The Relationship between Sedimentary History and Geotechnical behaviour of Quaternary Sediments in Holderness

Thesis submitted in accordance with the requirement of the University of Keele for the degree of Doctor of Philosophy

by

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December, 1985

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ABSTRACT

The stratigraphy, sedimentology and geotechnical properties of the Quaternary sequence in Holderness were examined in detail, with the aim of relating depositional history to observed geotechnical behaviour. Both the Withernsea and Skipsea Till units were found to possess the sedimentary and geotechnical characteristics of a diamict deposited beneath a wet based ice sheet. No evidence could be found for the downwasting of a complex stratified ice sheet as previously proposed for the sequence.

Critical state theory was found to accurately predict the reaction of the diamict to shear and was used to predict the behaviour under theoretical stress/environmental situations.

An alternative depositional model is proposed which explains the Skipsea - Withernsea Till succession as the product of the slow accretion of basal debris under an active ice stream. The multiple stratigraphy is interpreted in terms of a shift in the east coast flow units, carrying distinct mixes of lithologies along individual flow lines, within a single ice sheet.

The key sections through the Quaternary in Holderness are re-examined in terms of deposition from an active ice sheet. It is concluded that the Basement Till represents the initial advance of the cold-ice margin and is Devensian in age rather than pre-Devensian as previously proposed.

Acknowledgements

Most of the fieldwork upon which this thesis is based was completed during the tenure of an N.E.R.C. studentship held at ther Department of Geography, Keele University.

I am particularly grateful to my supervisors, Prof. E. Derbyshire (University of Leicester) and Mr. A. Marsland (Building Research Establishment) for their valuable guidance throughout this project.

Thanks also to Dr. A.J. Parsons (University of Keele) who provided many positive and constructive comments during the period of writing up.

Assistance with fieldwork and laboratory analysis from Mr. M. Love and Mr. M. Edge both former contemporary research associates, is also gratefully acknowledged.

Laboratory facilities were provided by Keele University with extensive onsite assistance granted by the Building Research Establishment at their test site at Cowden.

Details and sub-samples from offshore Quaternary sequences were kindly provided by the British Geological Survey with the assistance of Dr. D. Cameron.

Thanks also to Mr. T.S. Whittaker representing Holderness Sand and Gravel Ltd. for allowing free access to the sections exposed at the Mill Hill workings.

Liverpool University, Department of Geography kindly provided cartographic, photographic and secretarial expertise which helped bring this work to a conclusion.

Lastly, very special thanks must go to my wife, Gill, for her tolerance of my long hours of study, for her painstaking typing of this thesis and for her lasting encouragement.

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THE LAYER IMMEDIATELY UNDER OUR layer is the fourth or "quaternary"; under that is the third, or tertiary, etc. Each of these layers had its peculiar animal and vegetable life, and when each layer's mission was done, it and its animals and vegetables ceased from their labors and were forever buried under the new layer, with its new-shaped and new-fangled animals and vegetables. So far, so good. Now the geologists . . . state that our own layer has been ten thousand years forming. The geologists . . . also claim that our layer has been four hundred thousand years forming. Other geologists, just as reliable, maintain that our layer has been from one to two million years forming. Thus we have a concise and satisfactory idea of how long our layer has been growing and accumulating.

MARK TWAIN
"A Brace of Brief Lectures on Science"
Life As I Find It

CHAPTER 1

Regional Stratigraphy and Aims.

1.1 The Holderness-Lincolnshire sequence

Field study of the Quaternary succession in eastern England has a long history. Wood and Rome (1868) identified three main divisions in the glacial drift sequence of Holderness and Lincolnshire which they named, in ascending order, the Basement, Purple and Hessle clays. A further sub-division was added by Reid (1885) who suggested that the Basement Till could be sub-divided into an upper till (later renamed the Drab), and a lower Basement Till unit characterised by a distinct lithological assemblage and the inclusion of large lenses of fossiliferous sand and clays.

This nomemclature was adopted and expanded by Bisat (1939,1940) who sub-divided the succession based on detailed observations of sedimentary features, clast lithology and colour differentiation along the Holderness cliffline (Figure 1.1). A unique aspect of Bisat's work was his meticulous recording of the coastline exposure, summarised by Catt and Madgett (1981), which included a complete annotated section of the Holderness cliffline between Easington and Sewerby. This section shows that Bisat clearly recognised at an early stage several characteristic details of the coastal sequence, in particular the existence of sand and gravel lenses exposed at all levels and the close association between the Drab/Basement boundary and enclosed silt basins at Dimlington Highland (the Dimlington Silts, Catt and Penny 1966). The Purple Till was shown to have an exposure limited to the coastal section between Hornsea and Easington, underlain by the Drab Till at all points. Between Tunstall and Holmpton, Bisat drew

Bisat (1939, 1940)	Catt and Penny (1966)	Madgett and Catt (1978)	British Quaternary Stages, Mitchell *et al.* (1973)
Upper Purple Clays (2 beds) Gravels Lower Purple Clays (3 beds)	Hessle Till Purple Till	Withernsea Till	Late Devensian (18,000-13,000 B.P approximately)
Upper Drab Clay Middle Drab Clay Chalk rafts Lower Drab Clay Sub Drab Clay Basement Drab Clay	Drab Till	Skipsea Till	
	Dimlington Interstadial Beds	Dimlington Silts	Late Devensian (18,240±250 B.P)
Basement Clay Sub-Basement Clay	Basement series	Basement Till	Wolstonian

Figure 1.1 Subdivisions of the Quaternary in Holderness after various workers

the underlying Drab Till below present mean sea level, thus exposing the Purple Till in a type section (Figure 2.1). The lowest Quaternary unit, the Basement Till, was thought to have its greatest exposure between Easington and Dimlington, forming an undulating platform traceable for 2.5 km beneath the Drab Till. Lenses of fossiliferous sands and gravels described by earlier workers were given the descriptive term Sub-Basement Clay. Although a great deal of Bisat's work relied on semi-quantitative classification, (the intra-formational sub-divisions cannot be supported by any rigorous analysis), the recognition of erosional hollows, lag gravels, planation surfaces and incorporation across the junction led Bisat to the firm conclusion that the Drab and Purple tills were separated by a subaerial phase.

Within a regional context work by both Straw and Valentin attempted to identify morphological terrain units and equate these with theorised lines of terminal moraine. Valentin (1957) traced a westward line from Burton Agnes, south through Brandesburton to the North Sea close to Easington. It was proposed that this feature represented a Devensian ice limit associated with the deposition of the Purple Till and the establishment of the modern alignment of the Humber Estuary.

Straw (1958,1960,1969,1980) took a wider regional view. He equated the Marsh Till sequence of Lincolnshire, in part, to the Drab Till of Holderness and suggested that the Devensian advance involved at least three well defined stages, the last equated with the limits set by Valentin (1957). The model advocated by Straw (1979) proposes that the initial ice advance into the Holderness-Lincolnshire region was the most extensive and was responsible for the Lower Marsh Till, delimited in South Lincolnshire and North Norfolk by the Hunstanton, Heacham and Stickly moraine complex. This stage, in Straw's view, was an early Devensian event (pre 60,000 yr BP) related to the high-level period of Lake Humber and the initiation of Lake Fenland which is not represented in the Holderness sequence. The Purple-Drab succession is seen as a Late Devensian event (20-18,000 yr BP) with the limits of the Drab advance placed in central Lincolnshire at the Hogsthorpe Killingholme moraine. Straw's analysis is unique in proposing an early Devensian age for the Lower Marsh Till, but appears to be supported by the inclusion within the marginal tills of the later Devensian advance of fossiliferous sands and gravels containing a derived mixed fauna of Ipswichian and Devensian forms (ie Kelsey Hill, Keyingham, Brocklesby-Goxhill) which can be explained by ice advancing over a Middle Devensian sea floor and the Humber Estuary (Straw 1979).

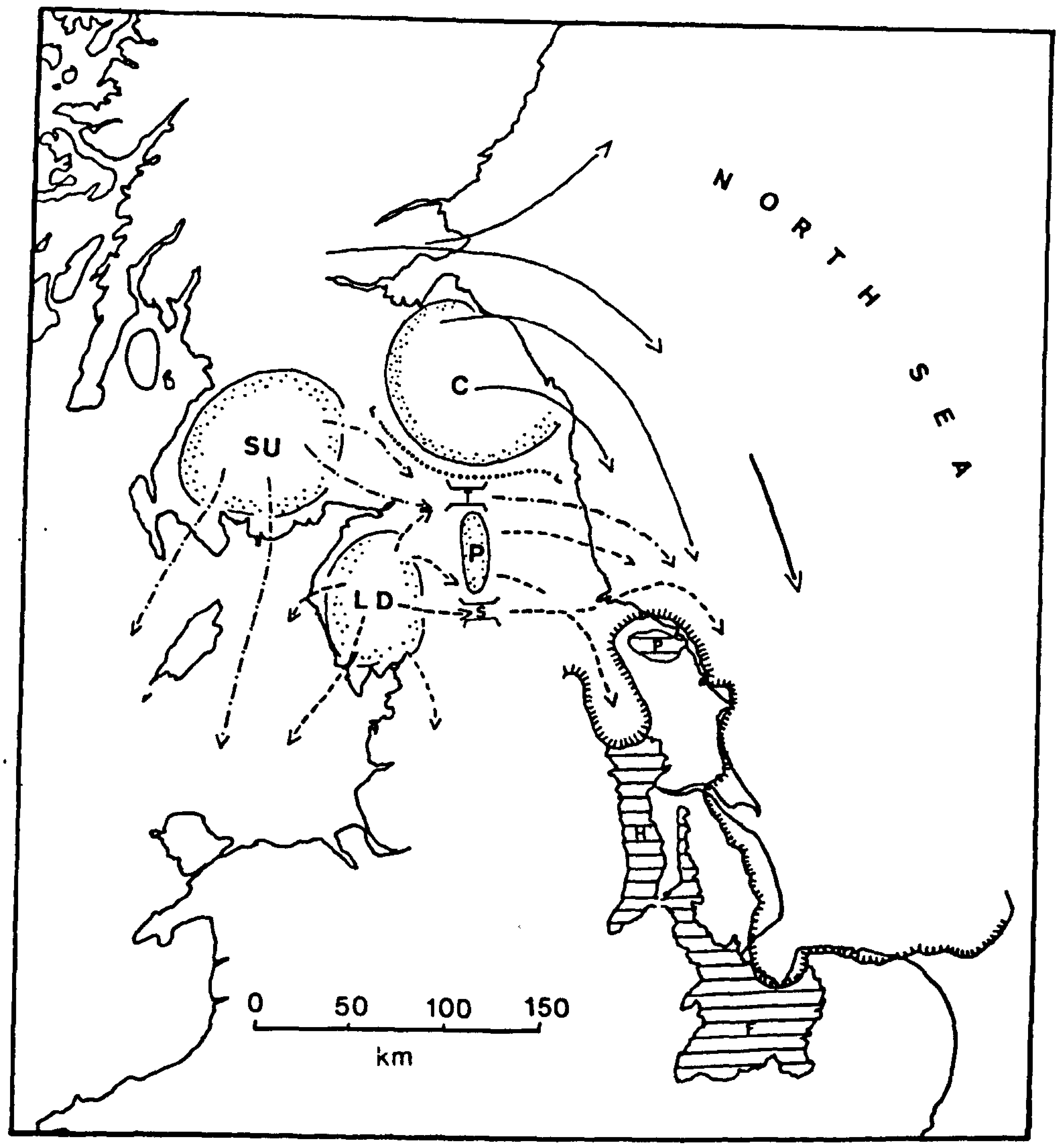
Work by Catt and Penny (1966) further sub-divided the Holderness sequence by suggesting that the weathering profile developed across both the Drab and Purple Tills was a fourth discrete till unit (the Hessle till), a theory later disproved by by Madgett (1974), who made a close study of the mineralogy and petrology of the Purple and Drab tills (Figure 1.1). Theories and observations proposed in this earlier work along with evidence cited by Penny Coope and Catt (1969) have provided Quaternary science in England with one of the most widely quoted radiocarbon "benchmarks" for the Late Devensian, namely the Dimlington Silts date and the inferred relationship between the Drab Till and lower Basement Till. Analysis of the silt basins has yielded a sparse Coleoptera assemblage and moss of the genus Bryum which has produced a radiocarbon date of 18,250∓250 yr BP (Birm 108). Further faunal analysis has shown that the assemblage is consistant with a proglacial, arctic environment immediately prior to the ice advance that deposited the Purple and Drab Tills. Since the oldest date yet obtained from deposits above either till is 13,045∓270 yr BP (Birm 317) at The Bog, Roos (Madgett and Catt 1978), the authors concluded that both till units were deposited within 5000 years in a Late Devensian event. Since Catt and Penny believe that the Drab and Purple Tills represent the full Devensian succession in Holderness, the underlying Basement Till was ascribed to the Wolstonian, with the included clay erratics, Hoxnian or older.

A major review paper by Madgett and Catt (1978), reformulating the work of Catt and Penny (1966) and introducing the analytical approach of Madgett's thesis, attempted to combine a stratigraphy based on strict sedimentological parameters with a deposition model first proposed by Carruthers (1953). Their proposals form the basis for modern stratigraphy in the Holderness-Lincolnshire region, and are summarised as follows.

1) The Devensian drift succession displays two tills only, the Purple and Drab, which can be distinguished on the basis of colour, mineralogy, clast lithology and particle size distribution in the coarse silt range.

2) Following modern terminology, the till sheets should be renamed after locations that provide a type section. Therefore the Skipsea Till equates with the Drab Till of Bisat (1940) and Catt and Penny (1966), and the Withernsea Till with the Purple Till of the same authors. (Note.... This is the nomenclature used from this point onwards.)

Figure 1.2 General pattern of ice flow lines in the East Coast Region during the Devensian



KEY

CENTRES OF ICE DISPERSAL

SU..... Southern Uplands
LD..... Lake District
P...... Pennines
C...... Cheviot

OTHER FEATURES

T...... Tyne Gap
S...... Stainmore Gap
H...... Humber Gap
F...... Lake Fenland
P...... Lake Pickering

(solid line) Cheviot/Scottish Ice
(dashed line) Pennine/Lake District Ice

3) The till suite is Late Devensian in age.

4) The Basement Till forms a third till distinct from the Skipsea Till which it underlies which is Wolstonian in age.

Following from these points, it was proposed that the Devensian sequence was the product of a multi-layered ice sheet which down wasted to form a duplex till complex with intercalated sand, silts and gravels. The ice mass was produced by Lake District and Pennine ice moving through the Stainmore Gap and down the Tees Valley, overriding a pre-existing North sea ice Sheet before surging as far south as Hunstanton in East Anglia and melting out as a stagnant ice body (Figure 1.2).

The model proposes that the basal North Sea ice deposited the Skipsea as a lodgement till, while the Withernsea, reddened by the incorporation of Keuper Marl from the Tees Valley, represents a subglacial meltout facies. No subaerial phase was envisaged between the deposition of the two till units and therefore all channel fills, apart from the basal Dimlington Silts, were regarded as subglacial in origin. The possibility that the Holderness sequence could have been emplaced by a glacial surge is supported by Boulton (1977) who used a mathematical approach to model the behaviour of the British ice sheet during the Devensian. More recently Boulton (1979) has suggested that the behaviour of the North Sea ice sheet could best be explained by a model of glacial motion which achieves a large proportion of forward movement through deformation of the bed rather than ice remoulding or slip on the ice-bed interface. The crucial difference between this approach and the surge hypothesis is that it allows the ice to maintain its activity, even at its extreme margins, rather than proposing stagnant meltout. This theory, although applicable to the east coast, has not been related to the stratigraphy.

1.2 The Vale of York.

Consideration of the Quaternary stratigraphy in the Vale of York is crucial to a complete understanding of the Holderness sequence, since not only does it contain a Devensian-Ipswichian sucession but there is also glacio-lacustrine phase assigned to the period of the glacial maximum (Gaunt 1971). Older glacial deposits are present but their situation does not allow them to be correlated with any specific stage. Sections through a deposit at Austerfield (GR SK 673974) were described by Gaunt et al (1972) and named the Older River Gravel. A lens of organic silt exposed in one pit contained pollen, suggesting an Ipswichian zone III age. The temperate assemblage was consistant with a marsh-bound lake surrounded by a thick forest of alder and hornbeam. The presence of a lake at approximately +4 m OD on a contemporaneous floodplain, implies that the base level was close to present m.s.l. Pollen and dinoflagellate cysts from a thin clay near Westfield Farm, Armthorpe (GR SE 633036) show that at Zones III/IV estuarine sediments were forming with sea level at or slightly above present sea level, in an area containing pine woodland.

The early Devensian is marked by prolonged denudation with rivers grading down to -19 m OD as sea level fell in response to the growth of the Laurentide and Scandinavian ice caps. The recession continued into the middle Devensian, by which time m.s.l may have been 120-130 m lower than present (Jelgersma 1978). This period is marked by the development of a periglacial surface

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which is coincident with the top of the Older River Gravels. Where this deposit is absent it transgresses on to older deposits or bedrock. The associated frozen ground structures indicate continuous permafrost (Gaunt 1976). Extensive work by the British Geological Survey (Formally I.G.S.) and Gaunt (Unpublished PhD Thesis) has identified three types of deposit attributable to Lake Humber, a proglacial lake originally proposed by Lewis (1887), as follows

1) High-level sands and gravel containing a clast assemblage derived from older glacial deposits. These occur along slopes at approximately +33 m O.D., overlying the lower periglacial surface.

2) Low-level sand, rarely rising above 9 m O.D. which passes laterally into a laminated silt and clay.

3) Laminated clay (25 foot Drift Silt and Clay of earlier workers) which is locally more than 20 m thick. Its surface is approximately 1 m below that of the adjacent sands.

This sequence is generally interpreted as representing a two-phase glaciolacustrine event (Figure 1.3). The high-level sands were deposited soon after transgression to the maximum level when ice closed both the Humber and Wash gaps. This period can only be correlated with Devensian ice maximum and the subsequent formation of Lake Humber I and Lake Fenland the levels of which which were equalised through the Lincoln gap (Straw 1979). A bone fragment on or near the base of these deposits at Brantingham (GR SE 940295) dates this phase at 21,835∓1600 yr BP, (Gaunt 1974). It is proposed that the extension of the North Sea ice sheet across Holderness was comtemporaneous with the Stainmore-Vale of York advance (Gaunt 1976). Although North Sea ice reached almost to Brough (GR SE 940265) there is no evidence that the Vale of York ice ever came into contact with North Sea ice. Gaunt (1976) suggests that the initial advance surged forward as far as Wroot (GR SE 715030) into the high-level waters of Lake Humber, depositing the 33m sands, before restabilizing at the York-Escrick Limits. The high-level phase was terminated when ice withdrew from the Wash re-establishing a low level drainage path through the Lincoln gap. Near Burton Hall (GR SE 585293) and South Cave (GR SE 585293) there is evidence that between the high and low level phases the base level was lowered to approximately 4 m O.D. After a period of stabilisation the thick sequence of low-level sands and clays was deposited within Lake Humber II. A buried soil, formed in the laminated clays at West Moor and dated to 11,100∓200 yr BP provides a minimum age for the final disappearence of the lake (Gaunt, Jarvis and Matthews 1971). A continuous gradation from glaciolacustrine sediments into river levee deposits shows that Lake Humber II silted up rather than being drained by incision through its moraine dam. Pollen from deposits in a hollow on the Escrick moraine near Tadcaster indicates that ice had retreated from the area prior to the Bolling climatic amelioration (Bartly 1962), a date comparable to that obtained from The Bog at Roos for deglaciation in Holderness.

1.4 North East England

The glaciation of north-east England proceeded under different glaciological conditions to that of Holderness. The stratigraphy of the region is based on the identification of localised high energy ice streams, close to their source areas carrying distinct erratic suites, coalescing and competing for space on the lowland plains. Unlike Holderness, the dominant process was erosion not deposition.

The earliest known Quaternary deposits, of supposed Middle Pleistocene age, are fissure fills in Magnesian Limestone situated in County Durham, which have yielded a diverse fauna including bone fragments, insects and freshwater shells. These fills are believed to antedate the "Scandinavian Drift", a stony clay exposed on bedrock at Warren House Gill which has been tentatively correlated with the Basement Till of Holderness (Mitchell 1973).

A simplified analysis of Devensian stratigraphy suggests three principal areas of independant ice accumulation and subsequent advance, namely the Lake District, the Pennines and the Cheviots-Southern Uplands of Scotland area. Early workers such as Kendall (1903,1902) recognised that Lake District ice was forced east by a congested Irish Sea Basin, to flow through the Stainmore Gap into the Lower Tees valley. In this initial phase, ice from the western Southern Uplands of Scotland merged with northern Lake District and Pennine ice (Western ice) to move through the Tyne Gap into the Durham area (Beaumont 1968). The till sheet associated with this composite advance has been variously described as the "Lower Boulder Clay" (Smith and Francis 1967) and "Lower Till" (Beaumont 1972). In line with modern nomenclature, Francis (1971) has proposed that this sequence be reclassified as the Wear and Blackhall Till complex, the latter being a Permian-rich facies variant directly comparable with the Skipsea Till of Holderness.

The deflection south of the initial advance and later stages may well have been the result of a Scandinavian ice sheet occupying the eastern North Sea Basin (Boulton, Jones, Clayton and Kenning 1977). Smith (1981) proposed that ice accumulation on the Cheviot

Hills and in south-east Scotland was slower than western ice centres. Subsequent advance eastward (Northern Ice Stream) moved south to bring it into conflict with the Western ice stream, displacing it along the coastal margins but pushing no further inland than the Tees Lowlands and possibly the Vale of York (Figure 1.2). The till associated with this ice stream is rich in Magnesian Limestone, southern Scottish and Cheviot erratics. Previously termed "Upper Boulder Clay", Francis (1971) proposed the term Horden Till after a coastal type section. The first stream to retreat at the end of this stage was the local ice in the Pennines. This left the mid-Durham valleys enclosed by Lake District ice in the east and Tees-Stainmore ice to the south, effectively blocking low level drainage paths and creating Lake Wear (Beaumont 1968).

Sediments of the Tyne-Wear complex comprise laminated silts and clays, locally interbedded with sand. The environment of deposition was primarily glacio-aqueous. In the lower Tyne valley the sequence is overlain by a water-sorted diamict suggesting the close association of the Cheviot ice stream. In the Wear valley the deposits merge with similar material described by Smith and Francis (1967) and Francis (1971). Here they rest unconformably on the Wear-Blackhall Till, but in places they can be traced to rockhead. Although representing a subaerial phase, no organic remains have been reported within the Tyne-Wear Complex and therefore there are no absolute dates for deposition of this unit.

Adopting a geotechnical approach, Eyles and Sladen (1981) have suggested that the Horden Till is not a distinct stratigraphic unit but a Holocene weathering profile, similar to the "Hessle" of

Holderness (Madgett and Catt 1966). Contrary to most views, they propose that the glaciation of the northeast was a single depositional event with no major retreat-readvance phases. More recently Eyles, Sladen and Gilroy (1982) have refined this theory to account for the "tripartite" lodgement till sequences found in Northumbria and the marked changes that occur in erratic content at till boundaries. Owing to the apparent similarity between the sedimentary features associated with the Northumberland and Holderness sequences, in particular the intraformational sands and gravels, a fuller consideration of this facies model is required.

The basic premise is that the Northumberland till complex was deposited during a single phase of subglacial deposition which was periodically interrupted by erosional episodes. Changes in the mixture of bedrock lithologies transported along a single flow line and/or lateral displacement of basal ice flow units is considered to be the main factor responsible for changes in till lithology. This process is referred to as "unconformable facies superimposition". The periodic oscillation between phases of activity and non-activity also controls the subglacial meltwater flow responsible for the deposition of channel fills grading between gravel and clay. Owing to subsequent deformation, these features are shown to be discontinuous, unlike the product of an ice advance over a proglacial environment, which might be expected to be laterally extensive. It follows therefore that the bipartite stratigraphy of Holderness and Lincolnshire may be a large scale example of unconformable facies superimposition as suggested by Gilroy (1980). However it should be pointed out that the glaciations of Holderness and Lincolnshire proceeded under different conditions, not least of which was the absence of any

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localised ice streams. The North York Moors and the Wolds were not glaciated and did not support ice masses. Any lateral shift in an ice stream entering the Holderness embayment must have been restricted by the North York Moors-Dogger Bank neck through which the ice sheet was maintained.

1.5 Offshore Quaternary Stratigraphy.

Unlike terrestrial stratigraphy the development of an accepted regional stratigraphy for the North Sea Basin is in its infancy. The Quaternary sequence, often lying conformably on the upper Pliocene succession is immense (1000m in the Central Graben) with a far greater representation of the Early Pleistocene than is found on land (Funnel 1972 Figure 1.4). This fact, added to the problems of obtaining representative samples, makes the task of regional correlation daunting. However it cannot be overemphasised that in Holderness the present coast is an arbitrary line through a laterally continuous sequence of sediments and that any terrestrial succession drawn without reference to the offshore logs will necessarily be incomplete and possibly inaccurate.

In the central North Sea, borings and seismic work have revealed a succession that appears to be mainly Devensian in age containing both marine and glacial deposits. In contrast, the southern North Sea contains a largely complete sequence from Anglian to present (McCave, Caston and Fannin 1977). Oele (1969) described the sediments in the North Sea close to the Netherlands. The succession commences with the Anglian (Elsterian) glaciation which is represented by the Peelo Formation of glaciofluvial clays. More recently, deeper borings have proved that these deposits of Scandinavian origin are partly younger and should be assigned to

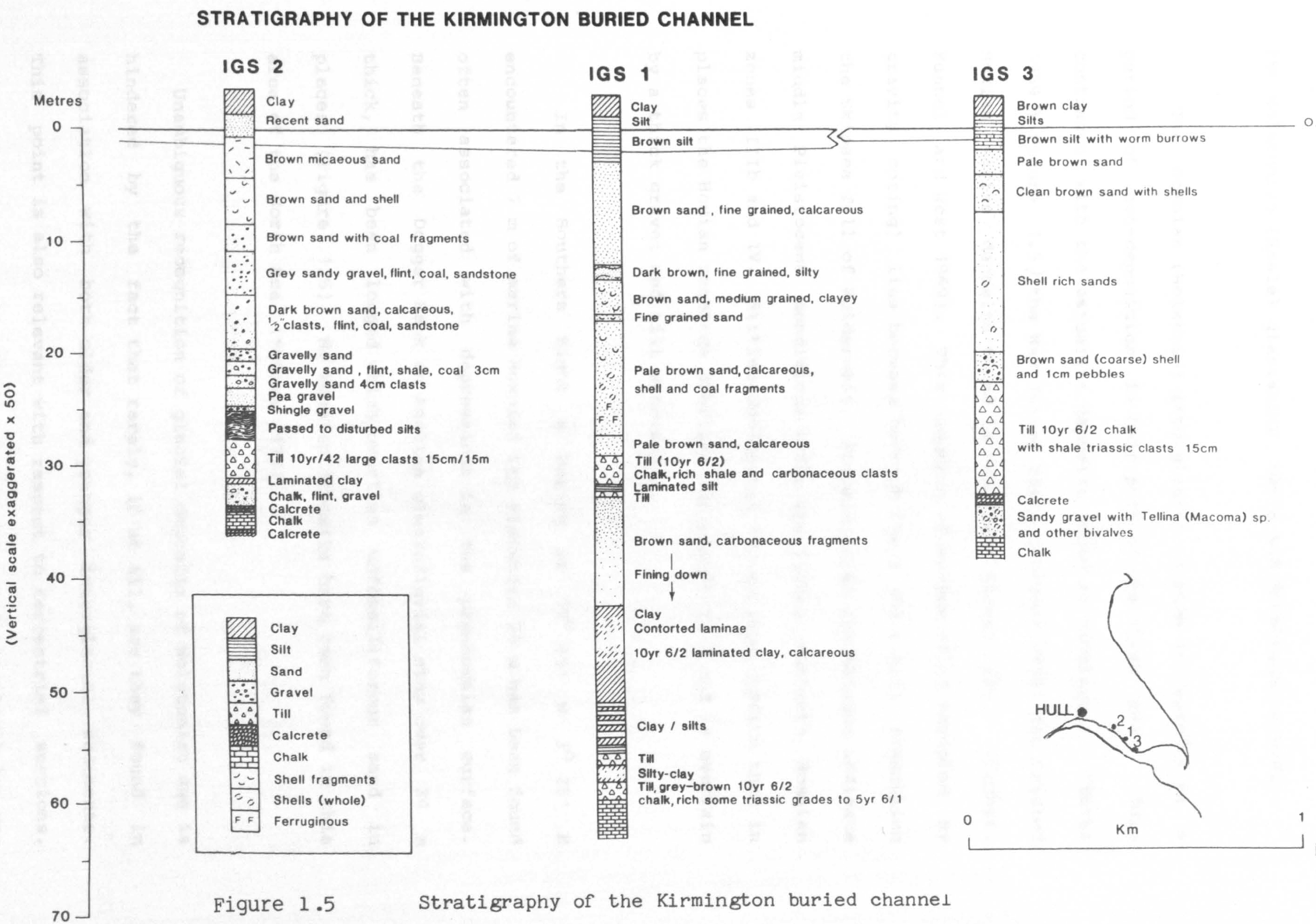

Figure 1.5 Stratigraphy of the Kirmington buried channel

the Wolstonian (Saale) glaciation (Oele and Schuttenhelm 1979).

The Hoxnian (Holstein) interglacial episode is regarded as a period of non-deposition in this part of the North Sea. This contrasts with the estuarine deposits found at Kirmington (Watts 1959 & Figure 1.5), the Nar Valley clays (Stevens 1968) and related Hoxian marine deposits found in the Inner Silver Pit (Fisher, Funnel and West 1969). This sequence of marine silts (sampled by gravity coring) lies between bedrock Chalk and a till resembling the Skipsea Till of Holderness. Foraminiferal assemblages indicate middle Pleistocene conditions while the pollen reflects Hoxnian zones IIIb and IV. British Geological Survey logs confirm that in places the Hoxian sequence overlies (Anglian?) till and is overlain by a thick gravel and till succession.

In the Southern Bight a boring at 52° 45' N 3° 25' E encountered 7 m of marine Hoxnian and elsewhere 20 m has been found often associated with depressions in the pre-Hoxnian surface. Beneath the Dogger Bank an Anglian glaciofluvial clay over 30 m thick, has been logged which overlies unfossiliforous sand in places (Figure 1.6). No Hoxnian deposits have been found in this area of the North Sea (McCave 1977).

Unambiguous recognition of glacial deposits of Wolstonian age is hindered by the fact that rarely, if at all, are they found in association with both older and younger interglacial sediments. This point is also relevant with respect to terrestrial sections. However, it is generally accepted that Wolstonian (Saalian) ice was responsible for till and outwash deposits recorded in the Outer Silver Pit area (54° 10' N 2° E). Although previously ascribed to

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an extension of the Scandinvanian ice (Oele 1969), later workers suggest that British land ice was responsible (Zagwijn and Veenstra 1966; Zandstra 1971,1972,1973). A Wolstonian age is supported by pollen analysis of underlying sediments. An associated glacigenic suite of sediments in the Southern Bight area, the Drenthe Formation, is recorded by Oele (1969) as far south as 52° 20' N where it forms ice-pushed ridges adjacent to the Dutch coast. Material in the Drenthe Formation is of undoubted Scandinavian origin, a fact which allowed Oele and Schuttenhelm (1979) tentively to propose a junction between Scandinavian and British ice North of the Brown Bank (53° N 2° E) during the Wolstonian. During this stage sea level is considered to have fallen 130m below present m.s.l (Emery 1969).

Ipswichian (Eemian) deposits have been logged in numerous offshore locations and can often be directly related to adjacent coastal exposures. Many offshore recordings are located in Dutch waters and in the German Bight sea area (Jelgersma 1979). In the northern sector deposits of this age are practically unknown, having been incorporated into the Devensian till complex. The Ipswichian can be described as a temperate transgressive phase that restored full marine conditions to the North Sea Basin. The relative height of interglacial sea levels is a matter under constant review, and has almost developed into a specialist subject within Quaternary science. Summarising the available data reveals that the proposed elevation of the Eemian marine maximum along the Belgium and Dutch coasts varies from present sea level to -7 m O.D. (Behre 1979). Along the coast of south-east England elevations have been reported that range between 8-15 m above present m.s.l to 1 m below. These differences in elevation might be an effect of tectonic downwarping in the area around the North Sea Basin (Jelgersma 1979). In the Vale of York-Humber region estuarine deposits of Ipswichian age are present at 7-12 m below present m.s.l at Langham (West 1968) and at +4 m O.D. at Austerfield near Doncaster (Gaunt et. al.1972). It has been previouly noted that the Langham deposits date from the early part of Ipswichian Zone IIb and the Austerfield sediments post-date these at Zone III-IV. Taken with evidence for an Ipswichian fossil shoreline at Sewerbv (Catt and Penny 1966; Gaunt 1974), this suggests that sea level rose by about 13m from a relatively low position in the early Zone IIb, to a maximum at approximately +2m O.D. during Zone III. Although, as a structural feature, the Sewerby cliffline predates the Ipswichian there is little doubt that it formed the shoreline during the interglacial (Jardine 1979). The raised beach, cut into chalk, bisects the present coastline North of Bridlington before running inland along the base of the Wolds to intersect the Humber Estuary west of Hull. Further south there are traces of a poorly defined transgression in the Wash and Lincolnshire Fens region (Jardine 1979). This feature has several implications for the glacial stratigraphy of the region.

a) Holderness and East Lincolnshire formed a marine basin during the Ipswichian; and

b) any pre-Ipswichian deposits must exist as a wave cut platform east of this line (Figure 2.1).

Most of the evidence suggests that the Ipswichian marine maximum was not maintained for any great length of time and should not be viewed as indicative of this period. In the Southern North Sea, the Eemian transgression is not represented below pollen Zone IIb which has led Jelgersma (1979) to suggest that part of the basin

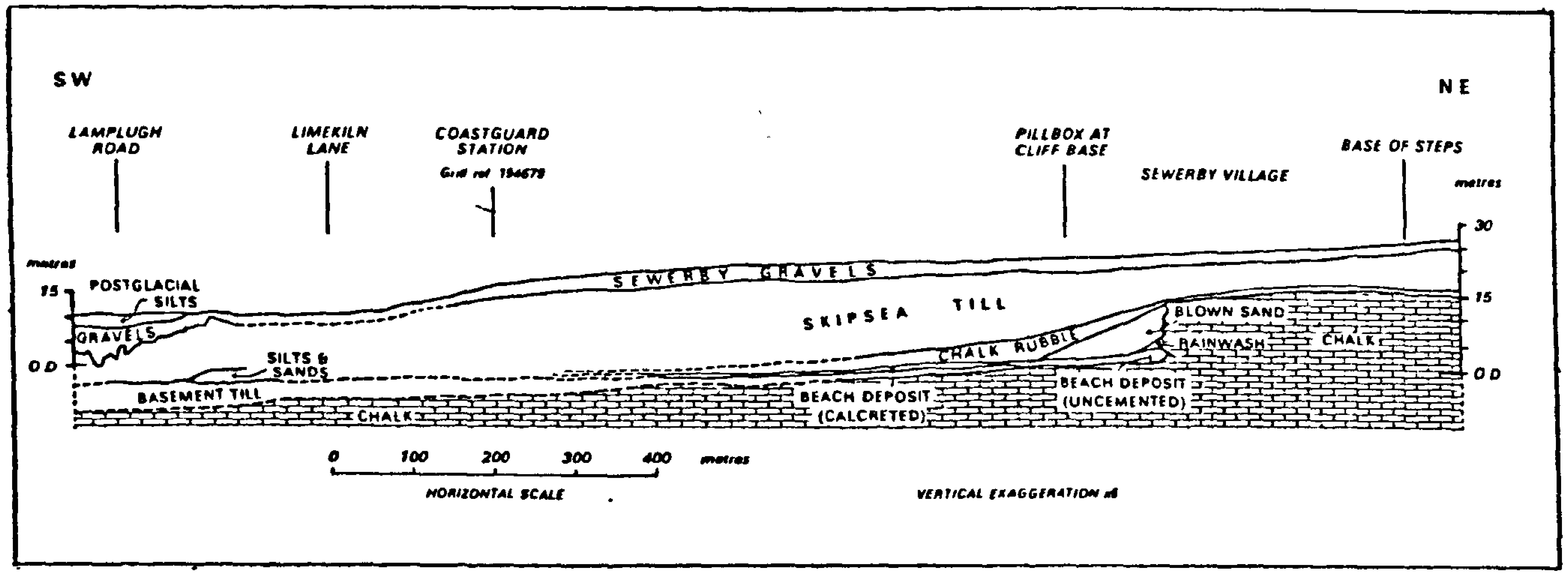

Figure 1.7 <u>Sewerby Cliff - after Inqua Guide (1977)</u>

was still dry land. The oldest deposits of marine origin, found in the Netherlands and adjacent North Sea Basin, were formed during pollen Zone E3 and represent a sandy littoral facies grading into a brackish clay deposit dated as Late Eemian (pollen Zones E5-E6 of Zagwijn 1961). Taking into account the postulated sea level stand and the known Eemian facies, Oele and Schuttenhelm (1979) have suggested that deposition in the North Sea must have consisted of transgressive sands moved back and forth over a non-depositional shelf environment. Further north any sand would be covered by finer-grained material reflecting deeper water conditions. This transgressive series was then reworked and overlain by a sandy regressive series that in depressed areas terminates with a brackish clay layer. The model is supported by evidence from the Sewerby beach section which clearly shows aeolian sands backed against the buried cliffline (Figure 1.7). These sands, possibly derived from the exposed shore platform during the Late Ipswichian regression, contain a rich mammalian fauna including Hyaena (Crocuta crocuta), Rhinoceros (Didermocerus hemitoechus) and Bison (pricus) (Catt 1977). The effect of the regression can be gauged from the fact that a freshwater clay, dated by pollen to the Early Devensian Zone EW Ia, has been recorded overlying marine Ipswichian deposits in the central part of the Southern Bight. This sequence is located between 37-42 m below present m.s.l. (Jelgersma 1979). The worldwide lowering of sea level during this period is directly related to the growth of the Laurentide and Scandinavian ice sheets (Dreimanis 1960) and is also reflected in the oxygene-isotope curve in deep-sea sediments where the boundary between the Ipswichian and Devensian has been fixed at 120,000 yr B.P. (Shackleton and Opdyke 1973).

The Devensian sequence can be sub-divided into two contrasting depositional areas. The first displays almost continuous till cover reaching as far south as the East Anglian coast and east to the median line. A second area, extending to the English Channel, is characterised by lacustrine and glaciofluvial deposition. The till succession rests directly on a peneplaned Mesozoic platform formed largely of Cretaceous chalk (B.G.S. personal communication). Both the Skipsea and Withernsea tills have been traced east of the Dogger Bank as far as 2^{o} E while the Withernsea Till has been reported outcropping in the Silver Pit (Donovan 1973). It is believed that these diamicts are the direct lateral equivalents of the Holderness sequence flooded by the Flandrian transgression. The Devensian ice advance appears to have stopped at the northwestern side of the Dogger Bank since the glacial sequence in this region is composed of glaciofluvial gravels and cover sands (Oele 1971).

The exact position of the ice front in the North Sea basin at glacial maximum is not known. Some workers have assumed a zone of confluence with Scandinavian ice in the northern North Sea based on the deflection of the ice flow lines to the north and south in east Scotland and north-east England and Hoppe's (1974) proposal that ice across Shetland in a westerly direction (Boulton, Jones, Clayton and Kenning 1977). Ice cover was thought to have been quite thin near the midline of the North Sea, with the ice sheets becoming detached as early as 16,000-17,000 BP (Jardine 1979).

Other authors support the theory that the British and Scandinavian ice sheets did not flow together and argue that the movement of ice down the east coast can be explained without the interaction of two ice sheets (Rienhard 1974). Recent evidence suggests that Scottish ice on the west coast was not as extensive as previously proposed and that the Late-Devensian ice sheet did

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not pass beyond the Outer Hebrides (Sutherland and Walker 1984). Jansen, Doppert, Hoogendoorntoering, de Jong and Splint (1982) descibe a belt of tunnel valleys cut into a subglacial lodgement till (Hills Deposit) in the Witch Grounds and Fladen sea areas off the east coast of Scotland, which are interpreted as marking the maximum extent of Scottish ice in this part of the North Sea.

In the southern North Sea basin the Devensian glacial stage in the Dutch sector is represented by the Twente Formation (mainly cover sands and glaciofluvial deposits), the Kreftenheye Formation (fluvial deposits) and the Brown Bank Beds consisting of lacustrine clays (Jelgersma 1979 Figure 1.8). Oele (1971) postulated an early Devensian "Brown Bank Lake", broadly coincident with the Southern Bight sea area. It is possible that this lake was formed when sea level fell at the end of the Ipswichian. Kirby and Oele (1975) describe an early Devensian lacustrine clay in the Sandettie Bank area.

1.6 Morphological Features Associated with the Late Glacial.

Successive marine surveys have established the existence of several isolated basins in the southern North Sea. East of Holderness and Lincolnshire the sea floor is covered by a till and gravel sequence and is trenched by a number of elongated hollows including the Inner and Outer Silver Pits, Sole Pit, Outer Dowsing Channel, New Sand Hole, Coal Pit, Well Hole and Markhams Hole (Donovan 1973). Although the nature and origin of these basins is a point of debate, the close association of offshore glacial sediments makes them worthy of comment, particularly since there is a distinct lack of terrestrial glacigenic morphology (Figure 1.9).

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Two theories have been proposed to account for these basins. Valentin (1957) and Robinson (1968) thought that the Silver Pit and associated basins were formed as subglacial drainage channels which marked a retreat stage during the last glaciation. Alternatively, Donovan (1965) proposed that the channels were formed by tidal scour in an estuary or inlet during the Flandrian transgression. Taking into account both theories, Donovan (1973) pointed out that neither theory is mutually exclusive and that a composite hypothesis should be adopted.

Shoals of sands and gravels are found in close association with these channel forms (Figure 1.9). Robinson (1968) recovered material from the Theddlethorpe Overfalls and the Protector Shoals which lie between the Lincolnshire coast and the southern end of the Silver Pit. The primary glacial origin of these gravels is accepted by Robinson (1968), since local rock types are rare while far travelled glacial erratics are relatively abundant. The commonest lithologies represented are those of the Palaeozoic formations of northern England and southern Scotland and include Carboniferous Limestone, Coal Measures Sandstone, Chert, Permian Sandstone and Cheviot Granite. Scandinavian erratics have not been reported (Robinson 1968).

1.7 Aims of Study

The study into the Holderness diamict sequence has several principal objectives,

1) To establish basic sedimentological and geotechnical properties for the Skipsea and Withernsea Tills.

2) To examine possible relationships between sedimentary properties and geotechnical behaviour.

3) To establish a sedimentary history for the sequence which takes into account the physical properties of the diamict, observed field relationships of the Withernsea and Skipsea Till units and the general stratigraphic framework for the North-east region outlined in sections 1.1 - 1.6.

This last proposal can be linked to a specific contention, concerning the nature of the Withernsea Till.

The current depositional model for the Devensian glacial succession in Holderness outlined by Catt and Penny (1966) and Madgett and Catt (1978) after the original suggestion by Carruthers (1953), proposes that the Withernsea and Skipsea till sheets were deposited contemporaneously by a stratified ice sheet containing distinct basal and englacial debris that moved into the Holderness embayment during the Late Devensian. Both till units have been shown to overlie organic rich silt lenses at Dimlington Cliff (TA 386224 - 408184) which have provided a radio-carbon date of 18,500 ∓ 400 BP (Penny, Coope and Catt, 1969). The oldest date yet obtained from material above either till is 13,045 ∓ 270 BP at The Bog, Roos (TA274288), (Catt, 1977). The decay of the ice sheet during the latter part of the period bracketed by these two dates, is thought to have resulted in the superimposition of two till sheets without the development weathering, contortion or incorporation across the junction, indicative of two separate ice advances (Madgett and Catt, 1978).

Analysis of the till petrography has shown that the diamicts possess specific mineralogical, sedimentological and lithological properties, the result of different zones of provenance (Madgett, 1975) and possibly reflecting transportation at discrete levels within the stratified ice sheet. This situation is believed to have occurred when "Withernsea" ice flowing east from the Lake District through the Stainmore Gap moved into contact with the outcrop of Mercia Mudstone (argillaceous facies of the former Keuper, Triassic) in the lower Tees valley, before overriding a pre-existing coastal ice stream carrying the Skipsea Till as basal debris (Madgett and Catt, 1978). Although the exact nature of the deglaciation is as yet undetermined, Catt (1977) suggests that both ice streams stagnated soon after moving into Holderness and features such as the Killingholme and Hogsthorpe ridges represent irregular deposition of flow till and melt-out till deposited during the slow decay of dead ice rather than the terminal moraine complex of an active ice front (Straw 1979).

Attempts have been made to rationalize the complexity of glacial deposits through the application of depositional theories which link process, landform and sedimentology into a single unifying model or landsystem (Boulton and Paul, 1976; Eyles, 1983). Of particular importance to the Quaternary deposits of Holderness is the recognition of "subglacial" and "supraglacial" landsystems which have proved useful in the interpretation of diamict sequences deposited by lowland ice sheets across areas of sedimentary strata (Boulton et al., 1977).

The subglacial model can be applied to warm based glaciers that transport a thin layer of debris at the glacier sole, maintained by high rates of basal melt. Deposition occurs when the tractive force imposed by the moving glacier is inadequate to maintain in motion the basal debris against the frictional resistance offered by the bed (Boulton 1975). The balance between lodgement and erosion is dependant on a critical balance between a number of inter-related variables e.g. water pressure at the ice base, nature of transported load, and the permeability of the subglacial bed (Boulton and Paul, 1979). The control of several critical lodgement parameters leads to the slow accretion of a massively bedded, overconsolidated, poorly sorted diamict which can possess remarkably uniform textural and mineralogical properties (Luttenegger, Kemmis and Hallberg, 1983). Particularly diagnostic of this system is the development of an anisotropic meso-fabric of blade shaped clasts, orientated with the long axis parallel to ice flow and localised clast "smudges" caused by the shearing out of soft incompetent lithologies (Eyles, 1983). Other significant components of a till sheet deposited in this manner include subglacial channel fill sequences which result from active basal drainage beneath melting ice. Such forms can be recognized as distinct from the proglacial sediment association by a marked lateral discontinuity, forming "stacked" sequences with direct contact with true basal lodgement tills. Channel cross-sections can show evidence of hydro-static flow and generally fall within a smaller size range (1.5-12m) than fully developed proglacial outwash sequences (Eyles and Sladen, 1981).

By way of contrast the supraglacial landsystem describes the sediment association produced by the decay of ice transporting significant quantities of supraglacial or englacial debris. In the case of lowland continental ice sheets, this is usually related to compressive flow or the development of a cold ice margin leading to refreezing at the sole and the thrusting of basal debris into an englacial position (Boulton and Paul, 1976), but would also be applicable to the melt of a stratified ice sheet as in the Carruthers (1953) model.

Ablation causes debris to be released and deposited by processes or mass wasting as mobile flow tills (Boulton, 1970, Lawson, 1982). Slow melting of buried ice beneath flow tills releases more debris in situ (meltout till) which can be more stable and retain its englacial structure. Diamict sequences deposited in this manner characteristically deform as a result of sediment collapse or settling during the melt of underlying or buried ice masses, and such features include faulting, folding and slump structures (Shaw, 1972). On final ice melt an irregular hummocky kamiform topography is produced with a complex vertical profile formed of inter-stratified reworked diamicts and melt water deposits (Paul, 1983).

The superimposition of these distinctive depositional landsystems creates a change in facies which can be recognised in a detailed examination of sedimentary and geotechnical properties (Lutteneggar, Kemmis and Hallberg, 1983) and so provide a test for the stratified ice sheet theory.

CHAPTER 2

Sampling and Data Acquisition.

2.1 Introduction.

Any attempt to relate depositional history to sedimentological properties and geotechnical behaviour requires undisturbed samples of testable quality that are precisely located within a profile. Tills are highly complex materials which often prove difficult to sample and test since, in a fissured state, three dimensional shear-strength anisotropy is often outside the bounds of conventional sample size (McGown, Saldivar-Sali, Radwan 1974).

The sampling method adopted for the terrestrial study was predetermined by the coring technique developed at the Building Research Establishment which has proved highly successful in producing high quality, medium scale cores through the entire Quaternary sequence in Holderness. Owing to problems in obtaining external drilling permission, all the boreholes studied were drilled at the Cowden test-bed site, 8 km south-east of Hornsea (Figure 2.1.) Information on the regional stratigraphy was supplemented by close examination of the coastal sections and borehole records kindly provided through the British Geological Survey. All offshore samples were supplied by .B.G.S who also provided access to over 150 vibrocore logs drilled in the Humber sea area.

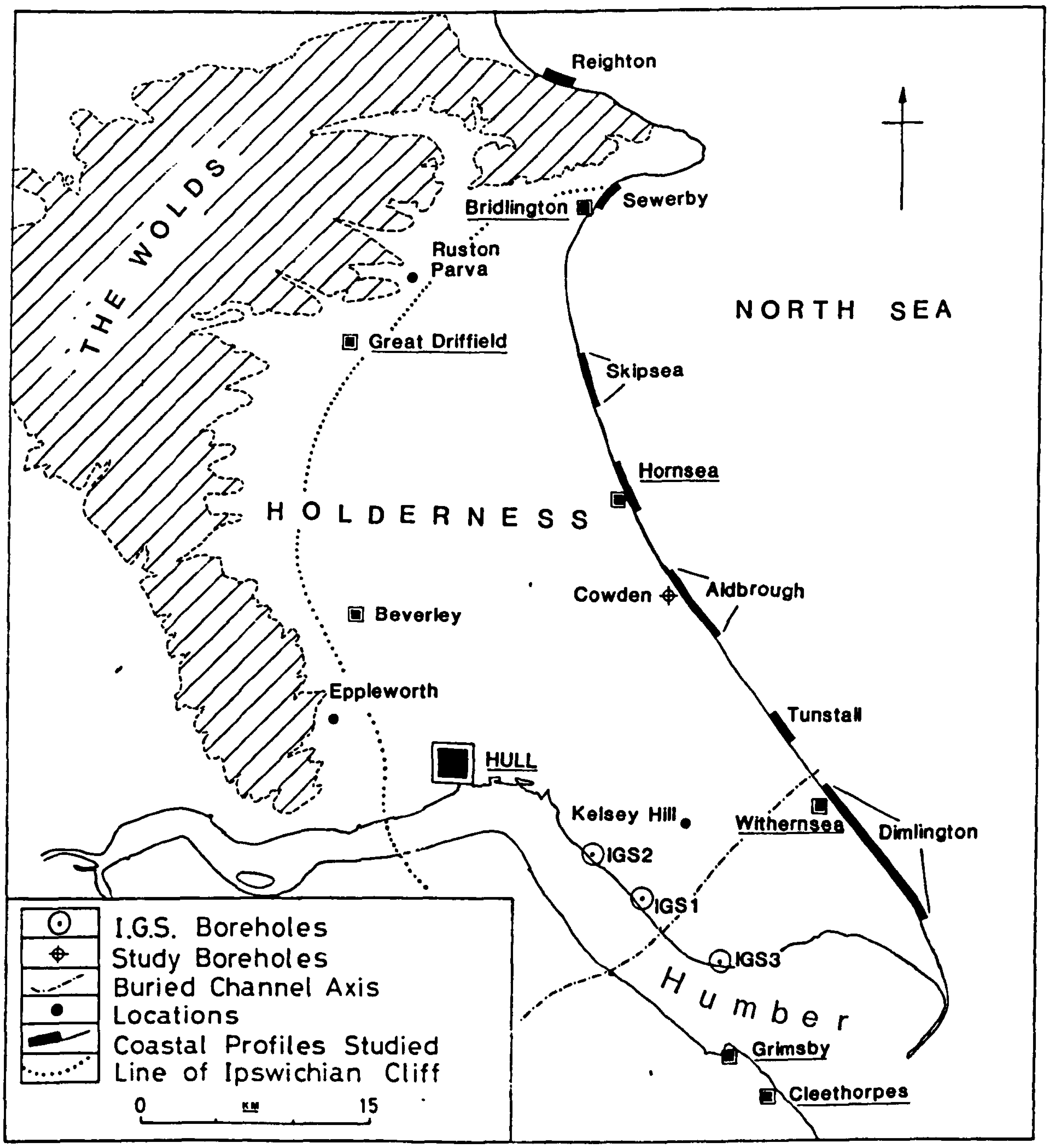

Figure 2.1 Location of study sites, borehole locations and places mentioned in text.

2.2 Cowden Test Bed Site

2.2.1 Boreholes.

Three dry boreholes (CS1-3) were sunk during the summer of 1982 at Cowden (GR TA 244403), each to over 10 m in depth. Drilling and testing of cores from boreholes CS1 and CS2 took place during a three week on-site programme from May to June 1982. CS3 was sampled a month later during a separate five day drilling schedule. Boreholes CS1 and CS2 were located within 10 m of each other. Borehole CS3 was drilled immediately adjacent to CS1 to provide a control on test results. In total, 47 samples were produced with a mean length of half a metre (Tables 2.1-2.3). Core recovery was good, averaging 73%. Weather during both phases was fine with minimal rainfall.

The problems of obtaining reasonably undisturbed samples of till have been reported by a number of workers (McKinlay, Tomlinson and Anderson 1974). Jorden (1975) noted that sample disturbance has a significant effect on the measured properties of a sediment causing a reduction in undrained strength, a decrease in preconsolidation pressure and a reduction in the coefficient of consolidation. The following procedures were adopted to minimise this crucial factor.

a) Thin walled tubes were used throughout the sampling programme. These were constructed from 1.5 mm gauge metal with an internal diameter of 98 mm which provided a cutting edge ratio of 3.5%. Standard U100 tubes with removable cutting shoes have an edge ratio of 25%.

b) Using a file, the cutting face was sharpened to a knife

Plate 2.1 Drilling rig used to produce thin wall push samples for boreholes CS1-3, Cowden Test Bed.

Plate 2.2 Mobile triaxial laboratory on site at Cowden (rear unit).

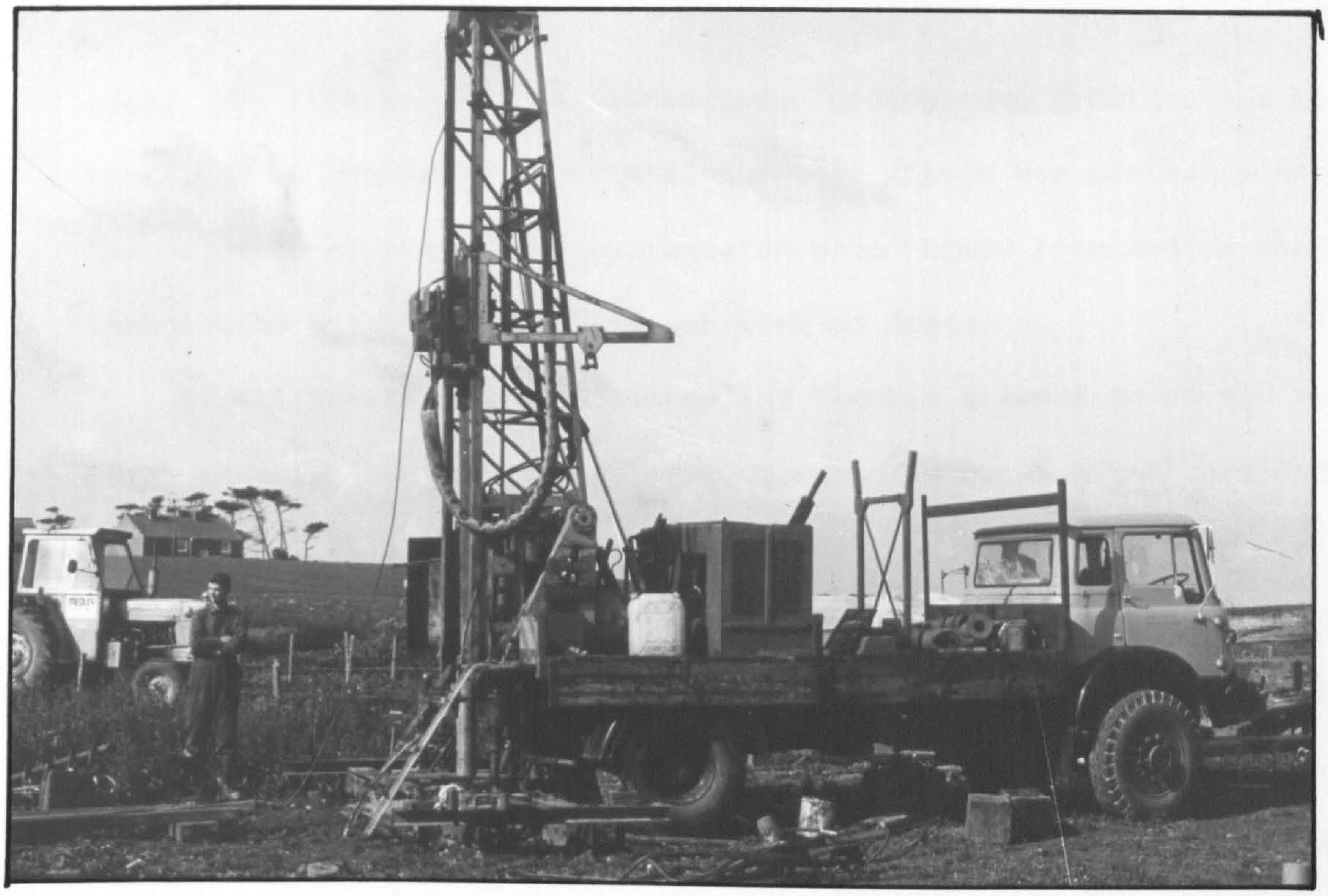

Plate 2.1

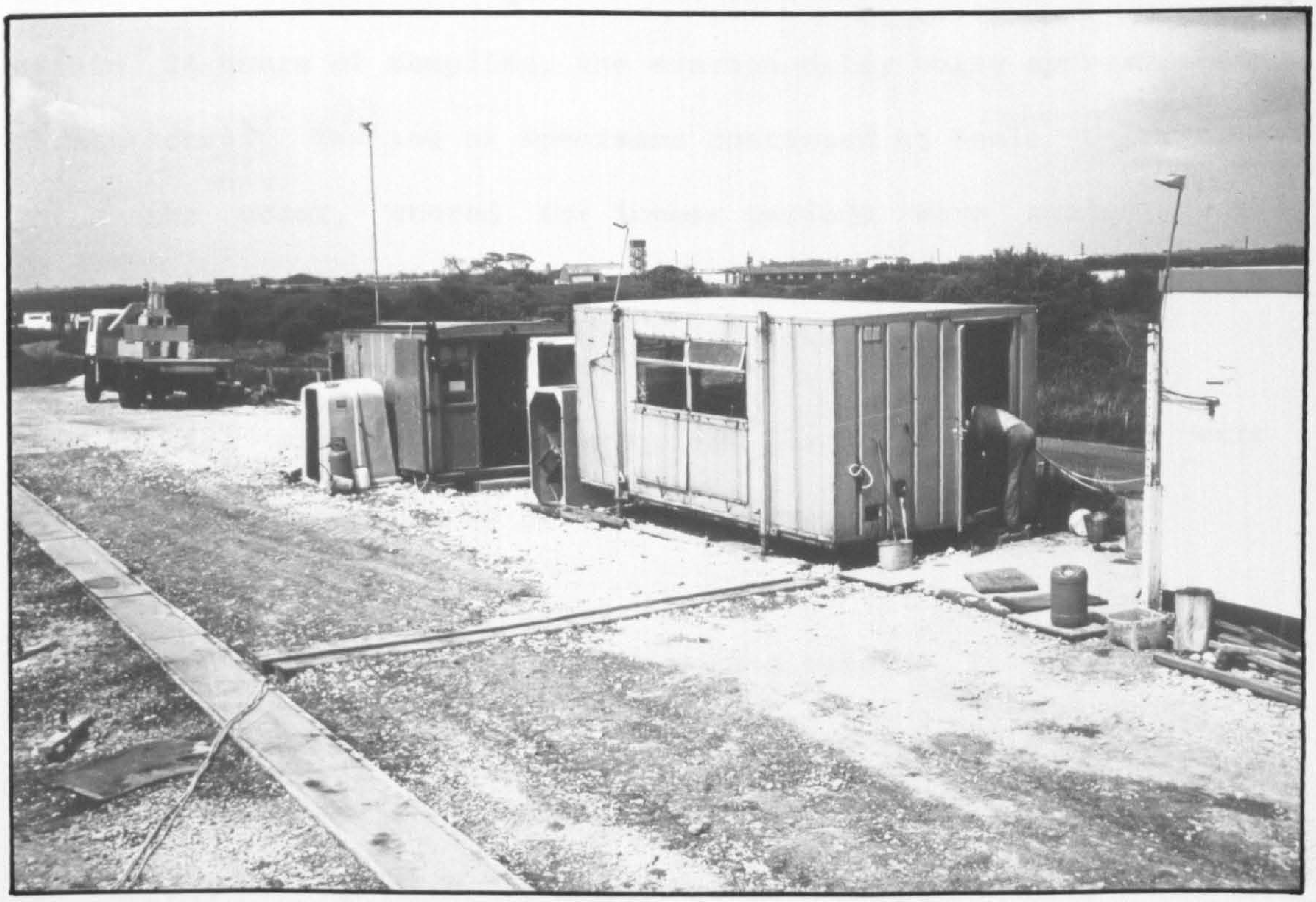

Plate 2.2

edge. The thinning of the leading edge caused some problems due to buckling in contact with flints, but this effect was minimal since the majority of the clasts encountered were formed from medium-hard lithologies which were cleanly cut with no dragging.

c) All the tubes were cleaned and lightly greased as an aid to both sampling and extrusion. Frictional drag between the core and the internal wall created a characteristic warping of the sample at the margins. However, the degree of disturbance was limited to within 1 mm of the circumference. Greasing also helped to prevent oxidation in sample tubes stored for long periods before extrusion.

d) The thin walled tubes were hydraulically jacked into the profile using a mobile rig (Plates 2.1 and 2.3). The straight drive was at a constant rate of approximately 1m/min.

e) The release of in situ stresses was minimised by on-site testing in a mobile triaxial laboratory supplied by the Building Research Establishment (Plate 2.2). Twenty samples were placed under confining stress equal to the calculated total overburden within 24 hours of sampling, the average delay being approximately three hours. Testing of specimens continued at Keele University where the cores, stored for longer periods were subjected to drained and undrained tests. Sample to cell times ranged from twenty minutes to twelve months.

f) All sample tubes not required for immediate testing were wax sealed at both ends to prevent moisture loss.

After extrusion the cores were dissected to provide the cleanest section for triaxial testing. Longer cores provided two specimens at a 1.5/1 height to width ratio. Undisturbed sub-samples were removed for S.E.M examination and on-site moisture determination. The top and bottom portions were taken to provide

Location.......... Cowden

Borehole.......... CS1

Sampled........... 13th-15th May 1982.

Sample	Depth m	Extruded Test	Unextruded Destination
CS1/ 1	0.8 - 1.3	A	
CS1/ 2	1.3 - 1.8		TRRL
CS1/ 3	1.8 - 2.4	A	
CS1/ 4	2.4 - 3.0		TRRL
CS1/ 5	3.0 - 3.6	A	
CS1/ 6	3.6 - 4.2		TRRL
CS1/ 7	4.4 - 4.9	A	
CS1/ 8	5.0 - 5.5		TRRL
CS1/ 9	5.6 - 6.1	A	
CS1/10	6.2 - 6.7	A/B	
CS1/11	6.8 - 7.4	A	
CS1/12	7.4 - 8.1	A/B	
CS1/13	8.1 - 8.6	A/B	
CS1/14	8.6 - 9.2	A/B	
CS1/15	9.3 - 9.9	A/C	
CS1/16	10.1 - 10.7	A/B	
CS1/17	10.7 - 11.2		KEELE

Table 2.1 Summary of drilling log, sample nomination and geotechnical test. CS1

Location.......... Cowden

Borehole.......... CS2

Sampled........... 17th-2nd June 1982.

Sample	Depth m	Extruded Test	Unextruded Destination
CS2/18	0.9 - 1.3		Keele
CS2/19	1.8 - 2.2	A	
CS2/20	2.4 - 2.9		TRRL
CS2/21	3.0 - 3.5	A/B	
CS2/22	3.6 - 4.1	B	
CS2/23	4.2 - 4.8	C	
CS2/24	4.9 - 5.5	B	
CS2/25	5.6 - 6.2		TRRL
CS2/26	6.2 - 6.9		Keele
CS2/27	7.0 - 7.6		TRRL
CS2/28	7.9 - 8.5		Keele
CS2/29	8.6 - 9.2	C	
CS2/30	9.3 - 9.9	A/C	
CS2/31	10.0 - 10.6		Keele
CS2/32	10.6 - 11.2		Keele
CS2/33	11.2 - 11.8		Keele

Table 2.2 Summary of drilling log, sample nomination and geotechnical test. CS2

Location.......... Cowden

Borehole.......... CS3

Sampled........... 2nd-11th July 1982.

Sample	Depth m	Extruded Test	Unextruded Destination
CS3/34	1.0 - 1.5		Damaged
CS3/35	1.5 - 2.2		Damaged
CS3/36	2.2 - 2.6	A	
CS3/37	2.8 - 3.4	A	
CS3/38	3.4 - 4.0	C	
CS3/39	4.0 - 4.6	A	
CS3/40	4.8 - 5.4	A	
CS3/41	5.6 - 6.1	A	
CS3/42	6.3 - 6.9	C	
CS3/43	7.2 - 7.8	A	
CS3/44	8.3 - 8.9	C	
CS3/45	9.0 - 9.6	A	
CS3/46	9.7 - 10.3	A	
CS3/47	10.6 - 11.0		BRE

Table 2.3 Summary of drilling log, sample nomination and geotechnical test. CS3

bulk index properties. All sub-samples were labelled with an abbreviated description and depth. These where then stored in plastic bags within wax-sealed cardboard containers. Trimmings were used for an on-site description of the sediments. Failed triaxial specimens were also stored in waxed cylinders for re-examination and dissection at Keele.

The scheme for the labelling of the sub-samples involved the consecutive numbering of each core regardless of the borehole nomination (Tables 2.1-2.3). As an example CS3/36 TX(A) describes the triaxial specimen used in an (A) test dissected from core 36, borehole CS3. This simple system prevented material from different boreholes being confused at a later stage.

Undisturbed sampling of the sand lenses periodically encountered at depths of 11 m and 18 m proved difficult using the thin walled coring method since samples recovered in the tubes were impossible to extrude. In this event bag samples were taken from augered recoveries. Data from the Cowden profile below 10 m were made available through the Keele records of previous B.R.E boreholes to chalk.

2.2.2 Trenching

The Soils Laboratory at Keele University was involved in an experimental programme initiated by the Transport and Road Research Laboratory in association with B.R.E to measure the effect of deep trenching on the dynamics of the adjacent soil. This gave access to an instrumented trench with dimensions 12m X 1.5m X 5m which was excavated directly between boreholes CS1 and CS2. Although the faces of the trench were shuttered it allowed a close examination of the fresh section to a depth of approximately 4.5 m which provided information on the weathering of the till

Plate 2.3 Drilling rig showing thin wall tube attached prior to lowering and sample push.

Plate 2.4 Undisturbed junction between the Withernsea and Skipsea Tills exposed in the Cowden trench wall at location B. See Figure 2.2.

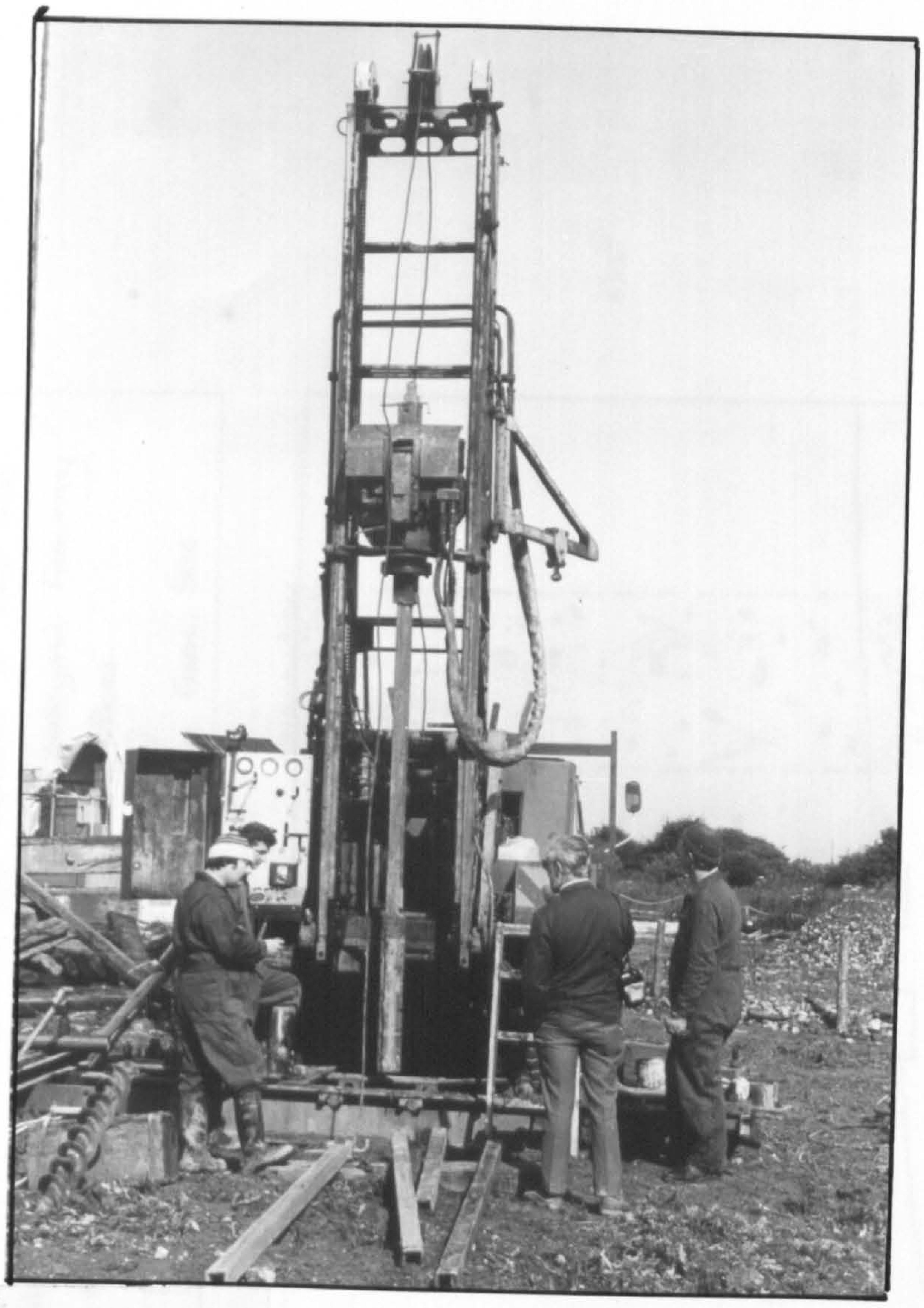

Plate 2.3

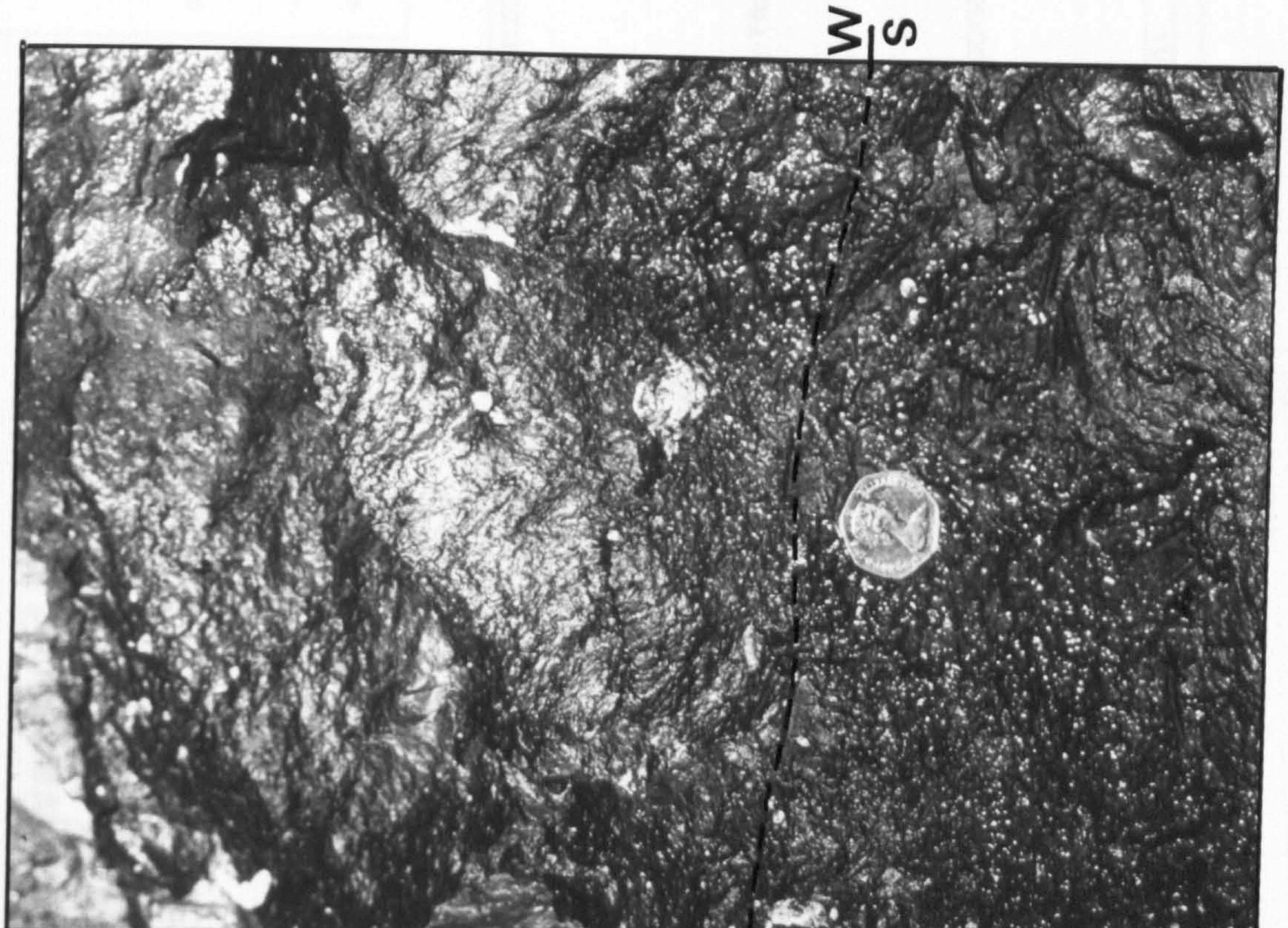

Plate 2.4

University of Keele
Department of Geography
Soils Laboratory

NOTES

Southwards Facing Side. (1)

Section comprises two superimposed Till units of Devensian age *. The junction is well defined with a westward dip. The lower till unit is not exposed at West end. The Withernsea Till shows extensive pedogenic fissuring down to ≈ 3·5 m, with gleyed surfaces.

* Ref. MADGETT PA & CATT JA 1978
VOL. 42 P1 No 5 PROC. YORK. GEOL. SOC.

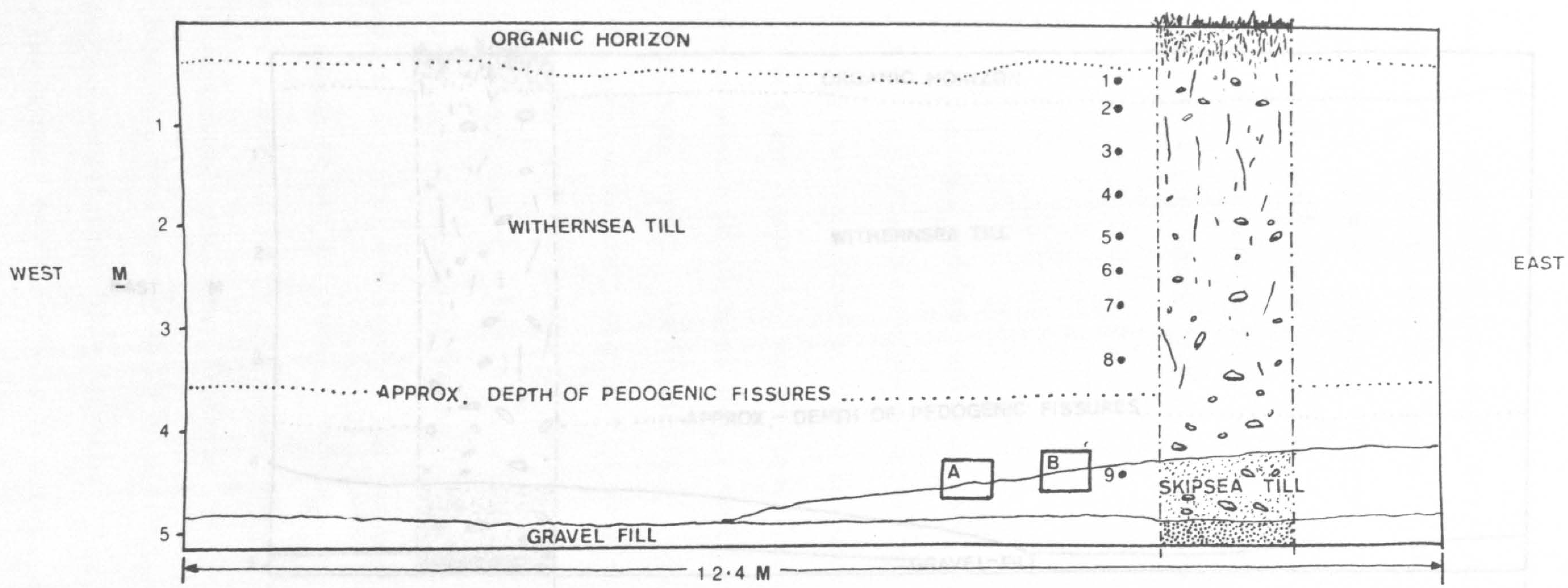

Figure 2.2 Cowden trench stratigraphy (South)

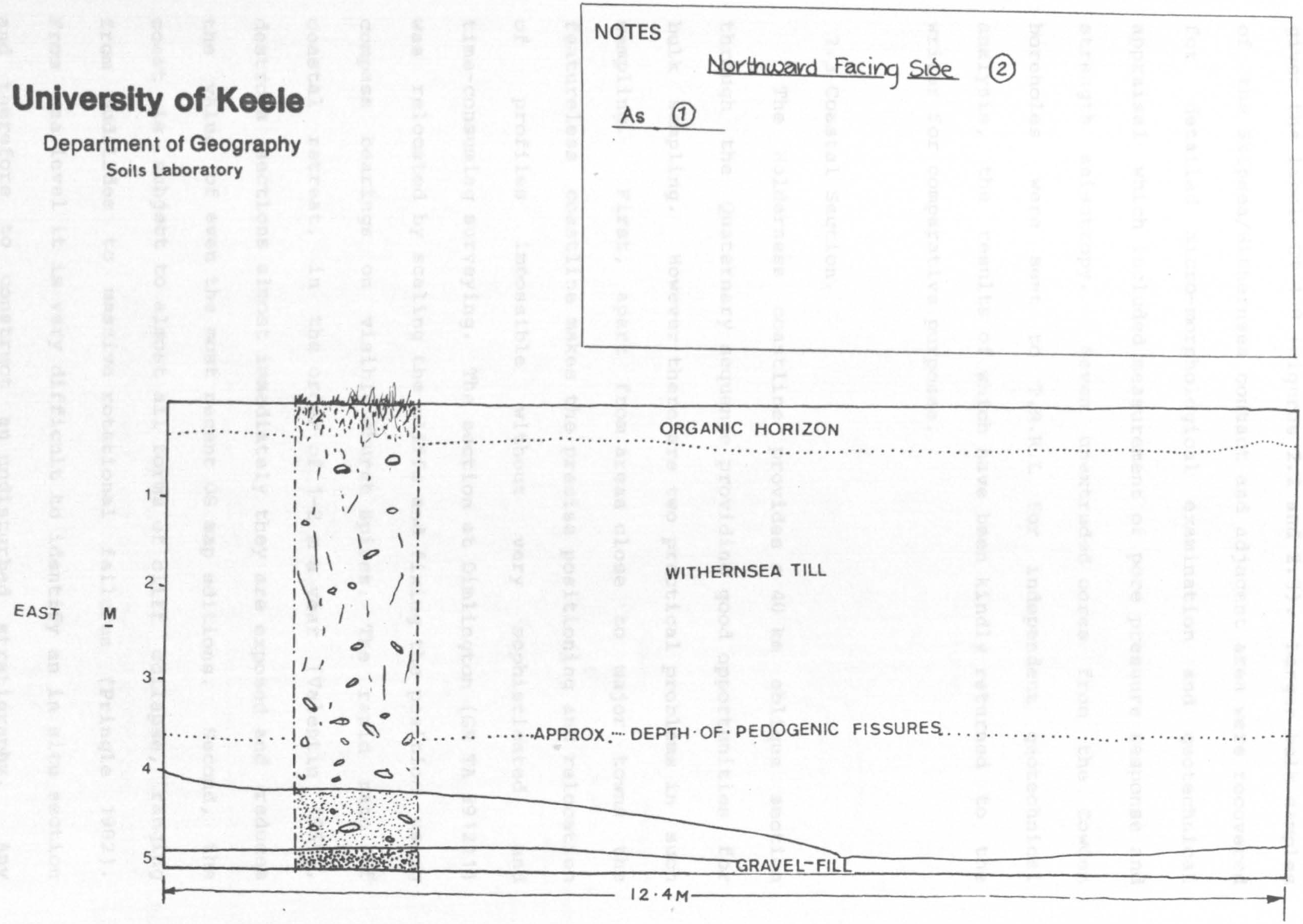

Figure 2.3 Cowden trench stratigraphy (North)

profile and the nature of the Skipsea/Withernsea contact (Plate 2.4). Samples were taken down the face at intervals of 0.5 m and given the labels CT 1-9 (Figures 2.2 and 2.3). Larger bulk samples of the Skipsea/Withernsea contact and adjacent area were recovered for detailed micro-morphological examination and geotechnical appraisal which included measurement of pore pressure response and strength anisotropy. Seven unextruded cores from the Cowden boreholes were sent to T.R.R.L for independent geotechnical analysis, the results of which have been kindly returned to the writer for comparative purposes.

2.3 Coastal Section.

The Holderness coastline provides a 40 km oblique section through the Quaternary sequence providing good opportunities for bulk sampling. However there are two practical problems in such sampling. First, apart from areas close to major towns the featureless coastline makes the precise positioning and relocation of profiles impossible without very sophisticated and time-consuming surveying. The section at Dimlington (GR TA 391211) was relocated by scaling the cliffs and fixing the position using compass bearings on visible church spires. The rapid rate of coastal retreat, in the order of 1-2 m a year (Valentin 1957), destroys sections almost immediately they are exposed and reduces the value of even the most recent OS map editions. Second, the coast is subject to almost all forms of cliff collapse, ranging from mudslides to massive rotational failures (Pringle 1982). From sea level it is very difficult to identify an in situ section and therefore to construct an undisturbed stratigraphy. Any attempt to trace a litho-stratigraphic unit laterally is hindered by the presence of debris slides and sheet-wash.

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Nevertheless, it must be recognised that the present terminology, stratigraphy, and depositional theory was developed by studying the coastal profiles. Many of the facies types described by Madgett and Catt (1978) could be sampled only by visiting the type sections particularly those at Dimlington, Aldbrough, and Sewerby. Samples obtained at these sites included the Basement Till (BT), Sub-Basement Clay (SBC) and the Dimlington Silts (DS) none of which was encountered in the Cowden boreholes to chalk. During the period 1982-5, the sections of coastline marked in Figure 2.1 were visited on numerous occasions to obtain photographic evidence of medium scale sedimentary features and bulk samples of intra-formational facies variations. Samples were gathered of a previously unrecorded fissured clay erratic termed the Beach Clay (BC) found within the lower Skipsea Till. Where possible the nature of the undisturbed Skipsea/Withernsea boundary was noted.

2.4 Inland Sections.

Previous workers in Holderness have reported the lack of clear exposures away from the coastline. Almost without exception they are limited to chalk quarries located at the base of the Wolds or disused and working gravel pits which tend to lie in an arcuate line close to the limit of the Withernsea Till as drawn by Madgett and Catt 1978 (Figure 2.4.) Quarries at Eppleworth (GR TA 021324) and Ruston Parva (GR TA 069617) were visited to examine the sections as described in the INQUA field guide (1977). However, the profiles were found to be badly exposed and of little practical value.

With the permission of the Holderness Sand and Gravel Company samples were obtained at Kelsey Hill (GR TA 236253) from the newly excavated Mill Hill workings (Figure 2.1). This type site is of particular value with respect to the clear exposure between the Devensian tills and a gravel complex which contains a well documented Late Pleistocene fauna. The samples from this site were given the nomination KHS.

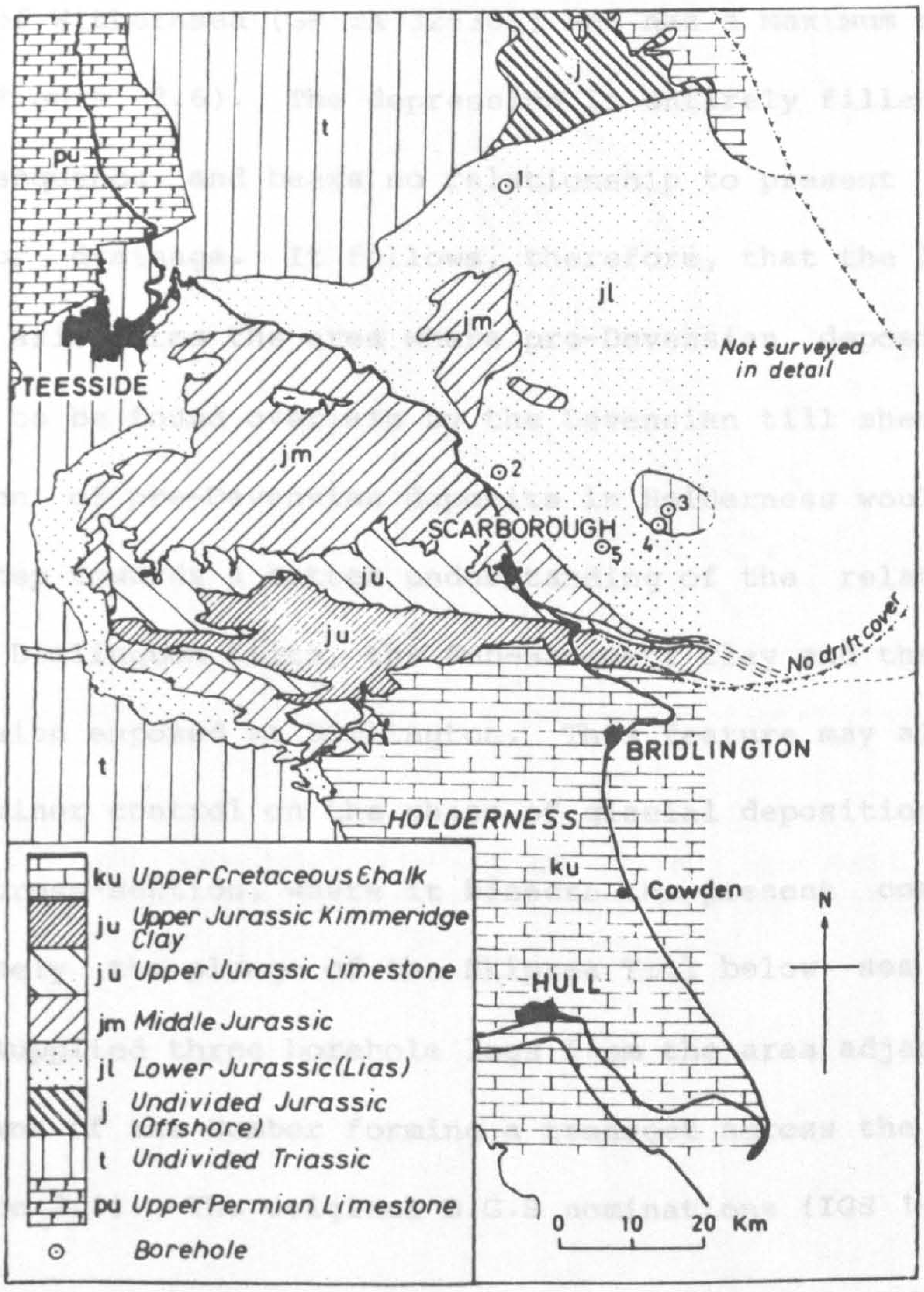

Figure 2.5 Regional geology showing the site location and limit of "drift" cover

2.5 Terrestrial Boreholes.

The sub-drift surface of Holderness is a dissected plateau of Cretaceous chalk which lies at an average depth of -15m OD forming the westerly extension of the East Midlands Shelf (Figure 2.5). Boreholes drilled by B.G.S have confirmed the existence of a buried valley cut into this platform which formed the northerly course of the proto-Humber during the Tertiary (Straw 1979). The channel axis runs from the Lincolnshire Wolds at Kirmington (GR TA 103116), under the present Humber Estuary at Immingham Dock to the coastline just north of Withernsea (GR TA 325305) and has a maximum depth of -75m OD (Figure 2.6). The depression is entirely filled by a Quaternary sequence and bears no relationship to present surface morphology or drainage. It follows, therefore, that the line of the valley axis forms the area where pre-Devensian deposits are most likely to be found overlain by the Devensian till sheet. The identification of pre-Devensian deposits in Holderness would be an important step towards a better understanding of the relationship between the Dimlington Silts, the Sub-Basement Clay and the lower till succession exposed at Dimlington. This feature may also have exerted a minor control on the phase of glacial deposition since the valley cross-section, where it bisects the present coastline, matches closely the plunge of the Skipsea Till below sea level. B.G.S have supplied three borehole logs from the area adjacent to the north bank of the Humber forming a transect across the valley axis (Figure 2.1). The original B.G.S nominations (IGS 1-3) were retained.

Sample	OS Grid Ref	Max Depth
IGS 1	TA 234 189	64 m
IGS 2	TA 217 207	45 m
IGS 3	TA 275 167	167 m

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2.6 Offshore Sampling.

Information on the offshore Quaternary stratigraphy was obtained through the Marine Geology Unit of the B.G.S based at Leeds and Edinburgh who also supplied bulk samples recovered during the 1981 drilling programme in addition to vibrocore returns from sample stations in the Spurn/California map areas.

Vibrocores. The present B.G.S vibrocoring system produces samples suitable for sedimentary analysis with a diameter of 85 mm which can be recovered from water depths up to 1000m. The method allows for a high sampling rate since the depth of penetration is limited to 6 m. It follows that the vibrocore cover of the Spurn/California map areas is far more extensive than the sampling net of rotary cored returns. The logs provided by B.G.S give a good indication of the superficial drift cover but little information on the change of lithology with depth since the cores of the Devensian till recovered were mostly less than 2 m in length.

The vibrocorer uses an internal barrel containing a C.A.B (Cellulose Acetate Buterate) transparent plastic liner which was sealed for long term storage. The seals were broken and the core split for examination and sub-sampling at Leeds before being passed to Keele in a semi-dry state. Accordingly it provided material suitable only for sedimentary analysis. A total of six vibrocores have been examined from various offshore locations. The original B.G.S. nominations were maintained.

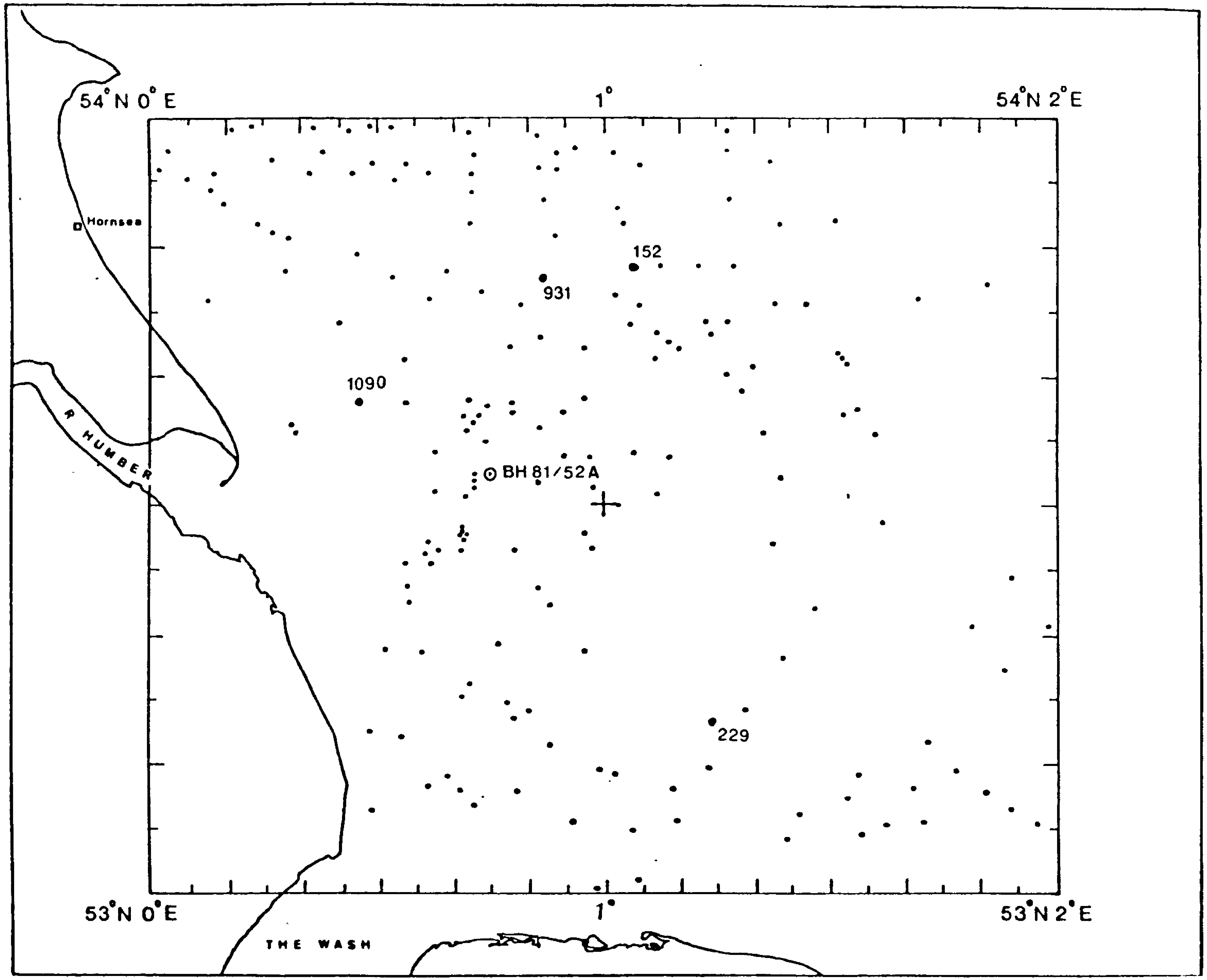


Figure 2.7 BGS Vibrocore cover in the Spurn map area

Sample	Depth	Location
VE 1090	1.1 - 2.0	
VE 931	1.0 - 1.9	
VE 152	0.0 - 0.9	See Figure 2.7.
VE 229	1.0 - 1.8	
VE 392	0.8 - 1.6	
VE 411	0.0 - 1.0	

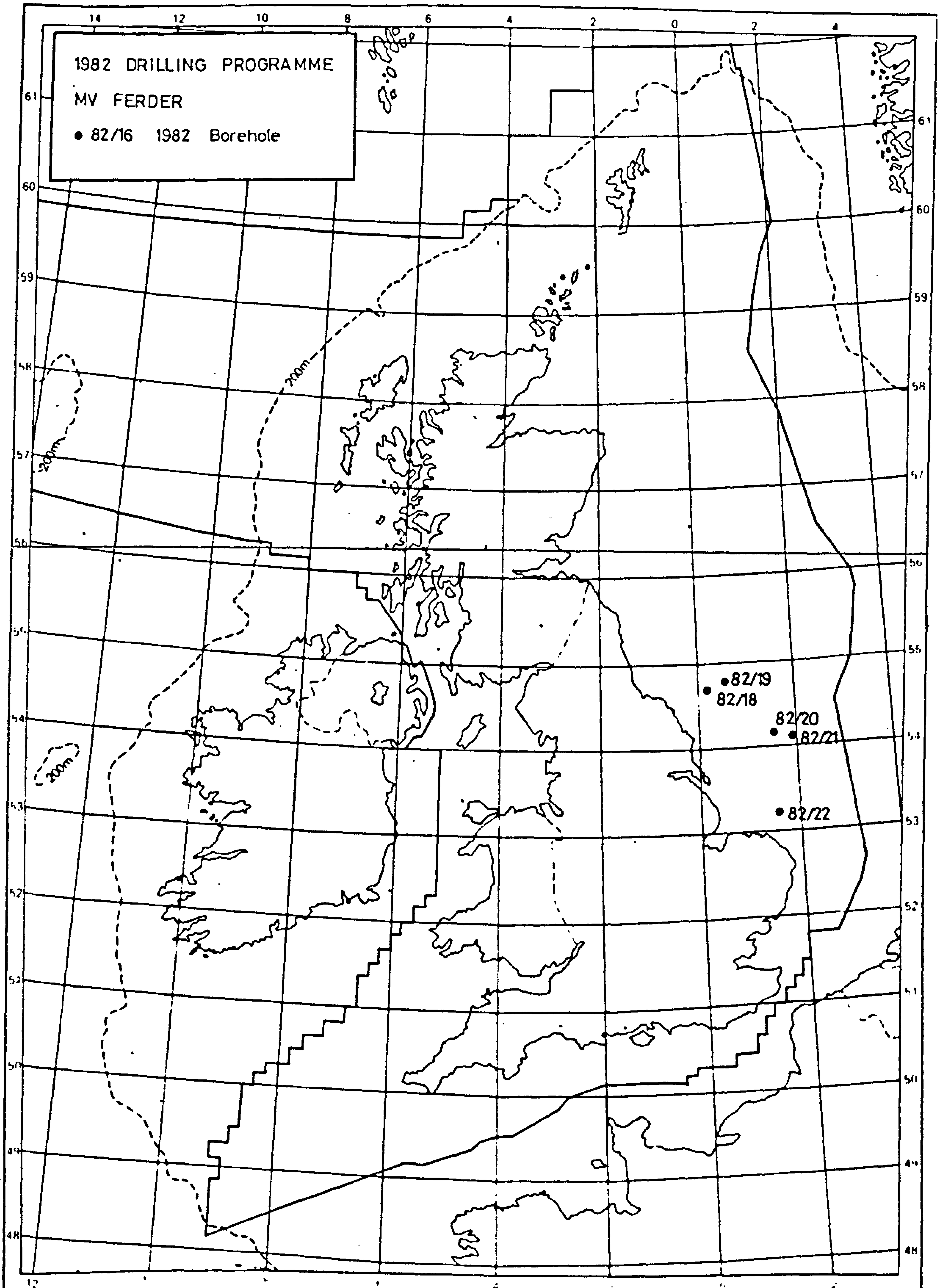
Table 2.4 Sampled Offshore Vibrocores

Over one hundred vibrocore logs from the region shown in Figure 2.7 were used to delimit, as far as possible, the till cover and recent sand/clay deposition in the offshore Holderness area. Unfortunately the Pleistocene sequence in these records was not divided on strict lithological grounds but was frequently grouped into a general "Quaternary" unit.

Supplementary evidence on sea floor bathymetry and drift cover in the area south of Spurn Point has been obtained from the work of Robinson (1968) and Donovan (1973).

Rotary Coring. B.G.S. rotary coring methods can penetrate up to 300m below the sea bed producing cores which are used primarily to establish lithological and stratigraphic control on seismic interpretations. High quality samples have been recovered from consolidated Quaternary sequences in the North Sea, including thirteen boreholes in map areas Spurn and California. Full access was given to the returns from BH 81/52A recovered from the Inner Silver Pit during the 1981 drilling programme. This 30 m sequence was particularly interesting since it appeared to show interglacial sediments underlying the Skipsea/Withernsea Till complex and a lower chalky diamict resting directly on bedrock. Recovery from a

Figure 2.8 Location of rotary cored boreholes drilled in the offshore area by BGS in 1982



thick sand and gravel body within the sequence was minimal. A total of fifteen sub-samples was taken, including small quantities for micro-faunal analysis. In addition to BH 81/52A the logs of the following cores were made available from the 1982 drilling programmes (Figure 2.8).

I.G.S Shallow Boreholes 1982.

Southern North Sea.

BH 82/18,18A	54° 42.55' N 00° 04.98' E
BH 82/19	54° 47.49' N 00° 34.13' E
BH 82/20	54° 06.05' N 01° 29.88' E
BH 82/21	54° 03.69' N 01° 58.96' E
BH 82/22	53°16.97' N 01° 42.32' E

Table 2.5 B.G.S. Shallow boreholes

Chapter 3

Analytical Methods.

Nomenclature

A	Activity of clay fraction	
e	Voids ratio	
e_i	Initial Voids ratio	
Ip	Plasticity index	
J	Percentage clay content	
LI	Liquidity index	
LL	Liquid limit	
M	Mass of soil specimen	M = Ms + Mw
Ms	Mass of soil particles	
Mw	Mass of soil water	
n	Porosity	
Gs	Specific gravity	
V	Volume of soil specimen	
Vp	Volume of pore space	
Vs	Volume of soil particles	
Vw	Volume of pore water	
w	Moisture content (%)	
ρ	Bulk density (Mg/m^3)	
ρd	Dry density (Mg/m^3)	

3.1 Introduction.

Although the presentation of analytical techniques has been broken down into sections concerned with sedimentary and geotechnical method, it should be noted that there is no strict dividing line between the two approaches. Soil analysis is a true inter-disciplinary science, existing in the area between the sedimentologist, chemist and engineer, all of whom have contributed in an attempt to understand the complex interrelationship between soil genesis, structure and mechanical behaviour under stress. Tests refered to by the prefix (BS 1377) are described in the British Standards Institution publication, Methods of Test for Soils for Civil Engineering Purposes (1975).

3.2 Sedimentological Analysis.

3.2.1 Initial Description. The sampling and testing programme provided three types of specimen, undisturbed terrestrial/marine core, failed triaxial specimen and bulk sample. As far as possible all were subject to a primary descriptive phase which followed a standard format. These observations, although essentially descriptive, provided an insight into the primary mode of deposition when used in conjunction with other empirical data. Close examinination was made of the meso-fabric, taking a particular note of structural discontinuities in undisturbed material as well as forming an assessment of sampling disturbance where appropriate. Moist colour was determined by reference to the Munsell soil colour chart (1954 edition). Dissection of the triaxial specimens involved the identification of planes of failure and the relationship between these and the primary fabric at all scales. Information was recorded as a three-dimensional sketch which was also used to register the position of various subsamples taken at this point ie. moisture content.

3.2.2 Moisture Content. Emphasis was placed on the rapid and accurate determination of moisture content particularly with respect to samples used in geotechnical tests. Determinations were made at both the top and base of the specimens in all triaxial tests carried out at on-site at Cowden and later at Keele University. The oven-drying method (BS 1377 Test 1/A) was used although it was clearly impractical to use a 3 kg sub-sample as recommended for a coarse-grained soil within the limits of a half meter core. Reproducable results were achieved using 300-400 gm "slices" of core dried at 105^{o}C in a thermostatically controlled oven. Since the samples were trimmed square using a former and the diameter was known, volume could be calculated as a simple function of thickness without recourse to more elaborate methods normally necessary with bulk samples. Offshore samples were received at Keele in a semi-dry condition and so did not provide suitable material for moisture content determination.

3.2.3 Specific Gravity. The Specific gravity of the solid phase (Gs) can be defined as a dimensionless ratio of the unit weight of solids to the unit weight of water and is usually applied as an average value of 2.65. This critical variable depends on the mineralogical composition of the soil and can be shown to vary between 2.4 and 3.2 with increasing quantities of dolomite, mica and associated heavy minerals. Previous work has shown that Gs can vary substantially within a single till body and that an average value is often not valid for these soils (Denness 1974). Values for specific gravity from the Cowden profile (BH1) range from 3.1 to 2.16 with a mean of 2.79 (Love 1979). Samples from BH CS1 (10.6m) produced a spread of data from 2.56 to 2.63 with a mean of 2.6. Ideally a determination of specific gravity should be made for each sample examined but the number of cores analysed and the lack of reproducibility in the test results made this impractical. An alternative method was adopted whereby the specific gravity was calculated from various mass/volume relationships assuming total saturation of the soil.

3.2.4 Soil Index Properties. Bulk density (ρ) of the diamicts was calculated from the trimmed triaxial specimens, which provided a 2.0-2.5 kg sample with a pre-determined volume (V). A simple calculation provides the bulk density

e1 $$\rho = M/V$$

:- where M = Mass of the specimen. Following current practice all densities are expressed in units of Mg/m^3.

Using the moisture content (w) of the adjacent sub-sample the dry mass of the solid particles (Ms) could be defined as :-

e2 $$Ms = M / (1 + w)$$

where w is expressed as a decimal between 0 - 1.

By definition the dry density (ρd) can be written as :-

e3 $$\rho d = Ms / V_s$$

The mass of water (Mw) was calcuated from e2 as :-

e4 $$Mw = M - Ms$$

assuming total saturation of the specimen.

