeontological information.

The area separates the middle valley from the lower valley of the Thames. Study of the Thames Gravels has established a number of morphogenic units to be present. These have been correlated with those described by others from the middle and lower valley. A further unit, termed the Silvertown Gravel, which lies about two metres below the expected lowest gravel unit has been identified.

A specific investigation of the character of the depressions at the base of the Thames Gravels described elsewhere in the Thames Valley proved to be inconclusive. A number of depressions of varying size have been identified. Other than for one major elongate feature in the vicinity of the present mouth of the River Lea the evidence suggests that these are approximately circular and in all instances closed. No conclusive evidence of disruption to the underlying solid geology was found. The features appear to be associated with a corresponding elevated area on the upstream side. The conclusion drawn is that that are the result of scour during times of high discharge in a braided stream environment.

The thesis has carried out a major revision of the structural geology of the area. The principal finding is that there is no evidence to support the presence of the Greenwich Fault which is traditionally shown to traverse the area. This has been achieved by detailed contouring of the base of the Formations in the area. The structural geology of the area is shown to be dominated by an approximately north south trending syncline termed the Greenwich Syncline. However, it appears to be relatively isolated within the mapped area and although complementary anticlinal structures have been identified these are of a lesser scale. Although the structural axes can be correlated with compression forces from the south the apparent uniqueness of the Greenwich Syncline suggests that it is more probably related to some structure within the basement.

The thesis has included an assessment of the engineering parameters of the principal stratigraphic units. This has drawn on previous work by others which has been reviewed accordingly. However, a number of advances in the understanding of those parameters has been achieved. In particular detailed work on the Thanet Sand has shown it to be a 'locked sand'. The importance of this on its engineering behaviour has been illustrated by the case history which describes the failure of a tunnel boring machine which encountered the Thanet Sand at a higher level than had been expected. The grading characteristics of the Thanet Sand confirm a very uniform material with a subtle overall fining and narrowing of the grading with depth. Findings also suggest that the lower five metres have a marked increase in fines content. Further work on the variation in grading of the Thanet Sand would be expected to add useful information to the depositional setting and wider engineering geology.

Similar work on the Woolwich and Reading Beds has established that there is uniformity within each of the facies but that there is a regional trend within the study area. This is concluded to be a function of the differing depositional setting identified in the depositional model. However, further work on this aspect is limited due to the erosion level having removed much of the upper facies over most of the area.

The engineering parameters of the London Clay have been compared with those reported elsewhere in the London Basin and show good agreement. However, some variation is established from that expected from the regional model developed by Burnett and Fookes (1974). An appraisal of the plasticity has shown an overall decrease with depth. However, this is most marked in the lower levels of the Formation in the east of the area and a more uniform trend in the west. Although the area is only a very small part of the total depositional basin this does coincide with the trends expected from the model. It is concluded that at the scale of the Docklands area that weathering of the London Clay would have the greatest control on

its shear strength and that any regional variation derived from depositional or lithological variation would be completely masked.

Within the context of this study made ground has been considered as an engineering geological formation. Its inherent variability has precluded a viable generalization of its engineering parameters as can be seen from a number of histograms of various parameters. However, an appreciation of the relevance of the made ground is crucial to the effective engineering geological assessment of urban renewal. The presence of chemical pollution is of particular concern. This is reviewed and discussed together with the options available to allow safe development of the area. The problems of waste disposal are described and procedure suggested to minimise growth of uncontrolled 'fly-tipping' which is a direct consequence of that disposal.

The hydrogeology of the area is modelled using data collected during various investigations. This shows that in the west of the area there is a drawdown in the water table in the lower aquifer as a result of historical abstraction in the central London area. The results have also been used to show that a return is occurring and has risen locally at rates of 1.2m/yr. In contrast, in the east observations indicate that hydrostatic conditions exist which suggests that the groundwater table is relatively stable. The importance of the influence of the construction of the docks on the near surface groundwater is demonstrated by a model which also shows how this reacts with the drawdown in the deeper groundwater to control the rate and distribution of saline intrusion into the subsoil.