Since the mass of water has a direct relationship with volume (1 gm = 1 ml at 20^{o} C) the volume of pore water was given by the same equation. The volume of solids could then be calculated as :-

e5 $$Vs = V - Vw$$

Given the mass of the dry solid particles (Ms) in grams and the volume of the same solid phase (Vs) in ml specific gravity becomes

e6 $$Gs = Ms / Vs$$

Porosity (n ..dimensionless) can be defined as the ratio of the volume of the pores (Vp) to the total volume (V) expressed in

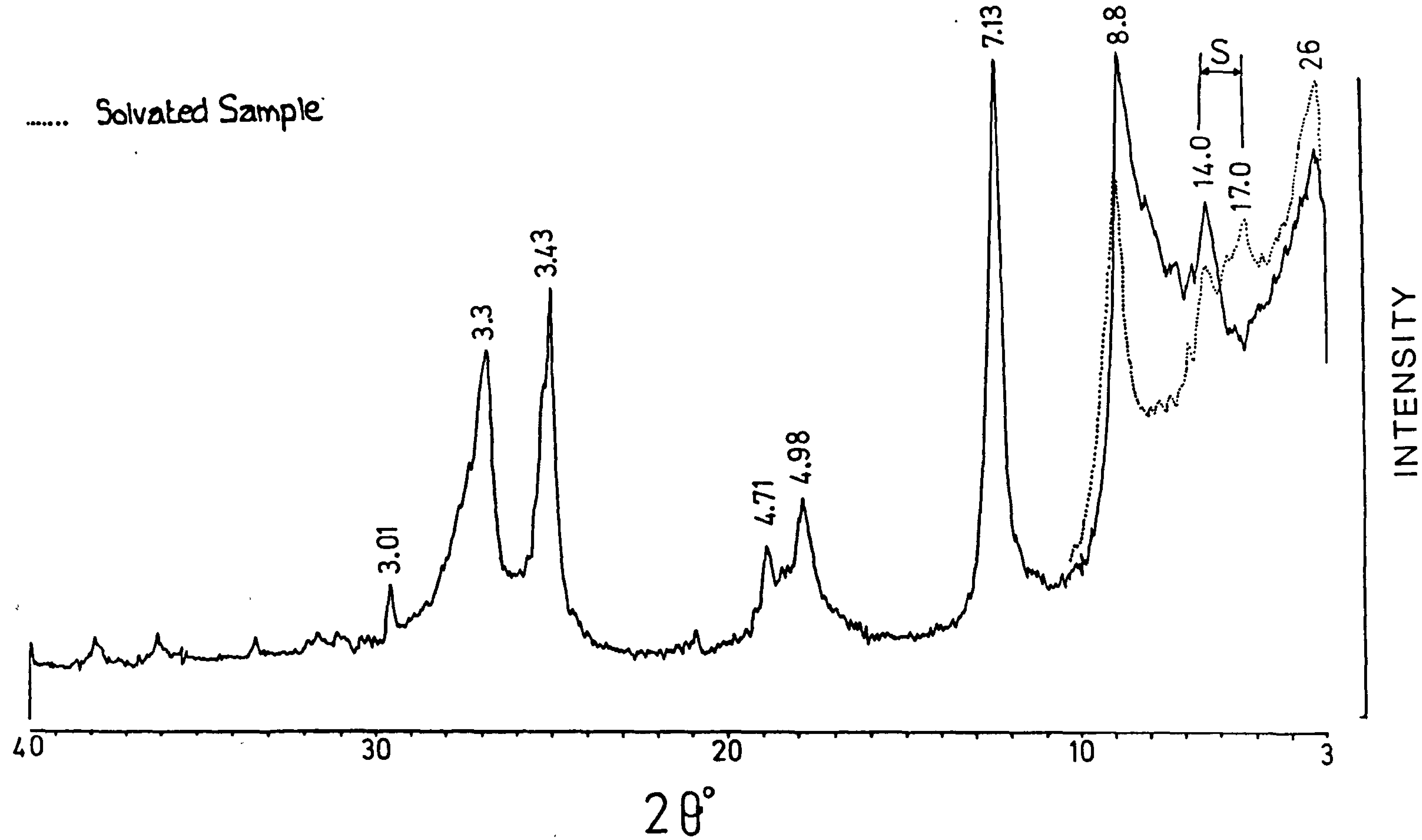


Figure 3.1 X-Ray diffraction pattern. Withernsea Till 4.3m (Trench sample JS5)

mathematical terms as :-

e7 $n = Vp / V$

Similarly the voids ratio (e) dimensionless was calculated as the ratio of the volume of the voids (Vp) to the volume of the solid phase (Vs) determined in the following equation :-

e8 $e = Vp / Vs$ ....or

e9 $e = n / 1 - n$

3.2.5 X-Ray Diffraction. The mineralogy of the clay fraction was determined by X-ray diffractometry, a technique that identifies mineral species by the interference created by the crystal lattice with a beam of directed X-rays. The intensity of X-rays reflected from the sample and entering the Geiger-Muller counter is recorded as a function of the angle θ. When θ corresponds to a distance (d) between the planes of a clay crystal required to bring the rays into phase, a reinforced peak in X-ray intensity will be measured by the counter. The number of counts per second is proportional to the number of X-rays reflected into the counter, producing a continuous pen trace as shown in Figure 3.1. This pattern, obtained from the Withernsea Till, shows the peaks used for the calculation of d spacings, which were converted from degrees 2 θ using the tables given by Carver (1971). For any one diffraction angle there may be several corresponding lattice spacings depending on the order of diffraction. This is particularly true of the lower angle reflections (0 - 10 2θ). Identification of particular mineral species was achieved by expanding or collapsing individual crystal lattices by the methods described below and re-running the test (Carrol 1969).

Orientated slides were produced from a 40 ml sub-sample of the < 63 μm pipette sub-sample which was centrifuged at 2000 rpm for thirty minutes to concentrate the clay suspension. The water was removed by pipette and the concentration placed evenly on a slide with an eye dropper to dry at room temperature before providing the initial trace. Further traces were produced from slides which received the following treatment before diffractometry.

(1) Solvation in ethylene glycol vapour at 80°C for six hours (Brunton 1955).

(2) Heating for four hours in a muffle furnace at 335°C, cooled and stored in a desiccator.

3.2.6 Interpretation Of Mineral Species.

Principal Clay Minerals. All the till samples gave strong reflections at the 14 Å spacing which may indicate the presence of vermiculite, smectite, chlorite or combinations of mixed layer minerals. Glycol solvation causes expansion of the smectite lattice to 17 Å whereas the d spacing of chlorites and vermiculites remain at approximately 14 Å. A clear example of this shift is seen in Figure 3.1. On heating to 335°C both the smectites and vermiculites collapse to 9 - 10 Å, isolating the chlorite peak at 14 Å. Iron rich chlorites give a weak 1st and 3rd order basal reflections but strong 2nd and 4th order reflections. Mixed layer chlorites occur frequently in most clay fractions (Weaver 1956) most commonly interlayered with mica. Swelling chlorites interlayered with montmorillonites are known, although rare (Lippman 1954). The 1st order kaolinite peak at 7.13 Å is coincident with the 2nd order spacing of chlorite at 7.12 Å. On heating to 550°C kaolinite collapses to amorphous allophane (metakaolin).

Moscovite is the most common mica encountered in the clay fraction since it adjusts very slowly to the equilibrium conditions of the environment. It produces an integral series of spacings, the most prominent (002) at 10 Å, with a 4th order reflection at 5 Å. Illite has a similar pattern but the (004) spacing at 5 Å is absent and the peak at 10 Å is less intense. Some expansion with glycol is often produced if the mineral is interlayered with montmorillonite. Glauconite has a coincident reflective pattern but can be distinguished by a strong secondary peak (020) at 5.5 Å.

Minor Minerals. The presence of quartz (rock flour) can be identified by a low intensity peak at 4.27 Å which remains unchanged in all treated states. Most of the samples displayed a carbonate content with a reflection for calcite at 3.04 Å. Treatment with 0.1 N HCL destroys this peak.

3.2.7 Heavy Mineral Analysis. Heavy minerals (Specific gravity > 2.9) and light separates (Specific gravity < 2.9) of the fine sand fraction were prepared from borehole CS1 to study the effects of weathering with depth. Tetra-bromoethane was used as the heavy fluid. The fractions were separated by the standard shaking and settling procedure using a 10 gram subsample with 120 ml of heavy liquid in 250 ml conical separating funnels. The normal yield was in the range 0.2 - 1 %, increasing with depth. The separates were filtered through Whatmans No 5 filter paper and washed thoroughly with acetone before air-drying. Permanent mounts were made up from a few thousand grains suspended in Canada Balsam and sealed with a cover slip. Using a petrological microscope approximately 200 grains were counted for each sample. Control over mineral identification was obtained by working with an optical field of 50 - 60 grains which where identified in full before moving to a new distribution.

3.2.8 Atterberg Limits and Related Parameters. The mechanical properties of cohesive soils depends to a large degree on their water content and on the mineralogical composition of the clay fraction. The engineering techniques of liquid and plastic limit determination were used to quantitatively describe this important relationship. These parameters can be defined as :-

Liquid Limit (LL). The lowest moisture content at which the soil behaves like a fluid ie. negligible resistance to shearing.

Plastic Limit (PL). The lowest moisture content at which the soil can be readily moulded without forming cracks and retain its new shape.

The liquid limit was determined using the Casagrande apparatus in accordance with BS 1377 Test 2A. The plastic limit was calculated using the thread rolling method (BS 1377 Test 3). Several independent tests were also carried out at the T.R.R.L laboratories using material from CS1.

The Plasticity Index (Ip) is defined as the difference between the liquid and plastic limit, expressed as a percentage.

e10 $$Ip = LL - PL$$

The ratio of the plasticity index to the total percentage of the clay fraction (<9ϕ) ? has been defined by Skempton (1953) as a measure of a soil's activity :-

e11 $$A = Ip/J$$

where A = Activity of clays

J = clay fraction expressed as a percentage

These parameters are related to the in situ state by the Liquidity Index, a dimensionless value defined as the difference between the natural moisture content (w) and the liquid limit divided by the plasticity index.

e12 $$LI = w - LL/Ip$$

3.2.9. Particle Size Analysis.

Particle size analysis is the collective name for a variety of techniques in which a disaggregated bulk sample is separated and graded by particle size. The use of size studies is based on the principle that sediments exhibit a characteristic response to generating processes. The poorly sorted nature of glacial diamicts requires that at least two methods be applied to construct a representative size distribution curve, wet sieving for the > 4 Ø fraction and pipette between 9 Ø and 4 Ø. The problem of non-normal data is overcome by the application of the Ø (phi) scale, which is a logarithmic transformation of the mm axis value so that,

e13 $$\emptyset = -\log_2 (X)$$

Where X = particle size in mm

The nature and quantity of sediment passed to wet sieving was largely predetermined by the coring technique which could not sample clasts with a diameter > 98mm. In practice single clasts fully retrieved in the push sample tube rarely exceeded 50mm diameter. The quantity of material wet sieved was limited by the necessity to produce at least one, sometimes two, good quality triaxial specimens from a single 0.5m core length. Consequently, destructive techniques were employed as the final element of analysis after the soil unit had undergone bulk index tests, triaxial shear, dissection and description. This material was then amassed with trimmings from the core to form a sub-sample of no less than 500 gms. This method was found to make very efficient use of the material sampled.

Disaggregation was achieved by soaking the hand-broken peds in a dilute solution of sodium hexametaphosphate for 24-48 hours. This achieved greater reproducability of results than the use of mortar and pestle since the diamict contains a significant quantity of friable clasts (mainly siltstone, mudstone and chalk lithologies) which broke down under the most careful crushing. The entire bulk sample was then washed through a 4 Ø sieve to remove the bulk of the silt and clay fraction before more careful sieving at 1 Ø intervals between - 4 Ø and 4 Ø.

The silt/clay fraction was analysed with Andreasen's pipette apparatus PBW-200W using a 20 gm subsample (<1 Ø). Complete dispersion was ensured by treatment in dilute sodium hexametaphosphate followed by brief ultrasonic agitation. Samples from the weathered horizons were also pretreated with hydrogen peroxide to remove the organic matter. Overlap with the results obtained by wet sieving was usually within 2%.

3.3 Geotechnical Analysis

All compression tests were carried out in Wykeham Farrance 4in (101mm) triaxial cells in a configuration similar to that shown in Figure 3.2. This device allows an isotropic stress (b_3) to be applied to a soil specimen by the pressurisation of a water jacket enclosed in a perspex cylinder, the soil element isolated by a rubber membrane held in place by "O" rings. The specimen can be connected to an external drainage path through a permeable disc set into the base. This provides drainage in a drained test and pore pressure measurement in an Undrained or Consolidated Undrained test. A stress (b_1) is applied to the top of the sample via a loading cap in contact with a ram. For undrained tests a plain disc of perspex was used with a central coned seating in its upper surface which registers with the end of the ram. This ensures that the load is applied centrally and allows some freedom of movement to the top of the sample during the test.

During shear, measurement is made of the applied axial load, pore pressure and axial strain. During long terms tests this normally requires manual reading of strain gauges proving rings and devices used to record pore pressure. While this is convenient in laboratory conditions the method becomes physically impractical in a mobile triaxial laboratory where space and time are at a premium. Consequently all cells were fitted with three transducers which provided a continuous electronic output which could be calibrated with load, strain or pore pressure. Such data easily lends itself to simultaneous automatic logging which releases the operator to prepare or disassemble other tests. The data sample can also be more frequent, producing an increased number of data points resulting in a more accurate record of shear.

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Approximately 60 readings of load strain and pore pressure were recorded on a test taken to 25% strain, with a greater frequency of sampling in the initial stages, so that between 1-5% strain, readings were taken at 0.25% strain intervals or less.

Data were transferred from magnetic tape to a mainframe file to allow further analysis by the TXANAL programme (Appendix III). This programme, written by the author, provided graphical and tabulated output of the major parameters of strain and effective stress calculated directly from the transducer readings.

The key to this system, which proved both rugged and reliable in the field, was the accurate calibration of the transducers. The load cells were calibrated at the Building Research Establishment before and after the test programme, as were the strain transducers, which could also be easily checked in the field by attaching them to a micrometer. Pore pressure transducers were calibrated in the triaxial cells by pressurising the empty cell with de-aired water up to 600 kN/m^2 before the test. This also helped de-air the porous disc and pore pressure system while also providing a check for possible leaks in the triaxial cell. Where time allowed, strain gauge and proving ring readings were also logged manually at points throughout a test to allow a double check of results and provide a back-up set of readings.

3.4 Triaxial sample preparation

Specimens were prepared by carefully trimming a length (147mm-200mm) from a 0.5m core, the precise length depended on the height/width ratio required and the quality of the core. The top and bottom "ends" of the core, up to 5cm, were never employed as part of test specimens due to the possible effects of end disturbance. The stiff, poorly sorted nature of the diamict required that the sample ends be trimmed square and flat by a clamped mould and sharp 12in blade. Care had to be taken at this stage to reduce disturbance to a minimum and not to "smear" the ends of the specimen so that contact between the porous disc and soil voids was disrupted when the sample was set into the cell. Moisture loss was countered by waxing the ends of the sample tubes directly on sampling unless the sample was to be extruded and tested directly. The sample was also covered with "cling film" during trimming and setting in the the cell. The onsite testing programme allowed the delay between sampling and testing to be reduced to less than 30 mins.

All cores were extruded by a hydraulic jack applying a constant drive in the same direction and speed as the sampling process. Cleaning and light waxing of the sample tubes produced high quality cores with a minimum of disturbance.

3.5 Details of main triaxial test programme

All tests carried out to produce the shear strength/depth plots shown in Figures 5.8 - 5.10 were variations on the Undrained Unconsolidated test procedure. The differences in method can be summarized by sub-division into three main types of test.

3.5.1 A Test (23 total)

Designed as a fast on-site test to provide a quick and accurate plot of undrained shear strength with depth while also maintaining a rapid turnover of freshly sampled material into the cell. All A tests were carried out at Cowden on 147 x 98 mm specimens. Pore pressure was not monitored, the cell base being fitted with a polypropylene cover and "free ends" to minimise end friction. Jacobsen (1967) found that the undrained shear strength of glacial diamict increased by up to 50% when provisions were made to decrease end friction by the technique outlined by Rowe and Barden (1964). This involves setting a greased rubber membrane between the specimen top and base to facilitate movement during shear. All tests were undertaken at a confining stress equal to calculated total overburden at a rate of strain (1.14 mm/min) giving 20% strain in 30 mins. Due to the high strain rate the test was logged both manually and automatically at times. Results were drawn up as simple deviator stress (b1 - b3), strain plots and the undrained shear strength taken as peak (b'1 - b'3)/ 2.

3.5.2 B Test (8 total)

An Undrained Unconsolidated test with pore pressure measurement that allowed a full analysis of shear in terms of effective stress. The specimen was prepared as "A" except that the sample pore pressure was monitored through the porous disc set into the base, with the polypropylene cap removed. Filter paper strips were also fitted to the sides of the specimen to aid the equalization of pore pressure (Bishop and Henkel 1957). The test was carried out under a confining stress equal to the calculated total overburden using a strain rate of 0.076 mm/min which ensured that the pore pressure was in constant equilibrium with applied stress, throughout the test. Data logging was automatic with an example of final computed output given in

UNDRAINED - CONSOLIDATED TRIAXIAL TEST

EFFECTIVE STRESS ANALYSIS

SAMPLE NO AND LOCATION : CM3 32 DEPTH 10.9M CONSOL.UNDR EOBX3*.

ORIGINAL LENGTH OF SAMPLE : 150.000 MM

VOLUME OF SAMPLE : 1131444.00 MM3

CELL PRESSURE AT TEST : 705.00 KN/M2

LOAD CELL CF.	STRAIN TRANS.CF.	POREWATER PR.CF.
0.20900	11.560	-42.400

DEVIATOR STRESS KN/M2	PERCENTAGE STRAIN	ACTUAL STRAIN MM	POREWATER PRESSURE KN/M2	EFF.MAJ. STRESS KN/M2	EFF.MIN. STRESS KN/M2	STRESS P' KN/M2	STRESS Q KN/M2	MAJ/MIN
0.00	0.000	0.0000	225.0000	480.00	480.00	480.00	0.00	1.000
0.22	6.242	9.3636	226.5264	478.69	478.47	478.54	0.11	1.000
0.73	6.266	9.3983	228.5616	477.17	476.44	476.68	0.36	1.002
17.07	6.327	9.4908	233.1408	488.92	471.86	477.55	8.53	1.036
22.76	6.358	9.5370	235.0912	492.67	469.91	477.50	11.38	1.048
31.31	6.389	9.5832	238.9072	497.40	466.09	476.53	15.65	1.067
54.61	6.435	9.6526	248.2352	511.38	456.76	474.97	27.31	1.120
67.81	6.458	9.6873	254.1712	518.64	450.83	473.43	33.91	1.150
90.32	6.489	9.7335	262.6511	532.67	442.35	472.46	45.16	1.204
104.28	6.512	9.7682	269.0110	540.27	435.99	470.75	52.14	1.239
118.24	6.535	9.8029	274.9470	548.29	430.05	469.47	59.12	1.275
131.67	6.558	9.8376	280.4590	556.21	424.54	468.43	65.83	1.310
143.00	6.589	9.8838	285.1230	562.88	419.88	467.54	71.50	1.341
165.67	6.643	9.9647	295.2991	575.37	409.70	464.92	82.84	1.404
187.28	6.697	10.0456	304.3303	587.95	400.67	463.10	93.64	1.467
206.00	6.759	10.1381	312.0046	599.00	393.00	461.66	103.00	1.524
216.51	6.790	10.1844	315.6511	605.86	389.35	461.52	108.26	1.556
241.82	6.882	10.3231	324.5552	622.27	380.44	461.05	120.91	1.636
251.77	6.921	10.3809	327.9470	628.82	377.05	460.98	125.88	1.668
263.26	6.959	10.4387	331.7632	636.49	373.24	460.99	131.63	1.705
280.30	7.028	10.5427	336.4270	648.88	368.57	462.01	140.15	1.761
298.33	7.106	10.6583	340.6670	662.66	364.33	463.78	149.16	1.819
315.75	7.198	10.7970	344.9070	675.84	360.09	465.34	157.88	1.877
334.42	7.290	10.9358	348.2991	691.13	356.70	468.18	167.21	1.938
348.76	7.368	11.0514	351.0974	702.66	353.90	470.16	174.38	1.985
362.04	7.445	11.1670	352.9631	714.08	352.04	472.72	181.02	2.028
391.00	7.622	11.4328	356.3550	739.64	348.65	478.98	195.50	2.121
405.67	7.714	11.5716	358.0510	752.62	346.95	482.17	202.84	2.169
424.14	7.861	11.7912	359.3230	769.82	345.68	487.06	212.07	2.227
437.39	7.969	11.9530	360.0862	782.30	344.91	490.71	218.69	2.268
448.50	8.138	12.2074	360.1711	793.33	344.83	494.33	224.25	2.301
463.72	8.292	12.4385	360.1711	808.55	344.83	499.40	231.86	2.345
477.75	8.470	12.7044	359.1958	823.55	345.80	505.05	238.87	2.382
485.01	8.624	12.9356	358.4751	831.53	346.52	508.19	242.50	2.400
491.02	8.770	13.1553	357.2031	838.82	347.80	511.47	245.51	2.412
496.46	8.924	13.3865	355.9312	845.53	349.07	514.56	248.23	2.422
501.25	9.102	13.6524	354.6592	851.59	350.34	517.42	250.62	2.431
506.33	9.310	13.9645	352.9631	858.37	352.04	520.81	253.17	2.438
510.09	9.525	14.2881	351.2671	863.82	353.73	523.76	255.04	2.442
511.75	9.626	14.4384	349.9951	866.76	355.00	525.59	255.88	2.442
515.29	9.872	14.8083	347.8750	872.41	357.13	528.89	257.64	2.443
515.92	9.934	14.9008	347.4512	873.47	357.55	529.52	257.96	2.443
516.91	10.019	15.0280	346.6030	875.30	358.40	530.70	258.45	2.442
445.44	10.049	15.0742	330.0671	820.38	374.93	523.41	222.72	2.188
395.85	9.996	14.9933	324.1311	776.72	380.87	512.82	197.92	2.039
321.44	9.888	14.8315	318.1951	708.25	386.80	493.95	160.72	1.831
296.61	9.849	14.7737	318.1951	683.42	386.80	485.68	148.31	1.767
246.93	9.757	14.6349	313.9551	637.97	391.04	473.35	123.46	1.631
222.07	9.703	14.5540	313.1072	613.96	391.89	465.92	111.03	1.567
197.18	9.649	14.4731	312.6831	589.50	392.32	458.04	98.59	1.503
147.36	9.518	14.2766	311.8350	540.52	393.17	442.28	73.68	1.375
122.42	9.433	14.1494	311.4111	516.01	393.59	434.40	61.21	1.311

Figure 3.3 Example of TXANAL tabulated output for multistage test on CS3 / 32

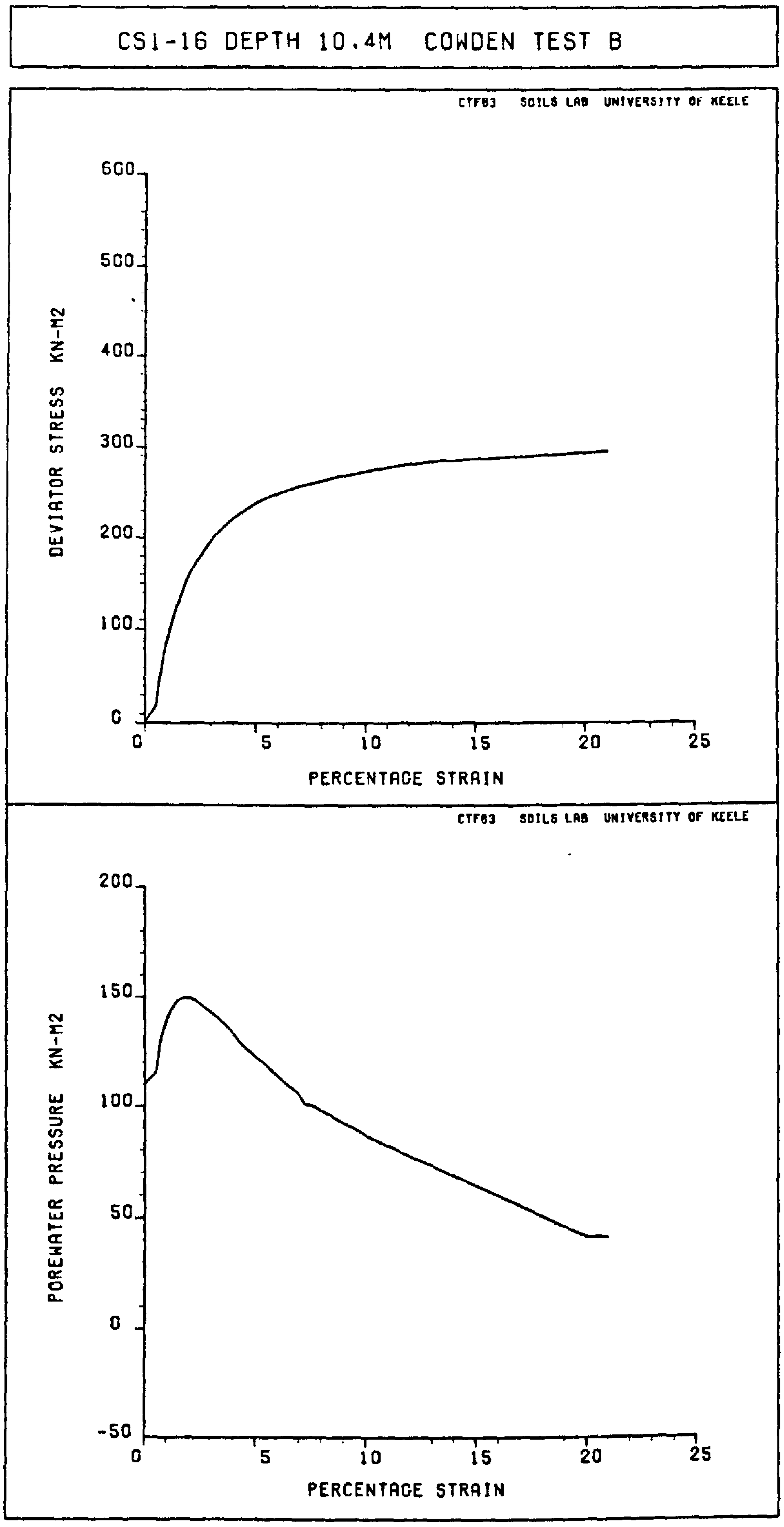

Figure 3.4 Example of TXANAL graphical output
Plot of Deviator stress / % strain and
Pore Pressure / % strain

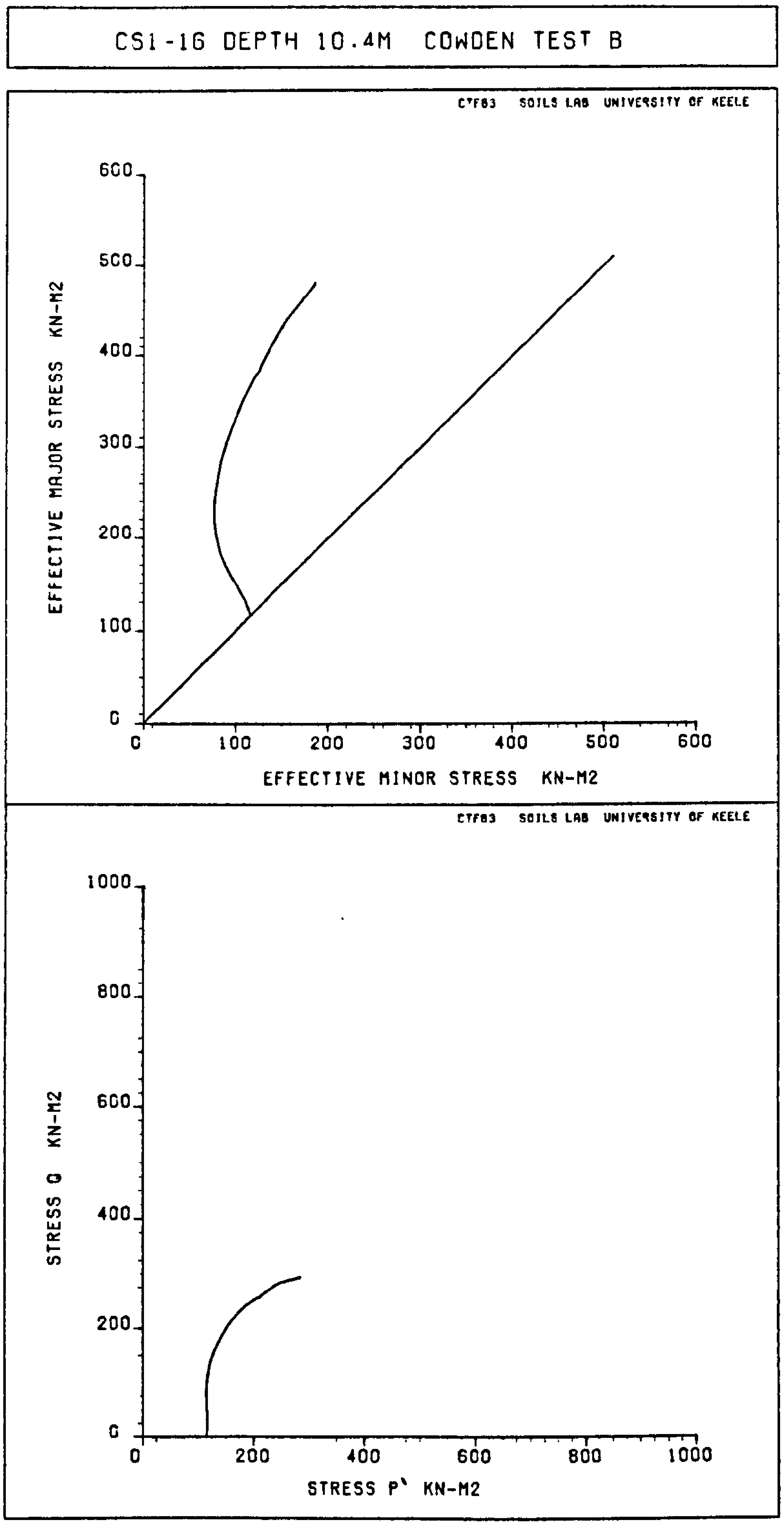

Figure 3.5 Example of TXANAL graphical output
Effective major stress / Effective minor stress
and q / p`

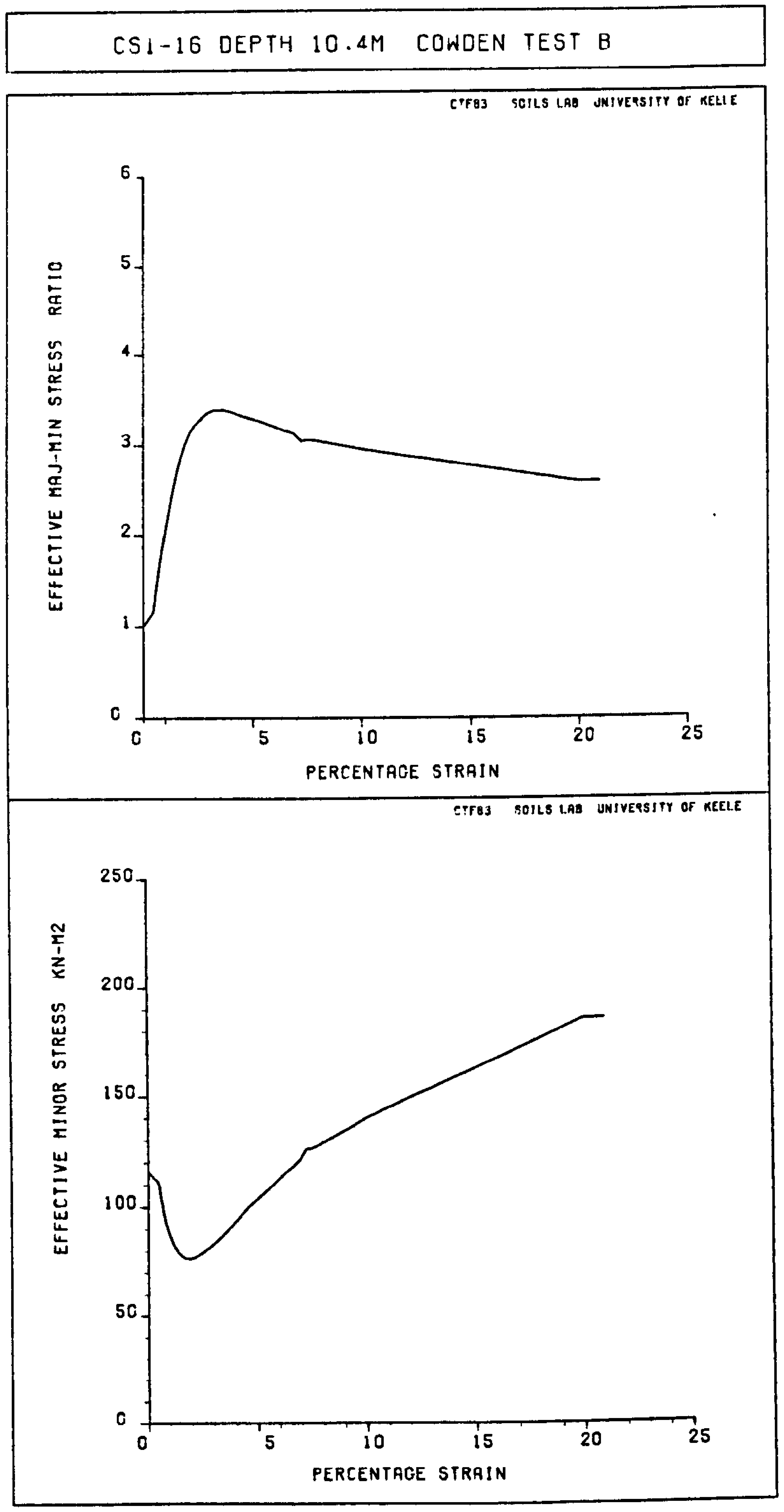

Figure 3.6 Example of TXANAL graphical output
Effective major-minor stress ratio / strain
and Effective minor / stain

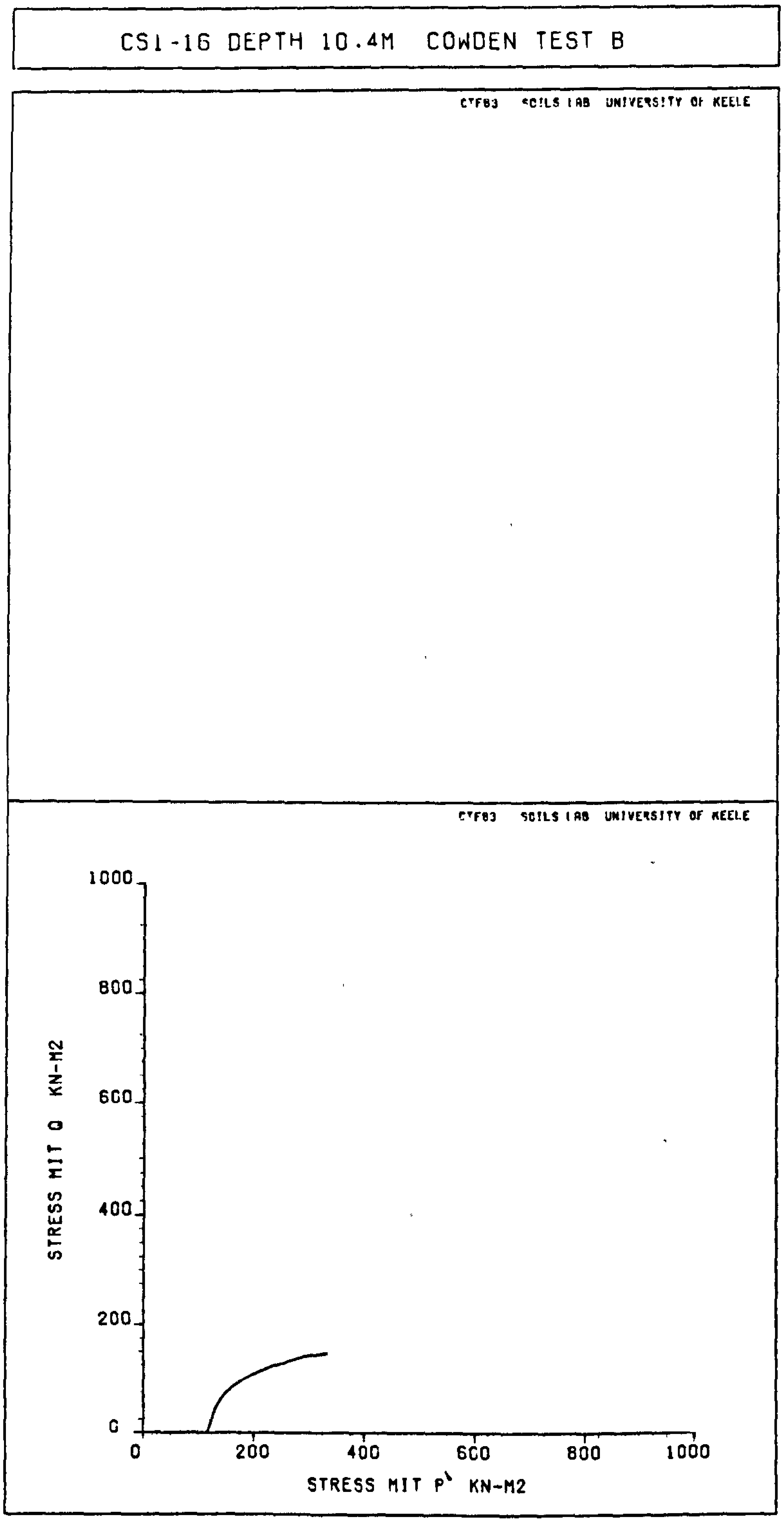

Figure 3.7 Example of TXANAL graphical output MIT q / MIT p'

Figures 3.3 - 3.7 Additional variables calculated in this analysis can be listed as

Pore pressure	u
Effective major stress	(b'1 - b'3)
Effective minor stress	b'3
Effective major/minor stress ratio	
p'	(b'1 + 2b'3) / 3
MIT p	(b'1 + b'3) / 2
MIT q	(b'1 - b'3) / 2

3.5.3 C Test (7 total)

These samples were set into the cell and moved to failure in the same manner as "B" with identical final analysis. However prior to shear the sample was subjected to a progressive increase in confining stress (b3) under undrained conditions, usually in stages of total overburden (see section 5.1), with the reaction of pore pressure noted at each stage. This allowed the calculation of the pore pressure co-efficient B (Skempton 1954) over a range of confining stress where,

$$\text{e14} \qquad B = \frac{\Delta u}{\Delta b3}$$

As the sample requires time to equilibrate at each stage this was a long-term test with the sample remaining in the cell, sometimes under considerable pressure, for up to 10 days. In all C tests double sheaths were used, with a thin layer of silicon grease between them to prevent the sample taking in moisture. The effect of the extra constraint during shear on a stiff clay is minimal but was allowed for in the final analysis.

3.6 Additional Tests

3.6.1 $\phi_u = 0$, Undrained (1 Test)

This test was carried out on a 190/90 mm specimen set into the cell with side drains and pore pressure measurement. The technique involves placing the sample under increasingly higher confining stress and moving the sample to the point of failure at each stage. Using this procedure a Mohr's stress envelope can be constructed defining the angle of shearing resistance under undrained conditions (ϕ_u). The value of ϕ_u reflects the degree of saturation, amount of sample disturbance and also reflects the size distribution of the material tested (Skempton and Bishop 1957). The results of this test are given in section 5.6.

The majority of the additional tests utilize the multistage technique outlined by Taylor (1951). The technique uses a single specimen which is continually monitored under shear so that the test can be stopped on or immediately before the point of failure. The sample is then unloaded and brought to a new equilibrium before the test is repeated. Multistage testing is very attractive to the testing of diamicts as it solves the problem of obtaining several specimens with comparable material properties from an inherently variable sediment. The point of failure, normally taken as peak major/minor effective stress ratio, is mobilized at low levels of strain, normally between 2-4% (see Figure 5.15).

The problem of isolating this precise point of failure was solved by feeding transducer readings into a micro-computer as the test progressed. This provided a constant appraisal of major stress parameters including all strain, filter paper and sheath corrections employed by the mainframe TXANAL programme.

3.6.2 Consolidated Undrained tests (2 total)

The Consolidated Undrained test is a shear test in which the soil specimen is first consolidated under an all round pressure in the triaxial cell before failure. Normally several stages are involved, each at increasingly higher consolidating pressure. The period of consolidation is necessarily under drained conditions so that the water can freely move out of the specimen as the voids ratio moves intc equilibrium with the applied cell pressure. In a simple case where drainage occurs against atmospheric pressure, the volume of fluid moving in or out of the specimen can be gauged by attaching a burette to the pore pressure outlet. Evaporation from the burette is reduced by a film of oil.

With complete saturation the volume of water drawn from the specimen is seen as a direct reflection of volume change as the sample consolidates. The sample is then loaded and moved to the point of failure under undrained conditions before being unloaded and reconsolidated under a higher cell pressure. Using this technique a Mohr's stress envelope can be constructed defining the angle of internal friction under effective stress (ϕ') and the value of the cohesive intercept (c').

The second Consolidated Undrained test was carried out in a similar manner except that drainage during stages of consolidation was carried out against a back pressure using a procedure outlined by Bishop & Henkel (1957). The use of back pressure ensures full and complete saturation of the specimen. The technique involves controlling the effective stress under which the sample consolidates by applying a pressure difference between the pore pressure and cell pressure systems.

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As an example, with a cell pressure of 250 kN/m^2 and an applied back pressure at 200 kN/m^2, the sample consolidates under an effective pressure of 50 kN/m^2. In practice a back pressure of 200 kN/m is sufficient to dissolve all air in the system. The pore water and pressure systems are isolated by means of a paraffin volume guage which allows drainage from the sample to be measured with an applied back pressure (Figure 3.8).

Once consolidation is complete the sample is sheared under undrained conditions. Two or three such stages are required to define the Mohr's stress envelope. Results obtained by this method, using a single specimen, were found to be directly comparable to the results obtained by the Transport and Road Research Laboratories, who employed at least two samples (Section 5.7).

Chapter 4

Diamict Sedimentology and Index Properties

Nomenclature

A	Activity of clay fraction	
e	Voids ratio	
e_i	Initial Voids ratio	
Ip	Plasticity index	
J	Percentage clay content	
LI	Liquidity index	
LL	Liquid limit	
M	Mass of soil specimen	M = Ms + Mw
Ms	Mass of soil particles	
Mw	Mass of soil water	
n	Porosity	
Gs	Specific gravity	
V	Volume of soil specimen	
Vp	Volume of pore space	
Vs	Volume of soil particles	
Vw	Volume of pore water	
w	Moisture content (%)	
ρ	Bulk density (Mg/m^3)	
ρd	Dry density (Mg/m^3)	

Diamict Sedimentology and Index Properties

4.1 Introduction   Returns from boreholes CS1, CS2 and CS3 prove a continuous diamict sequence to 10 m marked only by a change in matrix colour from 7.5 YR 4/6 to 7.5 YR 3/2 at an average depth of 4.5 m which can be equated with the Skipsea-Withernsea facies junction as defined by Madgett and Catt (1978). The trench excavated for the T.R.R.L research programme between boreholes CS1/2 and CS3 exposed the contact in an undisturbed section with a clearly defined westerly dip of 4°, unrelated to present surface morphology or the visible development of soil horizons. A channel fill was sampled in all three boreholes at a mean depth of 10 m, formed of a well sorted, medium to fine sand. The thickness of the deposit varied between 1.0 - 1.5 m although composite sequences alternating with thin diamict lenses have been reported approaching 5 m in thickness at other sampling locations on site (McGown and Haddidi 1981).

Boreholes sunk at Cowden during the period 1978-1980 have sampled through the channel fill to prove a massive diamict sequence to 28.5 m (Love 1981) with a second sand lens at 18 m. British Geological Survey records show that the Cretaceous chalk rockhead in the area of drilling lies at approximately 30 m.

4.2 Particle Size Distribution.

The particle size distribution is of primary importance since it exerts a strong influence on other parameters such as Atterberg limits and has a direct bearing on the engineering behaviour. The textural composition of diamicts is related to the environment of deposition and can be used to help distinguish between genetic till types (McGown and Derbyshire

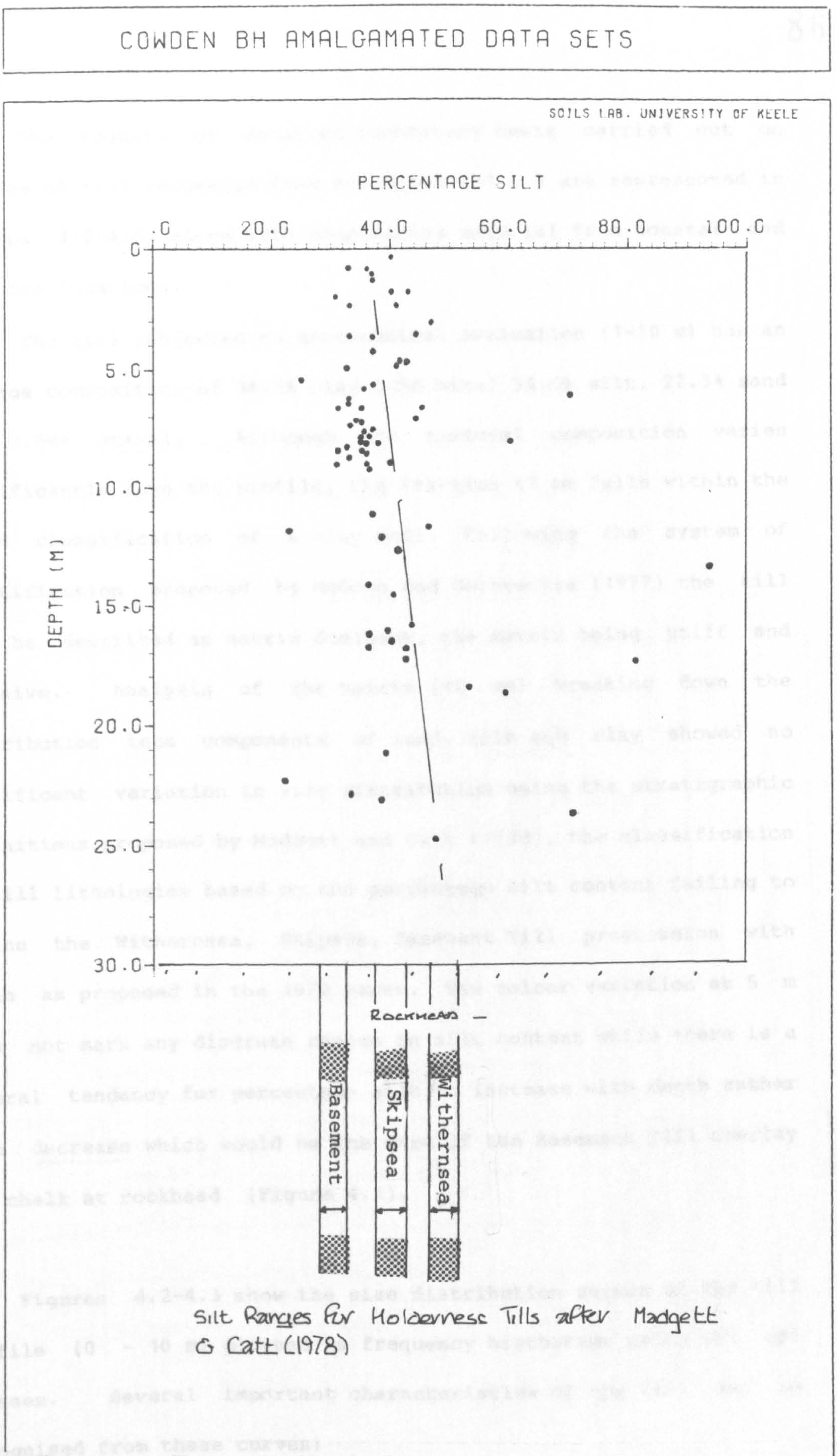

Figure 4.1 The percentage silt content of the Quaternary sequence sampled to rockhead at Cowden.

1977).

The results of detailed laboratory tests carried out on samples of till recovered from boreholes CS1 - 3 are represented in Figures 4.2-4.6 along with comparative material from coastal and offshore locations.

The till subjected to geotechnical evaluation (1-10 m) has an average composition of 34.5% clay (<9Ø size) 34.6% silt, 22.3% sand and 8.68% gravel. Although the textural composition varies significantly down the profile, the fraction <2 mm falls within the broad classification of a clay soil. Following the system of identification proposed by McGown and Derbyshire (1977) the till can be described as matrix dominant, the matrix being stiff and cohesive. Analysis of the matrix (<2 mm) breaking down the distribution into components of sand, silt and clay showed no significant variation in size distribution using the stratigraphic definitions proposed by Madgett and Catt (1978), the classification of till lithologies based on the percentage silt content failing to define the Withernsea, Skipsea, Basement Till progression with depth as proposed in the 1978 paper. The colour variation at 5 m does not mark any discrete change in silt content while there is a general tendency for percentage silt to increase with depth rather than decrease which would be the case if the Basement Till overlay the chalk at rockhead (Figure 4.1).

Figures 4.2-4.3 show the size distribution curves of the till profile (0 - 10 m) plotted as frequency histograms using phi (Ø) classes. Several important characteristics of the till can be recognised from these curves;

(1) The multimodal nature of the distribution, typical of a lodgement facies.

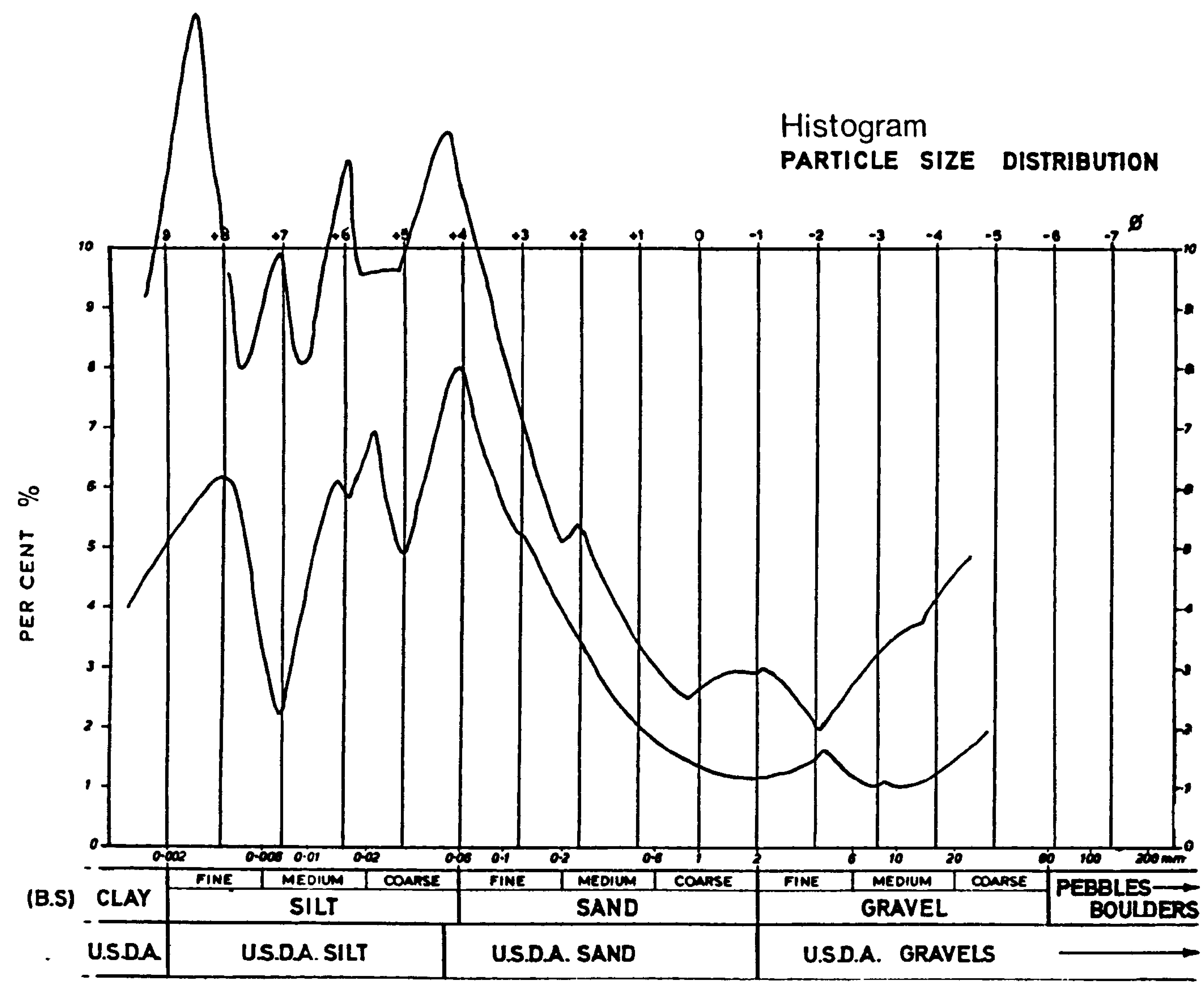

Figure 4.2. Size distribution envelopes 0-5m Cowden CS1

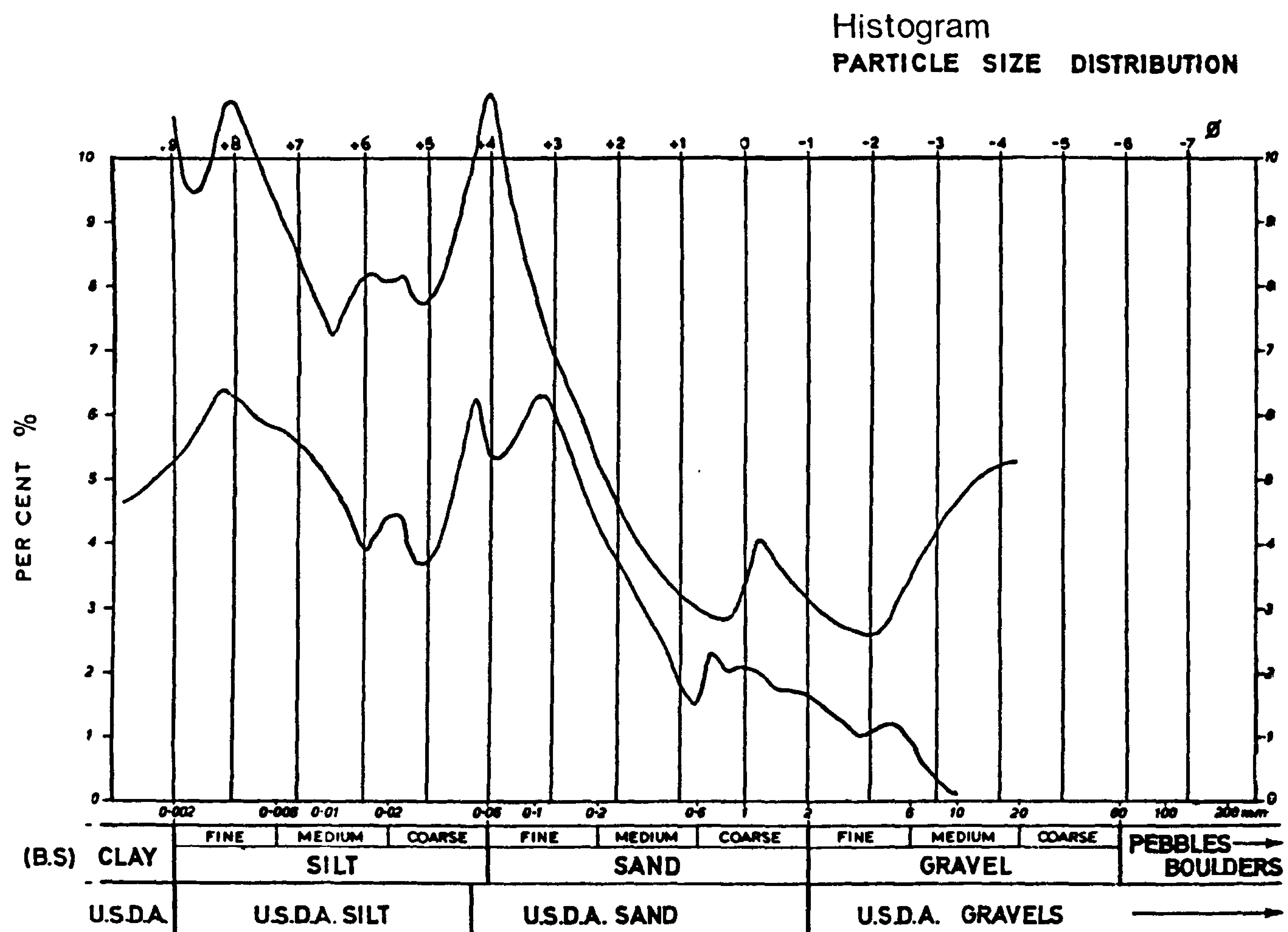

Figure 4.3 Size distribution envelopes 5-10m Cowden CS1

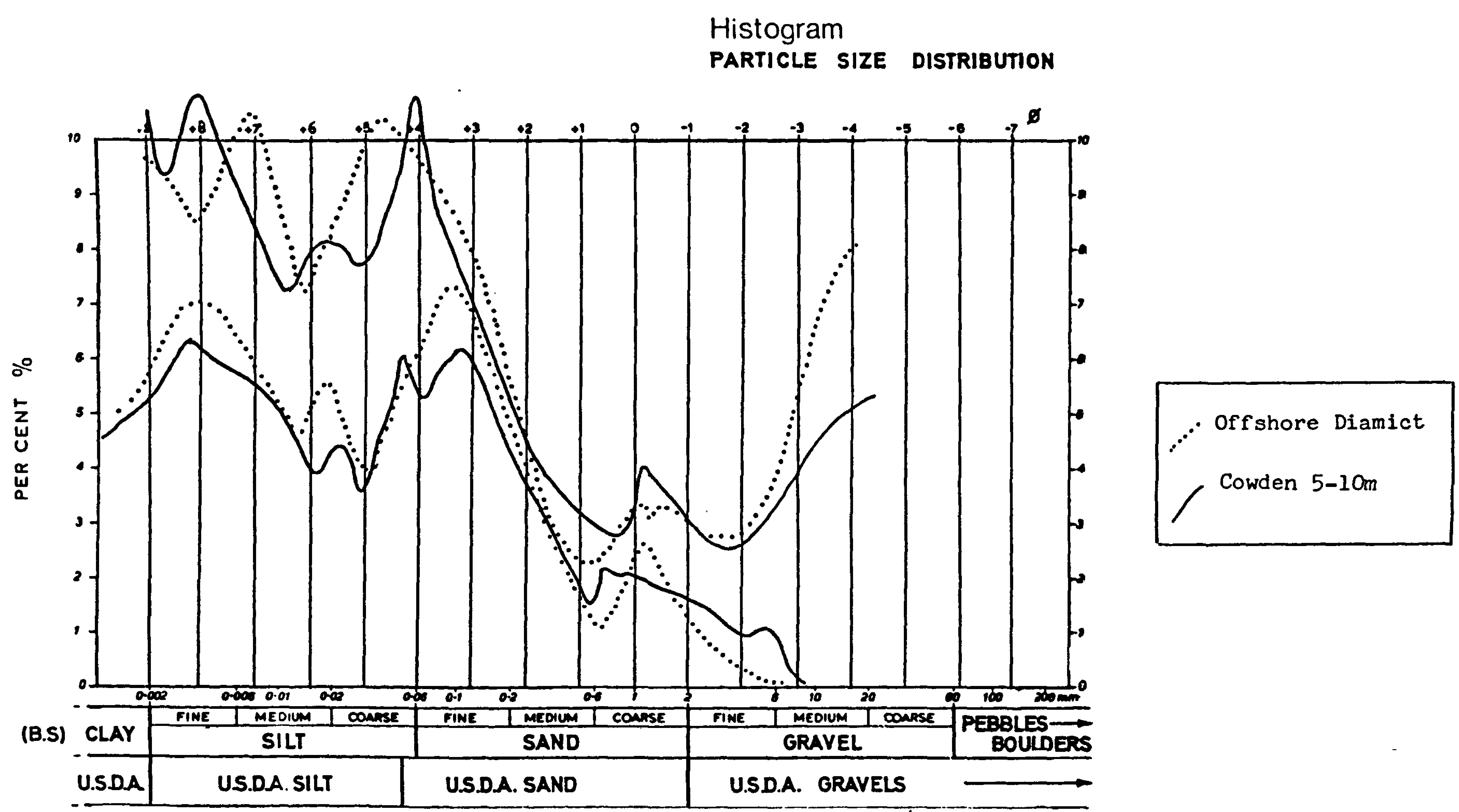

Figure 4.4 Comparison of Envelopes. Offshore Diamicts and Cowden 5-10m

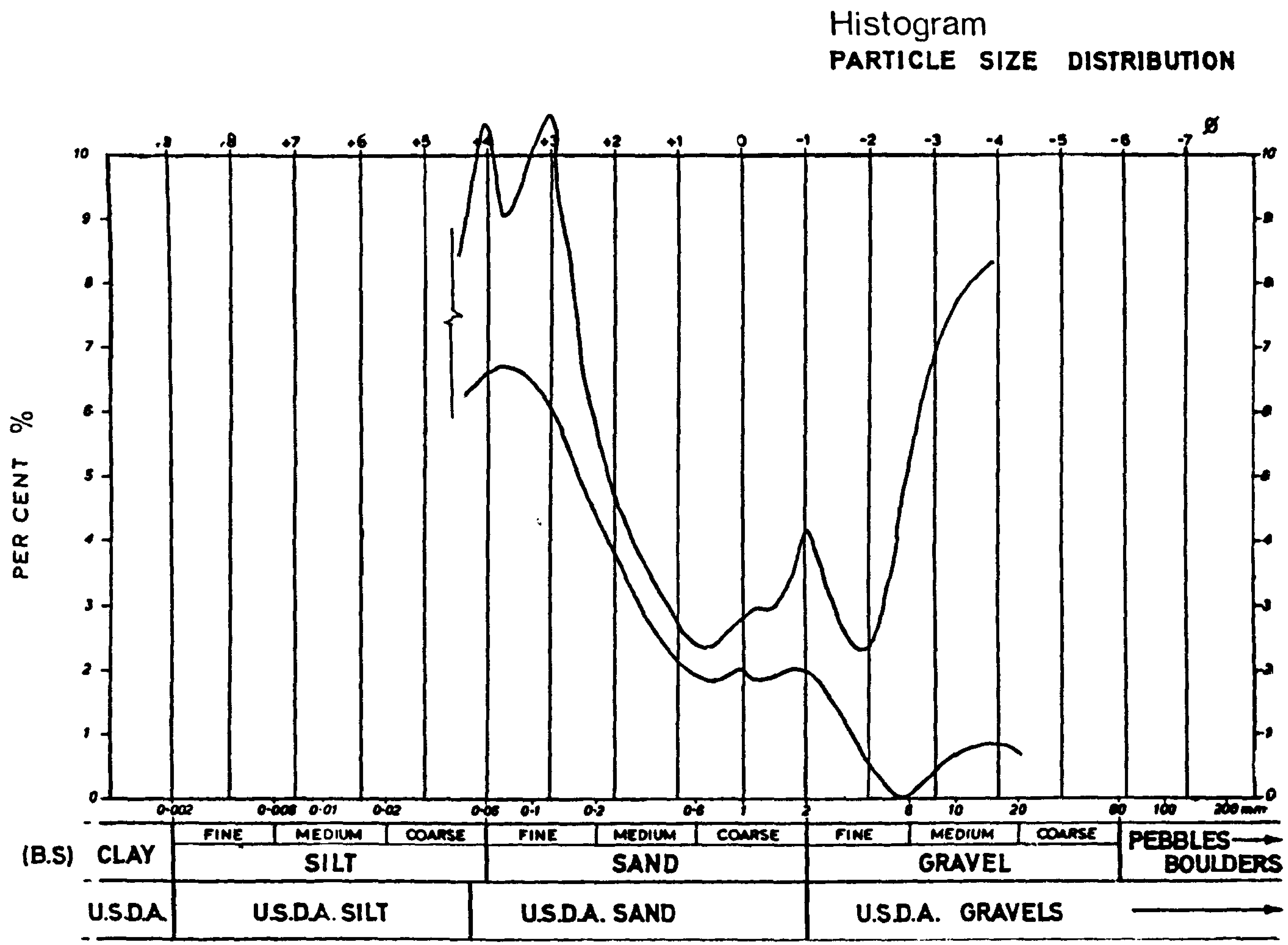

Figure 4.5 Size distribution envelope. Bulk samples from coastal sections. 4Φ → -4Φ

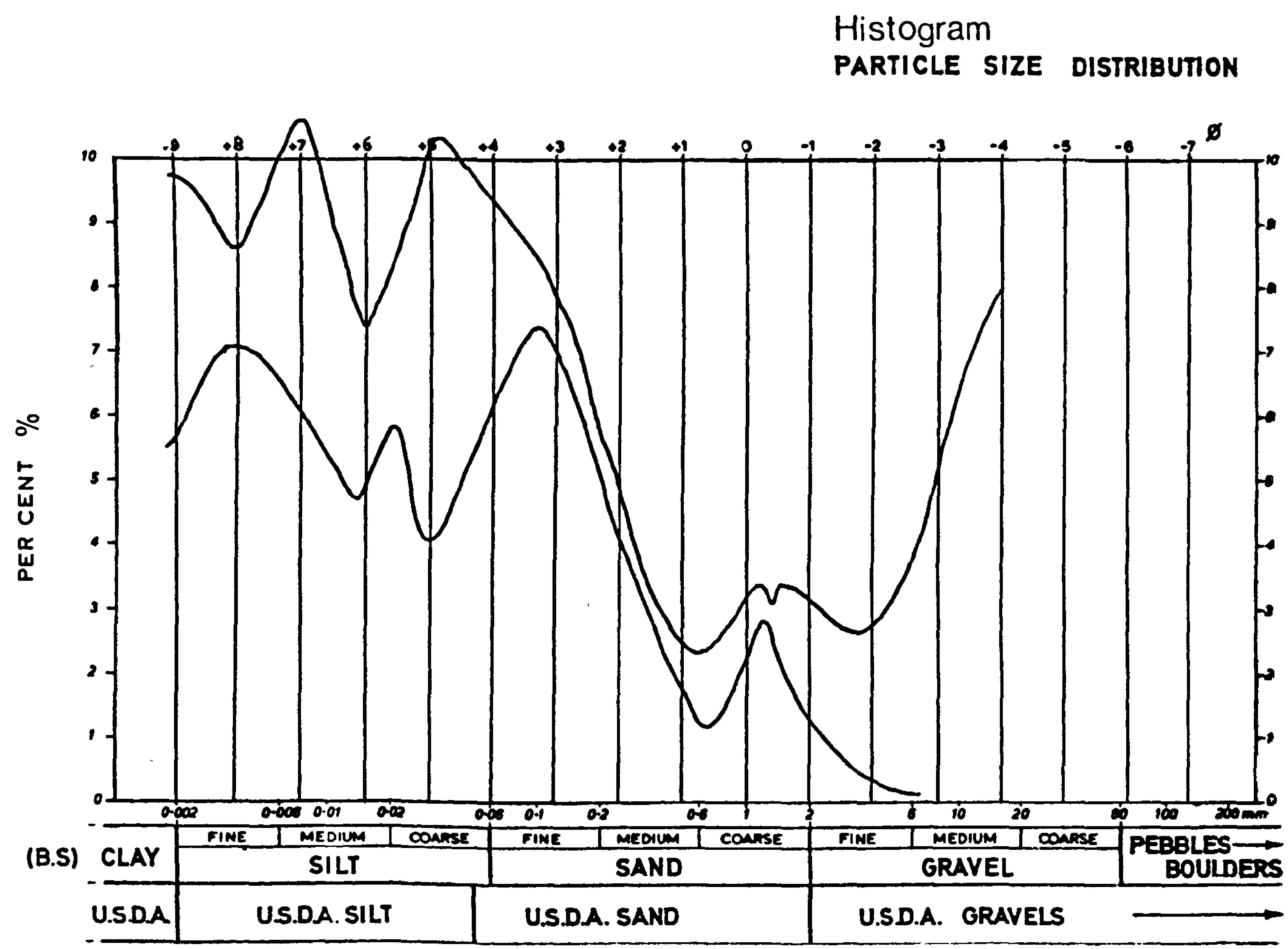

Figure 4.6 Offshore diamict sampled in BH 81, 52 A

(2) The close grading of the sand fraction (3Ø-0Ø).

(3) The variation within the silt fraction, tending to two peaks at 4Ø and 8Ø.

Studies by Dreimanis and Vaqners (1969) and McGown, Anderson and Radwan (1975) have shown that the particle size distribution of lodgement tills is generally multimodal and can be analysed by interpreting the peaks as modes of discrete distributions which combine in varying ratios to define the overall grading curve. It is further proposed that these modes remain quasi-constant over space, although tending to a terminal mode with increasing subglacial comminution. Application of this model to the results obtained from the upper profile at Cowden provides qeneral agreement, with a relatively constant particle size distribution envelope with depth. Figure 4.4 compares envelopes for Cowden with samples recovered from the coastal exposures and offshore locations (BH 81/52A). A strict bimodal distribution as predicted in the terminal mode model is unlikely to have developed in the Holderness tills since a large proportion of the matrix has been directly assimilated from disaggregated Liassic material eroded by the ice sheet north of Flamborough Head. Apart from the siltstone component, erosion of Liassic material is proven by the widespread incorporation of macro fossils gathered from both till units during study of the coastal sections. These include Gryphaea arcuata, Pentacrinites sp , Acrocoelites sp and Asteroceras obtusum. Examination of the heavy minerals in the 2Ø fraction revealed large quantities of pyrites and marcasite (up to 49% total heavy minerals in unweathered soil), species which form up to 90% by weight of the total mineral assemblage in the 2Ø fraction of the Kimmeridge and Speeton Clays.

Localised disaggregation of Liassic and Triassic clasts form a notable feature of the coastal exposures and were used by Bisat (1940) to further subdivide the till sequence into upper, middle and lower components. The incorporation of this material directly into the diamict matrix does not appear to allow for the development of a "terminal mode" and probably simply reflects the size distribution of mineral grains in the original clasts. This process of localised assimilation of Liassic siltstones and mudstones may account for the variation in silt grading between samples separated by less than 10 cm (Figure 4.11) and the high percentage clay content (up to 40% Figure 4.10). A range of values for silt content can be produced by inaccurate and inconsistant sample preparation. This allows flocculation of the clay and fine silt grades which leads to an inaccurate determination of both the clay and silt fraction and the grading curve within the silt range. This effect was mitigated by adopting a strict and consistant test procedure (Section 3.2.9).

The results suggest that when working with such poorly sorted material it is advisable to sample at half phi divisions, thus producing a more accurate determination of variation within the grading curve than presented in Appendix 1. Such a system would also help to isolate any problems in sample preparation. It must also be recognised that the size distribution curves may not record the most significant peak, that in the coarse clay fraction 10Ø-9Ø, owing to the fact that if the lower limit on clay grading is set at 14Ø, it is clear that with an average 34% of the distribution falling within four phi units, any single phi division could well exceed 10% and produce the most dominant peak in total distribution. This fact is acknowledged by Dreimanis and Vagners (1971) as a technical limitation to the study of terminal modes.

The variation in the grading within the silt range is contrasted directly with the least variability of the distribution in the 3Ø-1Ø range for the majority of the samples analysed. This is clearly shown in Figure 4.3 where 18 curves for the Cowden profile (5-10 m) fall within 0.5% at the 2Ø grading. A similar pattern can also be seen in the distributions of the coastal bulk samples and offshore material. The homogeneity of the sand fraction was also recognised by Madgett and Catt (1978), who used the standardised grading to prove a lack of contamination of loessic material in the upper soil profile (0 - 0.5m). Vagners (1969) noted that the modal phi class for sedimentary quartz was commonly found at 7-8Ø and 4-5Ø, so the 1-3Ø grading could represent the coarse limb of the latter mode. Sources of arenaceous rocks in the Holderness tills are varied. Beaumont (1971) recorded the incorporation of Coal Measures and Millstone Grit lithologies in the Lower Till sheet (Wear and Blackhall Till Complex) in East Durham, while any ice mass moving down the North East coast must have come into contact with the extensive Permo-Triassic sequence (New Red Sandstone) which has its most southerly outcrop offshore, 75 km north of Cowden. Examination of the 2Ø fraction showed it to be composed almost entirely of light minerals (<2.65 SG) principally quartz. Separation of the heavy fraction provided a maximum yield of only 1% by weight. Taking into account contrasting source lithologies, distances of transport, variation caused by the re-incorporation of proglacial sequences and the resistance of quartz to comminution (Vagners 1969), it is perhaps surprising that the most highly sorted grading in the till should occur in the medium fine sand range. The

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influence of varying volumes of fine modes in tills in relation to the maximum achievable dry density has been investigated by McGown, Anderson and Radwan (1975). A typical relationship for a till is shown in Figure 4.7 along with the average relationship for the till at Cowden. Disregarding the upper soil horizons the till profile has a well defined range of dry densities from 1.83-1.95 Mg/m^3 with a mean value of 1.8 Mg/m^3, which falls close to the lowest boundary achievable for a till with a 70% silt clay matrix. Boulton's (1975, 1982) theoretical treatment of the subglacial depositional process defines critical lodgement parameters for various phi sizes under changing conditions of normal effective stress and ice velocity and concludes that the 2-4Ø range could only lodge under extreme conditions of effective normal load. Within the <-3Ø range, particles will be deposited due to the ease of plastic flow around them while smaller particles (<4Ø) will lodge readily due to efficient pressure melting and regelation at the glacier sole. This analysis is necessarily limited in treating the subglacial load as discrete particles rather than a range of interacting particles. Indeed in the case of a matrix-rich till with a low percentage sand content fully supported by the matrix, it could be argued that the lodgement of the sand particles is more likely to be affected by the equilibrium conditions affecting the matrix rather than any individual constraints on the sand grains. A series of large scale triaxial tests on recompacted mixtures of gravel and sandy clay reported by Holtz and Ellis (1961) have shown that gravel contents of <40% have little effect on shear strength. However, with increasing sand content a point would be reached where the sand becomes the dominant soil fraction. This occurs when the effective load is partially supported by a fabric of interlocking sand grains with the till matrix acting solely as fines within the coarser matrix. As Figure 4.7 shows this condition can be produced at values as low as 20% <3Ø but in the case of the Cowden till this lower boundary would also be affected by the gravel content which would also be critical in supporting the normal load.

Under Boulton's model, with constant conditions of velocity and effective stress, the bed load with increased frictional potential would be reincorporated into the glacier sole rather than lodge a lens of sand-rich (Well-graded) till. It follows from this that there must exist a movable boundary for the sand-gravel content below which the till is in equilibrium and will lodge but above which the sediment is reincorporated or the lodgement process periodically suspended. With reference to Figure 4.8 it can be shown that although the sand content falls to <20%, no till sampled has a greater sand content than 32% with the bulk of the data points falling close to a line at 20-24%. The supplementary point that the till throughout the profile falls close to the maximum theoretical dry density also supports the view that the material is almost entirely subglacial in origin.

The multimodal nature of the till distribution and the possible existence of a secondary, but as yet undefined peak in the 9-14Ø range limits a strict interpretation along statistical grounds. As an example, the mean particle size (Folk and Ward 1957) for the Cowden profile is 6.75Ø (Medium silt .....Figure 4.12) which is the least common silt mode falling as it does between the general peaks at 7Ø and 4Ø (Figure 4.2-4.6). The tail of fine material is reflected in a positively skewed distribution (Range 0.0-0.28 mean 0.1) with some horizons showing a marked

BH CS1 COWDEN TEST BED SITE

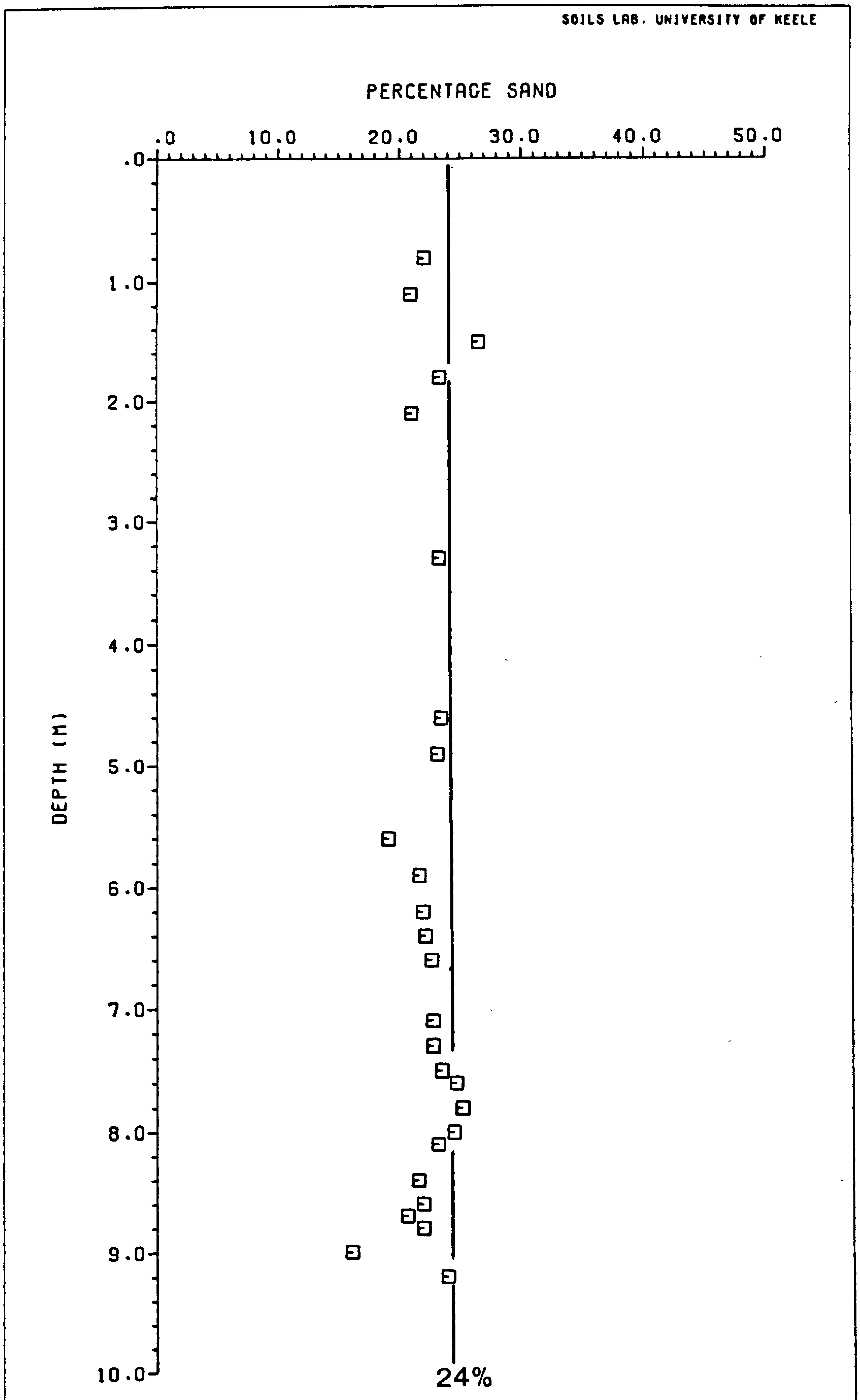

Figure 4.8 Percentage sand / depth CS1

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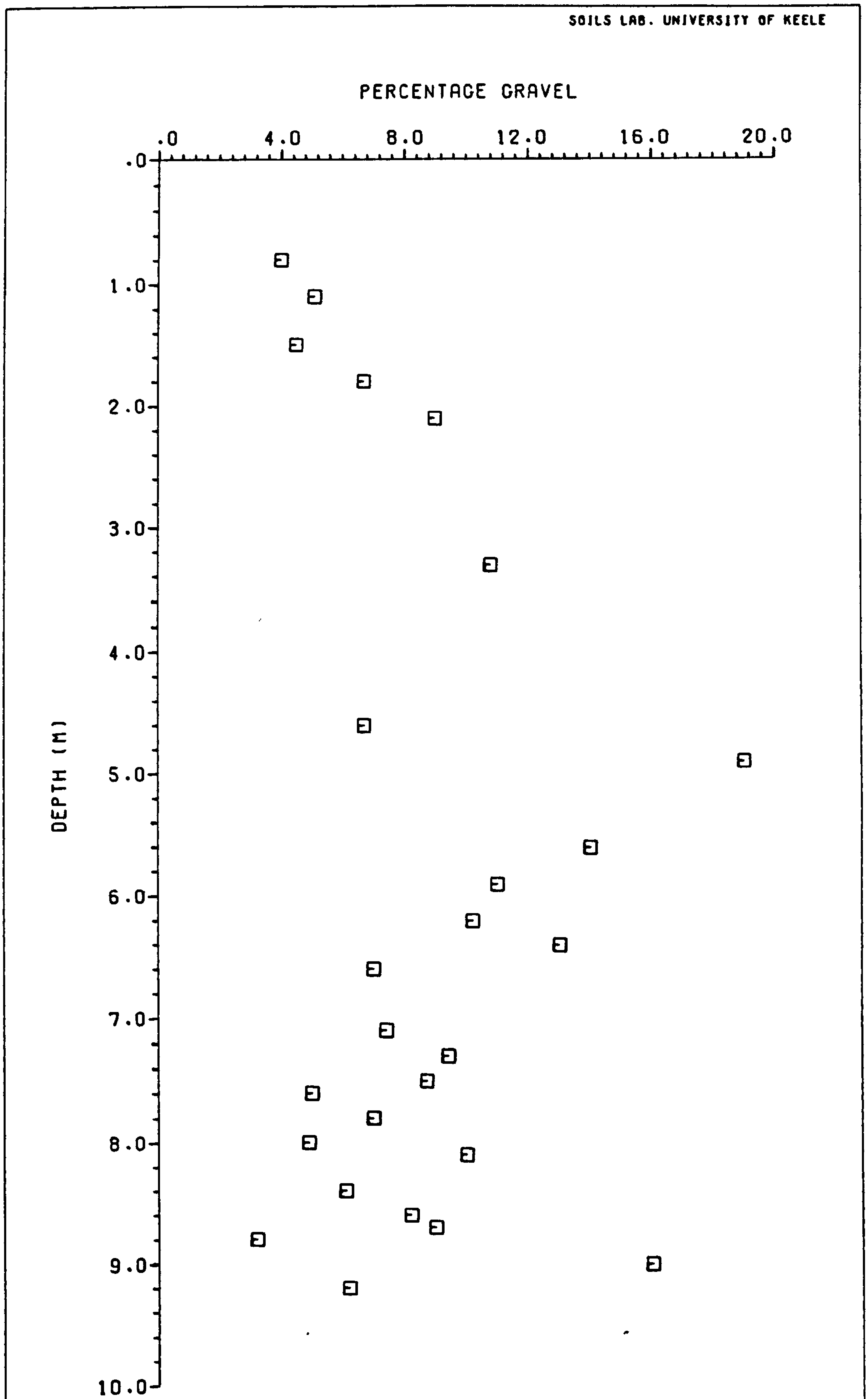

Figure 4.9 Percentage gravel / depth CS1

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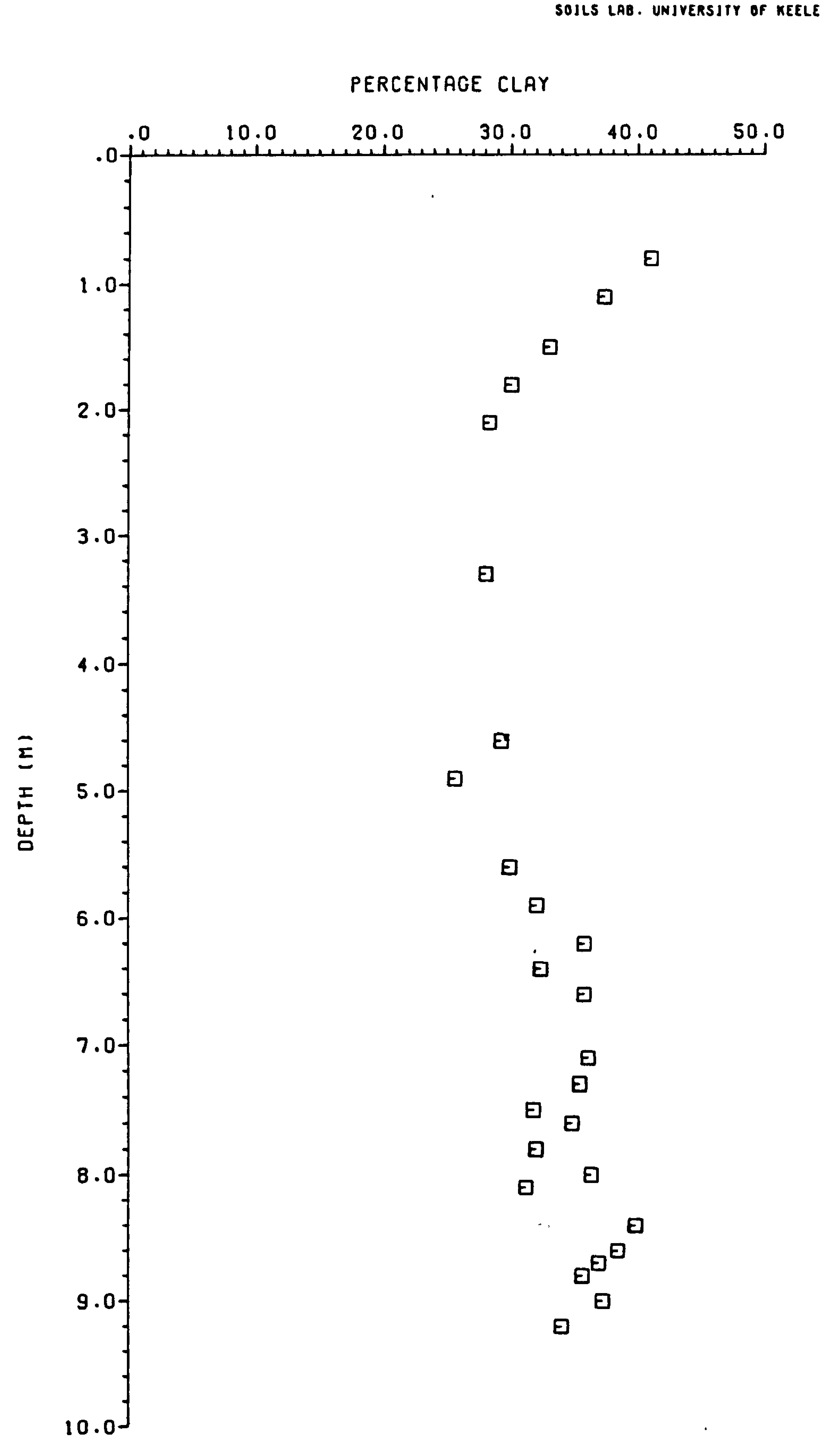

Figure 4.10 Percentage clay / depth CS1

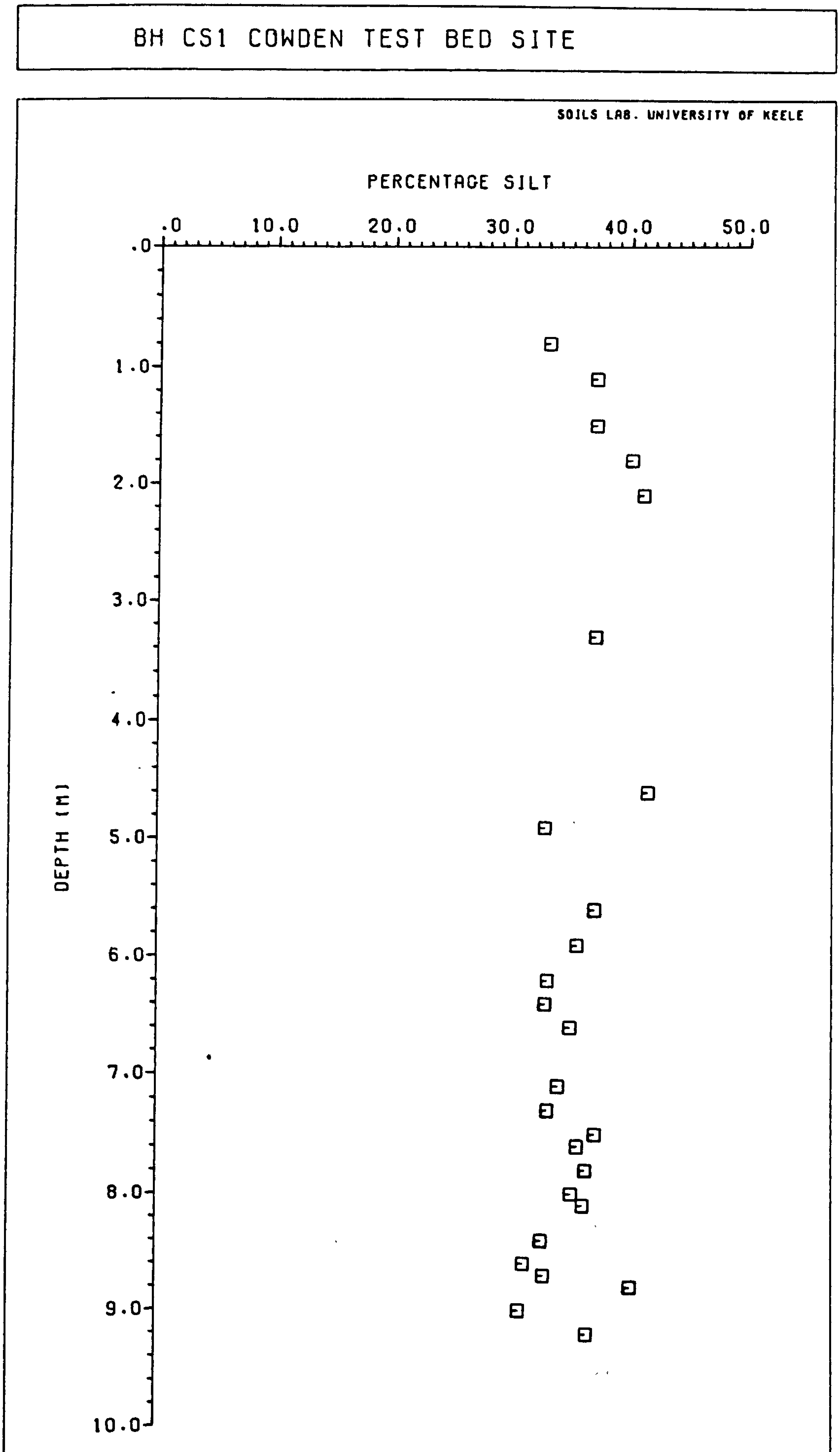

Figure 4.11 Percentage silt / depth CS1

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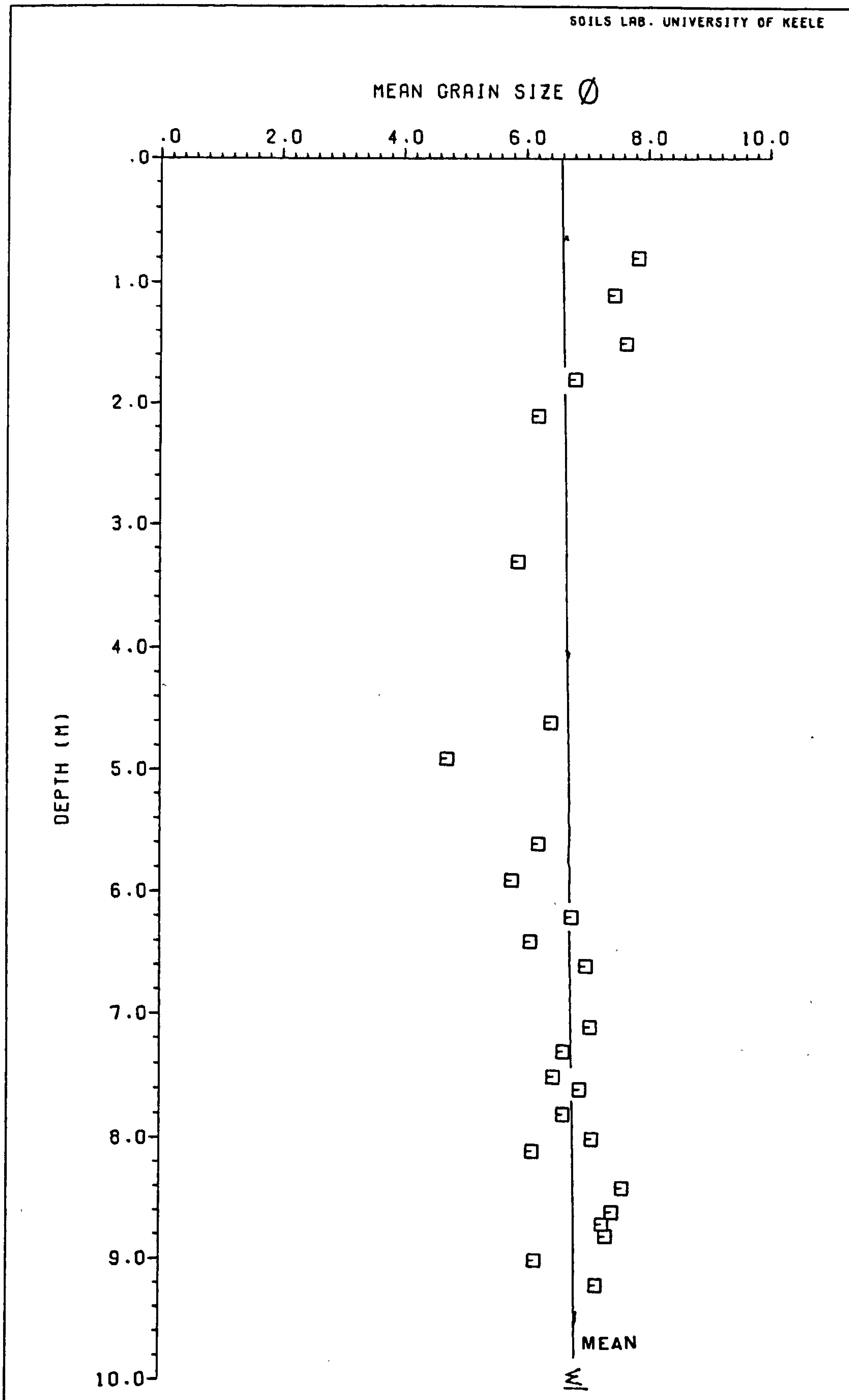

Figure 4.12 Mean grain size / depth CS1

positive skewness (1.9 m and 3.8 m Borehole CS1 .....Figure 4.13). The tendency towards negative skewness in the soil's upper horizons is an indication of the translocation of fines by eluviation Madgett (1974). The size distribution curves produce an average value of 0.95 for Kurtosis (Range 0.83-1.28) indicating a normal distribution (Mesokurtic) in terms of the peakedness of the main silt modes. Examination of the true frequency histograms shows this to be an oversimplification of the data probably representative of the limited number of data points required to calculate this parameter. Kurtosis values with depth show a good deal of scatter with little or no recognisable pattern (Figure 4.14).

All the tills studied are extremely poorly sorted, (Range 4.29-6.07 Mean 4.92) a characteristic of the inefficient subglacial sorting processes (Figure 4.15). Apart from the channel fill deposits there was no evidence of the higher degrees of sorting or interlayering associated with large-scale supra-glacial flow till deposition within the Withernsea Till as suggested by Madgett and Catt (1978). Within the limitations of the sampling programme no significant variation in the size parameters could be recognised between the Skipsea and Withernsea Tills at Cowden (Derbyshire, Foster, Love and Edge 1983, Foster 1985).

4.3 Development Of The Weathering Profile.

The effects of weathering were studied in order to gauge what controls this imposes on the engineering behaviour of the upper till unit (0-4.5 m). A more complete analysis of the development of soil horizons within the Devensian tills of Holderness is given by Madgett (1974). The broad classification

BH CS1 COWDEN TEST BED SITE

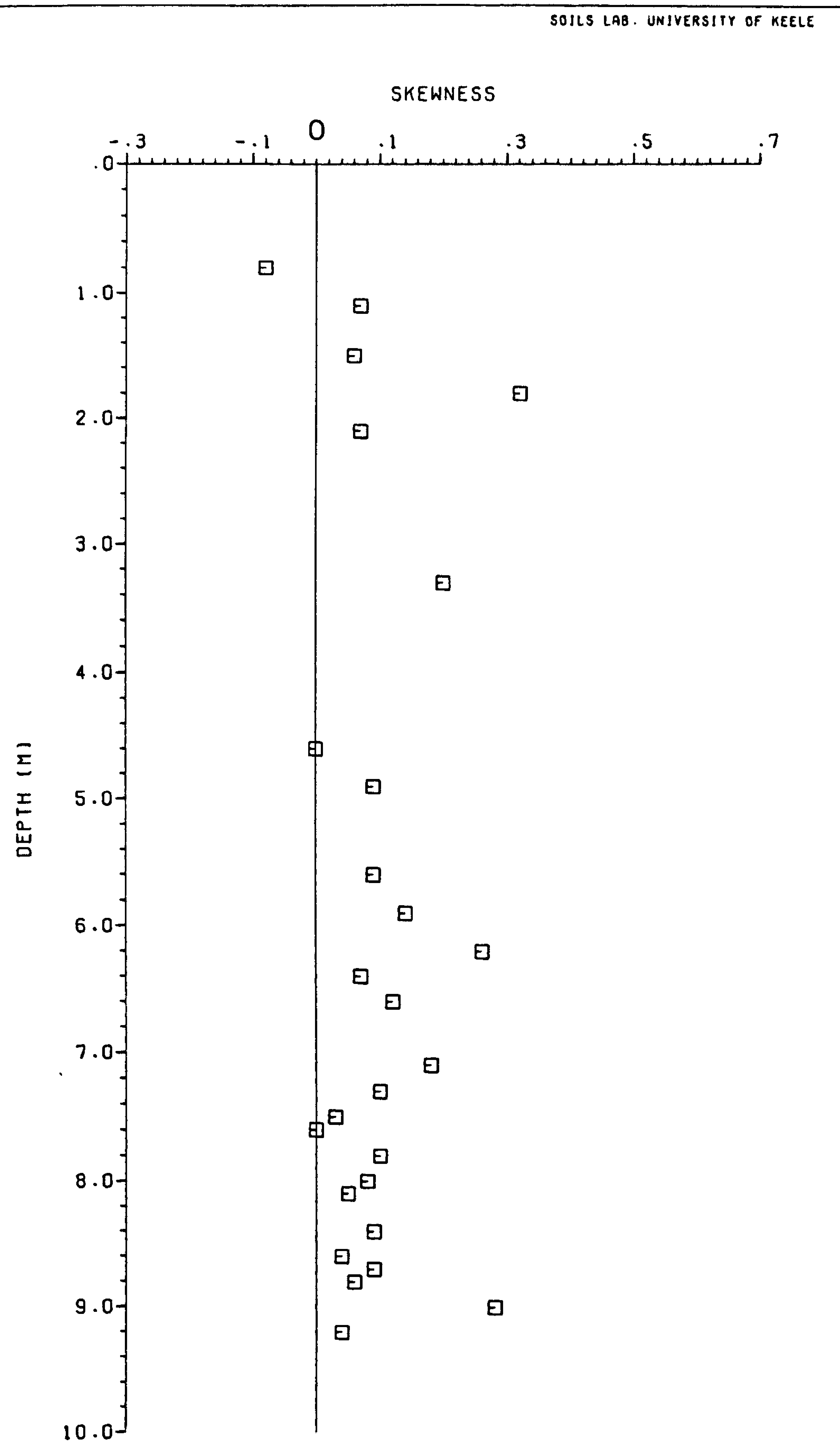

Figure 4.13 Skewness / depth CS1

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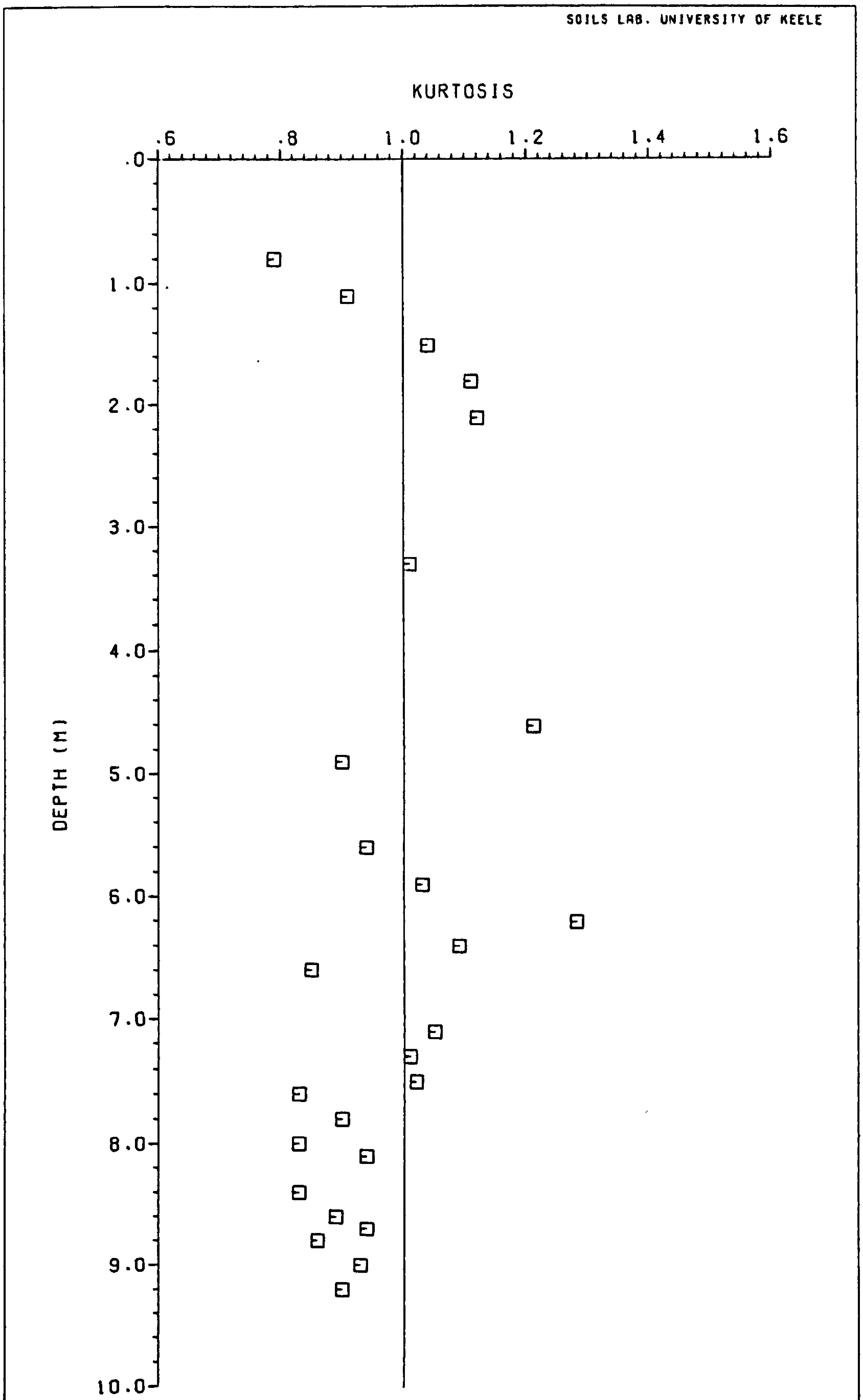

Figure 4.14 Kurtosis / depth CS1

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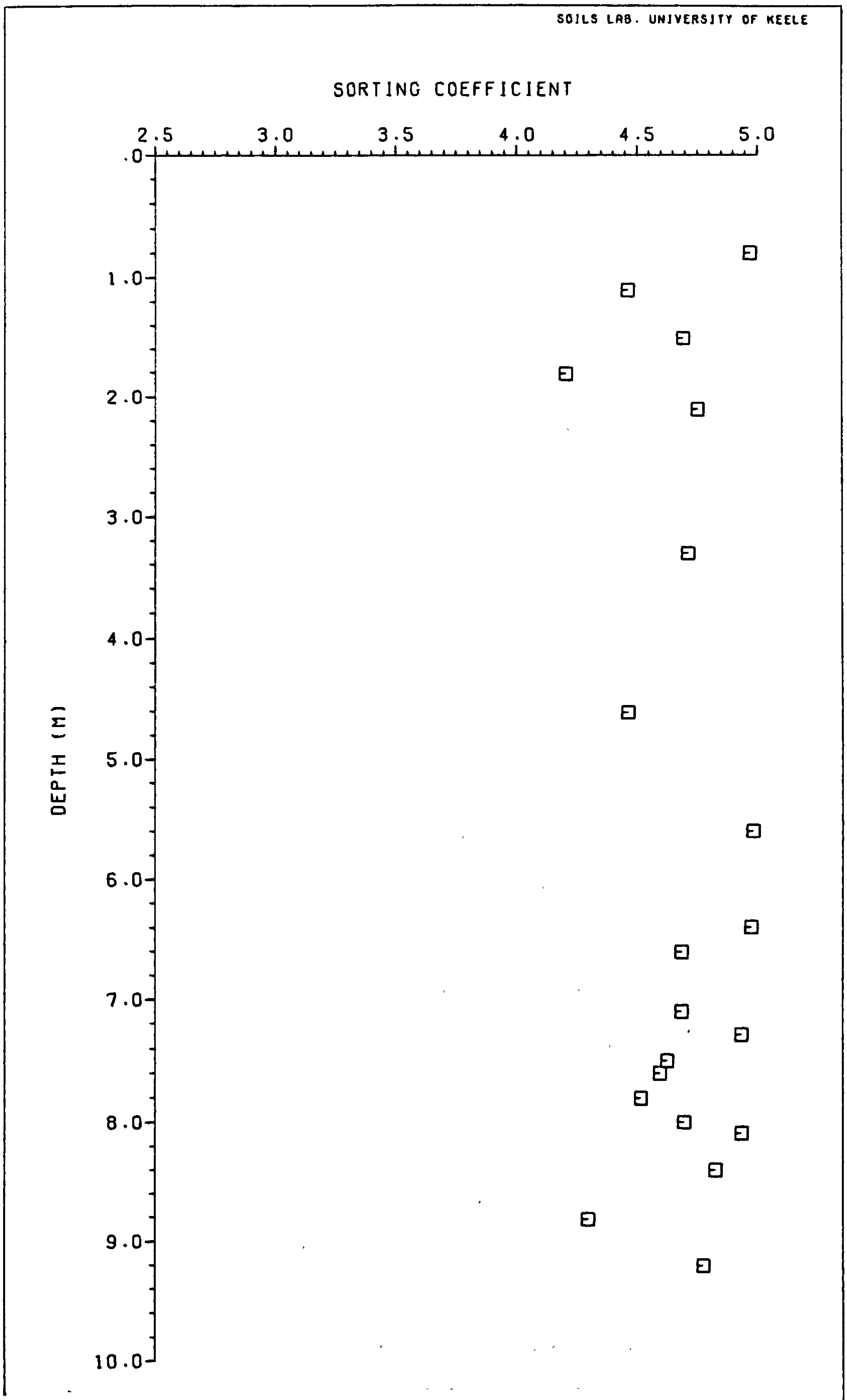


Figure 4.15 Sorting coefficient / depth CS1

adopted from Droste (1956) subdivides the profile into five zones (Figure 4.16).

Zone I.	A and B soil horizons.
Zone II.	Till, much weathered (below zone of eluviation)
Zone III.	Till, oxidized and leached
Zone IV.	Till, oxidized but unleached
Zone V.	Till, unaltered

Boundaries between these deep soil horizons were identified by analysis of the heavy mineral assemblage of the 2ϕ fraction (Oxidation), the carbonate content of the <63 μm fraction (Leaching), and the silt-clay percentage in order to establish any translocation of fines down the profile. The most visible aspect of weathering is the development of a coarse prismatic structure down to a depth of approximately 3 m, the surface of the peds covered with a reduced iron compound producing a pronounced grey colour (5GY 5/2). Cementation along these fissures can produce very strong bonds often more cohesive than the leached matrix. An orientated sample from the Cowden trench (3 m) failed along a line parallel to a localised gleyed fissure. A fissure surface was also recorded in CS1/3 (2 m), tested to failure at 220 kN/m^2, without any noticeable dislocation along the line of the fissure.

Zone I and II

With reference to Figure 4.16 it can be seen that the base of the B horizon lies at approximately 0.7 m above which a clay - loam soil has developed. Layer silicates in this region have undergone both physical and chemical weathering mainly in the upper 0.3 m (Madgett 1974), contributing to the percentage of fine clay which has been translocated to produce the clay peak at 0.7 m.

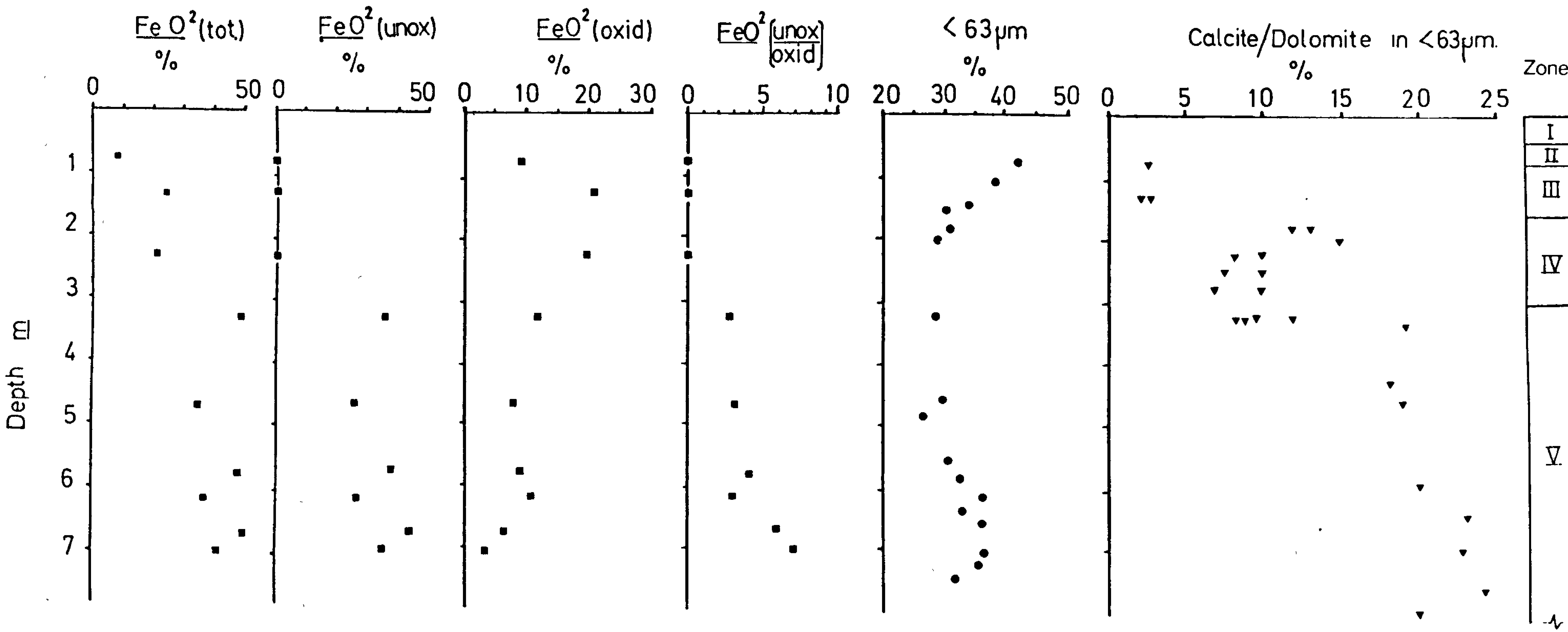


Figure 4.16

Analysis of oxidation of iron compounds, clay content and calcite/dolomite content with depth. Cowden.

Oxidation and removal of the pyrites and siderite in solution is complete with no measurable carbonate content.

Zone III.

The degree of oxidation and leaching is reduced in this zone possibly due to the close proximity to the zone of permanent saturation. The carbonate content (2%) is maintained by the continual breakdown of chalk and limestone clasts while the oxidised mass of pyrites increases with depth to form 20% of the total 2ϕ fraction at 1.3 m. The height of the permanent water table controls the depth of effective carbonate leaching at Cowden as well as having a bearing on the in situ effective stresses. Although there is no direct measurement of the piezometric surface at Cowden, a study by M.Bonell (1978) on the ground water fluctuations within the Catchwater Catchment (2 km N.W of Cowden) suggests that, allowing for the complexity of minor perched water tables in the A-B horizons, the base of the permanent water table lies between 1.75 and 0.34 m depending on winter recharge and local site topography. This is supported by the Cowden trench profile which displays a zone of secondary redeposition of calcite at 1.8 m.

Zone IV.

The effect of leaching is markedly reduced in this zone (1.7-2.5 m) with a 7% carbonate content, although the iron compounds show a high degree of oxidation. The clasts of siltstone, chalk and limestone, although softened, are not disaggregated. Igneous and metamorphic clasts are unaltered.

Zone V.

The depth of primary oxidation lies at approximately 3 m below which the till is largely unweathered. Minor amounts of oxidation was recorded at depths in excess of 3 m although the

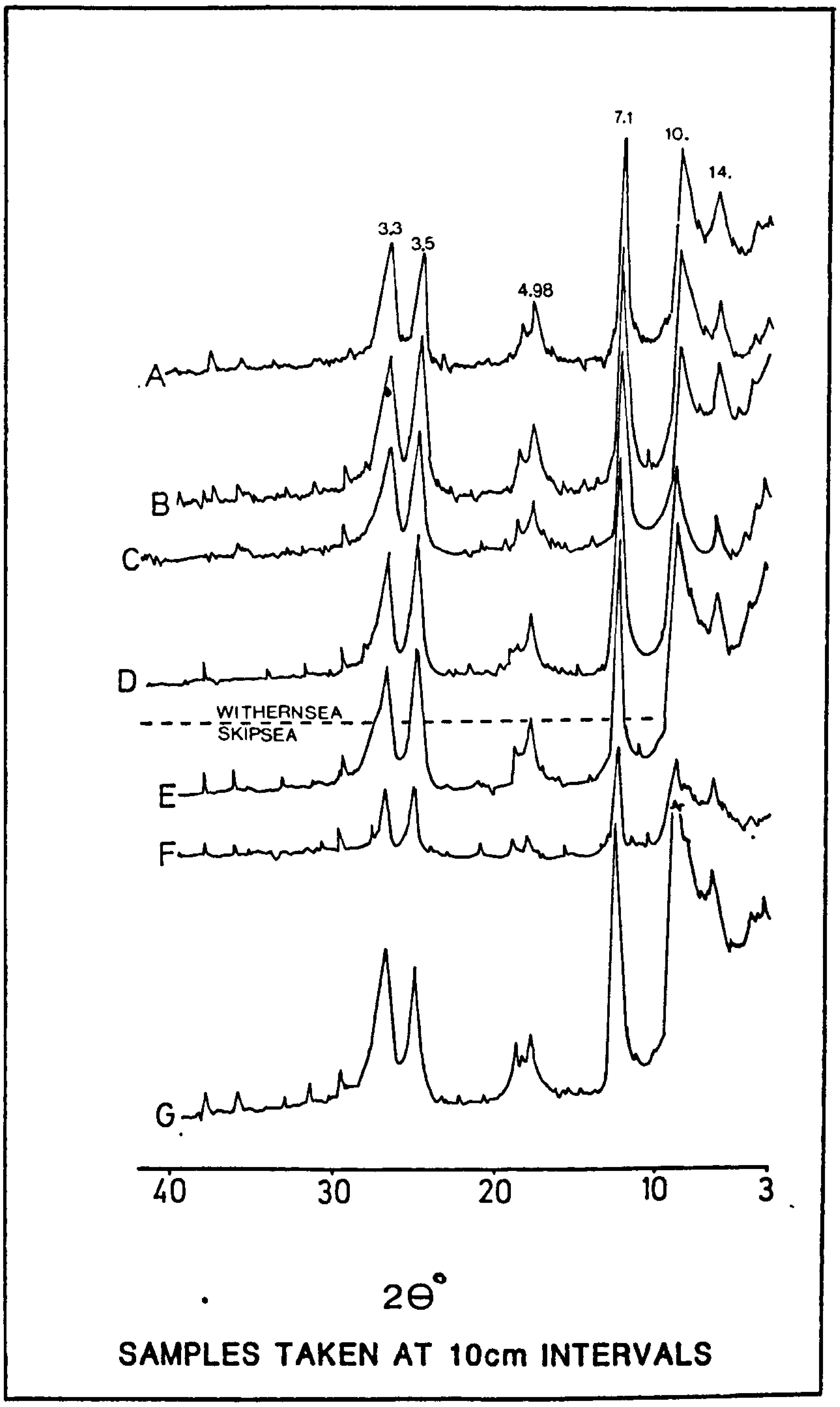


Figure 4.17 X-Ray diffraction of clay sub-samples removed at 10cm intervals across the Withernsea-Skipsea Till colour boundary.

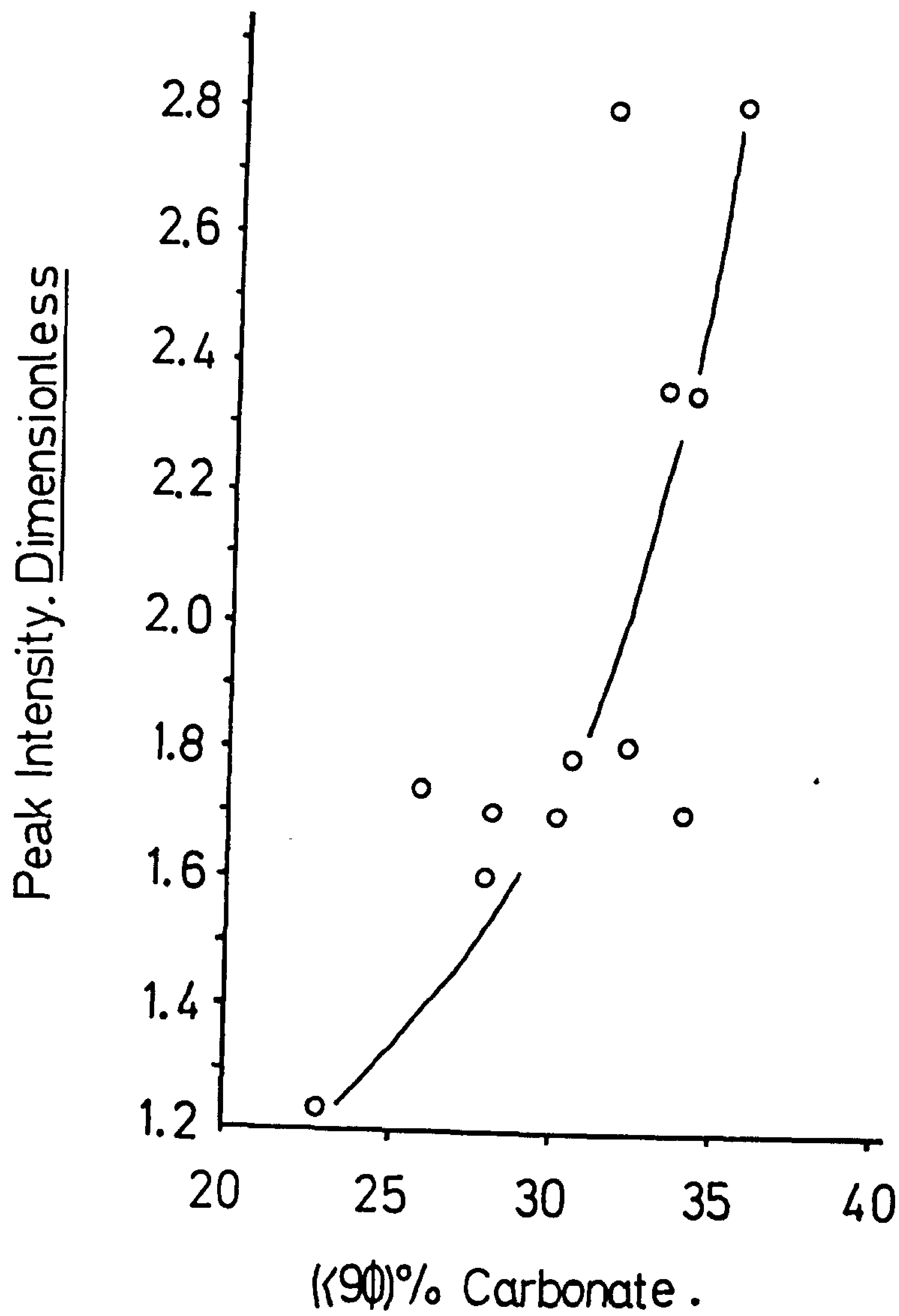
amount of unoxidised material was far greater in volume. Carbonate content increases with depth to 15% at 4.2 m. All clast lithologies remain unaltered.

4.4 Clay Mineralogy.

In his mineralogical study of the clay fraction of tills from East Yorkshire, Goodyear (1962) found few differences between the Skipsea and Withernsea tills exposed at Dimlington. These results were later supported by the work of Madgett (1974) who isolated mica, kaolinite, chlorite, vermiculite and smectite as the main layer silicates in the fraction <9ϕ . Samples removed from the base of the Withernsea-Skipsea Till junction were analysed in an attempt to identify any differences in the clay mineralogy possibly related to the colour change.

Figure 4.17 shows that there is very litle variation in clay mineralogy across the colour boundary, the main trend being an apparent change in the relative proportions of each mineral species, although this is very difficult to quantify due to the effect of sample concentration on the cover slip (Carrol 1968). The main mineral species can be identified as chlorite, illite, kaolinite, vermiculite and montmorillonite (smectite), with varying amounts of higher order mixed layer minerals. Significant peaks for calcite (3.04 Å) and less well defined quartz (4.25 Å) prove these to be important clay grade minerals in the <9ϕ fraction.

Analysis of the clay fraction by titration suggests that calcite constitutes up to 34% of the total clay mineral fraction by mass. A broad non-linear correlation between percentage calcite and peak intensity was found to exist (Figure 4.18). Such a high percentage calcite in the <9ϕ fraction unaffected by the colour



4.18 Figure % Carbonates in clay fraction against Peak intensity of X-Ray diffractogram.

boundary suggests that this junction does not mark any change in soil moisture conditions or the development of a deep soil profile but reflects a change in the lithology of the clasts comminuted to form the clay silt matrix from one dominated by Carboniferous/Liassic lithologies to a Permo-Triassic/Liassic mix. Study of the recognised lithologies of the 6-10 mm clasts from the Holderness tills has shown the Withernsea Till to be enriched with limestone, shale, siltstone, ironstone and coal, while the Skipsea Till has larger proportions of sandstone, quartzite, igneous and metamorphic rocks (Madgett and Catt 1978).

4.5 Bulk Index Properties Of The Cowden Diamict Profile.

The calculation of most of the basic index properties of the soil was undertaken using samples subjected to triaxial testing. This allowed very close correlation between the index parameters, shear strength and sedimentological parameters, while also overcoming the problems of sample size and quality which can produce a dispersion of data typical of diamict profiles (Vaughan, Lovenbury and Horswill 1975).

4.5.1 Bulk Density. (Mg/m^3).

The bulk density profile for Cowden (1-10 m) is shown in Figure 4.19 for the boreholes CS1-3. Although there is a spread in data with depth, all three boreholes trend close to the mean bulk density of 2.18 Mg/m^3. The major variation occurs in the upper weathering profile, particularly in zones I-IV (0-1.5 m) where the till is only partially saturated and the fabric has been disaggregated by the weathering process. Differences between the average bulk density of the Withernsea Till and the Skipsea Till can be attributed to the development of soil horizons, since there

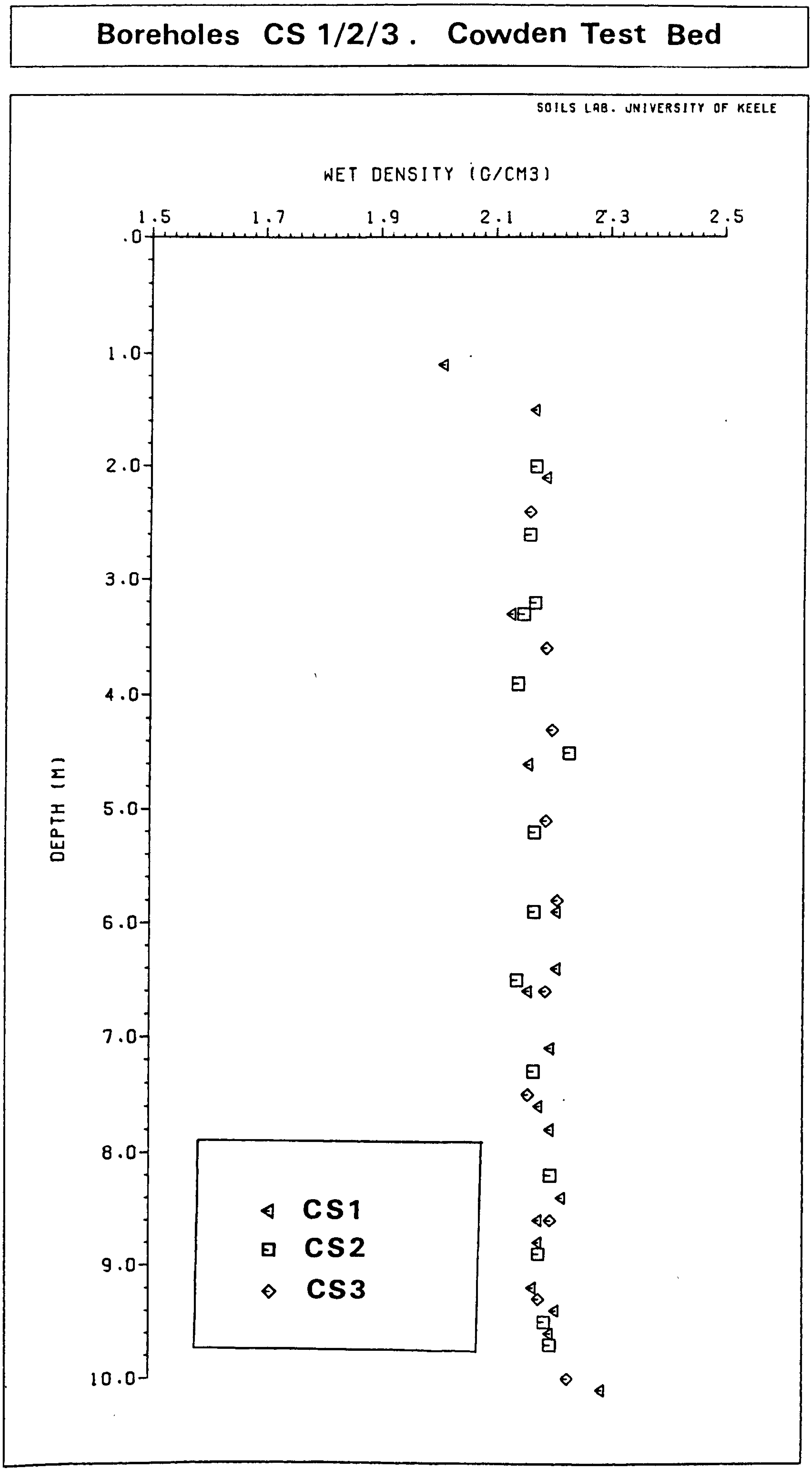


Figure 4.19 Wet density (ρ) / depth CS1-3

is no evidence for a significant change in bulk density across the colour boundary. A till of high density (2.29 Mg/m^3) was sampled in all three boreholes close to the basal channel fill, possibly reflecting conditions of improved subglacial drainage during deposition which allowed some degree of consolidation.

Table 4.1 Analysis and Summary Bulk Density CS1-3

	CS1	CS2	CS3	Mean
<5m	2.14	2.17	2.18	2.163
>5m	2.20	2.18	2.19	2.190
Total	2.18	2.17	2.18	2.18

4.5.2 Dry Density (Mg/m^3).

The dry density of a sediment is defined as the dry mass of the grains and particles per unit volume and is a reflection of the state of compaction independent of the degree of saturation. Owing to the lack of sorting and mix of lithologies in the Cowden till, dry density is a composite value subject to many controls. It can be shown that, assuming a dry density of 1.75 Mg/m^3 for the <4 ϕ fraction and 1.91 Mg/m^3 for the >4 ϕ fraction, the Skipsea and Withernsea Tills lie close to the line of theoretical maximum packing (Figure 4.7), This suggests a uniform process of subglacial compaction unlike the more scattered distribution created by the melt-out process (McGown and Derbyshire 1977), which lies between the Proctor optimum density and the dry tipping density. Calculated values for dry density have a mean of 1.866 Mg/m^3 for both till units. It is significant that below 5 m in all three boreholes the till has the same mean state of

Boreholes CS 1/2/3. Cowden Test Bed

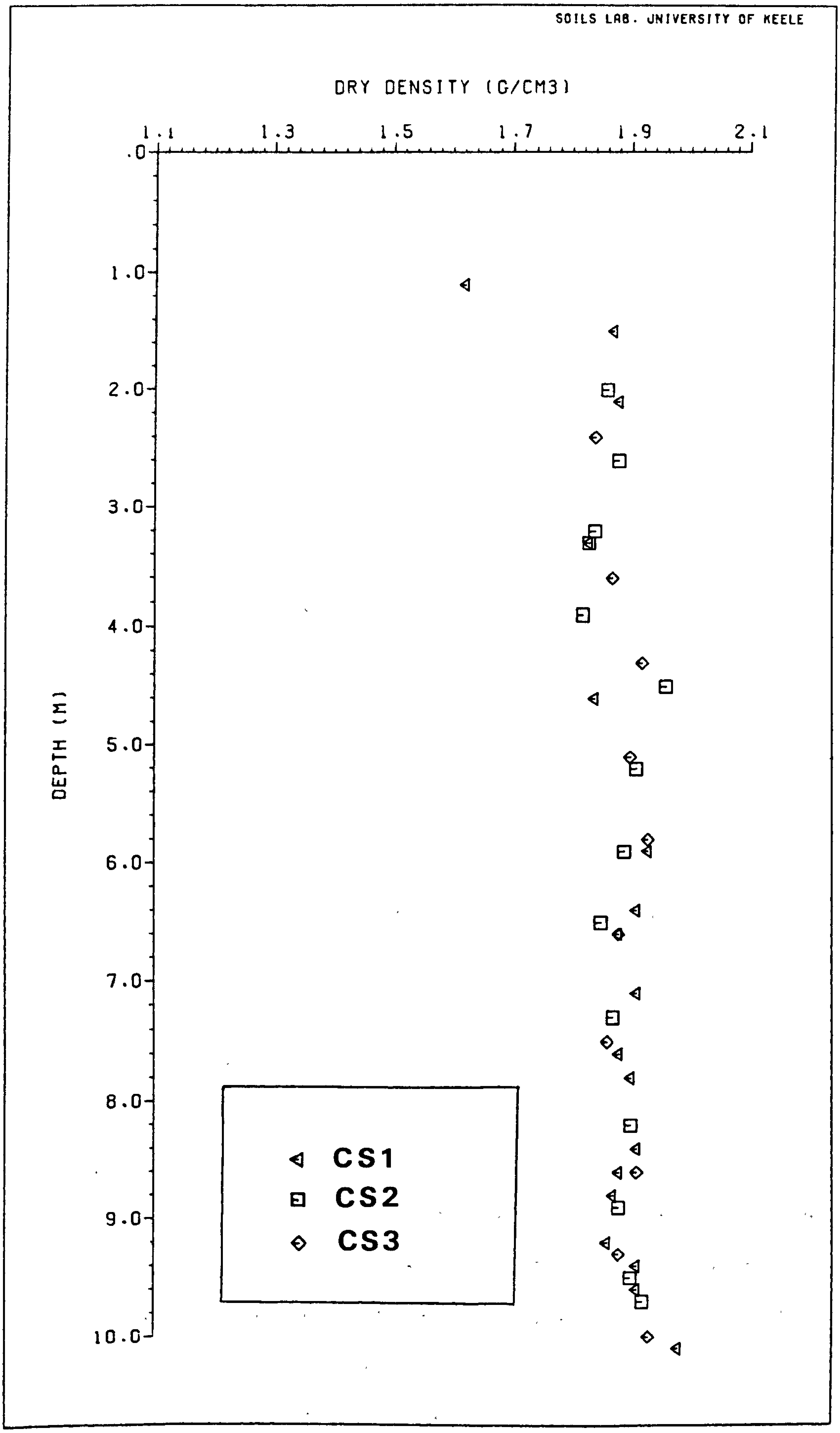


Figure 4.20 Dry density (ρd) / depth CS1-3

compaction despite changes in size distribution.

Table 4.2 Analysis and Summary, Dry Density CS1-3

	CS1	CS2	CS3	Mean
<5m	1.82	1.86	1.87	1.85
>5m	1.89	1.89	1.89	1.89
Total	1.85	1.87	1.88	1.86

4.5.3 Porosity.

The porosity is defined as a ratio of the volume of the pores (Vp) to the total volume (V) and is therefore related directly to the dry density (ρd) and specific gravity of the solid phase (Gs) by the equation

e1 $$n = Gs\ \rho w - \rho d/(Gs/\ \rho w)$$

where ρd = dry density

ρw = density of water

Using the cubic packing model, for spheres of equal size, a value for maximum porosity would be 47.6% while the highest degree of packing using the rhombohedral model, would achieve a value of 25.8% (Wilun and Starzewski 1975). The mean value for porosity for the Cowden diamict profile is 30.2% although significantly higher values were calculated for the upper soil horizons in all three boreholes. Tills and other cohesive soils commonly possess higher porosities than most well graded sands since clay particles arranged in a honeycomb or cardhouse structure can produce highly porous systems. However, since the pores in these soils are to a large extent filled with adsorbed water strongly attracted to the

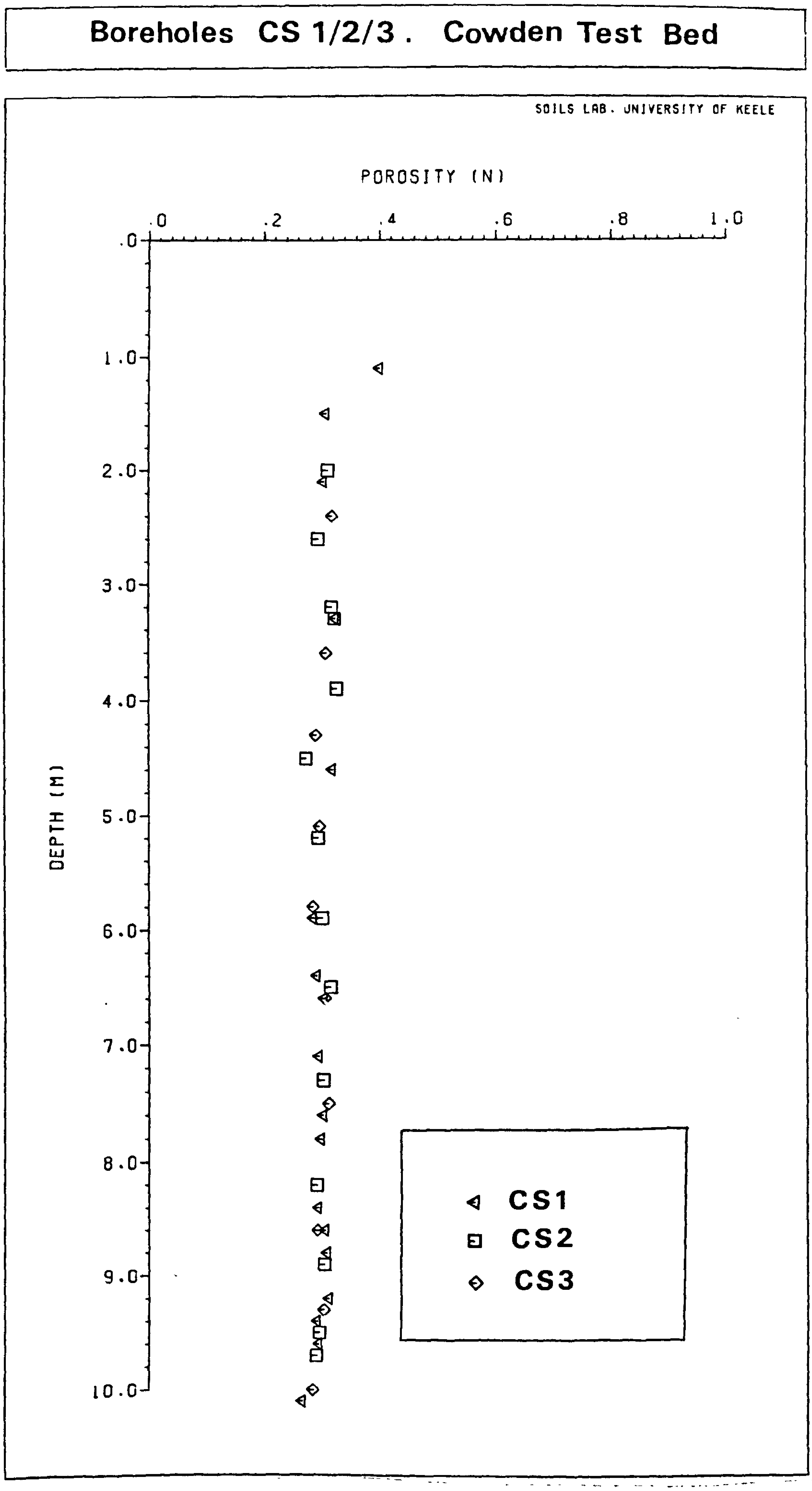


Figure 4.21 Porosity (n) / depth CS1-3

surface of the particles, permeability is extremely low. Bonell (1978) quotes values of 0.8 10^{-9}m/sec for the saturated permeability (k) of the Withernsea Till at a depth of 3 m for a location 2 km NE of Cowden. The degree of porosity will decrease with depth as the pore volume of the till is reduced with increasing effective stress (Figure 4.21). Within the till sequence of the upper Pennines comparative values of 0.26 10^{-9} m/sec have been recorded at a depth of between 11-20 m (Vaughan, Lovebury and Horswill 1975).

Table 4.3 Analysis and Summary, Porosity CS1-3

	CS1	CS2	CS3	Mean
<5m	33.0	30.7	30.0	31.2
>5m	29.0	29.0	29.6	29.3
Total	31.0	29.8	29.0	30.2

4.5.4 Voids Ratio And Natural Moisture Content.

The voids ratio is an important parameter since it is commonly used in geotechnical analysis as a volume change coefficient during stages of consolidation and can therefore be used to relate the in situ conditions to past conditions of effective stress. The mean value for the voids ratio (dimensionless) was calculated as 0.438, the data showing a consistant reduction with depth in all three boreholes through the range 0.66-0.36 (Figure 4.22). In an overconsolidated soil with a standard coefficient of consolidation (Cv) and initial voids ratio (e_i), the change in voids ratio with depth is directly related to the degree of unloading to the present in situ effective stress.

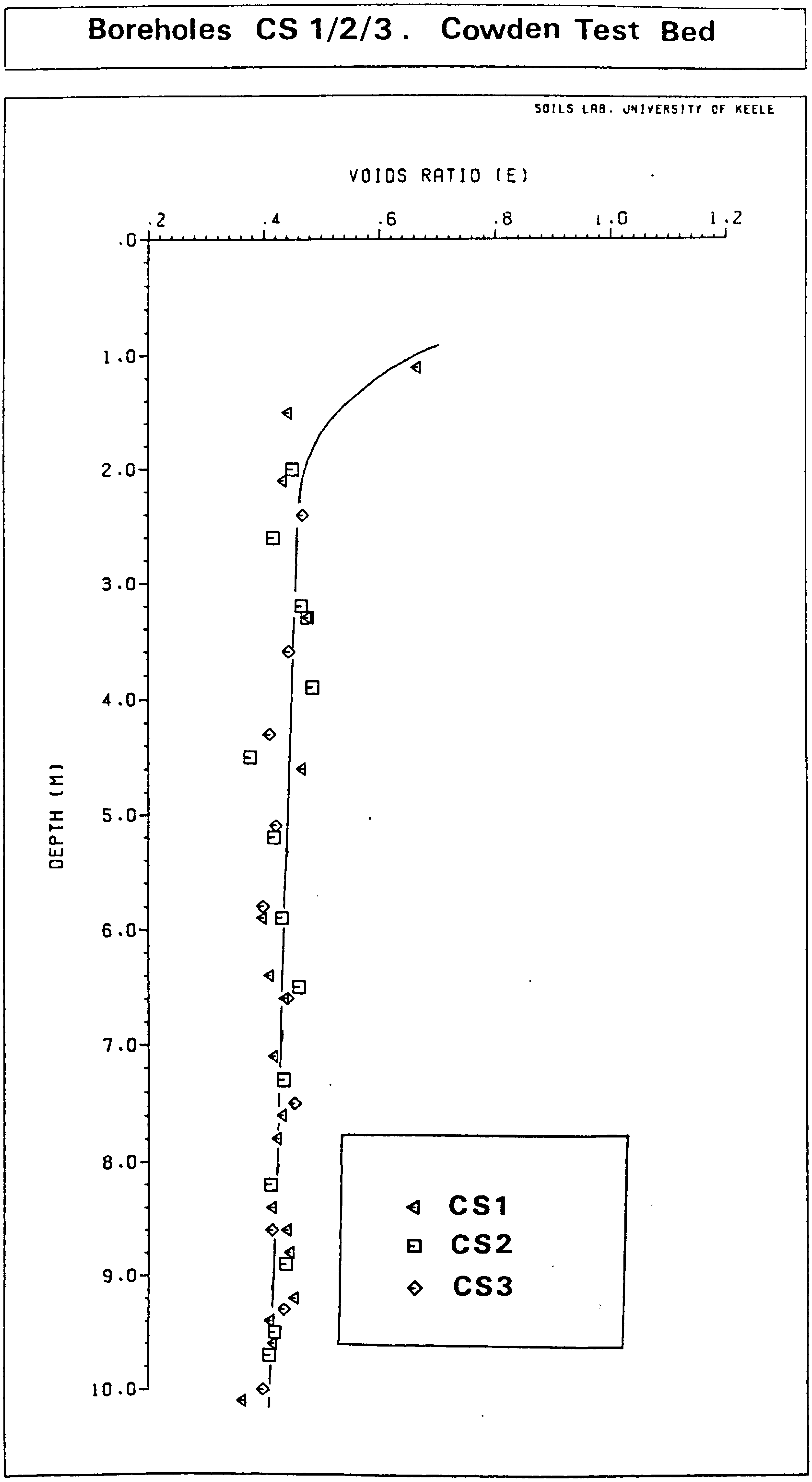


Figure 4.22 Voids ratio (e) / depth CS1-3

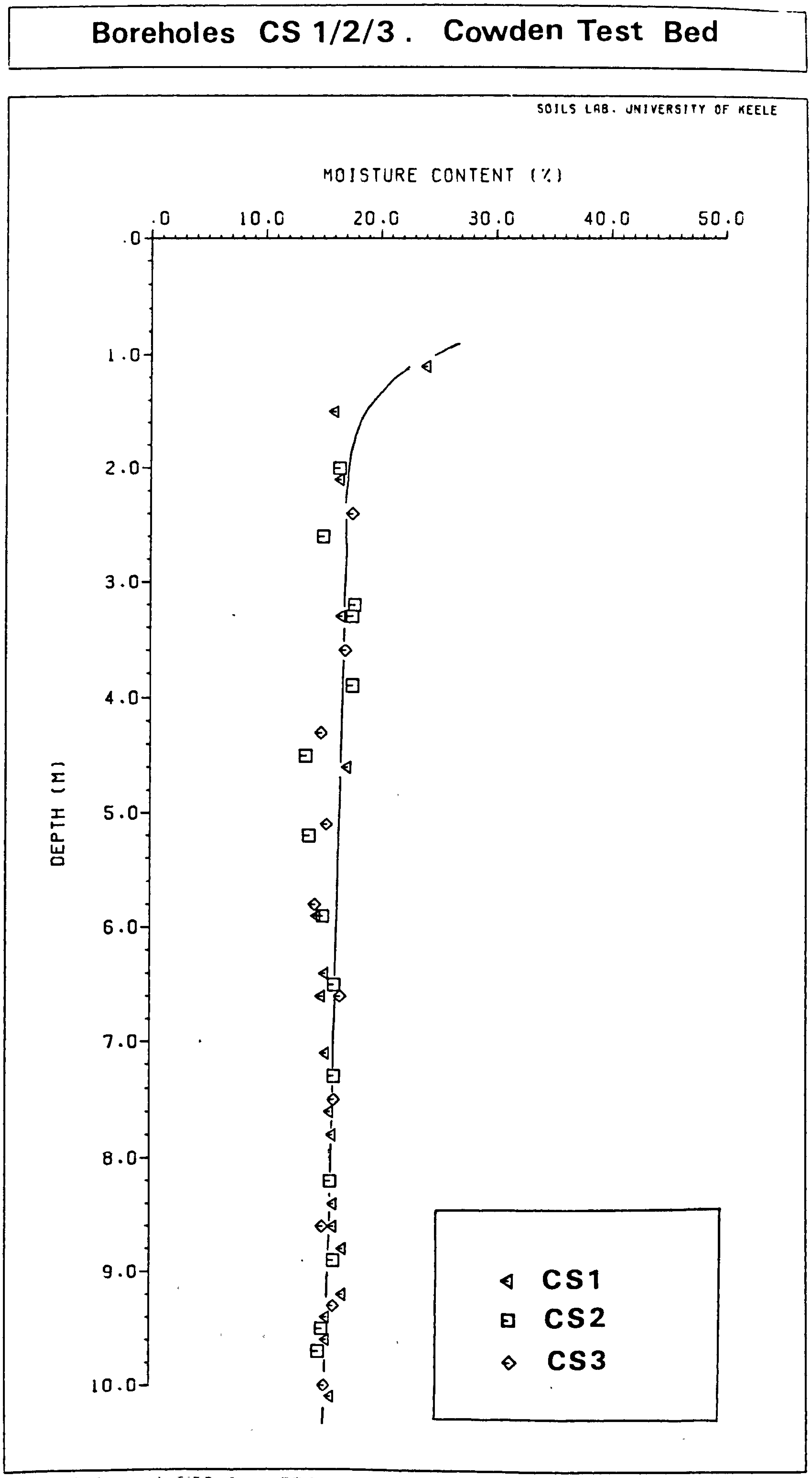


Figure 4.23 Moisture content (w) / depth CS1-3

The only area where the data moves away from this trend is in the upper soil profile. The voids ratio of a saturated soil is related to the moisture content by ;

e2 $e = w.Gs$

Since the specific gravity is taken as 2.7 for the purposes of calculation e2 becomes ;

e3 $e = w \cdot \text{constant}$

The direct relationship between voids ratio and natural moisture content can be seen in a similar distribution with depth of data points below the zone of permanent saturation at 1.5 m (Figure 4.23)

Table 4.4 Analysis and Summary, Voids Ratio and Natural Moisture Content. CS1-3

	CS1	CS2	CS3	Mean
>5m (e)	0.49	0.44	0.44	0.45
(m)	18.04	16.46	16.47	16.96
<5m (e)	0.42	0.42	0.42	0.42
(m)	16.97	15.32	15.47	15.92
Total (e)	0.46	0.43	0.43	0.438
(m)	17.50	15.86	15.75	16.40

4.5.5 Specific Gravity.

The specific gravity of solid particles (Gs) depends on the mineralogical composition of the sediment. For a monomineralic soil a standard specific gravity can be applied, usually 2.65 (BS 1377). Owing to the poorly sorted nature of the

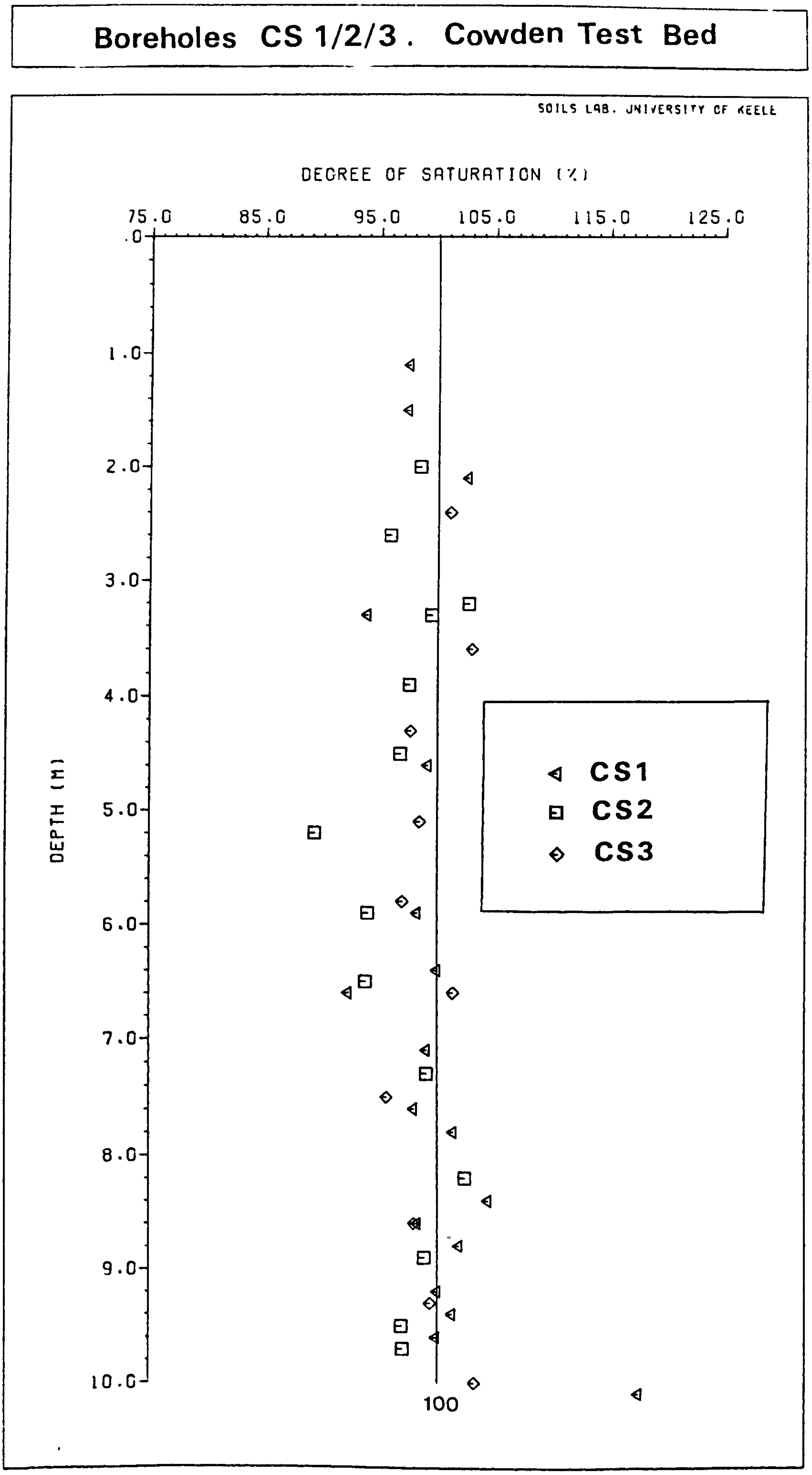


Figure 4.24 Degree of saturation (Sr) / depth CS1-3

COWDEN

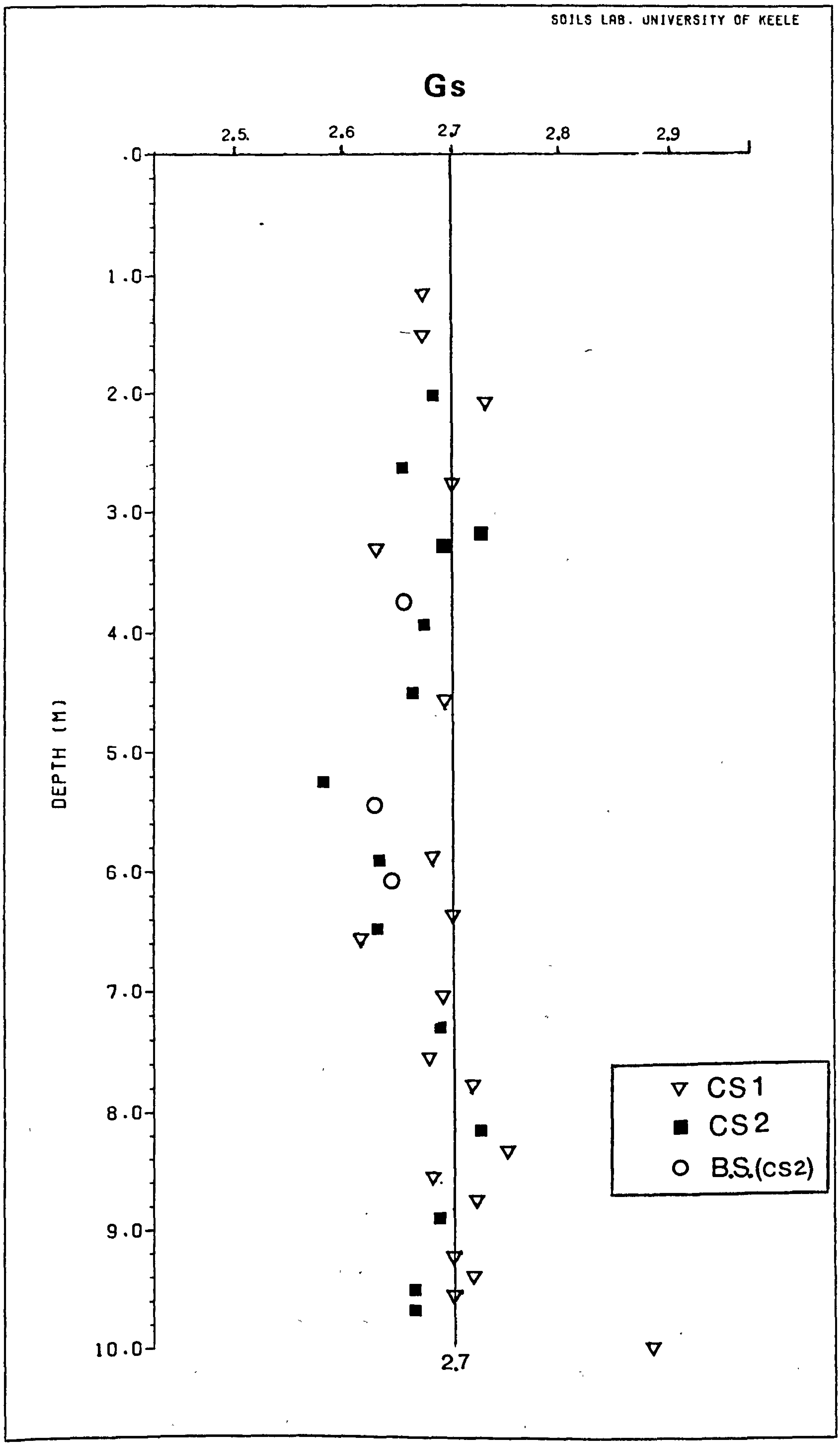


Figure 4.25 Specific gravity (Gs) / depth CS1-2

matrix this approach is invalid for diamicts and a wide variation in specific gravity can be expected. Denness (1974) reported a zonal variation in specific gravity within the range 2.45-2.65, in a 60 m^2 section of chalky-Jurassic till in Buckinghamshire. Love (1981) noted a similar variation in the Holderness tills and found a close relationship between specific gravity and carbonate content. For the practical purposes of calculation a standard value of 2.7 was adopted for the Cowden profile representitive of a cohesive sandy clay (Wilun and Starzewski 1975). This simplification produced a scatter of results for the degree of saturation (Sr) around 100% since this parameter is highly sensitive to inaccuracies in the calculation of specific gravity (Figure 4.24). Working back, with the degree of saturation equal to 100% produced estimates for specific gravity which were then plotted along with values calculated using BS 1377 (Figure 4.25). The variation of specific gravity with depth shows no obvious pattern, possibly reflecting the complex controls on this critical parameter. Since all the points obtained are technically feasible for a till profile it is assumed that the calculated variation of Sr with depth (Figure 4.24) is due principally to fluctuations in specific gravity away from the standard value of 2.7. The effect on other parameters, particularly voids ratio and porosity was not so marked. In the majority of cases calculations were not affected before the third decimal place (AppendixII).

4.5.6 Atterberg Limits.

The Atterberg Limits were determined for a number of samples from boreholes CS1 and CS2. The results from borehole CS1 were applied directly to the geotechnical data from CS3 owing

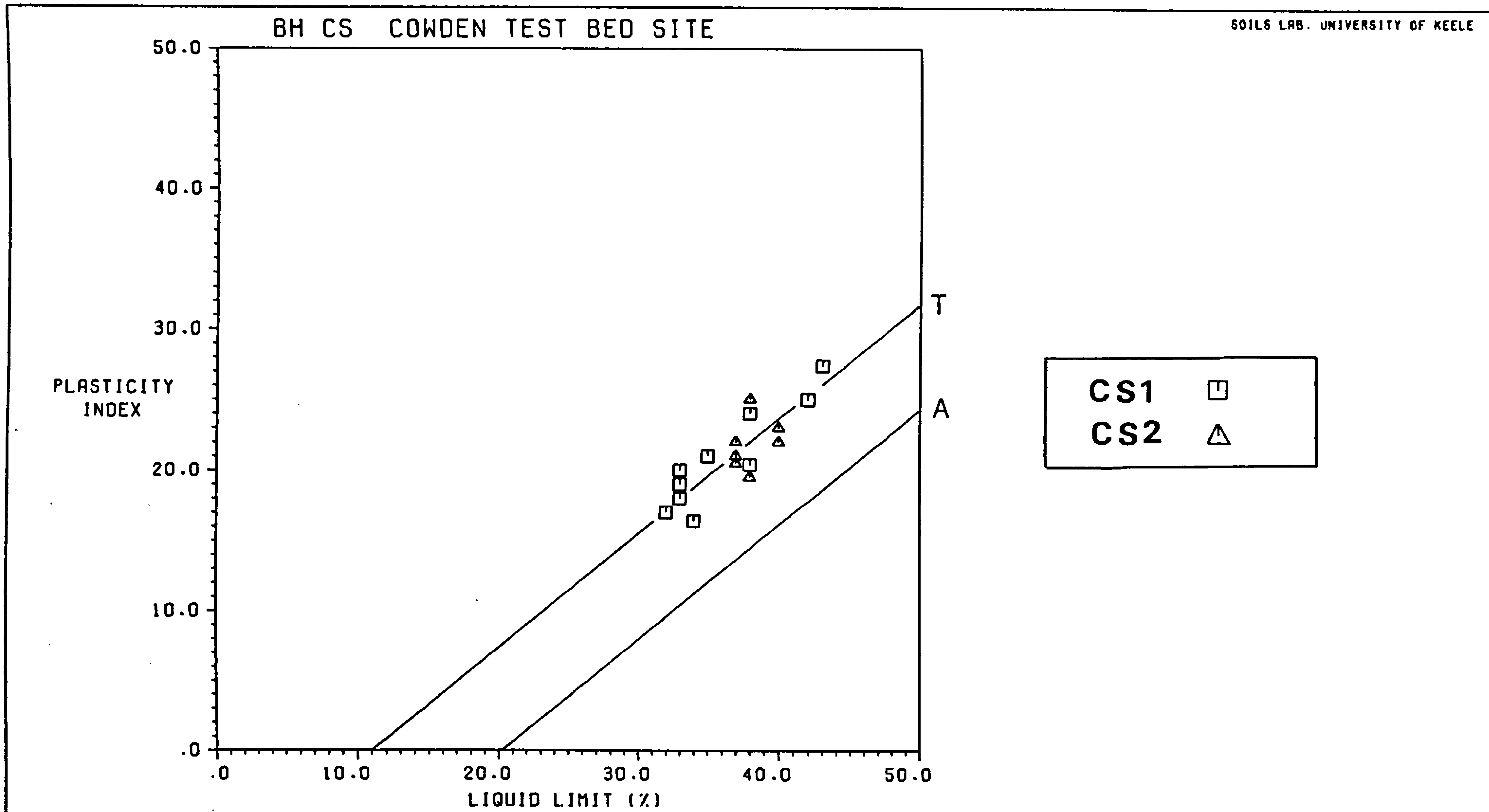


Figure 4.26 Plasticity index (Ip) / Liquid limit (LL) CS1-2

to the close proximity of the boreholes. The index limits show a similarity in range and mean values (See Table 4.5) between CS1 and CS2 and a comparative distribution with depth.

When the plasticity indices (Ip) of the Cowden diamicts are plotted against liquid limit (LL) on a conventional plasticity chart (Figure 4.26) the points fall on line parallel to, but above the Casagrande "A" line. This correlation has been termed the "T" line (Boulton and Paul 1976) and is common to most diamicts and several other soils of glacigenic origin. For the Cowden diamicts falling close to the T line

e4 $$Ip = 0.73(LL - 11.0)$$

The trend and position of the T line is controlled by the "dilution effect" of an increasing coarse fraction on the Atterberg limits of the clay end member. The liquid limit of a pure clay is governed by the relative proportions of clay species, each having distinct Atterberg limits.

	LL	PL
Montmorillonite	97%	700%
Kaolinite/Illite	30%	70%

Increasing amounts of montmorillonite within the clay fraction would significantly increase the plasticity index by increasing the clays ability to absorb water without deforming plastically. This effect is considered negligible for the Cowden borehole results, owing to the fact that the clay mineralogy has been shown to be relatively constant (Goodyear 1962) while containing a high proportion (>30%) of inert clay size particles. Although the liquid limit of the clay end member remains constant

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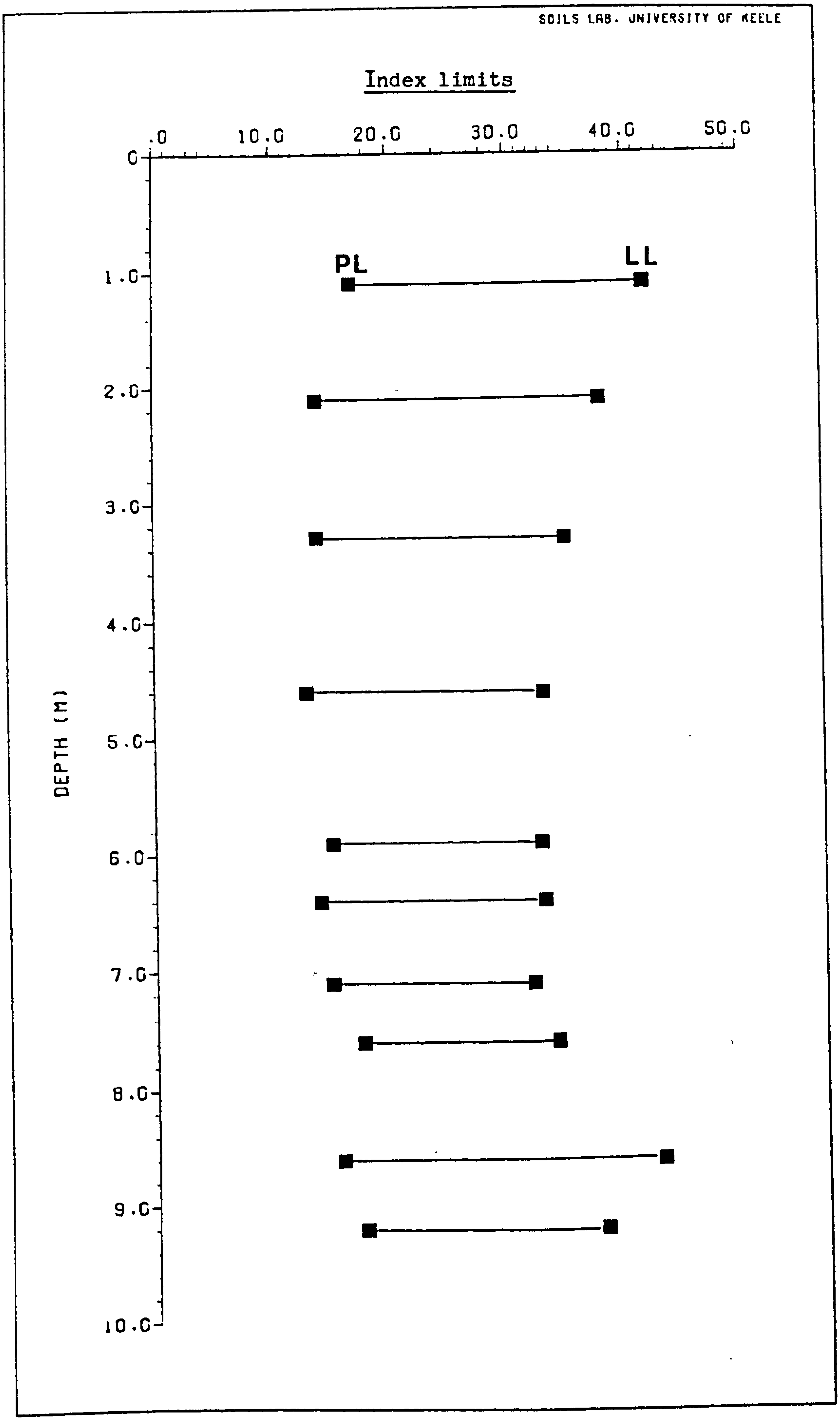

Figure 4.27 Liquid and Plastic limit / depth CS1

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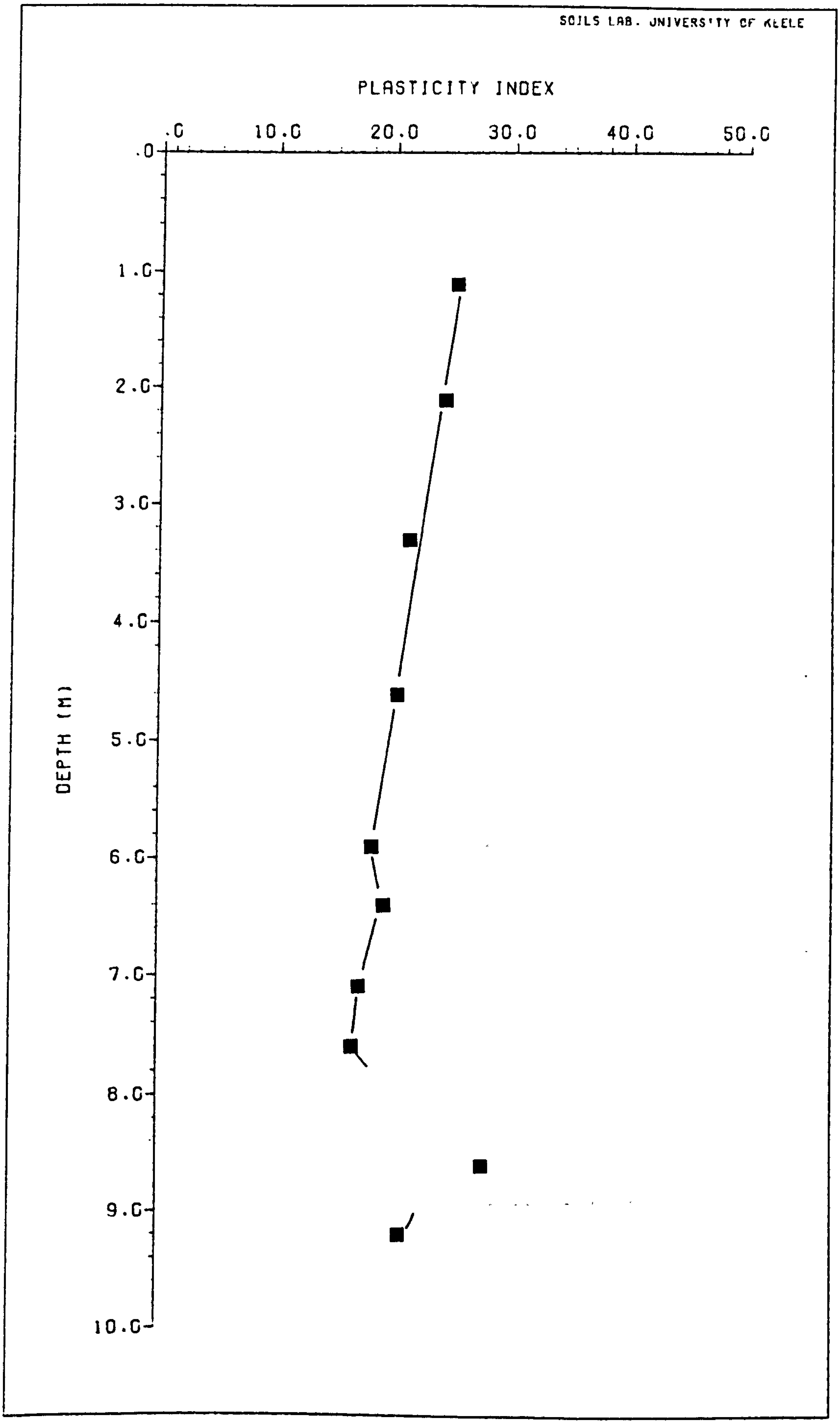

Figure 4.28 Plasticity index (Ip) / depth CS1

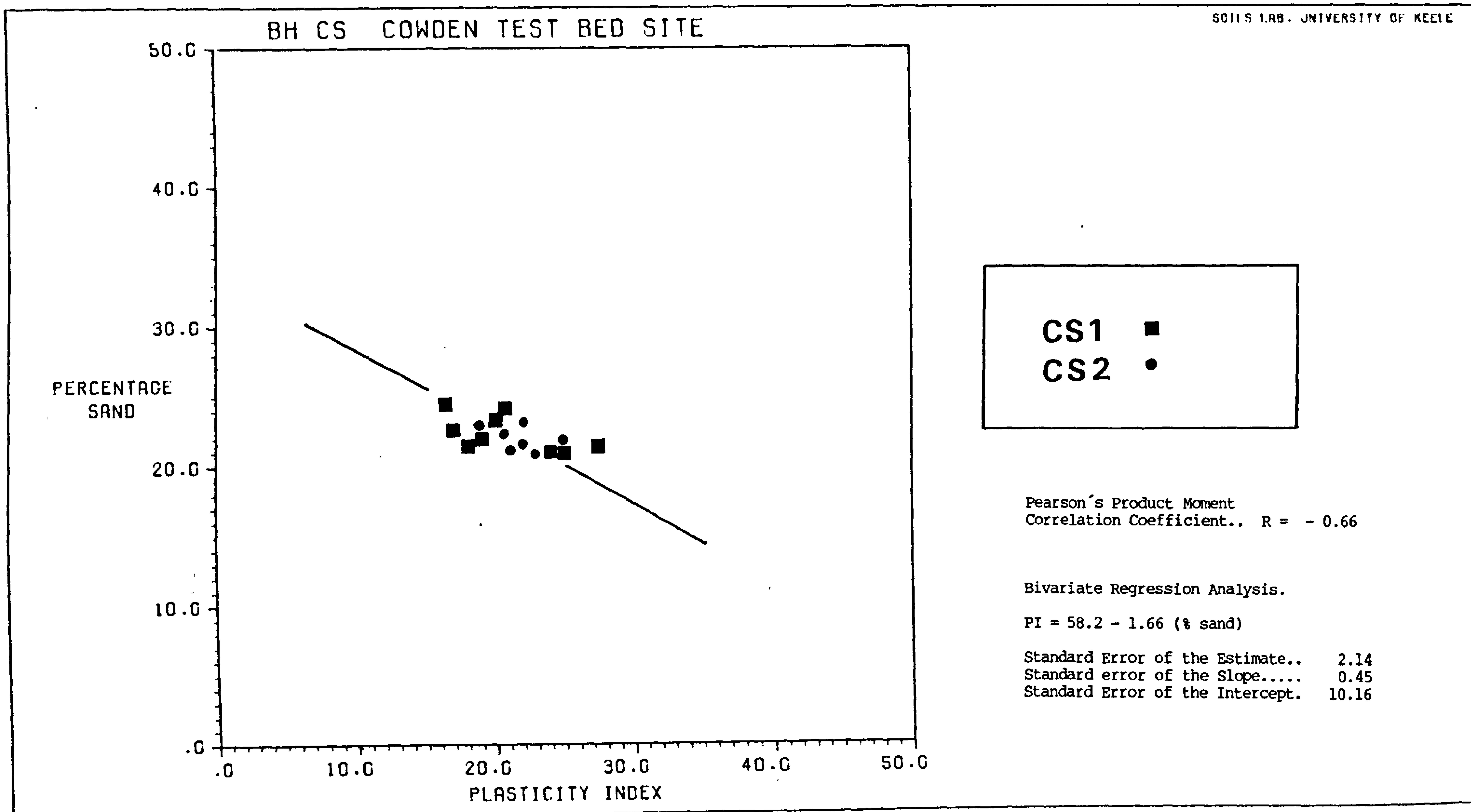

Figure 4.29 Plot showing the relationship between % sand and Plasticity index (Ip) CS1-2

it can be shown to vary inversely with sand content. For a given percentage of coarse material (>0.06 mm) the reduction in percentage moisture is greater for the liquid limit than for the plastic limit (Dumbleton and West 1966).

This effect can be seen when plotting the percentage of each major size fraction against plasticity index (Figure 4.29 and Figure 4.32). While variations in the percentage of silt and clay have very little control on the index properties, sand varies inversely. For the Skipsea and Withernsea Tills this relationship can be expressed as;

e5 $$Ip = 58.2 - 1.66(S)$$

where S = % sand

The disproportionate effect of increasing sand contents on the liquid and plastic limits can be seen in Table 4.5 when comparing the ranges of each index property for borehole CS1.

Table 4.5 Analysis and Summary, index limits CS1-2

	CS1	CS2 %
Plastic L.	13.- 17.	13.- 17.
Liquid L.	32.- 43.	37.- 40.
Plasticity I.	16.- 27.	19.- 25.

This is visually apparent in the plot of plasticity index with depth (Figure 4.27), where the reduction in Ip can be seen to be largely a function of a reduction in the liquid limit, the plastic limit varying over a far more restricted range.

Although a correlation was obtained between plasticity index and percentage sand, the controlling element of the coarse fraction is unlikely to be delimited solely by the arbitary size definition of sand (-2Φ - 4Φ). It should be noted that following standard practice, the index limits for clay rich diamicts only relate to that part of the soil matrix finer than 425 μm (1.25Φ ..medium sand) and so necessarily excludes any variation that may exist in the coarse to very coarse sand fraction (1.0Φ - -1.0Φ). Therefore the controlling coarse grades are likely to form a fraction containing both medium to fine sands and the coarse silts, acting on the clay end member; the mineralogy of which remains relatively constant for the Holderness tills (Section 4.4, Goodyear 1962).

The effect of an increasing coarse element within a fine silt-clay matrix can therefore be expected to have an important role in determining the Atterberg limits of a till and therefore ultimately effect the behaviour under stress.

4.5.7 Liquidity Index.

The relationship between the natural moisture content and the Atterberg limits gives a useful insight into the consistency of a cohesive soil at any point within a profile. True lodgement tills are invariably overconsolidated (Soderman and Yim 1970), owing to the fact that the lodgement process subjects the till to a greater normal load than exists in the exhumed section. As a result the matrix moisture content of unweathered lodgement till is low, generally slightly below the plastic limit, producing a typically negative liquidity index in the range -0.1 to -0.35 (Sladen and Wrigley 1983). The mean range of liquidity index for material recovered from boreholes CS1 and CS2 was 0.09 to -0.18 with the majority of the samples falling close to the Ip = 0 line (Natural moisture content = plastic limit). Although there is a general tendency for the liquidity index to decrease with depth (Figure 4.30), in line with reduced moisture content, the variation

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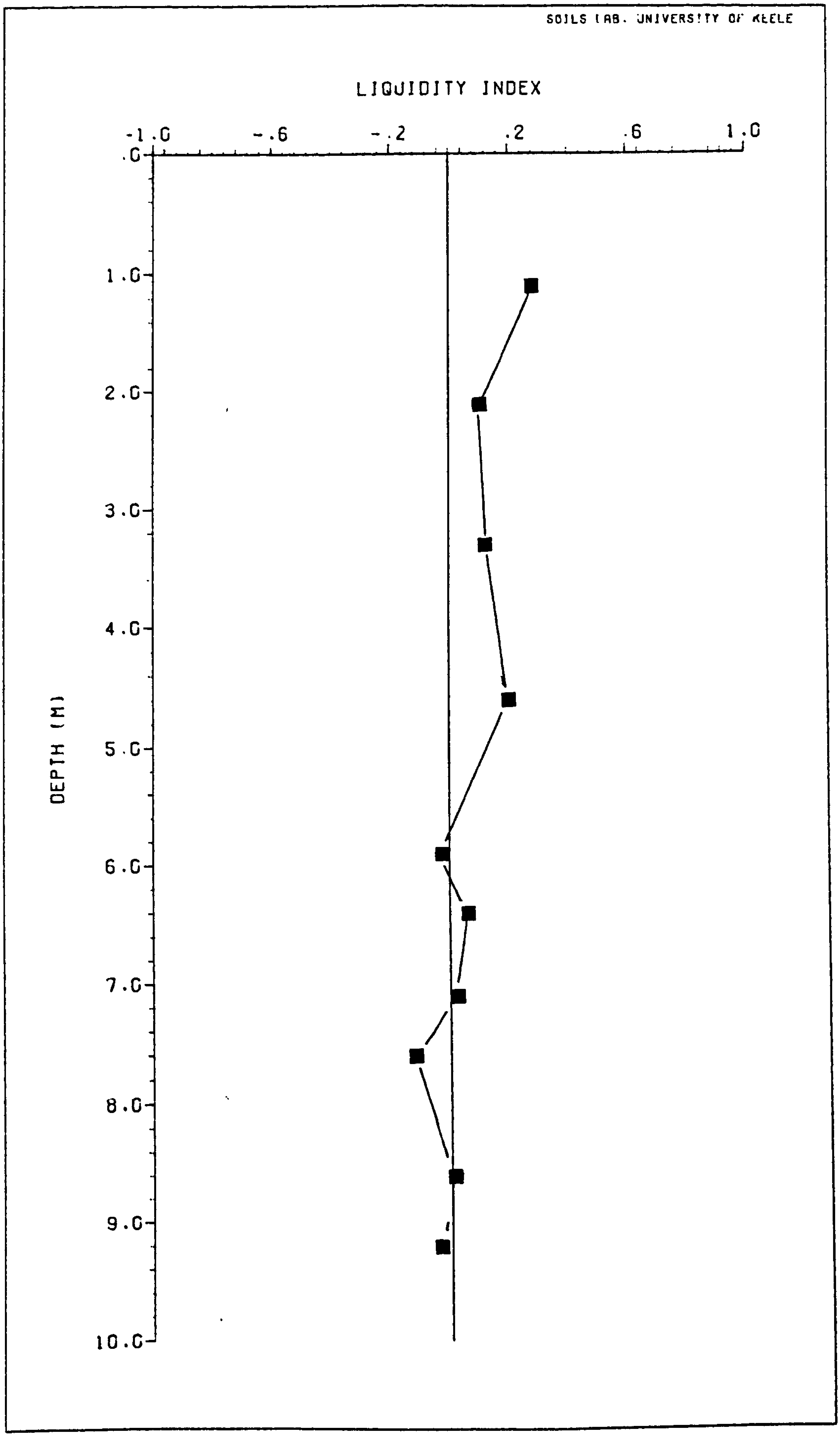

Figure 4.30 Liquidity index (LI) / depth CS1

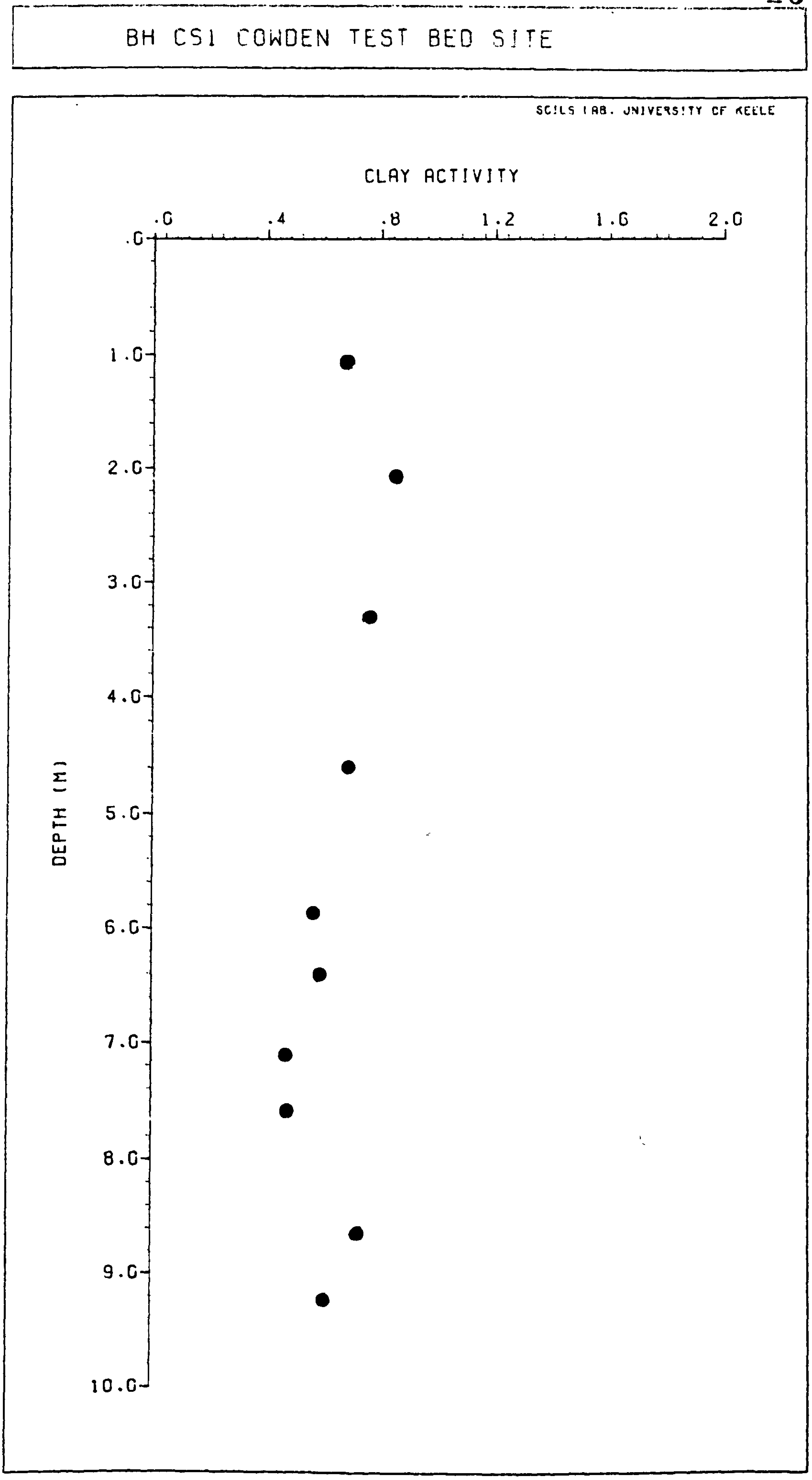

Figure 4.31 Clay activity (A) / depth CS1

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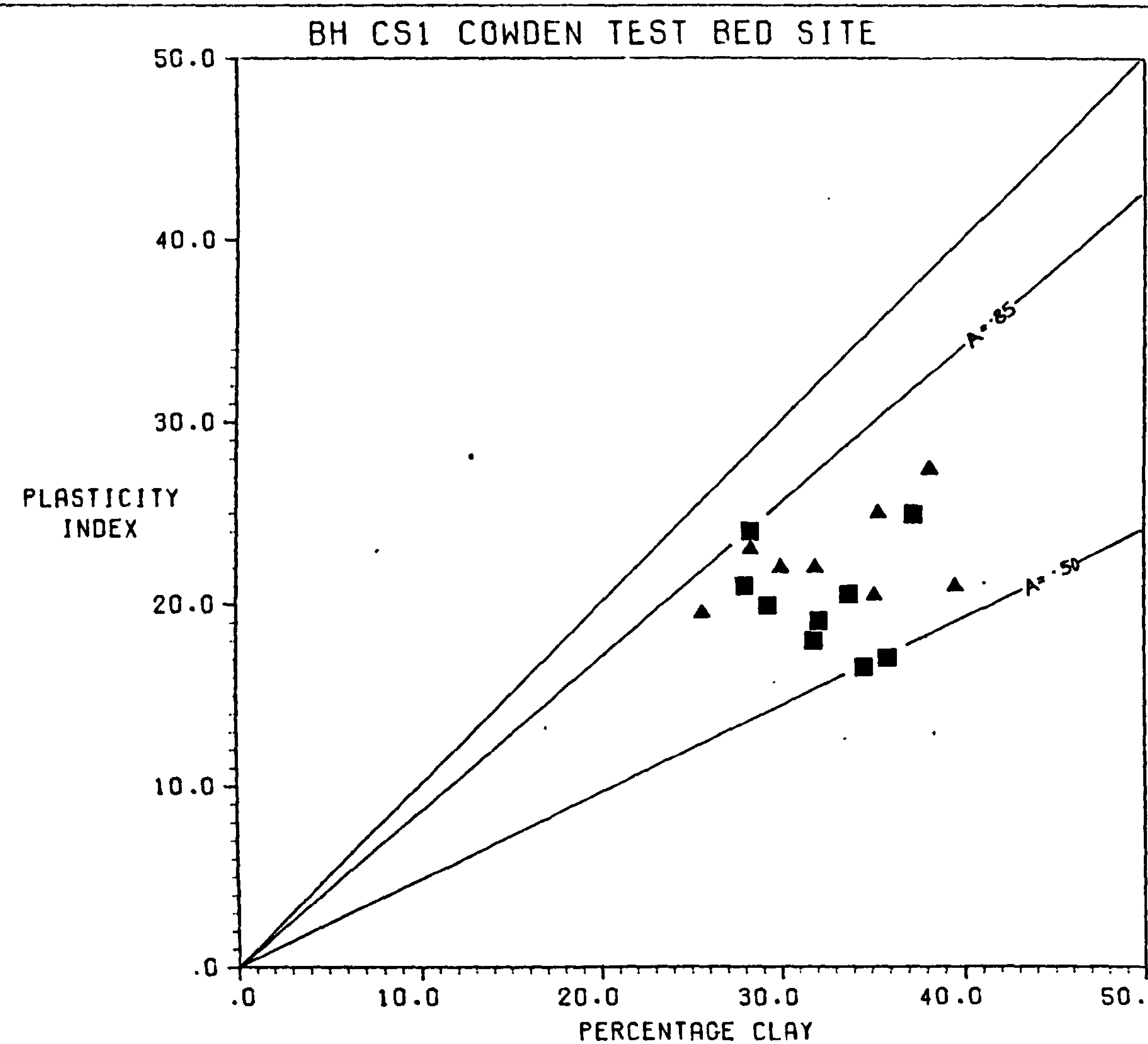

Activity of the Cowden Tills

■ BH CS1
▲ BH CS2

Plot showing the relationship of Plasticity Index (Ip) and % clay against the resultant ratios of Activity (Ip / % clay)

Figure 4.32

in plasticity index produces a considerable scatter of results. liquidity.

4.5.8 Activity.

Skempton (1953) defined "Activity" as the plasticity index divided by the percentage dry weight of the clay particles (Figure 4.32). Lodgement tills are inactive soils, a typical value being less than 0.8 (Sladen and Wrigley 1983). The range of activity down the Cowden profile forms a broad scatter between 0.85 and 0.5 (Figure 4.31) with a general reduction with depth. The level of low activity can be directly related to the large inert percentage of carbonates and quartz flour within the clay fraction.

CHAPTER 5

Geotechnical Behaviour

Nomenclature

A	Pore pressure coefficient (Skempton 1954)
A_f	Pore pressure coefficient A at a failure criterion
B	Pore pressure coefficient (Skempton 1954)
c	Cohesion with regards to total stress
c'	Cohesion with regards to effective stress
cu	Undrained shear strength
Cc	Compression index
Ce	Expansion index
Cp	Compression of pore fluid
Cs	Compression of soil skeleton
e	Voids ratio
g	Gravitational acceleration
H	Henrys coefficient of solubility
Ko	Coefficient of lateral stress of soil at rest
OCR	Overconsolidation ratio
n	Porosity
n_i	Initial porosity
p'	Mean effective normal stress = $(\sigma'_1 + 2\sigma'_3)/3$
pc	Maximum preconsolidation stress
po	Air Pressure (Absolute)
q	Deviator stress = $\sigma_1 - \sigma_3$

u	Pore pressure	
u_i	Initial pore pressure on application of cell pressure	
u_r	Residual pore pressure (pore suction)	
v	Voids ratio	
vcl	Virgin consolidation line	
V	Volume	
V_i	Initial volume	
z	Depth	
$\sigma 1$	Major principal stress	Total stress
$\sigma 2$	Intermediate principal stress	Total stress
$\sigma 3$	Minor principal stress	Total stress
$\sigma' 1$	Major effective stress	
$\sigma' 2$	Intermediate effective stress	
$\sigma' 3$	Minor effective stress	
σ	Total normal stress	
σ'_n	Effective normal stress	
σ'_r	Horizontal effective radial stress	
ϕ	Angle of internal friction (total stress)	
ϕ'	Angle of internal friction (effective stress)	
ϕ'est	ϕ' at $\sigma' 1/\sigma' 3$ maximum	
ϕ'f	ϕ' at a specified failure criterion	
τ	shear stress	
ρd	Bulk density of soil	
ρw	Density of water	

5.1 Conditions Of In Situ Stress.

Before the effects of imposed stress can be investigated it is essential to ensure that the state of stress imposed during testing resembles as closely as possible the in situ conditions. Assuming that the mechanical disturbance of the soil structure and change in moisture content was kept to an absolute minimum by careful preparation and on site testing, the only sample disturbance that requires consideration is the change in the state of stress imposed by sampling.

A simple condition of isotropic stress is considered (b'3= b'2) where the effective stress is the difference between the external load and the pore-pressure. Knowing the bulk density (ρd) of the till through the till profile, a theoretical effective stress (b'1) and pore pressure profile (u) can be drawn (Figure 5.1).

e1 $$b'1 = (\rho d - \rho w).g.z$$

where ρw = density of water

z = depth

On sampling, the external stresses on the sample are reduced to zero as the total in situ stresses are removed. To maintain equilibrium under the new conditions (ie. no volume change), a negative pore-pressure is induced which can be taken to be equal to the change in external mean stress. This principle relies on the ability of the pore water to withstand high tensile stress. The range of maximum tensile stresses induced at Cowden fall between 0-120 kN/m^2 (pF 1-3, Schofield 1935), which is well within the range of water under normal conditions (Smith 1980). However a loss of moisture at this stage would increase the pore suction and through the surface menisci force an isotropic compression of the

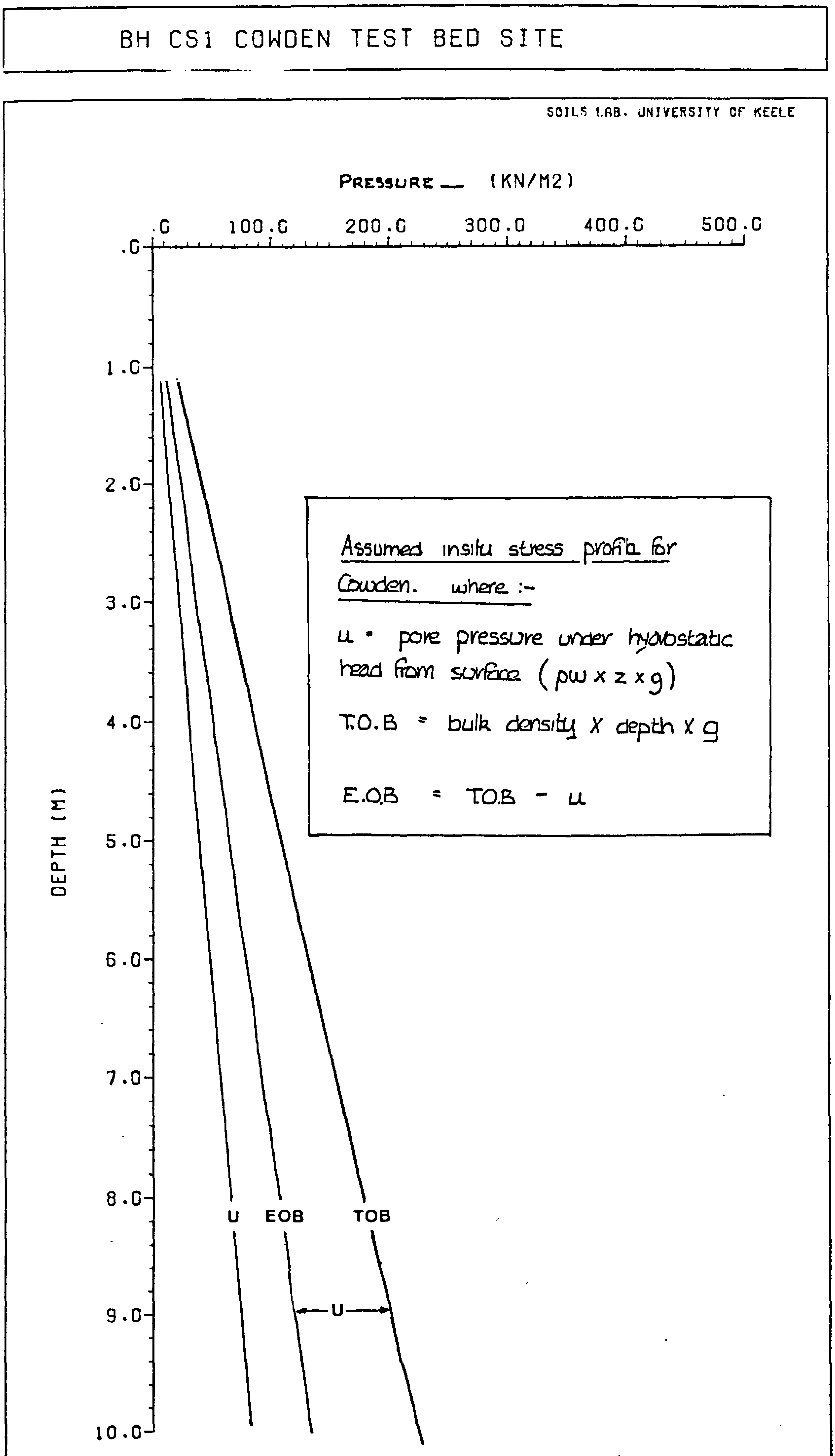

Figure 5.1 Calculated change in in situ normal load with depth based on the bulk density profile (Figure 4.19) with total saturation.

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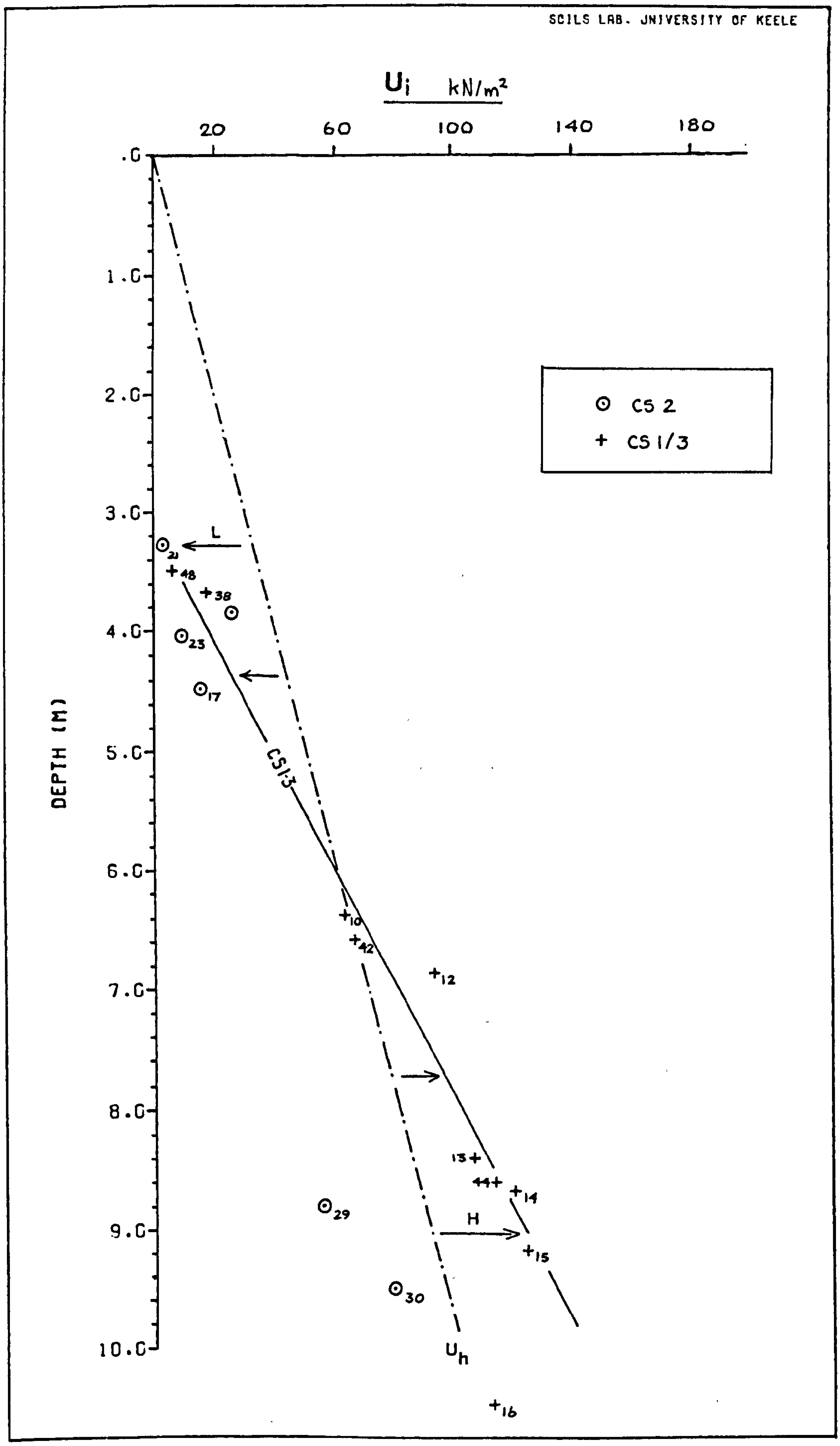
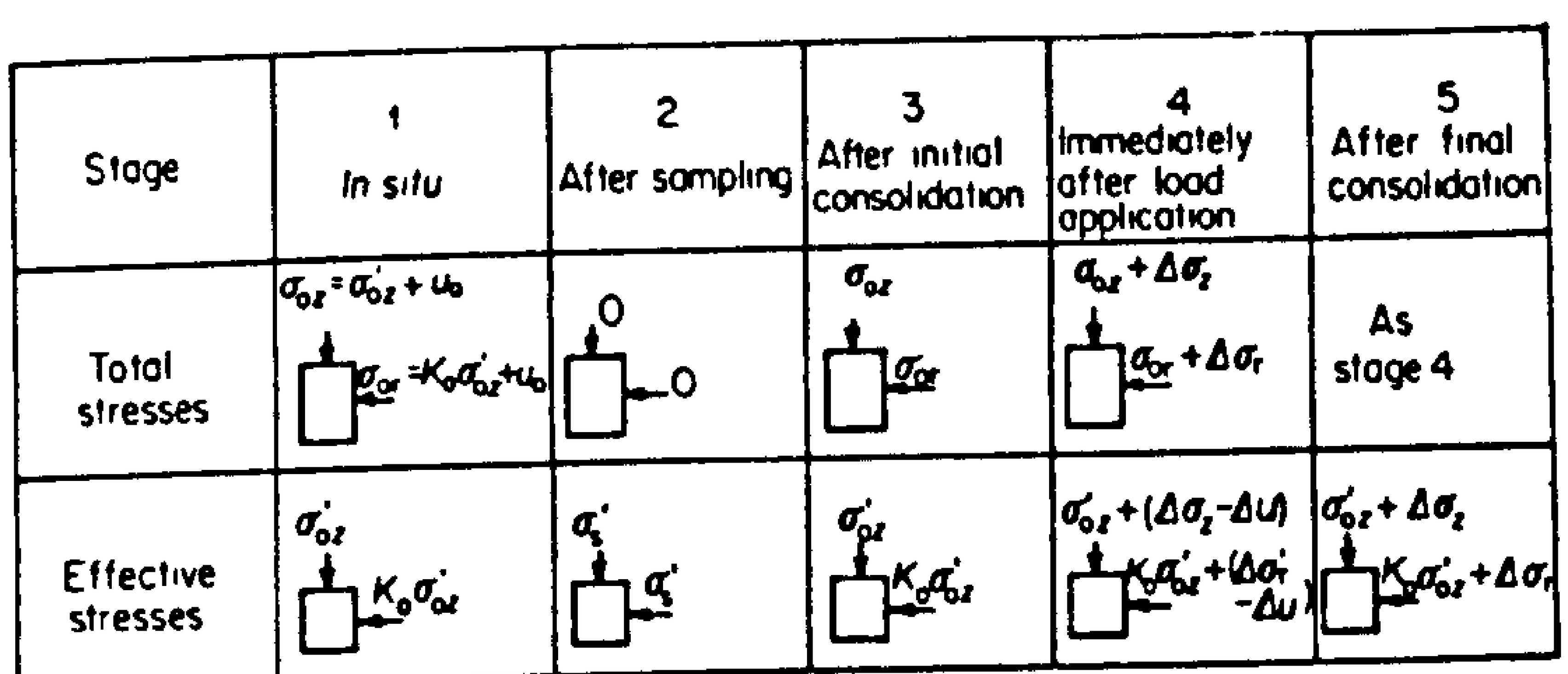


Figure 5.2

Pore pressure response in triaxial specimens on the re-application of the estimated total overburden pressure (T.O.B.), plotted as a function of depth.

soil skeleton. This process taken to its extreme produces the conditions of over-consolidation typical of desiccated profiles (Blight 1967).

In the case of a mechanically undisturbed soil, under the conditions outlined, reapplication of the calculated total overburden within the triaxial cell should restore the initial pore pressure (u_i).



Total and effective stresses on a soil sample at various stages prior to and during testing.

Figure 5.2 shows the variation with depth of the initial pore pressure response on application of the calculated total stress with depth, along with assumed pore pressure profile. The important feature of this curve is the steep gradient bisecting the pore pressure line at approximately 6.5 m. Material recovered above this point exibits an initial pore pressure lower than would be expected, while material below 6.5m shows the reverse response. This distribution could be an effect of sample disturbance although this is unlikely, considering the following points;

(1) The data follows a consistent trend with depth especially results from boreholes CS1 and CS3 which were drilled at the same location but sampled and tested one month apart.

(2) There is no obvious pattern consistent with sample storage delay.

(3) A triaxial specimen trimmed from a block sample falls within the same trend (CT 48).

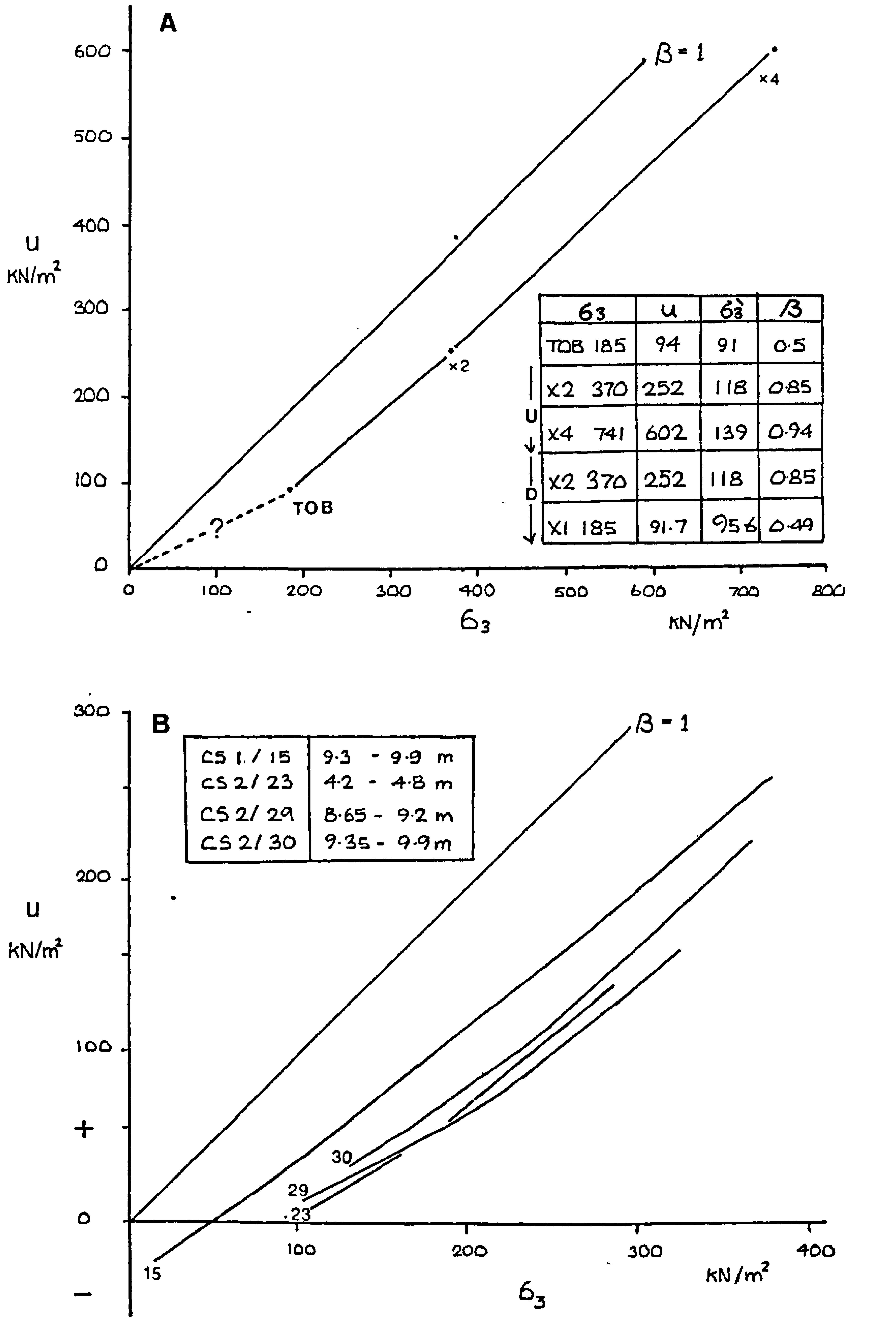


Figure 5.3 . Triaxial specimen pore pressure response to an increase in confining pressure (cell pressure) under undrained conditions.

A second explanation involves the effect of errors when setting the sample into the cell, although the variation in data does not reflect the fact that most combinations of test procedure were attempted including the use of side drains, free ends, double sheaths and varying specimen height-to-width ratios. It must be accepted that although the greatest care was taken, complete exclusion of air from the pressure transducers can never be totally ruled out as a possible error at this stage. Throughout the test programme a total of four triaxial cells were used and seven pressure transducers employed in rotation, each individually calibrated on the same machine to minimise measurement errors.

5.2 Pore Pressure Coefficient B

Close consideration was made of the possibility that the samples recovered from the upper profile were only partially saturated at test. With a saturated soil subject to an isotropic change in total stress the resulting change in pore pressure, under undrained conditions, is given as;

e2 $$\Delta u = B \Delta b3$$

where $B = 1/(1+(n\ Cp/Cs))$

and n = porosity

Cs = Compressibility of the soil skeleton

Cp = Compressibility of the pore fluid.

In a saturated soil Cp is considered far greater than Cs and it is assumed reasonable to take B = 1.

In a partially saturated soil the compressibility of the pore fluid becomes much greater and B will have some value between 0 - 1. Figure 5.3b shows a typical pore pressure response for the

Cowden tills with increasing total stress. It can be noted that at low confining stresses B<1 and only approaches unity at high cell pressures, where it is assumed that the pore pressures are high enough to drive the pore air into solution. The point where this takes place corresponds to the pressure required to produce saturation. The increase in effective stress during this stage causes a consolidation of the specimen to the point where the change in volume equals the initial volume of free air.

e3 $$\Delta V = V_i(1 - Sr)\, n_i$$

where V_i = initial volume

n_i = initial porosity

This condition will occur when;

e4 $$\Delta u = Po(1 - Sr)/Sr\, H$$

where Sr = degree of saturation

Po = air pressure (Absolute) = 100 kN/m^2

H = Henrys coefficient of solubility

For the Cowden diamict the B value rarely approaches the level usually taken as representing full saturation (0.98), even for the deeper specimens. Figure 5.4 shows that although the value of B (initial B value at total overburden calculated from u = 0 kN/m^2 at zero effective stress) increases with depth the maximum B values range between 0.5 - 0.6. Samples at 4m have a B value between 0.1 - 0.2.

A good example of this behaviour is shown with reference to Figure 5.3a, (sample CS3/44 8.3 - 8.9m), where a B value of 0.94 was obtained after subjecting the specimen to a total overburden

COWDEN TEST BED SITE

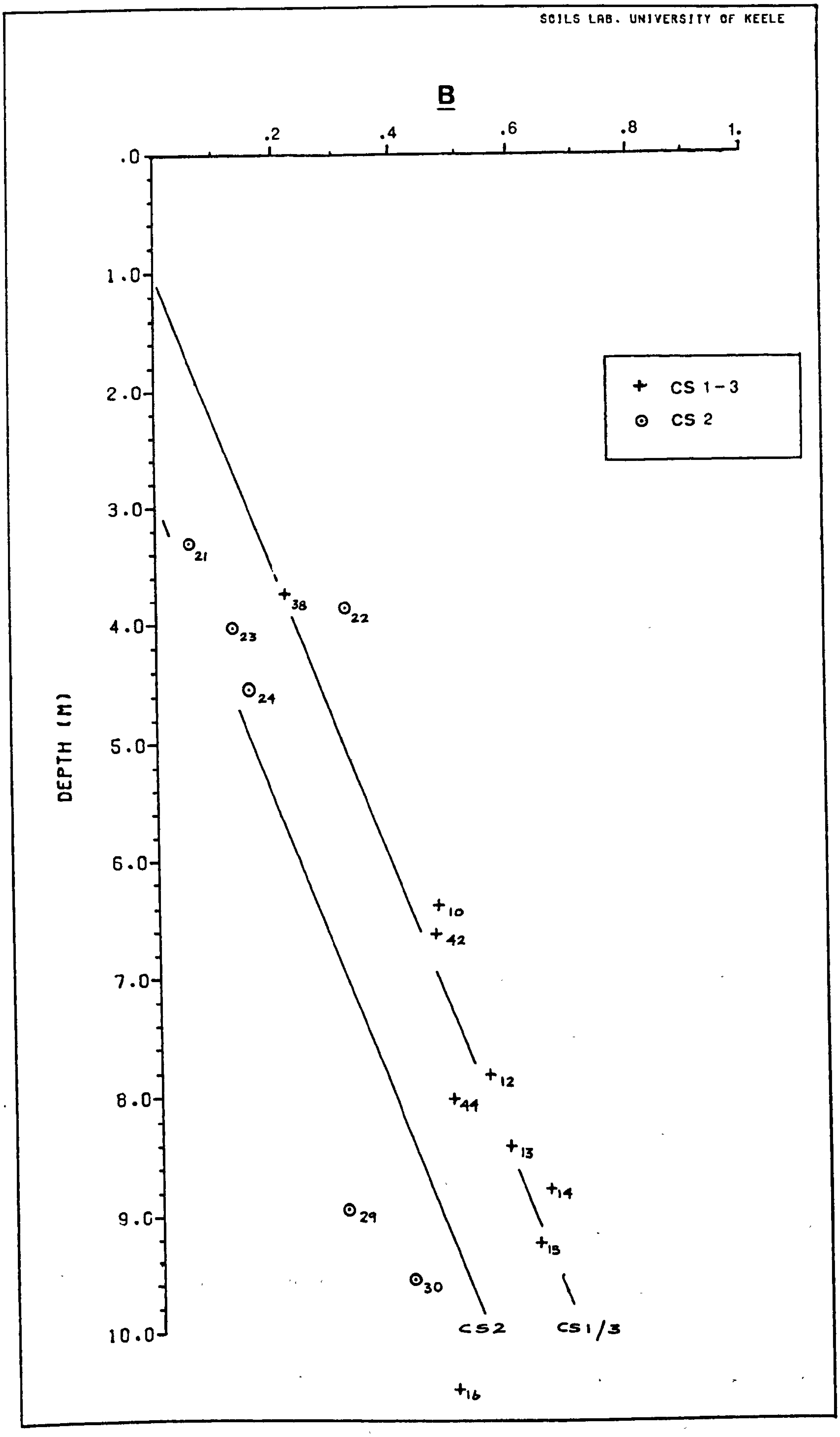


Figure 5.4 Plot of the pore pressure coefficient B calculated for an increment of confining pressure, 0 to total overburden, plotted as a function of depth CS1-3.

representing four times the calculated total overburden ($741 kN/m^2$). Maintaining a pore pressure in excess of 600 kN/m^2 would have driven the pore air into solution if the sample had been lightly undersaturated. Indeed for most cases pore pressures in excess of $200 kN/m^2$ are capable of producing total saturation in most soils. Using e4 it can be shown that for the sample to be undersaturated with a change in pore pressure in excess of $600 kN/m^2$ the value of saturation would have to be <87%, an unrealistic value for a highly impermeable clay soil recovered from 8.6 m and placed under a confining stress equal to the total overburden within 50 minutes of sampling. Calculated values for the degree of saturation (Sr), show that below soil horizon III (0.7m) all values fall close to 100% with most of the data scatter accounted for by the inaccurate determination of specific gravity.