A number of examples are presented to demonstrate the role of engineering geology in urban renewal and the need for it to interact with overall philosophy of the approach. One example describes the failure of a tunnel boring machine when it encountered ground conditions which were different to those expected by the Contractor.

The subsequent investigation to establish the facts was benefited by the availability of a fund of information within the GEODASY database. The detailed appraisal of the ground conditions which developed during the investigation itself improved the knowledge base for the area. The original and specific site investigation for the project was carried out under pressure of the renewal process itself to install a working infrastructure in order to service the requirements of the private sector development. Similar constraints existed during the investigation to establish the facts behind the failure and it is described how the investigation required to work closely with a number of other parties each with their own development pressures.

Two further examples illustrate some of the problems which are a direct function of the previous character of the area. One details the influence on subsequent development of the infilling of the Surrey Docks. This legacy of the area is further pursued in the last example which describes the reasoning behind the treatment required for an area formerly used for the disposal of gasworks waste. The decision to put housing on one of the worst contaminated sites in the area shows clearly how the engineering geological aspects may have no influence on the style of the development of the area. However, this does not eliminate its role, rather it must work within the renewal process and develop approaches and procedures which are in keeping with pressures felt by the other disciplines if it is to retain a viable voice.

The thesis describes the approach to engineering geology which has been developed during the renewal of the former docklands of east London by the London Docklands Development Corporation. Since its inception in 1981 further Development Corporations have been set up by the British Government. It is believed that the approach could be used in those areas or similar proposed cases of urban renewal abroad. The procedure is not sensitive to geological setting or political persuasion. However, it is fundamentally different to an

approach which might be adopted in a green field setting or for a new town development. Its principal requirements are;-

1. A coordinated and systematic approach to the collection of engineering geological data for the area by the development body. Although this does not necessarily require the use of a computerized system the procedure must be capable of rapid update and enquiry.
2. The formulation of a global appreciation of the engineering geology of the area and its relevance to engineering development.
3. An acceptance that the engineering geology per se will not affect the broader development issues but that its inclusion as a viable voice within the process will help to reduce difficulties which might otherwise arise as a consequence of the political and commercial pressures which exist.

The use of this in other areas of urban renewal would benefit further from the fact that the underlying procedures are now established and would not need to be developed in parallel with their implementation.