5.3 Values For Ko And Residual Pore Pressure.

An alternative explanation for low B values at high confining stresses could be that the calculation of B using u = 0 at b3 = 0 is unrealistic due to the fact that the pore pressure increases from a negative pore pressure equal to the effective in situ stress on sampling (u_r ..residual pore pressure). This value is given by the extension of the b3/u line to the base axis and is affected by the degree of disturbance on sampling. Although negative pore pressures were measured in most samples prior to the application of the confining stress few values were recorded lower than $-10 kN/m^2$. Direct measurement of u_r in the triaxial device is difficult due to the following points:

(1) The transducer devices were not calibrated to measure negative pore pressures and were set at a point below the sample base in an inappropriate position for the measurement of a suction

COWDEN TEST BED SITE

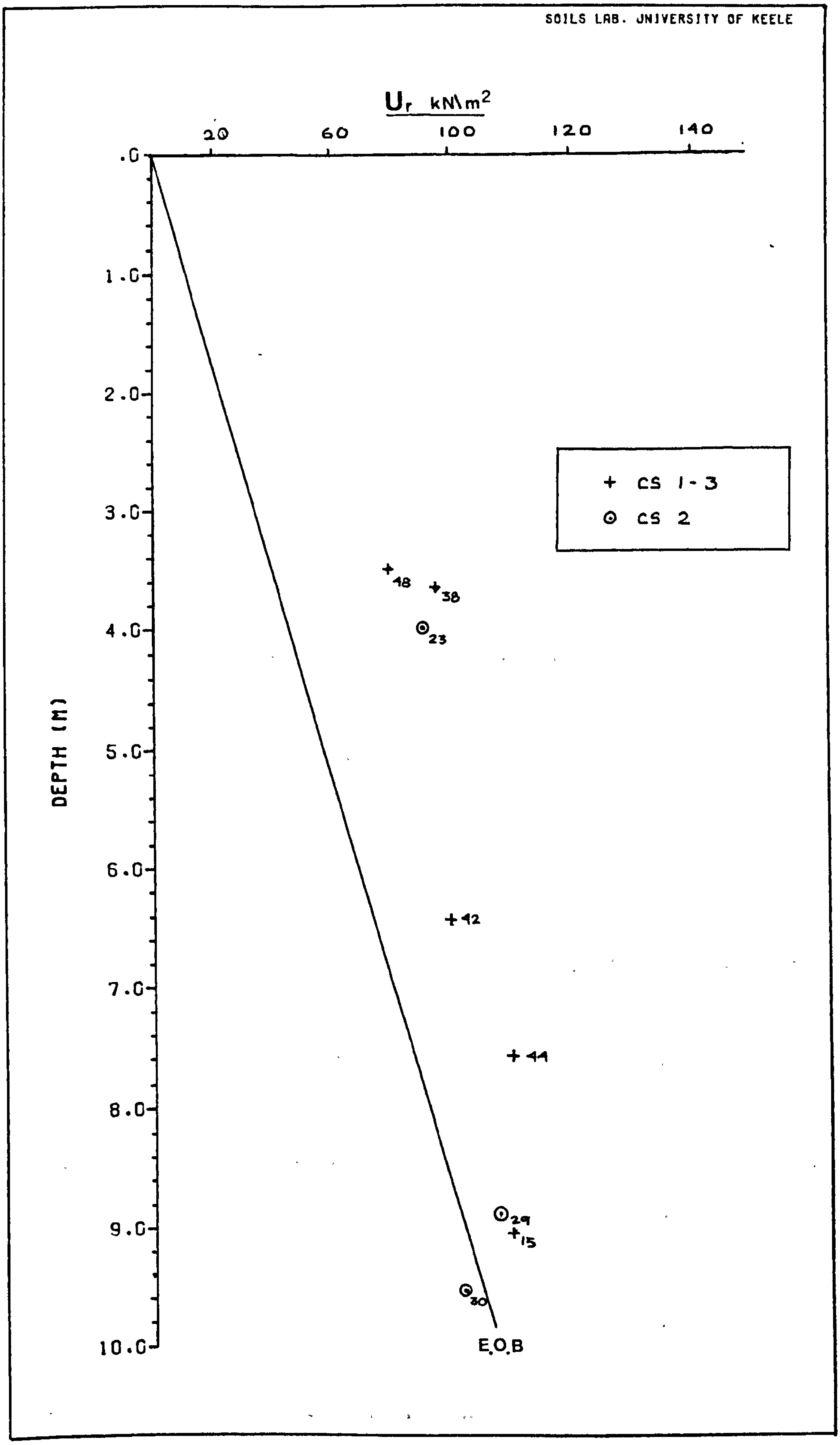


Figure 5.5 Plot of the estimated residual pore pressure (u_r) against depth CS1-3.

force.

(2) Any minor amounts of trapped air in the system would have a critical effect on the precise measurement of suction while becoming less important in a positively calibrated system.

(3) Without any confining stress it is difficult to force an effective connection between the sample pore water system and the porous base.

In relation to the latter point, the increasing effectiveness of the sample base connection may be one control on the increasing values of B with higher confining stress especially in the lower range.

Plotting the estimated residual stress (u_r) with depth shows that although the points fall close to the estimated effective in situ stress, a steeper trend is produced, bisecting the EOB line at approximately 8m in a similar manner to the trend of initial pore pressures (u_i). This effect could be due to the oversimplification caused by the isotropic stress system applied by the triaxial device. Using a more complex model the in situ effective stress acting on a soil unit can be sub-divided into the vertical effective overburden (b'1) and the horizontal effective radial stress (b'r) which are interdependent and linearly proportional.

e5 b'r = Ko b'1

where Ko = the constant of proportionality known as the coefficient of lateral stress at rest which for normally consolidated soils varies between 0.4-0.7 and for overconsolidated soils can be as high as 2.5.

Skempton (1961) showed that the value of Ko can be deduced by comparing the in situ effective overburden with the isotropic

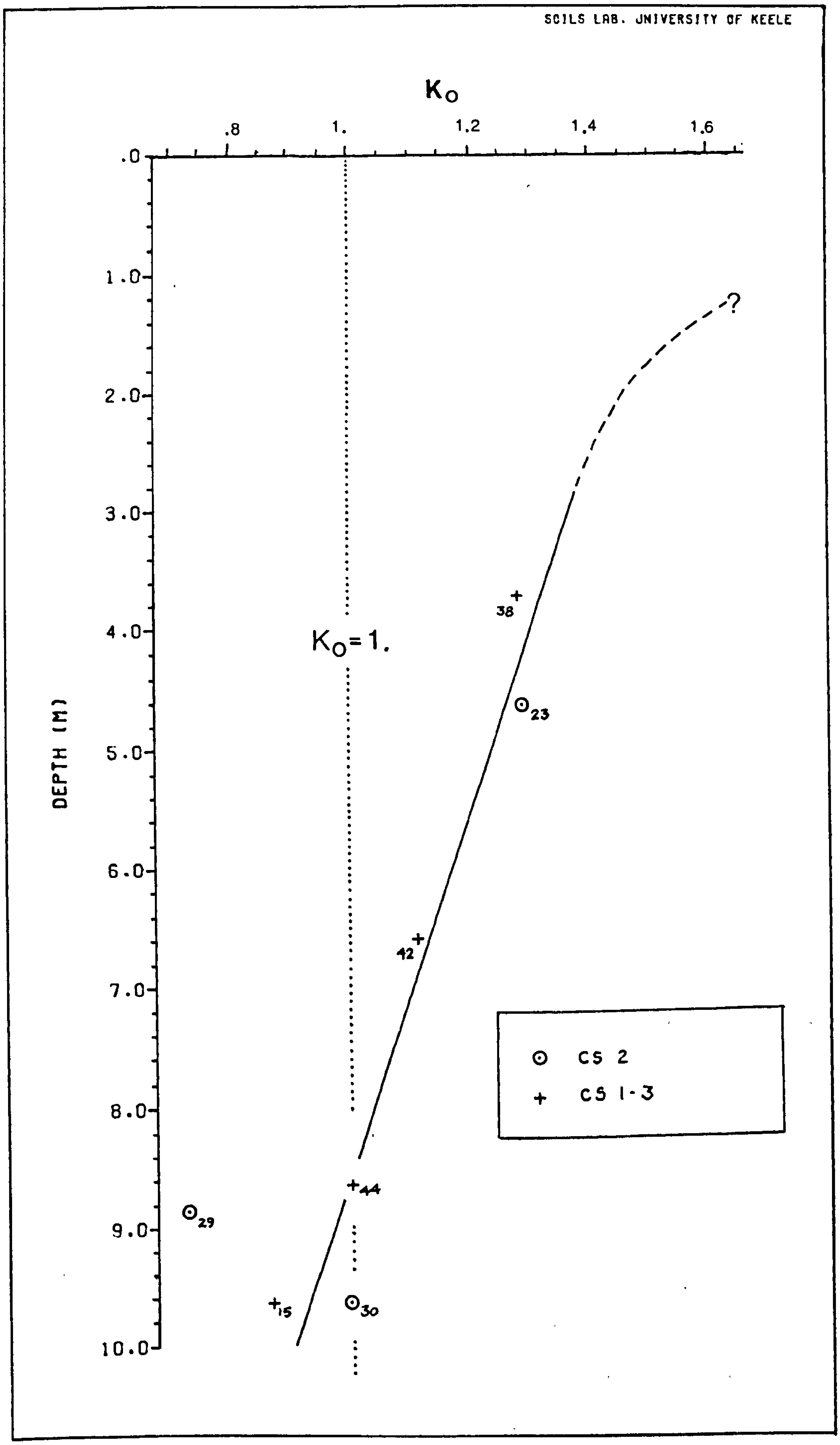


Figure 5.6 Plot of the coefficient of lateral stress at rest (Ko) with depth CS1-3.

effective stress, in this case taken to be equal to u_r. The relationship between the residual stress and the effective in situ stress can be more accurately represented by;

e6 $$-u_r = b'1\ (1 + 2Ko)/3$$

Since u_r and b'1 are known, estimates of Ko can be made (Figure 5.6). Data points from all three boreholes show a consistent trend falling from Ko = 1.3 to 0.9 with depth, similar to the findings of Powell, Marsland and Al Khafagi (1983). A strict interpretation of these results would suggest that the only triaxial specimens consolidated to the true in situ stress conditions (Ko = 1) were those recovered between 7.5 - 9.5m and for all the samples above this zone the radial stresses were underestimated although for the case Ko > 1.0, loading requires specialised testing equipment.

Lambe (1963) has related the dependence of Ko to the stress history and has shown that Ko increases with overconsolidation ratio approaching unity at OCR between 5-6, and rising to values of 1.4-1.7 at OCR of approximately 20.

The observations at Cowden are therefore consistent with a lightly overconsolidated clay with a value of preconsolidation of between 300 and 400 kN/m^2, supporting a highly overconsolidated soil in the upper 2-3m. The fact that subglacial lodgement till can exhibit such low values of OCR has been recorded frequently in published site reports (Vaughan, Lovenbury and Horswill 1975, Radhakrishna and Klym 1974), and has been linked to field observation and theoretical processes of deposition by Boulton and Paul (1976). The under estimation of effective radial stress in the soil above 7m would partially account for the low initial pore

BH CS1 COWDEN TEST BED SITE

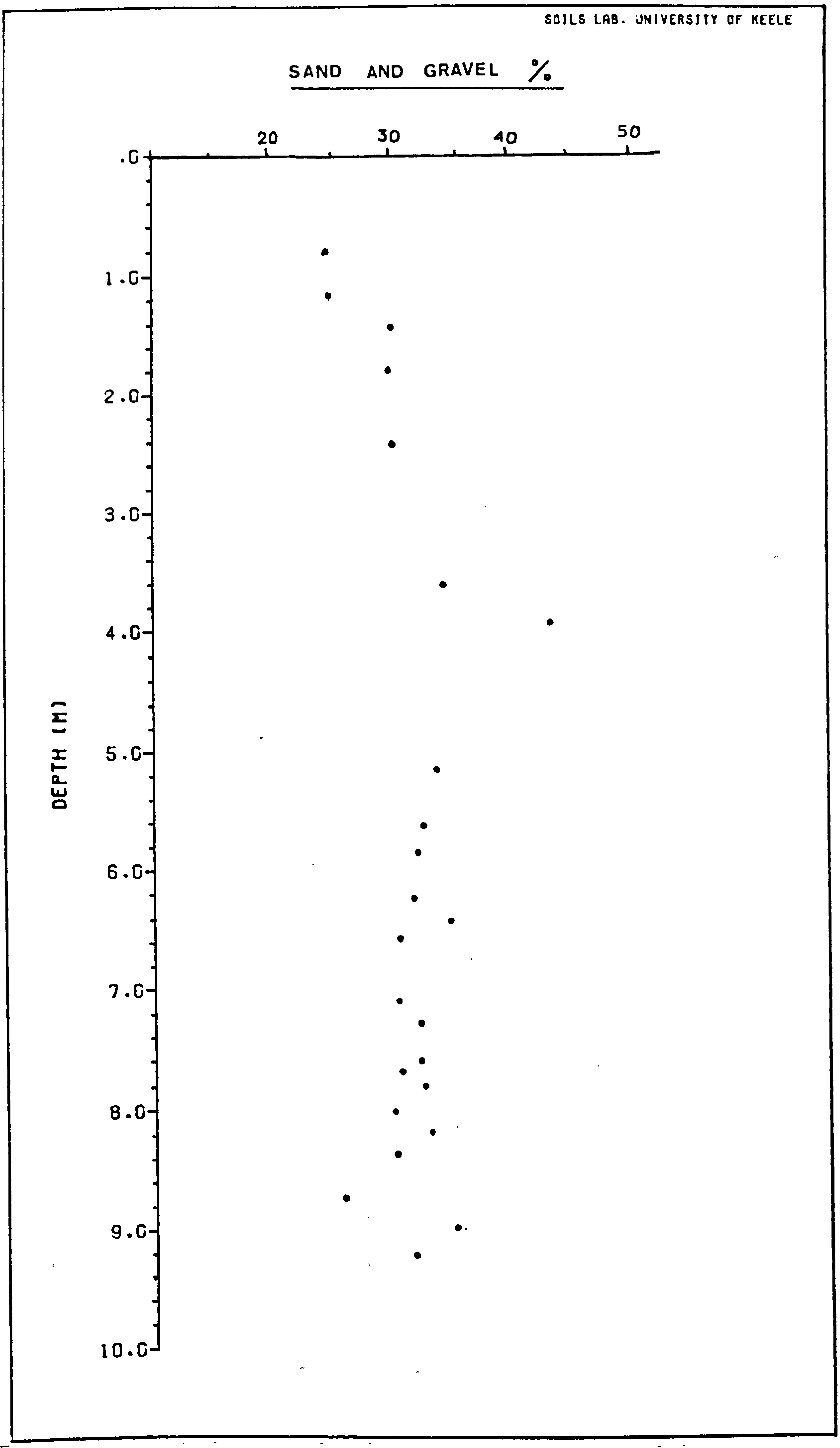


Figure 5.7 % Sand and Gravel / depth CS1

pressures while the converse applies to material recovered below 9m. Minor variations in the B value at lower cell pressures may also be due to the fabric of the till since it has been demonstrated that a close relationship between bulk index properties and the sand/gravel content. In order for Δu to be equal to b3 it is necessary to allow some volume distortion in order that the stress may be transmitted to the fluid phase. With a high percentage of sand and gravel within a densely packed finer matrix it may be possible that at low loads the rigidity does not allow any volume distortion. However, with increasing cell pressures, yielding at the contact points and relative particle movement will cause volume distortion and subsequent pore pressure increase. Since the volume of sand can be shown to be relatively constant in contrast to the gravel the latter is taken as the most important variable. Low values of B coincide with high gravel content at 4.9m and 8.9m (Figure 5.7).

5.4 Undrained Shear Strength (cu).

Data from the testing programme, as outlined in Chapter 3, are presented in Figures 5.8 - 5.10 as the distribution of undrained shear strength (cu) with depth. A summary of the results is given in the table below.

Table 5.1 Undrained shear strength (cu) CS1-3

	CS1	CS2	CS3
Range cu kN/m^2	70-211	92-220	86-22
Mean kN/m^2	123	138	129

where undrained shear strength was defined as ;

e7 $$cu = [b'1 - b'3 / 2] \text{ (peak)}$$

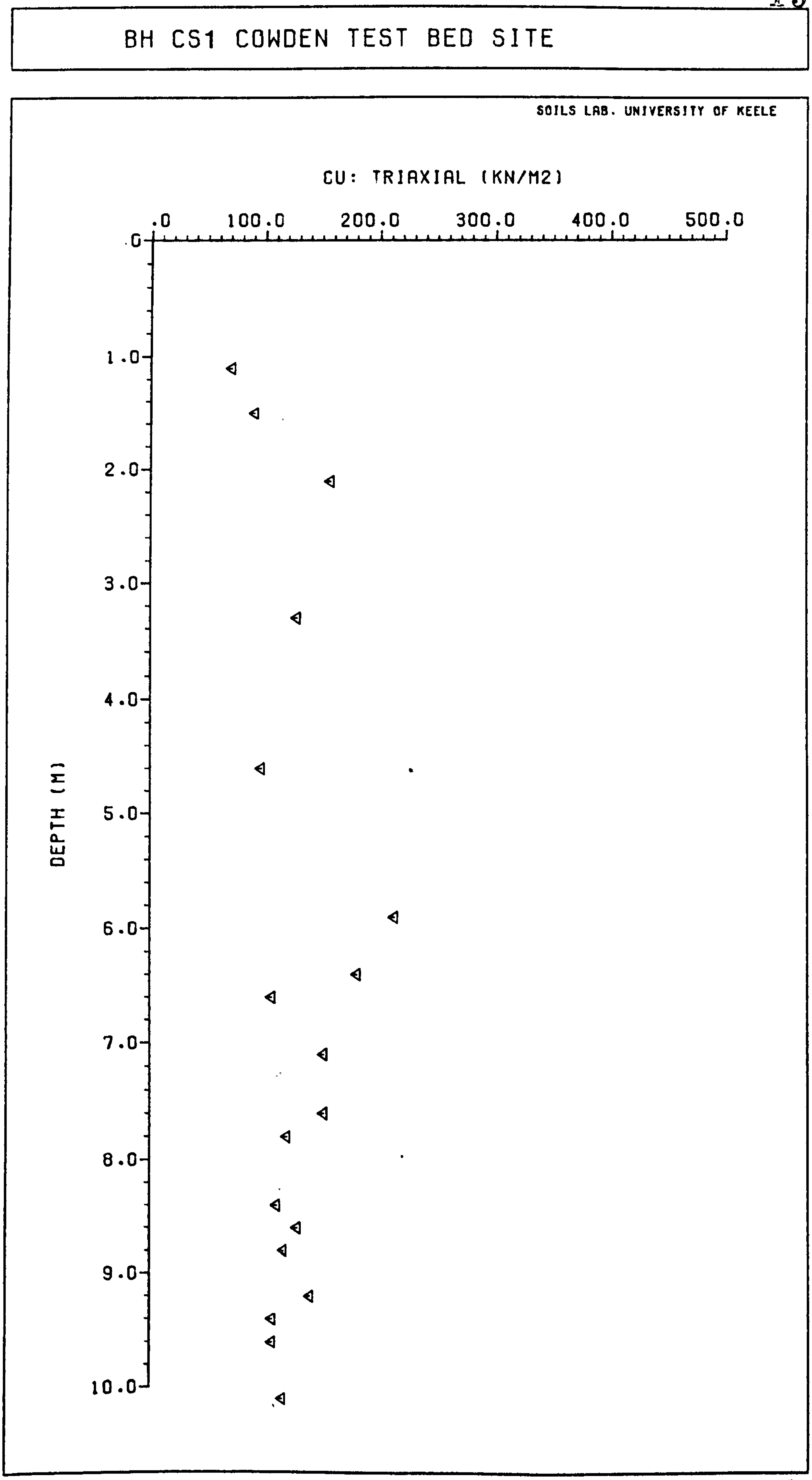


Figure 5.8 Undrained shear strength (cu) / depth CS1

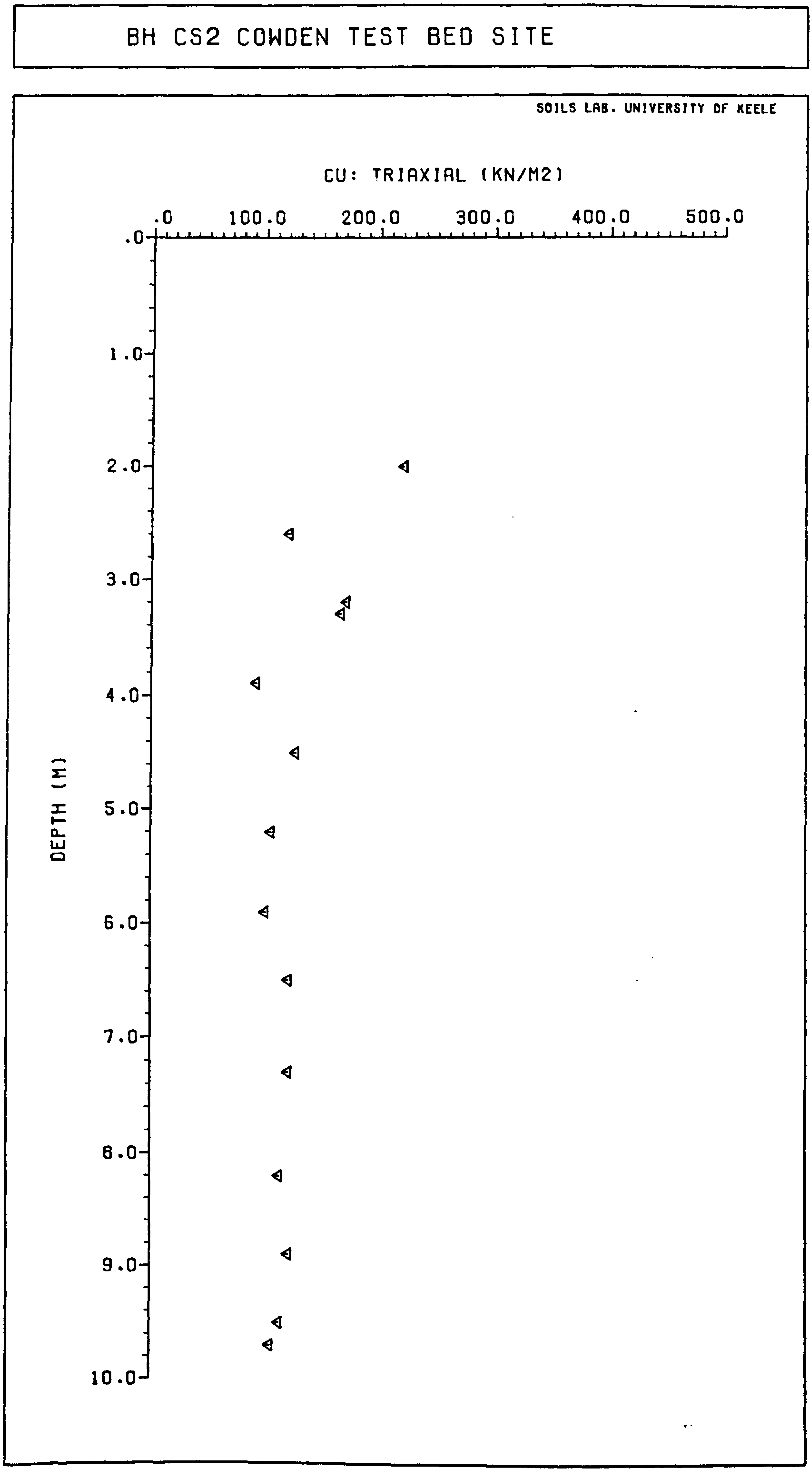


Figure 5.9 Undrained shear strength (cu) / depth CS2

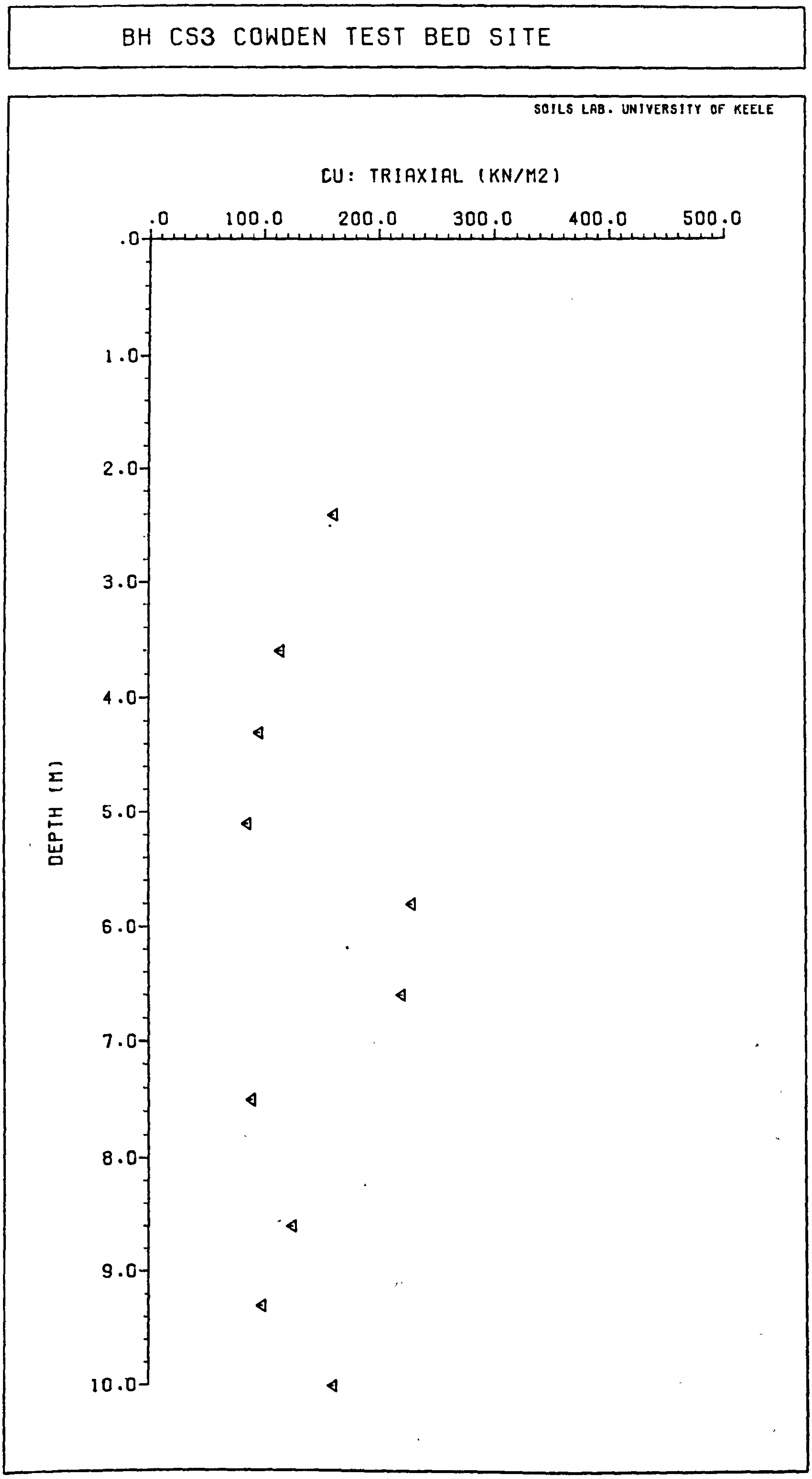


Figure 5.10 Undrained shear strength (cu) / depth CS3

Where the stress-strain curve showed no obvious peak, shear strength was taken at 20% strain to standardize the data. The scatter of results was not so large as frequently experienced in commercial site investigation. This in part reflects the care taken in laboratory procedure and in selecting and preparing material suitable for testing. The results from boreholes CS1 and CS3 show a close correlation with depth about a peak of shear strength at approximately 6.0 m, while all three boreholes exhibit a secondary peak of shear strength at 2.2m, probably related to soil profile development.

The effects of sample preparation and variation in test procedure on the measured strength can best be gauged by comparison of the A and B tests undertaken on material extruded from the same core. Five "paired" tests were carried out in this manner from the unweathered lower profile of borehole CS1. In all but one example the B tests exhibited a notable reduction in strength of approximately 20% when compared to the A test profile. The preparation of samples was identical, each trimmed to a 1:1.5 W/H ratio and tested at calculated total overburden with the sample set between lubricated ends to reduce the effect of end restraint (Taylor 1941). The B tests were subjected to pore-pressure measurement during shear, while the A samples were sheared between solid ends. Measurement of deviator stress in the latter tests utilised the proving ring rather than the internal load cell to release the data logging device to monitor longer term tests. Both the proving ring and load cells were calibrated on the same device. Friction on the loading ram was considered as a source of error, although measurements taken from both the proving ring and load cell during tests proved this function to be within the range of

0.5-1.0% total axial load, and certainly was not significant enough to produce the magnitude of error observed. A high frictional component would tend to produce a standard underestimation in the strength of the material subjected to the A test, exactly the opposite of the observed relationship.

The difference in measured strength is therefore attributed to the speed of the test and the fact that the B tests were fitted with side drains to facilitate the equalisation of pore-pressure during shear. The time to failure (20% strain) was significantly different in the two tests, the A procedure using a gearing producing 0.8% / min (30 min to failure) while the B tests were longer term using a strain rate of 0.05% / min (6.5 hours to failure). The configuration the stress-strain curve is strongly dependent on the development of pore-pressure during shear. In general the lower the pore water response the less the axial load transferred to the soil matrix and the smaller the deviator stress required to produce unit strain up to failure. In a cylindrical test specimen where the rate of loading exceeds the capability of the soil to maintain a state of equilibrium, the induced pore-pressures will tend to reduce considerably the deviator stress increment near the ends of the specimen relative to the value in the middle where the zone of failure develops. The A test response typically shows a reduced stress-strain increment at low stresses compared with the B tests (Figure 5.11). The extent to which equalisation of pore-pressure occurs within the sample depends on the rate of testing, sample dimensions and permeability. In the case of the B tests the side drains and slower rates of loading maintained a pore pressure in equilibrium with external stresses and therefore produced a more representitive stress-strain curve

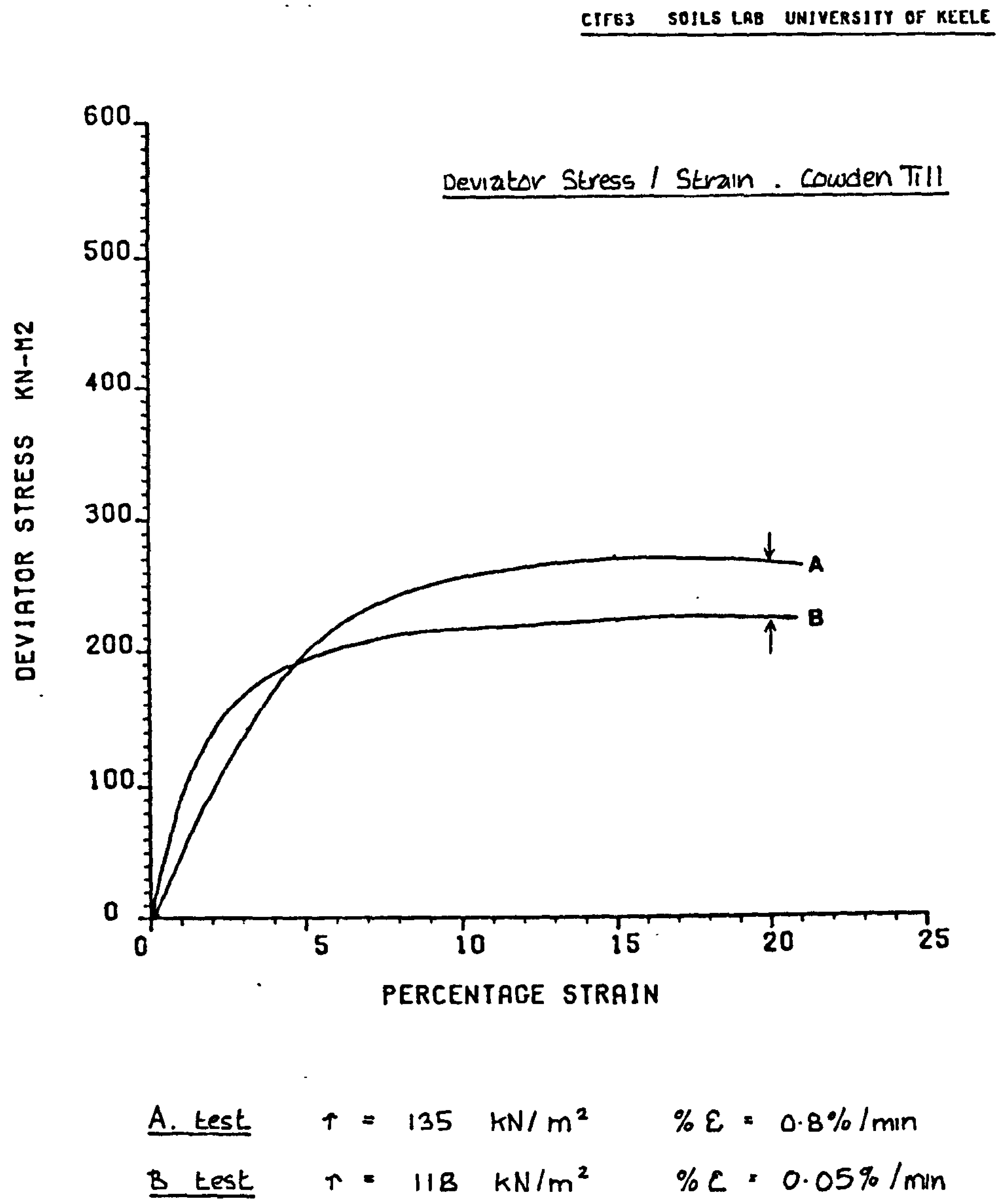


Figure 5.11 Comparison of stress/strain curves for diamict tested at varying rates of strain CS1/12 7.4 - 8.0m

during the initial loading. The relationship between stress and shear strain for the Cowden tills at higher levels of strain is more clearly examined using the pore-pressure coefficient A (Skempton 1954).

5.5 Pore Pressure Coefficient A.

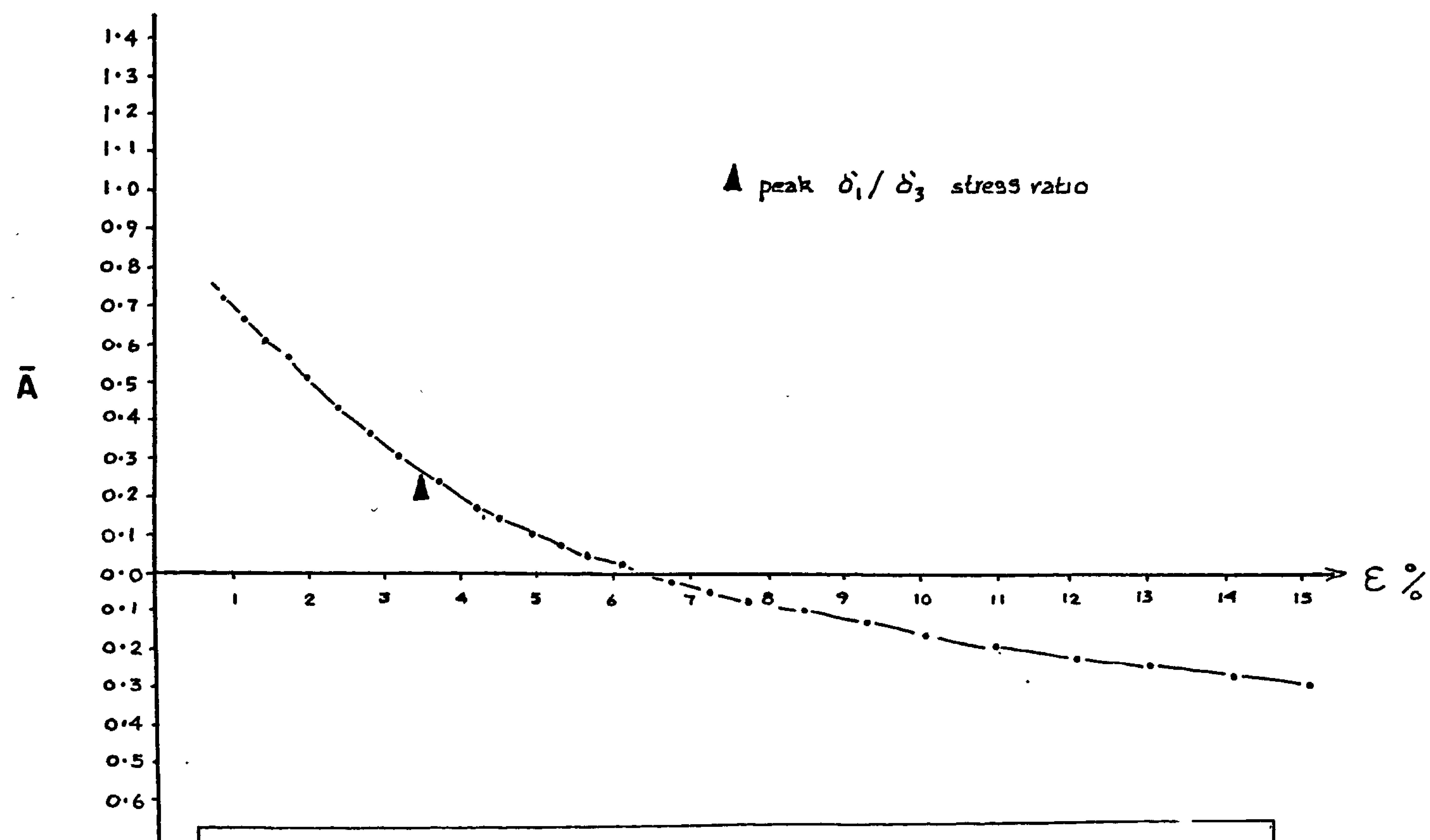
It has been shown through consideration of the in situ stresses and behaviour of the till to increasing isotropic stress that the Cowden till exhibits many of the properties typical of a lightly overconsolidated clay. Such material exhibits a higher strength at a given pressure than would be expected if the sample were normally consolidated and tends to dilate during shear (Smith 1980). In an undrained test where V=0, volumetric expansion is resisted by the development of pore-pressure producing a curve, which in fully saturated soils parallels exactly the drained volumetric response. Figure 5.14 shows a number of pore-pressure - strain curves each showing the typical response of an over-consolidated soil. It is noticeable that in the case of a specimen sheared under low confining stresses, negative pore pressures can be generated in response to sample dilation. The relationship between deviator stress and pore-pressure response during shear can be summarised by the pore-pressure coefficient A(Skempton 1954).

e8 $$A = (\Delta u/ \ b'1- b'3)/B$$

where Δu = change in pore-pressure

B = pore-pressure coefficient

Since the ratio of dilation throughout the test is not constant, A varies with strain (Figure 5.12) and can be defined for any specific stress - strain condition. Data for the Cowden profile has been calculated for maximum deviator stress (A_f). Plotting A_f for the B tests shows a considerable scatter with a



5.12 Variation in A with strain CS1/16 10.4m broad increase with depth. This is the reverse trend of what might be expected if the major controlling variable was overconsolidation ratio. A broad relationship between O.C.R and A_f is given by Skempton (1954) for clays (Table 5.2). These groupings, when applied to the data for Cowden suggest that the profile is heavily overconsolidated (>5 O.C.R), a conclusion which contrasts with the examination of in situ stress conditions and the results presented later for one-dimensional consolidation. Consideration of the data suggests several points which could have led to the over-estimation of A_f from the triaxial tests. First, it has already been noted that in the upper profile (<5m) the samples are placed under a confining pressure less than in situ stress due to the condition Ko >1. The measured pore-pressure response during shear would subsequently be reduced in a direct response to the under estimation of B. Second, in a dilatant soil a possible ambiguity arises with respect to the state of stress denoted by the term "failure". The deviator stress and pore-pressure changes occurring during an undrained test on a sample of lodgement till which dilates during shear is shown in Figures 5.14 - 5.15. With reference to the failure envelope as defined by the stress parameters p' and q it can be seen that values for c' and ϕ' equal to the maximum values are mobilised at a small fraction of the strain required to produce the maximum deviator stress, usually between 2-4%. The increase in deviator stress occurring after this point is almost entirely the consequence of the drop in pore-pressure, for example from A-B (Figure 5.14). The choice of stress circle used to express the result is of importance since c' and ϕ' decrease gradually after reaching their maximum values. For the Cowden till the prolonged drop in pore-pressure during shear results in the value of c' and ϕ' based on maximum deviator stress

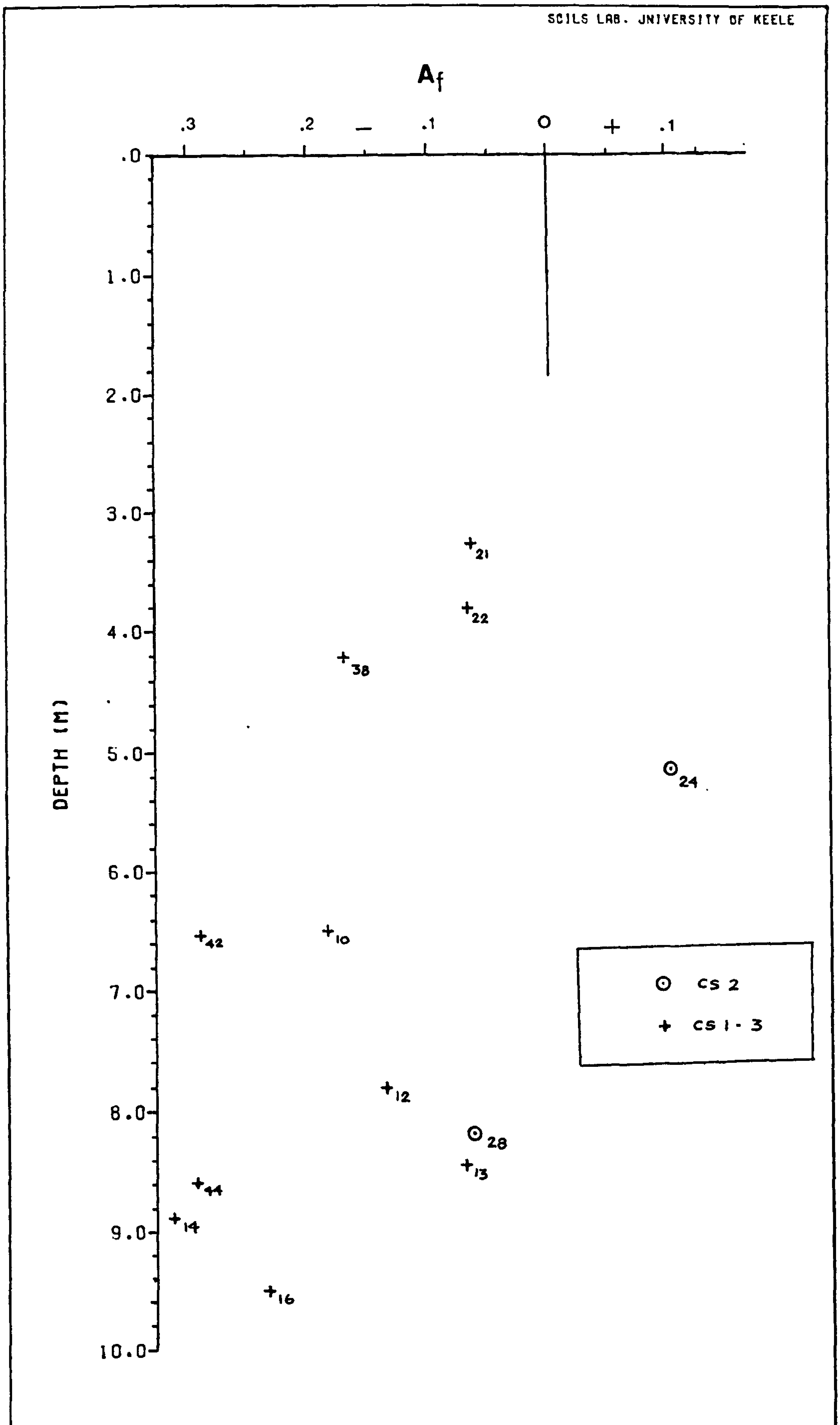


Figure 5.13 Plot of the pore pressure coefficient A_f, calculated at maximum deviator stress, with depth CS1-3.

- Type of Clay -	A_f
Clays of High Sensitivity	0.75 - 1.5
Normally Consolidated Clays	0.5 - 1.0
Lightly Overconsolidated Clays	0.0 - 0.5
Compacted Clay - Gravels	-0.25 - 0.25
Heavy Over-consolidated Clays	-0.5 - 0.0

Table 5.2 Relationship between A_f and OCR Skempton (1954)

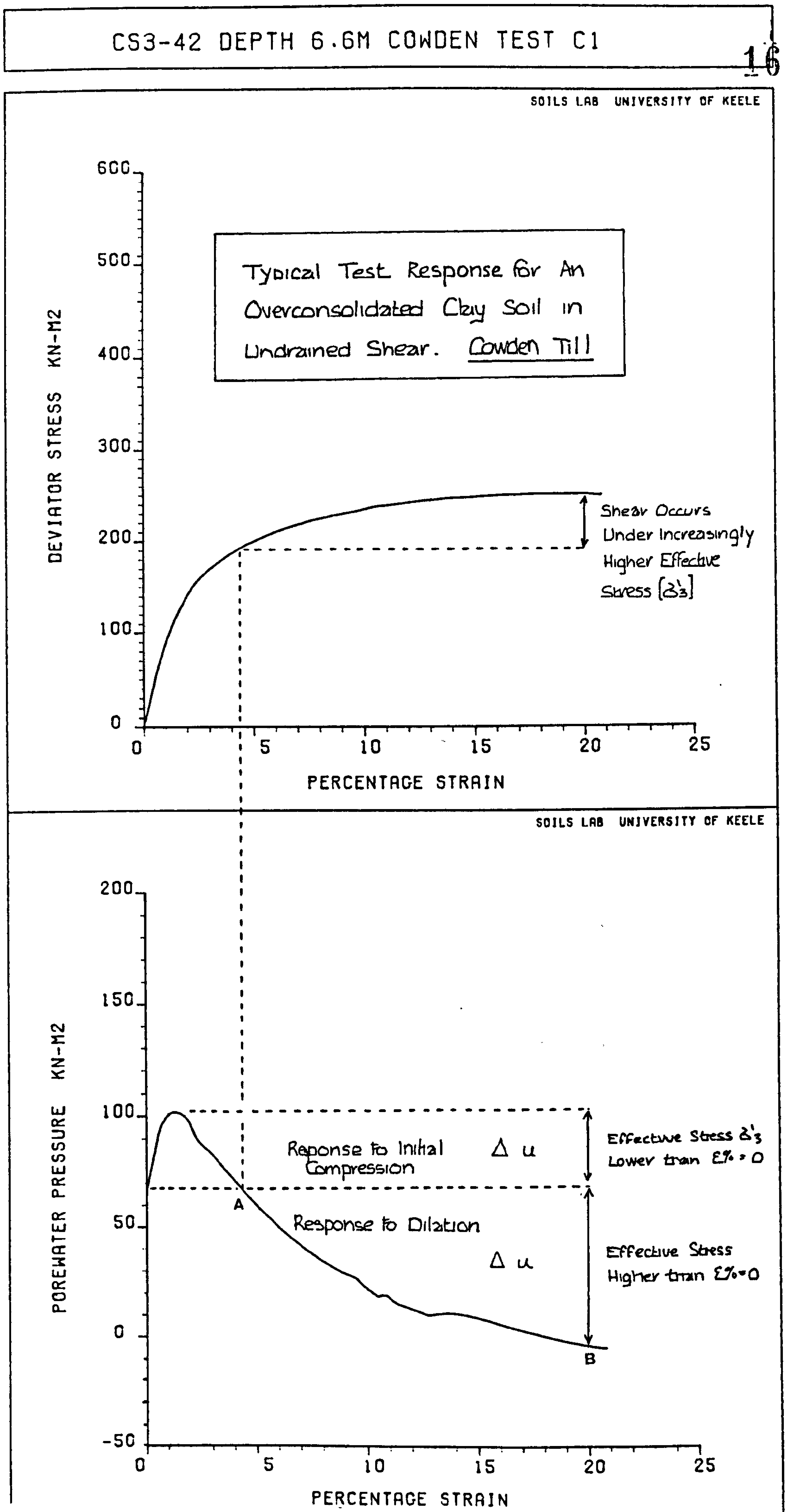


Figure 5.14 Typical test response for an overconsolidated clay soil in undrained shear CS3/42 6.6m

CS3-42 DEPTH 6.6M COWDEN TEST C1

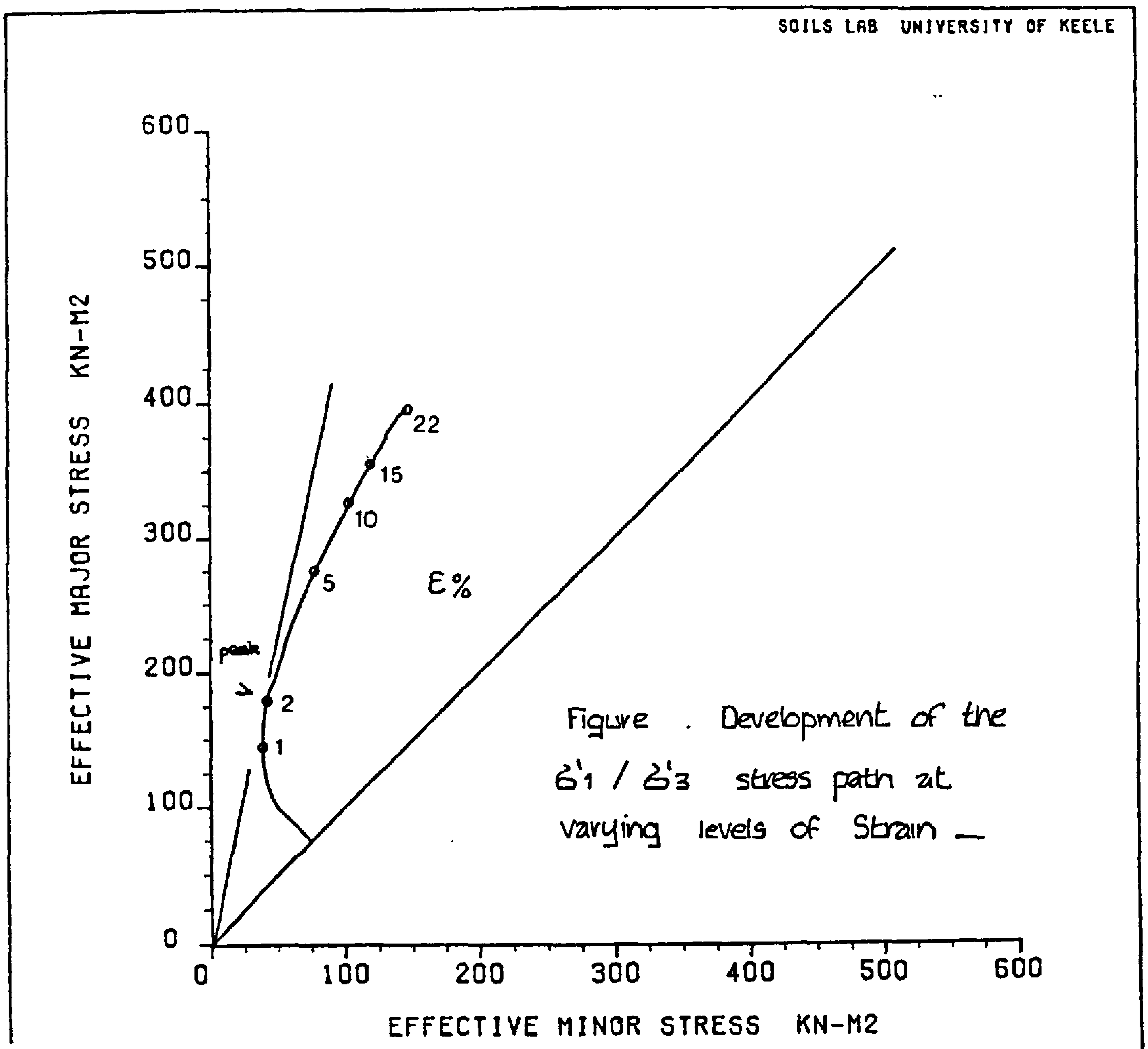
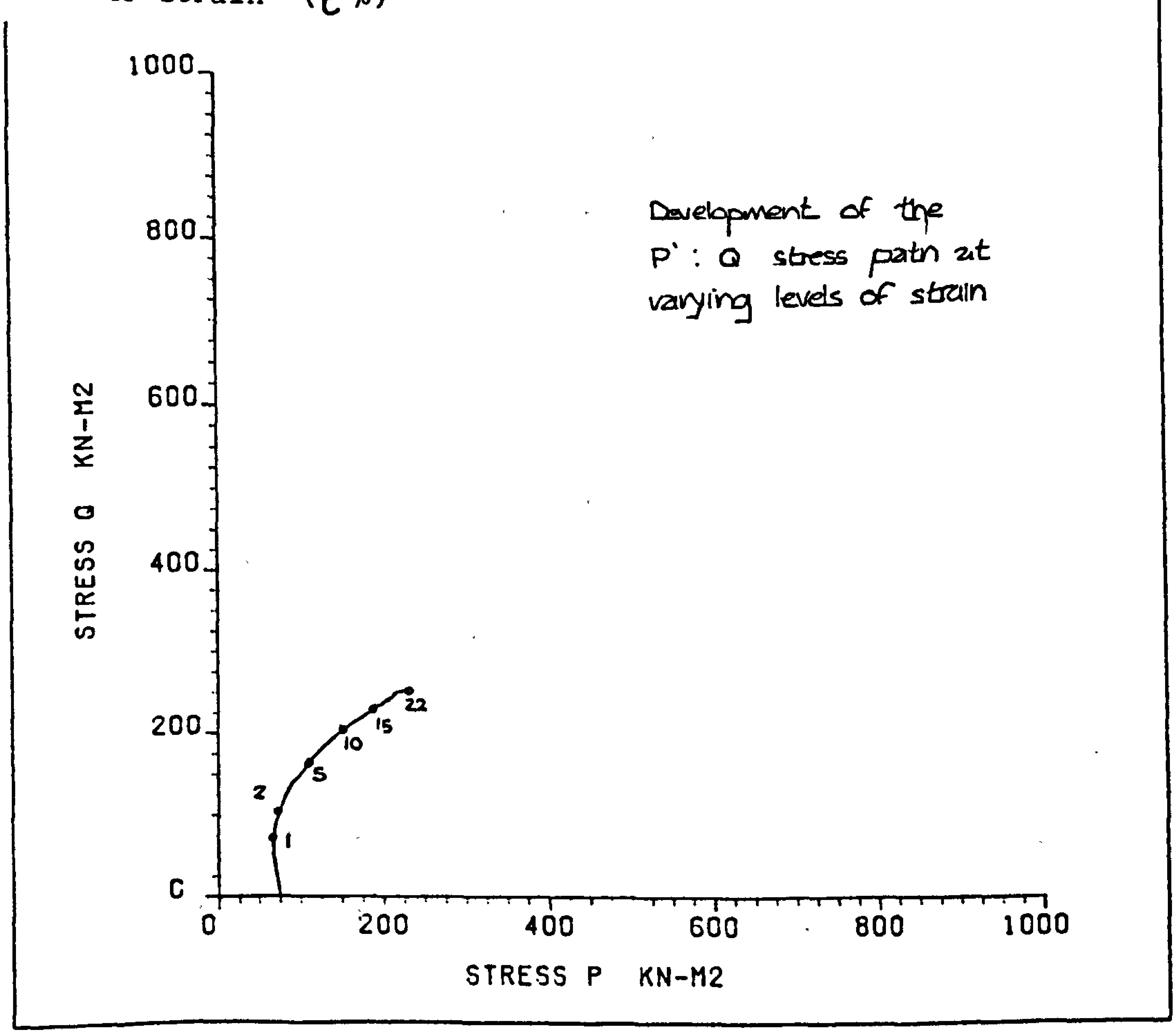


Figure 5.15 Development of the p`, q stress path at varying levels of strain (ε %)



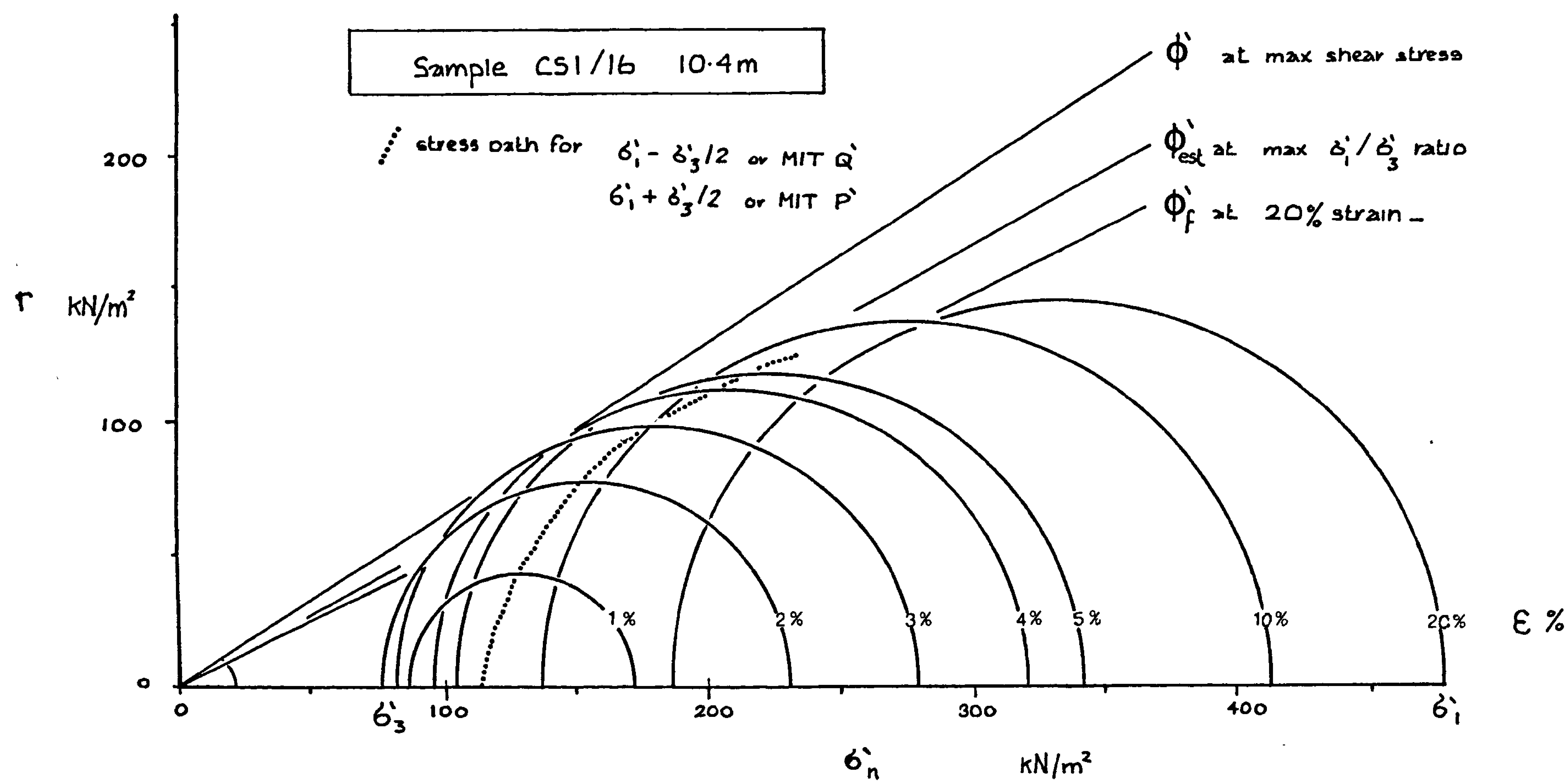
being slightly less than the peak value.

A series of Mohr's circles representing the states of stress at various strains is shown in Figure 5.16. It can be seen that the stress circles greater than 5% project above the failure envelope obtained by the maximum deviator stress at failure. In terms of the A value the degree of dilation will be affected by fabric interlocking controlled by the stress history and the size distribution of the matrix itself, since the larger the grains the wider the zone affected by internal friction. Greater angularity will also lead to higher frictional resistance at higher rates of strain. With reference to Figure 5.7, the variation in A_f with depth can be partially explained by the variation in sand and gravel content which has a peak at 9m matched with a region of higher plasticity at 8m.

Referring back to the variation in test data from the A and B procedures, this can now be explained by the high rates of strain prohibiting particle reorientation thus forcing a greater degree of dilation and correspondingly high values of deviator stress with increasing strain. It is perhaps significant that the difference between the A and B tests increases with increasing sand and gravel content to 9m.

Replotting A_f using b'1 / b'3(max) as the failure criterion produces a relationship more in line with previous tests results. This accurately reflects the lightly overconsolidated profile with the degree of overconsolidation decreasing with depth.

The effect on A of reducing O.C.R was investigated in a Consolidated Undrained test from 8.2 m (CS2/28). Comparison of the calculated values of A showed an increase from 0.2 (b3 = 176kN/m^2)



Variation in the Mohrs stress envelope with strain (ε%)
CS1/16 10.4m

Figure 5.16

COWDEN TEST BED SITE

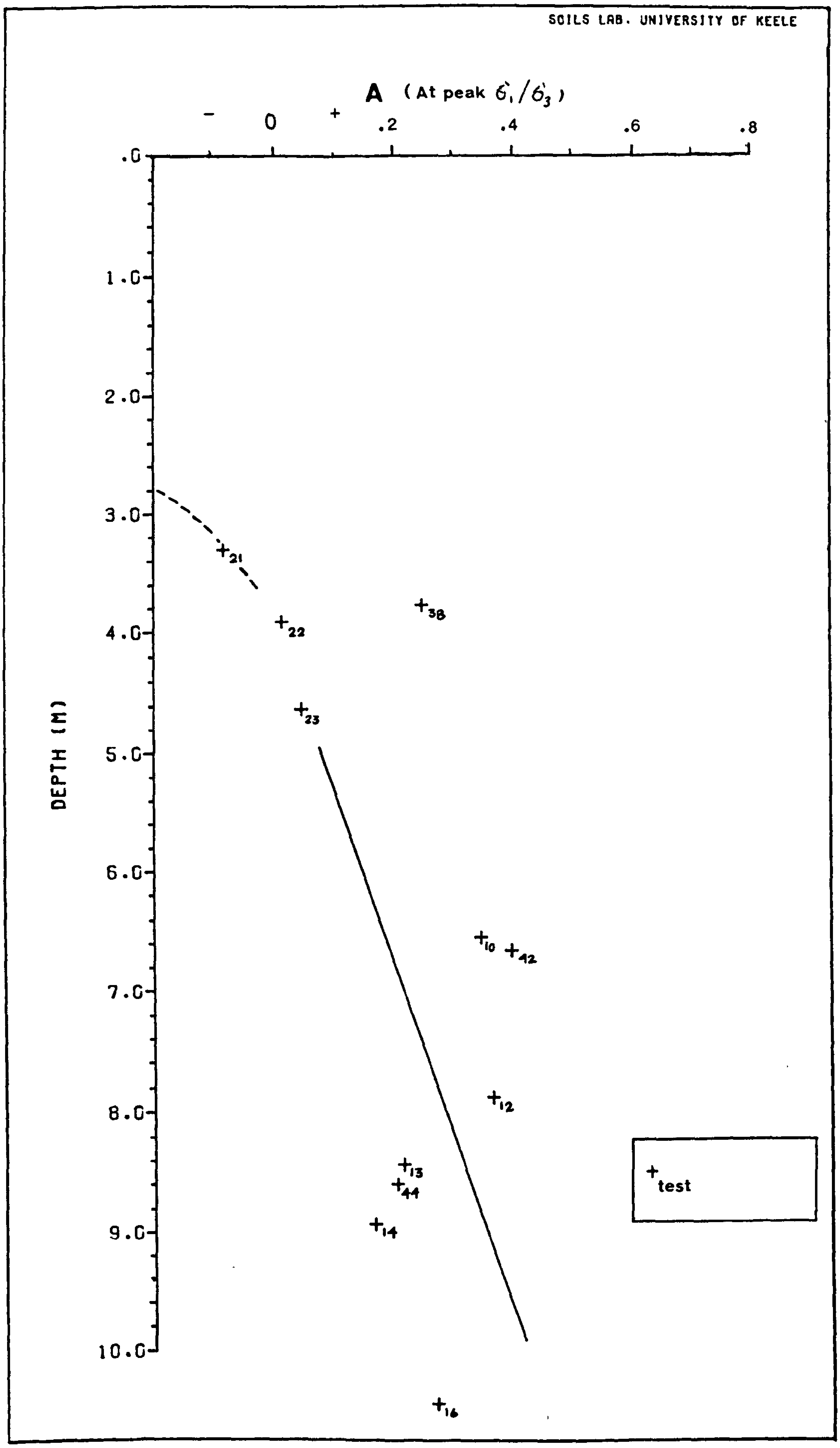
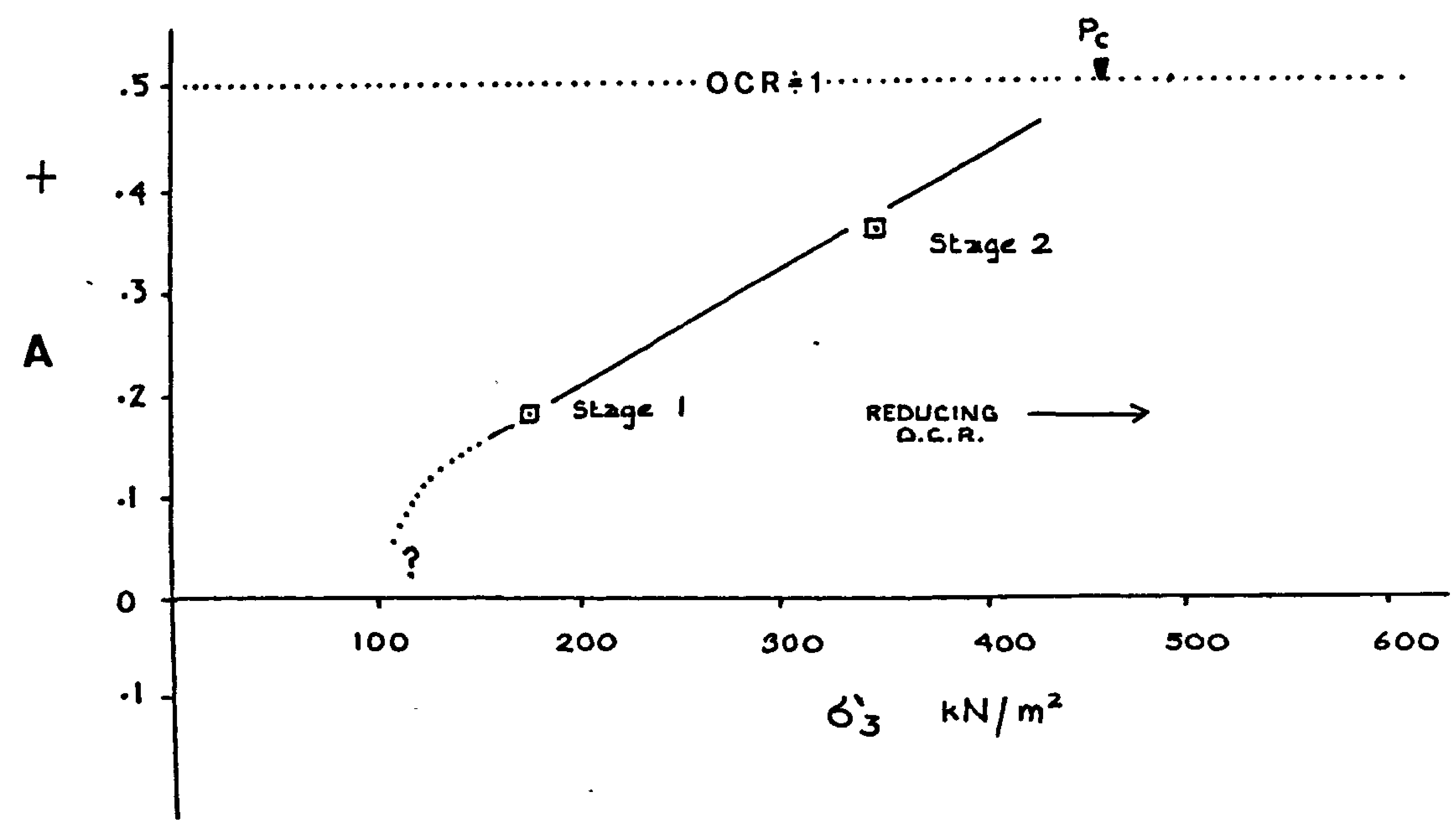


Figure 5.17 Plot of the pore pressure coefficient A calculated at (b'_1 / b'_3) peak, with depth CS1-3.



Calculated values for the pore pressure coefficient A at varying levels of consolidation CS2/32.

Figure 5.18

to 0.35 (b3 = 352kN/m^2), in line with the reduction in O.C.R caused by the reconsolidation of the specimen. Plotting these values against b3 shows that, if the relationship remains linear, a condition approaching 0.5 A, typical of a normally consolidated clay would be achieved at cell pressures between 400-450kN/m^2. This prediction was not tested since the combination of high cell pressures and correspondingly high deviator stresses required to produce shear (>700 kN/m^2) would have been close to the limits of the machinery employed using 98mm diameter specimens. The estimation of pc using this method shows a reasonable agreement with that obtained by one dimensional consolidation. Figure 5.31 shows a e/log p curve for CS2/27 (7.5m) which produced a slightly lower value for pc, depending on the construction employed, of between 300-325kN/m^2.

5.6 Apparent Cohesion with $\phi_u = 0$

The behaviour of the till under increased total stress allowing no drainage was examined using a single sample from 6.5m (CS2/26). Under such conditions applying a cell pressure b3 induces an increase in pore-pressure equal to:

e9 u = B b3

If the soil is saturated (B=1) then u = b3, and the change in effective stress is zero. As a consequence no matter what value of cell pressure is applied the effective stress should remain unchanged.

When taken to failure the compressive strength will be independent of cell pressure, the soil acting as a purely cohesive material with $\phi_u = 0$. Undrained strength is given by cu with $\phi_u = 0$, providing there is no change in water content. The test was

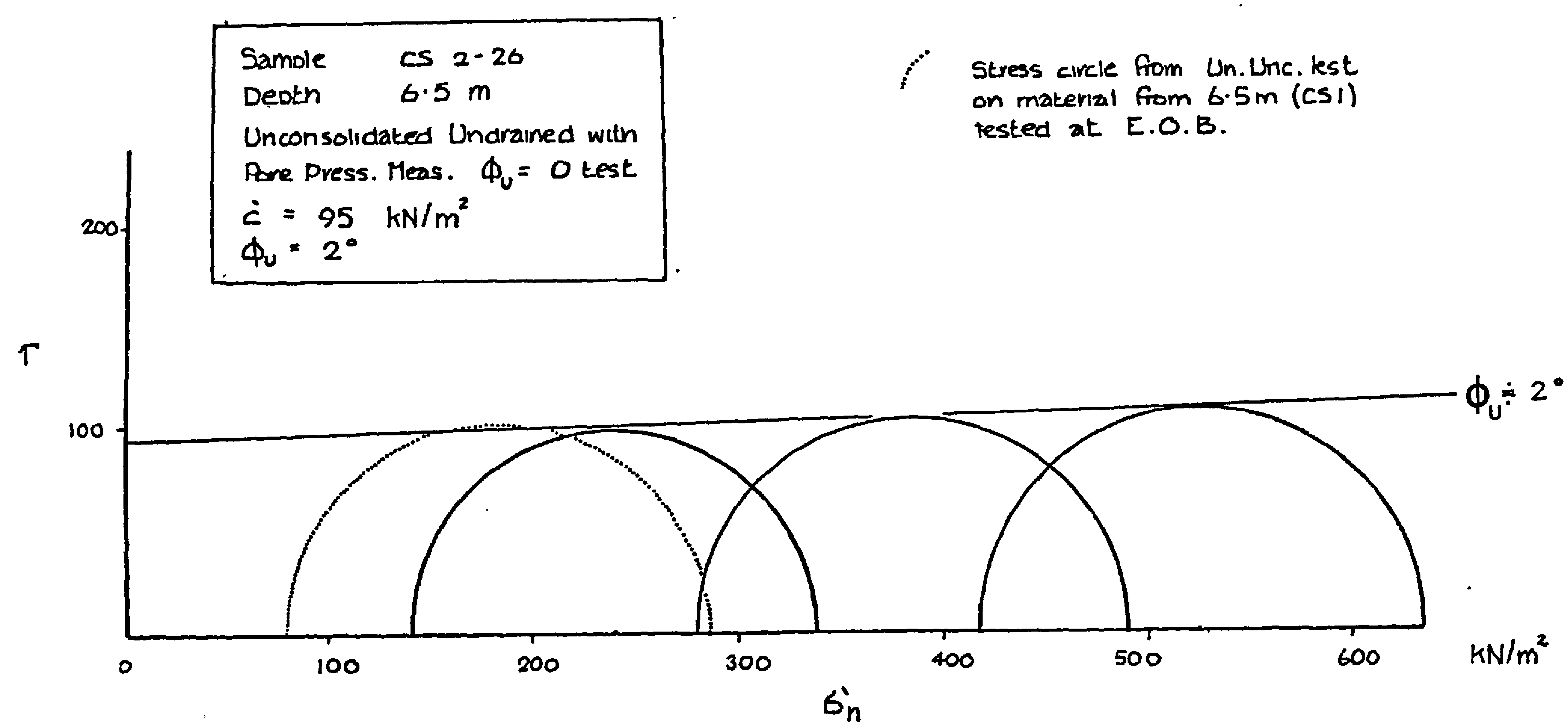


Fig 5.19 Mohr's stress envelope for ϕ_u = 0 test
CS2/26 6.5m

carried out using a multistage technique (Taylor 1951) where failure was taken as b'1/b'3 (peak). The sample was then allowed to equilibriate under a higher confining stress, increased in units of total overburden, and sheared again. It has already been shown that using this method a good approximation of ϕ'_f can be achieved at low levels of strain. Since the same failure criterion was applied to all three stages the effect on ϕ', measured at constant effective stress, should be minimal. The benefit of this approach is that constant moisture content is maintained and the problem of varying index properties between samples is negated.

Figure 5.19 shows the Mohr's envelope for CS2/26 along with the stress circles from material recovered from a similar depth tested at effective overburden. The condition $\phi_u = 0$ was found to exist with ϕ_u calculated between 1-2^o , findings similar to results on saturated clays obtained by Golder and Skempton (1948). The value of cu at b'1/b'3 (maximum) was taken to be equal to 95kN/m^2.

Several other points can be noted from the test. First, there was no measurable decrease in ϕ_u at low cell pressures typical of soils which are undersaturated. Second, the consistent response is unlike that recorded for overconsolidated clays with a well developed macrofabric such as fissured London clay (Bishop and Henkel 1957) which shows a reduction in cu at confining stresses less than the in situ overburden pressure.

5.7 Effective Cohesion (c') and the Angle Of Internal Friction (ϕ').

The component of shear strength

attributable to frictional resistance is not a constant value but varies with the degree of applied normal stress on the shear plane. The strength envelope of a soil may be expressed by the equation;

e10 $T = c + b_n \tan \phi$ .....(Coulomb's equation.)

where T = shear stress at failure

c = cohesion

b_n = normal stress on failure plane

ϕ = angle of internal friction

The $\phi_u = 0$ test proves that cu is independent of total stress in a saturated soil and an increase in strength can only be achieved by a change in effective stress leading to a change in volume. When a load is applied to a saturated soil it is carried initially by the pore fluid (pore-pressure) until drainage transmits the load to the soil matrix. For practical purposes the effective stress can be taken as;

e11 $b'_n = b_n - u$

where b'_n = effective normal stress on the failure plane

b_n = total normal stress on the failure plane

u = pore-pressure

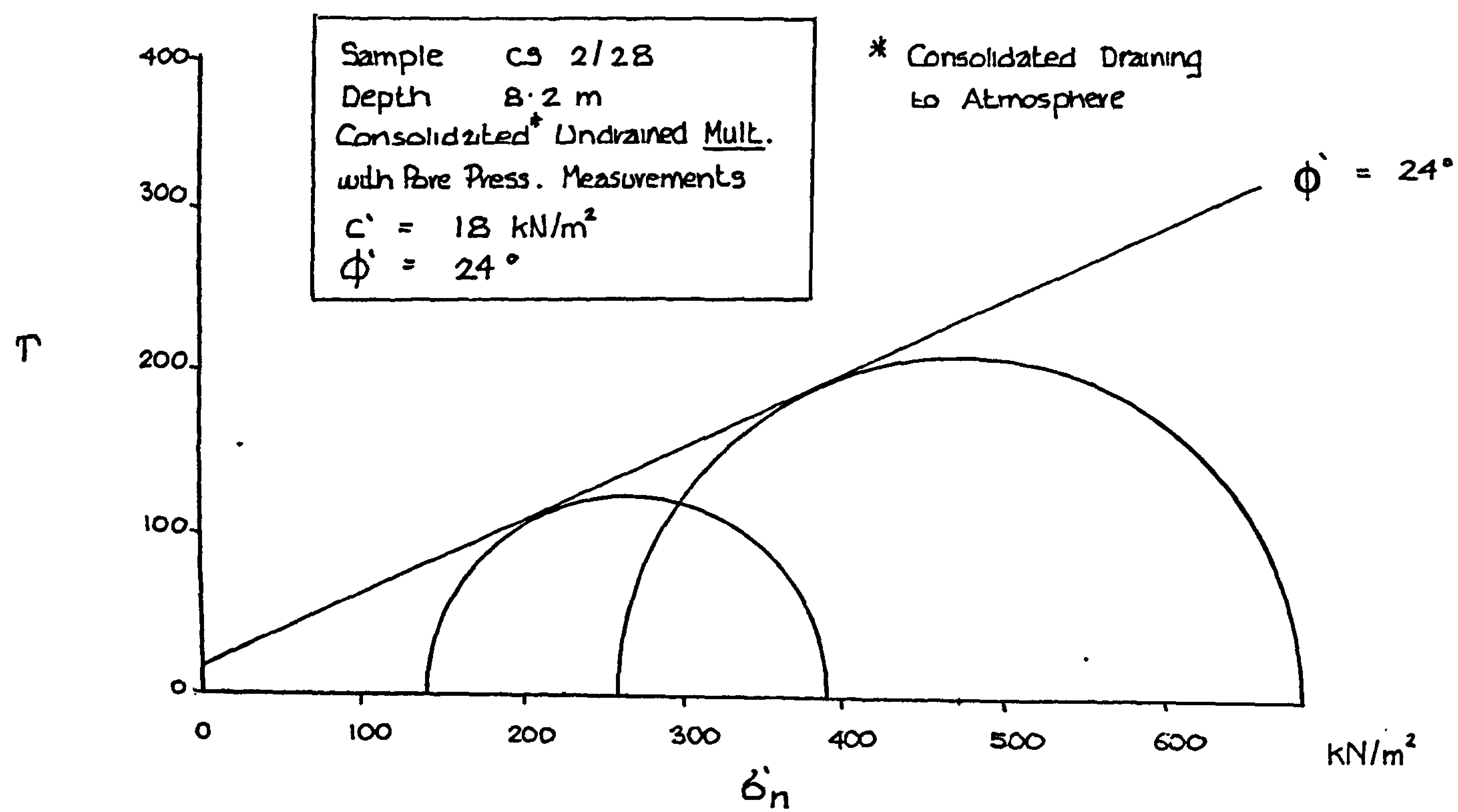
Coulomb's equation can therefore be modified in terms of effective stress;

e12 $T = c' + b'_n \tan \phi'$

where c' = cohesion with respect to effective stress

ϕ' = angle of internal friction with respect to effective stress

These parameters were examined in consolidated undrained tests outlined in Chapter 3, using the multistage technique with



Mohr's envelope CS 2/28 (8.2m)

Figure 5.20

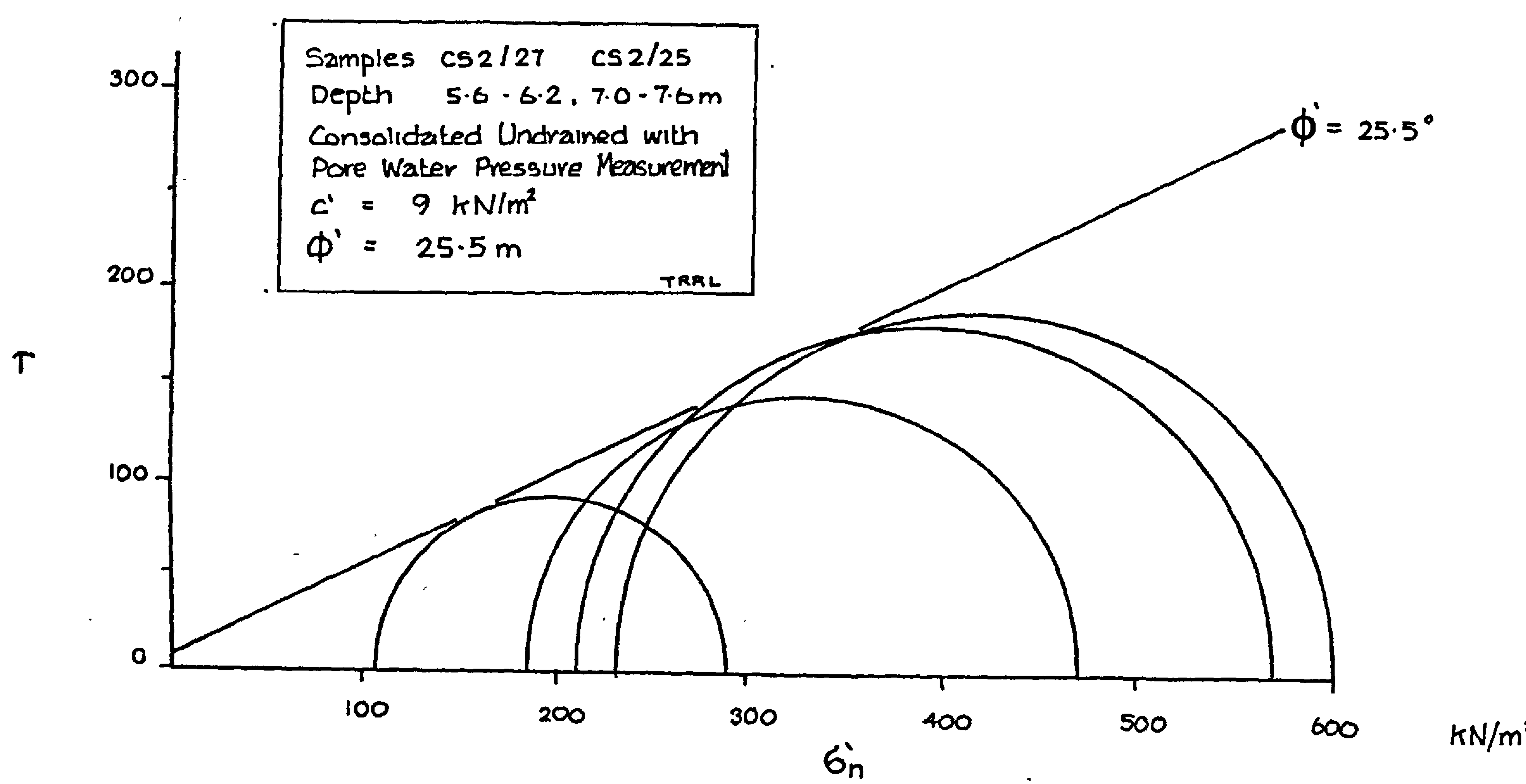
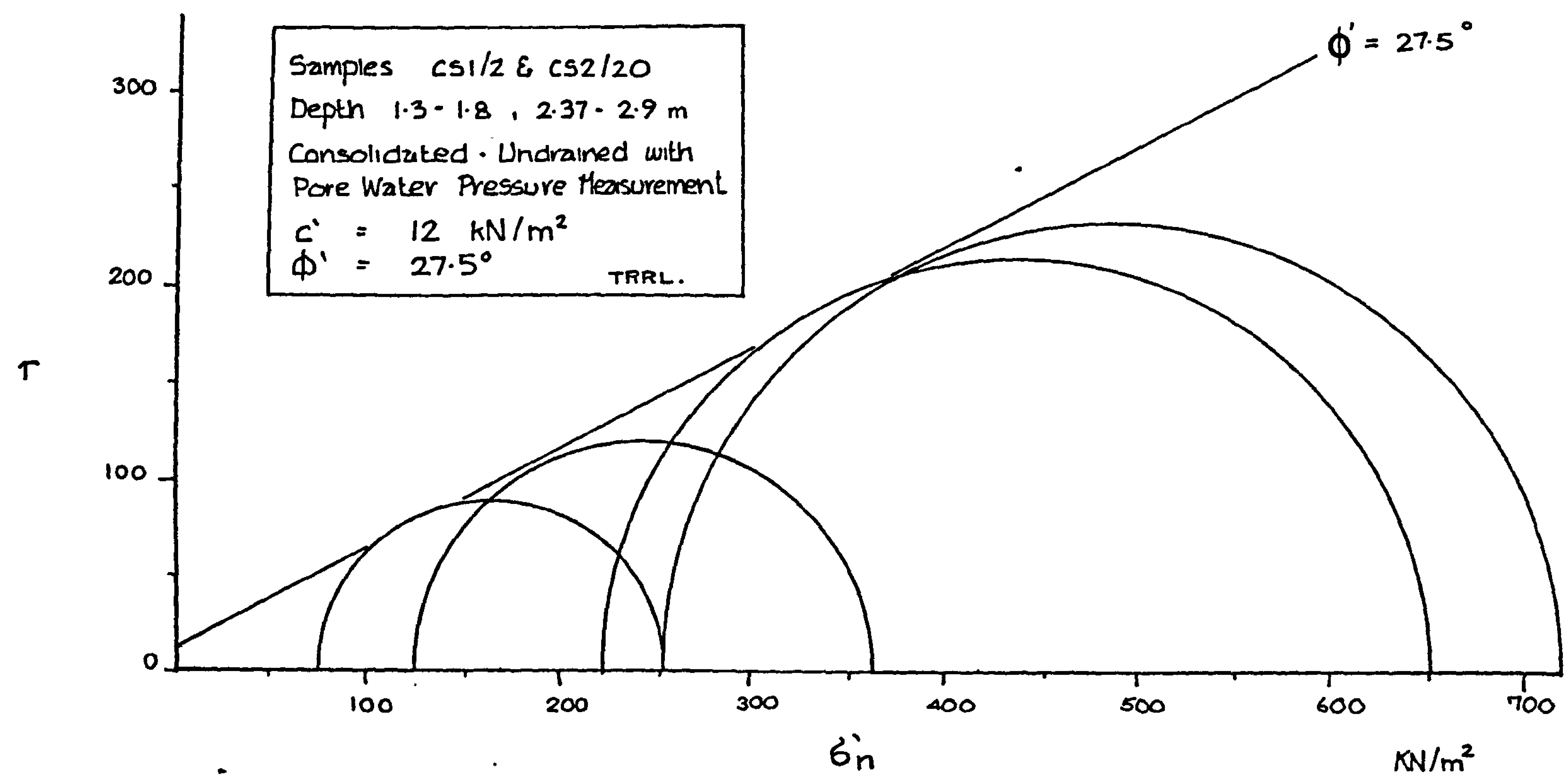


Figure 5.21 Mohr's envelope CS 2/25-27



Mohr's envelope CS1/2 (1.5m), CS2/20 (2.7m) Figure 5.22

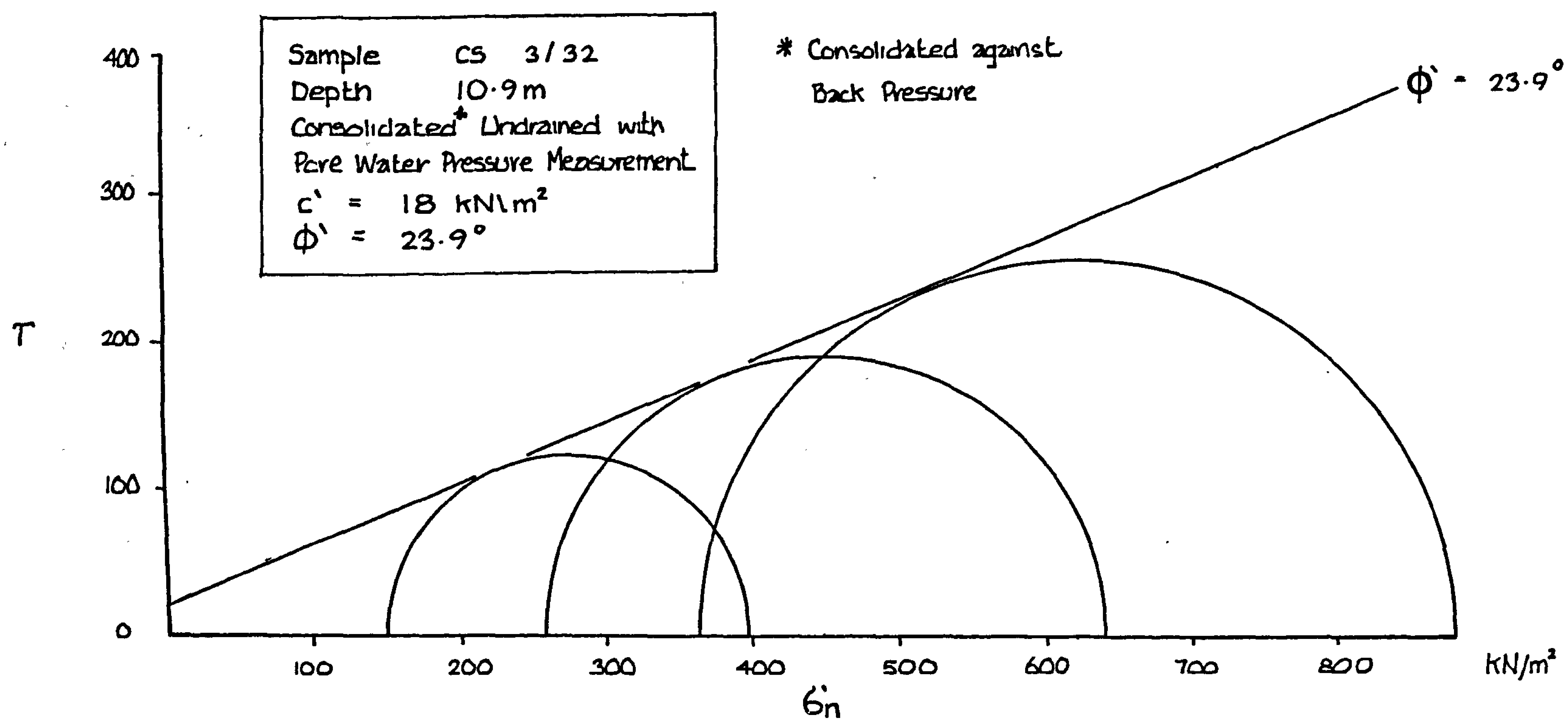


Figure 5.23 Mohr's envelope CS3/32 (10.9m)

failure taken at b'1/b'3 maximum. The results from both tests are given in Figures 5.20 - 5.23 and Table 5.3 along with data from standard consolidated undrained tests carried out at TRRL and kindly supplied for comparative purposes.

Sample	Depth (m)	ϕ'	c'
CS 2/28	8.2	24.0	15
CS 2/32	10.9	23.9	18
CS 1/12	1.5	TRRL	
CS 2/20	2.5	27.5	12
CS 2/25	5.8	TRRL	
CS 2/27	7.3	25.5	9

TABLE 5.3 Values for ϕ' and c' (Cowden)

Estimates of ϕ' were made using the B tests results and the method outlined by Holtz (1947). With reference to Figure 5.16 it can been that although ϕ' varies with strain a good approximation of the final failure envelope ϕ'_f can be formed by a line from the origin passing through the point defined by the maximum stress ratio b'1/b'3. At this point an estimation of ϕ' is given as;

e 13 $$\tan \phi'_{est} = \left[\frac{b'1 - b'3\ /\ 2}{b'1 + b'3\ /\ 2}\right]_{max} = \left[\frac{MIT\ Q}{MIT\ P}\right]_{max}$$

The assumption c' = 0 leads to an overestimation of ϕ' in the range 2-3^{o} although the variation in the angle of internal friction should be accurately represented.

The shear strength envelope of a normally consolidated soil when plotted in terms of effective stress is a straight line passing through the origin (c' = 0). When a overconsolidated soil is taken to failure a curved envelope is obtained which, for the range of stress under consideration, can be taken to equal a

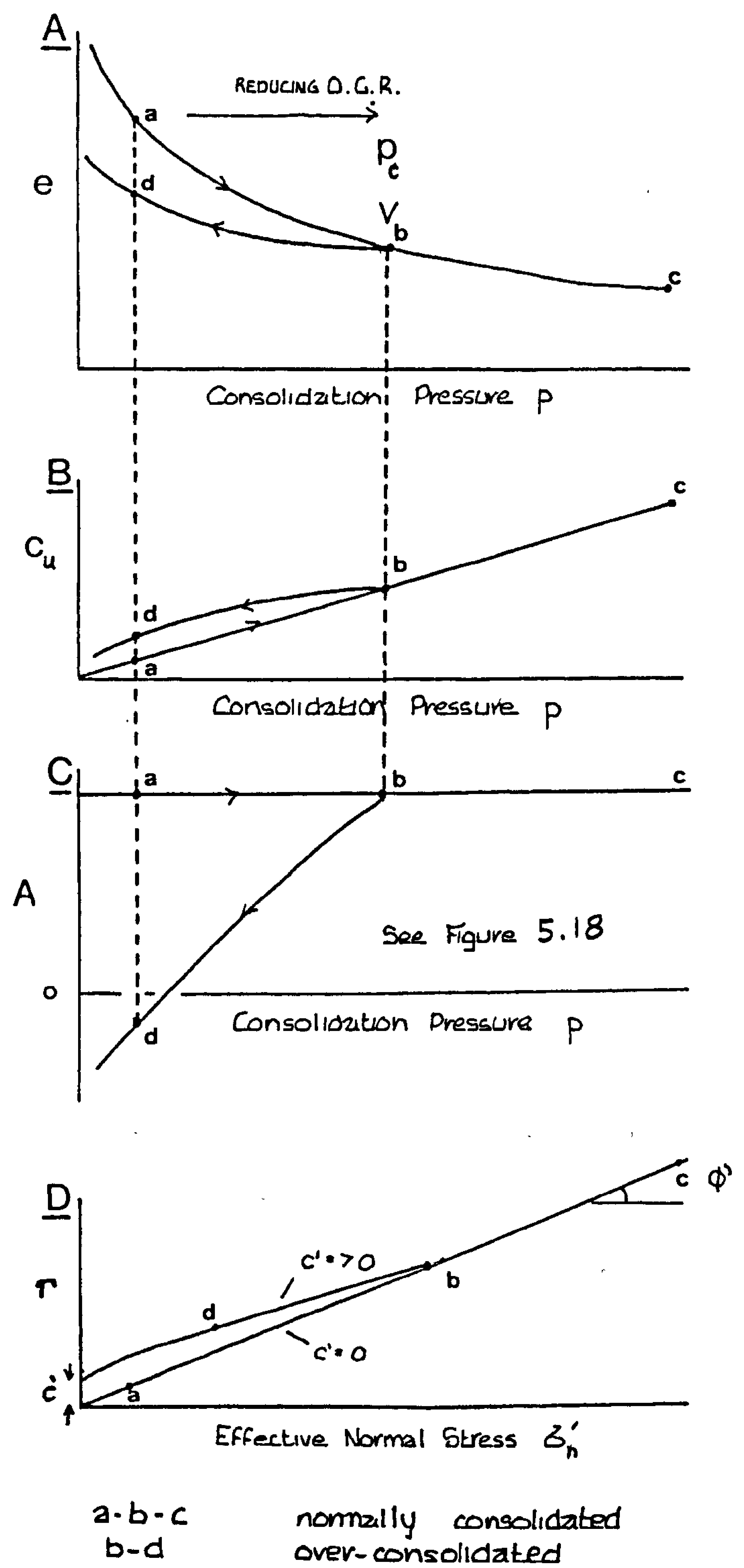


Figure 5.24 Inter-relationship between the soil parameters A, ϕ` and c` in an overconsolidated and normally consolidated soil (after Bishop and Henkel 1962).

after Bishop & Henkel 1962 pp 17

straight line with a cohesion intercept c' and slope ϕ'. With such soils Skempton and Bishop (1950) have shown that the value of c' and ultimately ϕ' is a function of consolidation pressure at test. Figure 5.24 shows that for consolidation pressures approaching the pre-consolidation stress ϕ' decreases as the curve d-h tends to the c' = 0 line. Conversely the value of c' increases with the higher range of consolidating pressures until the point pc is reached. The higher shear strengths responsible for the cohesive intercept in overconsolidated soils are a result of the dilation on shear in a manner examined in a previous section. Although A is affected by other factors such as the rate of strain and plasticity index a broad negative correlation was obtained between A and ϕ' for the Cowden profile (Figure 5.25).

Considering a simple model where the soil has been subjected to a constant pre-consolidation stress and then allowed to move to the present in situ stress condition, a trend of decreasing ϕ' and increasing c' with depth would be expected in line with the reducing overconsolidation ratio. The limited data set for the ϕ' tests shows this to be the case although the ϕ'_{est} profile suggests a spread of results with some variations between 6.0-7.0m (Figure 5.26). The data for c', although again limited, does reflect a constant increase with depth as predicted in the Skempton and Bishop model. The high values at 1.5m probably a function of carbonate redeposition within the silt clay matrix creating a stronger bonding unrelated to the stress history of the deposit. This is also reflected in the brittle fracture common at this depth in all three boreholes.

Comparison of data from the consolidated undrained tests CS2/28 and CS2/32 was used to examine the relationship between void

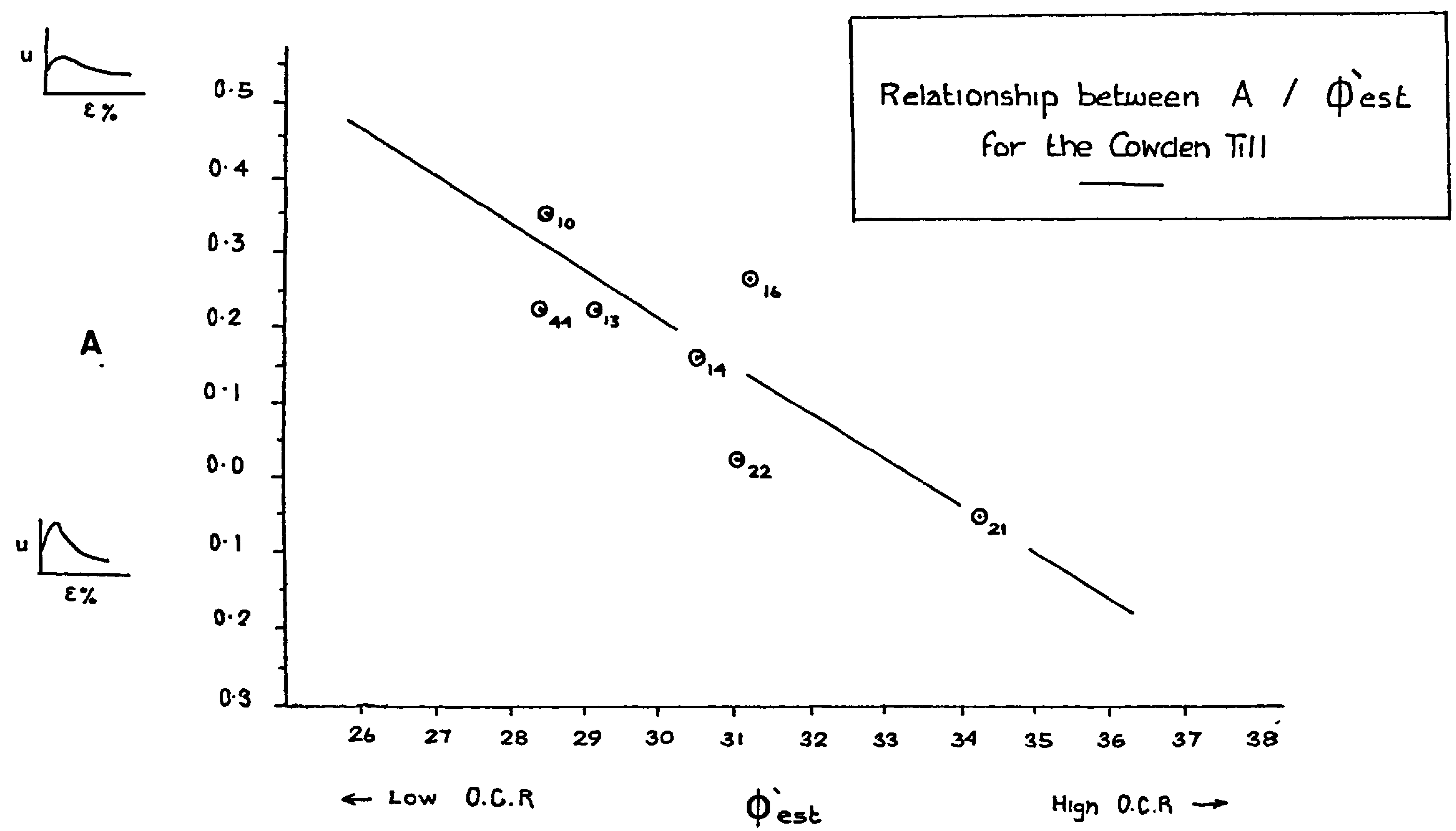


Figure 5.25 Relationship between A and ϕ'_{est} for the Cowden diamicts

COWDEN TEST BED SITE

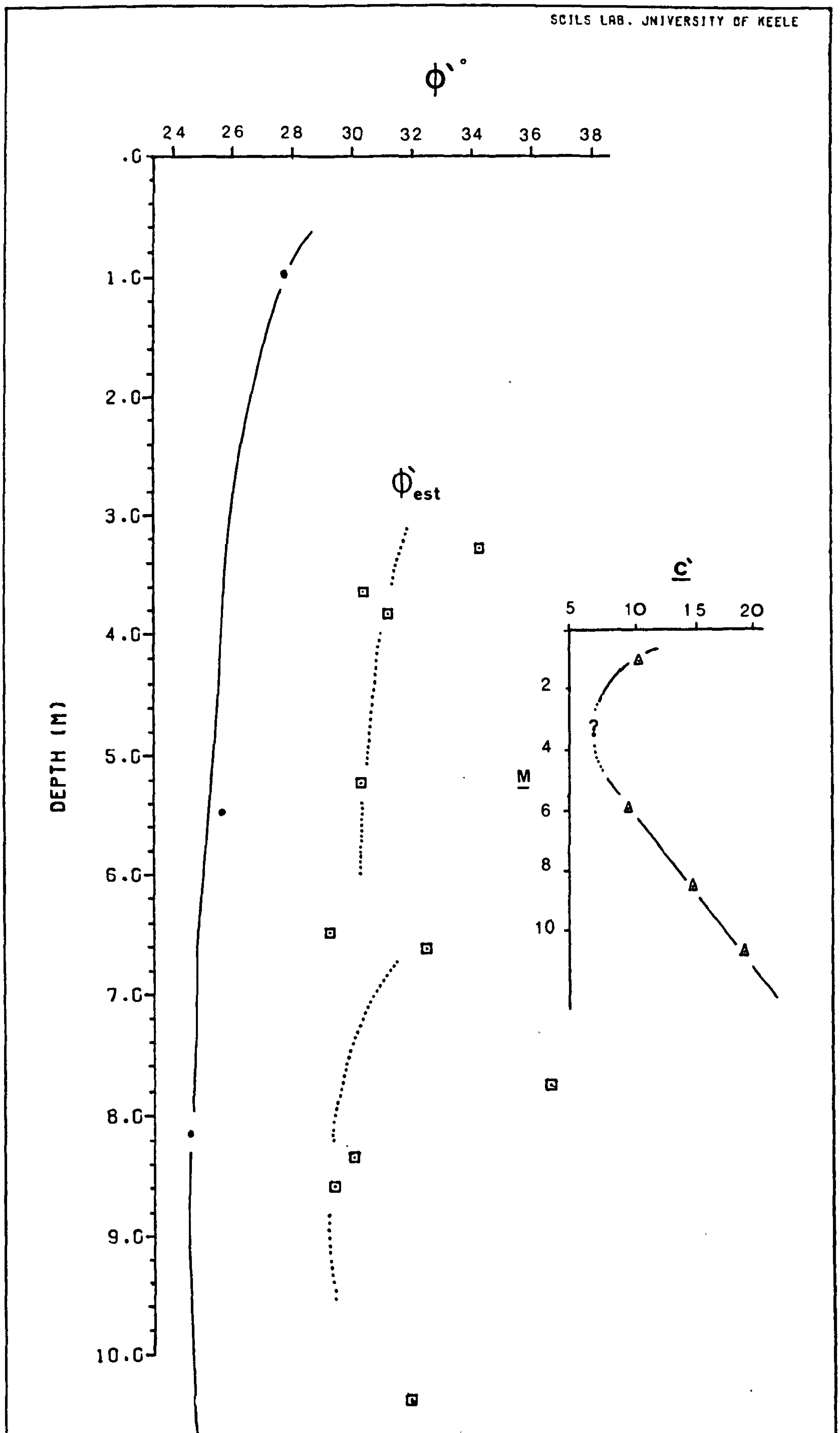
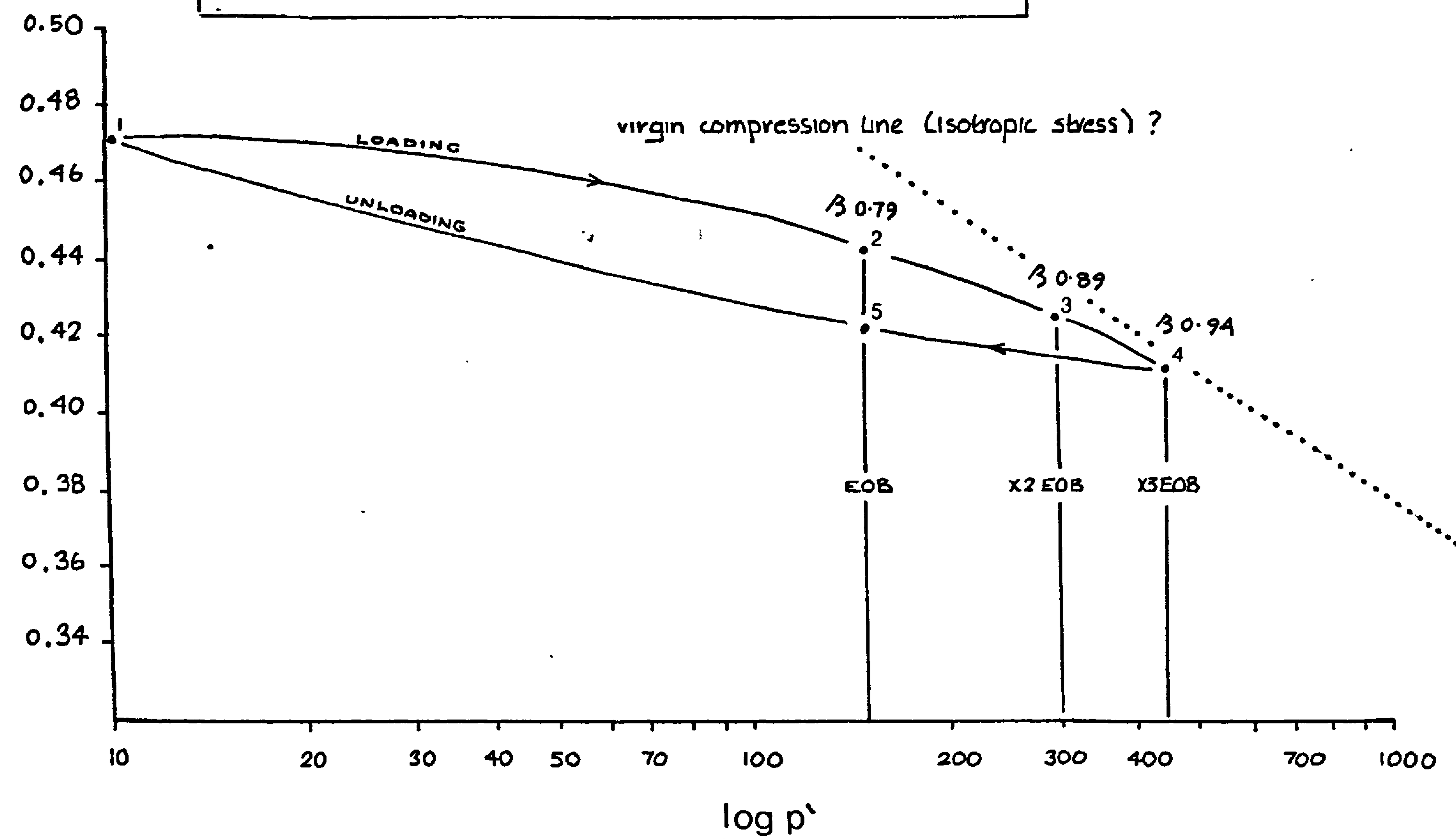


Figure 5.26 Plot of measured and estimated values for the effective angle of internal friction (φ') and effective cohesion (c'), with depth.

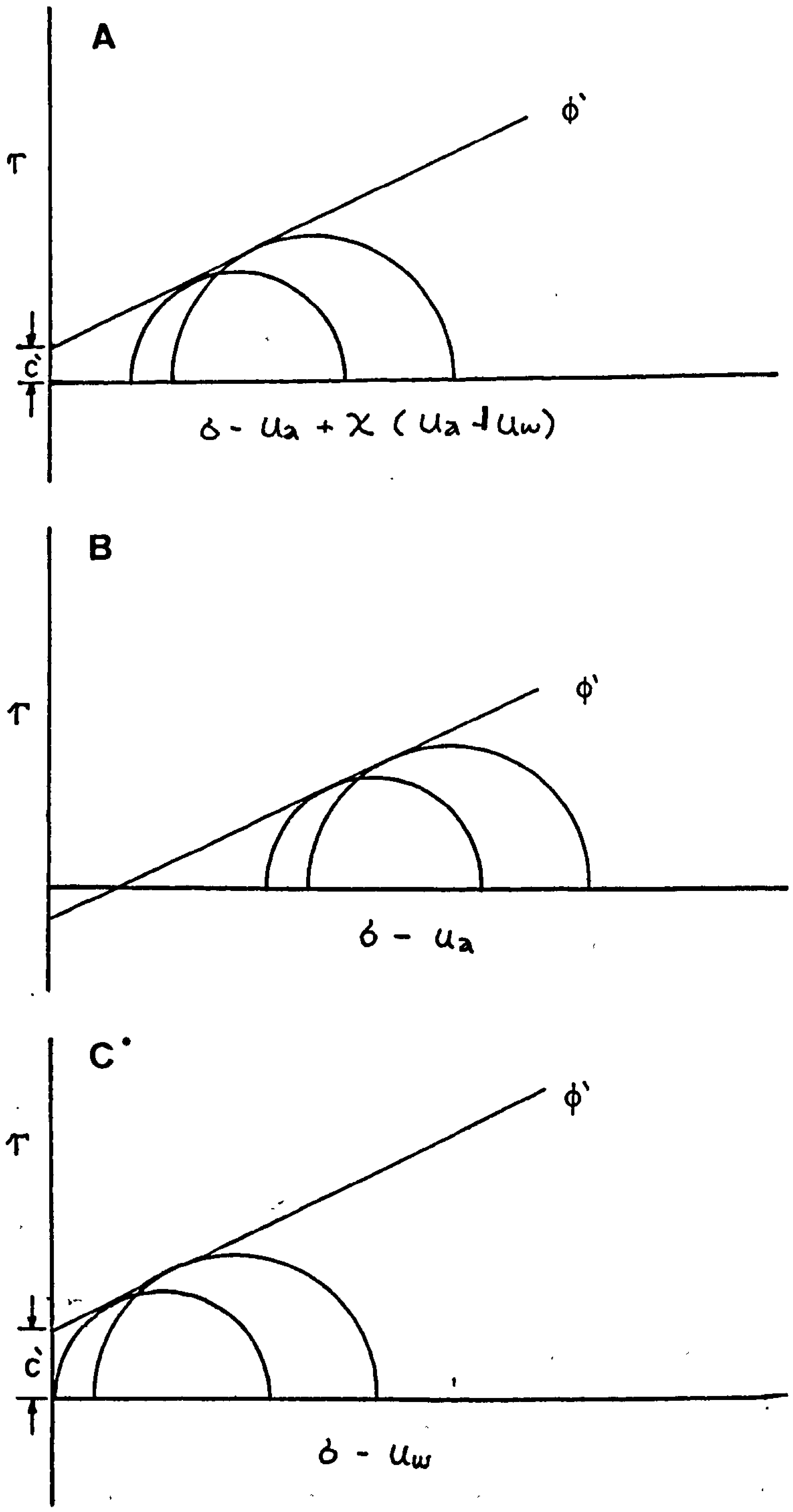
ratio (e) and the pore-pressure coefficient B with increased isotropic consolidation. In test CS2/32 the use of back pressure on the pore-pressure system ensured that any trapped air or pore air, in the case of under saturated specimens, was eliminated and the measured pore-pressure values therefore reflect a true effective stress response. Before consolidating to the calculated effective overburden, the sample was allowed to swell under a low confining stress ($10kN/m^2$). The cell pressure and back pressure were then increased in unison until the condition u = $240kN/m^2$, b3 = $250kN/m^2$, b'3 = $10kN/m^2$ was achieved. With reference to e4 it can be shown that such a pressure within the pore system is capable of achieving full saturation from a initial condition as low as 70% saturation (Bishop and Henkel 1957). From a voids ratio on sampling calculated at 0.42, the sample swelled to a new voids ratio of 0.48 at $10kN/m^2$ b'3 . When the confining stress was increased to place the sample under a pressure equal to the effective overburden, the sample reconsolidated to 0.437. The difference between the voids ratio on sampling and the voids ratio at effective overburden could reflect the volume of water replacing the pore air under high back pressures if the sample was only partially saturated. However the data shows that to account for the volume of water retained, percentage saturation (Sr) must have been <74%, an extremely low value for a clay recovered from 10.9m.

A more likely explanation is that the soil was fully saturated and was simply undergoing a response typical of overconsolidated soils on the rebound curve. Plotting all five points from the stages on a e/log p chart shows that the response was as expected of a soil reconsolidated to a pressure close to the pre-consolidation stress (Figure 5.27). A value for pc between 300-400 kN/m^2 is in line with values produced from one dimensional

Figure 5.27 e / log p curve CS2/32 (10.9m)



5.28 Effects of undersaturation on measures values of c and ϕ (Paul 1981)



A...... Pore Fluid System Fully engaged
Specimen Fully Saturated -

B...... Pore Air System Only engaged
Specimen Under-saturated - < 100%
c' incorrectly determined

C...... Pore Water System Only engaged
Specimen Undersaturated < 100%
c' overestimated

consolidation tests and examination of the pore-pressure coefficient A, although the results are not strictly comparable, due to the different stress systems employed.

A condition of full saturation on sampling is also supported by the fact that the tests CS2/32 and CS2/28 produced similar values for ϕ' and c' even though the latter tests consolidated against atmospheric pressure. Neither test produced an undersaturated response when the Mohr's envelope was plotted (Figure 5.28), which is typical of a soil where only the pore water system is engaged and the value of c' is over estimated. However the fact remains that the condition B=1 was not achieved for the Cowden tills under most stress conditions although Figure 5.27 suggests this can be approached as the overconsolidation ratio falls. A link between OCR and the measured B response is consistent with the gradual increase in B with depth as shown in Figure 5.4, although if the trend was continued, unity would be achieved at 16-17m depth at an effective overburden of only 200kN/m^2.

5.8 One Dimensional Consolidation.

This procedure tests the pressure/voids relationship at successively increasing pressures, whilst the soil specimen is laterally confined and allowed to drain freely from the top and bottom surface. The problems of applying this test to diamict has been adequately documented (McKinlay, McGown, Radwan and Hossain 1975). Problems centre on the unrepresentative sample size often employed in relation to the controlling features of macro-fabric, principally clasts and fissures spacings. Even using large size odeometer specimens 76mm X 19mm, difficulties are encountered during sample

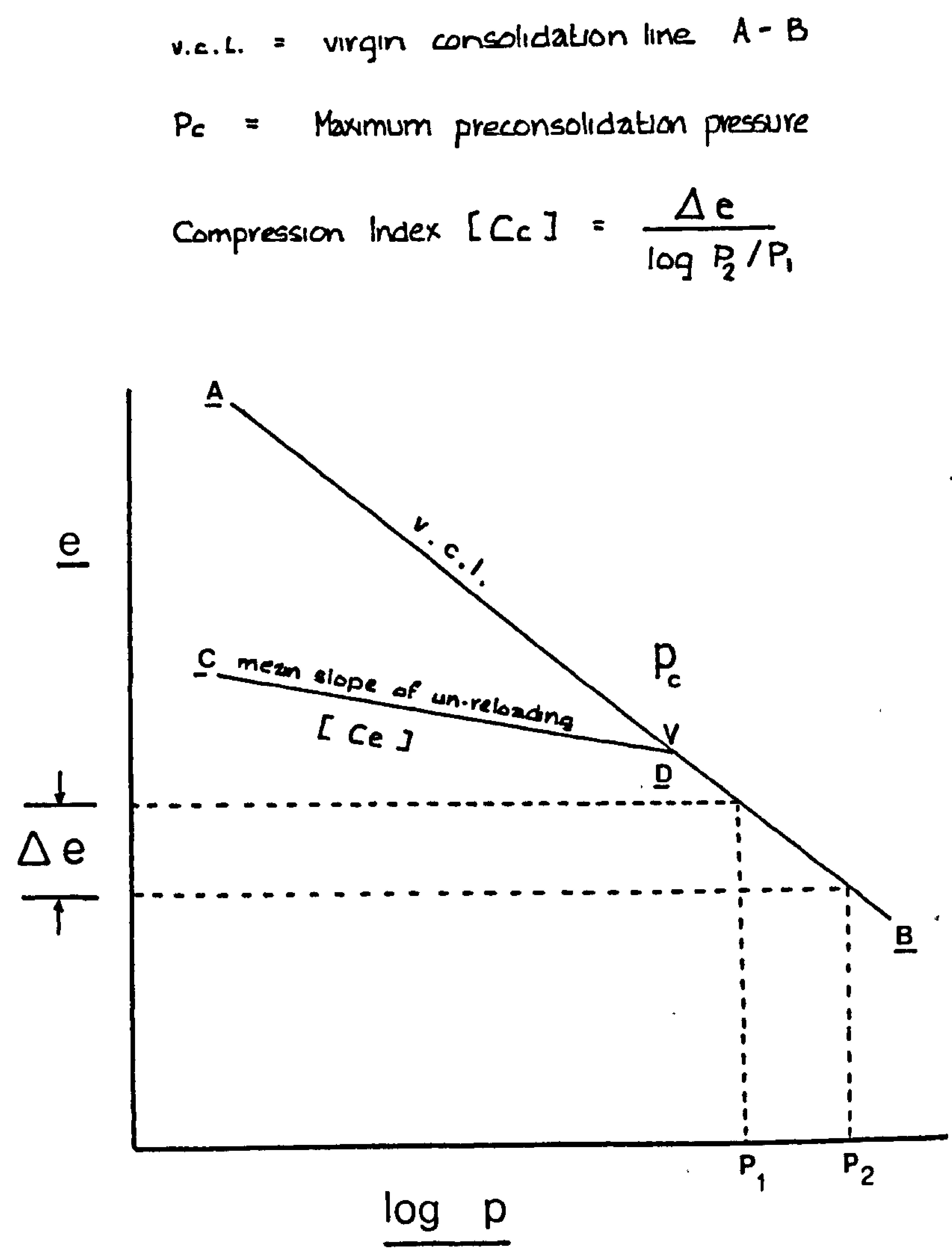


Figure 5.29 Idealized consolidation curve for clays after Terzaghi (1943).

preparation which are not so critical in triaxial testing. Even the smaller 1.5/1 triaxial specimens (150mm X 98mm) encompasses a soil volume thirteen times that of the odeometer specimen, while allowing complete control of drainage during consolidation.

A limited number of tests was carried out on material from boreholes CS1 and CS2 and the Cowden trench to provide comparative data for the triaxial programme, particularly with respect to estimated pre-consolidation stress. Apart from test CT 49 all tests were undertaken at the Transport and Road Research Laboratories, Crowthorne who are gratefully acknowledged for their assistance.

5.8.1 Compressibility Index.

According to Terzaghi (1943), the virgin compression curves for cohesive soils of plastic consistency are of a logarithmic type (Figure 5.29) and a change in stress can be defined by the empirical relationship containing the compressibility index (Cc) :

e14 $$e2 = e1 - Cc \log_{10} p2/p1$$

Similarly the expansion curves can also be represented by straight lines with the expansion index (Ce) defined as the mean slope of the unloading lines. With reference to Figure 5.29, a soil in a state represented by points on the line A-B (virgin consolidation line) is referred to as normally consolidated whereas a soil on the swelling/reloading line C-D is referred to as overconsolidated. The degree of overconsolidation is generally expressed by the overconsolidation ratio (O.C.R.) which is defined as the maximum past vertical effective pressure (pc) divided by the current value of vertical effective stress.

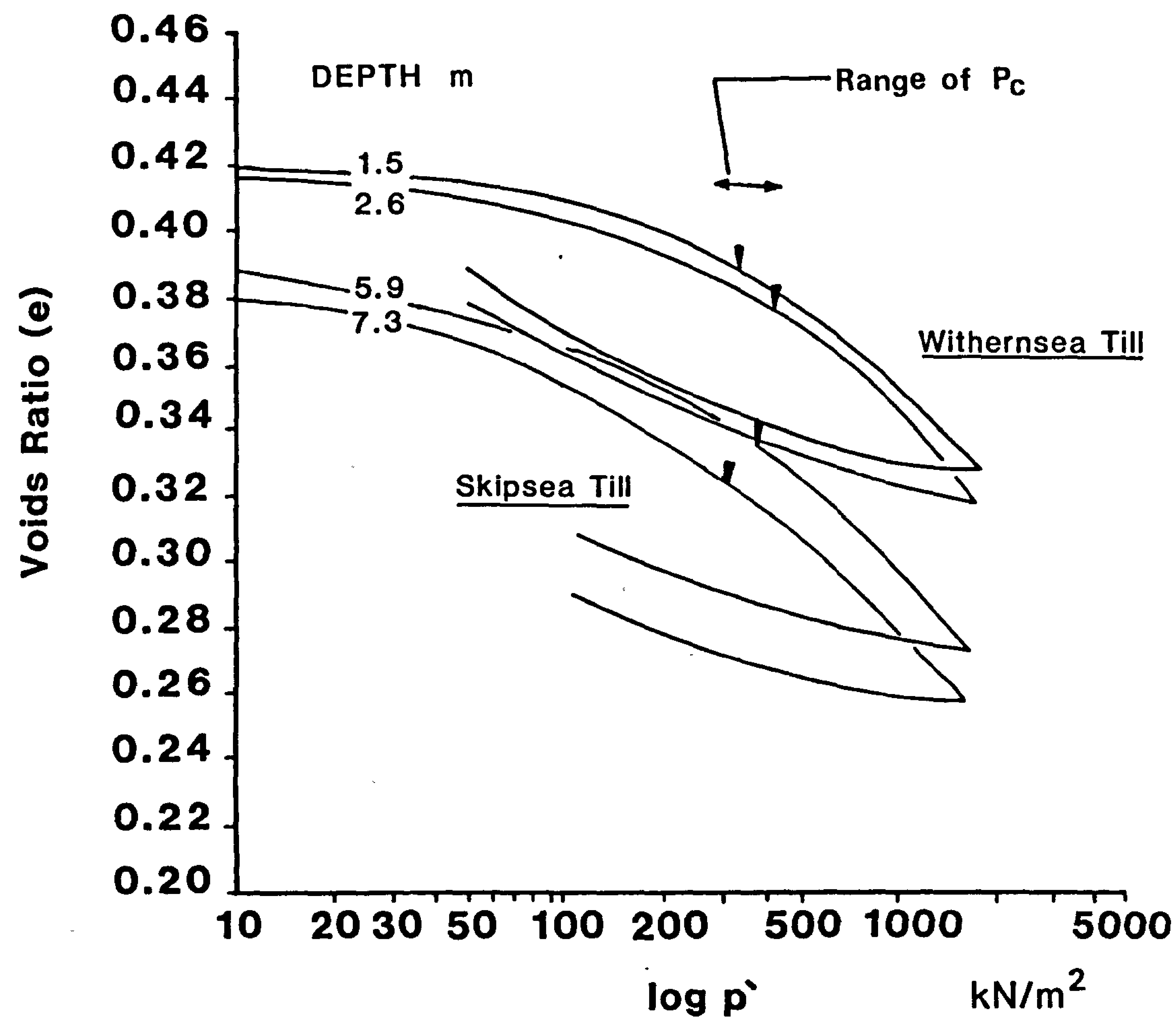


Figure 5.30 Consolidation curve for the Skipsea and Withernsea Tills

The e/log p curves for the diamict at Cowden (Figure 5,30) do not show a well defined break of slope under the normal range of consolidation pressures, a characteristic of overconsolidated clay-rich diamicts noted by other workers (Soderman and Yim 1970). It is, however, possible to determine a value for the pre-consolidation load using the graphical construction proposed by Casagrande (1936), described below with reference to Figure 5,31.

First estimate the point of greatest curvature, A, and draw a horizontal line through A, (AB), and the tangent to the curve at A, (AD). Bisect the angle BAD to give the line AC. An extension of the virgin consolidation line (EF) cuts the line AC at G. The projection of the point G onto the log pressure axis gives the pre-consolidation pressure (p_c). In this example p_c was calculated as 250 kN/m^2 resulting in an overconsolidation ratio of between 5-6 at a depth of 4.1m. The same construction applied to the e/log p curves supplied by TRRL gave a range of p_c values ranging between 300-425 kN/m^2 (Figure 5,30) for the diamict at Cowden at various depths. Similar preconsolidation pressures for material described as lodgement till are reported by Soderman and Yim (1970) and Luttenegger, Kemmis and Hallberg (1983), who recorded a range of values for North American basal tills between 75-536 kN/m^2 . Higher pre-consolidation loads in the order 1,700-2000 kN/m^2 calculated for the lodgement tills of Perthshire, (Sladen and Wrigley 1983) and 749 kN/m^2- 1284 kN/m^2 from clays within the Cromer Till sequence in Norfolk (Kazi and Knill 1969), suggests that the sub-glacial environment can exert a wide range of effective stresses, although there is no evidence for such extreme pressures within the stress histories of the Withernsea and Skipsea Tills.

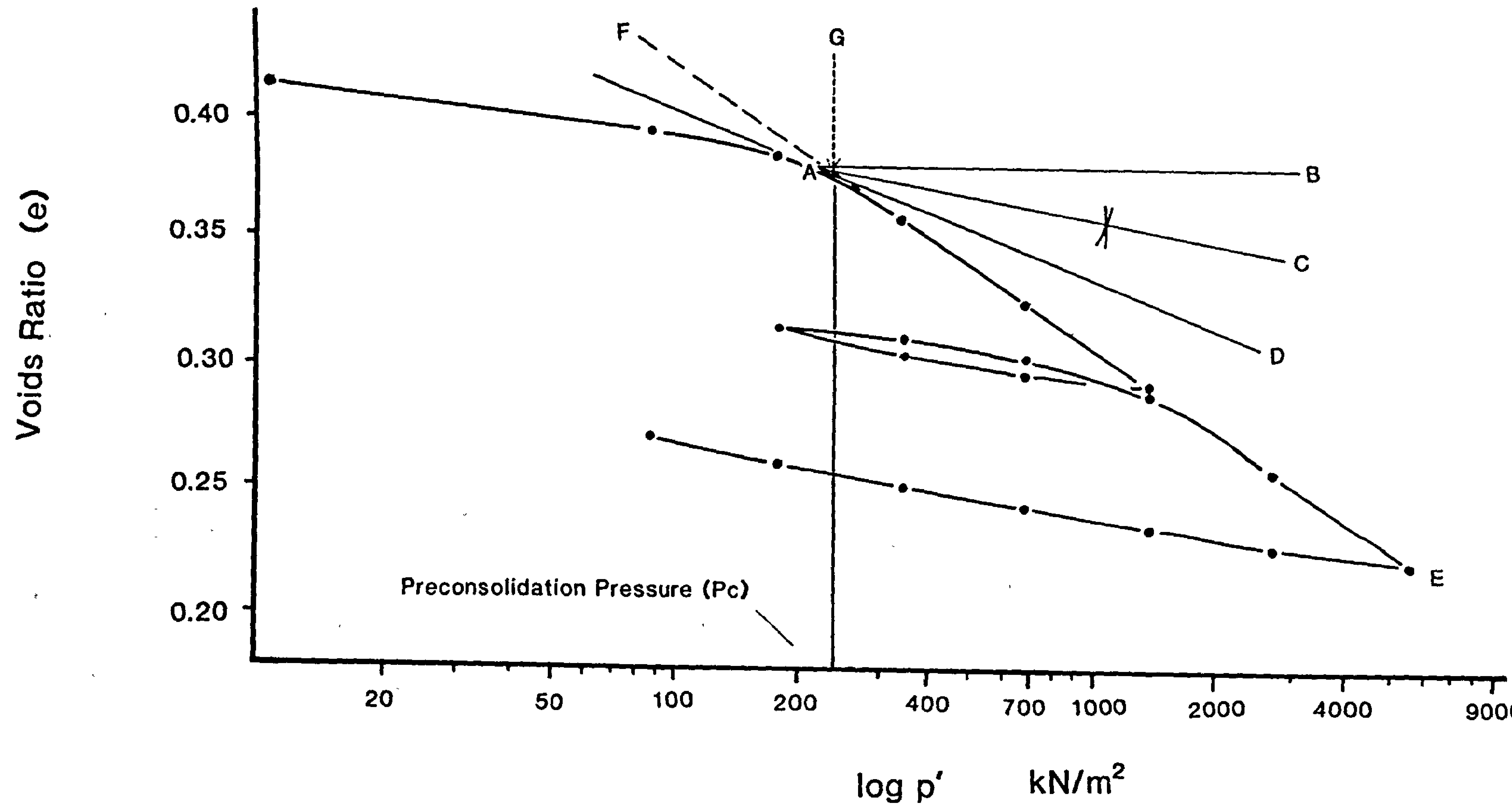


Figure 5.31 Consolidation curve taken to extremes of normal loading CS1 (4.1m) with a construction for the estimation of preconsolidation load after Casagrande (1936).

There are however, several fundamental considerations which prevent a simple conclusion being drawn for the consolidation test results.

First, the unrepresentative size of the sample test specimens (76mm x 19mm) in relation to the controlling elements of the soil structure such as clasts and fissures spacing can have an important effect on both the consolidation and shear characteristics. This factor can produce a significant discrepancy between results achieved with laboratory specimens and large scale in situ tests in diamict (Powell, Marsland and Al Khafagi 1983, Marsland 1977). In response to this problem McKinlay, McGown, Radwan and Hossain (1975) have proposed that, for diamicts containing clasts up to 20 mm in diameter, consolidation characteristics should be ascertained using specimens no smaller than 152 x 50 mm. Such a specification would, however, place the testing of such material outside the capabilities of all but the most well equipped research laboratories.

Apart from laboratory technique, an additional concern calls into question the assumption that lodgement tills conform to the model of gravitational compaction and consolidation applied to other clay rich deposits (Skempton 1970). Recent theoretical treatment of the basal boundary conditions between ice and bed has suggested that this provides a far more complex depositional environment than that produced by sedimentation through a water column (Boulton 1975, Boulton 1982). Oversimplified models of deposition have lead some workers into reconstructing ice sheet profiles on the pattern of pre-consolidation load exhibited by sub-glacial material (Kazi and Knill 1969, Harrison 1958) although it is now accepted that this approach is untenable taking into account the more detailed evidence emerging on effective stress beneath an ice sheet (Hodge 1979) and recent theoretical treatments of ice/bed dynamics, (Boulton and Jones 1979).

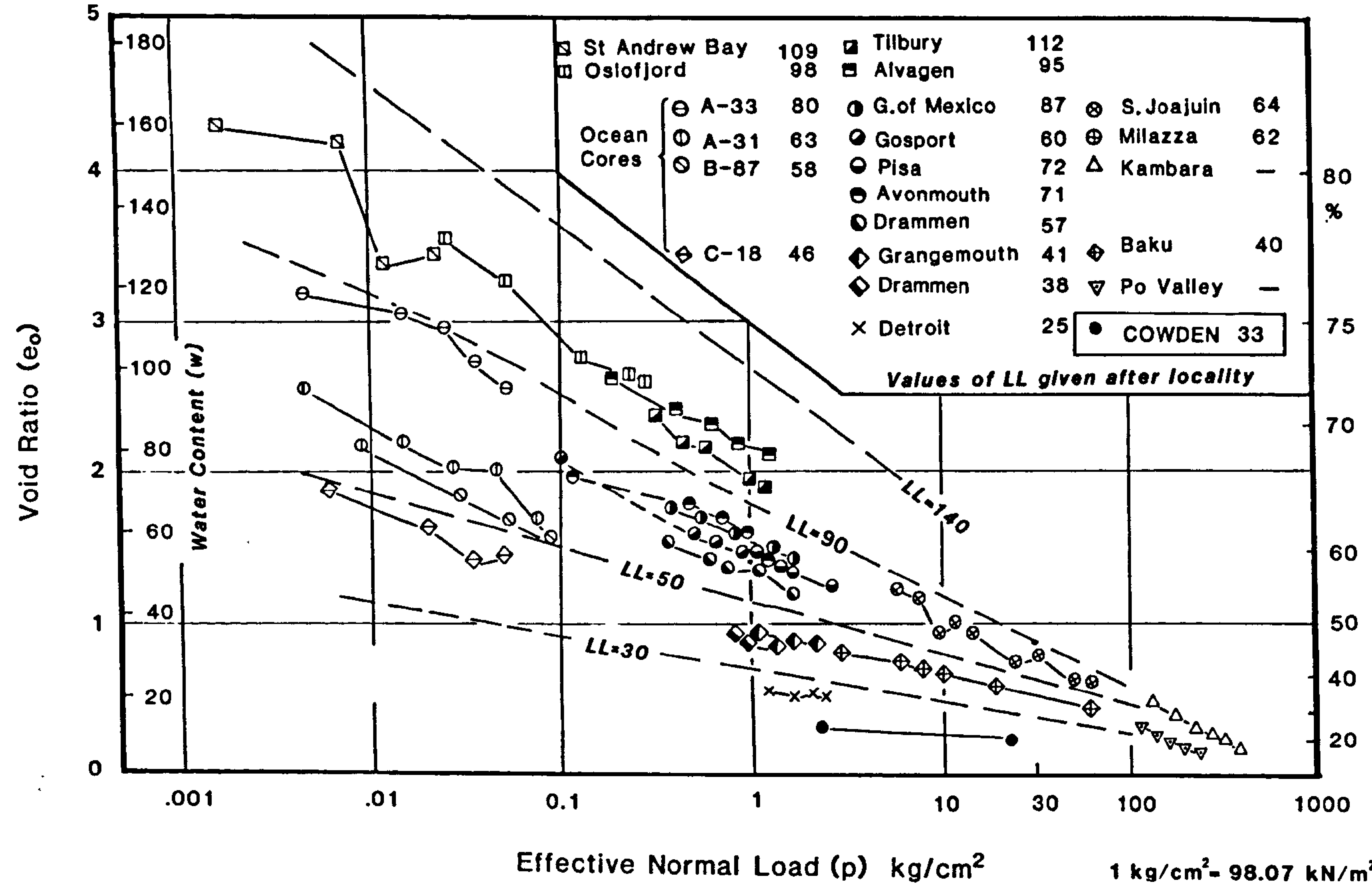


Figure 5.32 Consolidation curves for various soils (after Skempton 1970), with the consolidation curve for the Cowden diamict (CS1, 4.1m).

Consolidation theory for clay sedimented through a water column proposes that freshly deposited clay has an open pore structure (high voids ratio) under zero effective normal load. As the sediment column accumulates the effective normal load increases and the voids ratio is reduced as water moves out of the soil voids, assuming conditions of free drainage. The development of the soil fabric is seen as a direct consequence of the consolidation of the sediment under conditions of increasing effective normal load. The relationship between the voids ratio and the log of effective normal pressure as assumed to be linear and is represented by the virgin compression line (Figure 5.29).

The sedimentation of a massively bedded lodgement till sequence proceeds under quite different conditions. Boulton (1975) suggests that lodgement occurs when the frictional drag between particles in transport and the bed is such that the force imposed by the motion of the ice is insufficient to maintain the debris in motion. Since the bed must always maintain sufficient density and strength to overcome the force imposed by the velocity of the ice it cannot undergo a simple consolidation from high to low voids ratio, but must be deposited under conditions of significant normal load and high bulk density. Therefore the particle arrangement of a lodgement till will reflect the optimum packing conditions under a condition of stress rather than the re-arrangement of particles, to that point of stress, from an initially higher voids ratio. An indication of the efficiency of the particle arrangement in diamicts can be seen when plotting the sediment compression curve (CS1 4.1m) in relation to other Quaternary & Tertiary argillaceous sediments (Figure 5.32). Skempton (1970) has shown that a variety of deposits conform closely to the model of normal consolidation and that for any level of effective normal load the water content (voids ratio) is directly related to the collodial activity of the clay as represented by the liquid limit (LL). Replotting the virgin consolidation line for sample CS1 (4.1m) shows that the diamict possesses an exceptionally low compression index (C_c) and voids ratio in relation to the liquid limit. A correlation between the plasticity index and C_c (Skempton 1970) was not evident at Cowden. Similar findings using a larger data set from lodgement tills in the Pennines (Vaughan, Lovenbury and Horswill 1971) suggests that at the lower voids ratio exhibited by diamicts, this relationship ceases to be important. If the fabric of a lodgement till is determined at the point of deposition beneath active glacial ice then, unlike material undergoing gravitational sedimentation, it is subject to two principal forces, the effective normal load and the shear stress produced by the velocity of the ice (Boulton 1975). The response of the soil fabric is to develop an orientation along the plane of least resistance, thus producing the well documented phenomenon of alinement of clast and fines in lodgement till (McGown and Derbyshire 1977). Such a process may well be responsible for the anisotropy in the compression and strength indices reported in lodgement tills, (McKinlay, McGown, Radwan and Hossain 1974).

CHAPTER 6

Geotechnical and Sedimentological Associations: Current Models.

Nomenclature.

c s l	Critical state line.
e	Voids ratio
M	Soil constant analogous to ϕ'
p'	Mean normal effective stress
	$p' = (b'1 + 2.b'3)/3$ b not defined?
q	Deviator stress b1 - b3
q_f	Value q at the critical voids ratio.

6.1 Introduction.

Examination of the correlations between soil fabric, bulk index properties and the engineering behaviour of tills reveals a system of detailed complexity with few direct associations of cause and effect. The importance of studying these interrelationships lies in the knolwedge that with each link established, the behaviour of the soil under varying conditions of stress is better understood. This has practical applications since the labroratory analysis of soils is notoriously time-consuming and labour intensive, while the recovery of good quality samples, particularly from offshore locations is an expensive procedure. It is important therefore to extract the maximum amount of information from the minimum amount of material. A unifying approach has been adopted by a number of workers, principally Wroth and Wood (1978), Wroth (1979) and Atkinson and Bransby (1978), although its application to glacigenic sequences, particularly lodgement tills has not been studied in detail.

6.2 Basic Considerations.

The most widely established relationship for glacigenic material is the proposal that when plasticity index and liquid limit are plotted together on a conventional plasticity chart, the data points fall close to a line parallel to but above the Casagrande "A" line. This trend has been termed the "T" line by Boulton and Paul (1976), and has been examined with respect to the Skipsea and Withernsea Tills in Chapter four where the mathematical relationship for the two parameters was given as:

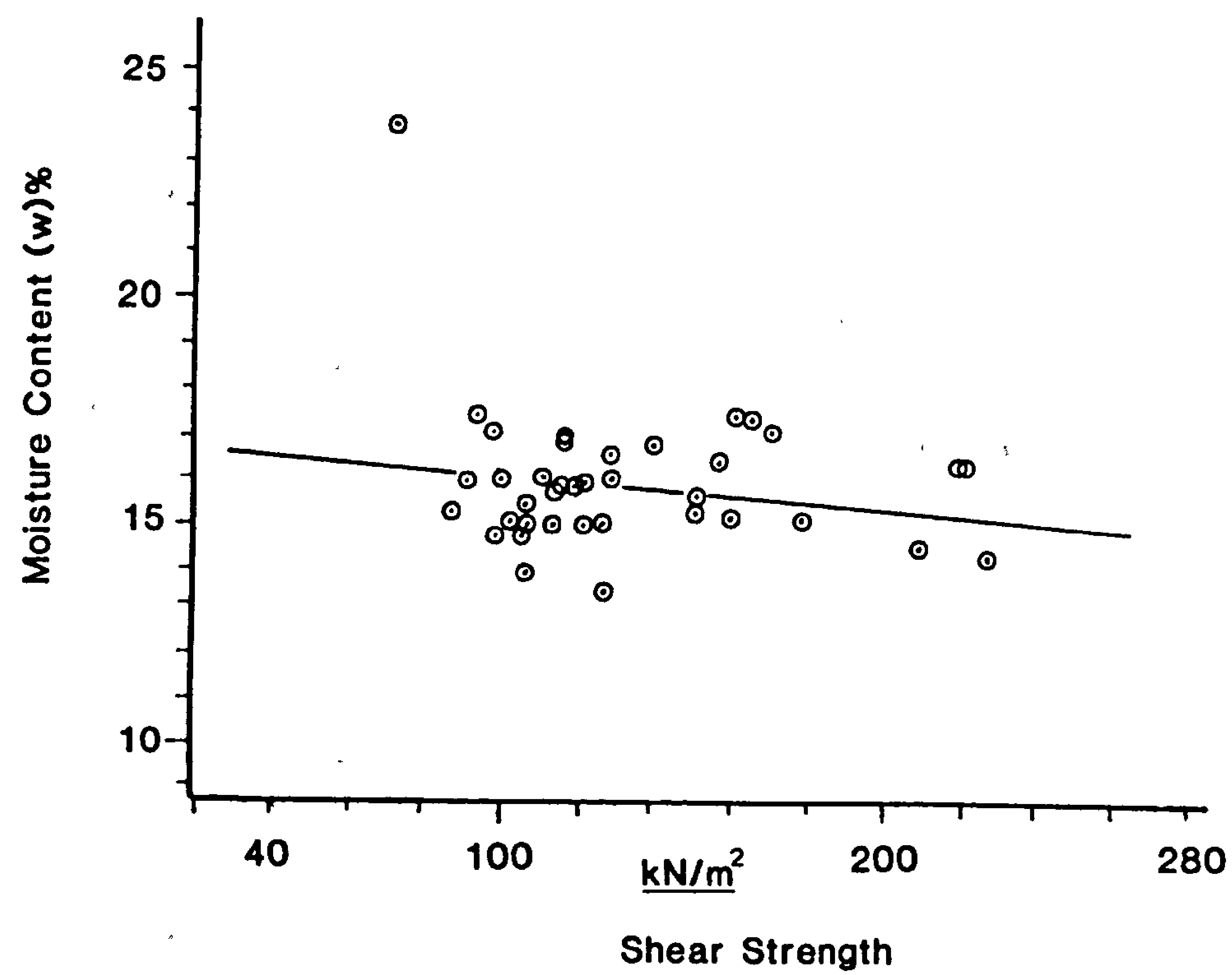
e1 $Ip = 0.73 (LL - 11\%)$

For most soils the principal controlling factors on the plasticity index are the percentage clay content (<63 μm BS1377) and the mineralogy of that fraction. Evidence from the Cowden profile suggests that these two parameters are relatively constant for the unweathered horizons and that plasticity forms an inverse relationship with percentage sand so that:

e2 $Ip = 58.2 - 1.66(s)$

where s = percentage sand

The importance of the plasticity index to any geotechical analysis is in the fact that it is one of the few parameters relatively unaffected by the stress history of the deposit subsequent to deposition and as such solely represents the mineralogy and grading of the soil. The liquid and plastic limits of clay soils are perhaps most usefully interpreted as the moisture contents at two crudely standardised remoulded undrained strengths. Consequently, the plasticity index can be seen as an indication of the rate of variation of remoulded undrained strength with moisture



<u>Shear Strength.</u>

Mean = 129.8 kN/m2
Standard Deviation = 37.8

<u>Moisture Content.</u>

Mean = 15.9 %
Standard Deviation = 1.5

Pearsons Product Moment Correlation Coefficient R = -0.173

Bivariate Regression Analyisis : y = a+bx

y = 16.88 + 0.00712 x

Standard error of the estimate = 1.53

Standard error of the slope (b) = 0.006

Standard error of the intercept (a) = 0.835

Figure 6.1 Relationship between shear strength (cu) and moisture content (w) for the Cowden diamict content.

6.3 Moisture Content / Undrained Shear Strength.

The moisture content in a saturated soil with constant specific gravity is directly related to the voids ratio and, as such, is a reflection of the state of consolidation. Lodgement tills, exposed by post-glacial erosion or mechanical excavation, are invariably overconsolidated in that they have been previously subjected to a higher vertical effective stress than currently exists. As a result the matrix moisture content is low and generally below that of the plastic limit, a condition reflected in the range of the liquidity index for the Skipsea and Withernsea tills (0.09 -0.35). In Figure 6.1, undrained shear strength is plotted against moisture content as measured previous to the test.

Unlike many laboratory soils the relationship between moisture content and shear strength for the diamict at Cowden was poorly defined (Pearson's Product Moment Correlation Coefficient R = -0.173). This may be due to several factors.

The determination of an accurate value for moisture content for lodgement till can be affected by the nature of the clasts. The amount of water contained within a specific volume is not only a function of the voids ratio but also a function of the volume of impermeable clasts, in particular, coherent igneous lithologies and flint. The problem is partially overcome by employing large bulk samples (300 - 400 gms) to determine moisture content, therefore reducing the possibility the a single large clast could bias the results (See section 3.22). The removal of the impermeable lithologies by dissection and careful sorting was found to be impractical since the imposed delay and opening of the soil matrix to the air was found to lead to increased amounts of drying.

Because of the limited range in the values of plasticity (16

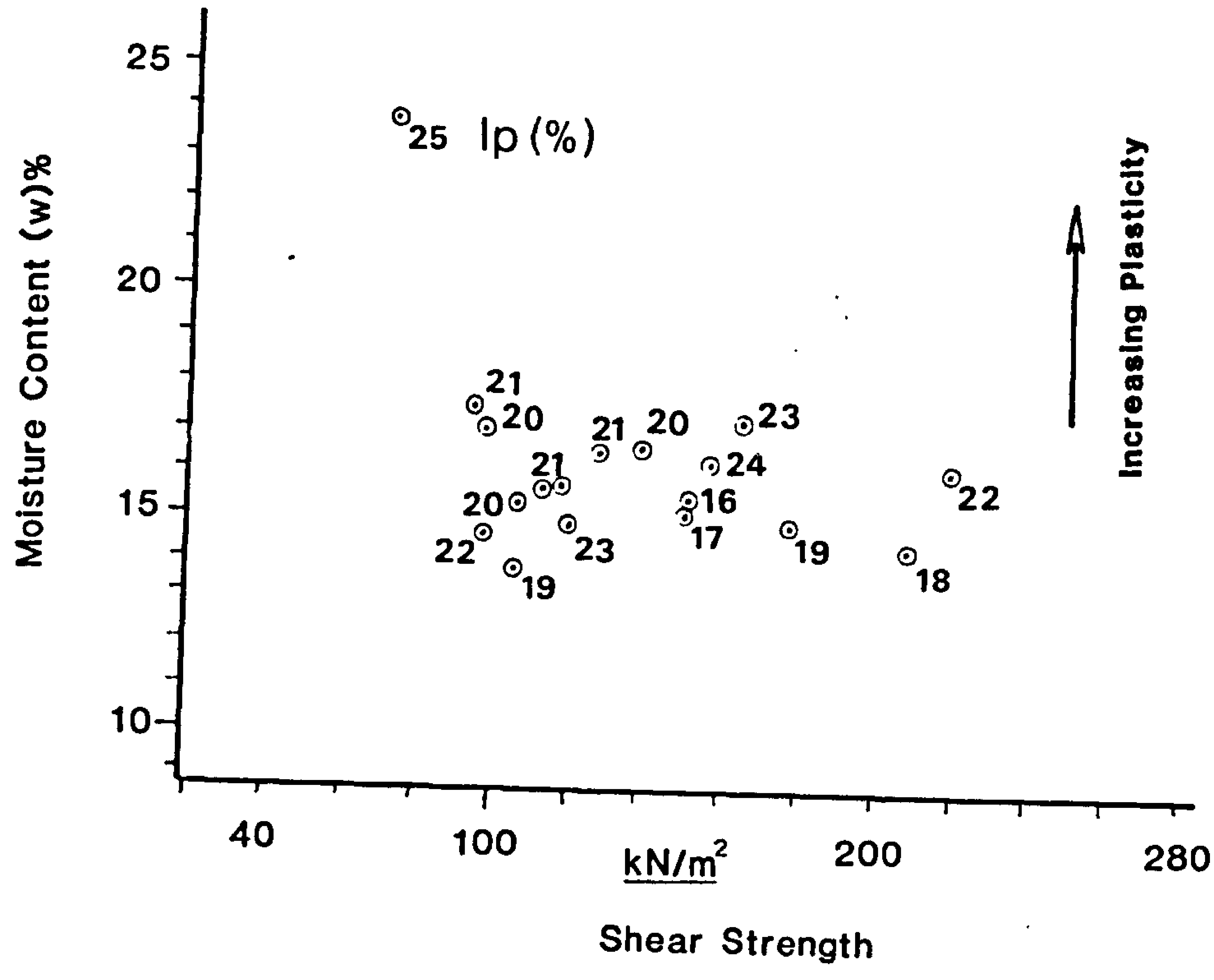


Figure 6.2 Relationship between shear strength (cu), moisture content (w) and Plasticity Index (Ip) for the Cowden diamict.

- 27 %), shear strength is particularly sensitive to moisture content change. Therefore inaccurate determination of either parameter is liable to lead to a scatter of results. While this remains an important aspect of the behaviour of lodgement tills it is a serious limitation to the application of such correlations as an aid to design practice. The relationship between shear strength and plasticity showed a general trend. For any range of shear strength, increased moisture content was also related to increased plasticity, although this relationship did not hold true for all the samples studied (Figure 6.2).

The examination of the moisture content/shear strength relationship demostrates that there is a limitation on the amount of variation which can be explained by consideration of only two or three parameters within a single model. A greater understanding of the behaviour of the soil is achieved if the voids ratio, shear stresses and volume changes can be modelled as a function of the change in in situ stress or an independent parameter such as plasticity index. The Critical State Model (Atkinson and Bransby 1978), provides such a suitable framework since its applicability is not confined to geotechnical relationships but also allows for the variation in plasticity index, therefore encompassing within a single theory many of the parameters presented in the preceding chapters.

6.4 Appicability of the Critical State Model to Diamicts.

The basic premise of the Critical State Model, and one of particular relevance to the Cowden diamict, is that in a drained triaxial test (volume change) whatever the initial density, with constant confining stress, the sample will always fail at the same voids ratio. If deformation is allowed to continue, the

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sample remains at the same voids ratio and deforms solely by shear distortion. This condition is known as the Critical State. This assumption is used to define a state of stress at failure in three-dimensional space with axis of shear stress, volumetric stress and volume change. For all two-dimensional theories previously considered, such as the Mohr's diagrams, it is convenient to represent test results in terms of (b'1 + b'3)/2 , which gives the centre of the effective stress circle and (b'1 - b'3)/2, defining the radius. In three-dimensional problems and in the specific case of the triaxial apparatus where b'2 = b'3, the following parameters can be defined:

e3 p' = (b'1 + 2.b'3)/3 ....Effective Mean Normal Stress

e4 q = b1 - b3 ....Deviator Stress

where p' is associated only with volumetric stress and q with shear stress.

The volumetric change parameter can be voids ratio (e), moisture content (w) or specific volume. For the following considerations, voids ratio is used being interchangeable with moisture content where :

e5 e = w / 2.70

and w = moisture content expressed as a decimal.

The three-dimensional space p',q,e can now be formed along common axis (Figure 6.3). It should be noted that the plane A-B-C (q/e) is directly related to the shear strength/moisture content plot considered earlier (where q = 2cu and e = w/2.70) while the plane C-B-D (e,p'), defines the surface of isotropic compression upon which can be drawn the line of normal consolidation (L-L). All soils in equilibrium, with Ko = 1, must initially lie on, or close to the C-B-D plane either on the line L-L (normally consolidated) or on a rebound line (overconsolidated). No soil can

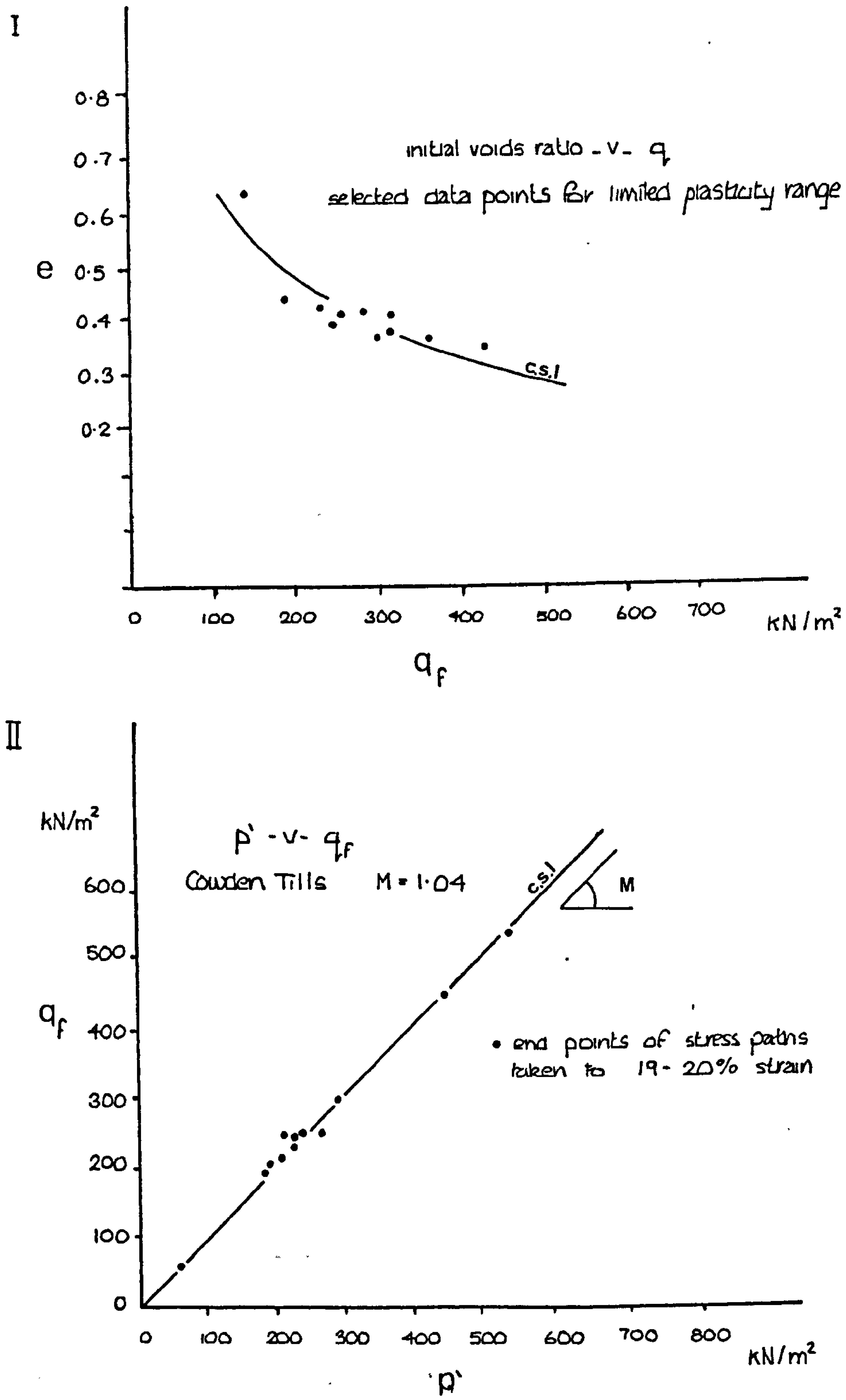
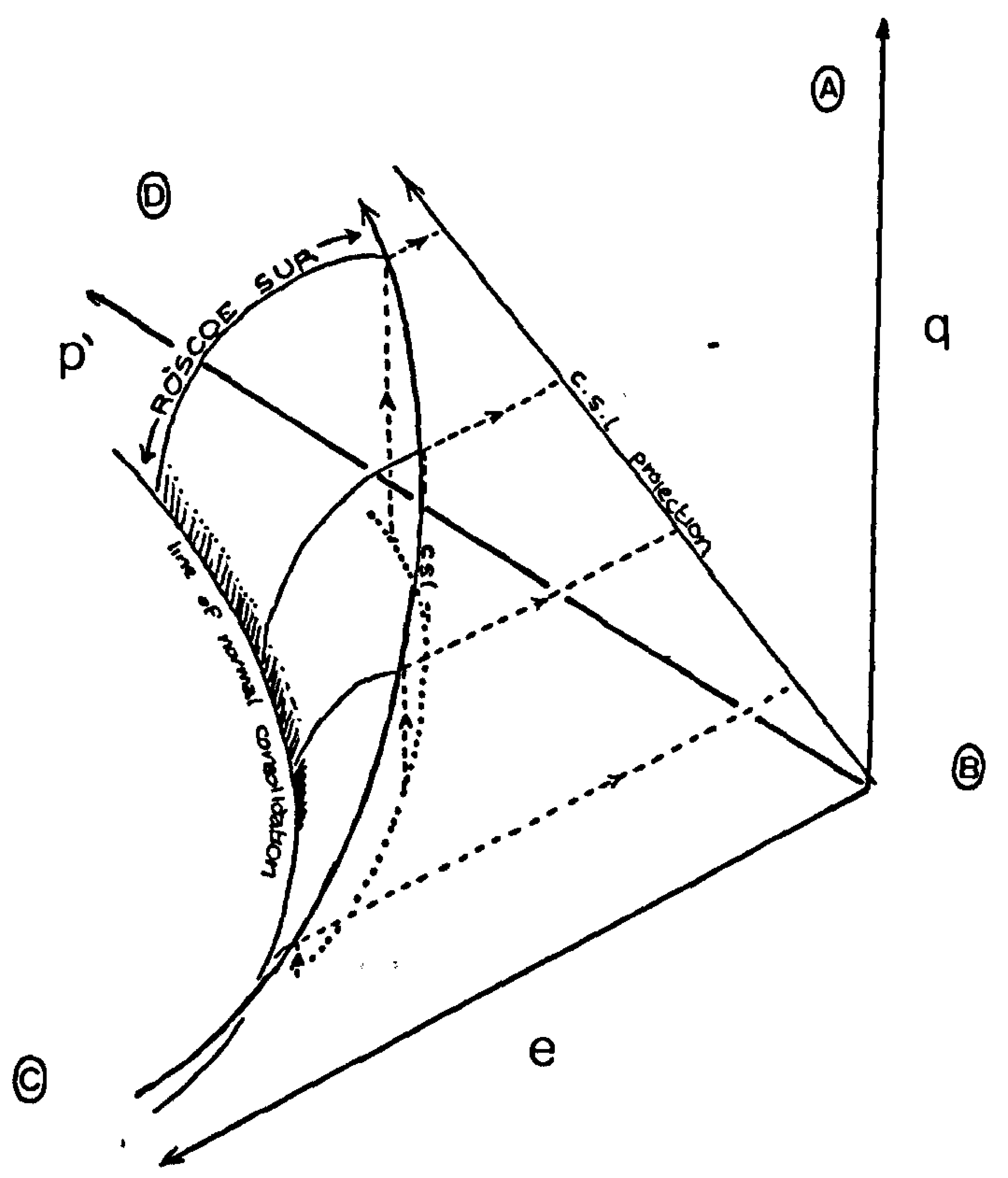


Figure 6.4 Experimental determination of the Critical State Line for the Cowden diamict

Figure 6.5



The Critical State Line in p', q, e space constructed from projections from the q, p' and e, p' planes

See Figure 6.4

exist outside the area defined by the e/p' axis and the normal consolidation line and therefore L-L is said to represent a "state boundary".

The p'/q plane holds a failure envelope which represents the shear strength of the material at the critical voids ratio (qf), as a function of p'. The slope of the line is given by:

e6 $$qf = Mp'$$

were M is a soil constant analogous to the angle of internal friction (Φ') in the Coulomb model.

e7 $$M = 6 \sin \phi'/3 - \sin \phi'$$

This envelope represents the end states of all tests where the critical voids ratio is attained. Figure 6.4II shows the p'/q plane for twelve tests on the Skipsea and Withernsea tills taken to >19% strain (M = 1.04).

Figure 6.3II is an e/p' diagram which shows the critical void ratio as a function of p'. For all soils it follows a line parallel to the virgin consolidation line of Atkinson and Bransby (1978). If the three dimensional model is now re-examined it is clear that whichever plane is considered the plot of the critical void ratio is simply the projection of a single line in p',q,e space, termed the critical state line (Figure 6.5).

6.5 Stress Paths for Drained and Undrained Shear.

All samples stressed to failure move from the base (p',e) plane to the critical state line regardless of the initial density or type of test. The factor which controls the behaviour under shear, is the path that the sample takes to reach the critical state line. State paths in p',q,e space when projected on to the confining planes are termed stress paths.

Stress paths in q, p` and e, p` space for drained tests on normally consolidated samples tested at various pre-consolidation loads. (Atkinson and Bransby 1978)

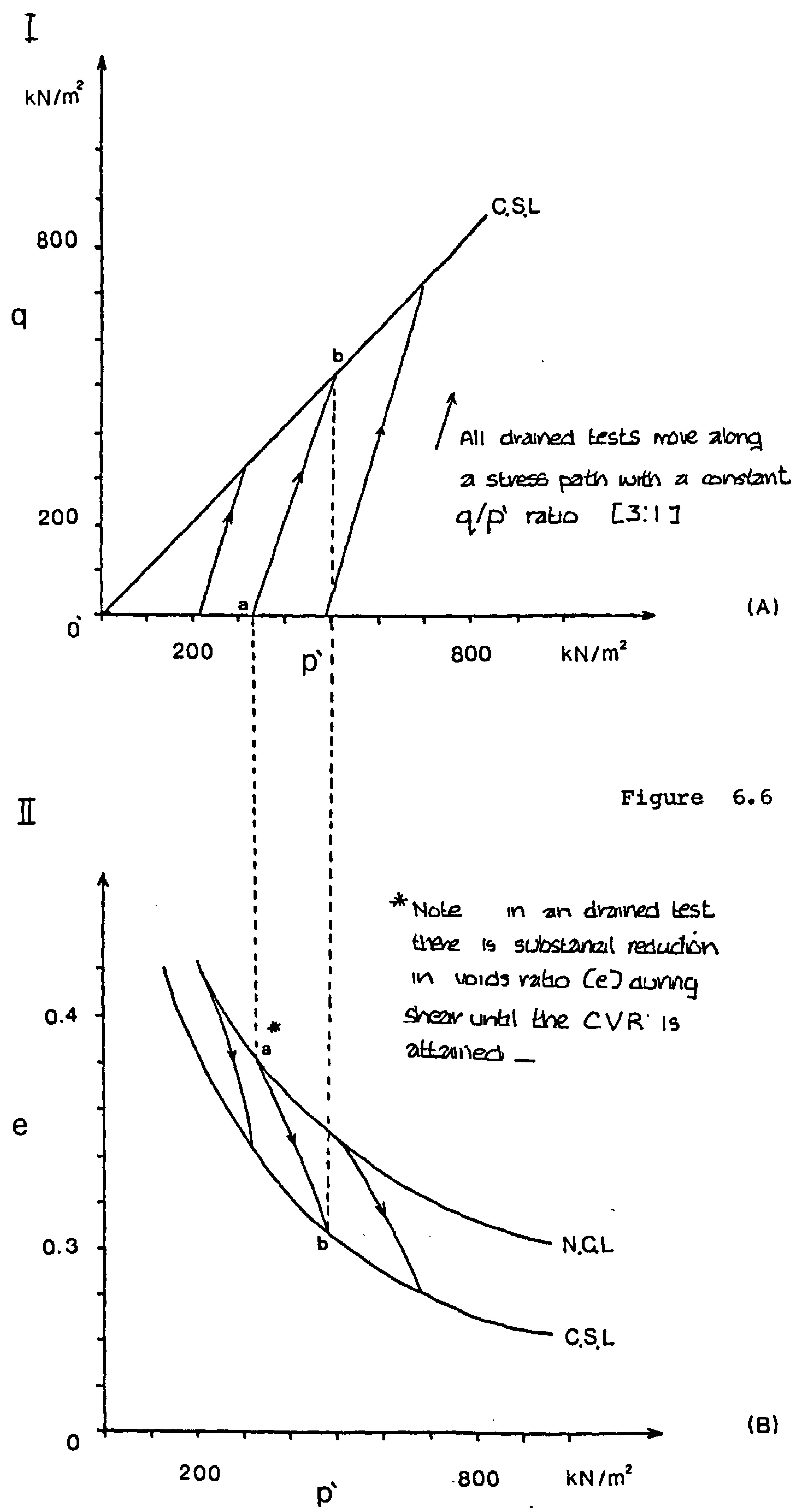


Figure 6.6

after Atkinson & Bransby 1978 pp 188

Stress paths in q, p` and e, p` space for undrained tests on normally consolidated samples tested at various pre-consolidation loads (Atkinson and Bransby 1978)

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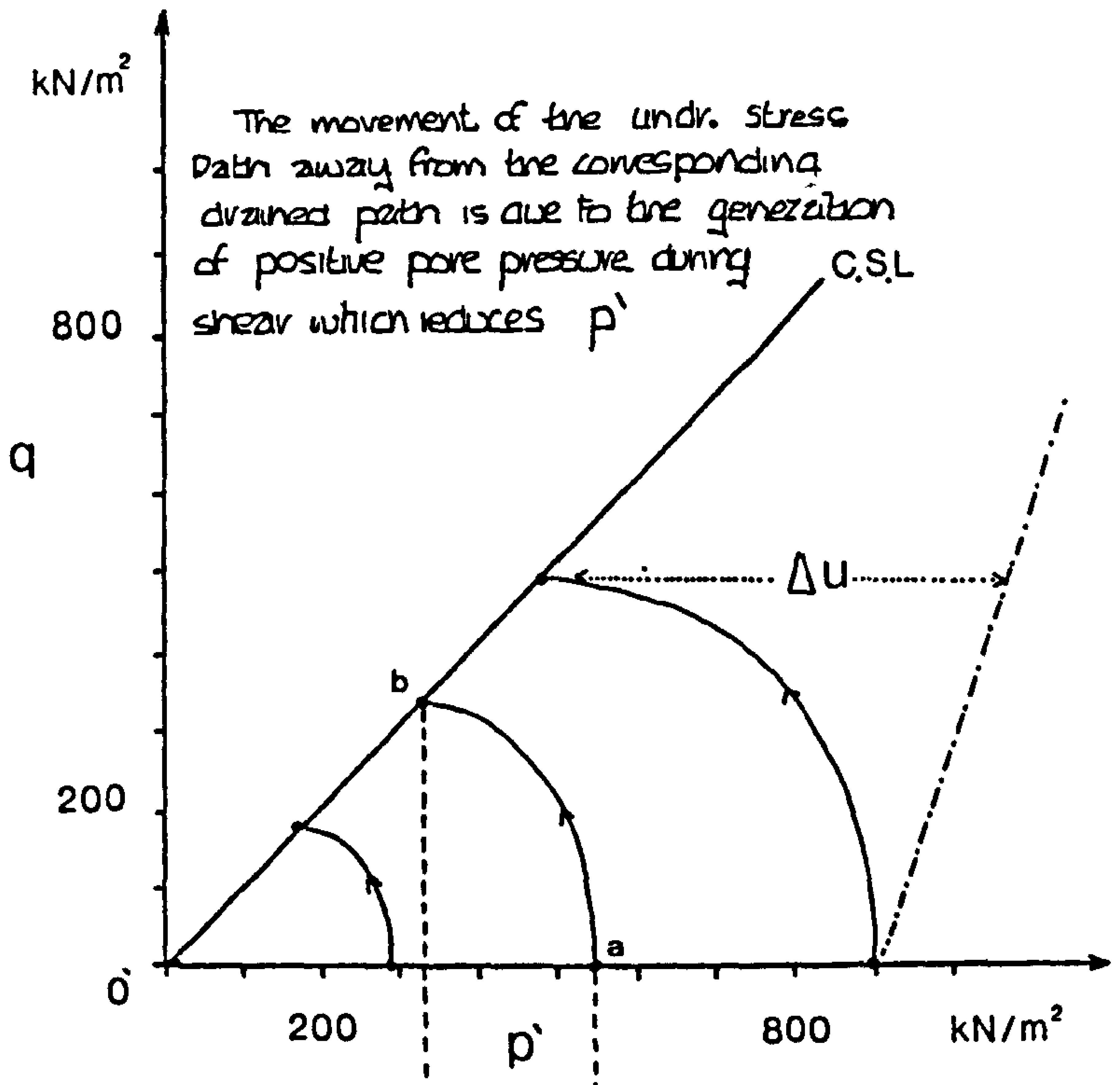

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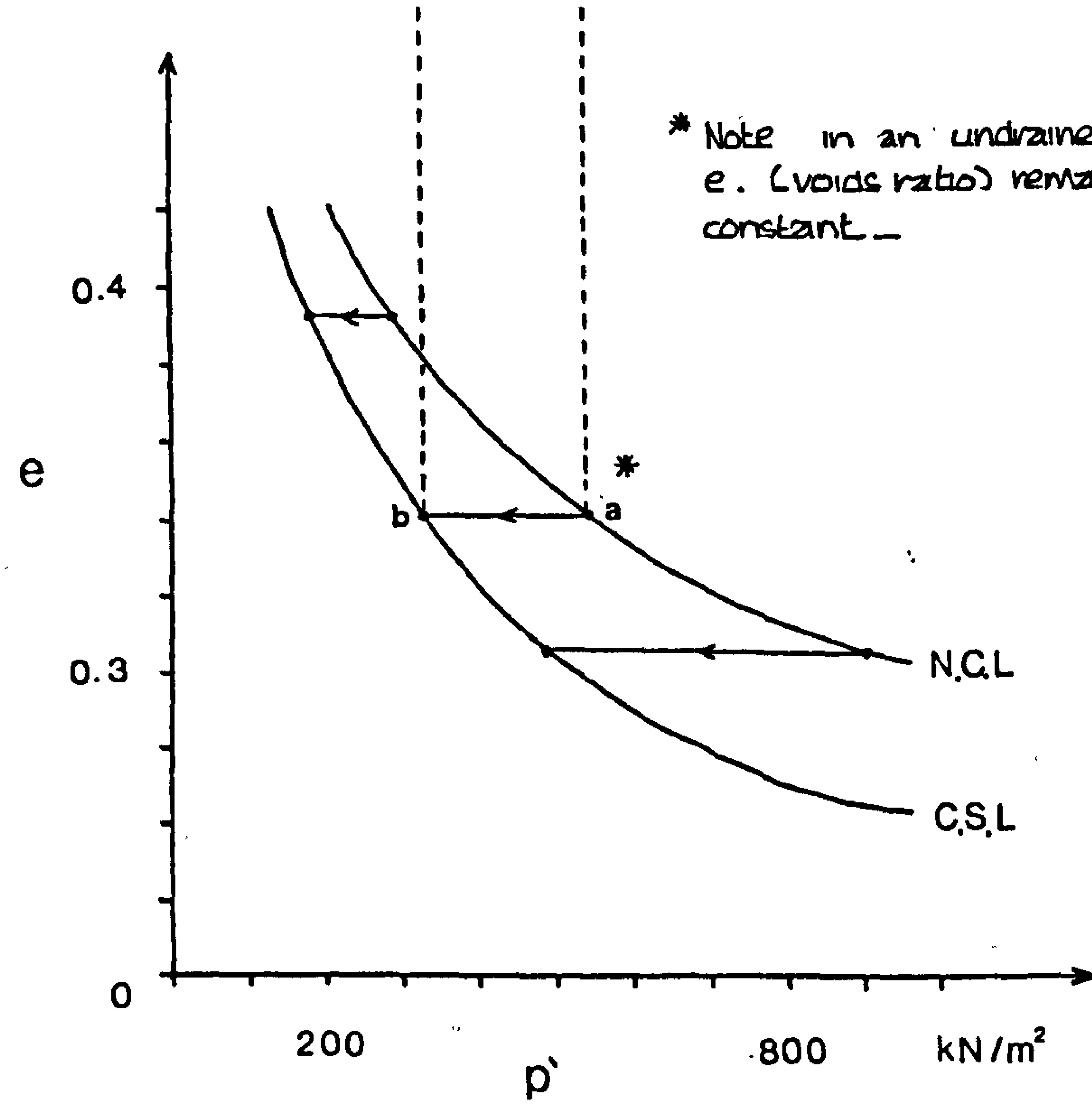
Figure 6.7



after Atkinson & Bransby 1978 pp 186

Figures 6.6 and 6.7 show the respective projections for state paths in drained and undrained failure for a normally consolidated soil. In the case of the drained test there is volume reduction during shear whereas in the case of the undrained test a positive pore-pressure is generated to resist the volume change. In q,p' space the stress path for undrained shear can be modelled as a point moving to the critical state line with a gradient of 1:3. This is true for all drained tests since with no change in pore-pressure:

e8 $2b'3 = 0$

e9 As $p' = (\Delta b'1 + \Delta 2b'3)/3$

this reduces to $p' = \Delta b'1/3$

The situation in an undrained test is significantly different since the generation of positive pore-pressures leads to a reduction in p' as the test progresses. The stress path for undrained shear moves away from the drained stress path a distance equal to the pore-pressure generated during shear and fails at a significantly lower value of q. Examination of the stress paths in e/p' space accurately reflects the changes in volume during drained shear, while following a line of constant volume for undrained shear. Atkinson and Bransby (1978) show that if the stress paths for undrained shear in q,p' space are compared for different values of p' they are all of similar shape and define a surface along which all tests on a normally consolidated soil must move, termed the Roscoe surface (Figure 6.5). Stress paths on all three axes can be analysed by interpreting how the drained and undrained planes intercept this surface. While the undrained plane lies perpendicular to the state surface, the stress path in q,p' space defining the curvature of its surface, the change in volume during drained shear causes this state path to cut successive undrained

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planes, although still remaining on the Roscoe surface before finally reaching the critical state line (Figure 6.8).

A similar analysis can be made for overconsolidated clay soils using the same concepts of drained and undrained planes intercepting and then moving across a state surface, the crucial difference being that, unlike normally consolidated soils which must by definition lie on the virgin consolidation line, an overconsolidated clay can lie at any point within the state boundary.

6.6 Theoretical Behaviour Of An Overconsolidated Clay Till.

With reference to Figure 6.9 it can be seen that for points on the rebound line (overconsolidated soils), some lie to the right and some to the left of the critical state line. Samples represented by points A and B will therefore exhibit different behaviour during shear since at the current value of p' sample B is at a higher than critical voids ratio ("wet") and during a drained test will contract undergoing a reduction in voids ratio as the sample moves to the critical state line. This behaviour in an undrained test, typical of the Cowden procedures, might be expected to show an increasing pore-pressure in a similar manner to that described for a normally consolidated soil. In contrast, a sample represented by point A has a voids ratio lower than the critical voids ratio and can be described as "dry". This soil should exhibit dilation during a drained test matched by a reduction in pore-pressure for undrained shear.

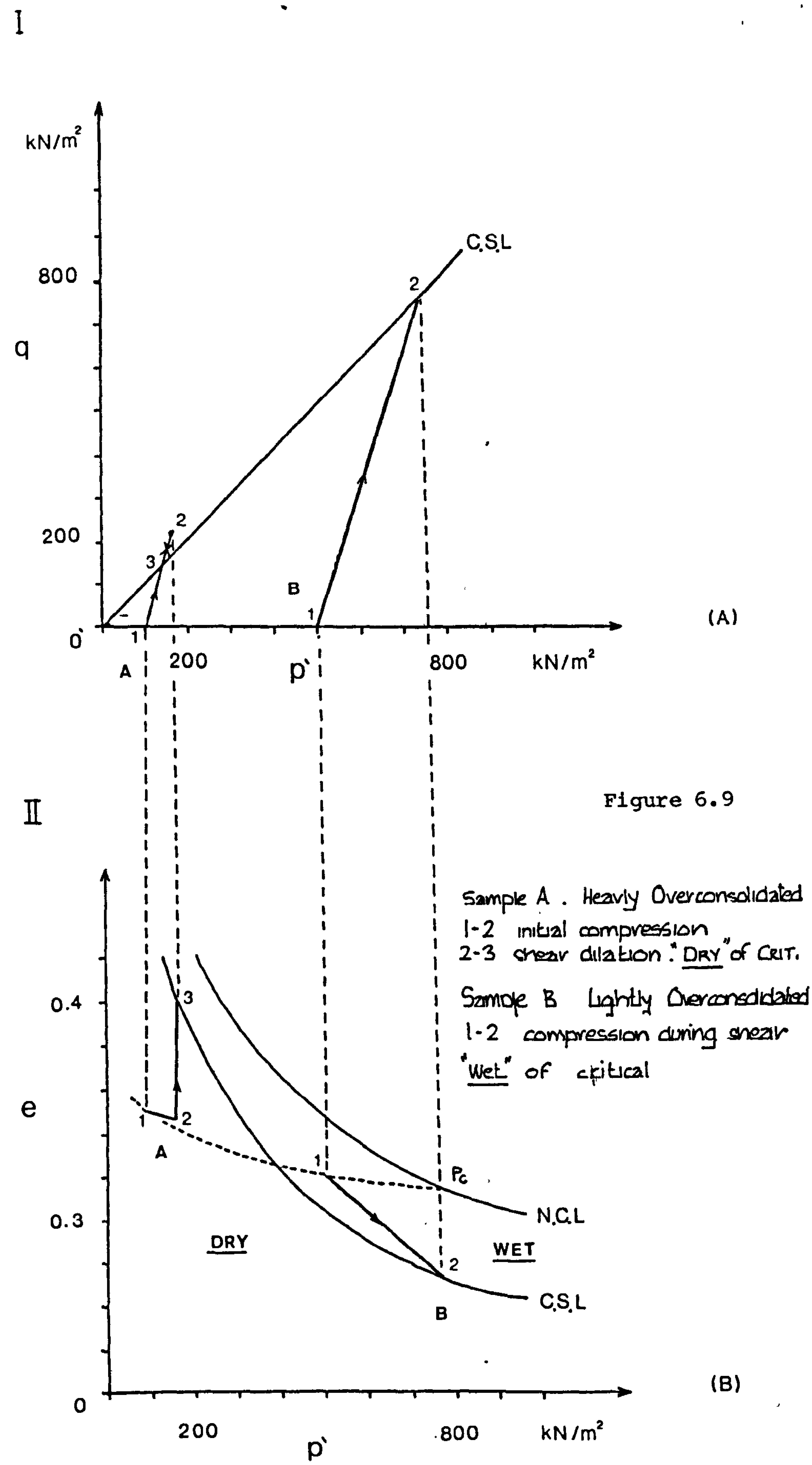
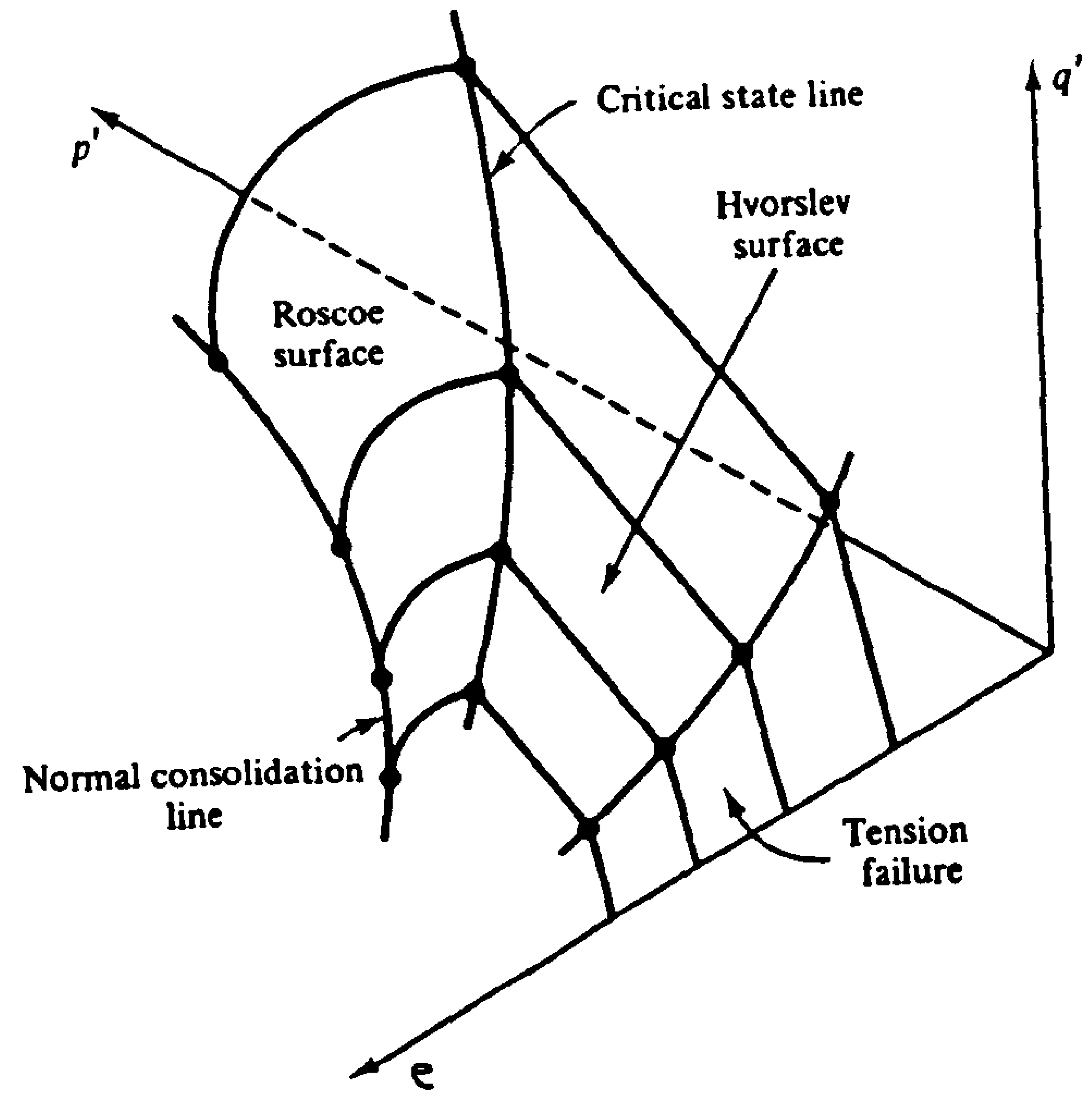


Figure 6.9

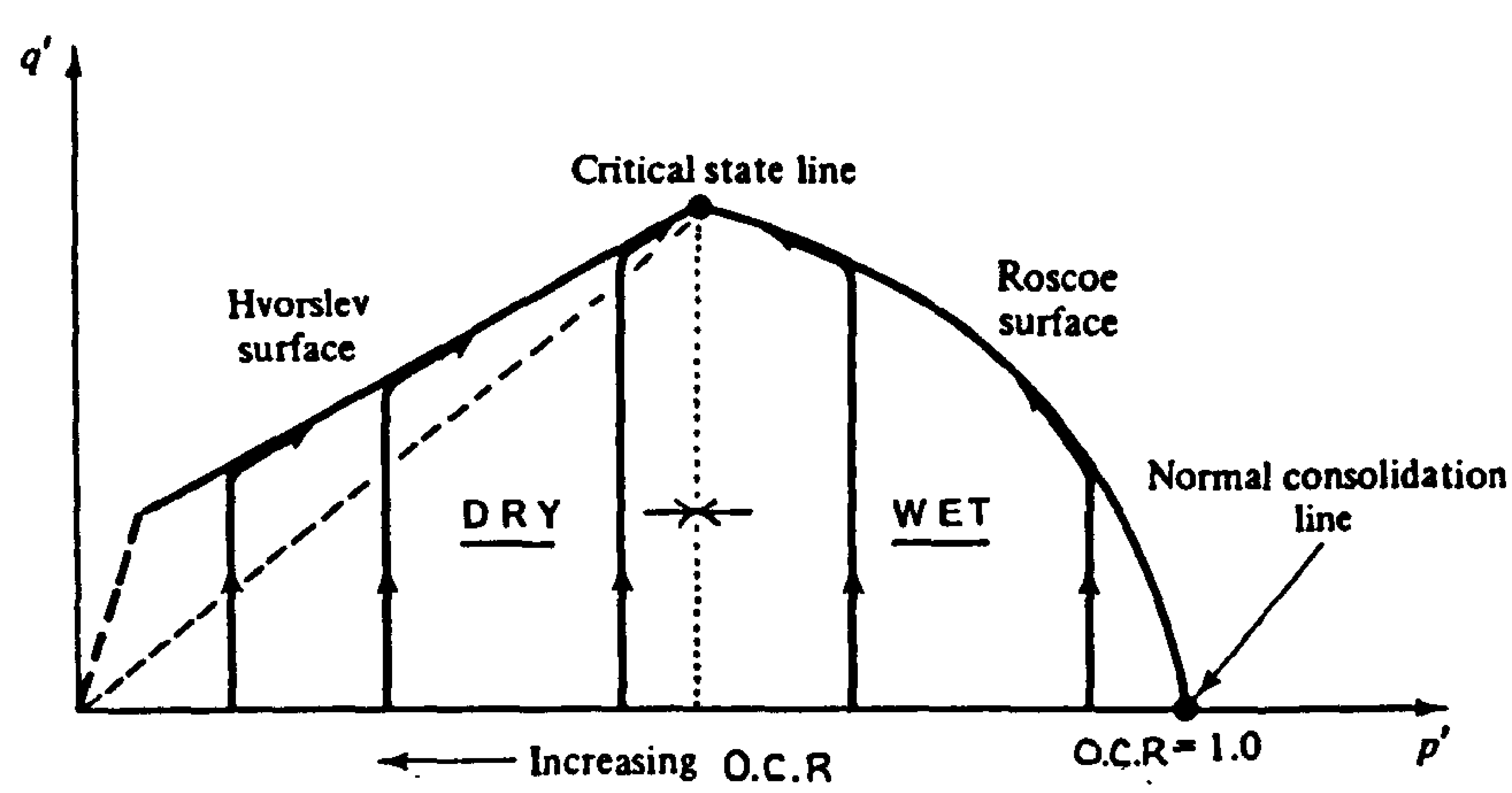
Failure states and stress paths on samples at varying overconsolidation ratios in drained shear

Figure 6.10.

A) The complete State Boundary surface in q, p', e, space with the Hvorslev surface



B) Ideal undrained test results for samples at different overconsolidation ratios
Atkinson and Bransby (1978)



adapted from Atkinson & Bransby 1978 pp 222

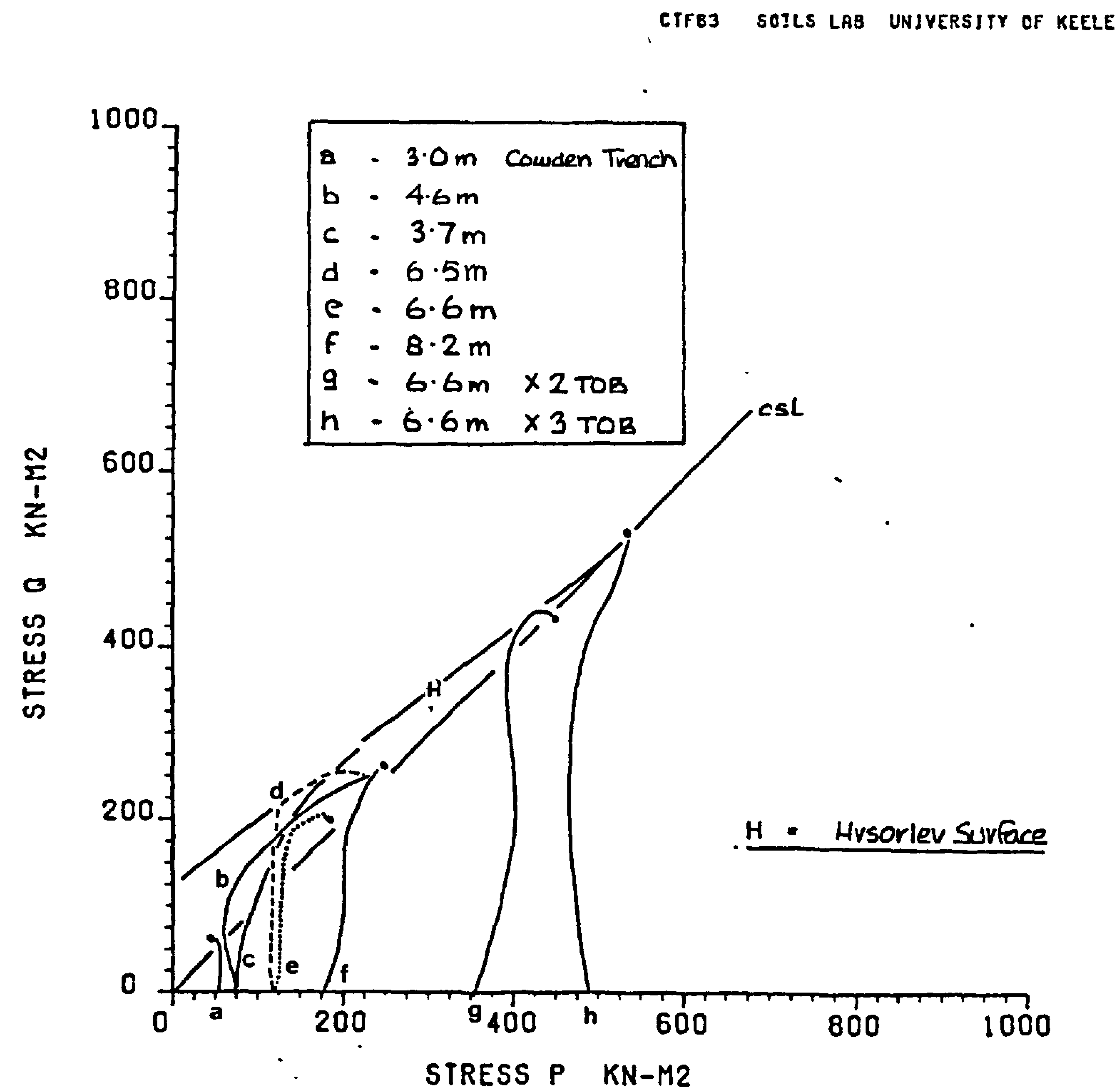


Figure 6.11

Stress paths for various undrained tests on the Cowden diamict plotted in p'/q space

According to Atkinson and Bransby (1978) the stress paths for overconsolidated soils tested at constant ratios of p/pe should define an envelope contiguous with the Roscoe surface at the critical state line which forms a complete state surface as shown in Figure 6.10. This has been termed the Hvorslev surface. Figure 6.11 displays the complete stress paths for selected undrained tests on the till profile at Cowden which generates a surface as predicted.

Figures 6.12 and 6.13 show a typical surface for the Cowden diamict and its interception with a drained and undrained plane. It can be seen that in a drained test the Hvorslev surface is attained a higher value of q and moves down towards the critical state line. The sample will soften as it dilates and takes in moisture. This path will be used extensively when considering the depositional model in Chapter seven. An undrained plane, typical of the test results, contacts the critical state line at its highest point, thus the maximum stength occurs at the critical void ratio and the stress strain curve will not display a well defined peak.

Figure 6.14 shows the state paths associated with undrained tests on the till at various overconsolidation ratios (Sample CS3/32 10.9m), plotted on normalised axis. The Hvorslev surface is attained at peak b'1/b'3 ratio after which the sample moves along the surface to intercept the critical state line. In the multi-stage test the shear was stopped at the Hvorslev surface and the sample reconsolidated to be sheared again at a lower O.C.R. As described in Chapter three, within the context of the Mohr-Coulomb failure model, the degree of dilation or development of negative

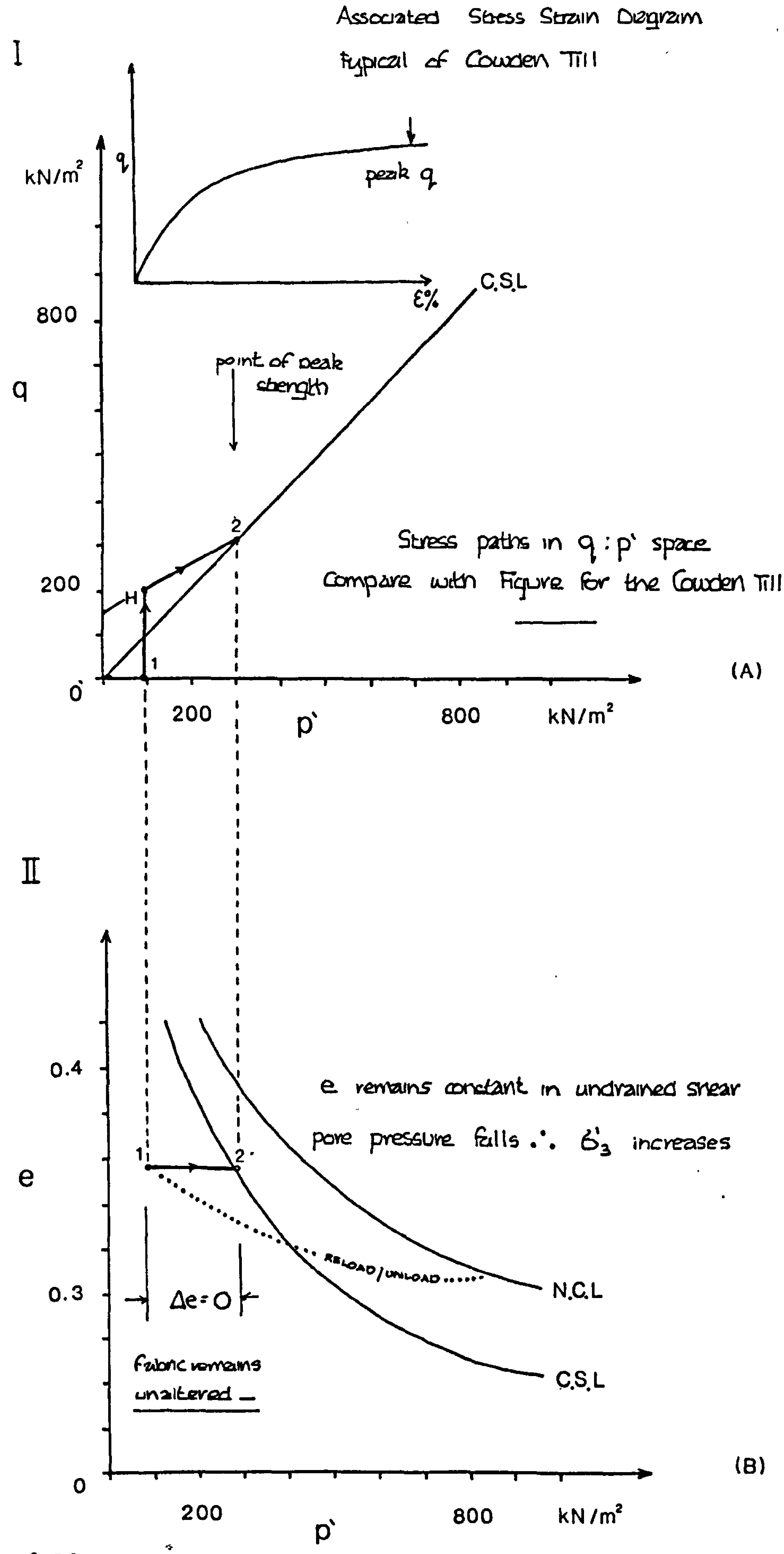
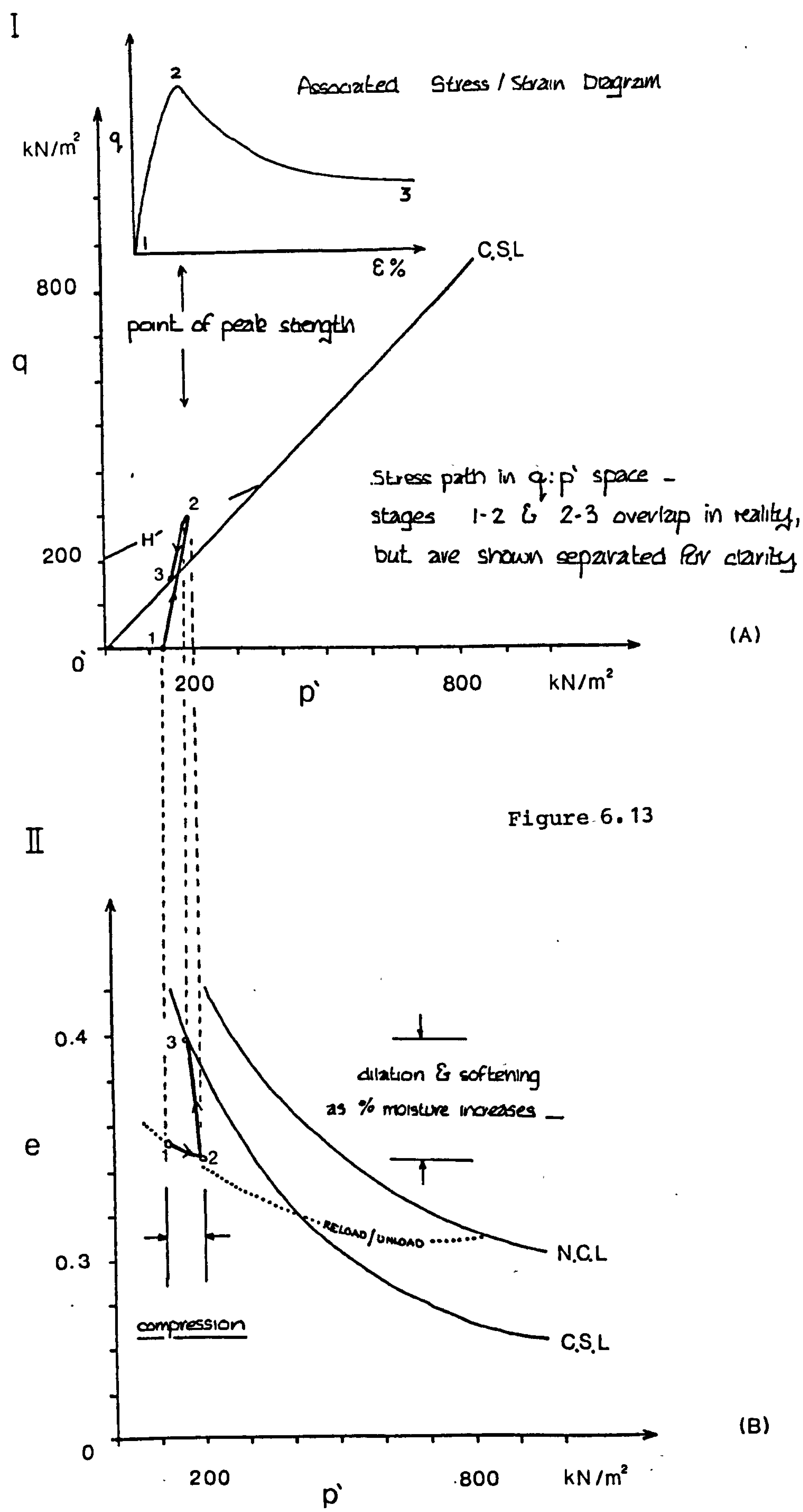


Figure 6.12

Associated stress/strain diagram typic of the Cowden diamict



6.13 Relationship between the Hvorslev surface and drained planes for an overconsolidated clay till

Stress paths in normalized q, p' space for a consolidated undrained multistage test
CS 3/32 10.9m Cowden

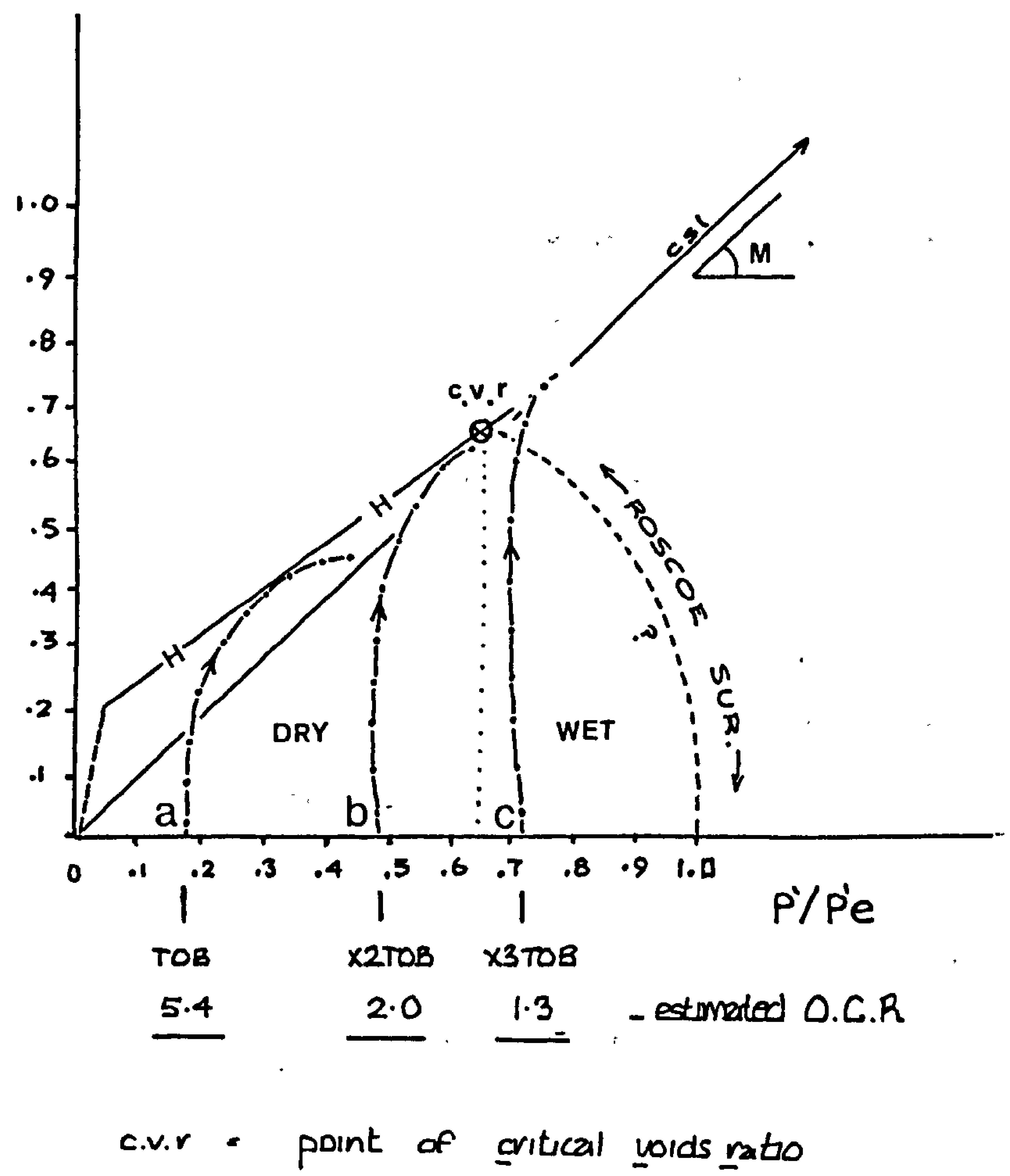


Figure 6.14

pore-pressures (as reflected in Skempton's A coefficient) during shear is a function of O.C.R. This is directly reflected in the distance between the failure state and the critical void ratio. Significant development or re-orientation of soil fabric can only take place under drained conditions when volume change is allowed.

Anomalies in the Model For The Cowden Tills.

With reference to Figure 6.14 it should be clear that at higher consolidating pressures the till should begin to show a degree of compression/positive pore-pressure response with shear as the soil moves to a position "wet" of critical. However even at consolidating pressures <400 kN/m^2 the sample continued to show a significant generation of dilation/negative pore-pressure although reduced in range. This can be explained by the fact that after the initial failure, deformation and strain becomes non-uniform with secondary zones of failure forcing further dilation, so that, even at high strains, the critical voids ratio is never truly reached throughout the entire specimen. It should be noted that for many of the tests, deviator stress was still rising at strains in excess of 24%. The poorly sorted nature of the till could also be a factor contributing to this effect, since the high densities attained in the initial packing could result in higher than average dilation resulting from partical interaction once sheared. The fact remains that lodgement till, for whatever reason, is highly dilatant when sheared at low effective stresses.

CHAPTER 7

A Geotechnical Model for an Active Ice Sheet in Eastern England.

7.1 Introduction.

The basis of any model is the acceptance of certain conditions which both clarify and simplify the modelling process. This is particularly true when analysing the Pleistocene ice sheets at maximum extension since no area in the world today supports an ice sheet, overlying unlithified sediments, at such low latitudes. Consequently, precise information on glacier dynamics or the climatic/physical situation must remain purely speculative since there can be no modern analogies on the macro scale. It is not within the terms of reference of this study to analyse critically the broad spectrum of lodgement theory on physical grounds, only to assess whether the sedimentology, fabric and geotechnical behaviour observed can be explained in terms of the mode of deposition and subsequent modification. The depositional models used as a basis for study are those proposed by Boulton (1972) and Boulton and Jones (1979), which are particularly well suited to the analysis of low latititude ice sheets.

The assumptions embodied in the preceding analysis, using p',q,e space, can be listed as follows.

(1) The ice sheet was wet-based and active at its maximum extension.

(2) The effective stresses at the glacier sole were low, not exceeding 600 kN/m^2. The lodgement process was active at stresses in excess of 200 kN/m^2.

(3) Effective stress was controlled primarily by the efficiency of the drainage pathways and as such, was intimately related to the

permeability of the bed and the subglacial hydrology.

(4) Shear, both at the glacier sole and in the proglacial environment, followed drained paths.

7.2 Initial Conditions: Thermal Regime and Glacier Load.

The assumption of a wet-based (temperate) ice sheet is central to the theory since the geotechnical relationships of an ice body frozen to its bed cannot be accurately represented by simple effective stress theory. Previous depositional theories, related to the North Sea ice sheet, propose an active subglacial hydrological system, implicit with temperate ice bodies, from purely sedimentological evidence, (Eyles, Sladen and Gilroy 1982, Eyles and Sladen 1981), while the same assertion has also been supported by a more mathematical approach (Boulton et al 1977). The evidence from Cowden and coastal locations supports these findings particularly with respect to the intra-formational sand and gravel lenses which were well documented during fieldwork. If the greater proportion of the Withernsea/Skipsea till succession is subglacial in origin, and all the evidence points to this being the case, it is difficult to envisage any other mechanism, other than an active wet-based glacier which could have produced such a thickness of deposit (30-40m) in the short time period allowed within current chronological theory (Madgett and Catt 1978).

In line with observations of modern temperate glaciers, it is proposed that the majority of the debris transported by the North Sea ice sheet was carried in a thin (<0.5m) basal zone. The vertical movement of such debris would be limited by the process of plastic flow and pressure melting. Unlike modern glaciers however, the supraglacial load would have been minimal since the sources of such debris, nunataks and valley sides, were limited to the North York Moors (Upper Jurassic outcrop) and upper Pennine Peaks (Carboniferous outcrop) and therefore could have supplied only the western flank of any North Sea ice sheet. As a consequence, the englacial load, starved of both a subglacial and a supraglacial supply, would have been a minor component of the total transported load creating essentially "clean ice". The implications of this analysis to the sedimentary succession is to limit severely the importance of meltout or flow till in any interpretation placed on the Holderness till succession, since englacial and supraglacial debris provides the principal source of supply at the ablating ice margin for both facies types (Boulton 1970, Paul 1981). Any theory which attempts to propose such an origin for the Withernsea Till must first explain how the material moved into an englacial position without widespread basal freezing and thrusting, for which there is no evidence at this level, or was derived from a supraglacial position, without any exposed Permo-Triassic sequences, and then melted out while retaining the geotechnical and sedimentological characteristics of the basal Skipsea Till ...(See Chapters 3-4).

These assumptions do not totally rule out the possibility that basal freezing or some elements of flow are not recorded in the Holderness sequence, only that the sources of such sediments were primarily subglacial. Indeed some degree of basal refreezing must have occurred in view of the evidence of contemporary permafrost beyond the margins of the Pleistocene ice sheets, although this may only have been important in the initial advance over the pre-Devensian sediment suite. It is notable that the only evidence of widespread incorporation involving "raft erratics" and brittle fracture occurs at the base of the Skipsea Till with the inclusion of the highly slickenslided "Beach Clay" exposed at Aldbrough (TA 258397) and Dimlington Cliff (TA 386224 - TA 408184).

7.3 Subglacial Pressure : Effective Stress At The Glacier Base.

The effective pressure at the glacier/bed interface may be much less than the ice overburden if a high subglacial water pressure exists. Subglacial water is derived at the base of temperate ice by melt created by frictional heat allied with the geothermal heat flux. To maintain equilibrium, this water must move to the ice margin along several possible pathways as follows.

1) Subglacial channels moving under a hydrostatic head (Rothlisberger 1972)

2) As a thin layer at the ice/bed contact.

3) As pore water under a hydraulic gradient.

Weertman (1972) suggested that a dense interconnecting channel system cut into the bed, (Nye channels), or incised up into the ice (Rothlisberger or R channels), cannot exist beneath a glacier taking into account normal ice dynamics. He concluded that drainage normally occurs along a single large subglacial channel found along the glacier thalweg. This hypothesis can be compared to the lobate pattern of "channels" that exist offshore, described by Robinson (1968) as subglacial drainage conduits for the Holderness ice sheet. A study by Hodge (1979) concludes that similar channels under a modern glacier carry water principally from englacial and supraglacial melt rather than draining directly from the ice/bed water system. Even in these actively draining areas, the water pressures were in the range 50-75% ice overburden pressure. The effective stress over the great proportion of the glacier bed can therefore be seen to be primarily controlled by the

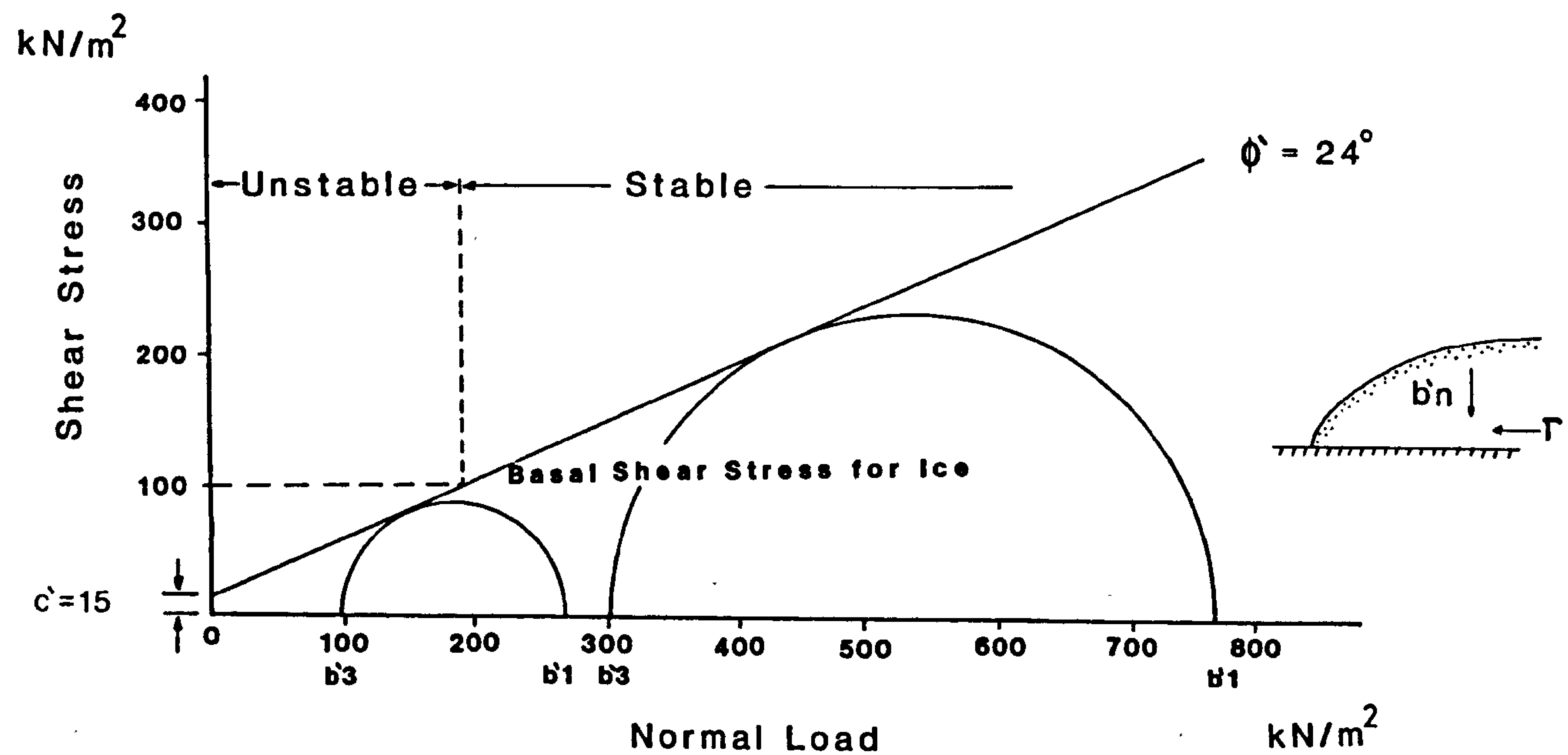


Figure 7.1 Stability of a till bed with properties $c' = 15$ kN/m, $\phi' = 24^{o}$ under basal shear = 100 kN/m^2

permeability of the bed itself. This principle forms the basis of the theory presented by Boulton and Jones (1970) who suggest that if bed transmissibility is high and meltwater is readily discharged, a stable bed creates a glacier profile controlled by the rheological properties of the ice alone. If bed transmissibility is low, pore pressures increase and reduce the strength of the bed as the effective stress decreases. The bed will eventually deform and a lower equilibrium profile will develop so that in the extreme case the glacier profile approximates a flat sheet similar to an ice shelf. Under such conditions, the glacier might be expected to maintain its activity since a thin ice body would be more responsive to changes in mass balance, even though several hundred kilometres from its source area (Boulton and Jones 1979).