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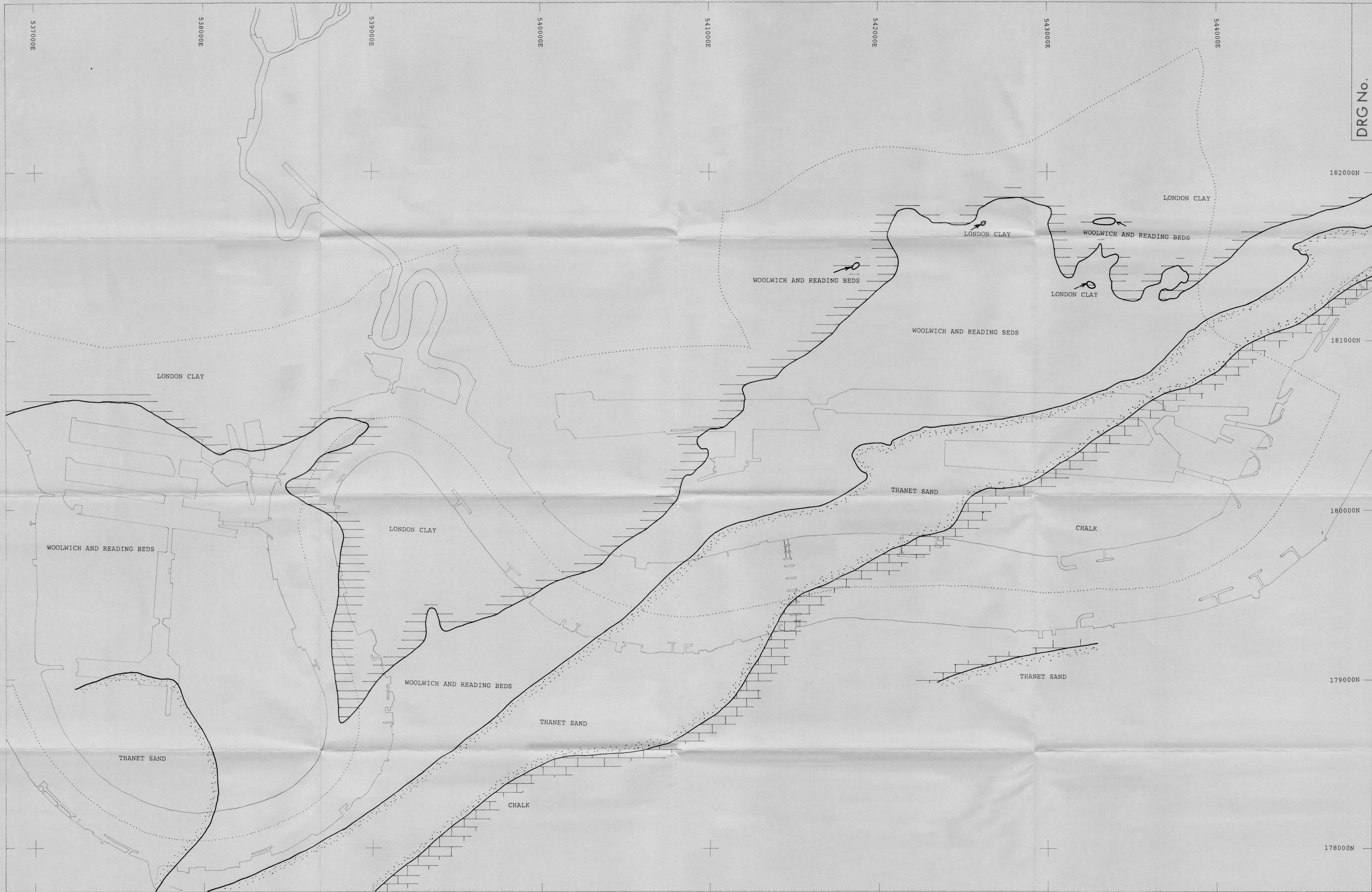
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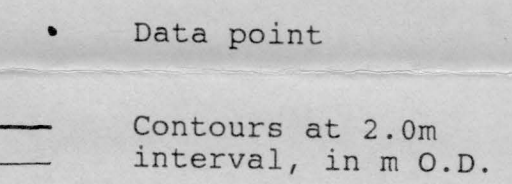
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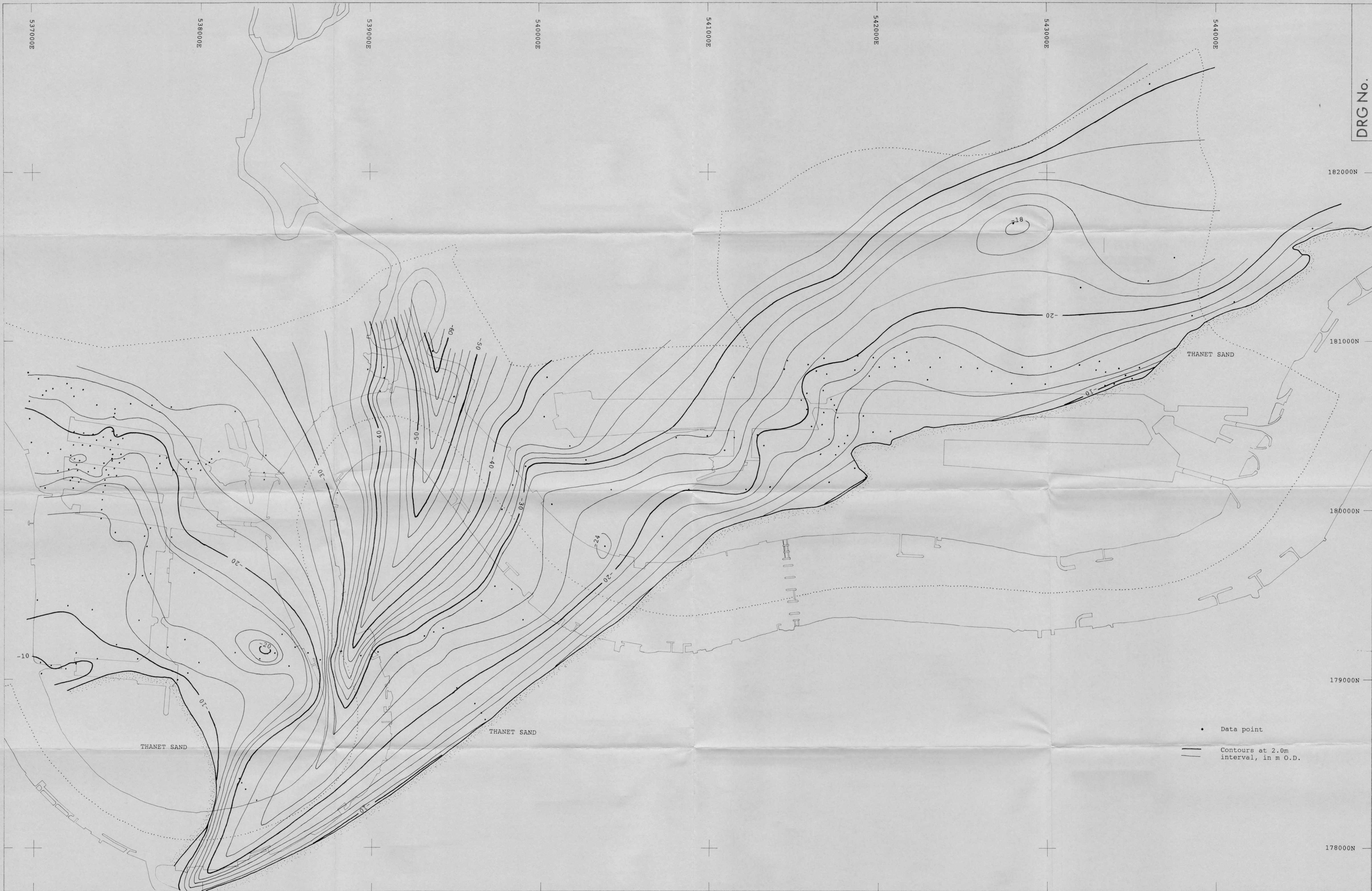