Actual figures for effective stress at the glacier sole are harder to estimate although it can be seen that for a till bed with $c' = 15kN/m^2$ and $\phi' = 24$, with a constant basal shear stress in the order of 100 kN/m^2 (Boulton 1975), effective pressures lower than 200 kN/m^2 are likely to permit deformation the bed (Figure 7.1). Data for such a theoretical till bed placed into Boulton's model suggest that a steady state ice profile would develop with an ice thickness approaching 400m at a distance 200km from the source. This creates a basal pressure approaching 3570 kN/m^2 for a dry bed. If the pc pressures of the Cowden till (275 kN/m^2) represent the true basal effective stress at the time of deposition, this suggests that the basal water pressures must have been in excess of 90% the total overburden, not an unrealistic figure when the highly impermeable nature of the till is taken into account. Engelhardt et. al. (1978) recorded a layer of material between bedrock and

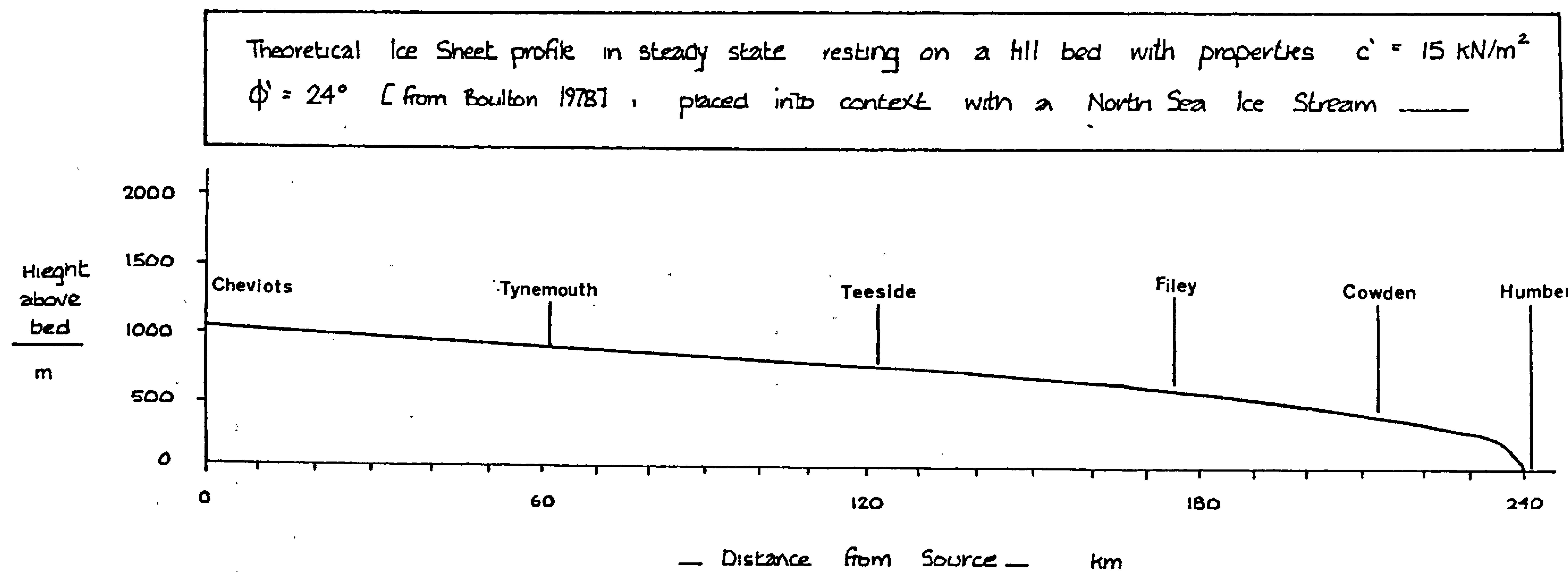


Figure 7.2 Theoretical ice sheet profile in steady state resting on a till bed with properties $c' = 15$ kN/m^2, $\phi' = 24^{\circ}$ placed into context with a North Sea ice stream (after Boulton 1978)

glacier sole which was saturated with water at a pressure "near the ice overburden" for the Blue Glacier, Washington State, U.S.A.

7.4 Proposed Stress Paths For Deposition And Subsequent Modification Of Basal Till.

The geological history of the till profile can be broken down into a series of events, the definition of an event being that it must be representable by a line segment in effective stress space. As noted above the shape of the segment will be controlled by drainage as well as external stress changes. Difficulties occur when two or more events are concurrent rather than sequential. In such a case the stress paths must be superimposed and a composite segment obtained for them. Since an active ice sheet is proposed, modification at the ice margin is considered as well as the effect of a glacial readvance. In total four situations are examined :

1) The subglacial environment, erosion and deposition.
2) Proglacial environment.
3) Readvance of the ice margin.
4) Deglaciation and post-glacial modification.

7.4.1 The Subglacial Environment.

At the point of deposition at the glacial base, till must be considered as a normally consolidated clay since, by strict definition, it has previously encountered no greater normal load. Similarly, with constant effective stress and further accretion at the glacier sole, a depth of sediment must develop which possesses the characteristics of a dense, but normally consolidated soil moving on or just above the $K_o = 0.7$

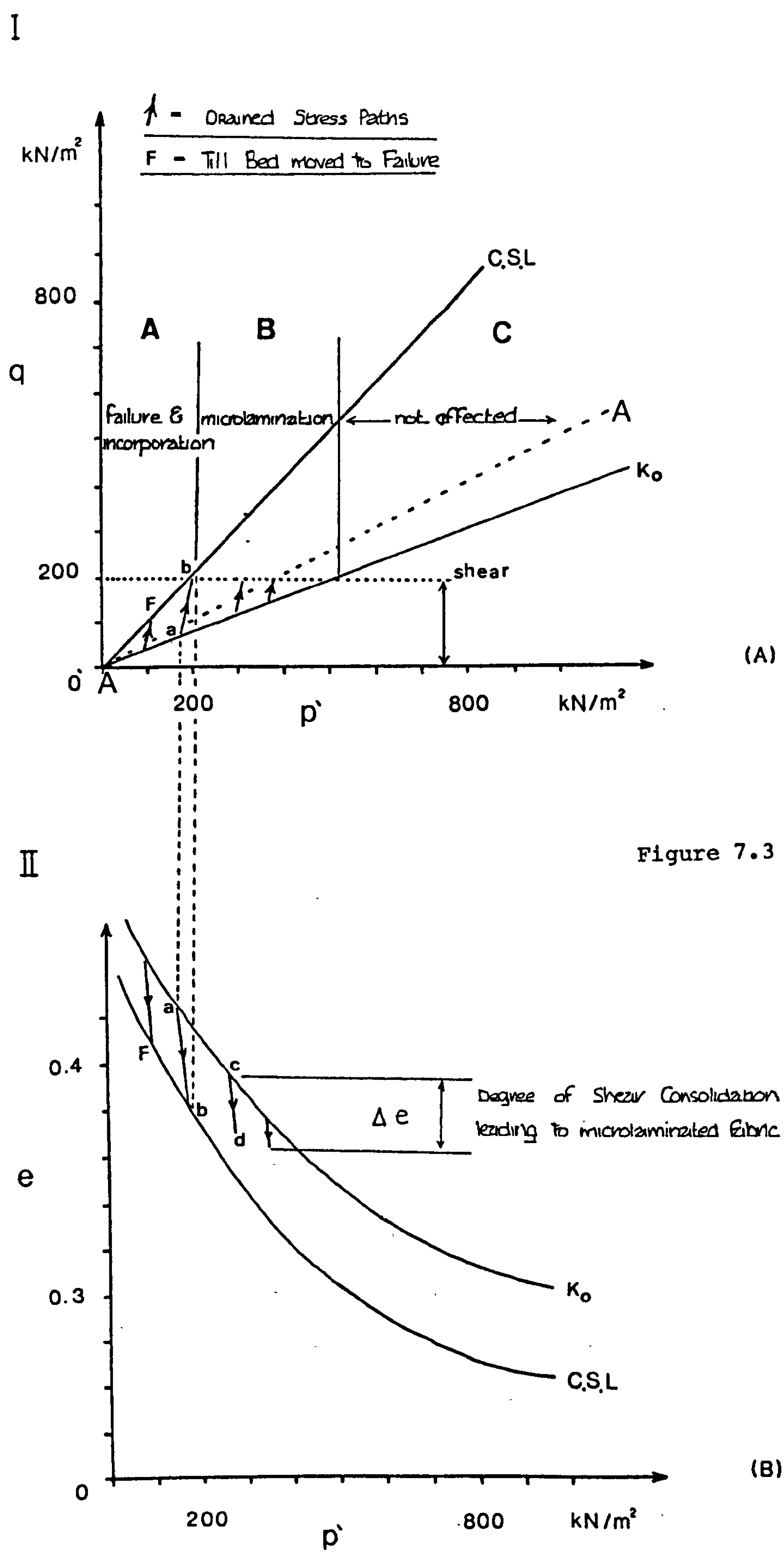


Figure 7.3

Proposed Stress Paths for a Till Bed undergoing shear in the subglacial environment line in q/p' space. An alternative model could incorporate the observation that basal diamicts are deposited under conditions of both normal load and shear (Boulton 1975 and Section 5.8) by varying the initial ratio of q/p' (increasing the slope of the line A-A so that it lies between the line for Ko and the CSL (Figure 7.3). The shear stress at the till/ice interface is limited to a value between 50-150 kN/m^2, depending on the frictional resistance of the bed and ice velocity (Nye 1957). To standardise the plots, a basal shear of 100 kN/m^2 has been used. Considering an effective stress of 450kN/m^2 and the slope of the critical state line derived from the analysis of the tills (Figure 7.3), it can be seen that under drained shear and low effective stress (<200kN/m^2) the bed would readily deform. The effect of bed deformation on the stability of the till depends to a large extent, on the rate of strain. Under the low effective stresses and increased strain the dense interlocking fabric will be destroyed creating a more open, dilatant structure. The higher voids ratio would allow the pore fluid to move away from the zone of failure, transmitting the normal load back to the soil structure and therefore maintaining stability. If, however, the rate of strain exceeds the capability of the soil to increase the normal load by increased fluid transmissability the bed may well move to failure. Under such conditions the shear strength of the bed will be reduced to a level where it would be unable to resist the frictional drag of the basal ice, forcing the layer back into traction. This process is seen as acting in localised areas in reponse to a change in the pattern of subglacial drainage and variations in ice velocity.

At intermediate levels of p' (200-500kN/m^2), the bed might be expected to undergo a degree of fabric reorientation related to shear,following a line c-d (Figure 7.3) although failure is not initiated and the bed remains stable. The degree of fabric reorientation would vary inversely with the rate of strain and the depth beneath the glacier sole, since shear stress decreases while effective stress increases, both effects tending to mitigate the amount of shear consolidation.

This mechanism could account for the micro-lamination encountered at the Cowden profile at depths of 3m and 6.4m. Similar features are described in North American tills of the last glacial stage (Wisconsin) by Sitler and Chapman (1955), who dismiss the possibility that the fabric could simply be the result of isotropic compression since they describe positive evidence of anisotropy in the study of thin sections induced by subglacial shear. It should be noted that the high degrees of orientation observed in the natural state were never achieved in the laboratory consolidation of the Holderness tills, even to the extremes of normal loading (4600 kN/m^2 Sample CT 49).

Figure 7.3 suggests that although sample B has undergone shear consolidation, the difference in the final voids ratio and a sample at point b will be negligible, the distiction between the till types being one solely of fabric orientation. One important point is that there is no noticeable fissility along these micro-planes which also supports the theory that they have never been mobilised to the point of ultimate failure, although it is possible that in long-term drained tests these could act as points for the development of low angle shears.

Within the limitations of the initial conditions, the effects of an increase in pore-pressure under stagnant ice can be modelled. This could be due to an increase in basal melt or a short term

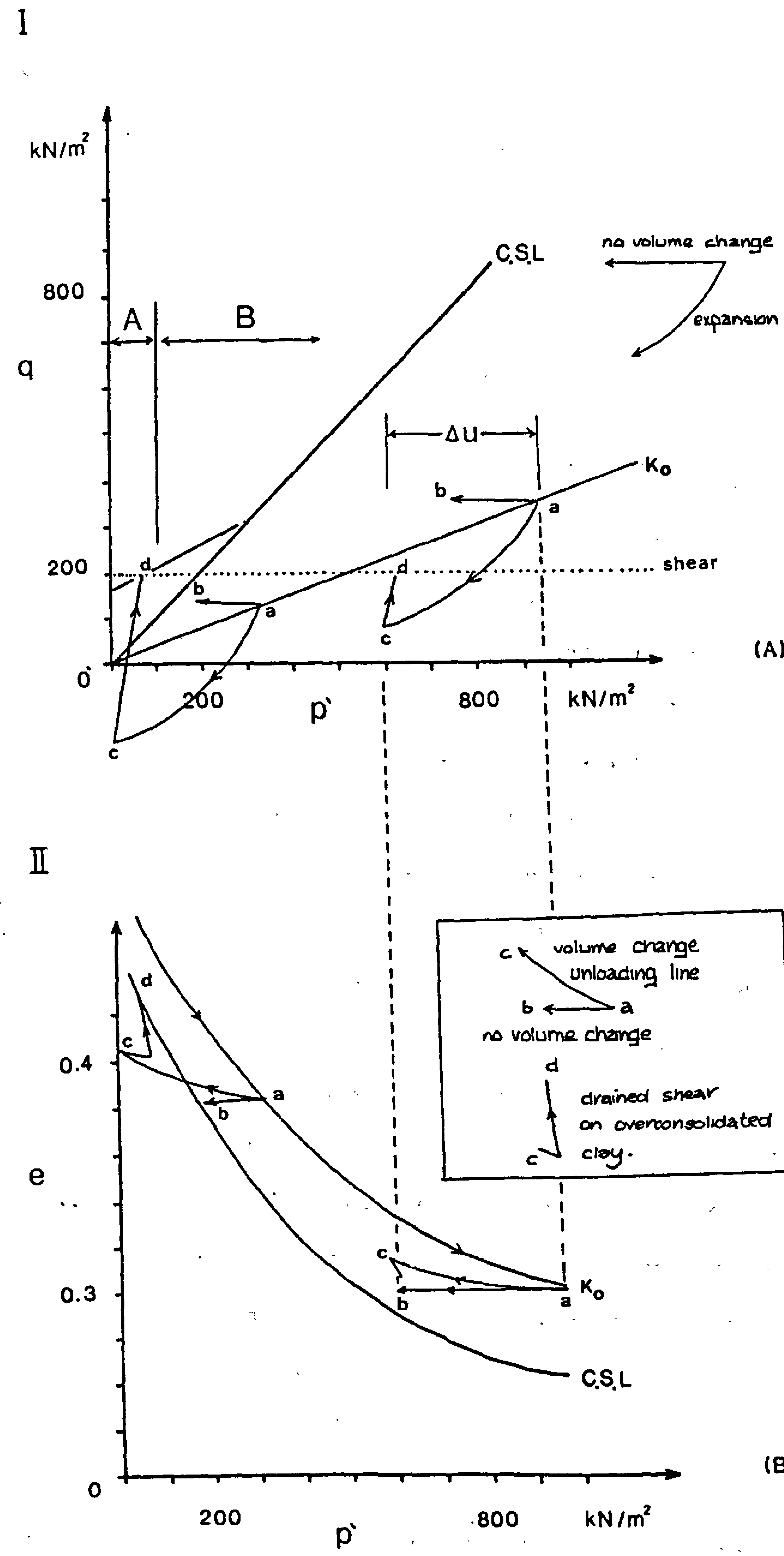


Figure 7.4 Proposed stress paths for two samples at varying pre-consolidation loads subjected to an increase in pore pressure followed by basal shear

change in the balance of the shifting subglacial drainage system, for example, a channel becoming clogged, diverted or closed by ice pressure (Eyles and Sladen 1981). Two stress paths can be proposed (Figure 7.4). The first involves the development of excess pore-pressure with no associated volume change, caused by the contact with a large hydrostatic head, which would move the till bed along an undrained plane ($\Delta e = 0$, a - b) to the new position of p'. If this stress path intercepts the Critical State Line for the material, failure would be induced once shear was reimposed. However, this situation is unlikely to be achieved in reality, owing to the highly impermeable nature of the bed and the fact that an overconsolidated clay till would immediately react to the lower values of p' by moving along a swelling line a-c to reach an equilibrium with the lower confining pressure.

Once equilibrium is obtained activity at the glacier base would reimpose basal shear stress creating highly unstable conditions with samples in Zone B being recompacted and samples in Zone A reincoporated into the sole under drained shear.

Figure 7.5 shows the proposed stress path in q,p',e space for dilation at the ice margin. Increased volumes of water at the glacier snout would raise pore-pressure while the total stress imposed by the ice thickness would decrease. Most workers accept that the snout is an area of low effective stress where shear is most likely to occur (Rotnicki 1983). For an active ice sheet where frequent retreat and readvance events are likely, the till profile would be subjected to shear during both phases.

As the ice retreats and the area of low effective stress approaches the till sheet deposited under conditions pc = 500 kN/m^2, the bed would move on a rebound line to a point where b'3 = 75 kN/m^2, in equilibrium with conditions at the snout. The

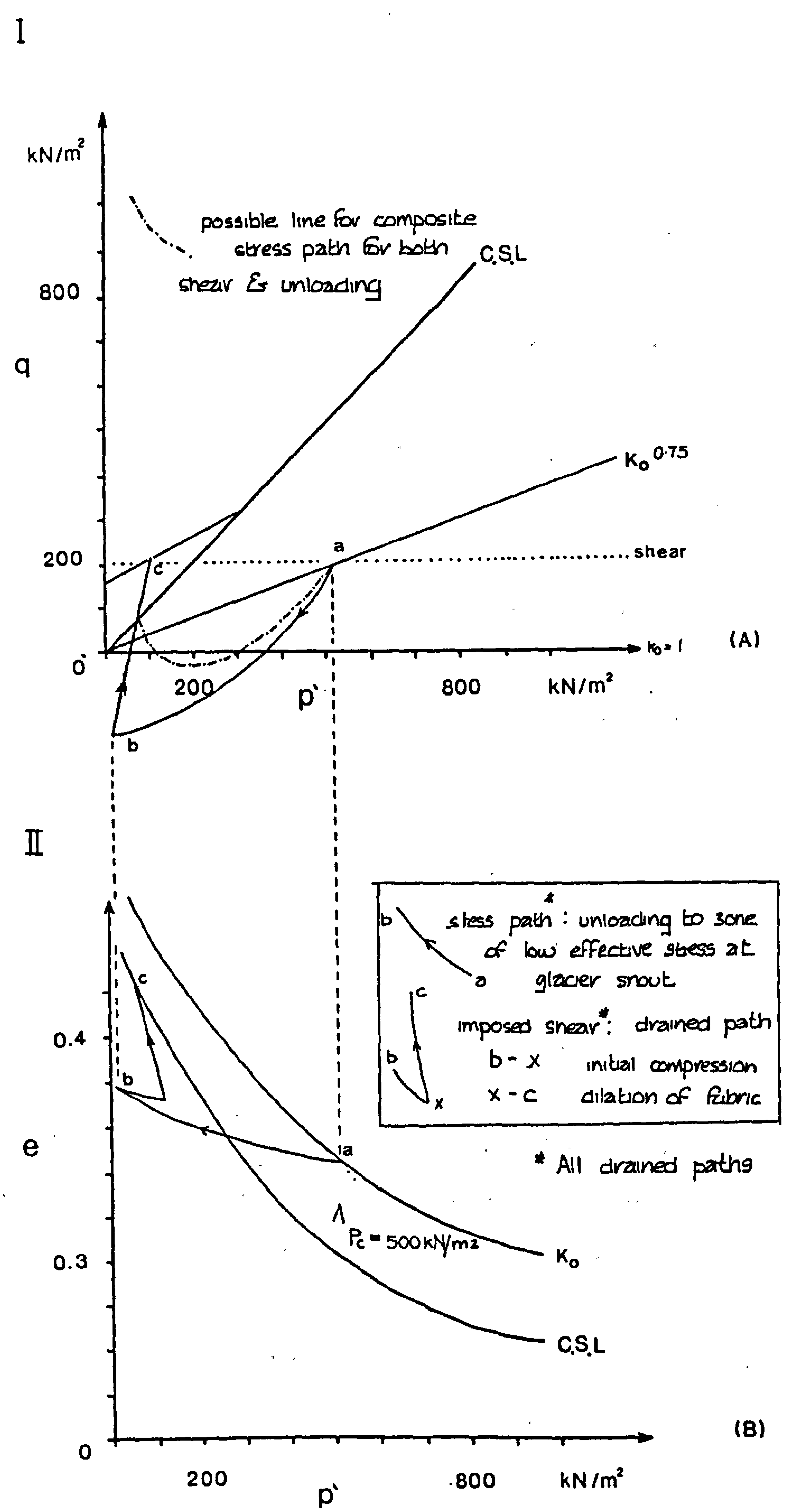


Figure 7.5 Proposed stress path for a till bed undergoing shear in the zone of low effective stress at the glacier margin

overconsolidation ratio of the sediment would approach 10 (Ko = 2), with a slight increase in moisture content allied with volume expansion. Under such circumstances a shear stress of 100 kN/m^2 would be sufficient to move the bed along a drained path to the Hvorslev surface where it would then move to the Critical State Line undergoing substantial dilation. The previous dense fabric would be destroyed to create a more open particle arrangement as observed by Boulton and Dent (1974), in the proglacial zones of modern glaciers. Subglacial till exposed at the retreating margin of Breidamerkurjokull, Iceland was described as possessing a two-layer structure; an upper horizon of high void ratio (0.68) and an underlying denser horizon (0.38) with a "platy" microfabric.

Several points are worth considering at stage. Basal shear stress is controlled principally by ice velocity and bed friction to a threshold value. At the snout of a retreating glacier, by definition, ice velocities are liable to be low and shear stress reduced from the more extreme values. Secondly, Penny and Catt (1969) have associated the development of micro-lamination in till fabrics to subglacial shear by overiding ice during a later glacial stage. Although a degree of compression is likely in a till bed sheared under low effective stress, this movement occurs along a plane which displays an elastic response which appears to rule out any substantial reorientation of the fabric. Owing to the fact that the surface shear stress would be initially lower and would attenuate with depth, the conditions are unlikely to be met where substantial compressive reorientation of the fabric could occur.

7.4.2 The Proglacial Environment.

The complete modelling of the

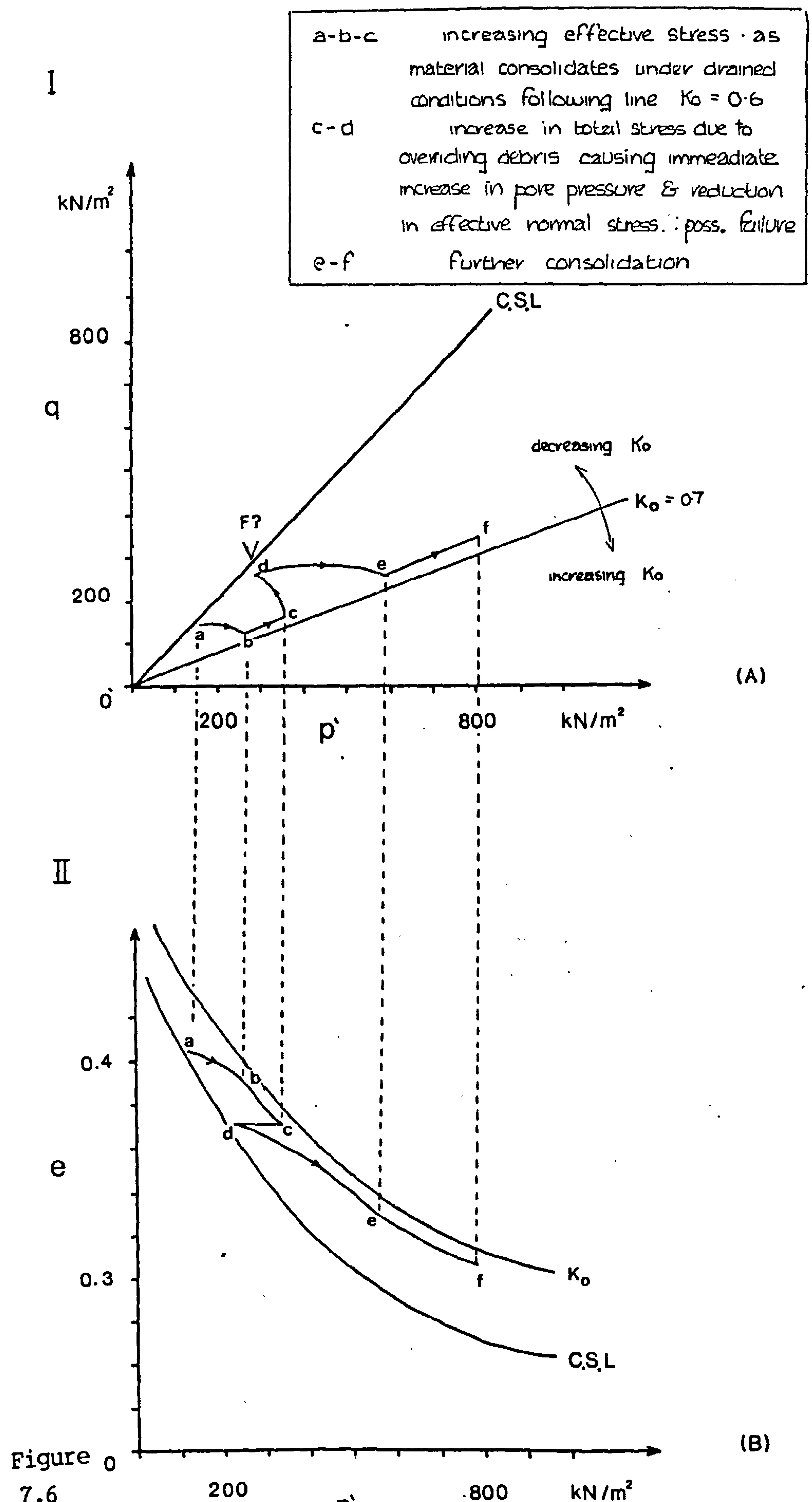


Figure 7.6

Proposed stress paths for an episodic increase in total stress due to the superimposition of debris at the glacial margin stress history of a soil subject to subaerial periglacial processes is outside the scope of the model, although several stress paths can be suggested, without reference to absolute values, based on the observations of Boulton and Dent (1974) as follows,

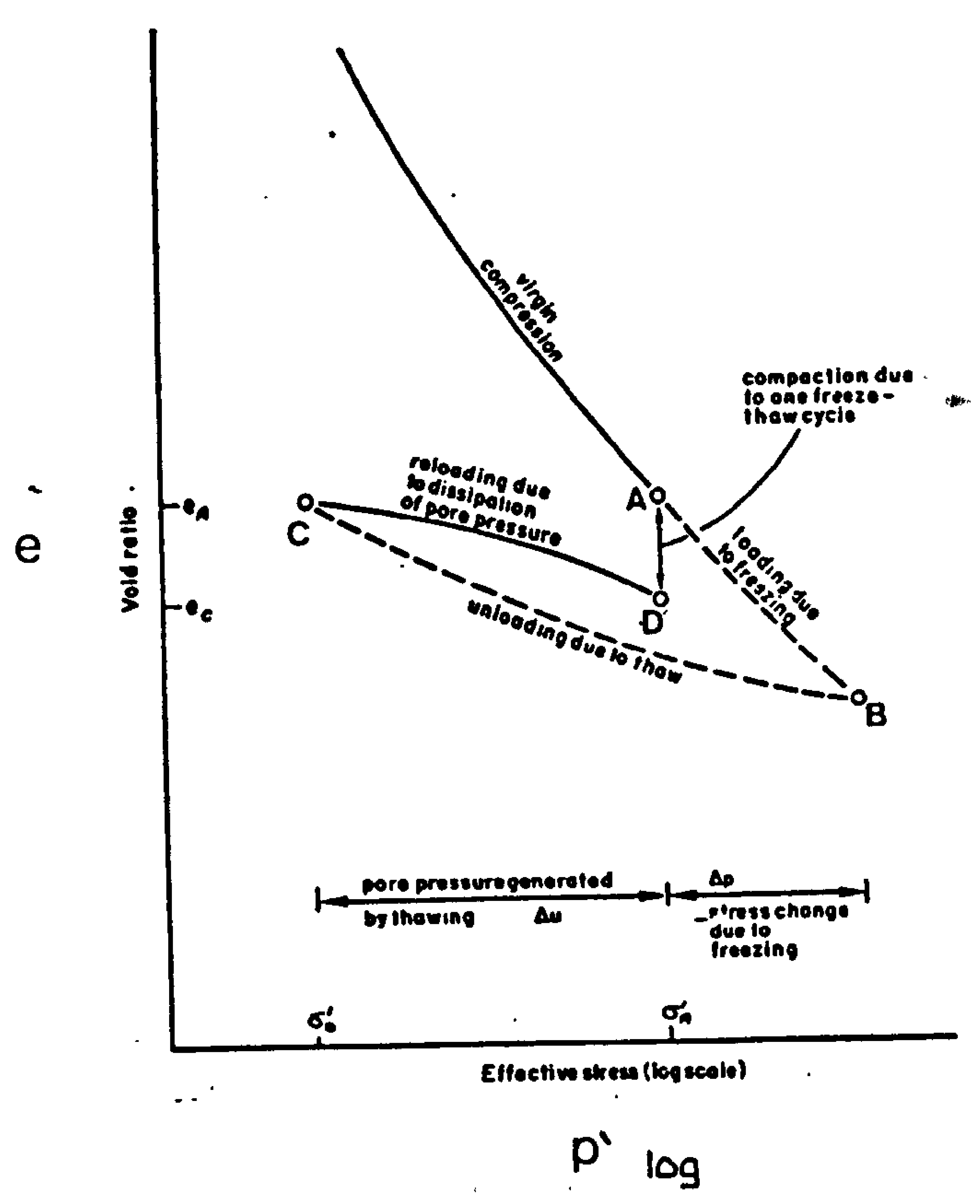
1) Increased drainage leading to fines depletion and collapse of the dilatant structure.

2) Freeze-thaw activity leading to consolidation of the soil matrix.

Once a till is exposed, the dilatant structure is quickly destroyed by the removal of fines by translocation creating a dense silt-rich layer and a lag gravel surface. At this stage the profile will be susceptible to loading by the superposition of debris from the glacier snout in a manner similar to that described by Paul (1981) for supraglacial till associations. The stress profile for an episodic increase in total stress is given in Figure 7.6. This consists of an increase in stress under drained or partially drained conditions followed by a period when total stress is constant and the pore-pressure dissipates. The actual path c-d is controlled by the drainage situation. It is obvious that the point F would lead to failure of the upper soil profile and its incorporation into a proglacial flow till unit.

Similarly, the consolidation of the soil is affected by the slope of the ground. If the ground is flat, the initial point must lie on the Ko line (Ko = 0.7) or if the ground slopes, the consolidation line moves towards the Critical State Line (Paul 1978). As a conseqence, melting of adjacent ice masses could steepen the local slope to a point where the Critical State Line was reached and failure initiated.

Figure 7.7



Effect of freezing on Compaction (based on Nixon & Morgenstern (1973) .... diagram adapted from Paul 1981 pp 65

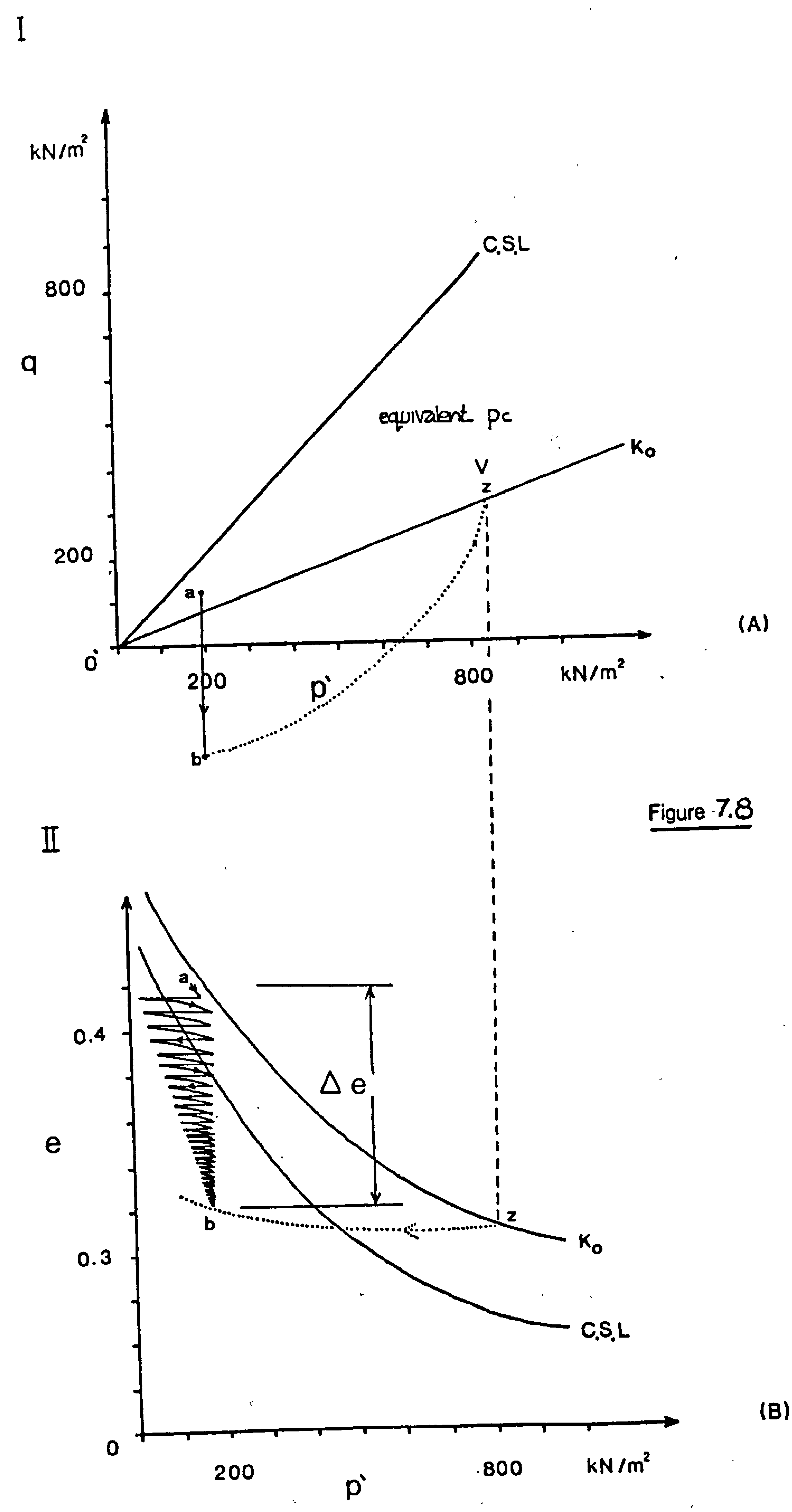


Figure 7.8

Possible stress paths followed by a till horizon with an open pore structure subject to repeated freeze-thaw cycles.

Effects Of Frost Action in the Proglacial Zone: A detailed examination of the effects of frost action, as given by Morganstern and Nixon 1971, is outside the scope of this study although it is necessary to examine how this process could produce a heavily overconsolidated soil which could be then incorporated into a till sequence by the readvance of the ice margin. Figure 7.7 shows a log p'/e curve for a normally consolidated soil undergoing a single freeze-thaw cycle. The p' is increased due to pore suction on freezing and the soil is effectively consolidated. On thawing an excess pore pressure is generated and the soil moves along the rebound curve to C. As the pore-pressure dissipates the soil moves back along the rebound line to the in situ effective stress with the new voids ratio (e1). The thaw settlement is thus the volume change in the reduction of voids ratio from A-D. If the soil is subjected to several freeze-thaw cycles there is further consolidation on each cycle until a lower limit is reached at constant stress (Figure 7.8).

The degree of consolidation is dependent upon the intensity and number of the freeze-thaw cycles as well as the frost susceptibility of the soil. Figure 7.9 shows that the size distribution envelopes of both the Skipsea and Withernsea tills fall well within the range of frost susceptibility and so might be expected to show the effect of freeze-thaw cycles. In addition, any dilatant soil, with an open structure enriched with silt at depth, would be particularly affected by such proceses. It is clear that frost action is capable of producing highly dense overconsolidated horizons characterised by high shear strengths and low coefficients of consolidation (Boulton and Dent 1974). The contention that the micro-laminated fabric could be the product of

Size Limits For The Frost Susceptability of Soils - Cowden Till Curves -

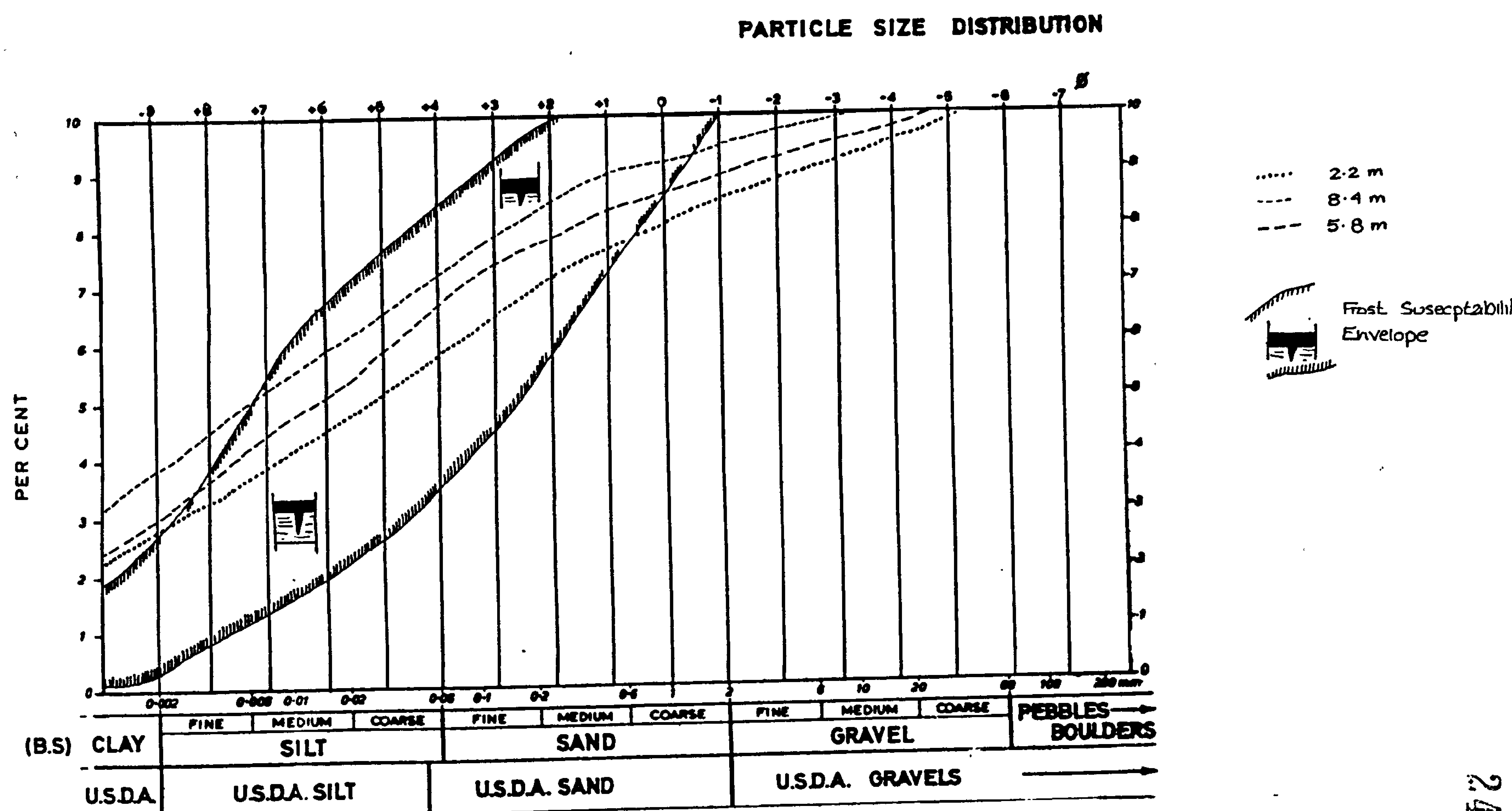


Figure 7.9 Size limits for the frost susceptability of soils

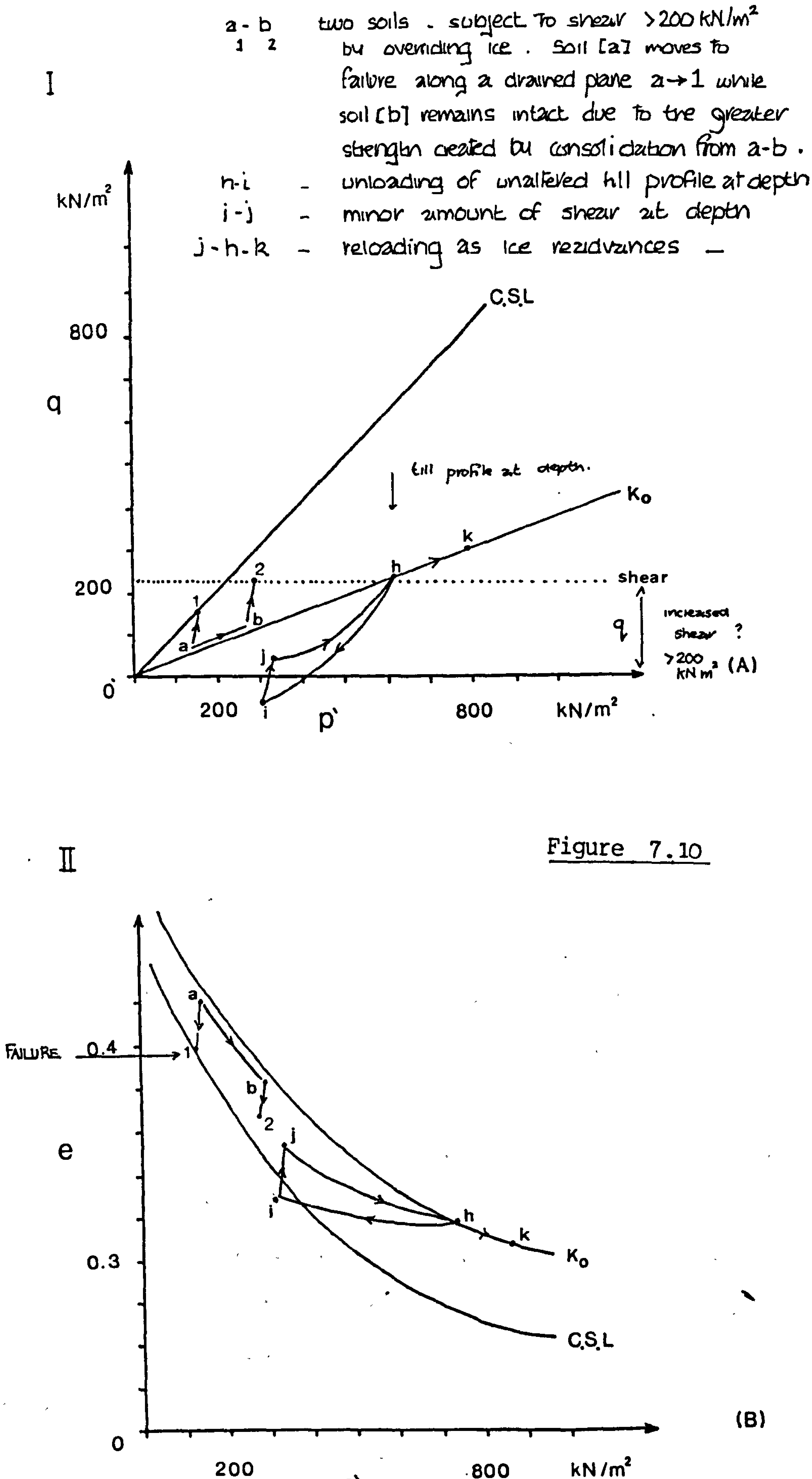
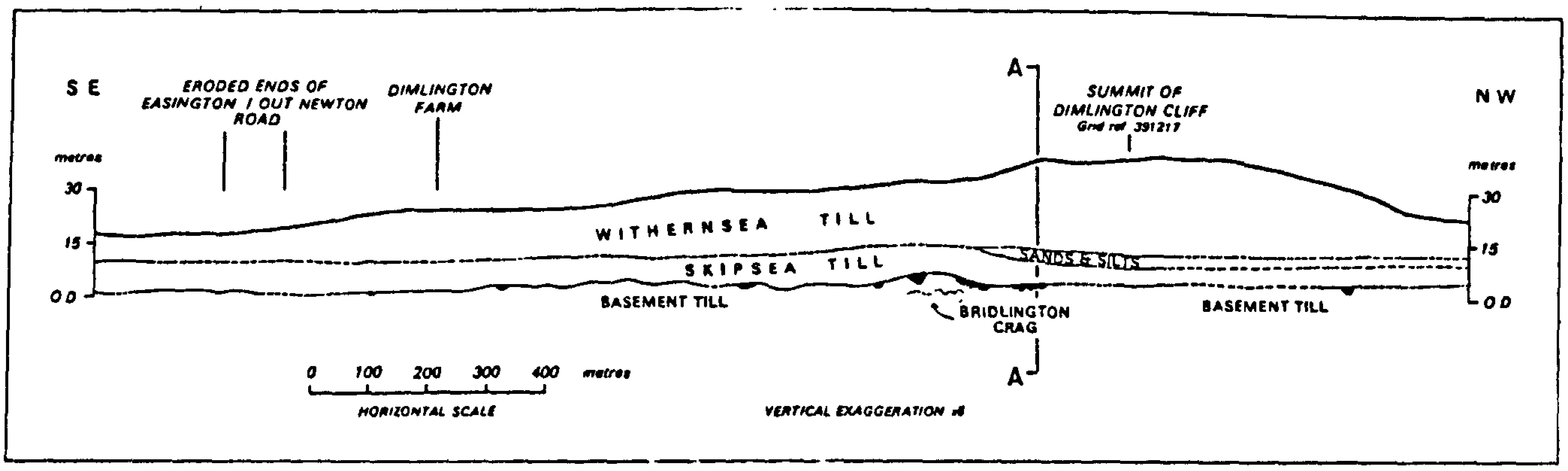


Figure 7.10

Proposed stress paths for material at varying levels of consolidation prior to ice readvance compaction of the soil by segregated ice lenses is not supported since it is difficult to see how the low permeability of the till at depth could support the growth of such features. Ice lenses have been reported within the upper profile (<0.5m) of modern proglacial zones where permeability is greater although no soil structure has been reported surviving a single season (Boulton and Dent 1974).

7.4.3 Readvance of the Ice Margin.

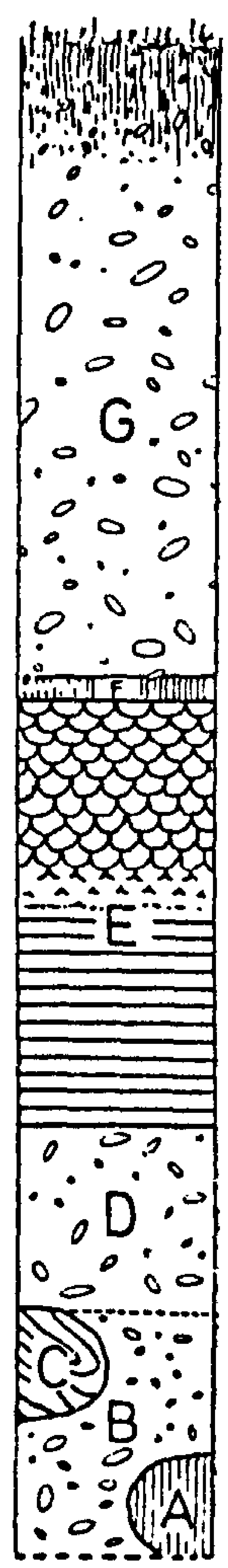
The readvance of the ice front would re-establish conditions of basal shear on the proglacial sequence. For flow tills and meltout tills which remain saturated at a high voids ratio this would result in remoulding and possible reincorporation into the glacier sole following a path of drained shear to the Critical State Line (Figure 7.10). Evidence of such processes could only survive where the soil has undergone some degree of consolidation, either through drying or an increased surcharge, which would ultimately lead to higher strength. Such a succession is seen at Dimlington cliff (TA 193678 - TA 202686) where a sequence of laminated grey clay-silts grade upward into silts with intercalated ripple and cross bedded fluvial sands (Figure 7.11). These are often conformable with a band of almost stoneless clay, although local erosional contacts can be seen. The transition from bedded sand, through flaser and lenticular bedding to banded stone-free clays suggests a progressive inclusion of saturated flowtill into a subaerial, ice-proximal environment. The type of till sequences described by Boulton (1967) provide a likely analogue, although for reasons explained earlier, the degree to which englacial or supraglacial material provided a likely debris source are questioned. The consolidation of the flow tills on a base of free-draining sand could therefore explain their survival



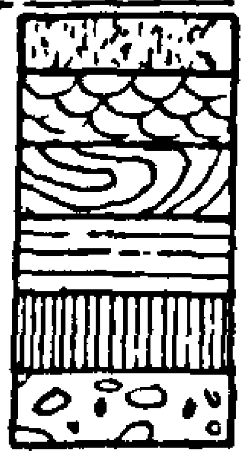
Dimlington Cliff after Inqua Guide (1977)

Section on A-A

Figure 7.11 Dimlington cliff profile



Lithology



Weathering Zone
Cross-Bedded Sands
Contorted Silts
Sub-Horizontal Silts
Clay
Till

0 5

M

in the face of a glacial readvance. It is noticeable that although flows of this type can be quite extensive at the snouts of modern glaciers, it is difficult to trace the existence of the "fossil" flows laterally where basal sands are absent. The possibility that these surface sediments were frozen prior to the ice readvance must also be considered when analysing the incorporation of this facies type into the Pleistocene record.

The character of a remoulded till sequence, sheared at low effective stress, marking the initial readvance of the ice margin over a proglacial association might be expected to be quite different from the equilibrium conditions of subglacial lodgement. Although basal remoulding would allow a degree of intermixing of soils and destroy all previous stress histories, this zone might expect to display a greater variation in size distribution which would ultimately affect the geotechnical behaviour through the plasticity index. The establishment of higher effective stresses and stabilized subglacial lodgement as the ice front advances further south would load this profile to the value of pc associated with the lodgement process and, allowing for free drainage, consolidate the dilatant fabric to a density close to that of the till.

The effect of a glacial readvance across unaltered lodgement till at depth would be to reload the profile to the point of maximum normal effective stress (pc), as ice thickness increases. For the reasons outlined earlier, when a phase of glacial retreat was under consideration, any soil at depths greater than 1-2 m is unlikely to be affected by the basal shear as the zone of low effective stress passes. Such material would therefore show little evidence of the activity of the ice front and would maintain the subglacial fabric imposed by the initial advance.

7.4.4 The Post-Glacial Period.

For the application of this model to the sequences exposed in Holderness, it is proposed that, apart from the gradual unloading caused by the the final decay of the ice sheet and the development of the Flandrian weathering profile, few events of any significance have occurred to alter radically the stress history of the deposits.

Features undoubtebly caused by stress relief are commonly observed in the coastal sections where cliff collapse causes rapid unloading, although these were not encountered in the Cowden boreholes which only sampled to a moderate depth.

The weathering profile has been examined in chapter 5 and was found to impose a consistent pattern across all three boreholes to a depth of approximately 4 m, below which the till is largely unaltered. The effect of weathering, and more importantly deforestation and cultivation, has been to destroy any remaining features of periglaciation in the upper profile which may have developed during the immediate post-glacial period. Indeed, Holderness is notable for the complete absence of such features (Eyles 1983).

Soderman and Yim (1969) have stressed the importance of considering the change in water table when assessing the geotechnical history of a sequence of deposits. Since the eustatic rise in sea level during the Flandrian, the base level has remained high, the only variation being the sporadic flooding of the Humber estuary around 4,500 BP and 2,000 BP (Catt 1977).

CHAPTER 8

Application of the Model to the Situation, Characteristics And Observed Geotechnical Behaviour Of The Holderness Till Sheet.

8.1 Introduction.

Although any model is, by definition, a simplification of reality it should attempt to explain the major characteristics of the till associations as defined by both geotechnical and sedimentological analysis. The processes outlined in Chapter 7 are therefore examined in relation to the known bedrock geology, accepted regional stratigraphy (Chapter 1) and the major features of the Withernsea and Skipsea tills as outlined in Chapters 5 and 6.

8.2 Surface Geology Prior To The Ice Advance.

Any ice mass moving down the East coast of England during the Devensian would have moved into contact with the offshore sequences recently mapped by the British Geological Survey (Sub-Pleistocene Map of the British Isles and Adjacent Continental Shelf 1979). It is a feature of the bedrock geology that, within a zone 20-30 km offshore north of Flamborough Head, no significant Pleistocene drift cover has been discovered (Figure 8.1, Caston 1977). The absence of a drift sequence may be explained by post-glacial marine erosion with the rise in sea level during the Flandrian, although the thickness of the Quaternary succession to the east and south, also affected by the transgression, appears to contradict this assumption. A more realistic proposal would be that this area was primarily a zone of erosion beneath the Devensian ice mass which stripped any pre-existing sediment and

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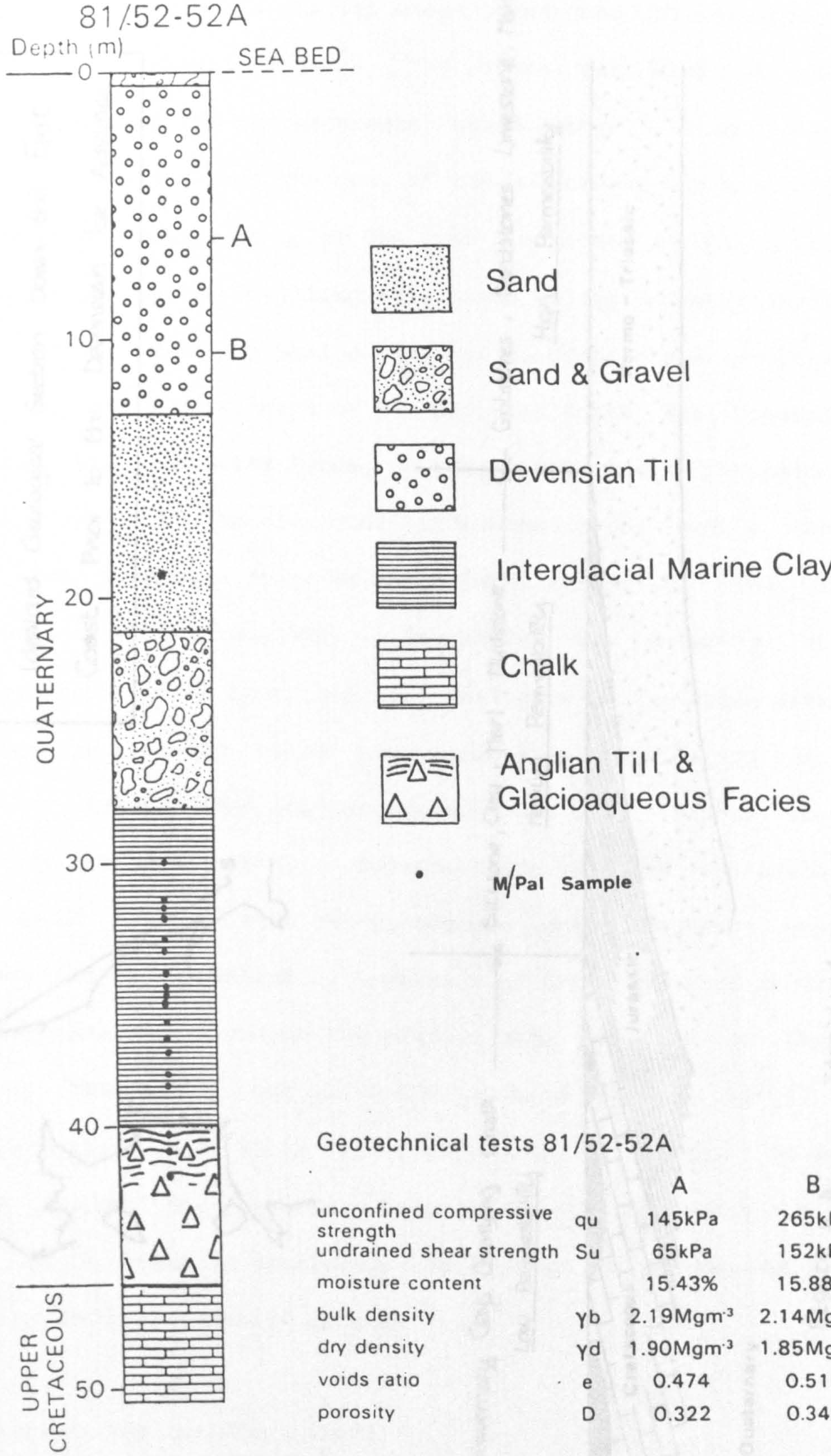
eroded deep into the underlying bedrock. Any unconsolidated sediments such as glacial outwash or thin till cover remaining from the wane of the Devensian ice sheet were then reworked during the Flandrian transgression.

The nature of the subglacial bed along a flow line, south of the Cheviots to a position North of Flamborough Head, can be realistically assumed to be close to the current outcrop pattern (Figure 8.2), simplified into a Permo-Triassic - Jurassic progression. With reference to Figure 8.2 it can be seen that a major outcrop of chalk, east of the Permo-Triassic sequences, would provide a major source of this lithology to the eastern flank of any glacier moving south and is certainly not limited to the Flamborough Head exposure as previously suggested by Madgett and Catt (1978). In relation to the depositional model, the bedrock sequence creates a situation of reducing permeability as the lithology changes from limestones and sandstones, through marls to the upper Jurassic clays, along a single flow line.

The situation within the Holderness area prior to the ice advance is far more contentious since there is strong evidence for a pre-existing Pleistocene drift cover overlying the Cretaceous chalk of the East Midlands Shelf, which would have had a strong control on the behaviour of the ice sheet under the Boulton and Jones (1979) hypothesis. This is demonstrated in the returns from BH 81/52A, supplied by the B.G.S, which proves the Devensian till sequence overlying a marine clay and gravel succession (Figure 8.3). The age of the marine clay is disputable but present evidence suggests a Hoxnian age based on microfauna (Fisher, Funnel and West 1969). Borehole BH 81/52A is an important type of section for the regional stratigraphy since this would date the basal till as Anglian, and provide the only indisputable evidence



Geotechnical tests 81/52-52A

		A	B
unconfined compressive strength	qu	145kPa	265kPa
undrained shear strength	Su	65kPa	152kPa
moisture content		15.43%	15.88%
bulk density	γb	2.19Mgm^{-3}	2.14Mgm^{-3}
dry density	γd	1.90Mgm^{-3}	1.85Mgm^{-3}
voids ratio	e	0.474	0.516
porosity	D	0.322	0.340

Figure 8.3 Stratigraphy of the offshore borehole BH81/52A, for location see Figure 8.1

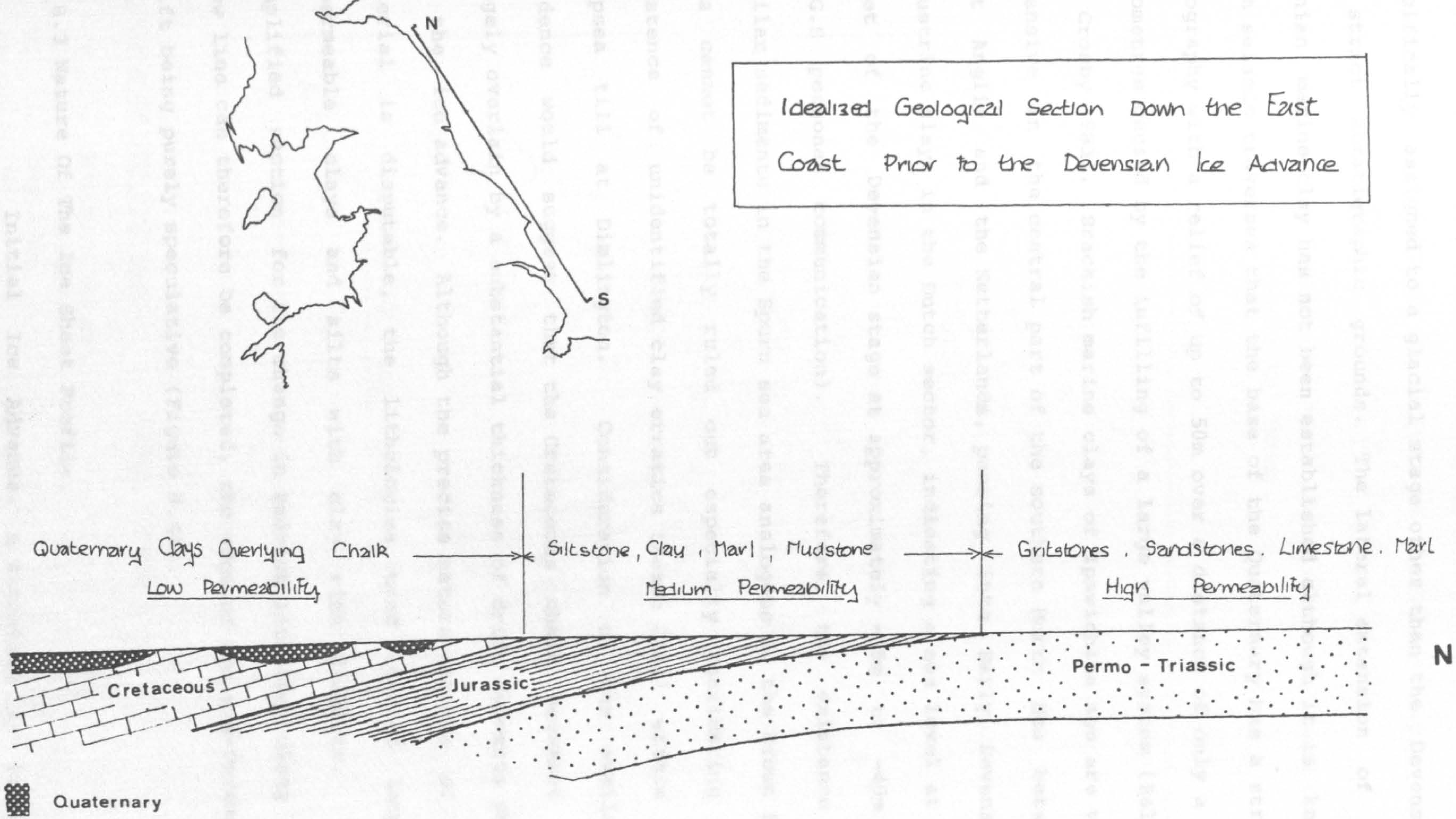


Figure 8.4 Idealized geological section down the east coast prior to the Devensian ice advance

for a till in the Holderness - Spurn sea area which can be specifically assigned to a glacial stage other than the Devensian on strict stratigraphic grounds. The lateral extension of the Hoxnian marine clay has not been established although it is known from seismic traverses that the base of the Quaternary has a strong topography with a relief of up to 50m over a distance of only a few kilometres caused by the infilling of a large valley system (Balson and Crosby 1983). Brackish marine clays of Ipswichian age are very extensive in the central part of the southern North Sea between East Anglia and the Netherlands, passing into Early Devensian lacustrine clays in the Dutch sector, indicating a sea level at the onset of the Devensian stage at approximately -35m to -40m OD (B.G.S personal communication). Therefore, the existence of similar sediments in the Spurn sea area analogous to the Brown Bank Beds cannot be totally ruled out especially considering the existence of unidentified clay erratics (Beach Clay) within the Skipsea till at Dimlington. Consideration of the available evidence would suggest that the Cretaceous chalk basement was largely overlain by a substantial thickness of drift deposits prior to the ice advance. Although the precise nature and age of the material is disputable, the lithologies tend towards largely impermeable clays and silts with clay rich diamicts. The simplified section for the change in bedrock lithology along the flow line can therefore be completed, the edge of the pre-Devensian drift being purely speculative (Figure 8.4).

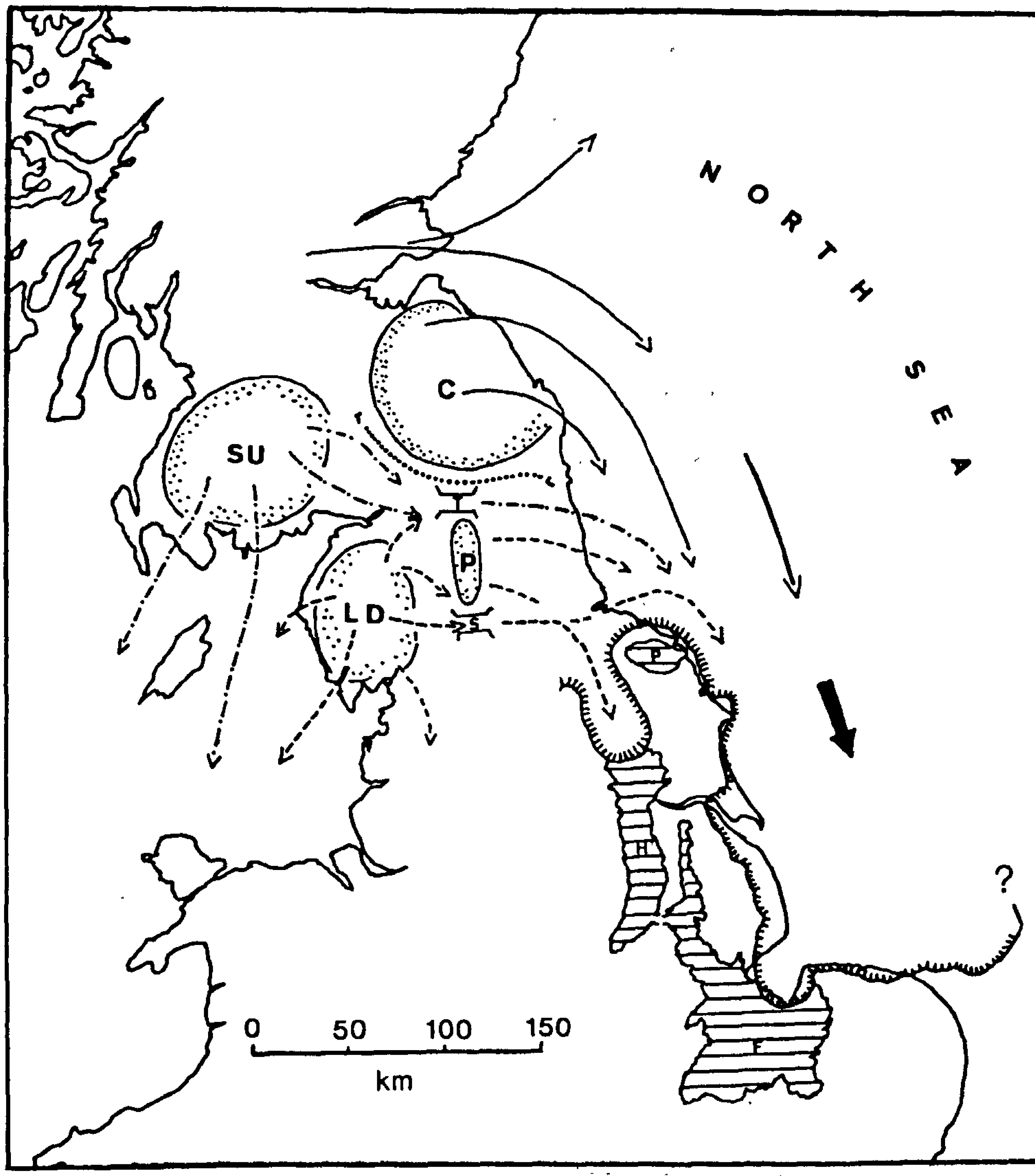
8.3 Nature Of The Ice Sheet Profile.

Initial Ice Advance: A situation is proposed whereby the early development of the North Sea Ice Sheet was controlled by ice streams moving east from centres of accumulation

Various Centres of Ice Dispersion During the Devensian - East Coast Ice Stream & Glacial Features —

L........L Northern Limit to Lake District Erratics - Beaumont (1968)
Devensian Ice Maxima

Figure 8.5



KEY

CENTRES OF ICE DISPERSAL

SU..... Southern Uplands
LD..... Lake District
P...... Pennines
C...... Cheviot

OTHER FEATURES

T...... Tyne Gap
S...... Stainmore Gap
H...... Humber Gap
F...... Lake Fenland
P...... Lake Pickering

Cheviot/Scottish Ice
Pennine/Lake District Ice

in the Pennines, Lake District and western Southern Uplands of Scotland passing through the Tyne and Stainmore - Tees gaps (Figure 8.5). Boulton and Jones (1979) propose that the profile of any ice sheet is a function of the stability of the underlying bed under the prevailing conditions of subglacial drainage. The movement of the ice margin across the offshore Permo-Triassic sequences would have produced a highly stable ice body in this area, with a well developed basal drainage network and correspondingly high effective normal loads at the ice/bed interface (Figure 8.6). Although the initial conditions would appear to favour subglacial deposition, incorporation of increasing amounts of arenaceous sediments would require very high normal stress to facilitate lodgement. Boulton's (1975) theoretical treatment of the subglacial bed has shown that for most conditions, material in the medium-fine sand range (1Ø - 2Ø) is least susceptible to lodgement. Allowing for sliding velocities in the order 15 - 20 m/year, an effective normal stress in excess of 30,000 kN/m^2 would be the limiting value to lodgement at the glacier sole. With further movement south (Figure 8.7), contact with Jurassic strata, in particular the Speeton and Kimmeridge Clays, would have altered the nature of the subglacial load so that the systematic change in both debris shape and size distribution would have led to a progressively finer bedload, which would be more susceptible to lodgement, as the glacier moved into the Holderness embayment (Figure 8.7). This effect would have been enhanced by the continuous comminution of Carboniferous, Permian and Triassic lithologies along the flow line. At this point, the less permeable Liassic sequences may have reduced the effective stress at the glacier base, through reduced bed transmissibility, which would have acted against the tendency of the till to lodge.

Stage 1

Initial Advance over Permeable Permo-Triassic Sequences. Well Developed Basal Drainage Maintains High Basal Stress. Lodgement Minimal due to extremely coarse nature of transported bedload

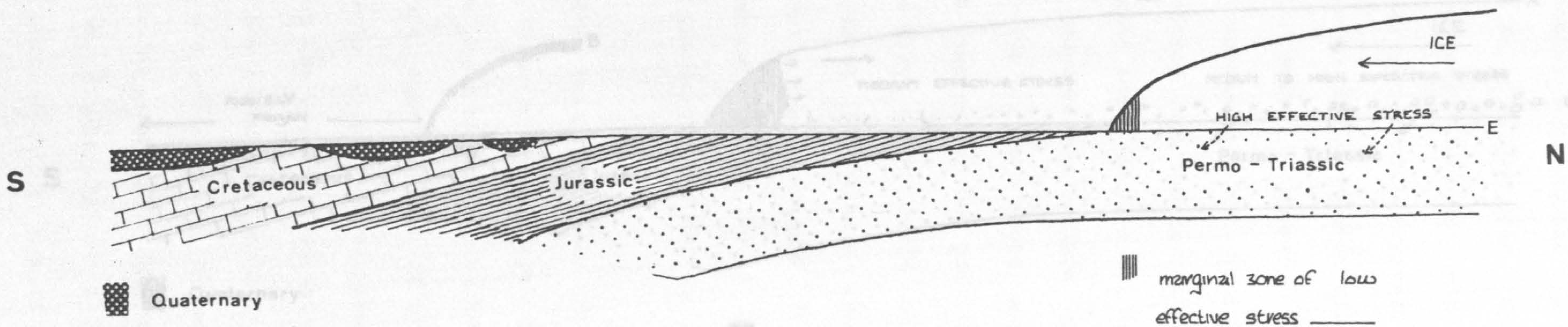


Figure 8.6 Ice Profile. Initial advance over permeable Permo-Triassic sequences

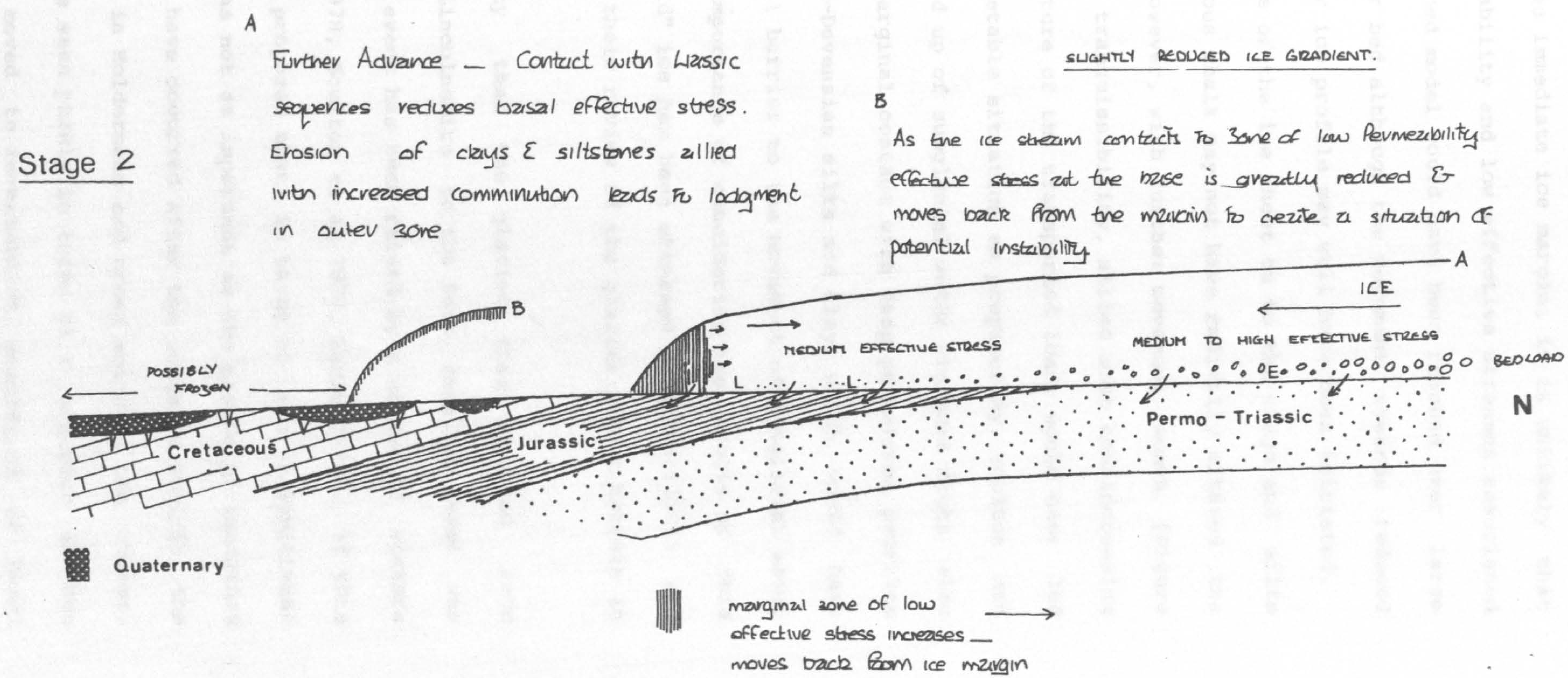


Figure 8.7 Ice Profile. Further advance, contact with Liassic

However, apart from the immediate ice margin, it is unlikely that the conditions of instability and low effective stresses associated with the deformable bed model could have been reached over large areas of the glacier bed although the movement towards reduced normal load and a lower ice profile may well have been initiated.

The initial advance of the ice sheet on to the clays and silts overlying the Cretaceous chalk may not have radically altered the ice/bed dynamics. However, with further movement south (Figure 8.8), the reduced bed transmissibility, allied with the increasing clay and silt rich nature of the transported load, would have led to a potentially unstable situation as proposed by Boulton and Jones (1979). A build up of subglacial water pressure might also have been caused by marginal contact with deep permafrost profiles developed in the pre-Devensian silts and clays which would have acted as a substantial barrier to the movement of subglacial water to the margin. The importance of considering the effects of this outer margin of "cold" ice has been stressed by Moran (1971) and Moran et al (1980) in their review of the glacier thrust terrain in North America.

The possibility that the glacier that advanced from Holderness through Lincolnshire to the East Anglian coast was emplaced by a surge event has been raised by a number of workers (Madgett and Catt 1978, Boulton et al 1977, Straw 1979). If this is the case, it is proposed that, in terms of the depositional history, this event was not as important as the period of sustained lodgement which must have occurred after the surge to explain the thickness of diamict in Holderness and areas south of the Humber. This phase should be seen purely in terms of a vigorous advance which then quickly moved to re-establish conditions of basal stability, since a theory encompassing a surge event in isolation

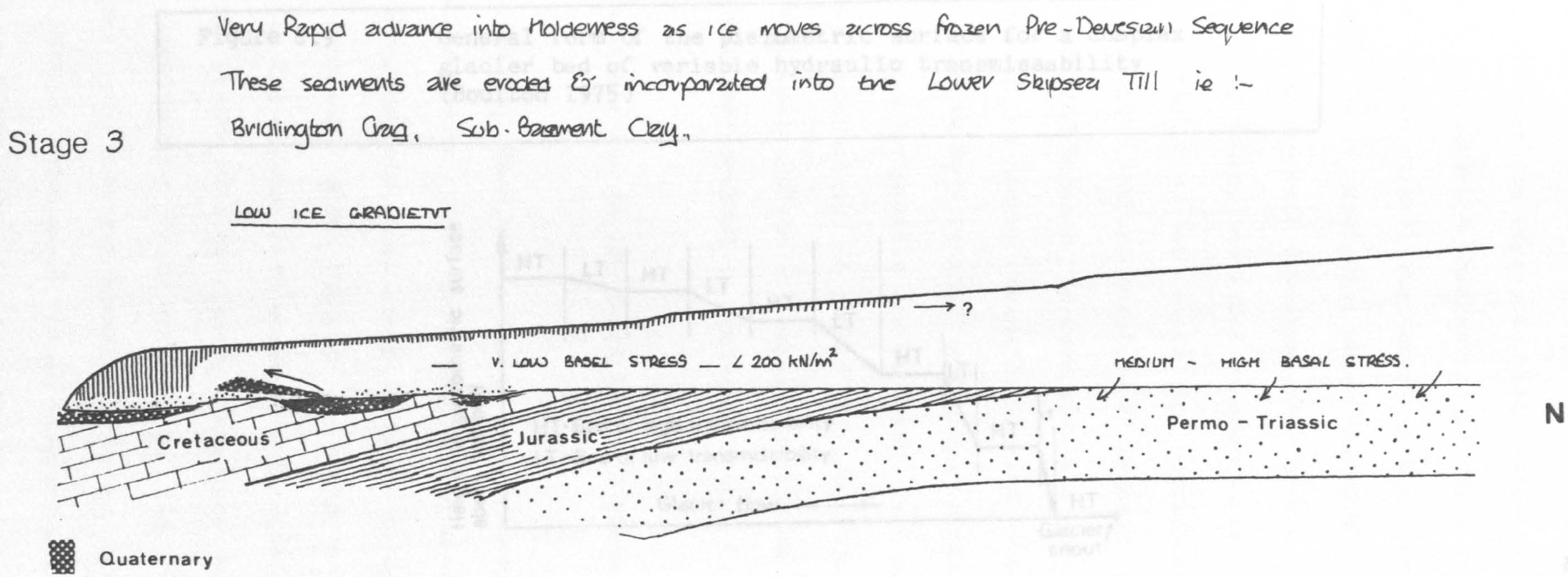
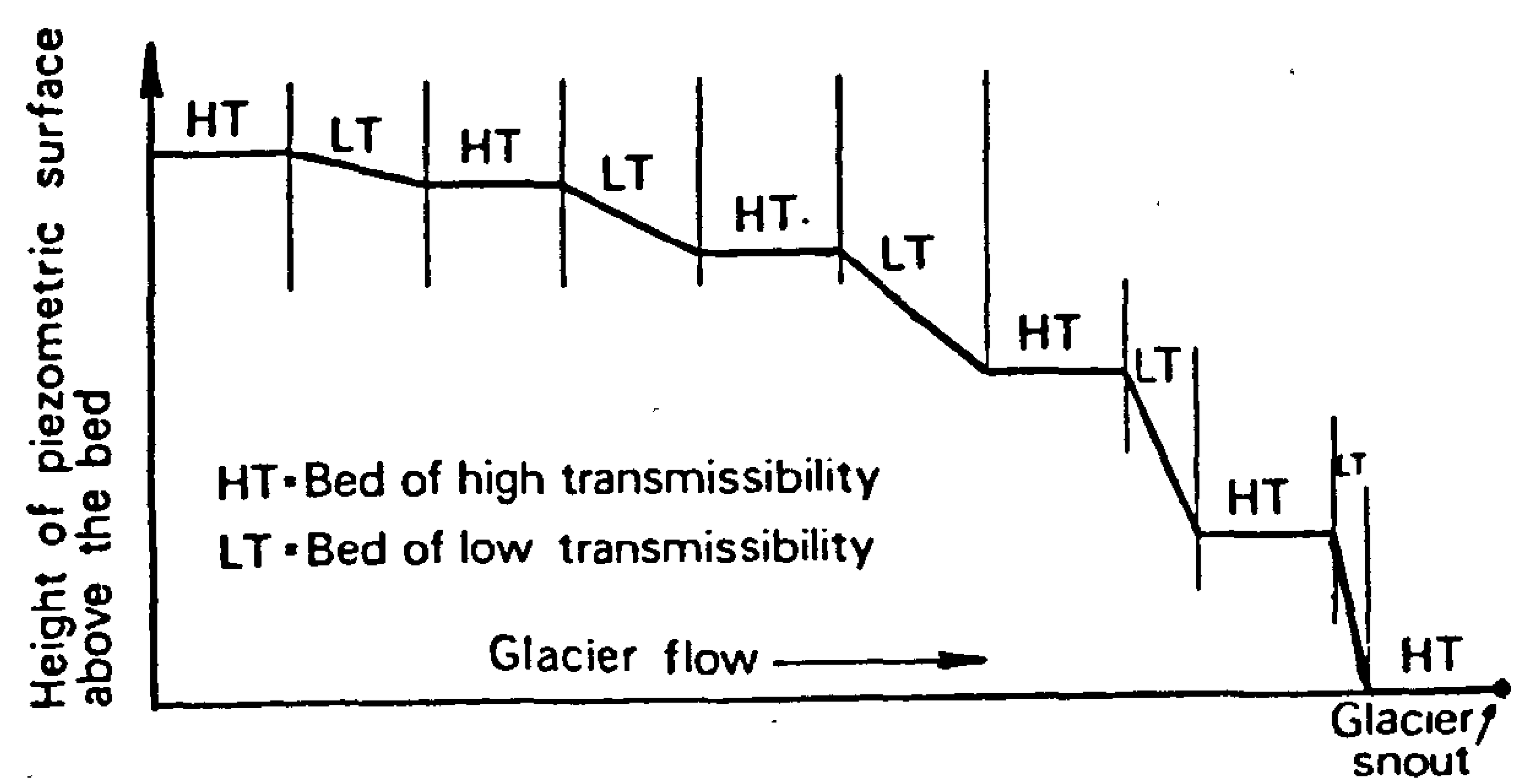


Figure 8.8 Ice Profile. Advance into Holderness

Figure 8.9 General form of the piezometric surface for a complex glacier bed of variable hydraulic transmissability (Boulton 1975)



cannot explain the lodgement tills of the Killingholme - Hogsthorpe moraine complex (Straw 1979) or the Devensian till described at 90 m OD at Welton le Wold, Lincolnshire (Alabaster and Straw 1976).

The mechanism for the initial ice thrust to the maximum limits may lie in the build up of subglacial water pressures. As Boulton's (1975) theoretical approach confirms, when beds of low transmissibility lie down glacier, the water pressures in beds where permeabilities are high are also raised to corresponding levels, so that the piezometric surface develops a stepped form (Figure 8.9). If this occurred beneath the Devensian ice sheet it is possible that the zone of low normal stress could have extended back from the snout to the Permo - Triassic sequences north of Flamborough Head where the glacier profile was steepest, leading to a situation of potential instability. A period of rapid advance would then create a shallower profile as basal equlibrium was re-established and the glacier regained is activity (Figure 8.11).

8.4 Equilibrium Conditions For An Ice Sheet During A Phase Of Sustained Lodgement.

Once an extended ice sheet with a low profile, overlying a relatively impermeable sediment suite, had become established in the area south of Flamborough Head, conditions closely matching those presented in the subglacial model (Chapter 7), would exist. Low effective stresses at the glacier base would be maintained by the low transmissibility of the till bed, while lodgement would continue due to the predominance of the material in the >0 ϕ fraction, which requires only moderate normal loads to effect deposition (Boulton 1975). Lodgement would effectively be controlled by comminution along flow lines from the areas of net erosion immediately north of Flamborough Head. It is proposed that

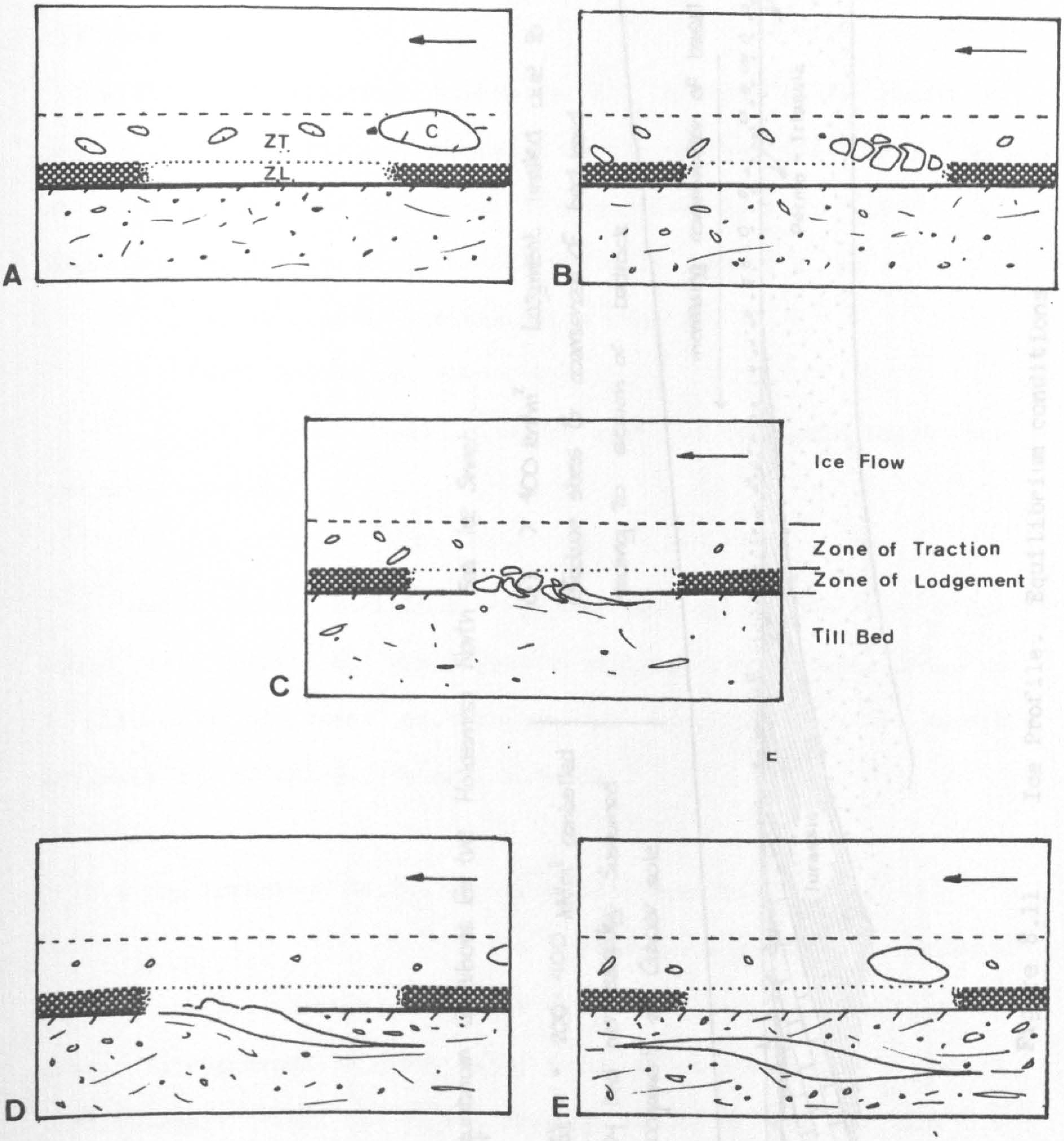


Figure 8.10 Possible mode of formation of crushed clast "smudges", characteristic of both the Skipsea and Withernsea Tills ... see Plate 9.2

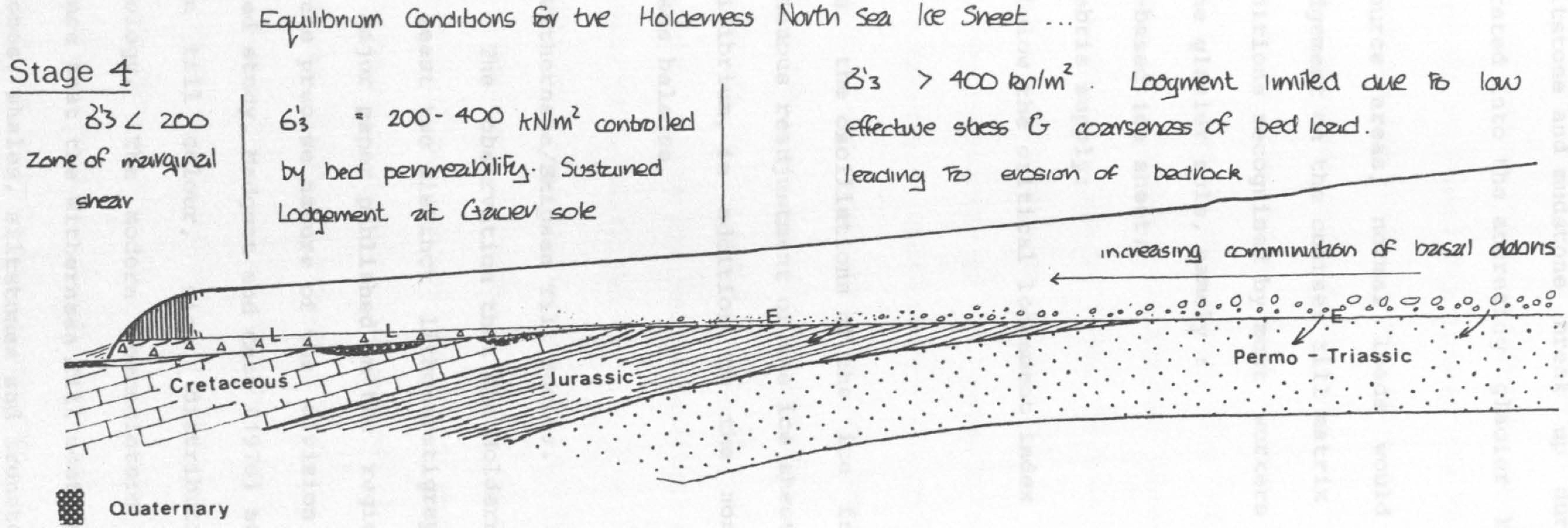


Figure 8.11 Ice Profile. Equilibrium conditions

this process is actively displayed in the development of "streaks" or "crushed stringers" characteristic of the Holderness diamict where clasts of chalk, siltstone and mudstone break up during transport and are incorporated into the accreting glacier base (Figure 8.10).

Within the internal source areas, normal loads would be insufficient to initiate lodgement on the coarser till matrix and as such would lead to conditions recognised by most workers as ideal for rapid erosion at the glacier sole, namely :

a) An active, wet-based ice sheet;

b) A continuous debris supply;

c) Normal loads below the critical lodgement index for the basal debris.

Under such conditions, the oscillations of the ice front could well reflect the continuous readjustment of the ice sheet to a situation of basal equilibrium, in addition to the normal activity due to changes in mass balance.

8.5 The Formation Of The Withernsea/Skipsea Till Facies.

The observation that the Holderness diamict suite possesses at least two distinct lithostratigraphic units is supported by every major paper published on the regional stratigraphy, even though the precise nature of the division is often disputed. In a detailed study, Madgett and Catt (1978) noted significant variations in till colour, size distribution, mineralogy and clast lithology. The modern nomenclature was adopted partly on the evidence that the Withernsea Till contains a higher proportion of limestones, shales, siltstones and ironstones and that its red colour can be ascribed to the incorporation of

Keuper Marl into the till matrix. In the depositional model proposed by the same authors, after Carruthers (1953), it was postulated that the Skipsea Till was the product of a North Sea ice stream, with the Withernsea Till deposited by a separate glacier which crossed the Pennines via the Stainmore Gap eroding the Keuper Marl and overiding the North Sea ice sheet before moving into Holderness and melting out as a stagnant ice body (Chapter 1).

Under the alternative model proposed in this thesis, the Withernsea/Skipsea till facies is seen as the product of a single ice stream eroding through the major litho-stratigraphic boundary in the source area north of Flamborough Head. It can be seen from Figure 8.2 that any ice sheet actively eroding the bedrock in this area would incorporate increasing quantities of Permo-Triassic material as the Liassic cover is reduced thus altering the mix of lithologies transported along a single flow line. If incorporation of this material preceded a period of reduced lodgement or a partial retreat of the ice margin, increased activity of the ice sheet would lodge the Withernsea facies without necessitating a second ice stream or major phase of deglaciation.

Alternatively the streams of ice coalescing to form the North Sea ice sheet may have been subjected to a subtle change, from one dominated by a Pennine, Lake District, western Southern Uplands ice, to a more direct supply from the emerging ice centres of the Cheviots and eastern Southern Uplands (Smith 1971). The Quaternary stratigraphy of North East England (Chapter One) has been interpreted in terms of these two conflicting ice streams with the Pennine/Lake District ice responsible for the Blackhall Till complex, which was later displaced from the coastal margins by the Cheviot stream which deposited the lithologically distinct Horden Till (Francis 1971). The correlation of these units with the divisions in Holderness is unlikely to prove decisive since they were deposited under different glaciological conditions at the margins of the ice sheet rather than originating in a position central to an extensive ice body. If, during glacial maxima, the source regions were undergoing an erosive phase the greater proportion of the Quaternary sequence in the north-east would date from the phase of retreat rather than being directly contemporaneous with the Holderness tills. The difficulties of correlating sequences deposited in elevated valley relief with apparently similar sequences on a sedimentary lowland arises from the fact that these environments are essentially independent depositional landsystems (Eyles 1983).

8.6 Application Of The Model To The Interpretation Of The Borehole Results.

Consideration of the processes outlined in Chapter 7 and the conditions outlined above suggest that the following propositions should apply to the till profile at Cowden.

1) During phases of lodgement under conditions of basal equilibrium, the till bed produced should be broadly homogeneous with constant effective stress and basal shear. Localised variations would be created solely by readjustments to the subglacial hydrological system and comminution of debris along the flow line. The thickness of a till body encountered in a vertical section will therefore be a function of the stability of the ice sheet, debris supply and general mass balance considerations at the time of deposition. The till fabric will be dense, with a voids ratio controlled by effective normal stress and shear consolidation leading to the development of microlaminated till fabrics at lower effective stresses.

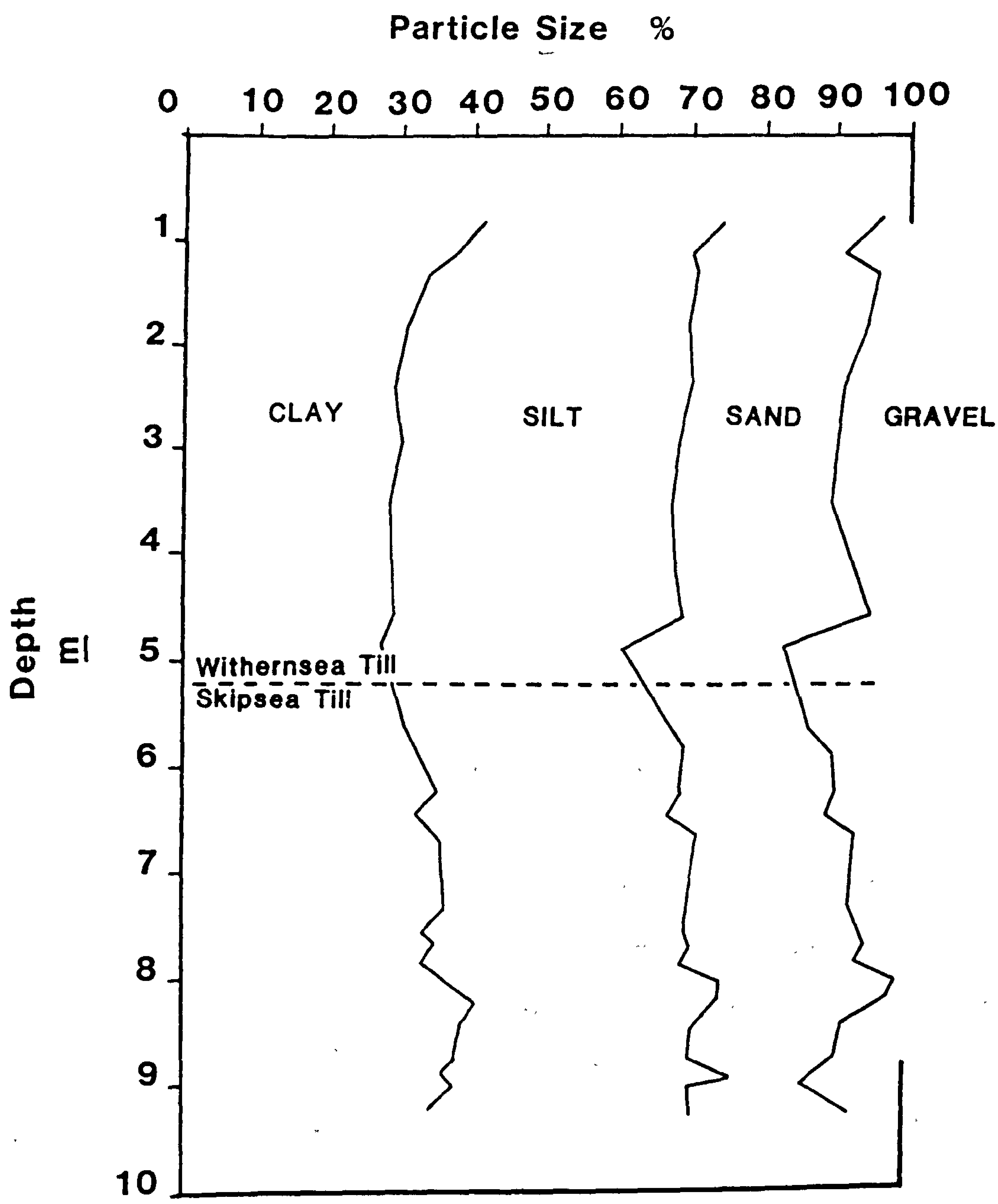


Figure 8.12 Particle size against depth, CS1.

2) Major variations in soil properties, such as in the vicinity of the Skipsea/Withernsea Till facies junction, marks the oscillation in the ice front where the till profile was subjected to extreme modification in the region of the ice margin and proglacial environment as outlined in Chapter 7. Similar sequences may occur several times within the Skipsea Till but are only visually apparent if there is a major change in till lithology and/or colour across the boundary.

3) The deposits of the initial advance, lying at the base of the Skipsea Till, would be expected to show an individual fabric characteristic of the brittle fracture and thrusting related to cold ice in the glacier margins.

The conditions outlined in the first proposal are applicable to the till profile at Cowden from 6 - 10 m. The relationship between the silt and sand content has been shown to be almost constant below 6 m (Figure 8.12), which can now be explained in terms of the equilibrium conditions of low effective stress maintaining in traction coarse aggregates until sufficient comminution occurs for the matrix to become susceptible to lodgement. Since a detailed analysis of the sediment was undertaken for only one borehole (CS1), the horizontal variation in fabric cannot be evaluated. Even if this were possible, the problems of isolating and defining a single level of homogeneous till would necessitite only the broadest classification.

Using the more complete geotechnical data sets, a high degree of correlation can be achieved below 6 m, across all three boreholes particularly with respect to shear strength and volume related parameters such as voids ratio and porosity (Figures 8.13 and 8.14). It is noticeable that for many of the plots with depth, data points from CS2 produced the same trend but were slightly

BH CS1 COWDEN TEST BED SITE

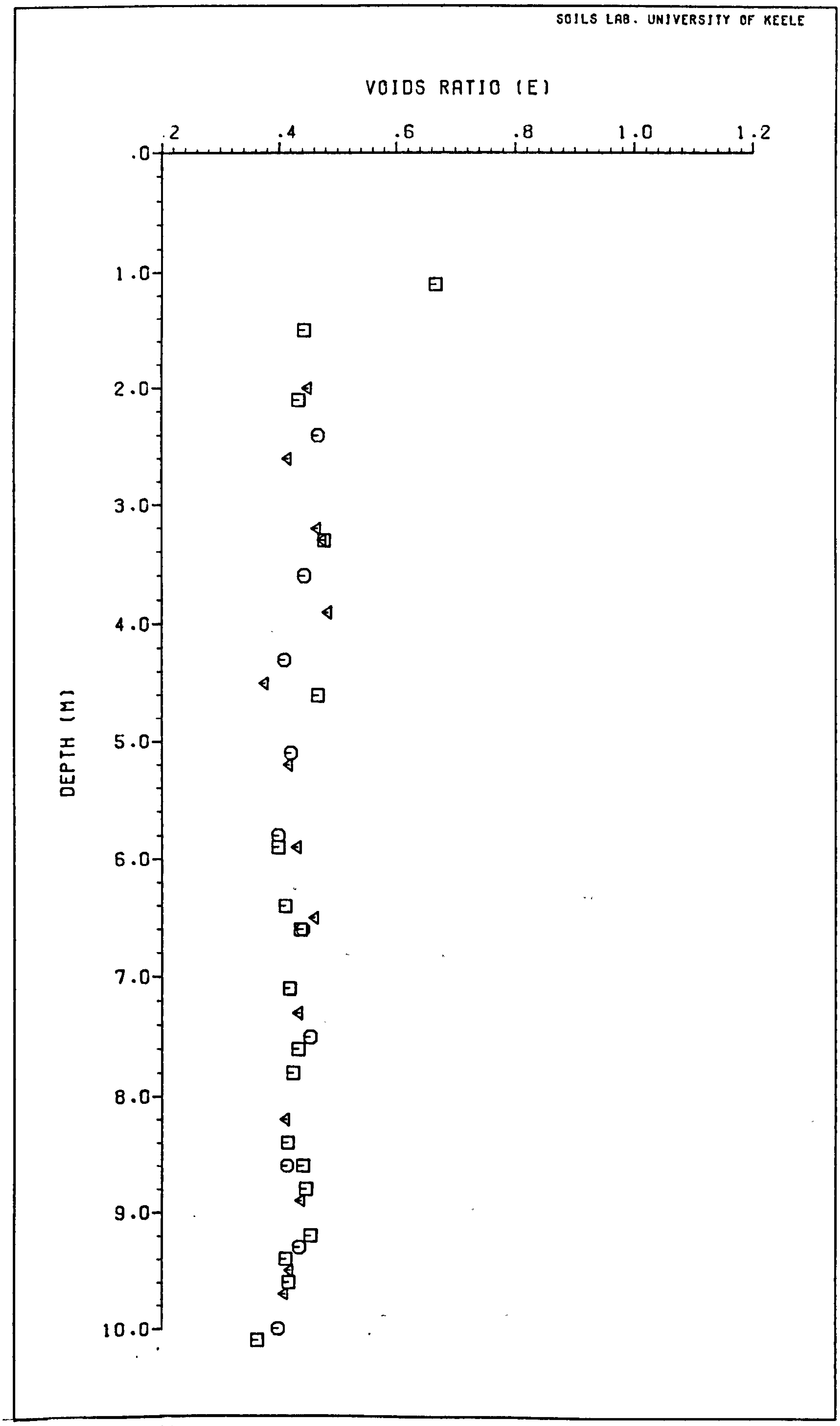


Figure 8.13 Voids ratio (e) / depth CS1-3

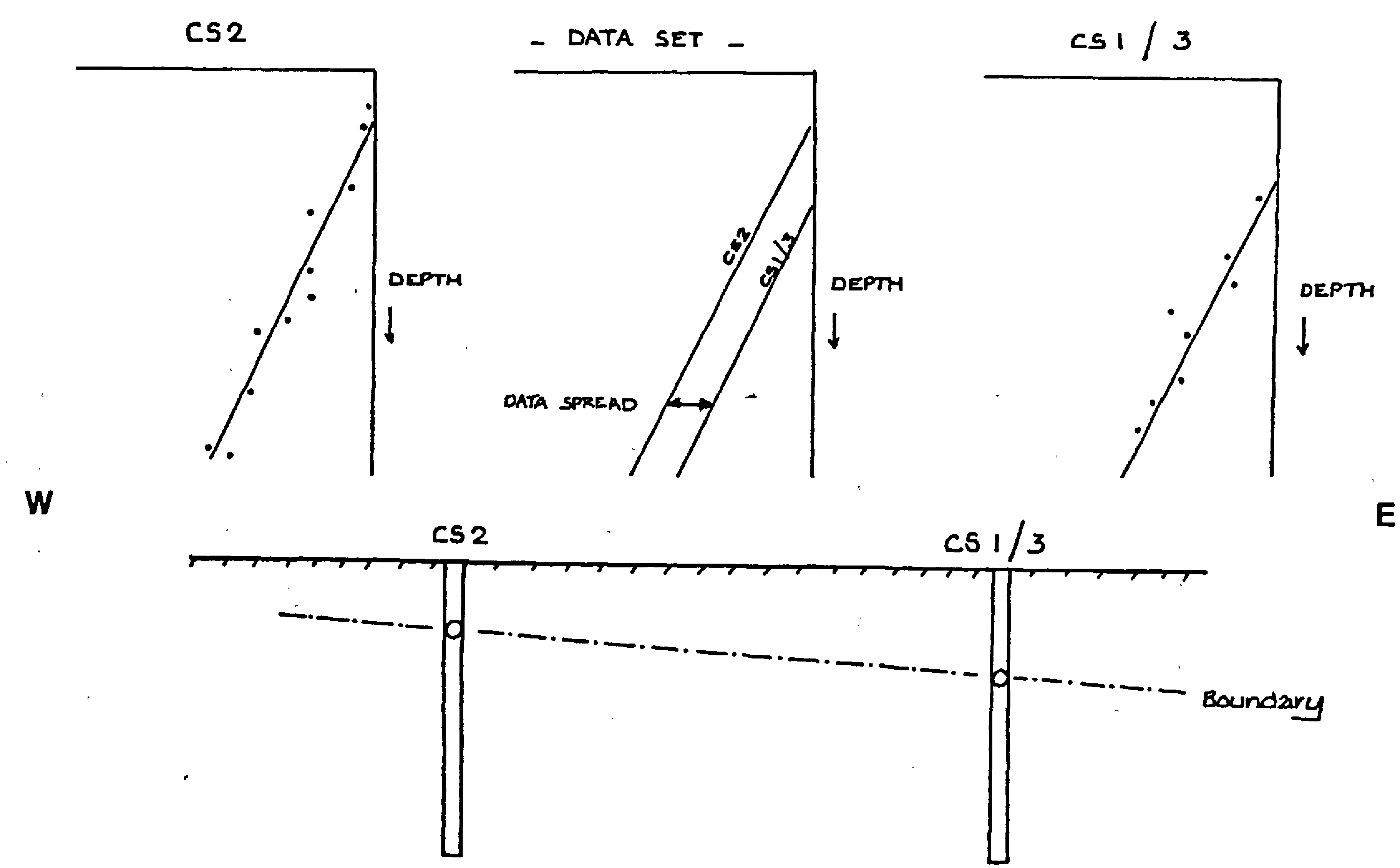


Figure 8.14 Possible offset in test results caused by the variation in depth of the Withernsea, Skipsea Till junction across the drill site.

offset. Good examples of this behaviour are figures for initial pore pressure, B value and Ko with depth given in Chapter 5. This may be explained in terms of the till facies junction which, for CS2, lies at a shallower depth (3.8 m) owing to the dip in the contact of 4^{o} across the site as proven in the trench section. If the parameters were related to the boundary, or more likely, processes operating parallel to the boundary, this would explain the anomally since, owing to the plane of the present ground surface and the practice of classification with depth, like sediments across boreholes would not be compared (Figure 8.14). A similar effect has been reported by Vaughan, Lovenbury and Horswill (1975), who reduced the amount of data scatter during a site invesigation into Pennine tills by plotting data points with elevation rather than depth.

The profile between 3 - 6m in boreholes CS1 and CS3 is consistent with a phase of glacial retreat and shear dilation with an inferred proglacial phase. This centres around the zone of high density and strength at 5.9m which provides a major peak in the shear strength plot with depth. Chapter 4 shows how such a layer could have developed in a proglacial environment subjected to freeze-thaw action.

The effect on the size distribution is clearly seen in Figure 8.12 where a zone of silt enrichment caused by the translocation of fines from the upper dilatant profile during the initial proglacial phase is in the precise position described by Boulton and Dent (1974), from their study of modern proglacial sediment associations. Apart from the high strengths created by the collapse of the open till fabric and subsequent consolidation it is notable that the till immediately below (6.4m) possesses the type of micro-lamination indicative of a reduction in effective stress

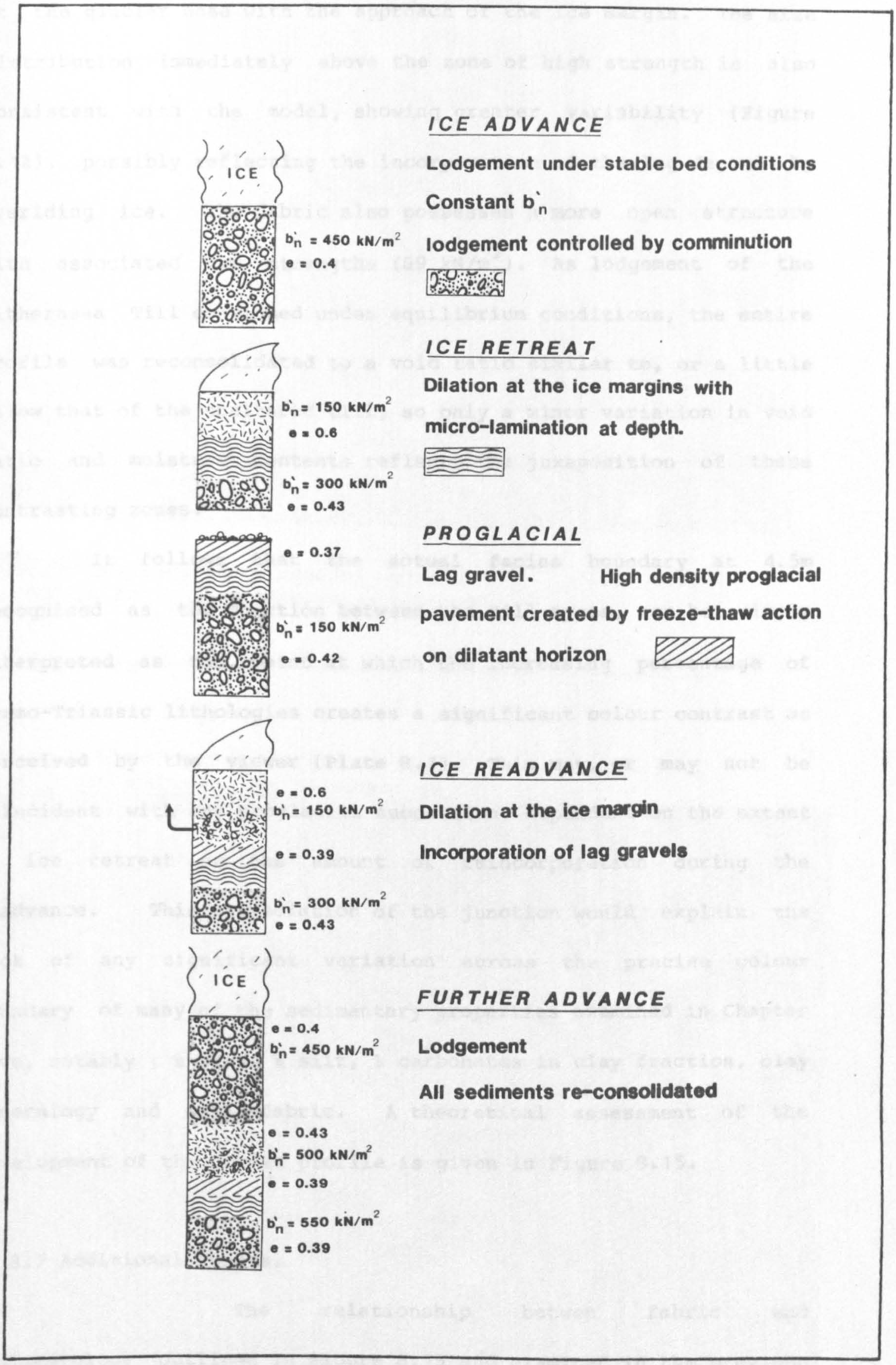


Figure 8.15 Idealized stress history for the Cowden diamict profile 1-10m

at the glacier base with the approach of the ice margin. The size distribution immediately above the zone of high strength is also consistent with the model, showing greater variability (Figure 8.12), possibly reflecting the incorporation of the lag deposit by overiding ice. The fabric also possesses a more open structure with associated low strengths (89 kN/m^2). As lodgement of the Withernsea Till continued under equilibrium conditions, the entire profile was reconsolidated to a void ratio similar to, or a little below that of the unaltered till, so only a minor variation in void ratio and moisture contents reflects the juxaposition of these contrasting zones.

It follows that the actual facies boundary at 4.5m recognised as the junction between the till types, can be simply interpreted as the point at which the increasing percentage of Permo-Triassic lithologies creates a significant colour contrast as perceived by the viewer (Plate 8.1). This may, or may not be coincident with any proglacial succession, dependent on the extent of ice retreat or the amount of reincorporation during the readvance. This appreciation of the junction would explain the lack of any significant variation across the precise colour boundary of many of the sedimentary properties examined in Chapter Five, notably ; % clay, % silt, % carbonates in clay fraction, clay mineralogy and soil fabric. A theoretical assessment of the development of the Cowden profile is given in Figure 8.15.

8.7 Additional Points.

The relationship betwen fabric and sedimentology outlined in Figure 8.15 and examined in the previous chapter for the Holderness tills should not be taken to apply precisely to all exposed sections which expose the

Plate 8.1 Junction between Withernsea and Skipsea Tills as exposed at Cowden Cliff. (TA 253404).

Plate 8.2 Detail of clast "smudge" created by the disintegration and shearing out of a chalk cobble at the glacier base, Cowden Cliff (TA 253404).

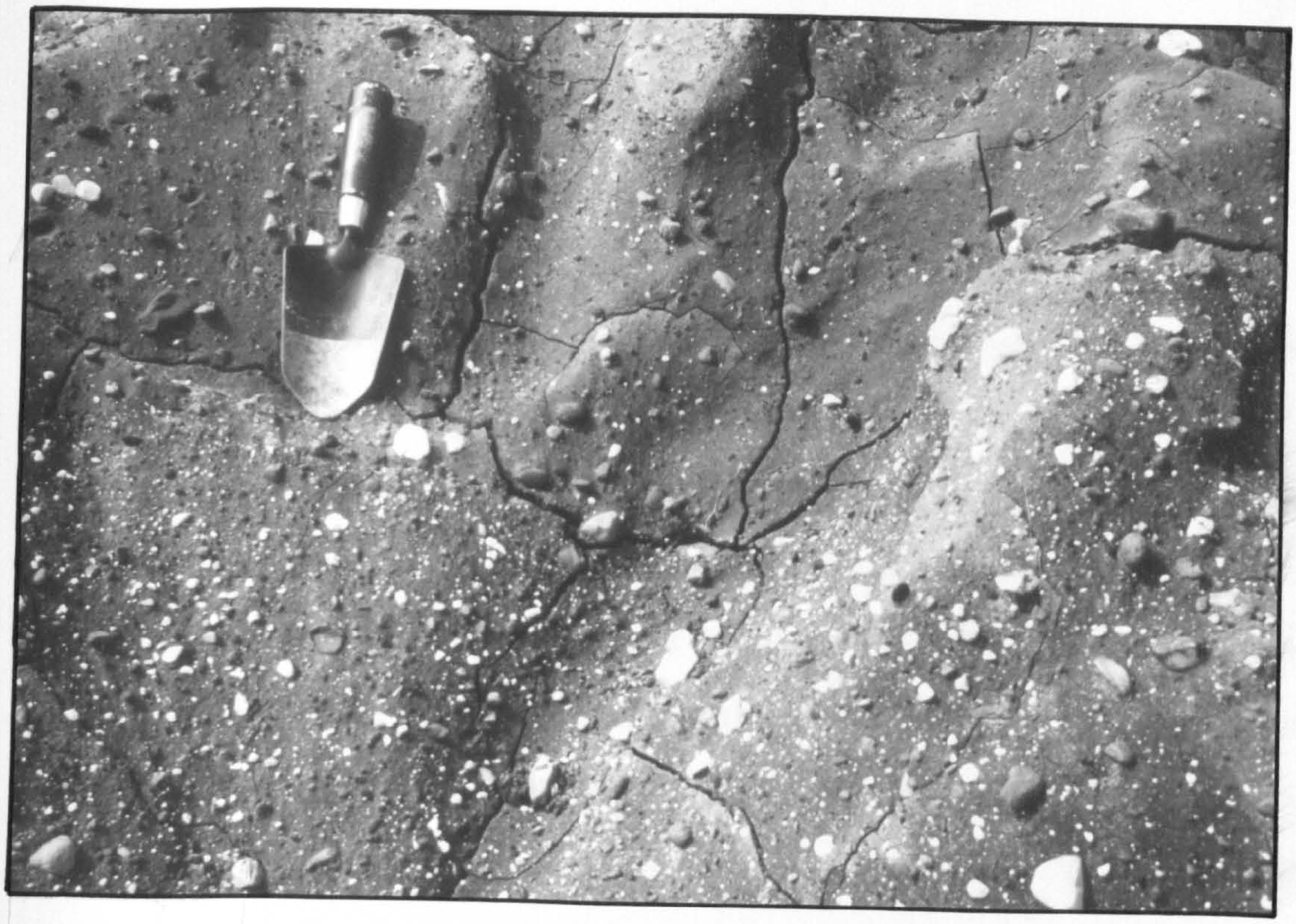


Plate 8.1

Plate 8.2

Skipsea/Withernsea junction. Indeed, there is no evidence for a zone of high strength in borehole CS2 associated with the proglacial pavement, possibly because the sampling net simply missed it, but more likely because it was either weakly developed or reincorporated during the overiding ice advance. For example, north of Aldbrough (TA 258397), laterally extensive gravels can be seen on or slightly below the facies change with the underlying zone of high strength picked out by cliff collapse. The massive fining down sequence at Dimlington (TA 386224) has already been described as a possible site where the entire sequence of proglacial sands and silts, overlain by flow tills is preserved between the Skipsea and Withernsea tills. In strict contrast, at other locations, particularly north of Hornsea, the vicinity of the colour junction is undistinguished, with no visible change in fabric or sedimentology.

When studying the coastal profiles it is important to appreciate that the cliffs provide a strangely oblique section through the margins of the Devensian ice sheet and that no simple north-south pattern in sedimentation should be expected. Since the thalweg of the ice sheet must have passed several tens of kilometres offshore, Holderness represents deposition at the flank of the ice sheet. For this reason it is possible that at some stage Holderness may have experienced ice-proximal conditions with true subglacial lodgement occurring further south in Lincolnshire.

CHAPTER 9

Deposition From An Active Ice Sheet.

A Re-examination of Regional Stratigraphy

9.1 Introduction.

The following chapter re-examines the accepted Quaternary stratigraphy of Eastern England, with particular emphasis on Holderness, in terms of deposition from an active ice sheet during the Devensian. It is necessary that type sections other than those already introduced are interpreted to create a true regional synthesis and as such, many of the relationships described are reliant on the observational accuracy of previous workers. It is important to realise that, owing to the nature of glacial geology, few interpretations can be definitive and are therefore open to constant reappraisal with changing ideas and increased knowledge. The prevailing theory at any time should be the one within which the greatest amount of field data can be explained, taking into account the framework of accepted factual knowledge and the proposals of others.

9.2 The Skipsea-Withernsea Till facies.

9.2.1 Composite ice sheet. The "duplex ice sheet model" and theory of "undermelt" first proposed by Carruthers (1953) and later adopted with revisions by Madgett and Catt (1978), has been described by Boulton (1972) as " almost entirely erroneous " and is clearly challenged in this thesis as an adequate explanation for the deposition of the Holderness tills, taking into account the whole range of sedimentary and geotechnical evidence presented so

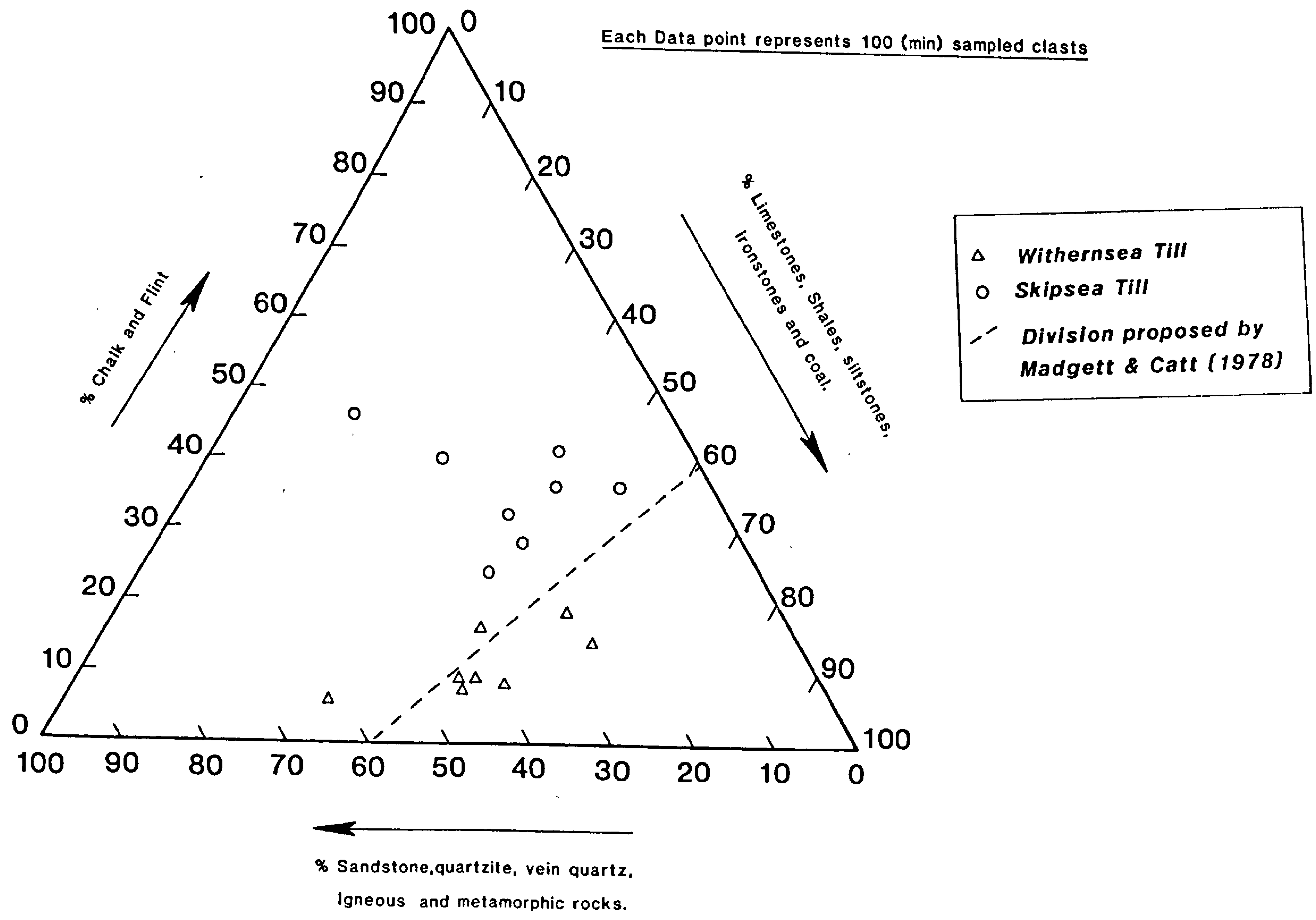


Figure 9.1 Composition of 6-16 mm clasts from till samples at Aldbrough, Holderness

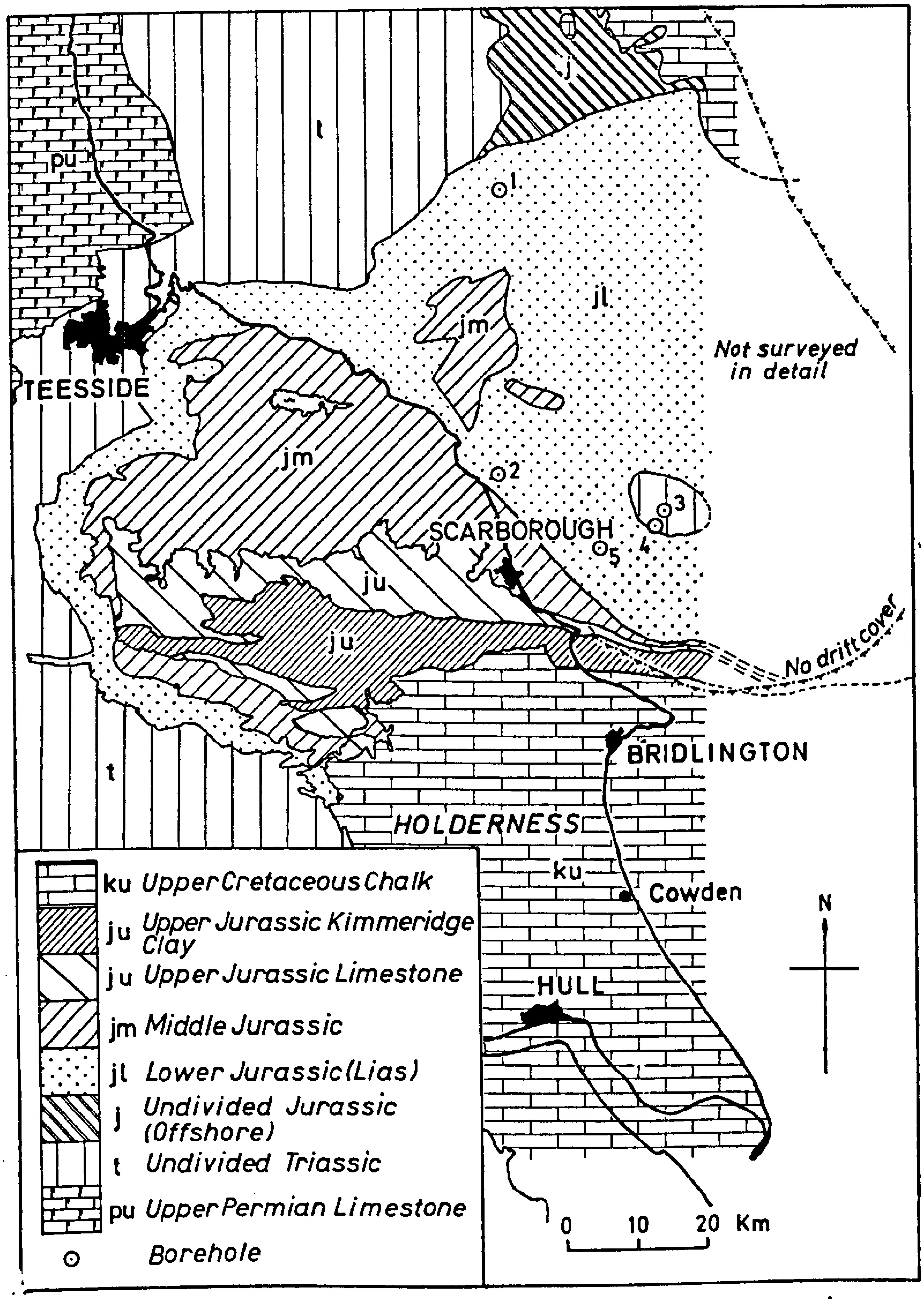


Figure 9.2 Regional geology showing the site location and limit of "drift" cover

far.

The strength of the duplex model lies in the fact that the separate ice sheets can be used to account for the variation in till petrography within a single advance during the 5000 year time period bracketed by the Dimlington Silt date for glacial maxima (18,240±250 years BP, Penny, Coope and Catt 1969), and the earliest date for deglaciation (13,045±270 years BP, Catt 1977)

Madgett and Catt (1978) concluded that the Withernsea and Skipsea Tills could be differentiated on the basis of the clast content (6 - 16 mm), using a broad lithological sub-division of stone type. Their results showed that the Skipsea Till contained more chalk and flint, but less shale and limestone, than the Withernsea Till. This conclusion is supported by 16 samples removed from from a 100m section of cliff immediately south of Aldbrough (GR 258395), which were subject to the same analysis of clast content (Figure 9.1).

The depositional model,proposed by Madgett and Catt (1978) to account for the nature of the clast content of the two tills, was formulated without any reference to the offshore geology, so that the ice streams appear to "skirt" the coast to remain in contact with the required lithologies. For example, the explanation of the clast assemblage in the Withernsea Till and, in particular, the derivation of the chalk from Flamborough Head is an unnecessary postulate in the light of the evidence of the eastward extent of this till unit in the North sea basin (Donovan 1973), and the recent improved knowledge of the bedrock geology of the floor of the North Sea, where there is abundant chalk (Figure 9.2). Indeed, the rich content of chalk clasts in the Withernsea Till at least 100 km offshore would necessitate a quite bizarre ice flow pattern in order to derive it all from Flamborough Head. A simpler explanation of the change in clast lithology and till matrix colour is proposed which involves erosion through the major lithostratigraphical boundary between the Liassic and Triassic formations in the offshore source region to the north northeast (Figure 9.2) under the conditions outlined in chapter eight.

Although the composite ice sheet model proposes a large intra-formational ice mass separating the till facies, there is no evidence for the melt of such a layer within the fabric and sedimentology of the Withernsea Till. Although this unit must originally have been derived subglacially, the debris, once melted out on to the surface of the composite ice sheet would have been subject to various mass wasting processes such as sediment flow and slump (Boulton 1971 , Lawson 1981). While in many cases the sediment may have retained its subglacial characteristics, the bulk of the material would inherit a new set of properties related to the rapid melt of the underlying ice sheet and subsequent resedimentation (Paul 1981). These new properties would include disaggregation, reduction in density and textural changes resulting from sorting, winnowing and fabric reorientation - none of which was observed in the Cowden profile or on any visible scale within the coastal sections. Indeed, even taking into account the effects of weathering, the data from the study site showed no significant variation in size distribution and/or index properties across the colour boundary while features associated with subglacial processes, micro-lamination and clast streaking, were observed in both facies types. The remote possibility that the entire diamict sheet could have been lowered by a slow melting process on to the basal Skipsea Till while still retaining its subglacial fabric, requires the entire 15 m sequence to be emplaced by a single surge event, a clearly implausable proposition.

The observation by Catt and Penny (1966) that there is... " no weathering, contortion or incorporation " across the till facies junction is certainly an oversimplification of the field evidence since the contact can be seen in a variety of situations. These include incorporation across the boundary, intervening sand and gravel lenses as well as in extremely sharp association with large clasts passing across the contact. In addition, the authors do not consider the possiblity that the colour junction may not represent the precise stratigraphic level marking the readvance of the ice front.

Lastly, the geotechnical analysis proved that both tills possess similar strength and consolidation characteristics which can be interpreted in terms of related stress histories. The wide variations in strength (cu), preconsolidation stress (pc) and compression index (Cc) reported by Lutenegger, Keminis and Hallberg (1983) as marking the junction between basal and supraglacial sediment associations were simply not observed at Cowden.

9.2.2 Postglacial Weathering. The Devensian till sequence in Northumbria has a superficial similarity to that of Holderness, in so far as a "reddish" upper till overlies a grey till with intervening sand-gravel lenses. Eyles and Sladen (1981) have proposed that the upper unit is a post-depositional weathering profile and not a petrologically distinct till unit. It is further suggested that the intensity of weathering is partially controlled by the drainage afforded by the intraformational sands and gravels and can extend to depths in excess of 8 m.

While this remains a valid interpretation for the

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Northumbrian tills it cannot be applied to Holderness for the following reasons. First, the analysis by Madgett (1974), which remains the most complete petrological treatment of the Holderness tills, found distinct mineralogical and lithological assemblages in the Skipsea and Withernsea tills, while recognising a separate and distinct weathering profile across both diamict units, previously termed the Hessle Till (Catt and Penny 1966). Second, the Withernsea/Skipsea till boundary, as defined by the colour change, can be very sharp, unlike most soil horizons, and at Cowden maintains a constant 4^{o} dip across the site unrelated to surface morphology. In the trench, where the contact was exposed in a fresh undisturbed section, desiccation fissures bounded by gleyed surfaces were observed passing through the boundary with discolouration progressing inward from the ped surfaces. Primary oxidation of the till was found to extend to a depth of approximately 3m, below which the till was largely unaltered. Lastly, the colour variation extends offshore and has been noted by a number of workers (Robinson 1967, and Fisher, Funnel and West 1969) as well as in the B.G.S vibrocore survey of the Spurn sea area (B.G.S personal communication). For the upper till to be a product of weathering, the horizon could only have developed prior to the postglacial rise in sea level which has been dated in the area of the Dogger Bank to between 9000-8700 years BP (Jelgersma 1979). Since most workers agree that the onshore exposure of the Withernsea Till is limited to the area shown in Figure 9.3, the question arises how a soil horizon could exist in offshore formation exposed for a brief period during the postglacial while being completely absent from onshore sequences subject to subaerial weathering since the retreat of the ice sheet.

9.2.3 Active Ice Sheet Model. The evidence in support of a low profile, substratum controlled glacial margin for the Pleistocene ice sheets has been listed by Boulton and Jones (1979) as;

1) anomalously low values of postglacial isostatic rebound;

2) margins which are extremely difficult to explain using surface profiles of modern glaciers; and

3) high retreat rates which are difficult to explain using typical modern profiles.

All these points can be applied to the Late Devensian glacial lobe which flowed down the east coast of England, while the model also places into context many of the properties of the Holderness diamict observed in the Cowden profile and coastal sequences. By closely linking the processes of deposition and erosion to conditions at the glacier sole it is possible to define zones where erosion of the bedrock would have directly contributed to the nature of the till deposited further down the flow line. It is proposed that a change in the bedrock lithology in such a source area, caused by erosion through the Liassic - Triassic boundary under the conditions outlined in chapter eight, was the major factor in the development of a dual till sheet in Holderness. This theory is glaciologically less complex than the model of a composite ice sheet since only one ice stream is required depositing a single, essentially homogeneous, till at any one time which slowly accreted at the glacier base. The lithological and mineralogical distinctions drawn by Madgett (1974) can therefore be maintained without the necessity of involving a second ice stream, while also explaining the many similarities that the till bodies possess, particularly with respect to the inclusion of chalk and

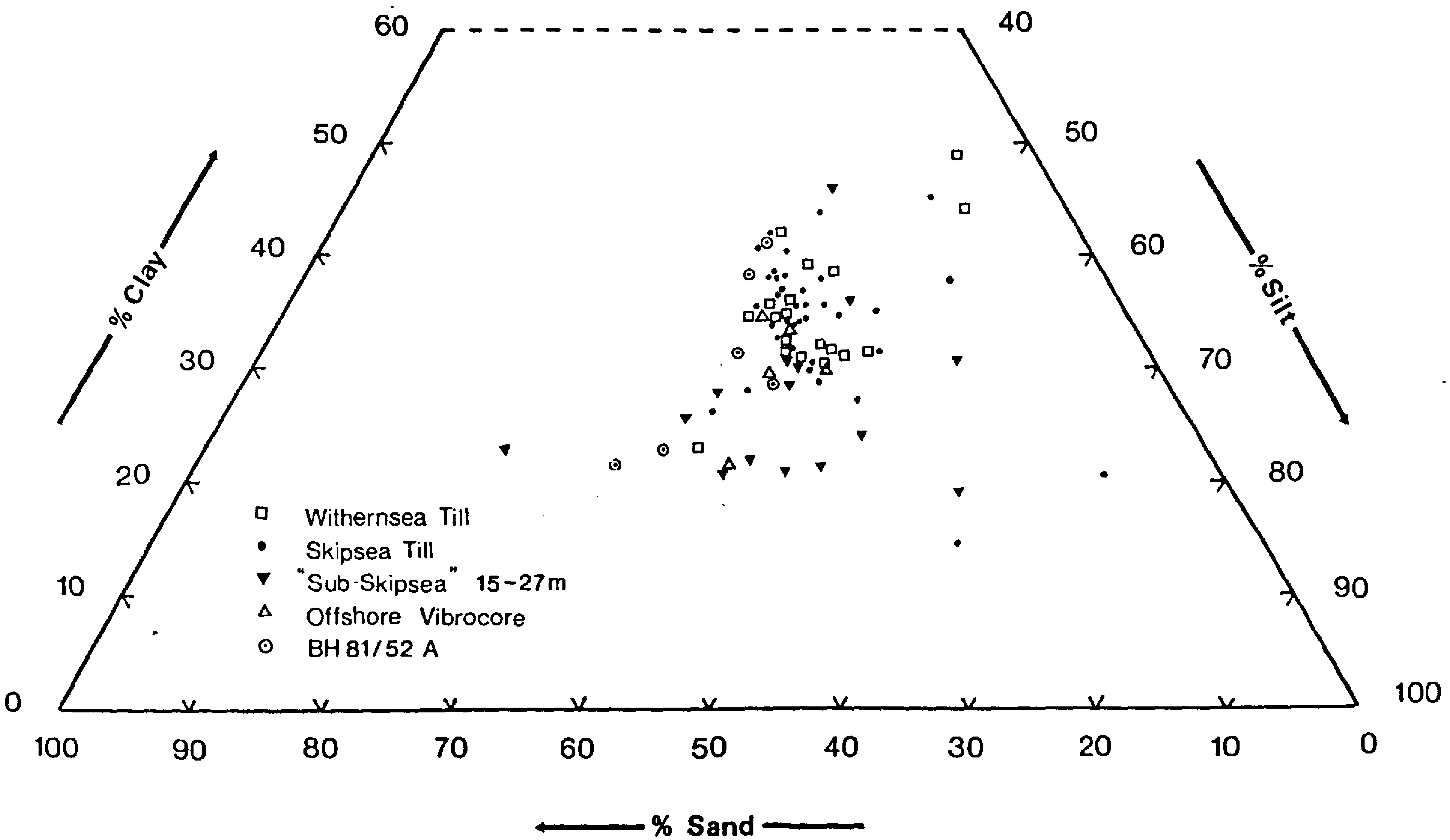


Figure 9.4 Ternary plot of particle size data

flint in the offshore Withernsea Till, Triassic clasts in the Skipsea Till and the overlapping particle size distribution envelopes (Figure 9.4).

The depositional model is essentially that proposed by Eyles, Sladen and Gilroy (1982) of "unconformable facies deposition", with the essential difference that any substantial lateral shift of the ice sheet is ruled out, the principal control being the change in the mix of bedrock lithologies transported along individual flow lines. The variation in the nature of the facies contact is accounted for by phases of activity and inactivity related to oscillations of the ice margin. Considering the position of Holderness lateral to any North Sea ice sheet, it is proposed that a subaerial phase may have preceded the deposition of the Withernsea Till in areas east of Cowden leading to the complex variation in till lithology, fabric and strength, as seen at Cowden, close to the colour-change boundary.

Lastly, the active ice sheet model is the only proposal which satisfactorily predicts the nature and reponse of the till sheet under geotechnical analysis, particularly with respect to its behaviour under shear, low pre-consolidation values and observed structure (micro-lamination, dilatant fabric and crushed clasts).

9.3 Interpretation Of The Skipsea-Basement Till Boundary.

If the possibility of an active ice margin is accepted, then this calls for a close re-examination of the relationship between the Skipsea Till, Basement Till and associated silt basins exposed at Dimlington. The radiocarbon age of 18,240±250 years BP for the Dimlington Silts (Penny, Coope and Catt 1969) has long been used as a basis for inter preting the overlying Skipsea and Withernsea tills as representing the Devensian ice sheet maximum in eastern Yorkshire and, by inference, a penultimate (Wolstonian) age for the underlying Basement Till. The possibility that the Basement Till at Dimlington was laid down by a Devensian ice advance before the cold stadial event marked by the Dimlington Silts is worthy of consideration on the following grounds. Given that the last interglacial (Ipswichian) shoreline lay at +1.5 to 2m above sea level at the fossil cliff line 20-30km inland, till from any earlier glaciation which is still in situ must be below sea level.

The fact that the Basement Till surface rises above sea level forced Catt (1977) to propose that both the assumed Wolstonian Till and the overlying Dimlington Silts were lifted into the "core of a push moraine" by the advancing Devensian ice. The thickening of the succession at Dimlington is largely a function of a much thicker sand and gravel unit of an important subaerial glaciofluvial input. While this might well mark a stillstand of the ice margin, there is no structural evidence to suggest that the thickening is the product of a push moraine genesis. Indeed the silt basins do not lie at any particular level but can be found at a number of levels within the Skipsea Till between Dimlington High Land and Old Hive (TA 381232) in a manner similar to that described by Bisat (1939). In addition, it should be noted that massive silt sequences were exposed during the summer of 1982 and 1985 in a complex proglacial association between the Skipsea and Withernsea Tills. These were commonly moved to beach level due to the rotational collapse of the unstable cliff face and often appeared to represent an in situ section after being reworked by the tide.

Even accepting the validity of the Dimlington silt date it is perhaps unjustified to use it to support a Wolstonian age for the

COWDEN BH AMALGAMATED DATA SETS

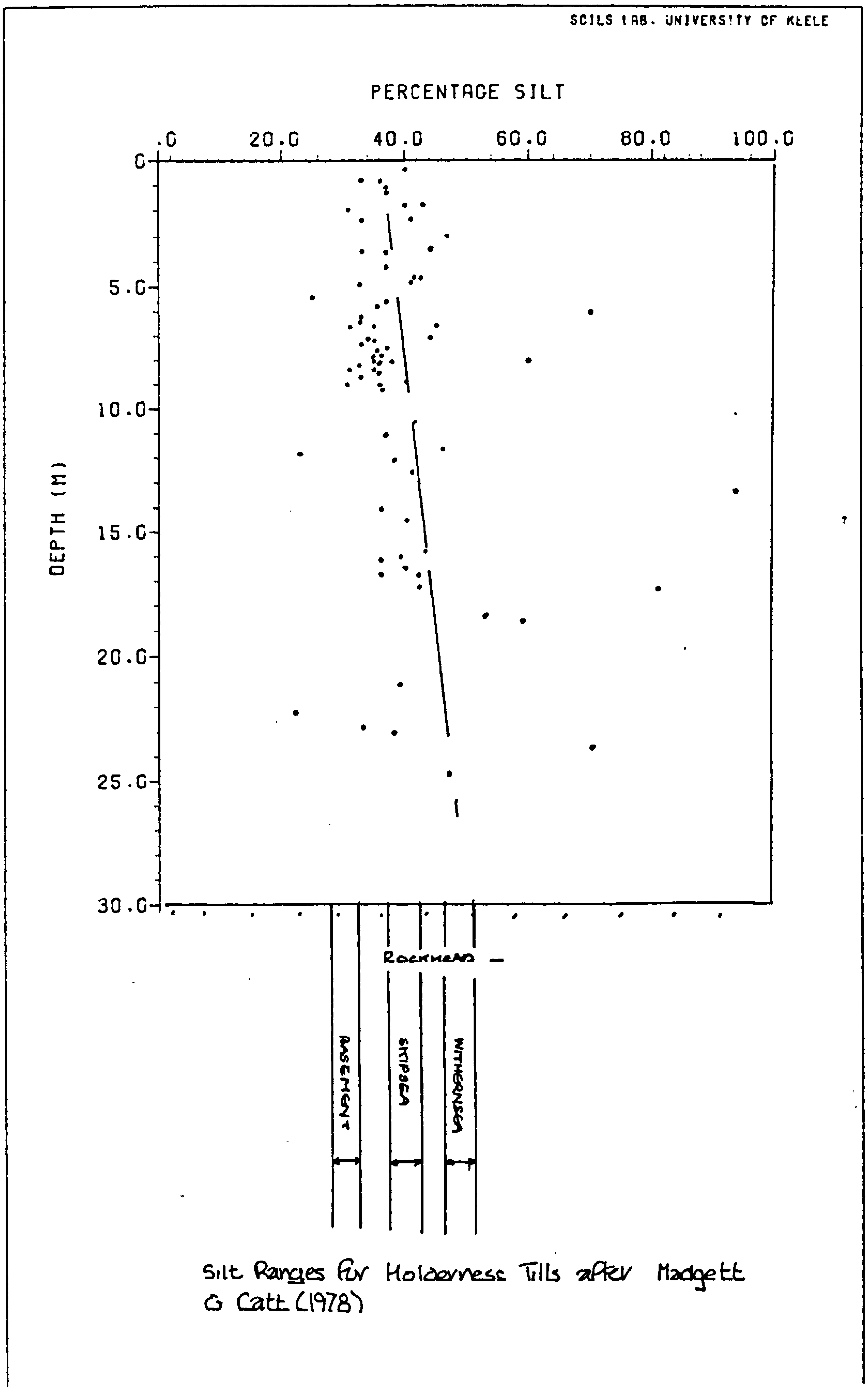


Figure 9.5 The percentage silt content of the Quaternary sequence at Cowden sampled to rockhead.

underlying till since this completely disregards the 25,000 years of marine Ipswichian conditions and 50,000 years of the early-middle Devensian before the approach of the ice front. Equally anomalous is the identification of birch and pine pollen within the silt basins which originly led Catt and Penny (1966) to suggest a boreal climate representative of an interstadial or late glacial phase rather than ice proximal conditions suggested by the later radiocarbon date.

The recognition of the Basement Till as a separate unit has long been established on the basis of a unique petrography and sedimentology. The quantitative approach of Madgett (1974) supports the premise that the Basement Till can be identified by a low silt content although there is no evidence in the Cowden boreholes to chalk of any till body which approaches the proposed range of silt content (Figure 9.5). The conclusion that the Basement Till contains a distinct lithological clast assemblage was dismissed by Madgett and Catt (1979) who stated,

"A tradition has emerged that the Basement Till is characterised by Scandinavian erratics, the Drab (Withernsea Till) and Purple (Skipsea Till) by Northern English clasts ......, but this is certainly an over-simplification, as all the Holderness tills have a wide range of erratics and no objective assessment of the relative abundance of different types in each till has yet been made."

Madgett and Catt. (1978) pp 68-69

Although the evidence for a distinct mineral assemblage was supported by the same authors, a re-analysis shows that if the data

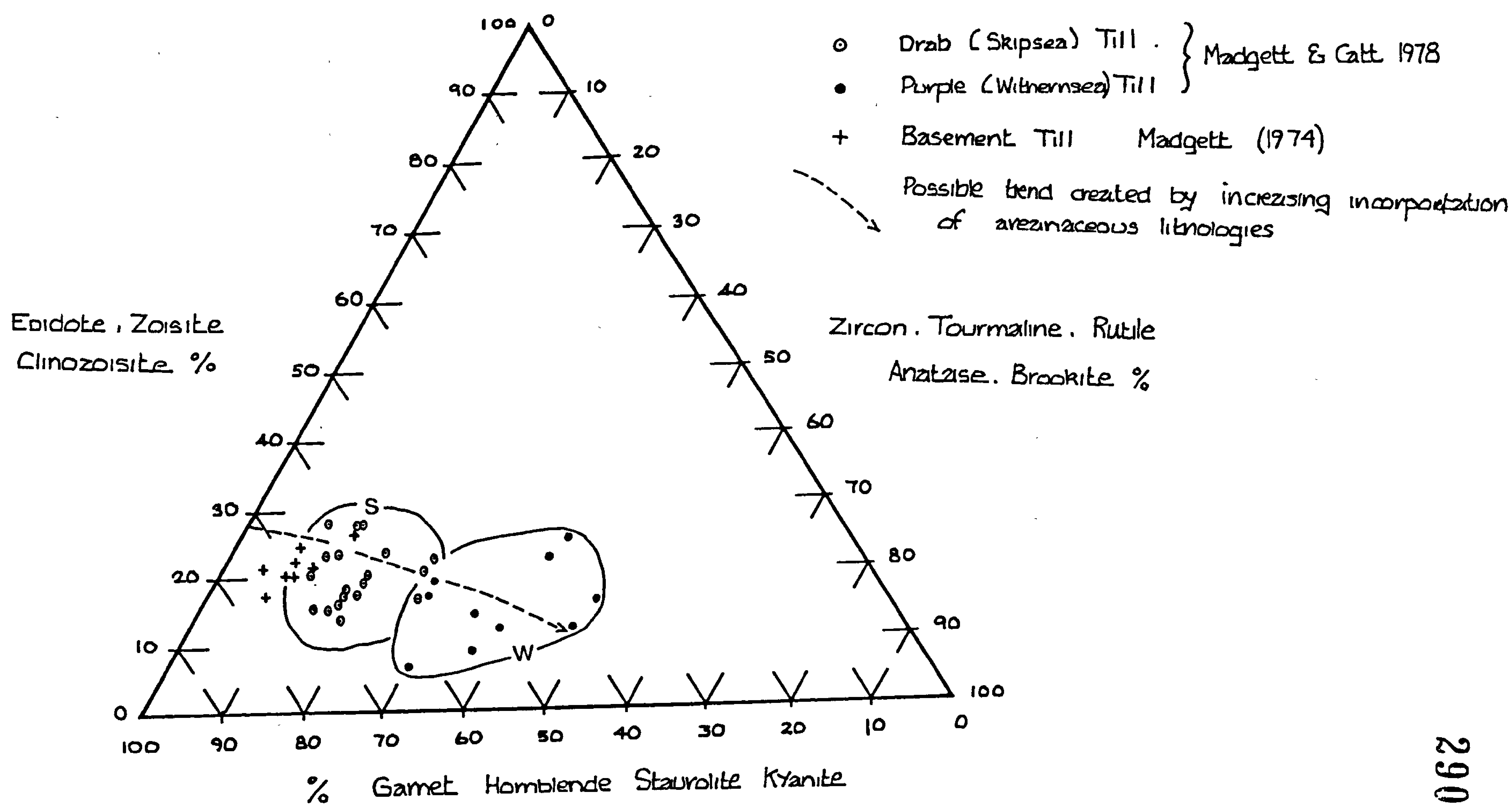


Figure 9.6 Heavy mineral composition of the Holderness diamicts redrawn from data presented by Madgett (1974)

given for the Basement Till by Madgett (1974) is replotted on the relevent diagram, the till falls close to, or within, the envelope defined for the Skipsea Till (Figure 9.6). Indeed, using this diagram it would appear that the change in mineralogy of the till profile is largely due to the increased quantities of Zircon, Tourmaline, Rutile, Anatase and Brookite. Since both Zircon and Rutile are common accessory minerals in detrial sands this could simply reflect the increased incorporation of Triassic lithologies as proposed in the active ice sheet model.

The rationale behind any such analysis when applied to a stratigraphic context is, however, defective since even if the Basement Till proved to be entirely distinctive this does not imply a pre-Devensian age, merely different source lithologies for the ice sheet. At present the till stratigraphy in Holderness is divided into three units, the upper tills "proven" to be Devensian despite their distinct petrography and the lower till "proven" to be Wolstonian because of its distinct petrography.

Taking into account this evidence, an alternative depositional model is proposed in which the till underlying the Dimlington Silts is also Devensian in age and the stratigraphical relationship between the Basement Till, Dimlington Silts and lower Skipsea Till simply represents a lateral shift in the western flanks of an extended ice body occupying the North Sea basin, in a manner similar to that which created the Skipsea-Withernsea facies change.

9.4 The Sewerby Type Locality.

The locality which provides the strongest evidence for a pre-Devensian till in Holderness is Sewerby (TA 193678 - TA 202686) where the contact between the Devensian tills and the chalk sub-drift occurs across a buried raised beach,

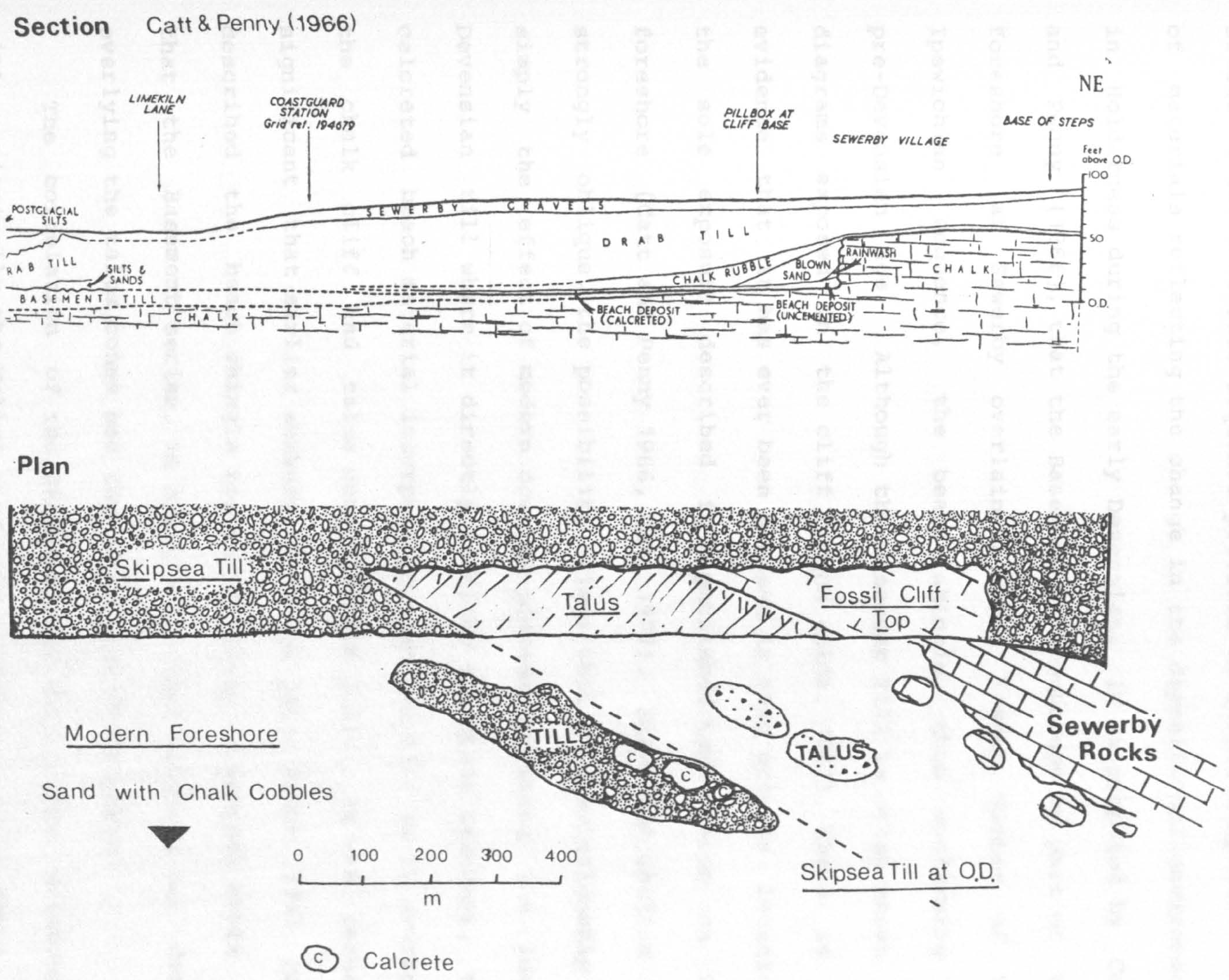


Figure 9.7 Interpretation of the Sewerby cliff section ... see Plates 9.1 and 9.2

running obliquely into the modern cliff profile (Figure 9.7 and Plates 9.1 - 9.2). The colluvium, shingle and sand bodies have yielded a wide range of Ipswichian mammalian fauna and there is little doubt that this sequence provides an almost complete suite of materials reflecting the change in the depositional environment in Holderness during the early Devensian. It is proposed by Catt and Penny (1966), that the Basement Till outcrops as part of the foreshore at Sewerby overlain by the lowest member of the Ipswichian sequence, the beach shingle, thus confirming a pre-Devensian age. Although the Basement Till is often shown in diagrams exposed in the cliff (INQUA guide, 1977), there is no evidence that it has ever been exposed in this precise location, the sole exposure described in a published text being on the foreshore (Catt and Penny 1966, Catt 1977). Since the section is strongly oblique, the possibility arises that this relationship is simply the effect of modern coastal processes planing the lower Devensian till where it directly overlies the chalk basement, the calcreted beach material incorporated into the till as it overrode the chalk cliff and talus cones (Figure 9.7). It is perhaps significant that earlier workers (Lamplugh 1891, Bisat 1939) have described the beach shingle resting directly on bedrock chalk so that the Basement series, in Bisat's original sections was drawn overlying the talus cones and therefore post-dating them.

The correlation of the Basement Till with other Wolstonian tills, principally the Welton till of Lincolnshire (Straw 1969), is inconclusive and speculative, and is best described by Straw (1983) as an "affinity". Without a close re-examination of the Sewerby section it is difficult to see any conclusion being drawn from the Holderness profile which can be used to support the case for a glaciation of Lincolnshire during the Wolstonian.

9.5 Raft Erratics In The Basement Till.

Enclosed within the Basement Till are several types of deposit which, most workers agree, can only be regarded as erratic masses picked up by the ice which deposited the till. The best documented of these is the Bridlington Crag which is described in its type location at Bridlington as,

"Greenish-grey, glauconitic silty sand, contorted and streaked out with the surrounding Basement Till, and in places crowded with shells"

Catt and Penny (1966) pp 380.

This inclusion has been directly related to the Sub-Basement Clay exposed at Dimlington on the basis of the microfauna, although Catt and Penny (1966) noted that a number of different lithologies may be present at the latter locality. This was confirmed during the summer of 1983 and 1985 when high water stripped a large portion of the foreshore at Dimlington exposing the Sub-Basement series at low tide. At least two facies were identified. The first was a very dark grey/ (5Y 3/1) friable silt-rich clay, with well developed slickenslides, highly calcareous and fossiliferous with large quantities of broken shell fragments (SBC 2). The second was dark greyish brown / (10 YR 3/2), very friable and fissured silt-clay with no observed slickenslides, few shell fragments and an assemblage of chalk, flint, and siltstone clasts (<2mm) (SBC1). Few stratigraphic inferences can be drawn from the relationship between the two facies types or their possible connection with the third common basal erratic, the Beach clay (BC) exposed at Aldbrough, except the fact that all existed at depth within the till sections.

Plate	9.1	Sewerby Cliff showing the interglacial cliff profile (extreme right). The Sewerby Gravels are well exposed (upper pale unit) as is the underlying darker Skipsea Till which clearly covers the entire glacial sequence.

Plate	9.2	Cemented talus exposed on the beach foreshore at Sewerby close to the point where Plate 9.1 was taken. See figure 9.6.

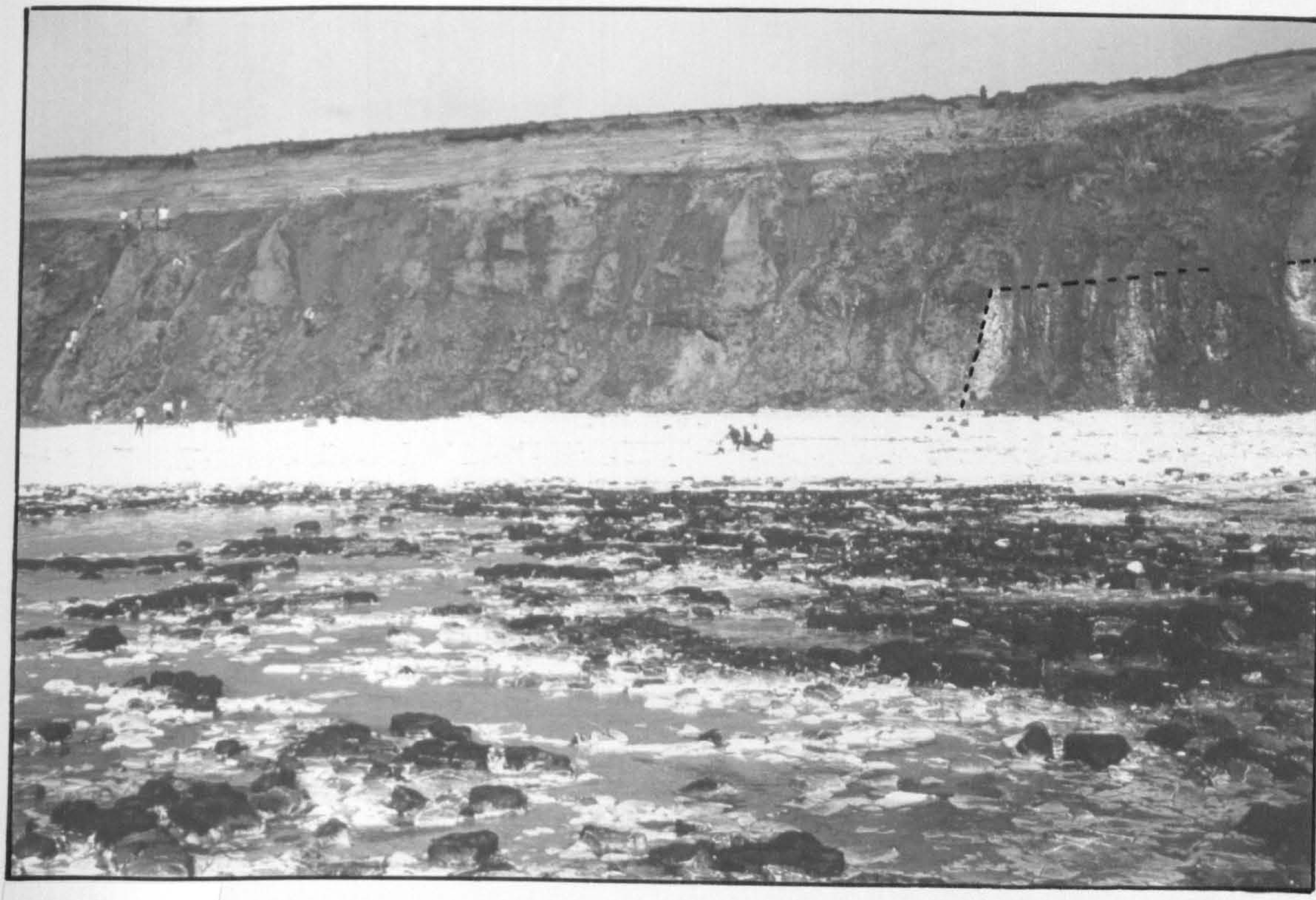


Plate 9.1

Plate 9.2

The importance of the erratics, in terms of the regional stratigraphy, lies in the fact that they provide a maximum age for the enclosing till body. The evidence presented by Catt and Penny (1966) for a Hoxnian age based on microfauna, therefore brackets the till between the Hoxnian and the Late-Devensian Dimlington silt date, being compatable with, but not proving a Wolstonian age. However this interpretation may be challenged on a number of grounds. First, samples of the Bridlington Crag removed from the type location during the Yorkshire Geological Society field meeting in 1964, supervised and reported by Catt (1965), were subjected to two independent studies neither of which could support an unequivocal Hoxnian age on the basis of microfauna. Indeed, the strict palynological analysis of Reid and Downie (1973), produced a rich assemblage of dinoflagellate cysts and pollen which, in their view suggested a Middle Pleistocene (Pastonian) age while Black's (1970) analysis of coccoliths yielded no Pleistocene or Tertiary species only species derived from the Jurassic Speeton and Kimmeridge Clays. This conflicting evidence may result from the variety of facies which have been grouped under the titles of Bridlington Crag and Sub-Basement Clay, since it is unlikely that all the deposits are contemporaneous or even representative of the same interglacial.

The original Hoxnian date for the Sub-Basement Clay is based on a comprehensive Ostracoda and Foraminifera assemblage recovered from one of the facies types at Dimlington (Catt and Penny 1966). The assigning of an interglacial date is perhaps surprising since the assemblage is notably arctic in nature, the most prominent species of Ostracoda being <u>Krithe glacialis</u>, which has previously been recorded only from arctic seas in latitudes higher than 77^{o}-78^{o} N. Similarly, many of the Foraminifera are found only in arctic seas at present, for example Elphidium subarcticuim and Elphidiella arctica. Although it is accepted that the Bridlington Crag may well represent a late Hoxnian cold phase, no evidence has ever been presented for a comparable assemblage in any in situ Hoxnian section within the British Pleistocene. This led Reid and Downie (1973) to point out that,

"Comparisons of this assemblage with the Hoxnian Kirmington silts show that they again differ significantly and must almost certainly be of different ages".

Reid and Downie (1973) pp 137.

Therefore, the main line of evidence for a Hoxnian age is reduced to the proposal that the enclosed erratics at Dimlington and Bridlington are directly comparable and the latter is enclosed in a till lying beneath an Ipswichian calcreted beach deposit, a fact which itself is questionable.

9.6 Offshore Hoxnian Deposits.

Marine clays have been recovered by gravity coring from the Inner Silver Pit (53^{o} 28'N, 0^{o} 41'E), 45km south-east of Dimlington, outcropping between bedrock chalk and material identified as Purple (Skipsea) Till (Fisher, Funnel and West 1969). Microfauna assemblages were dominated by Elphidium clavatium indicating middle Pleistocene conditions. Using the type sites of Marks Tey (Turner 1966) and the Nar Valley (Stevens 1958), pollen spectra indicating zones IIIb and IV of the temperate Hoxnian stage were identified. Although these clays may not provide a strict comparison with the Bridlington Crag, the microfauna provided a poor correlation with only seven of the forty

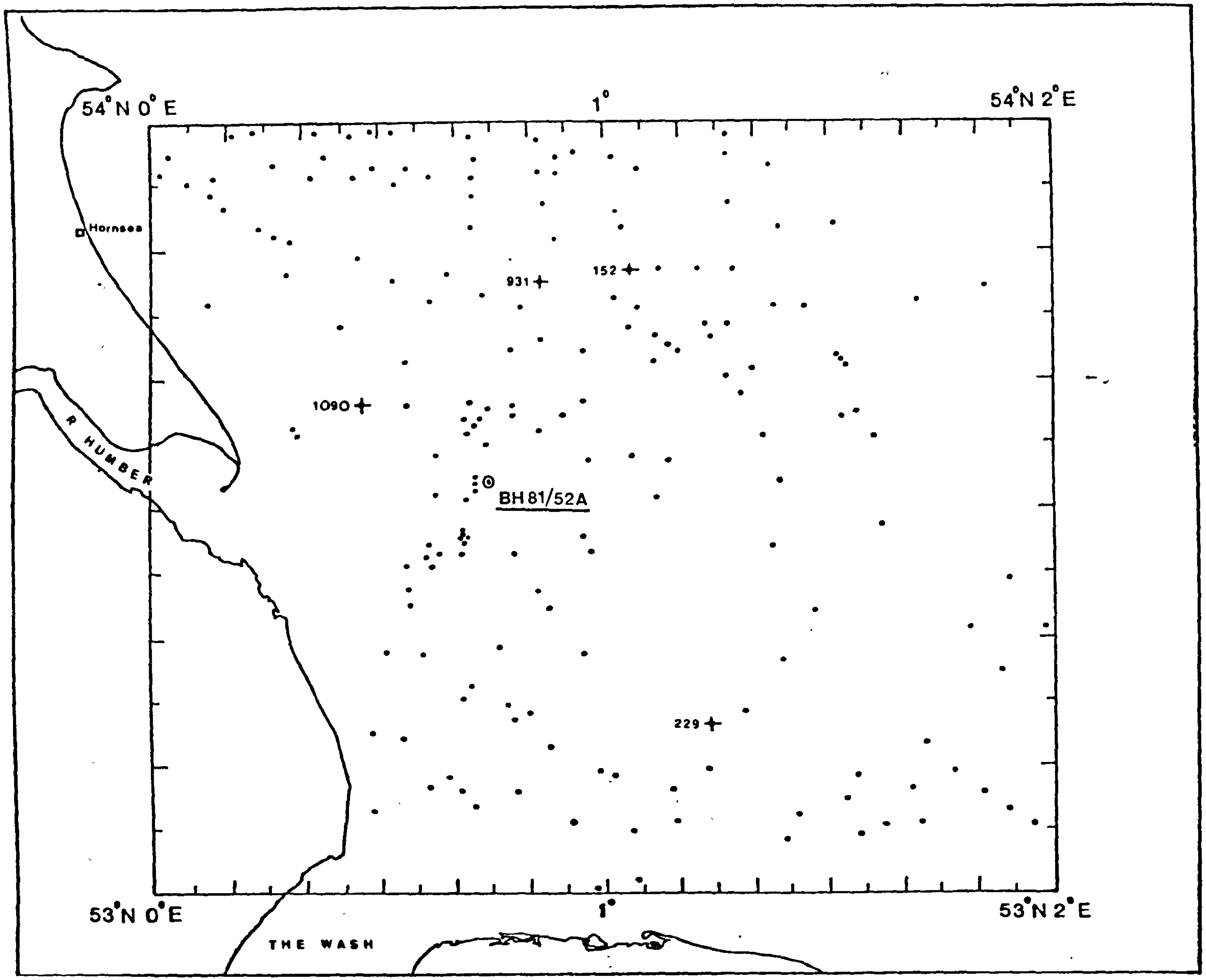


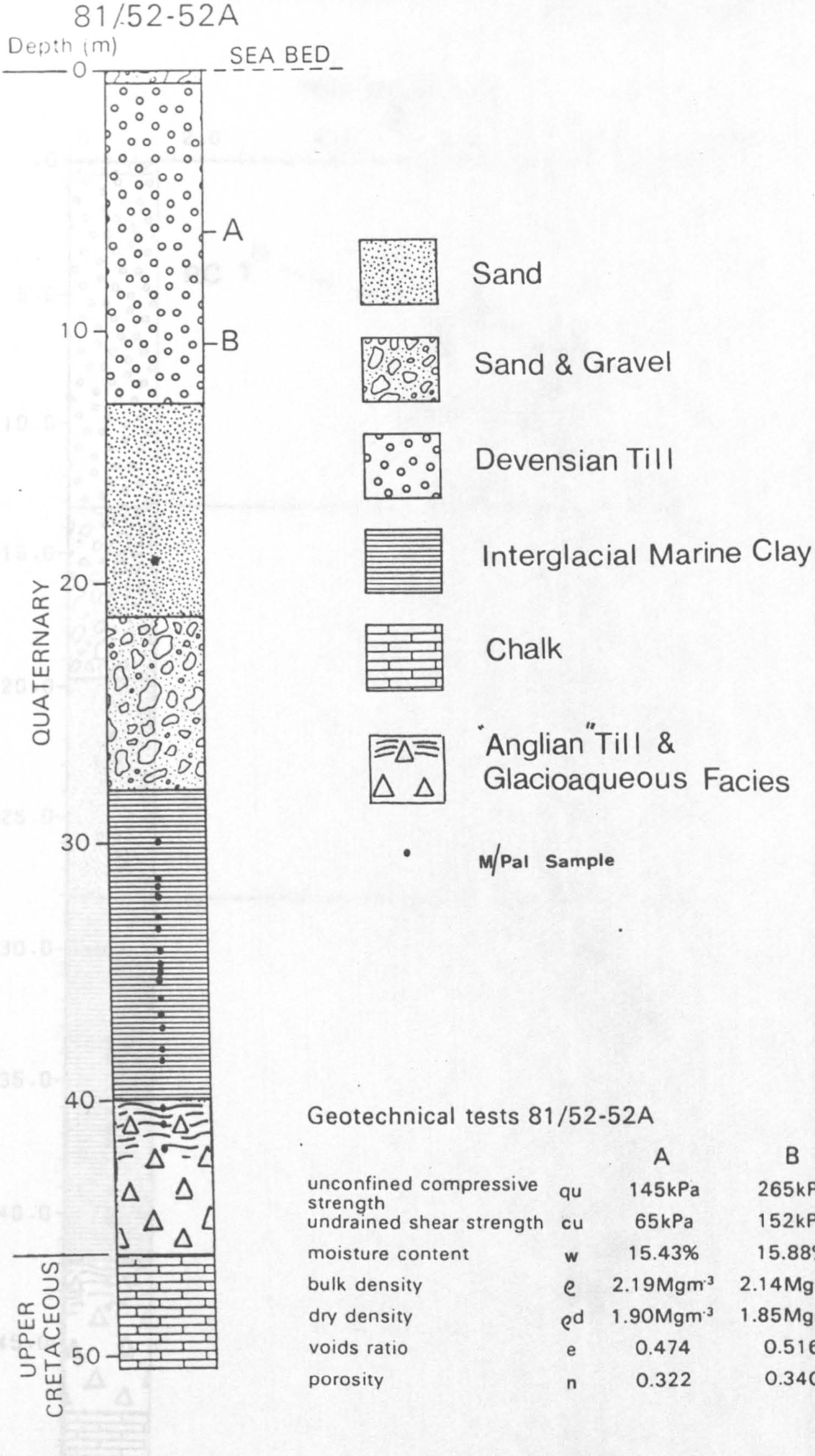
Figure 9.8 BGS Vibrocore cover in the Spurn map area

four foraminifera species common to both sets of sediments.

The in situ relationship of these clays to the Devensian tills and rockhead has since been proven by British Geological Survey borehole BH 81/52A, which was drilled at the head of the Inner Silver Pit (53^{o} 31' N, 0^{o} 44' E), 35km east of the Humber Estuary (Figure 9.8). The logs and associated sub-samples were kindly passed to Keele for further examination. Palynological studies were carried out at B.G.S and the results forwarded. A complete presentation of the results is given by Cameron (To be published). The facies units recognised in BH 81/52A are as follows,

Depth below seabed.	Brief Lithological Description.
0-13 m	Devensian till, with inclusions of sand and gravel at base. Stiff reddish brown 7.5YR 4/2 rich with chalk, Jurassic and Permo-Triassic clasts. Brown till at depth, 7.5YR 32, poorly sampled.
13-28 m	Sand and gravel sequence, very poorly sampled. Sands dark greenish grey 5G 4/1, moderate clay content, with shells coarsening down to gravel in sand matrix. Many flints in dark greyish brown matrix, 10YR 3/2. Sparse shell content.
28-40 m	Marine clay, very friable, grey-brown 5Y 4-5/1, with diffuse laminae.
40-37 m	Intercalated diamict - silt sequence overlying a dense, chalk-rich diamict, 2.5 YR 4/1.
43.5 m	Bedrock. Cretaceous chalk, unlithified and friable

Table 9.1 Lithostratigraphy of BH81/52A



Geotechnical tests 81/52-52A

		A	B
unconfined compressive strength	qu	145kPa	265kPa
undrained shear strength	cu	65kPa	152kPa
moisture content	w	15.43%	15.88%
bulk density	ϱ	2.19Mgm^{-3}	2.14Mgm^{-3}
dry density	ϱd	1.90Mgm^{-3}	1.85Mgm^{-3}
voids ratio	e	0.474	0.516
porosity	n	0.322	0.340

Figure 9.9 Stratigraphy of BH81/52A ... see Plates 9.3 and 9.4

After Balson & Crosby 1983.

BH81/52A SEA AREA. SPURN N.SEA

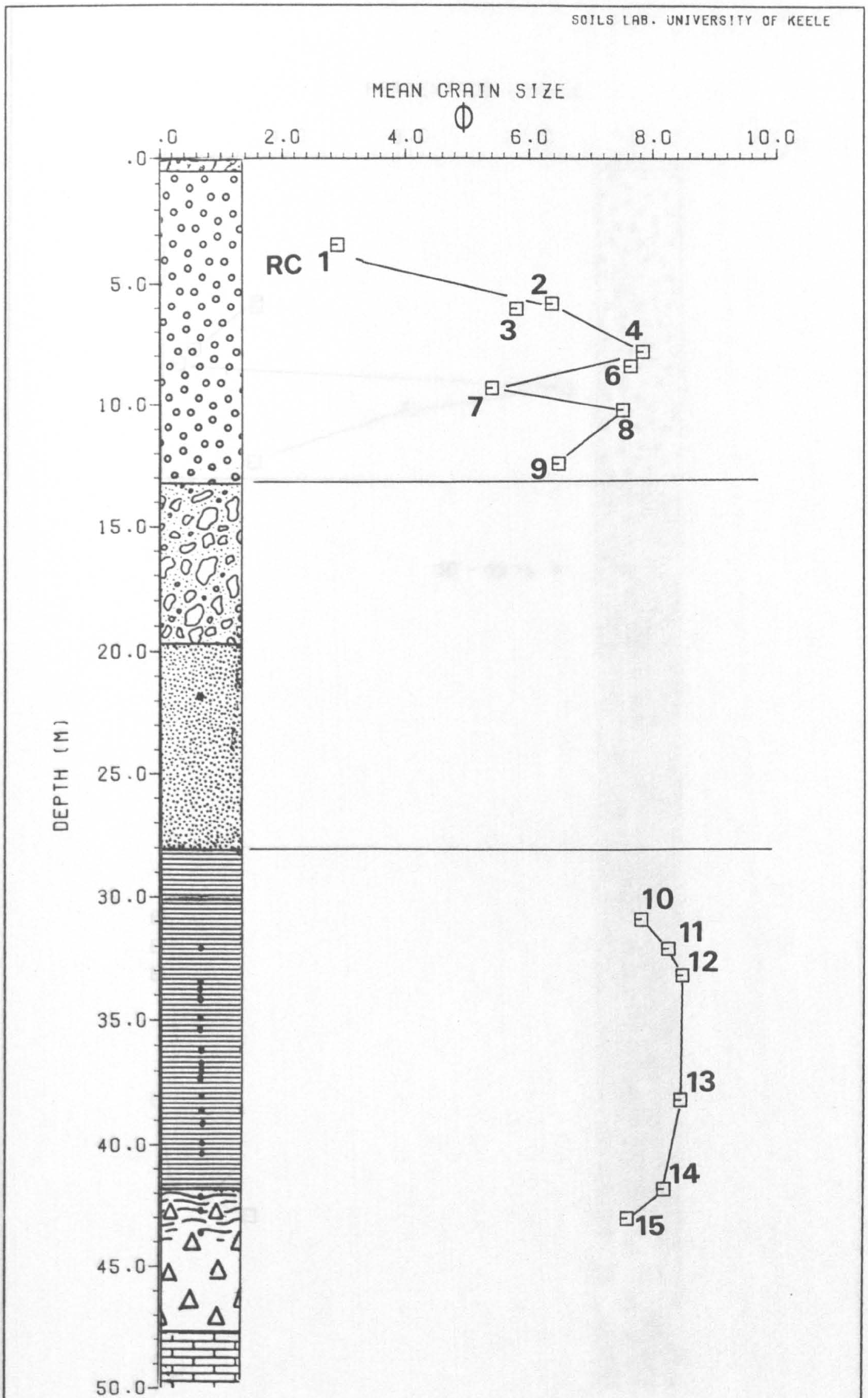


Figure 9.10 Mean grain size / depth BH81/52A

BH81/52A SEA AREA. SPURN N.SEA

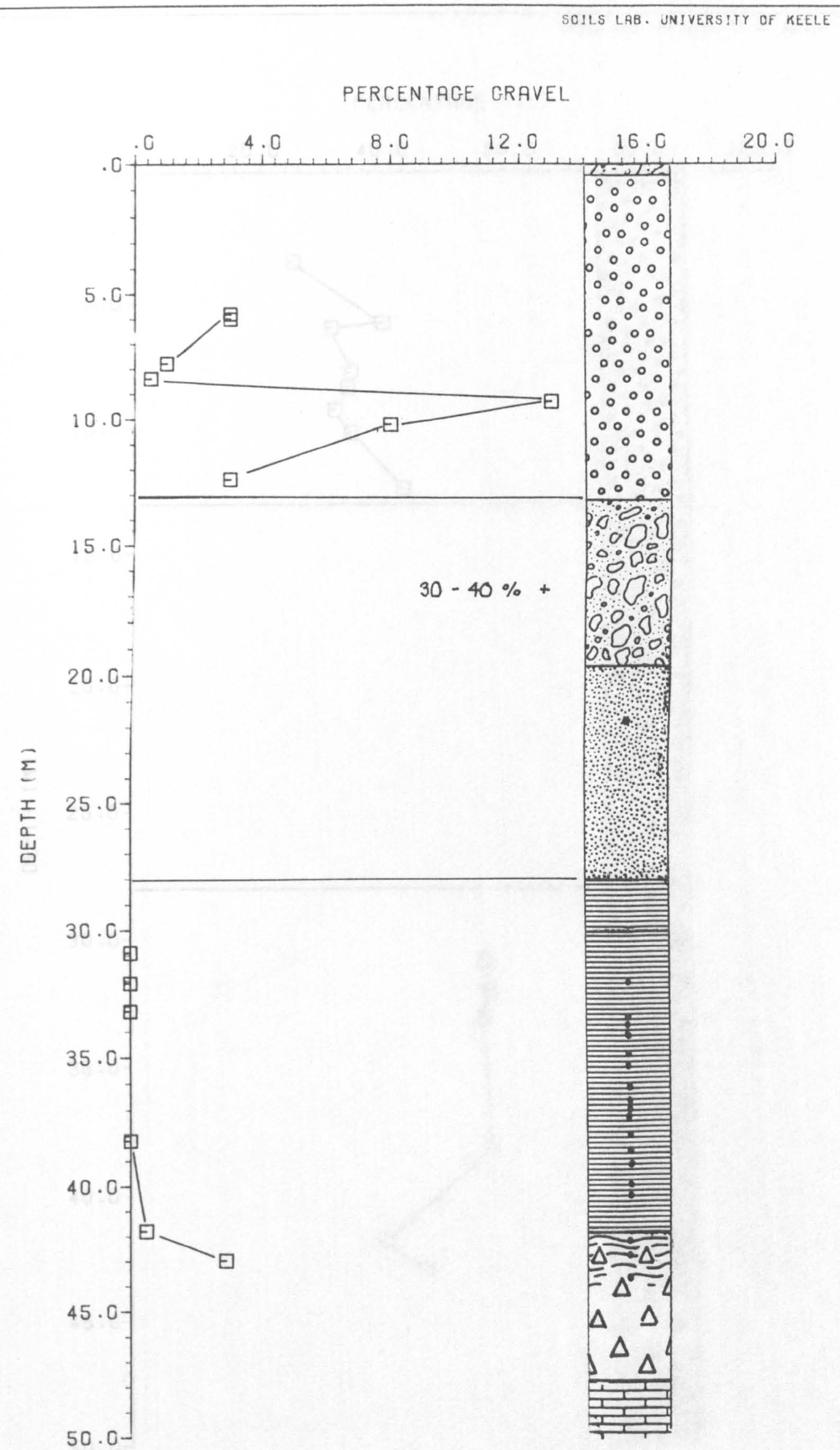


Figure 9.11 % Gravel / depth BH81/52A

BH81/52A SEA AREA. SPURN N.SEA

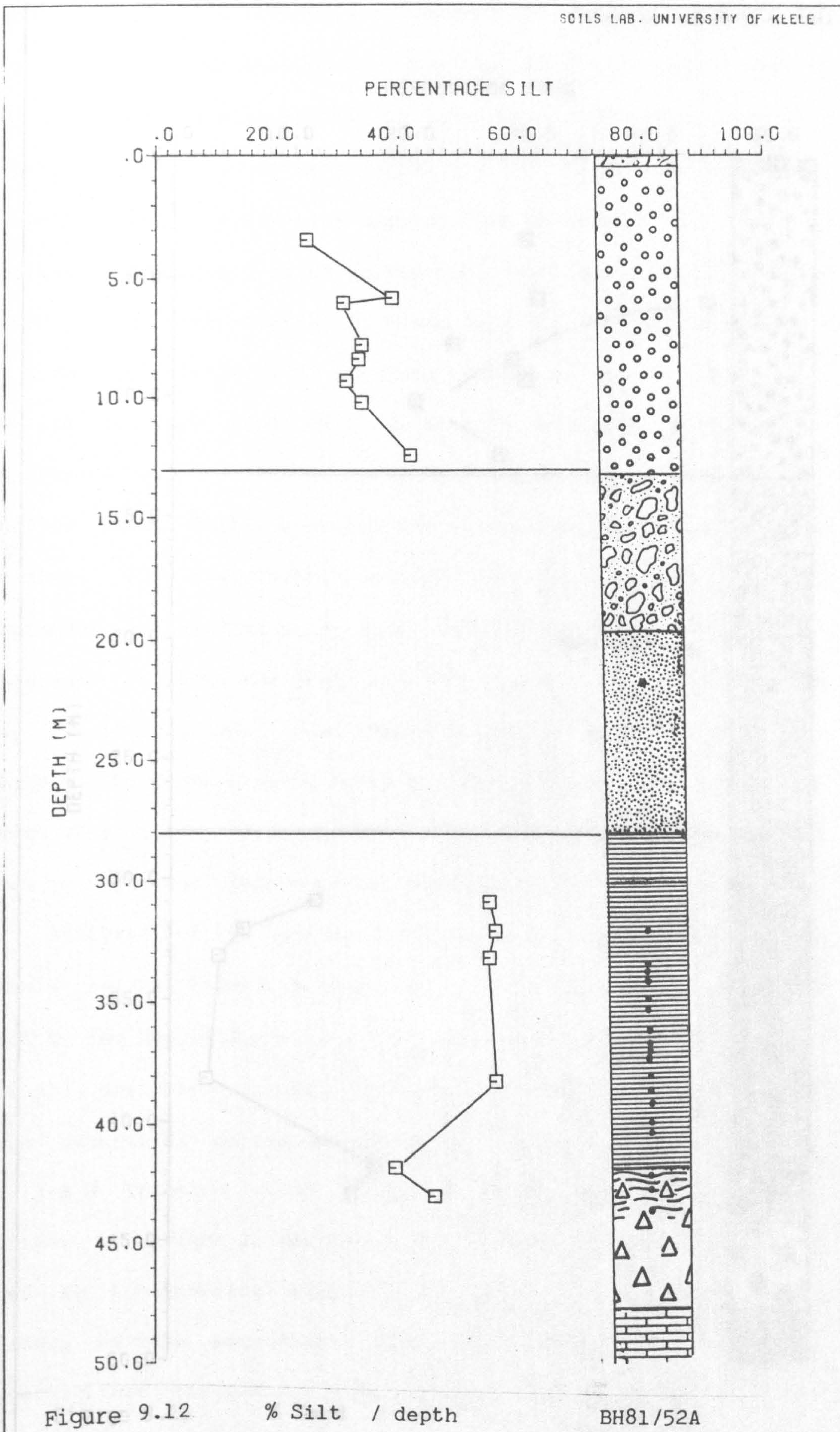


Figure 9.12 % Silt / depth BH81/52A

BH81/52A SEA AREA. SPURN N.SEA

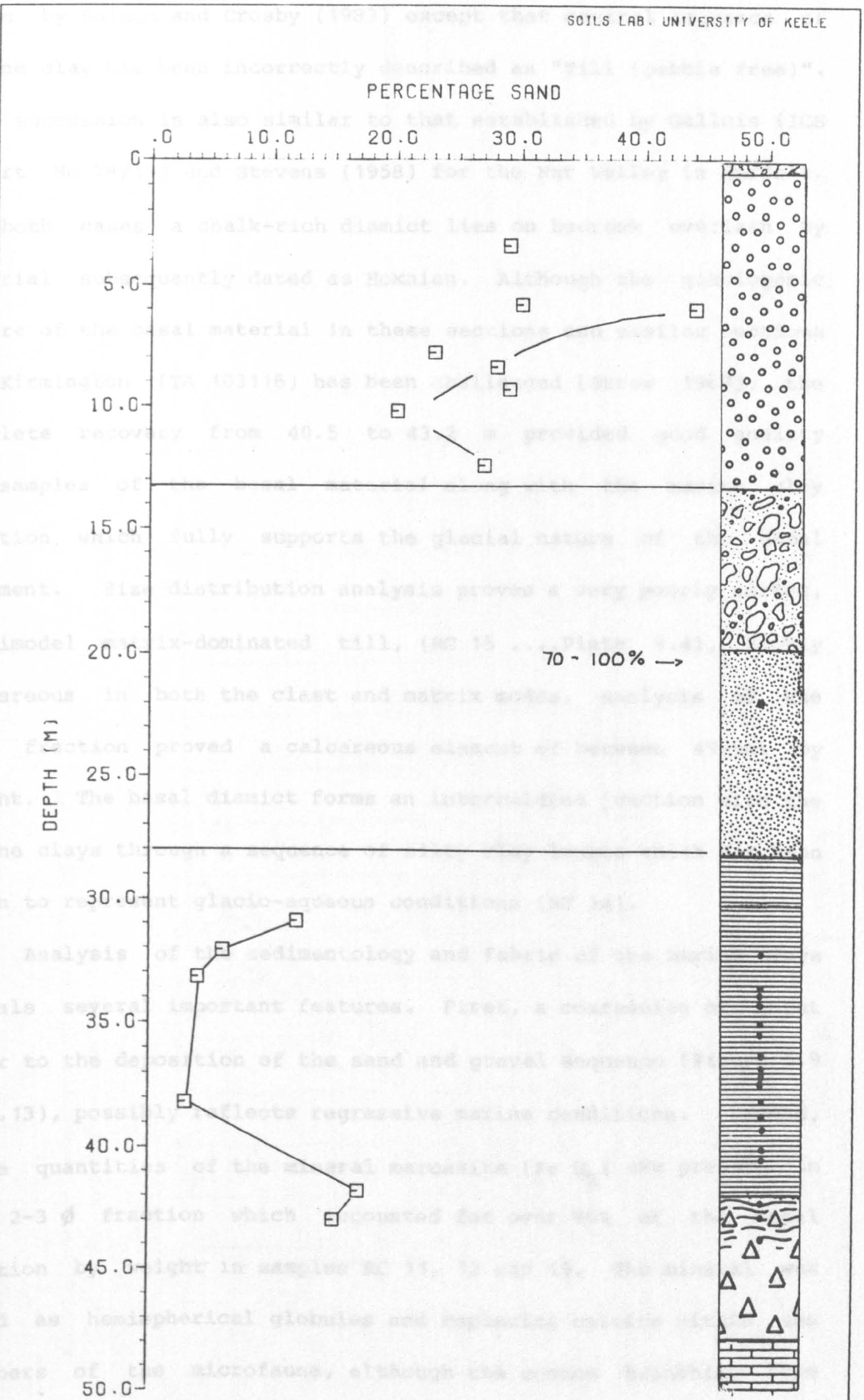
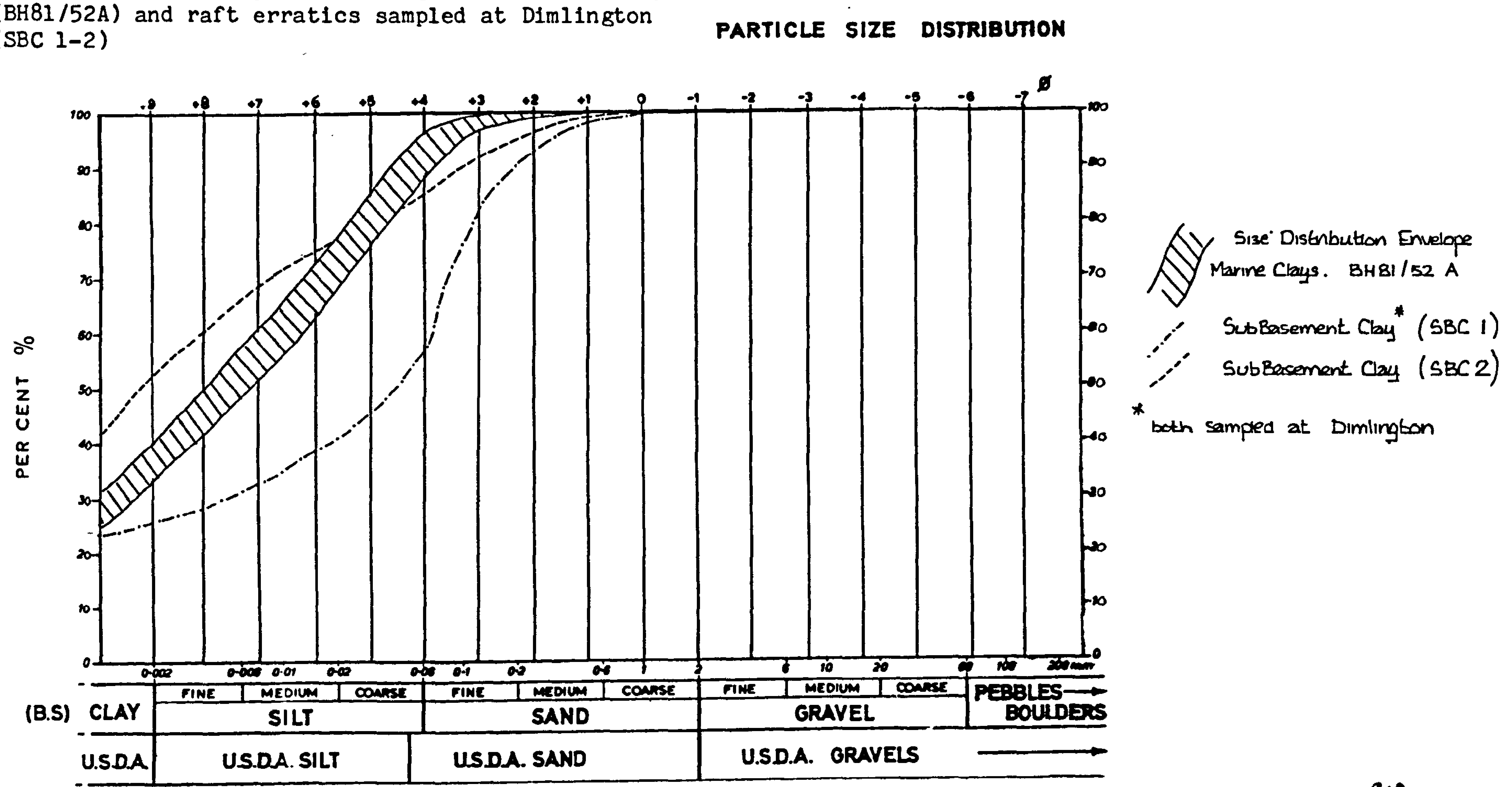


Figure 9.13 % Sand / depth BH81/52A

This is essentially the same interpretation for BH 81/52A as given by Balson and Crosby (1983) except that central sequence of marine clay has been incorrectly described as "Till (pebble free)". The succession is also similar to that established by Gallois (IGS report No 78/19) and Stevens (1958) for the Nar Valley in Norfolk. In both cases a chalk-rich diamict lies on bedrock overlain by material subsequently dated as Hoxnian. Although the glaciogenic nature of the basal material in these sections and similar sections at Kirmington (TA 103116) has been challenged (Straw 1969), the complete recovery from 40.5 to 43.2 m provided good quality sub-samples of the basal material along with the marine clay junction which fully supports the glacial nature of the basal sediment. Size distribution analysis proves a very poorly sorted, multimodel matrix-dominated till, (RC 15 ....Plate 9.4), highly calcareous in both the clast and matrix modes. Analysis of the clay fraction proved a calcareous element of between 49-56% by weight. The basal diamict forms an intercalated junction with the marine clays through a sequence of silty clay lenses which has been taken to represent glacio-aqueous conditions (RC 14).

Analysis of the sedimentology and fabric of the marine clays reveals several important features. First, a coarsening of input prior to the deposition of the sand and gravel sequence (Figure 9.9 - 9.13), possibly reflects regressive marine conditions. Second, large quantities of the mineral marcasite ($Fe\ S_2$) are present in the 2-3 Ø fraction which accounted for over 90% of the total fraction by weight in samples RC 11, 12 and 13. The mineral was found as hemispherical globules and replacing calcite within the chambers of the microfauna, although the common branching form suggests that the mineral also replaced vegetal debris. All the available evidence suggests a high organic input. The major clast

Figure 9.14 Particle size envelopes of interglacial marine clays (BH81/52A) and raft erratics sampled at Dimlington (SBC 1-2)



lithology was siltstone with minor chalk input. Size distribution characteristics are summerised in Figure 9.14.

A notable feature of samples RC12 and RC11 was the highly friable nature, created by a well developed fabric of interconnecting concave fissile surfaces, which existed within a layered structure approximately 5-6cm thick and bounded on the upper level by a "desiccated" surface (Plate 9.3). These features are similar to those created by sub-sea permafrost and may represent a deterioration in climate with the onset of full glacial conditions (Derbyshire, Love and Edge 1985).

Independent analysis of the micro-palaeontology by B.G.S, reported here in summary, was based on 26 sub-samples taken between 19.09 m and 42.2 m which identified a total of 32 species of benthonic foraminifera. In terms of the environment of deposition, three main units were identified (Table below D. Gregory, personal communication).

Unit 1 35.5-42.2 m A shallow cold water foraminiferal fauna was recovered. The dominant species being Elphidium clavatum. Below 41.5m fauna are sparse indicating inhospitable conditions.

Unit 2 31.6-35.1m A strong influx of southern species, including Bulimina marginata, Buccella vicksbulgensis, Cassidulina laevigata and Nonion barleeanum, indicating a considerable level of amelioration, probably to interglacial conditions. Significant deepening to 50m is also suggested by these assemblages. At 32.61m a horizon exists with relatively few southern species where cold water conditions are again postulated. A similar situation was recorded in the northern North Sea by Skinner and Gregory (1983).

Plate 9.4 Split subsample (RC15) recovered from BH81/52A (43.1m b.s.b.) within 1m of chalk bedrock, from beneath interglacial marine clays.

Plate 9.3 Split subsample (RC 12) recovered from BH81/52A (33.3m b.s.b.) within an extensive interglacial marine clay sequence (28-40m).

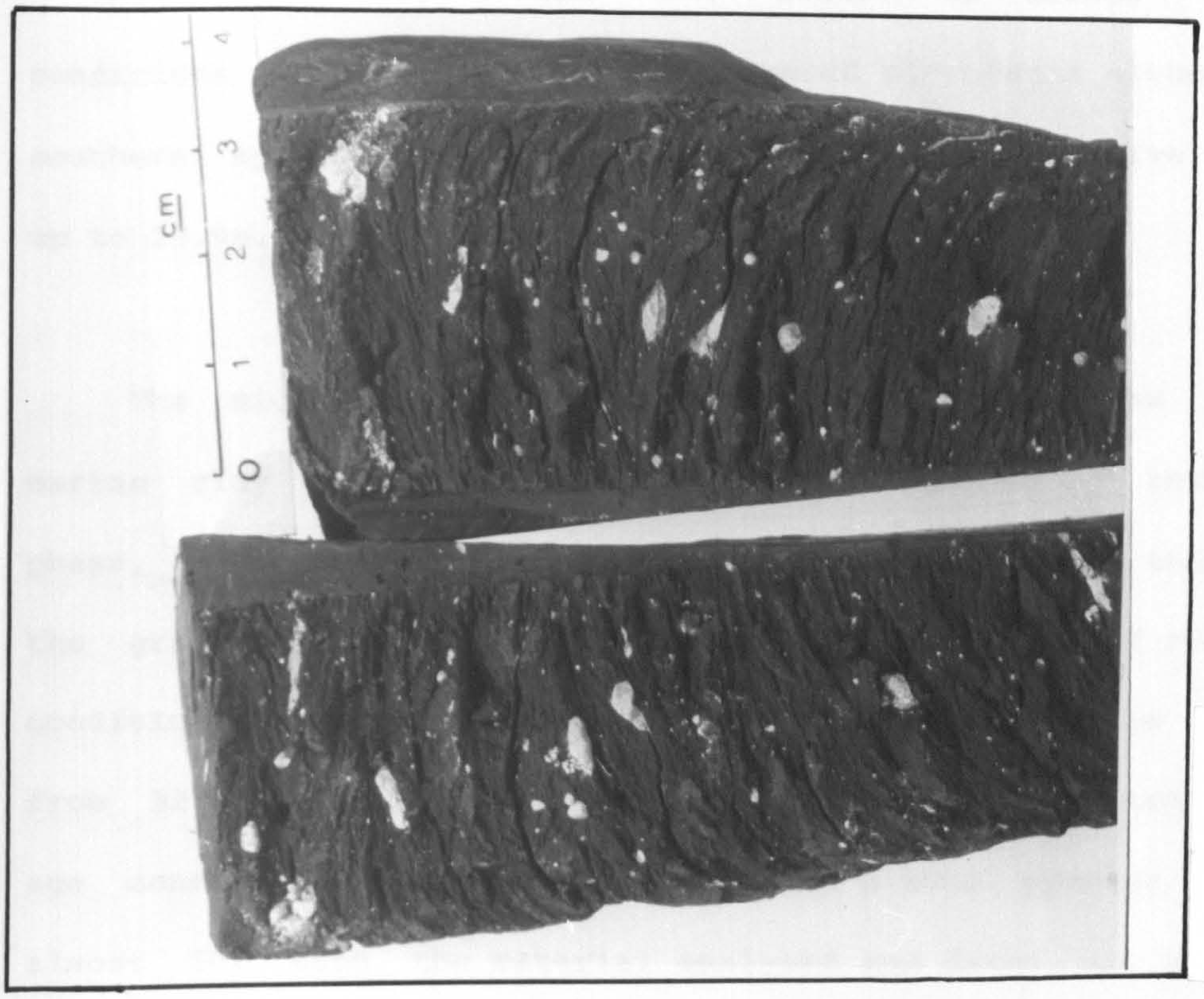


Plate 9.4

Plate 9.3

Unit 3 19.09-31.03m A return to colder shallower conditions is indicated by the recovered microfauna although a few southern species remain to suggest a slight ameliorative influence up to 29.9m.

The micro-palaeontologal spectra support the view that the marine clay sequence represents at least part of an interglacial phase, with evidence for a climatic deterioration at the base of the gravels. It is also significant that evidence of cold water conditions (Unit 3) matches closely the friable fabric recovered from 32.2 and 33.3m. Although the foraminiferal spectra cannot be age conclusive, the assemblage provides a total species overlap of almost 50% with the material analysed and dated as Hoxnian by Fisher, Funnel and West (1969), from further south in the Inner Silver Pit, while also proving that the clays overlie a chalk rich till which may well represent the Anglian-Hoxnian boundary. If the Sub-Basement Clay and Bridlington Crag represent Hoxnian marine clay erratics rafted in by the Wolstonian ice, then it might be expected to provide a good comparison with the material from BH 81/52A on both sedimentological and palaeontological grounds, although this was not found to be the case.

1) The size distribution curves fall well outside the envelope defined by the marine clays (Figure 9.14).

2) Analysis of the fine sand fraction of the Sub-Basement Clay reveals little marcasite, a mineral highly characteristic of the marine clays.

3) Taking into account the diversity of climatic regimes represented within the marine clay sequence, the overlap of the foraminiferal assemblages showed a correlation of only eight species in thirty two and a total absense in the Sub-Basement Clay

of the most dominant species in both the Fisher, Funnel and West (1969) and the BH 81/52A returns, namely Elphidium clavatium.

Although most of these arguments can be countered by the proposal that the Sub-Basement Clay represents a late interglacial phase not represented by the BH 81/52A sequence, the fact still remains that although the Sub-Basement Clay is dated as Hoxnian, this conclusion is not based on a type section, while the closest possible section, namely the Inner Silver Pit, does not provide any supporting evidence for a Hoxnian age. To explain an exclusive Hoxnian date for the Sub-Basement Clay under the composite ice sheet model it is necessary to postulate that the Wolstonian ice mass initially incorporated the material into the basal till as it moved south. The till sheet was than eroded to a wave cut platform during the 20,000 years of the Ipswichian transgression, of which no trace remains of offshore marine sedimentation, before being thrust for a second time into the base of the advancing Devensian ice sheet along with the surrounding till, associated weathering profile and the overlying silt cover (Catt 1977), and then lifted tens of metres to the same level as the undisturbed Bridlington Crag exposure to a point just below mean sea level.

The model of an oscillating ice front allows for a far simpler explanation, whereby the Basement till is also Devensian in age, possibly the product of the initial advance into Holderness, which incorporated a variety of pre-Devensian marine sediments from the North Sea basin. The observation of slickenslides, thrusting and brittle fracture in these sediments, which can be highly plastic, is compatible with the incoporation of this material as frozen blocks caught up in the base of a "cold

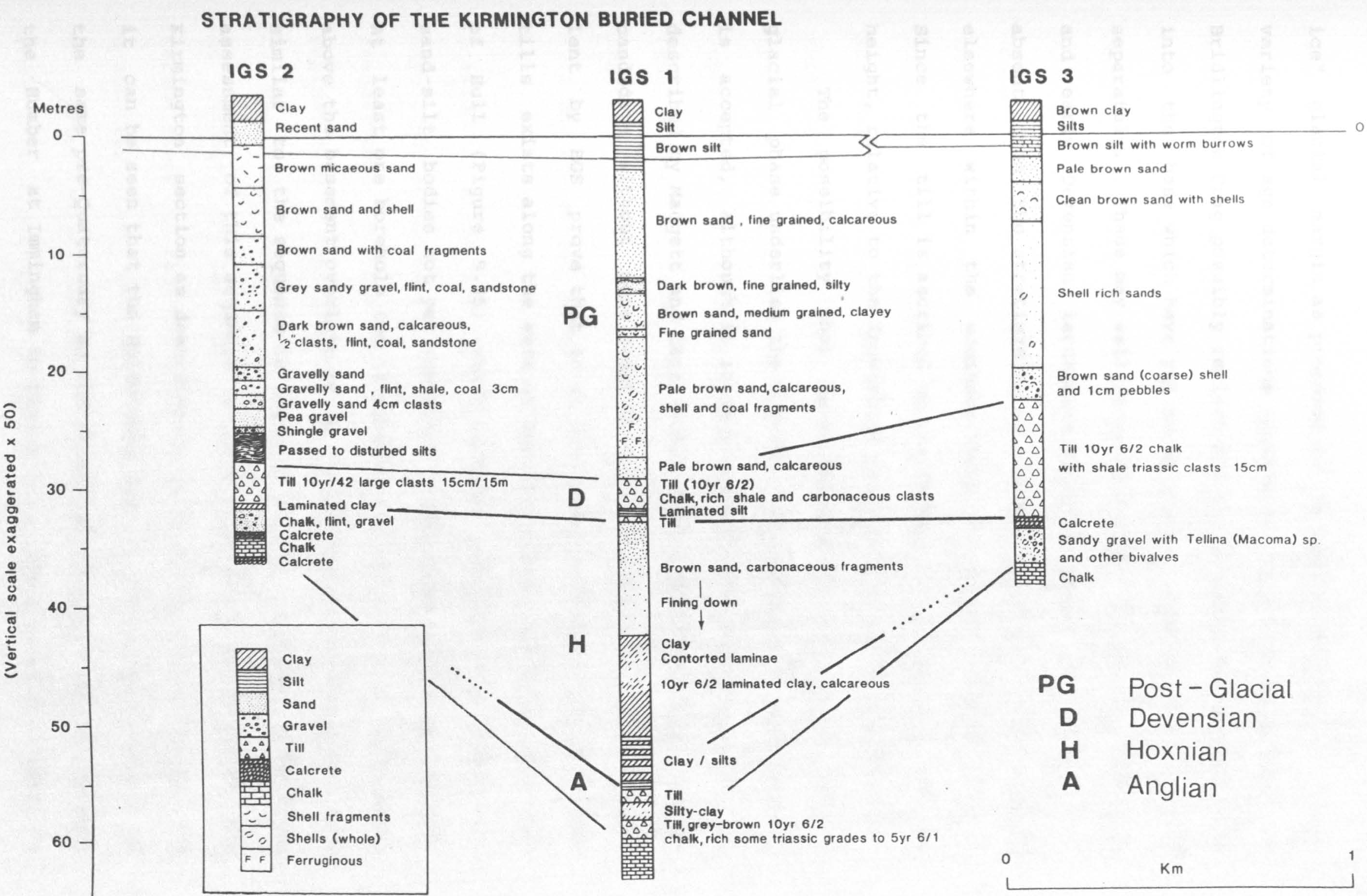


Figure 9.15 Stratigraphy of the Kirmington buried channel

ice" glacial margin as proposed in the depositional model. The variety of age determinations applied to the Sub-Basement Clay and Bridlington Crag possibly reflect the mix of sediments incorporated into the base which have yet to be closely examined and analysed separately. These may well prove to contain the marine Ipswichian and early Devensian lacustrine sediments which are at present absent from the stratigraphy of Holderness but have been sampled elsewhere within the southern North Sea basin (Caston 1969). Since the till is ascribed to the Devensian the argument of its height, relative to the Ipswichian interglacial beach, is negated.

The possibility that an eroded till sheet from an earlier glacial phase underlies the Devensian sediment suite in Holderness is accepted, although it is proposed that the Basement till, as described by Madgett and Catt (1978) cannot be accepted as a likely candidate without more complete borehole evidence. Logs kindly lent by BGS prove that an in situ sequence below the Devensian tills exists along the axis of the Kirmington buried channel, west of Hull (Figure 9.15) which includes fossiliferous sands and sand-silt bodies not yet subjected to any rigorous dating method. At least one borehole (No 1) sampled a chalk rich till immediately above the basement overlain by an intercalated till succession very similar to the sequence in borehole 81/52A. A purely subjective assessment of this sequence is given in Figure 9.15, based on the Kirmington section as described by Watts (1959). From Figure 2.6 it can be seen that the Holderness deposits lie within the axis of the same pre-Quaternary as the Kirmington deposits, which crosses the Humber at Immingham to bisect the present coastline near to Tunstall.

In summary, owing to the absence of any indisputable evidence for a Wolstonian age for the Basement till, it is suggested that, for the purpose of regional correlation, its usage should be strictly limited. It is further proposed that from the weight of evidence from in situ sections recovered from the Inner Silver Pit and similar sequences in the Kirmington buried channel that the most likely till to be recovered from depth in Holderness is Anglian in age. Since nowhere in the North Sea or within the British Quaternary have the two interglacials (Ipswichian and Hoxnian) been recognised within the same section this leads to the suspicion that, as suggested by Bristow and Cox (1973), that they are closer in time than is generally accepted, possibly being separated only by a cold phase rather than by a period of full glacial conditions over lowland Britain. This view is supported by Sumbler (1983) in terms of the stratigraphy of the Midlands and has been argued for some time by Bristow and Cox (1973) for East Anglia.

9.7 The Age Of The Initial Ice Advance: The Dimlington Silts.

The proposal that the Dimlington Silts are entirely contained within a Devensian Till deposited at the margins of an active ice sheet forces a complete reassessment of the radiocarbon date of 18,240±250 B.P as representive of the initial ice advance into Holderness.

The interpretation of this date can be challenged on a number of grounds, not least the possiblity of contamination by modern carbon since the recovery of pine and birch pollen fron the organic assemblage (Catt and Penny 1966), is completely incongruous with the later radiocarbon date. All species of trees were eliminated from Britain during the cold phase which immediately preceeded the Upton Warren Interstadial (43,000 years B.P: Morgan 1973 , Kerney et al. 1982 , Girling 1974).

The date is also out of phase with equivalent dates for organic material underlying Devensian till in western England which tends to suggest that the cold phase prior to the build-up of the ice sheets was initiated as early as 28,000 years B.P (Briggs and Gilbertson 1975, Coope 1977, Coope et al 1971). Dates for deglaciation on the East coast, in some extreme cases, predate the deposition of the Dimlington Silts, which represents the glacial maximum a fact which has forced many workers (Mitchell 1972) to consider whether the late Devensian ice advances in western and eastern England were synchronous. The oldest organic material overlying the Withernsea Till is from Roos Bog which gave a radiocarbon age of 13,045 ± 270 years B.P (Birm. 317, Catt 1977) suggesting that the whole of the till succession in Holderness was emplaced within a period of only about 5000 years. Only 80km to the north at Kildale, a rich moss flora in a kettle hole within late glacial glaciofluvial sands and gravels yielded a radiocarbon age of 16,713 ± 340 years BP (Jones 1971). If deglaciation had set in by this time, as the evidence suggests, the maximum ice sheet extension in Holderness lasted for barely 2,000 years.

An earlier date for the initial advance would resolve many of these problems and provide a date more comparable to the Irish Sea ice sheet series. Straw (1969) has made a convincing case for an early Devensian (>60,000 years BP) age for the Lincolnshire tills based on his observations of the terminal moraine complexes, although it is difficult to see how ice could have moved so far south without leaving a wealth of supporting evidence in other regions. There is also no evidence for the high interstadial sea levels which are also proposed in the model from the known sequences in the southern North Sea (Oele and Schuttenhelm 1979).

Since it is accepted by most workers that the most extensive advance (to the Hunstanton terminal moraine) was also responsible for the initiation of Lake Humber by blocking both the Humber and Wash gaps, it is proposed that the radiocarbon date of 21,835±1,660 years B.P from a bone recovered from littorial sediments deposited in the high level Lake Humber (Gaunt 1974,1976) is more representitive of the advance of ice into Holderness.

9.8 Summary of Principal Conclusions

1) The Withernsea and Skipsea Tills display similar sedimentary characteristics. Both units are matrix-dominant, multimodal diamicts with overlapping size distribution envelopes. Classification on the basis of silt content as suggested by Madgett and Catt 1978 was not supported by this analysis.

2) The contact between the two units is marked by a change in till matrix colour from 7.5 YR 4/6 (Withernsea Till) to 7.5 YR 3/2 (Skipsea Till). There is a significant uniformity across the colour junction of many sedimentary properties, notably % clay, % silt, % carbonates in clay fraction, clay minerals and sedimentary fabric.