No	DESCRIPTION	CHK'D	APP'D	DATE	
REVISIONS					

DRAWN	TRACED	CHECKED	APPROVED	DATE	SCALE
				June 1989	1:10000
Figure 14 A revised solid geology subcrop for the Docklands after the present study					



DRAWN	TRACED	CHECKED	APPROVED	DATE June 1989	SCALE 1:10000
Figure 17 Contours in metres O.D. on the base of the London Clay					



• Data point
Contours at 2.0m interval, in m O.D.

No.	DESCRIPTION	CHK'D	APP'D	DATE
REVISIONS				

DRAWN	TRACED	CHECKED	APPROVED	DATE	SCALE
				June 1989	1:10000
Figure 18 Contours in metres O.D. on the base of the Woolwich and Reading Beds					

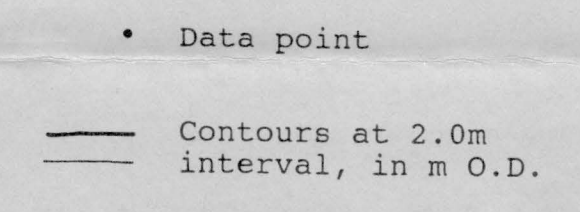


Figure 19 Contours in metres O.D. on the
base of the Thanet Sand