3) The Skipsea and Withernsea Tills possess a dense interlocking fabric reflected in the values for dry density and voids ratio.

4) The index limits of the Skipsea and Withernsea Tills conform closely to the "T" line relationship suggested for glaciogenic soils by Boulton and Paul (1976).

5) The Withernsea and Skipsea Tills have similar strength and consolidation characteristics which, it is felt, reflects a related stress history. Both units display a highly dilatant response under shear, behaviour commonly recorded for dense, overconsolidated clay soils. Preconsolidation stress was estimated to lie between 250-425 kN/m^2.

6) Geotechnical and sedimentary evidence is consistant with both units being deposited as lodgement tills beneath an active wet-based ice sheet. There is no evidence for any reworking of the Withernsea Till caused by the melt of an intra-formational ice sheet as proposed in the "Undermelt Theory" of Carruthers (1953).

7) Critical state theory (Atkinson and Bransby 1978) was found to accurately predict the behaviour of the diamict under stress and can be used, in a manner similar to Paul (1981), to predict the behaviour of the sediment under theoretical stress/environmental situations.

8) Using the critical state model and theories of ice-bed stability proposed by Boulton and Jones (1979) an alternative model of glacier dynamics for the east-coast ice stream is proposed which attempts to synthesise observations concerning sedimentary and geotechnical properties of the diamict profile, regional sub-drift geology and patterns of deposition and erosion. It is concluded that the pattern of sedimentation can best be explained by a prolonged period of basal lodgement beneath a wet-based sub-stratum controlled ice stream, which remained active to its extreme margins.

9) The Withernsea-Skipsea Till contact is seen as a product of a change in the pattern of ice streams coalescing to form the North Sea ice-sheet, from one dominated by a Pennine, Lake District, western Southern Uplands flow to a more direct supply from emerging ice centres of the Cheviots and eastern Southern Uplands. It is also concluded that the change must

also reflect erosion through the major lithostratigraphic boundary between the Liassic and Triassic formations in the offshore area north of Flamborough Head. A major phase of deglaciation between the deposition of the Withernsea and Skipsea Tills is not supported by the analysis.

In general, the conclusions provide an alternative view of events than that proposed by previous workers in the Holderness area. It is clear that the region still provides ample scope for original research into the subjects of Quaternary stratigraphy, sedimentology and soil mechanics, and it is hoped that this work highlights a number of problems which still remain and require further attention.

Briefly, they are:

1) The controls imposed by the dense packing arrangement of the diamict on shear and consolidation characteristics and further study into the sub-glacial process which could account for such a dense fabric under such a low range of effective stresses.

2) The nature and origin of intra-formational sand and gravel units, particularly the massive sequence exposed at Dimlington.

3) The nature and origin of clay raft erratics within the lower till sequence exposed at Bridlington and Dimlington.

4) A complete analysis of the important pre-Devensian succession contained within the Kirmington buried channel.

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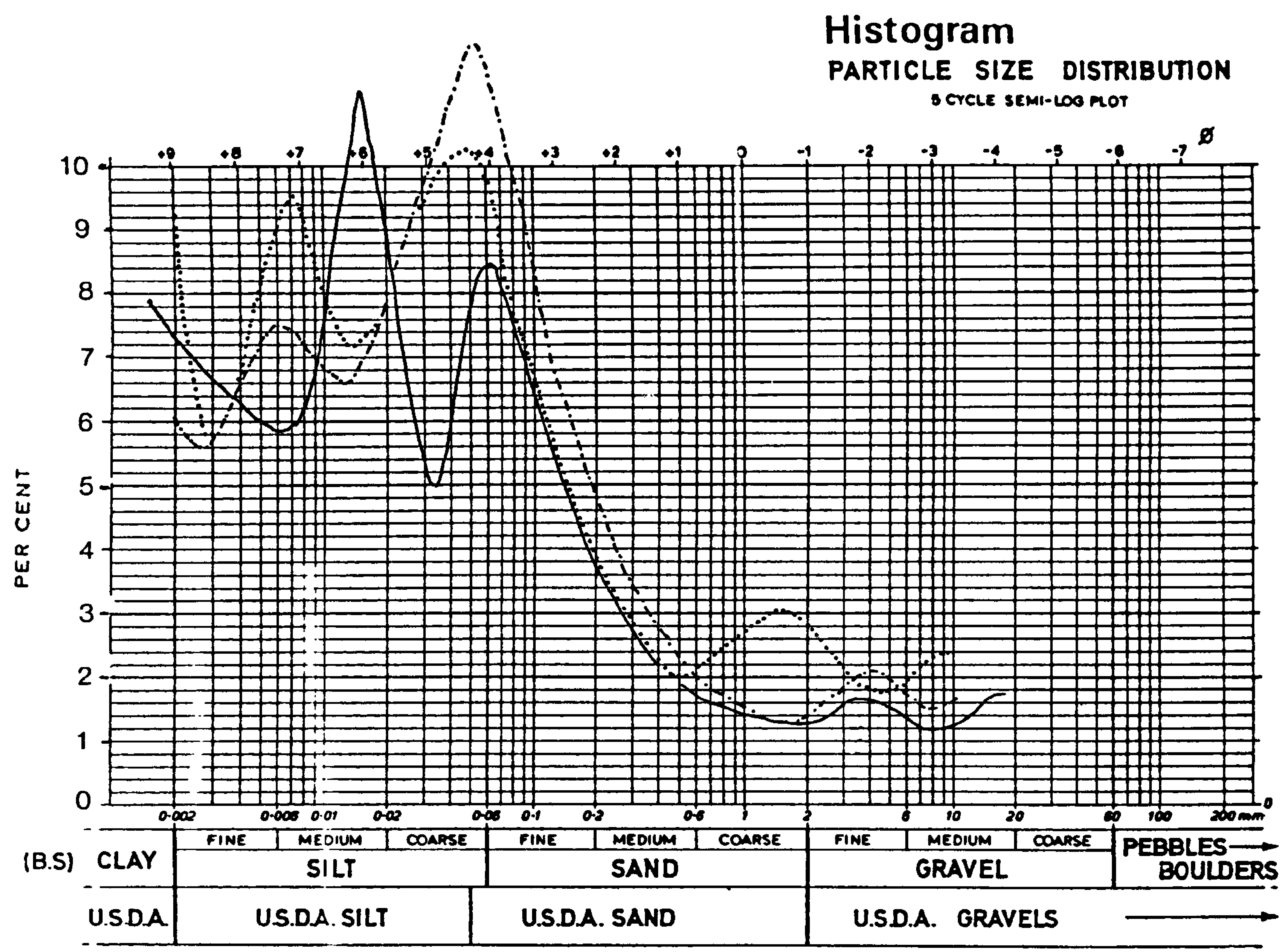
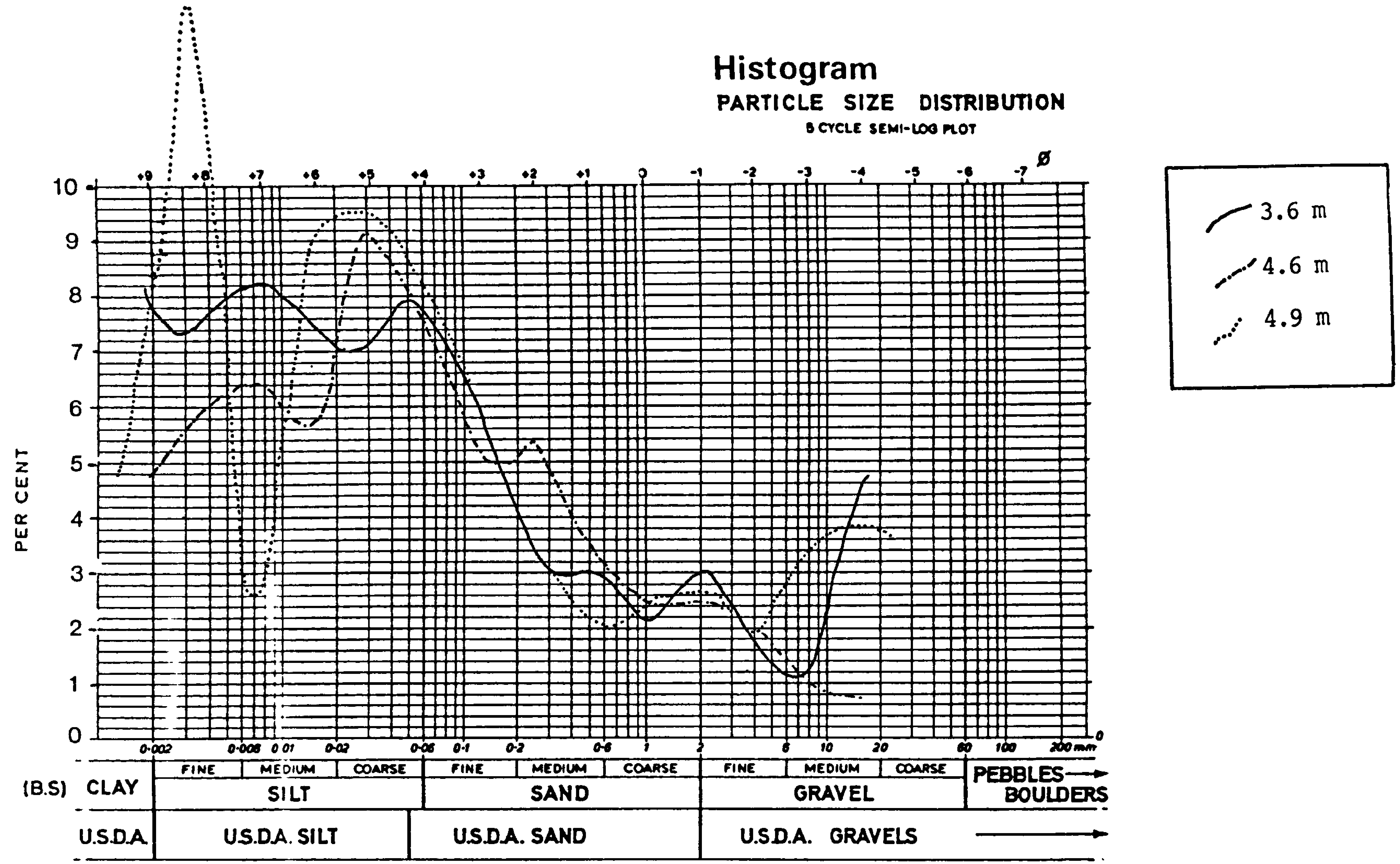
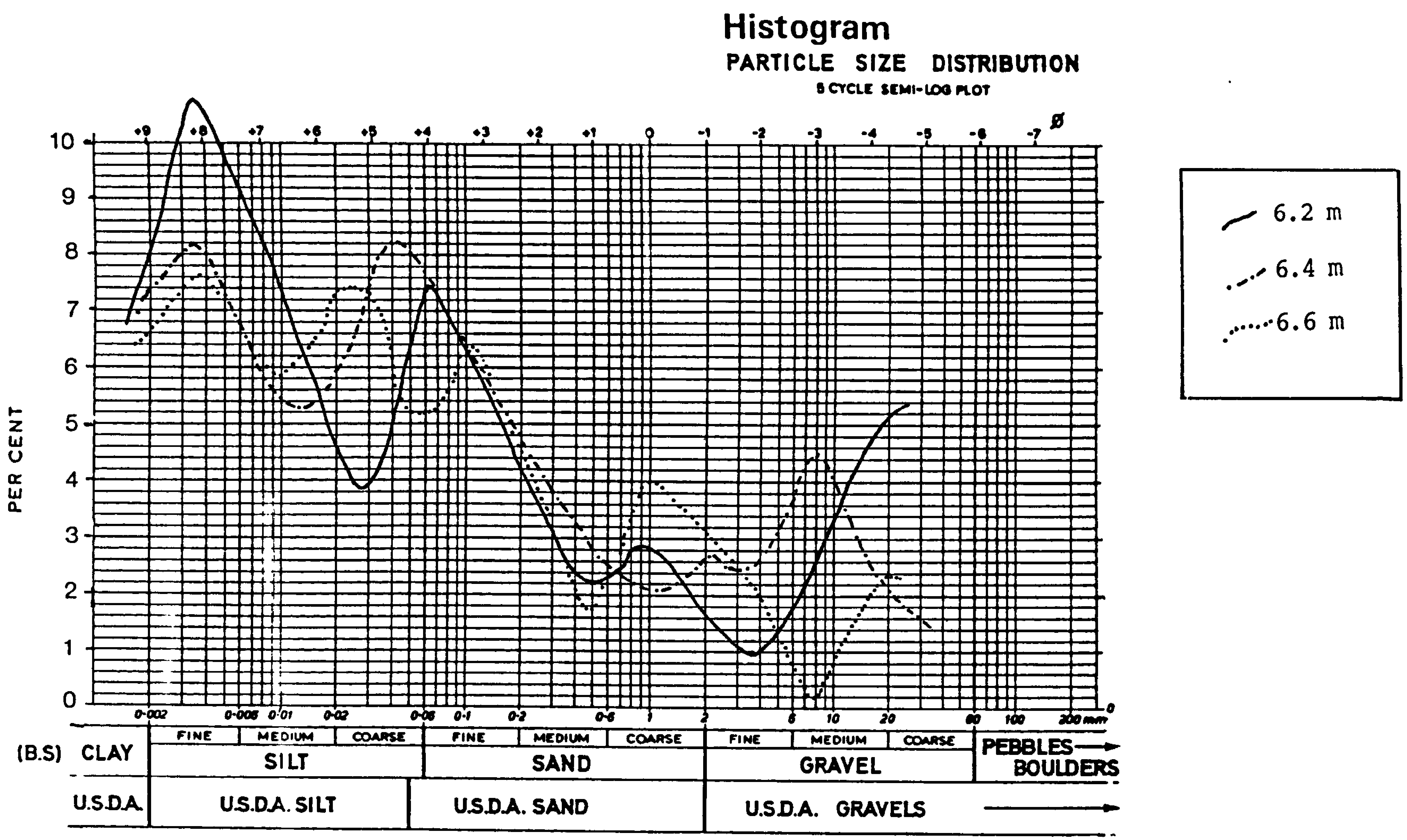
APPENDICES



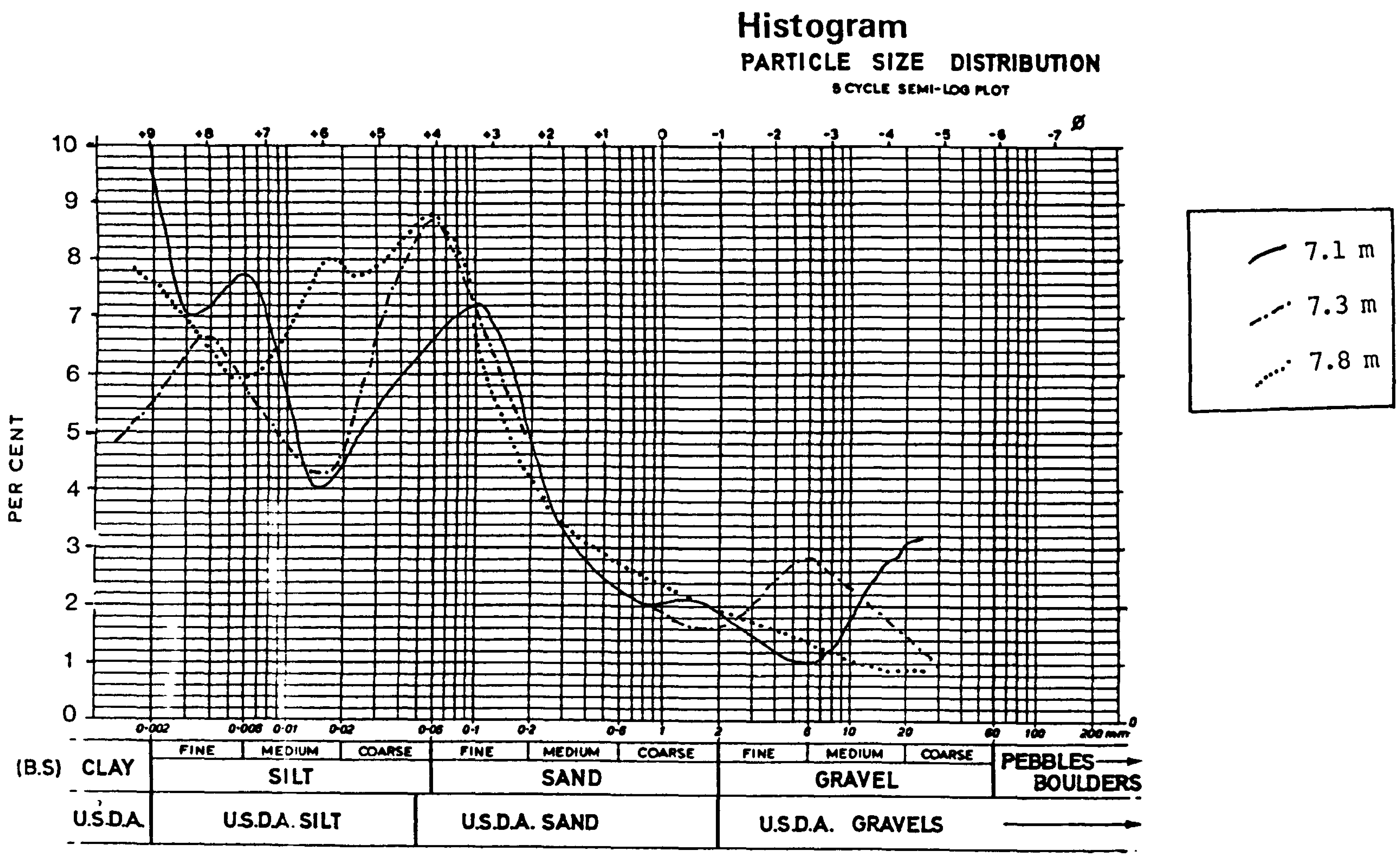
Appendix I (1). Particle Size Distribution Histograms of Diamict sampled in CS1 from 1.1 m, 1.3 m, 1.8 m.



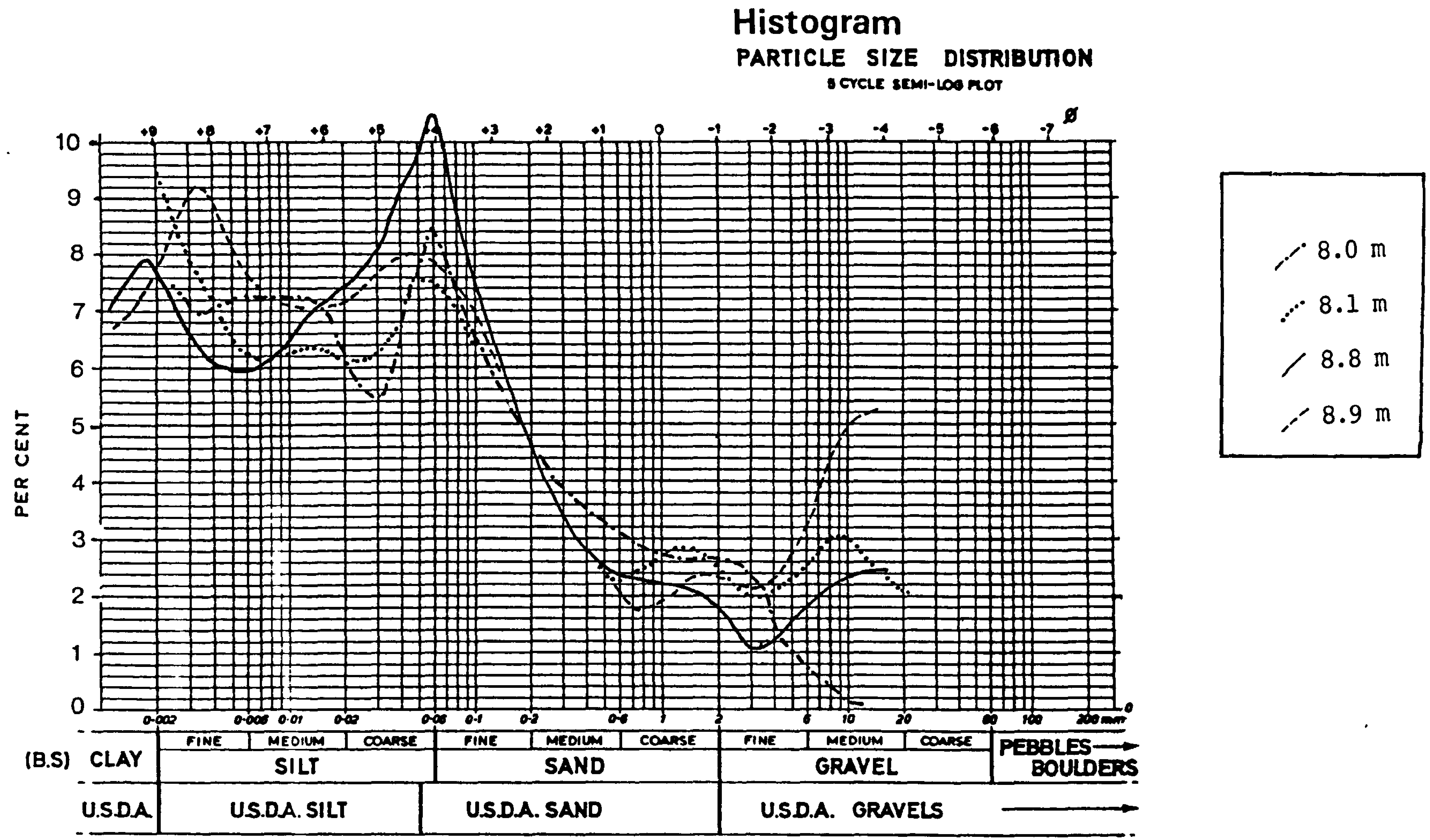
Appendix I (2). Particle Size Distribution Histograms of Diamict sampled in CS1 from 3.6 m, 4.6 m, 4.9 m.



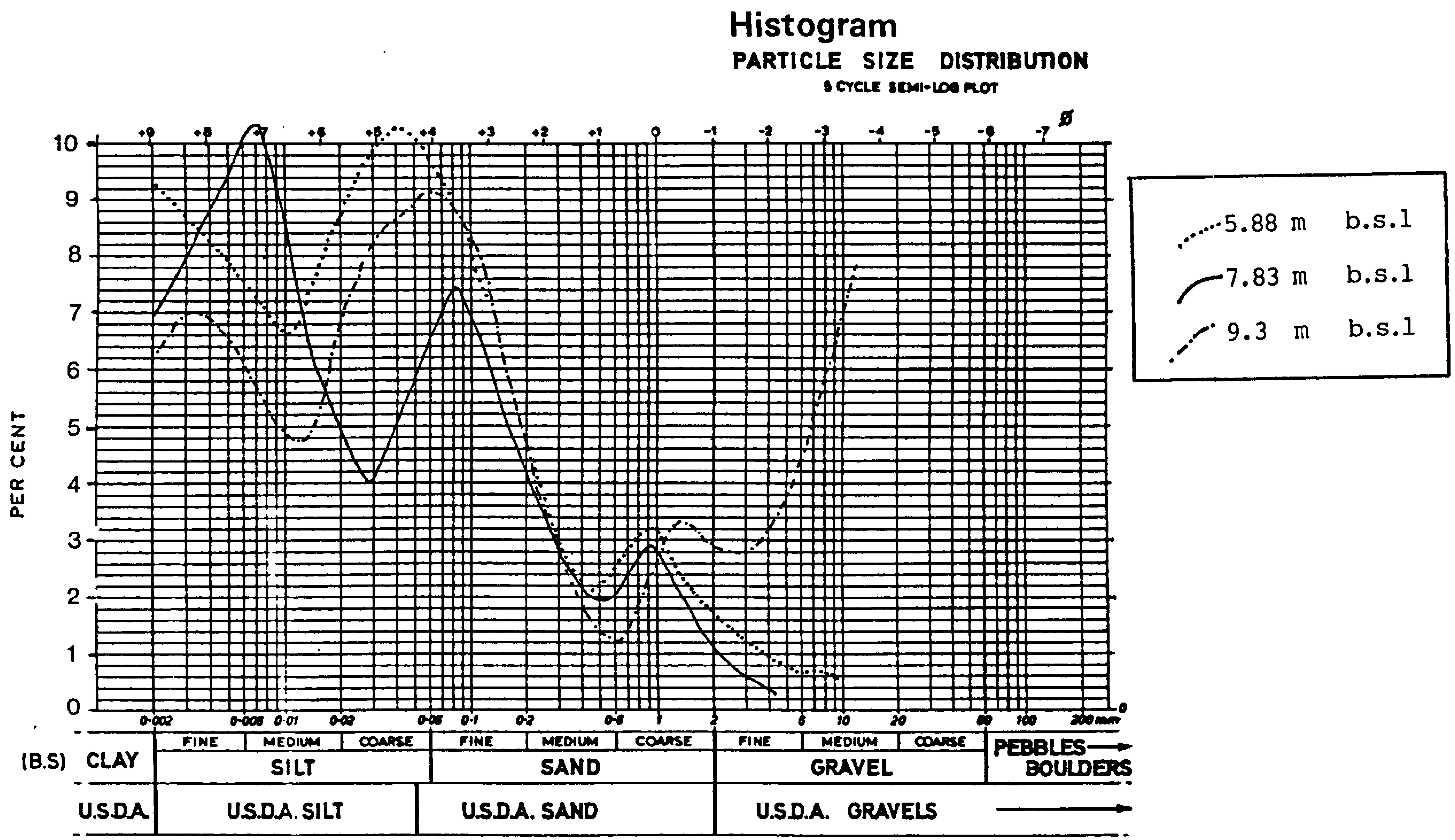
Appendix I (3). Particle Size Distribution Histograms of Diamict sampled in CS1 from 6.2 m, 6.4 m, 6.6 m.



Appendix I (4). Particle Size Distribution Histograms of Diamict sampled in CS1 from 7.1 m, 7.3 m, 7.8 m.



Appendix I (5). Particle Size Distribution Histograms of Diamict sampled in CS1 from 8.0 m, 8.1 m, 8.8 m, 8.9 m.



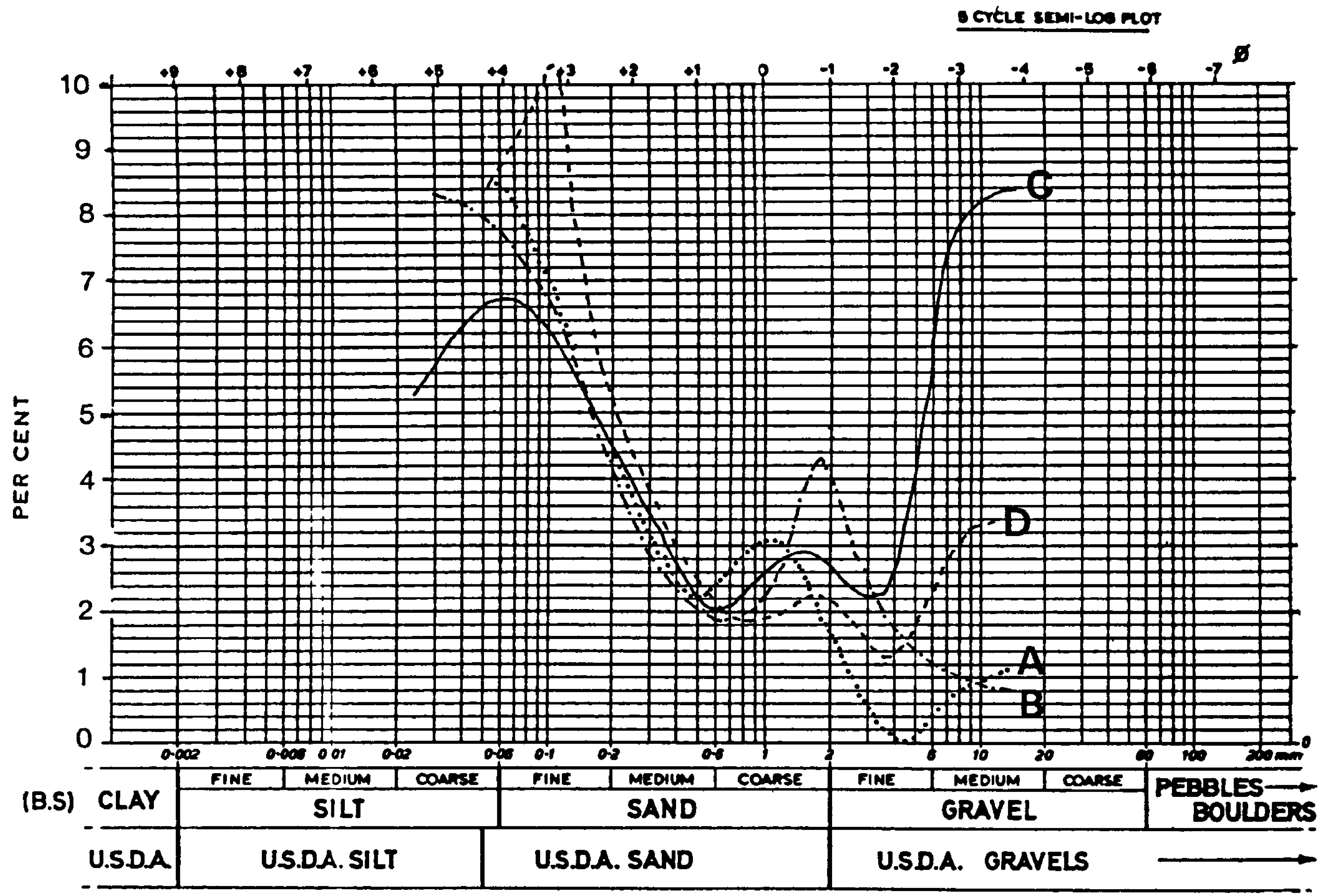
Appendix I (6). Particle Size Distribution Histograms of Diamict sampled in Offshore Borehole BH81/52 A from 5.88 m, 7.83 m, 9.3 m below sea bed.

A.... Withernsea Till (Cowden Cliff)

B.... Withernsea Till (Cowden Cliff)

C.... Skipsea Till (Cowden Cliff)

D.... Skipsea Till (1km north, Cowden Cliff)



Appendix I (7). Particle Size Distribution Histograms of Diamict sampled at Cowden Cliff.

1. DENSITY DATA

		DENSITIES			UNIT WEIGHTS		
DEPTH (m)	NMC (%)	BULK	DRY (Mg/m3)	SAT.	BULK	DRY (kN/m3)	SAT.
1.1	24.0	2.01	1.62	2.02	19.72	15.91	19.82
1.5	16.0	2.17	1.87	2.18	21.28	18.35	21.36
2.1	16.5	2.19	1.88	2.19	21.51	18.46	21.43
3.3	16.6	2.13	1.83	2.15	20.90	17.93	21.09
4.6	17.1	2.16	1.84	2.16	21.16	18.07	21.18
5.9	14.5	2.21	1.93	2.22	21.68	18.94	21.73
6.4	15.2	2.21	1.91	2.21	21.63	18.77	21.63
6.6	14.9	2.16	1.88	2.18	21.19	18.44	21.42
7.1	15.3	2.20	1.91	2.20	21.55	18.69	21.57
7.6	15.7	2.18	1.88	2.19	21.39	18.49	21.45
7.8	15.9	2.20	1.90	2.19	21.56	18.60	21.52
8.4	16.0	2.22	1.91	2.20	21.73	18.73	21.60
8.6	16.0	2.18	1.88	2.18	21.33	18.39	21.39
8.8	16.8	2.18	1.87	2.18	21.40	18.32	21.34
9.2	16.8	2.17	1.86	2.17	21.28	18.22	21.28
9.4	15.4	2.21	1.91	2.21	21.66	18.77	21.63
9.6	15.4	2.20	1.91	2.20	21.57	18.70	21.58
10.1	15.8	2.29	1.98	2.25	22.49	19.42	22.04

DEPTH	Gs	n	e	Sr (%)	Gs	n	e
						ESTIMATED	
1.1	2.70	0.399	0.665	97.5	2.66	0.389	0.637
1.5	2.70	0.307	0.443	97.4	2.67	0.299	0.427
2.1	2.70	0.303	0.434	102.6	2.73	0.311	0.451
3.3	2.70	0.323	0.477	93.9	2.62	0.303	0.436
4.6	2.70	0.318	0.466	99.2	2.69	0.315	0.460
5.9	2.70	0.285	0.398	98.3	2.68	0.280	0.389
6.4	2.70	0.291	0.410	100.0	2.70	0.291	0.410
6.6	2.70	0.303	0.436	92.3	2.61	0.280	0.389
7.1	2.70	0.294	0.417	99.1	2.69	0.292	0.412
7.6	2.70	0.302	0.432	98.0	2.68	0.296	0.420
7.8	2.70	0.298	0.423	101.4	2.72	0.302	0.432
8.4	2.70	0.293	0.414	104.4	2.75	0.306	0.440
8.6	2.70	0.305	0.440	98.3	2.68	0.300	0.429
8.8	2.70	0.308	0.445	101.9	2.72	0.314	0.457
9.2	2.70	0.312	0.453	100.0	2.70	0.312	0.454
9.4	2.70	0.291	0.411	101.3	2.71	0.295	0.418
9.6	2.70	0.294	0.416	99.9	2.70	0.294	0.416
10.1	2.70	0.266	0.363	117.5	2.88	0.313	0.455

3. ATTERBERG LIMITS DATA

DEPTH (m)	NMC (%)	PLASTIC LIMIT	LIQUID LIMIT	SHRINKAGE LIMIT	PLASTICITY INDEX	LIQUIDITY INDEX
1.1	24.0	17.0	42.0	-	25.0	0.28
1.5	16.0	-	-	-	-	
2.1	16.5	14.0	38.0	-	24.0	0.10
3.3	16.6	14.0	35.0	-	21.0	0.12
4.6	17.1	13.0	33.0	-	20.0	0.20
5.9	14.5	15.0	33.0	-	18.0	-0.03
6.4	15.2	14.0	33.0	-	19.0	0.06
6.6	14.9	-	-	-	-	-
7.1	15.3	15.0	32.0	-	17.0	0.02
7.6	15.7	17.6	34.0	-	16.4	-0.12
7.8	15.9	-	-	-	-	-
8.4	16.0	-	-	-	-	-
8.6	16.0	15.6	43.0	-	27.4	0.01
8.8	16.8	-	-	-	-	-
9.2	16.8	17.6	38.0	-	20.4	-0.04
9.4	15.4	-	-	-	-	-
9.6	15.4	-	-	-	-	-
10.1	15.8	-	-	-	-	-

4. STRENGTH DATA

	Cu (kN/m2)						Cu TEST RATIOS		
DEPTH (M)	CPT	TRIAX	PP	OCR	TOB	EOB	CPT _ TRIAX	CPT PP	PP TRIAX
1.1	-	70	-	32.0	21	10	-	-	-
1.5	-	90	-	-	30	15	-	-	-
2.1	219	156	220	40.0	43	22	1.40	1.00	1.41
3.3	175	127	-	17.0	68	35	1.38	-	-
4.6	140	96	98	17.6	95	49	1.46	1.43	1.02
5.9	-	211	225	18.7	123	64	-	-	1.07
6.4	-	179	171	12.4	134	70	-	-	0.96
6.6	140	105	173	-	138	72	1.33	0.81	1.65
7.1	-	150	172	11.5	149	78	-	-	1.15
7.6	-	150	170	12.5	160	84	-	-	1.13
7.8	-	118	165	-	164	86	-	-	1.40
8.4	145	109	170	-	177	93	1.33	0.85	1.56
8.6	-	127	-	10.5	182	95	-	-	-
8.8	-	115	-	-	186	98	-	-	-
9.2	-	138	170	10.2	194	102	-	-	1.23
9.4	-	105	-	-	199	104	-	-	-
9.6	150	105	-	-	203	107	1.43	-	-
10.1	-	114	-	-	214	113	-	-	-

1. DENSITY DATA

DEPTH (m)	NMC (%)	DENSITIES (Mg/m3) BULK	DRY	SAT.	UNIT WEIGHTS (kN/m3) BULK	DRY	SAT.
2.0	16.4	2.17	1.86	2.17	21.26	18.26	21.31
2.6	15.0	2.16	1.88	2.17	21.18	18.42	21.30
3.2	17.7	2.17	1.84	2.16	21.27	18.07	21.19
3.3	17.5	2.15	1.83	2.15	21.10	17.95	21.11
3.9	17.5	2.14	1.82	2.15	20.96	17.84	21.04
4.5	13.5	2.23	1.96	2.24	21.83	19.24	21.92
5.2	13.8	2.17	1.91	2.20	21.27	18.69	21.58
5.9	15.0	2.17	1.89	2.19	21.28	18.51	21.46
6.5	16.0	2.14	1.85	2.16	21.03	18.13	21.22
7.3	16.0	2.17	1.87	2.17	21.28	18.35	21.31
8.2	15.7	2.20	1.90	2.19	21.55	18.63	21.48
8.9	16.0	2.18	1.88	2.18	21.38	18.43	21.41
9.5	15.0	2.19	1.90	2.20	21.47	18.67	21.56
9.7	14.7	2.20	1.92	2.21	21.55	18.79	21.64
10.3	15.7	2.27	1.96	2.21	22.22	19.21	21.71

DEPTH	Gs	n	e	Sr (%)	Gs	n	e
						ESTIMATED	
2.0	2.70	0.310	0.450	98.5	2.68	0.305	0.440
2.6	2.66	0.294	0.416	95.9	2.62	0.282	0.392
3.2	2.70	0.317	0.465	102.7	2.73	0.326	0.484
3.3	2.70	0.322	0.475	99.5	2.69	0.320	0.471
3.9	2.70	0.326	0.484	97.6	2.67	0.318	0.467
4.5	2.70	0.273	0.376	96.8	2.67	0.265	0.360
5.2	2.70	0.294	0.417	89.4	2.59	0.263	0.357
5.9	2.70	0.301	0.431	94.0	2.63	0.283	0.395
6.5	2.70	0.315	0.460	93.8	2.63	0.296	0.420
7.3	2.68	0.302	0.433	99.1	2.67	0.299	0.427
8.2	2.68	0.291	0.411	102.4	2.71	0.298	0.425
8.9	2.70	0.304	0.437	98.9	2.69	0.301	0.430
9.5	2.70	0.295	0.418	96.9	2.67	0.286	0.400
9.7	2.70	0.290	0.409	97.0	2.67	0.282	0.392
10.3	2.63	0.255	0.343	120.4	2.83	0.307	0.444

3. ATTERBERG LIMITS DATA

DEPTH (m)	NMC (%)	PLASTIC LIMIT	LIQUID LIMIT	SHRINKAGE LIMIT	PLASTICITY INDEX	LIQUIDITY INDEX
2.0	16.4	18.0	40.0	-	22.0	-0.07
2.6	15.0	17.0	40.0	-	23.0	-0.09
3.2	17.7	17.0	40.0	-	23.0	0.03
3.3	17.5	-	-	-	-	-
3.9	17.5	16.0	37.0	-	21.0	0.07
4.5	13.5	-	-	-	-	-
5.2	13.8	18.5	38.0	-	19.5	-0.24
5.9	15.0	15.5	37.0	-	22.0	0.00
6.5	16.0	-	-	-	-	-
7.3	16.0	16.5	37.0	-	20.5	-0.02
8.2	15.7	16.0	37.0	-	21.0	-0.01
8.9	16.0	13.0	38.0	-	25.0	0.12
9.5	15.0	-	-	-	-	-
9.7	14.7	-	-	-	-	-
10.3	15.7	-	-	-	-	-

4. STRENGTH DATA

Cu (kN/m2)							Cu TEST RATIOS		
DEPTH (M)	CPT	TRIAX	PP	OCR	TOB	EOB	CPT / TRIAX	CPT / PP	PP / TRIAX
2.0	245	220	-	43.0	42	22	1.11	-	-
2.6	-	120	-	41.3	55	29	-	-	-
3.2	-	170	-	30.0	67	35	-	-	-
3.3	175	165	-	-	70	36	1.06	-	-
3.9	-	92	131	18.6	82	43	-	-	1.42
4.5	140	126	-	-	95	50	1.11	-	-
5.2	-	105	-	86.2	110	58	-	-	-
5.9	-	100	-	9.0	125	66	-	-	-
6.5	140	120	-	-	138	72	1.17	-	-
7.3	-	120	-	17.2	155	81	-	-	-
8.2	145	112	-	11.2	174	92	1.29	-	-
8.9	-	120	-	12.0	189	100	-	-	-
9.5	-	112	-	-	202	107	-	-	-
9.7	150	104	-	-	206	109	1.44	-	-
10.3	-	150	-	-	220	116	-	-	-

1. DENSITY DATA

		DENSITIES			UNIT WEIGHTS		
DEPTH (m)	NMC (%)	BULK	DRY (Mg/m3)	SAT.	BULK	DRY (kN/m3)	SAT.
2.4	17.5	2.16	1.84	2.16	21.20	18.05	21.17
3.6	16.9	2.19	1.87	2.18	21.45	18.35	21.36
4.3	14.8	2.20	1.92	2.21	21.57	18.79	21.64
5.1	15.3	2.19	1.90	2.20	21.51	18.65	21.55
5.8	14.3	2.21	1.93	2.22	21.65	18.94	21.73
6.6	16.5	2.19	1.88	2.18	21.43	18.39	21.39
7.5	16.0	2.16	1.86	2.17	21.16	18.24	21.29
8.6	15.0	2.20	1.91	2.20	21.55	18.74	21.61
9.3	16.0	2.18	1.88	2.19	21.41	18.46	21.43
10.0	15.2	2.23	1.93	2.22	21.83	18.95	21.74

DEPTH	Gs	n	e	Sr (%)	Gs	n	e
					ESTIMATED		
2.4	2.70	0.318	0.467	101.1	2.71	0.322	0.475
3.6	2.70	0.307	0.443	103.0	2.74	0.316	0.463
4.3	2.70	0.290	0.409	97.7	2.67	0.284	0.396
5.1	2.70	0.296	0.420	98.5	2.68	0.291	0.410
5.8	2.70	0.285	0.398	97.0	2.67	0.276	0.382
6.6	2.70	0.305	0.440	101.4	2.72	0.309	0.448
7.5	2.70	0.311	0.452	95.6	2.65	0.298	0.424
8.6	2.70	0.292	0.413	98.0	2.68	0.287	0.402
9.3	2.70	0.303	0.434	99.4	2.69	0.301	0.431
10.0	2.70	0.284	0.398	103.2	2.74	0.294	0.416

3. ATTERBERG LIMITS DATA

DEPTH (m)	NMC (%)	PLASTIC LIMIT	LIQUID LIMIT	SHRINKAGE LIMIT	PLASTICITY INDEX	LIQUIDITY INDEX
2.4	17.5	-	-	-	-	-
3.6	16.9	-	-	-	-	-
4.3	14.8	-	-	-	-	-
5.1	15.3	-	-	-	-	-
5.8	14.3	-	-	-	-	-
6.6	16.5	-	-	-	-	-
7.5	16.0	-	-	-	-	-
8.6	15.0	-	-	-	-	-
9.3	16.0	-	-	-	-	-
10.0	15.2	-	-	-	-	-

	Cu (kN/m2)						Cu TEST RATIOS		
DEPTH (M)	CPT	TRIAX	PP	OCR	TOB	EOB	CPT / TRIAX	CPT / PP	PP / TRIAX
2.4	-	161	-	-	50	26	-	-	-
3.6	-	115	-	-	76	40	-	-	-
4.3	-	97	-	-	91	48	-	-	-
5.1	-	86	-	-	108	57	-	-	-
5.8	-	229	-	-	124	65	-	-	-
6.6	-	220	214	-	141	75	-	-	0.97
7.5	-	90	-	-	160	85	-	-	-
8.6	-	125	-	-	183	97	-	-	-
9.3	-	99	-	-	198	105	-	-	-
10.0	-	160	215	-	214	113	-	-	1.34

```
C
C
C     **********************************************************************
C
C     PROGRAMME TO CALCULATE GEOTECHNICAL PARAMETERS FROM TRIAXIAL MV
C     INPUT WITH .P AND GINO OUTPUT
C
C     WRITTEN BY CT FOSTER, DEPT OF GEOG, JAN 1983
C
C     **********************************************************************
C
      REAL DEVMAX,EMASMX,EMSMX,PWPMX,EMMSMX,AA,BB
      REAL DLENTH,DIAM,CELLP,PWPS,PWPCF,XLCCF,STCF,AREA,VOL
      INTEGER ISCF,N,NRUNS
      DIMENSION DEVST(100),PERST(100),ACTST(100),PWPST(100),EFMAS(100)
      DIMENSION CAMP(100), CAMQ(100),STMITQ(100),STMITP(100),TRLC(100)
      DIMENSION TRPWP(100), EMMST(100),ISAMPL(10),EFMS(100),TRST(100)
C
C
      WRITE(6,1)
    1 FORMAT(3X,70H****************************************************
     1*****************)
      WRITE(6,2)
    2 FORMAT(3X,1H*,68X,1H*)
      WRITE(6,3)
    3 FORMAT(3X,1H*,15X,38HUNDRAINED UNCONSOLIDATED TRIAXIAL TEST,15X,1H
     1*)
      WRITE(6,2)
      WRITE(6,7)
    7 FORMAT(3X,1H*,21X,25HEFFECTIVE STRESS ANALYSIS,22X,1H*)
      WRITE(6,2)
      WRITE(6,1)
C
C
      READ(5,102)(ISAMPL(S) ,S=1,10)
  102 FORMAT(10A4)
      READ(5,100)NRUNS
  100 FORMAT(I3)
      DO 10 II=1,NRUNS
      READ(5,101)N
  101 FORMAT(I2)
      READ(5,103)DLENTH,DIAM,CELLP,PWPS,ISCF
  103 FORMAT(2X,F5.1,2X,F4.1,2X,F5.1,2X,F5.1,2X,I1)
      READ(5,104)XLCCF,STCF,PWPCF
  104 FORMAT(2X,F6.4,2X,F5.2,2X,F6.1)
      READ(5,105)(TRLC(J),TRST(J),TRPWP(J), J=1, N)
  105 FORMAT(2X,F5.2,2X,F7.3,2X,F7.3)
C
C     CALCULATION OF INITIAL AREA AND VOLUME
      AREA=((DIAM/2.0)**2.0)*3.1415927
      VOL=AREA*DLENTH
C     ALL INPUT FROM CH5
C     ALL OUTPUT TO CH6
C     PRODUCTION OF HEADINGS
      WRITE(6,106)(ISAMPL(S),S=1,10)
  106 FORMAT(///1H ,24HSAMPLE NO AND LOCATION :,1X,10A4///)
      WRITE(6,107)DLENTH
  107 FORMAT(1H ,27HORIGINAL LENGTH OF SAMPLE :,F9.3,1X,2HMM///)
      WRITE(6,108)VOL
  108 FORMAT(1H ,18HVOLUME OF SAMPLE :,F11.2,1X,3HMM3///)
      WRITE(6,109)CELLP
  109 FORMAT(1H ,23HCELL PRESSURE AT TEST :,F8.2,1X,5HKN/M2///)
      WRITE(6,110)
  110 FORMAT(1H ,2X,13HLOAD CELL CF.,10X,16HSTRAIN TRANS.CF.,10X,
     116HPOREWATER PR.CF.)
      WRITE(6,111)XLCCF,STCF,PWPCF
  111 FORMAT(5X,F7.5,17X,F7.3,19X,F8.3///)
      WRITE(6,112)
  112 FORMAT(2X,8HDEVIATOR,3X,10HPERCENTAGE,4X,6HACTUAL,5X,9HPOREWATER,
     14X,8HEFF.MAJ.,4X,8HEFF.MIN.,5X,6HSTRESS,6X,6HSTRESS,4X,7HMAJ/MIN)
      WRITE(6,113)
  113 FORMAT(3X,6HSTRESS,6X,6HSTRAIN,6X,6HSTRAIN,6X,8HPRESSURE,5X,
     16HSTRESS,7X,6HSTRESS,8X,1HP,11X,1HQ)
      WRITE(6,114)
  114 FORMAT(3X,5HKN/M2,21X,2HMM,9X,5HKN/M2,7X,5HKN/M2,8X,5HKN/M2,7X,
     15HKN/M2,7X,5HKN/M2//)
C
      TRLC1=TRLC(1)
      TRST1=TRST(1)
      TRPWP1=TRPWP(1)
      P=0
C     START OF MAJOR LOOP
      DO 5  P=1,N
C
      TRLC(P)=(TRLC(P)-TRLC1)* XLCCF
      TRST(P)=(TRST(P)-TRST1)* STCF
      TRPWP(P)=(TRPWP(P)-TRPWP1)* PWPCF
C
C     CORRECTION FOR AREA DEFORMATION
C
      DEVST(P)=TRLC(P)/((AREA * (DLENTH/( DLENTH - TRST(P)))))*1000000.0
      PERST(P)=(TRST(P) / DLENTH) * 100.0
      PWPST(P)=TRPWP(P)+PWPS
C     SHEATH CORRECTION
      IF (ISCF.EQ.0)   GO TO 117
      IF (ISCF.EQ.1)   GO TO 115
      IF (ISCF.EQ.2)   GO TO 116
C
  115 DEVST(P)=DEVST(P)-0.1365 * (PERST(P)+(0.0013 * (PERST(P)**2.0)))
      GO TO 117
  116 DEVST(P)=DEVST(P)-0.2121 * (PERST(P)+(0.00236* (PERST(P)**2.0)))
  117 CONTINUE
C
      EFMS(P)=CELLP - PWPST(P)
      EFMAS(P)=EFMS(P)+DEVST(P)
      CAMQ(P)=DEVST(P)
C
      CAMP(P)=( EFMAS(P)+(2*EFMS(P))) / 3.0
C
      STMITP(P)=(EFMAS(P)+EFMS(P))/2.0
C
      STMITQ(P)=(EFMAS(P) - EFMS(P))/2.0
C
      EMMST(P)=EFMAS(P)/ EFMS(P)
C
      WRITE(6,118)DEVST(P),PERST(P),TRST(P),PWPST(P),EFMAS(P),EFMS(P),
     1CAMP(P),STMITQ(P),EMMST(P)
  118 FORMAT(1X,F8.2,4X,F6.3,7X,F7.4,5X,F8.4,4(4X,F8.2),5X,F6.3)
C
C
```

```
C
C
C
C
      IF (P .GT. 1) GOTO 130
      PWPMX  = PWPST(1)
      DEVMAX = DEVST(1)
      EMASMX = EFMAS(1)
      EMSMX  = EFMS(1)
      EMMSMX = EMMST(1)
C     GOTO 5
  130 IF (DEVMAX .LE. DEVST(P)) DEVMAX=DEVST(P)
      IF (EMASMX .LE. EFMAS(P)) EMASMX=EFMAS(P)
      IF (EMMSMX .LE. EMMST(P)) EMMSMX=EMMST(P)
      IF (EMSMX  .LE. EFMS(P))  EMSMX=EFMS(P)
      IF (PWPMX  .LE. PWPST(P)) PWPMX=PWPST(P)
C
C
C
C
    5 CONTINUE
   10 CONTINUE
C
C
C
      AA =  PWPMX / DEVMAX
      BB =  PWPST(1)/CELLP
C
C
      WRITE(6,124)DEVMAX
  124 FORMAT(1H ,/////23HPEAK DEVIATOR STRESS = ,F9.2,1X,5HKN-M2//)
      WRITE(6,125)PWPMX
  125 FORMAT(1H ,26HPEAK POREWATER PRESSURE = ,F9.2,1X,5HKN-M2//)
      WRITE(6,126)EMASMX
  126 FORMAT (1H,30HPEAK EFFECTIVE MAJOR STRESS = ,F9.2,1X,5HKN-M2//)
      WRITE(6,127)EMSMX
  127 FORMAT(1H ,30HPEAK EFFECTIVE MINOR STRESS = ,F9.2,1X,5HKN-M2//)
      WRITE(6,128)EMMSMX
  128 FORMAT(1H ,40HPEAK EFF.MAJOR EFF.MINOR STRESS RATIO = ,F6.2///)
      WRITE(6,129)AA
  129 FORMAT(1H,19HA VALUE FOR TEST = ,F5.2//)
      WRITE(6,135)CELLP,BB
  135 FORMAT(1H ,25HB VALUE AT CELL PRESSURE ,F5.1,3H =,F5.2//)
C
      IF(PWPST(N).LE.-50.0)GOTO150
      IF(DEVMAX.GE.640.)GOTO150
      IF(EMASMX.GE.1000.)GOTO150
      IF(EMMSMX.GE.7.5)GOTO150
      IF(EMSMX.GE.600.)GOTO150
      IF(PWPMX.GE.600.0)GOTO150
      GOTO180
  150 WRITE(2,160)
  160 FORMAT(///1H ,10X,13H***WARNING***//)
      WRITE(2,170)
  170 FORMAT(1H ,36HGRAPH AXIS NOT WITHIN RANGE OF DATA.)
      GOTO900
  180 CONTINUE
C
      CALL DEVBEG
      CALL WINDO2(0.,230.,0.,300.)
```

```
      CALL SHIFT2(0.,0.)
      CALL BOX
      CALL A4
      CALL TITLE(ISAMPL)
      CALL UNI(132.,262.)
      CALL UNI(132.,132.)
C
      CALL CHAHAR(3,0)
      CALL ANNO(75.,150.,100.,5,25,1,1)
      CALL ANNO(75.,150.,100.,6,600,2,10)
      CALL ANNO(75.,20.,100.,5,25,1,1)
      IF(PWPMX.LT.230.)CALL ANNO(75.,40.,80.,4,200,2,10)
      IF(PWPMX.LT.230.)CALL MOVTO2(67.,20.)
      IF(PWPMX.LT.230.)CALL CHAHOL(5H-50*.)
      IF(PWPMX.GT.230.)CALL ANNO(75.,20.,100.,6,600,2,10)
      CALL MOVTO2(105.,139.)
      CALL CHAHOL(19HPERCENTAGE STRAIN*.)
      CALL MOVTO2(105.,9.5)
      CALL CHAHOL(19HPERCENTAGE STRAIN*.)
      CALL CHASWI(0)
      CALL CHAHAR(3,1)
      CALL MOVTO2(60.,45.)
      CALL CHAHOL(27HPOREWATER PRESSURE  KN-M2*.)
      CALL MOVTO2(60.,180.)
      CALL CHAHOL(24HDEVIATOR STRESS  KN-M2*.)
C
      CALL AXIPOS(75.,150.)
      CALL SCALE2(4.0,0.1666667)
      CALL POLTO2(PERST,DEVST,N)
      CALL TRANSF(2)
      IF(PWPMX.LT.230.)CALL AXIPOS(75.,40.)
      IF(PWPMX.LT.230.)CALL SCALE2(4.,.4)
      IF(PWPMX.GT.230.)CALL AXIPOS(75.,20.)
      IF(PWPMX.GT.230.)CALL SCALE2(4.,0.1666667)
      CALL POLTO2(PERST,PWPST,N)
      CALL TRANSF(2)
      CALL CHASWI(0)
C
      CALL PICCLE
      CALL SHIFT2(0.,0.)
      CALL BOX
      CALL A4
      CALL TITLE(ISAMPL)
      CALL UNI(132.,262.)
      CALL UNI(132.,132 .)
      CALL MOVTO2(75.,150.)
      CALL LINTO2(160.,235.)
      CALL CHAHAR(3,0)
      CALL ANNO(75.,20.,100.,5,1000,1,25)
      IF(EMASMX.GT.640.)CALL ANNO(75.,150.,100.,5,1000,1,25)
      IF(EMASMX.LT.640.)CALL ANNO(75.,150.,100.,6,600,1,10)
      IF(EMASMX.GT.640.)CALL ANNO(75.,150.,100.,5,1000,2,25)
      IF(EMASMX.LT.640.)CALL ANNO(75.,150.,100.,6,600,2,10)
      CALL ANNO(75.,20.,100.,5,1000,2,25)
      CALL MOVTO2(97.,139.)
      CALL CHAHOL(31HEFFECTIVE MINOR STRESS  KN-M2*.)
      CALL MOVTO2(105.,9.5)
      CALL CHAHOL(17HSTRESS P  KN-M2*.)
      CALL CHASWI(0)
      CALL CHAHAR(3,1)
```

```
      CALL MOVTO2(60.,52.)
      CALL CHAHOL(17HSTRESS Q  KN-M2*.)
      CALL MOVTO2(60.,170.)
      CALL CHAHOL(31HEFFECTIVE MAJOR STRESS  KN-M2*.)
C
      CALL AXIPOS(75.,150.)
      IF(EMASMX.GT.640.)CALL SCALE2(0.1,0.1)
      IF(EMASMX.LT.640.)CALL SCALE2(0.1666667,0.1666667)
      CALL POLTO2(EFMS,EFMAS,N)
      CALL TRANSF(2)
      CALL AXIPOS(75.,20.)
      CALL SCALE2(0.1,0.1)
      CALL POLTO2(CAMP,CAMQ,N)
      CALL TRANSF(2)
      CALL CHASWI(0)
C
C
C
      CALL PICCLE
      CALL SHIFT2(0.,0.)
      CALL BOX
      CALL A4
      CALL TITLE(ISAMPL)
      CALL UNI(132.,262.)
      CALL UNI(132.,132 .)
      CALL CHAHAR(3,0)
      CALL ANNO(75.,20.,100.,5,25,1,1)
      CALL ANNO(75.,150.,100.,5,25,1,1)
      CALL ANNO(75.,150.,100.,6,6,2,1)
      IF(EMSMX.GE.280.)CALL ANNO(75.,20.,100.,6,600,2,10)
      IF(EMSMX.LE.280.)CALL ANNU(75.,20.,100.,5,250,2,10)
      CALL MOVTO2(105.,139.)
      CALL CHAHOL(19HPERCENTAGE STRAIN*.)
      CALL MOVTO2(105.,9.5)
      CALL CHAHOL(19HPERCENTAGE STRAIN*.)
      CALL CHASWI(0)
      CALL CHAHAR(3,1)
      CALL MOVTO2(60.,52.)
      CALL CHAHOL(31HEFFECTIVE MINOR STRESS  KN-M2*.)
      CALL MOVTO2(60.,170.)
      CALL CHAHOL(33HEFFECTIVE MAJ-MIN STRESS  RATIO*.)
C
      CALL AXIPOS(75.,150.)
      CALL SCALE2(4.,16.666666)
      CALL POLTO2(PERST,EMMST,N)
      CALL TRANSF(2)
      CALL AXIPOS(75.,20.)
      IF(EMSMX.GT.280.)CALL SCALE2(4.0,0.1666667)
      IF(EMSMX.LT.280.)CALL SCALE2(4.0,0.4)
      CALL POLTO2(PERST,EFMS,N)
      CALL TRANSF(2)
      CALL CHASWI(0)
C
C
C
C
      CALL PICCLE
      CALL SHIFT2(0.,0.)
      CALL BOX1
      CALL A4
      CALL TITLE(ISAMPL)
      CALL UNI(132.,262.)
      CALL UNI(132.,132 .)
      CALL CHAHAR(3,0)
      CALL ANNO(75.,20.,100.,5,1000,1,25)
      CALL ANNO(75.,20.,100.,5,1000,2,25)
      CALL MOVTO2(105.,9.5)
      CALL CHAHOL(21HSTRESS MIT P  KN-M2*.)
      CALL CHASWI(0)
      CALL CHAHAR(3,1)
      CALL MOVTO2(60.,52.)
      CALL CHAHOL(21HSTRESS MIT Q  KN-M2*.)
C
      CALL AXIPOS(75.,20.)
      CALL SCALE2(0.1,0.1)
      CALL POLTO2(STMITP,STMITQ,N)
      CALL TRANSF(2)
      CALL CHASWI(0)
C
C
C
C
      CALL DEVEND
  900 STOP
      END
      SUBROUTINE ANNO(X,Y,ALEN,INT,MAX,ID,INN)
      DIMENSION AINT(150),ICHAR(50),DASH(200)
      REAL X,Y,ALEN
      INTEGER INT,MAX,INN,ID
      II=IFIX(MAX/INT)
      ICHAR(1)=0
      N=1
      IN=INT+1
      DO 5 J=2,IN
      ICHAR(J)=II*N
      N=N+1
    5 CONTINUE
C
      C=ALEN/FLOAT(INT)
      DO 10 K = 1,INT
      AINT(K)=C*K
   10 CONTINUE
      D=FLOAT(MAX/INN)
      EE= ALEN/D
      LL=IFIX(D)
      DO 7 KK=1,LL
      DASH(KK)=EE*FLOAT(KK)
    7 CONTINUE
      IF(ID.EQ.1)GO TO 25
      YY=Y
      DO 8 MM=1,LL
      YYY=YY+DASH(MM)
      CALL MOVTO2(X-0.8,YYY)
      CALL LINTO2(X,YYY)
    8 CONTINUE
      XPO = X - 10.0
      CALL MOVTO2(XPO,Y)
      CALL CHAINT(ICHAR(1),3)
      CALL MOVTO2(X-1.5,Y)
      CALL LINTO2(X,Y)
```

```
      M=2
      DO 20 L=1 , INT
      YO=Y+AINT(L)
      CALL MOVTO2(XPO,YO)
      CALL CHAINT(ICHAR(M),4)
      CALL MOVTO2(X-1.5,YO)
      CALL LINTO2(X,YO)
      M=M+1
   20 CONTINUE
      GO TO 30
   25 XX=X
      DO 9 II=1,LL
      XXX=XX+DASH(II)
      CALL MOVTO2(XXX,Y-0.8)
      CALL LINTO2(XXX,Y)
    9 CONTINUE


      YPO =Y-4.5
      CALL MOVTO2(X-2.,YPO)
      CALL CHAINT(ICHAR(1),1)
      CALL MOVTO2(X,Y-1.5)
      CALL LINTO2(X,Y)
      M=2
      DO 30 L=1,INT
      XO=X+AINT(L)
      CALL MOVTO2(XO-5.0,YPO)
      CALL CHAINT(ICHAR(M),4)
      CALL MOVTO2(XO,Y-1.5)
      CALL LINTO2(XO,Y)
      M=M+1
   30 CONTINUE
      RETURN
      END
C
C
      SUBROUTINE TITLE(ISAM)
      DIMENSION ISAM(10)
      CALL MOVTO2(70.,272.5)
      CALL CHASWI(0)
      CALL CHAHAR(4,0)
      CALL CHAARR(ISAM,10,4)
      CALL CHASWI(0)
      RETURN
      END
C
C
      SUBROUTINE AXIPOS(XAXI,YAXI)
      REAL XAXI, YAXI
      CALL MOVTO2(XAXI,YAXI)
      CALL SHIFT2(XAXI,YAXI)
      RETURN
      END
C
      SUBROUTINE BOX
      CALL SHIFT2(0.,0.)
      CALL MOVTO2(190.,135.)
      CALL LINTO2(50.,135.0)
      CALL LINTO2(50.,265.)
      CALL LINTO2(190.,265.)
      CALL LINTO2(190.,5.)
      CALL LINTO2(50.,5.)
      CALL LINTO2(50.,135.)
      CALL MOVTO2(50.,269.)
      CALL LINTO2(190.,269.)
      CALL LINTO2(190.,280.0)
      CALL LINTO2(50.,280.)
      CALL LINTO2(50.,269.)
      CALL MOVTO2(175.,150.)
      CALL LINTO2(75.,150.)
      CALL LINTO2(75.,250.)
      CALL MOVTO2(175.,20.)
      CALL LINTO2(75.,20.)
      CALL LINTO2(75.,120.)
      RETURN
      END
C
C
C
      SUBROUTINE UNI(X,Y)
      REAL X , Y
      CALL MOVTO2(X,Y)
      CALL CHASWI(0)
      CALL CHAHAR(2,0)
      CALL CHAHOL(40HOCT83   SOILS LAB  UNIVERSITY OF KEELE*.)
      CALL CHASWI(0)
      RETURN
      END
C
C
      SUBROUTINE A4
      CALL MOVTO2(0.,293.)
      CALL LINTO2(2.,293.)
      CALL MOVTO2(205.,293.)
      CALL LINTO2(208.,293.)
      CALL LINTO2(208.,290.)
      CALL MOVTO2(208.,140.)
      CALL LINTO2(208.,136.)
      CALL MOVTO2(14.,105.)
      CALL SYMBOL(3)
      CALL MOVTO2(14.,184.)
      CALL SYMBOL(3)
      RETURN
      END
C
C
C
      SUBROUTINE BOX1
      CALL SHIFT2(0.,0.)
      CALL MOVTO2(190.,135.)
      CALL LINTO2(50.,135.0)
      CALL LINTO2(50.,265.)
      CALL LINTO2(190.,265.)
      CALL LINTO2(190.,5.)
      CALL LINTO2(50.,5.)
      CALL LINTO2(50.,135.)
      CALL MOVTO2(50.,269.)
      CALL LINTO2(190.,269.)
      CALL LINTO2(190.,280.0)
      CALL LINTO2(50.,280.)
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CALL LINTO2(50.,269.)
CALL MOVTO2(175.,20.)
CALL LINTO2(75.,20.)
CALL LINTO2(75.,120.)
RETURN
END
```

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A Re-examination of the Dimlington Stadial glacigenic Sequence in Holderness

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ABSTRACT

Sedimentary and geotechnical properties of the Dimlington Stadial tills (Skipsea, Withernsea Tills) of Holderness were identified from three boreholes. Both sedimentary units were found to possess characteristics typical of diamicts deposited by lodgement beneath a wet based sliding ice sheet. No evidence could be found for the downwasting of a complexly stratified ice sheet as previously proposed for the sequences. A depositional model is proposed which explains the multiple till stratigraphy, in terms of a lateral shift in the east coast ice flow units carrying distinct mixes of lithologies along individual flow lines within a single ice sheet.

Introduction

Glacial sequences are often regarded as one of the most complicated and variable suite of sediments in the geological record. Attempts have been made to rationalize the complexity of these deposits through the application of depositional theories which link process, landform and sedimentology into a single unifying model or landsystem (Boulton and Paul, 1976; Eyles, 1983). Of particular importance to the glacial deposits of Holderness is the recognition of "subglacial" and "supraglacial" landsystems which have proved useful in the interpretation of diamict sequences deposited by lowland ice sheets across areas of sedimentary strata (Boulton et al., 1977).

The subglacial model can be applied to warm based glaciers that transport a thin layer of debris at the glacier sole, maintained by high rates of basal melt. Deposition occurs when the tractive force imposed by the moving glacier is inadequate to maintain in motion the basal debris against the frictional resistance offered by the bed (Boulton 1975). The balance between lodgement and erosion is dependant on a critical balance between a number of inter-related variables e.g. water pressure at the ice base, nature of transported load, and the pérmeability of the subglacial bed (Boulton and Paul, 1979). The control of several critical lodgement parameters leads to the slow accretion of a massively bedded, overconsolidated, poorly sorted diamict which can possess remarkably uniform textural and mineralogical properties (Luttenegger, Kemmis and Hallberg, 1983). Particularly diagnostic of this system is the development of an anisotropic meso-fabric of blade shaped clasts, orientated with the long axis parallel to ice flow and localised clast "smudges" caused by the shearing out of soft incompetent lithologies (Eyles, 1983). Other significant components of a till sheet deposited in this manner include subglacial channel fill sequences which result from active basal drainage beneath melting ice. Such forms can be recognized as distinct from the proglacial sediment association by a marked lateral discontinuity, forming "stacked" sequences with direct contact with true basal lodgement tills (Figure 1). Channel cross-sections can show evidence of hydro-static flow and generally fall within a smaller size range (1.5-12m) than fully developed proglacial outwash sequences (Eyles and Sladen, 1981).

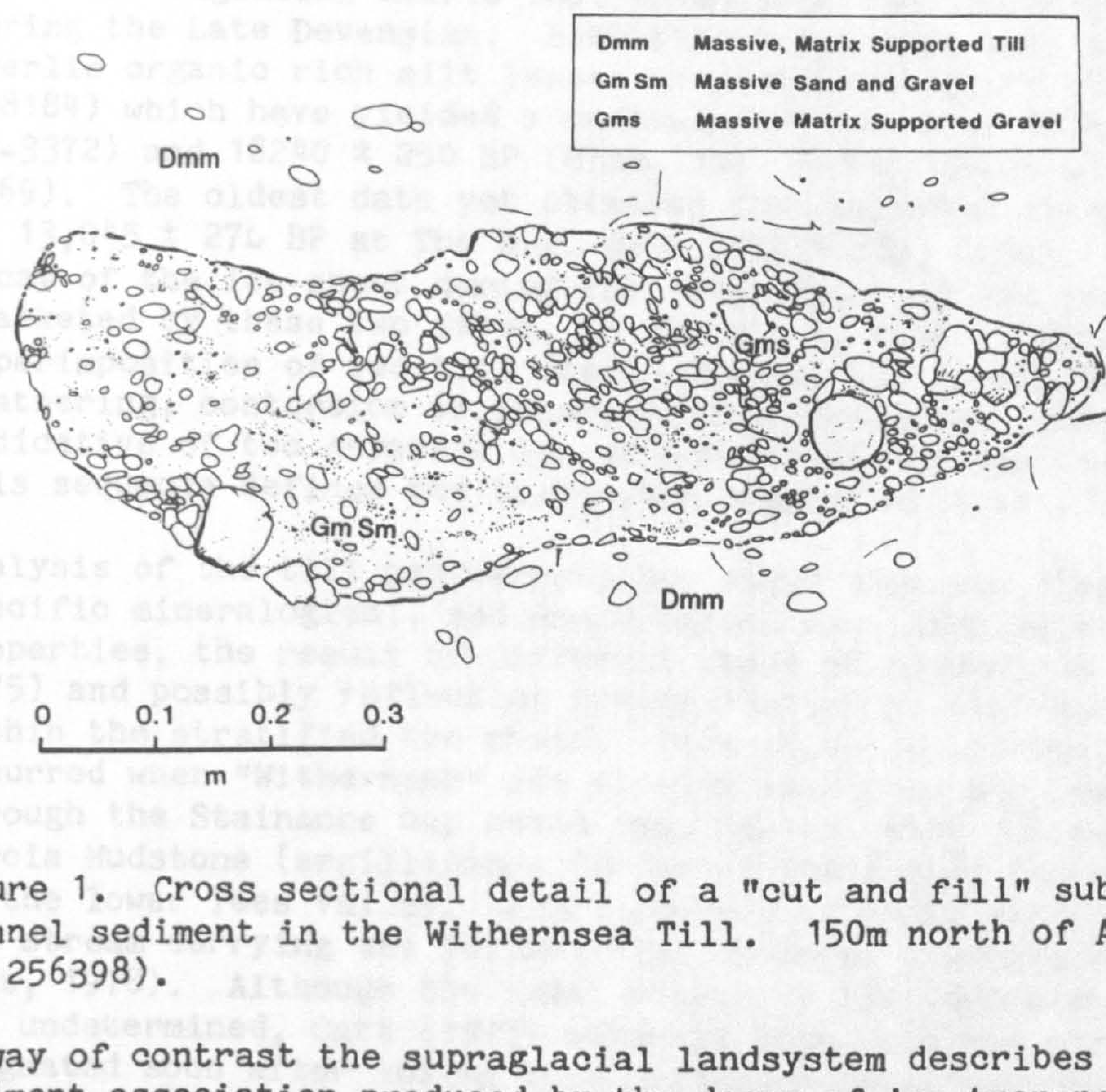

Figure 1. Cross sectional detail of a "cut and fill" subglacial channel sediment in the Withernsea Till. 150m north of Aldbrough (TA 256398).

By way of contrast the supraglacial landsystem describes the sediment association produced by the decay of ice transporting significant quantities of supraglacial or englacial debris. In the case of lowland continental ice sheets, this is usually related to compressive flow or the development of a cold ice margin leading to refreezing at the sole and the thrusting of basal debris into an englacial position (Boulton and Paul, 1976).

Eventually ablation causes debris to be released and deposited by processes of mass wasting as mobile flow tills (Boulton, 1970, Lawson, 1982). Slow melting of buried ice beneath flow tills releases more debris in situ (meltout till) which can be more stable and retain its englacial structure. Diamict sequences deposited in this manner characteristically deform as a result of sediment collapse or settling during the melt of underlying or buried ice masses, and such features include faulting, folding and slump structures (Shaw, 1972). On final ice melt an irregular hummocky kamiform relief is produced with a complex vertical profile formed of inter-stratified reworked diamicts and melt water deposits (Paul, 1983).

Regional Synthesis

The current depositional model for the Devensian glacial succession in Holderness outlined by Catt and Penny (1966) and Madgett and Catt (1978) after the original suggestion by Carruthers (1953), proposes that the Withernsea and Skipsea till sheets were deposited contemporaneously by a stratified ice sheet containing distinct basal and englacial debris that moved into the Holderness embayment during the Late Devensian. Both till units have been shown to overlie organic rich silt lenses at Dimlington Cliff (TA 386224 - 408184) which have yielded a radio-carbon dates of 18,500 ± 400 BP (I-3372) and 18240 ± 250 BP (Birm-108) (Penny, Coope and Catt, 1969). The oldest date yet obtained from material above either till is 13,045 ± 270 BP at The Bog, Roos (TA274288), (Catt, 1977). The decay of the ice sheet during the latter part of the period bracketed by these two dates, is thought to have resulted in the superimposition of two till sheets without the development weathering, contortion or incorporation across the junction, indicative of two separate ice advances (Madgett and Catt, 1978). This sequence defines the Dimlington Stadial of Rose (1985).

Analysis of the till petrography has shown that the diamicts possess specific mineralogical, sedimentological and lithological properties, the result of different zones of provenance (Madgett, 1975) and possibly reflecting transportation at discrete levels within the stratified ice sheet. This situation is believed to have occurred when "Withernsea" ice flowing east from the Lake District through the Stainmore Gap moved into contact with the outcrop of Mercia Mudstone (argillaceous facies of the former Keuper, Triassic) in the lower Tees valley, before overriding a pre-existing coastal ice stream carrying the Skipsea Till as basal debris (Madgett and Catt, 1978). Although the exact nature of the deglaciation is as yet undetermined, Catt (1977) suggests that both ice streams stagnated soon after moving into Holderness and features such as the Killingholme and Hogsthorpe ridges represent irregular deposition of flow till and melt-out till deposited during the slow decay of dead ice rather than the terminal moraine complex of an active ice front (Straw 1979).

Aims

The Withensea-Skipsea diamict sequence has been re-examined within the context of recent work on subglacial and supraglacial sedimentation in order to determine whether the sequence was deposited in a sub or supraglacial setting. This has been done using new borehole information and field work in the Cowden - Aldbrough area (TA 254404-258373).

Methods and Sampling

Three dry boreholes nominated CS 1 - 3 were sunk during the summer of 1982 at Cowden, Humberside, each to a depth of 10m (Figure 2). Drilling and testing of the cores recovered from CS1 and CS2 took place during a three week on-site programme. CS3 was sampled a month later during a separate five day drilling schedule. All three boreholes were located in a 5m radius. In total 47 samples were produced with a mean length of half a metre. Core recovery was good, averaging 73%.

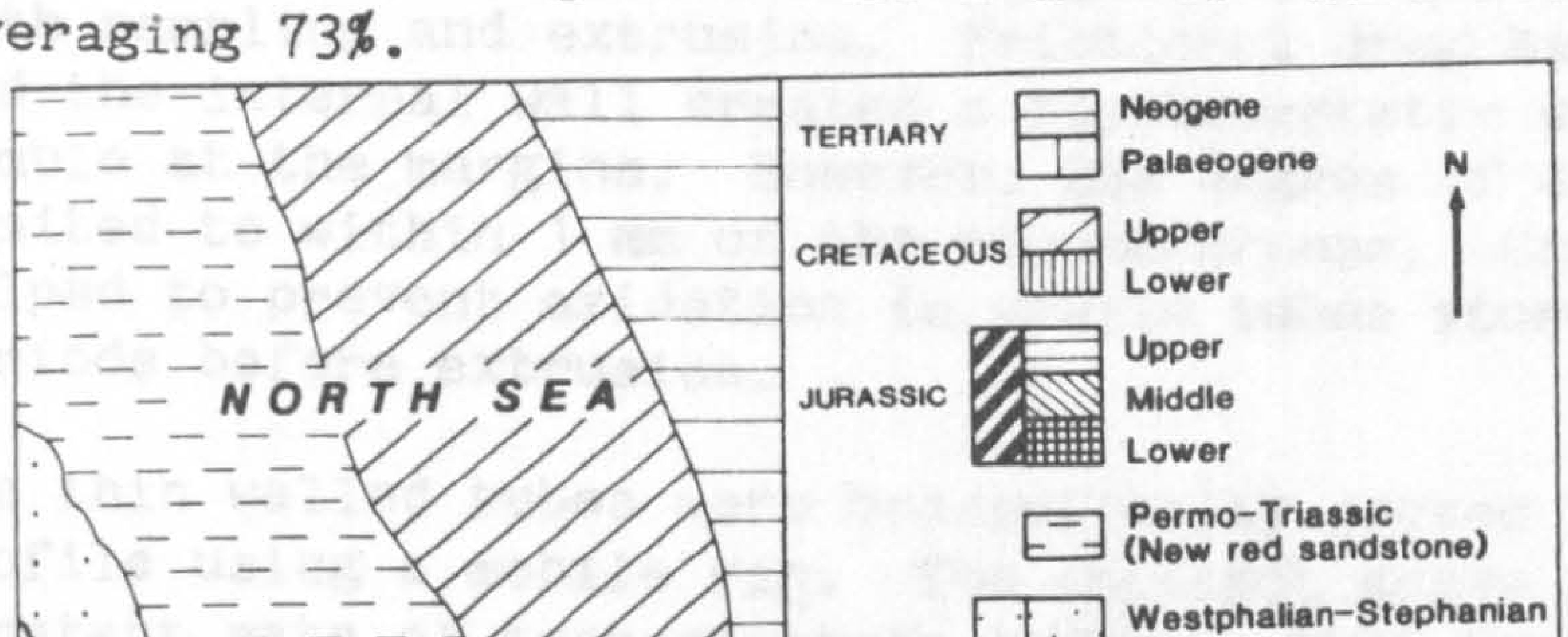

Figure 2. Regional geology and site location.

The problems of obtaining reasonably undisturbed samples of till have been reported by a number of workers (McKinlay, Tomlinson and Anderson 1974). Disturbance leading to significant re-moulding, can have an important effect on the measured properties of a sediment causing a reduction in undrained strength, a decrease in preconsolidation pressure and a reduction in the coefficient of consolidation. The following procedures were adopted to minimise this crucial factor.

a) Thin walled tubes were used throughout the sampling programme. These were construced from 1.5 mm gauge metal with an internal diameter of 98 mm which provided a cutting edge ratio of 3.5%. Standard U100 tubes with removable cutting shoes have an edge ratio of 25%.

b) Using a file, the cutting face was sharpened to a knife edge. The thinning of the leading edge caused some problems due to buckling in contact with flints, but this effect was minimal since the majority of the clasts encountered were formed from medium hard lithologies which were cleanly cut with no dragging.

c) All the tubes were cleaned and lightly greased as an aid to both sampling and extrusion. Frictional drag between the core and the internal wall created a characteristic warping of the sample at the margins. However, the degree of disturbance was limited to within 1 mm of the circumference. Greasing also helped to prevent oxidation in sample tubes stored for long periods before extrusion.

d) The thin walled tubes were hydraulically jacked into the profile using a mobile rig. The straight drive was at a constant rate of approximately 1m/min. This technique has been shown to produce less disturbance than either driven or cored sampling methods.

The release of in situ stresses was minimised by on-site testing in a mobile triaxial laboratory supplied by the British Building Research Establishment. Twenty samples were placed under confining stress equal to the calculated total overburden within 24 hours of sampling, the average delay being approximately three hours. All of the tests followed standard undrained unconsolidated test procedures. Pore pressure was monitored throughout by pressure transducers to allow complete effective stress analysis. One dimensional consolidation was carried out using an oedometer with a 76 x 19 mm sample size.

A 500 gm sub-sample was wet sieved to provide the size distribution of the 4Øto - 5Ø fraction. Complete dispersion was ensured by pre-treatment in dilute sodium hexametaphosphate solution followed by ultrasonic agitation. The particle size characteristics of the 4Ø - 9Øfraction was determined by the Andreasen's pipette apparatus (BS 3406).

Bulk index properties were calculated from the mass of the geotechnical specimens, trimmed to a known volume. Additional till samples were kindly supplied (for comparative purposes) by the British Geological Survey from offshore vibro-core returns. Large scale structural detail of the tills was gained through field work undertaken on the Cowden-Aldbrough cliff section (TA 254404 - 258373), which exposes the Skipsea-Withernsea boundary at 1-2m OD. The same feature was recorded in all three boreholes at an average depth of 5.2m below ground level.

Results

Diamict lithofacies and fabric.
The boreholes prove two diamicts differentiated in the field largely on the basis of colour, the Withernsea Till being dark greyish brown (10 YR 4/2) and the Skipsea Till dark brown (7.5 YR 3/2). This interpretation was supported by the adjacent coastal section. There was little visual evidence in the upper profile of significant reworking or dissaggregation of the Withernsea Till, both units are massively bedded, matrix dominated tills, the groundmass being stiff and cohesive. Apart from the superficial effects of desiccation in the upper 1-2m and stress relief features developed parallel to the free face, both tills display a distinct lack of fissuring or structural discontinuity. Fissuring was not recorded from depth in any of the boreholes, a fact noted by previous workers on the Holderness tills who have had access to good quality borehole returns (Marsland, Prince, and Love 1982). A weakly developed micro-foliation created by the parallel alignment of silt grains, as described by Sitler and Chapman (1955) for basal tills in Pennsylvania and Ohio and Penny and Catt (1969) for the Holderness tills, was observed in the lower Skipsea Till at a depth of 6-7m.

The existence of crushed clast "smudges" was noted from both till units, being particularly noticeable in the Skipsea Till where shattered chalk clasts provide a strong visual contrast against the darker matrix (Figure 3). Similar structures could be seen in the Withernsea Till commonly developed in Triassic and Liassic lithologies.

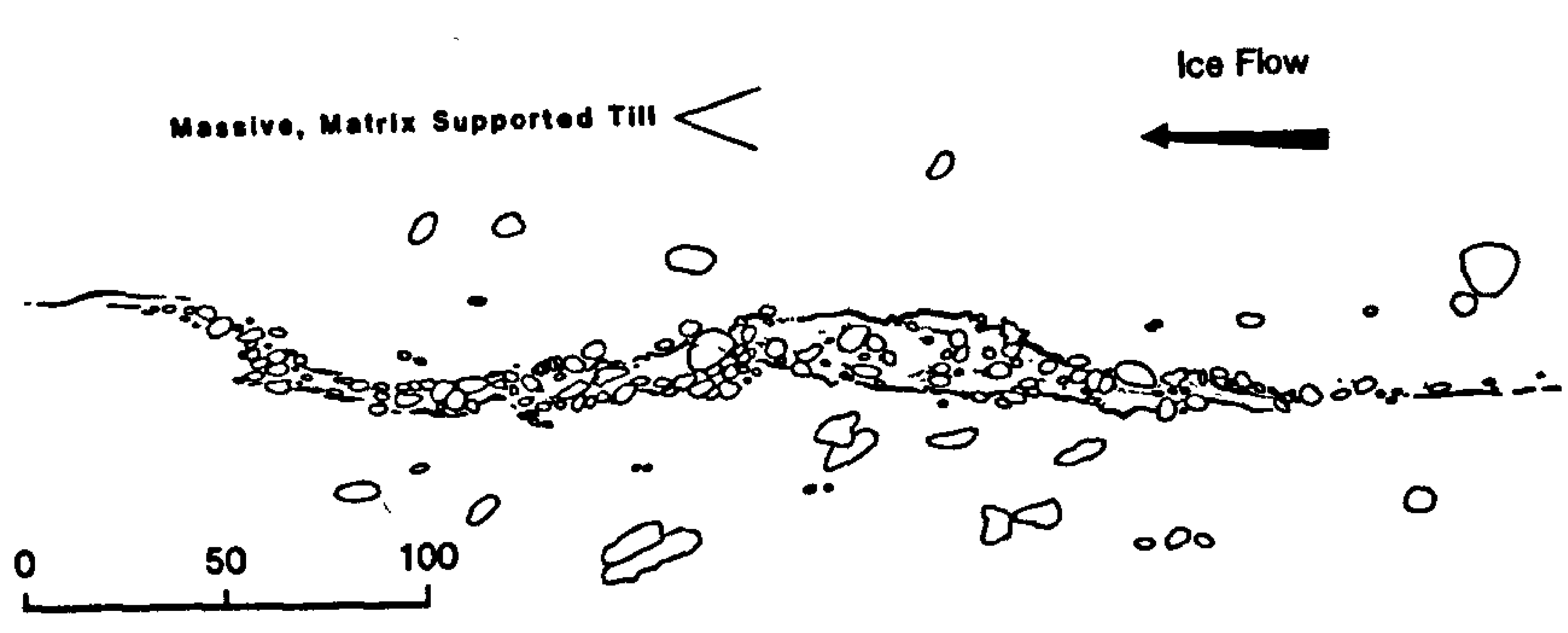

Figure 3. Detail of a clast "smudge" created by the distintegration and shearing out of a chalk cobble at the glacier base. These features form without any visible fracture development in the adjacent till. Skipsea Till, Cowden Cliff (TA 253404).

Although no measurement was taken of clast meso-fabric, strongly orientated fabrics have been previously recorded from both till units throughout the whole length of the Holderness coastline. (Penny & Catt 1969). This is unlike those fabrics reported for melt-out units (Lawson 1982).

Particle Size Distribution.

The particle size analysis of the borehole samples supports the visual evidence, as to the lack of any obvious reworking or disaggregation of the Withernsea Till. Both units possess a narrow range of matrix texture, a uniformity characteristic of basal lodgement tills (McGown and Derbyshire, 1977). Further treatment of the data shows that a classification of clay 27-44%, silt 34-48%, sand 18-31% accounts for 83% of all samples analysed, including offshore material (Figure 4). Within this classification no clear distinction could be made between the Withernsea and Skipsea Tills on the basis of silt content as proposed by Madgett and Catt (1978).

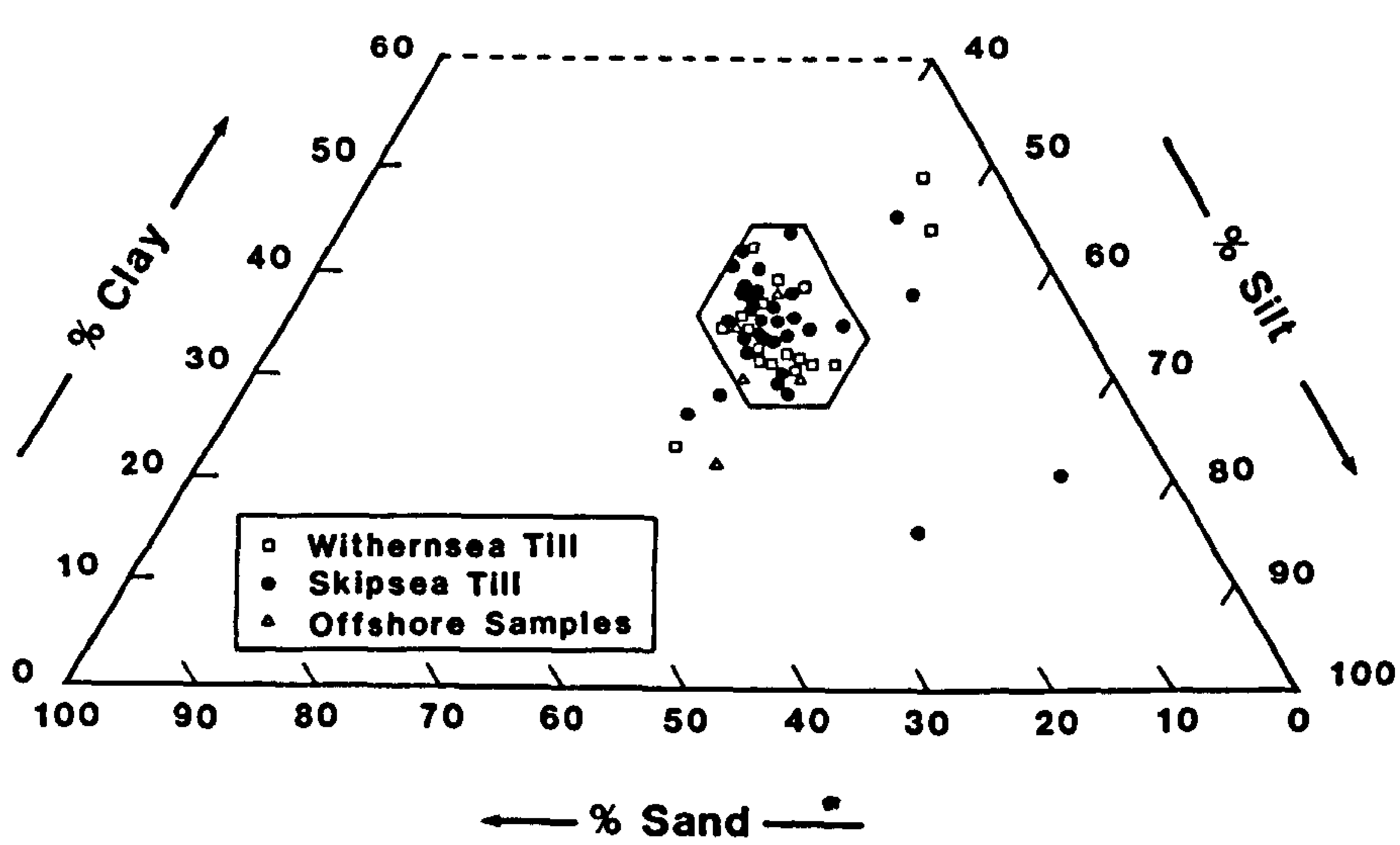

Figure 4. Textural envelopes for the Holderness tills as sampled in boreholes at Cowden and offshore returns. Total 56 samples.

The range of matrix texture and complex interbedding with fluvioglacial material as predicted by the supraglacial model was not observed in the vertical section, where the Withernsea Till maintains the general sand-silt-clay ratios which characterize the Skipsea Till (Figure 5). The Withernsea Till does not possess higher degrees of sorting, both units being extremely poorly sorted (sorting coefficient 4.2 - 5.46, Folk and Ward 1957).

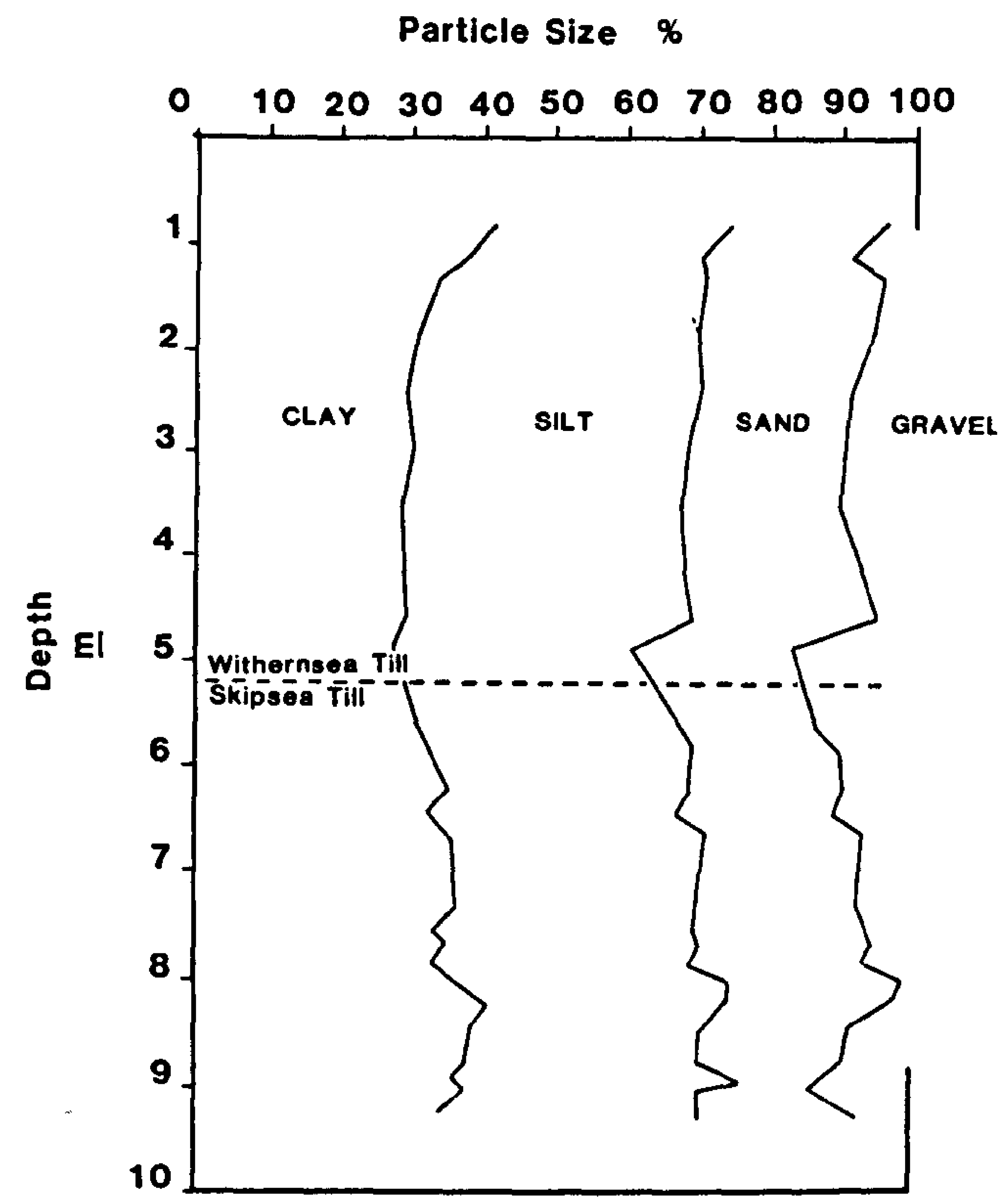

Figure 5. Textural variation in major particle size groupings with depth. Borehole CS1, Cowden, Humberside. Total 27 samples.

Bulk Index Properties

In studies of supraglacial deposition, (Boulton and Paul 1976; Paul, 1983) it is suggested that differences in density exist between supraglacial materials and basal tills, with the latter being significantly more dense than supraglacially deposited materials. Both bulk density and voids ratio provide a suitable index of compaction. Voids ratio is frequently used in geotechnical analysis as a volume change coefficient during stages of consolidation and can be used to relate the in-situ conditions to past conditions of effective stress.

A summary of density measurements for the till sequence sampled in boreholes CS1-3 is shown in Figure 6. Both the Withernsea and Skipsea Tills fall within the range of densities typically associated with basal tills (2.13 - 2.3 Mg/m^3) as reported by Eyles and Sladen (1981) and Radhakvishna and Klym (1973). Differences between the average bulk density of the two units can be attributed to soil development in the upper profile, since there was no evidence for a change in bulk density across the colour boundary. The mean value for voids ratio, 0.438, reflects the dense nature of

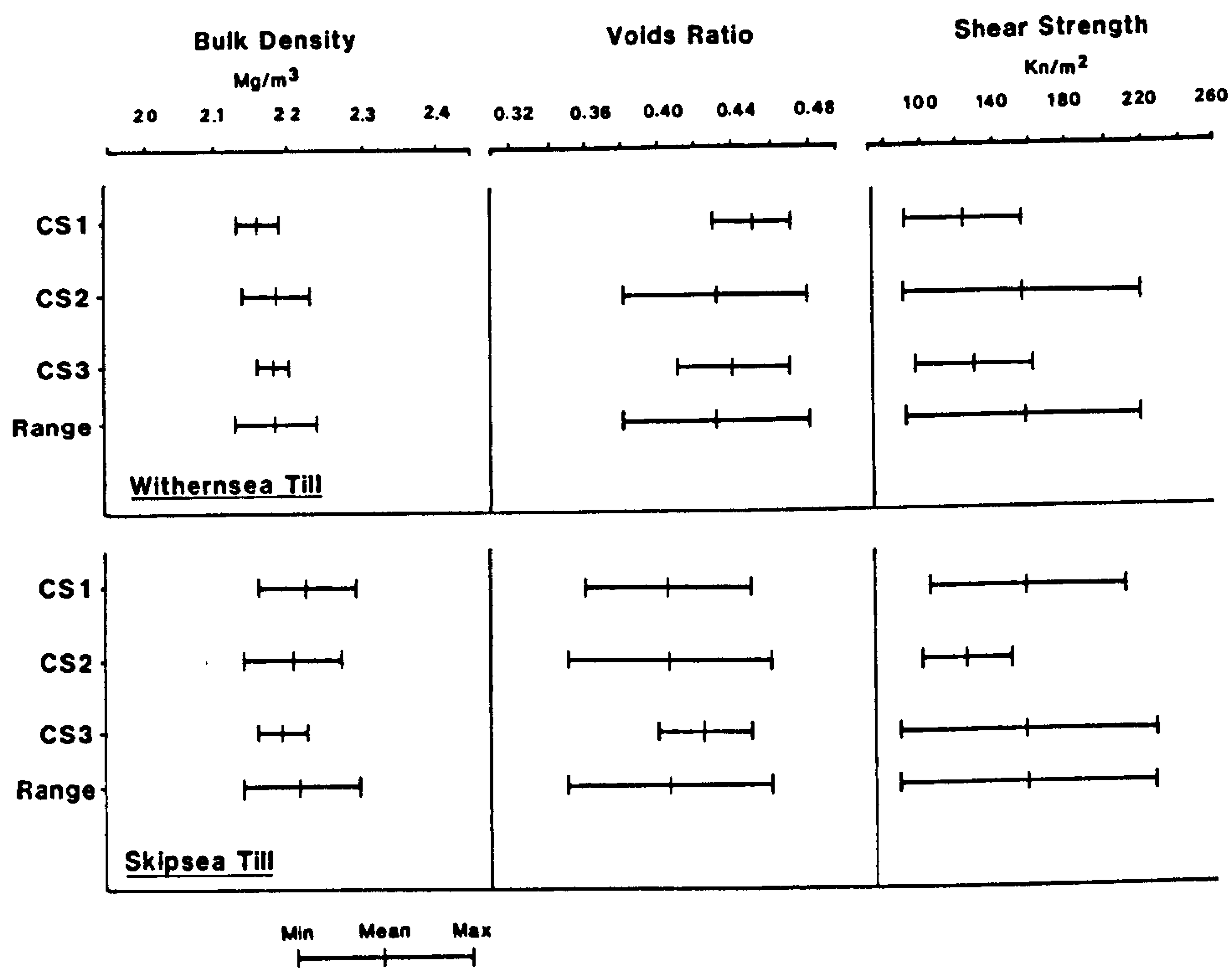

Figure 6. Variation of basic soil parameters for the Skipsea and Withernsea Tills. Boreholes CS1-3, Cowden, Humberside. Total 43 tests.

the material, the data showing consistent reduction with depth in line with the corresponding increase in confining stress. The high densities and reduced range of data values across all three boreholes suggest a uniform process of subglacial deposition rather than the increased scatter of values and reduced densities characteristic of supraglacial processes.

Stress History and Consolidation

Owing to the disaggregation and fluvial reworking suffered by debris in the supraglacial environment most workers recognize that significant differences in consolidation exist between basal and supraglacial material (Boulton and Paul 1977; Marcussen 1975). Assuming fully drained conditions, subglacial till can experience normal loads in excess of 2000 kN/m² (Sladen and Wrigley 1983) producing the typically overconsolidated condition in exhumed sections. Owing to the lack of any significant depositional load, supraglacial material commonly displays lower pre-consolidation loads, of order 150-250 kN/m², related to post-depositional drying (Paul, 1983).

Results of oedometer tests show that both tills possess similar consolidation characteristics, with pre-consolidation pressures between 300-425 kN/m² indicating moderately overconsolidated soil (Figure 7). At all depths the till displayed a highly dilatant response in shear typical of a dense overconsolidated deposit. A similarity in stress history for the two tills is also suggested by the range of shear strengths recorded.

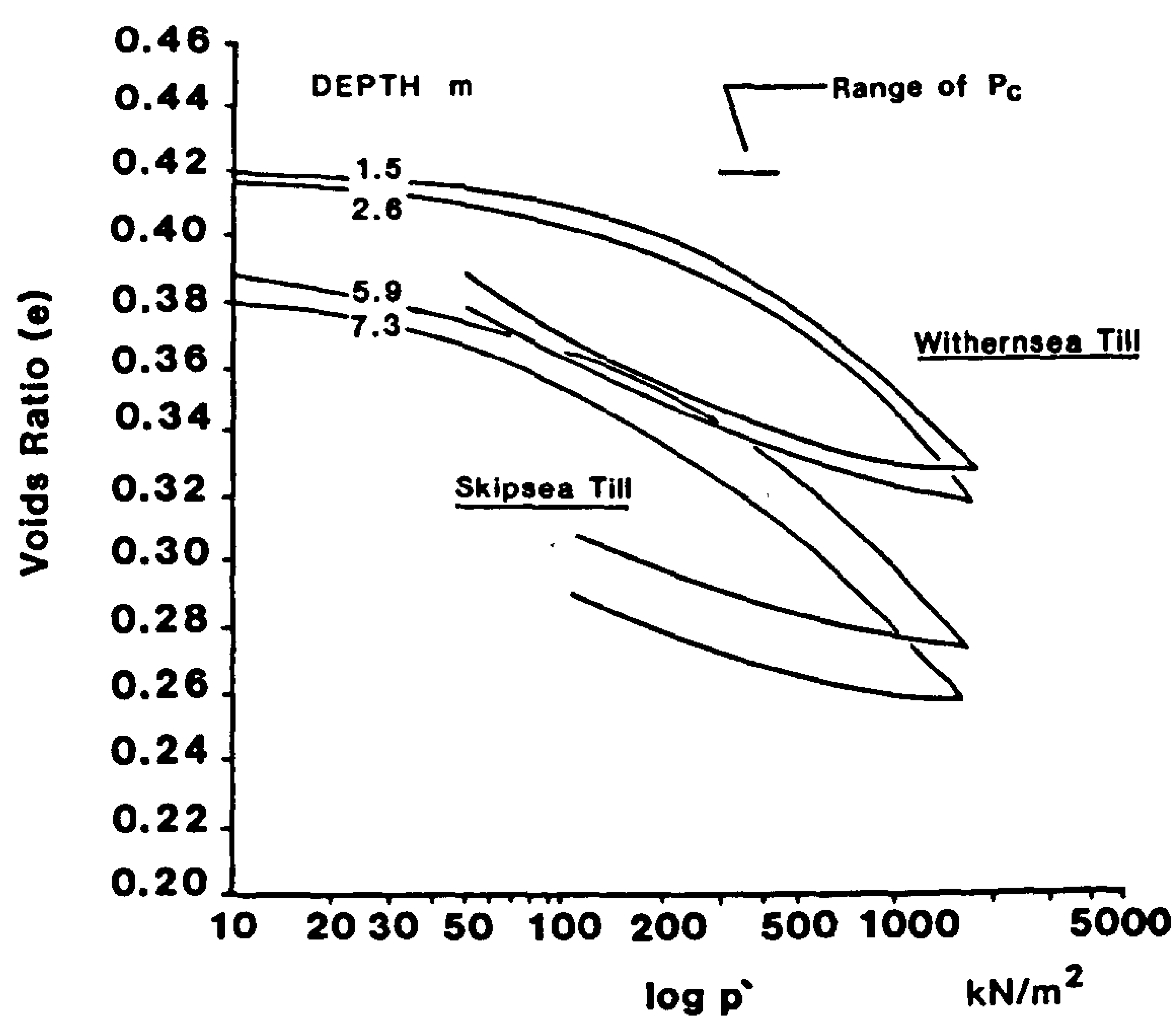

Figure 7. Consolidation curves for the Withernsea and Skipsea Tills. Samples recovered from borehole CS1, Cowden, Humberside.

The low values of pre-consolidation load displayed by material which otherwise shows all the sedimentary features of basal lodgement tills has been reported by a number of workers, (Dremanis, 1974) and has been accommodated in models of subglacial deposition (Boulton, 1975).

Discussion

A complexly stratified ice sheet model involving basal melt-out, clearly forms an inadequate explanation for the deposition of the Holderness tills, taking into account the range of sedimentary and geotechnical evidence presented so far. There is no evidence for the melt-out debris from a stagnant ice mass. If melt-out had occurred the sediment may have retained its subglacial characteristics, but the material would inherit a new set of geotechnical properties and a rather different stratigraphy and geometry related to the rapid melt at the underlying ice sheet and subsequent resedimentation.

The suggestion that the melt of the intervening ice sheet might not have produced sufficient water to rework the upper till (in discussion, Catt and Penny (1966) p.419) is improbable, considering that the terminus of the lower advance is generally accepted to be marked by the Hunstanton moraine, 100 km further south and that, during its passage through Holderness, the same ice stream was responsible for the deposition of 15-20 m of lodgement till (Skipsea Till).

Similarly, the possibility that the englacial fabric of the till could have been wholly preserved by intense levels of sublimation has been dismissed by Eyles, Sladen and Gilroy, (1982) as an unrealistic proposal for the east coast tills, partly on the grounds that the process is too slow, (2m of sublimation till c 7000 years - Shaw, 1980). The margins of the Devensian till sheet in Holderness and Lincolnshire possess clear depositional and erosional evidence for the passage of water during deglaciation (Robinson, 1968; Dingle, 1970; Catt, 1977).

The geotechnical analysis proved that both tills possess similar strength and consolidation characteristics which can be interpreted in terms of related stress histories. The wide variations in strength and preconsolidation stress reported by Lutenegger, Kemmis and Hallberg (1983) as marking the junction between basal and supraglacial sediment associations were simply not observed at Cowden. The results support the view that both tills were deposited beneath warm based ice and that the Withernsea Till has experienced little post-depositional modification apart from the development of a Flandrian weathering profile (Madgett, 1974).

The distinct till lithology and petrography (Madgett and Catt, 1978) can be explained by a change in the mix of lithologies deposited at any one point due to a lateral shift in ice flow or by the alteration of lithologies carried along a single flow line. This is essentially the process of "unconformable facies superimposition" as proposed by Eyles, Sladen and Gilroy (1982) for the basal tills of Northumberland. The ice streams in question can be defined as a Pennine - Lake District flow moving through the Stainmore and Tees Gaps providing the initial advance which deposited the Skipsea Till, only to be displaced in the coastal regions by a rigorous ice stream moving out from the eastern Southern Uplands and Cheviots via the Tweed lowlands and down the east coast, a route which provides the Triassic/Chalk mix typical of the Withernsea Till. The area of the Tees lowlands is still seen as critical, not as an area of overriding, but as a region of confluence of active ice streams.

Acknowledgements

I am grateful to Edward Derbyshire, Nicholas Eyles and Mike Love for their critical assessment of this paper. My thanks also to A. Marsland and the British Building Research Establishment, Geotechnical Division who kindly allowed the use of equipment, on-site facilities and drilling crew.

Martin Edge provided assistance during the testing programme at Keele University and in Holderness. This work was supported a Research Studentship awarded by the Natural Environment Research Council.

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