The Hydrogeological Classification of Superficial Clay:

The hydrogeological characterisation of glacial till in East Anglia

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The hydrogeology characterisation of glacial till in East Anglia.

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EXECUTIVE SUMMARY

The following is an account of the main findings of the Environment Agency - British Geological Survey (BGS) co-funded project on the hydrogeological characterisation of superficial clays with special reference to the Lowestoft Till of East Anglia. The primary objective of this study was to review the hydrogeology of superficial clays and evaluate their influence on water resource management in relation to the NRA Groundwater Protection Policy. The corollary was to examine the effectiveness of superficial clay in providing a barrier to infiltration and hence groundwater pollution.

As an means of achieving the project objectives detailed studies were carried out at Hall Farm and Uphall Farm in Norfolk and Hobs Aerie in Essex. The study involved geological mapping and the use of remote sensing, geophysical surveys, drilling, hydraulic testing, and undisturbed sample acquisition for comprehensive laboratory studies of pore water chemistry, rock properties and mineralogy. The synthesis of this extensive data set has enabled the recognition of the main controls on fluid transport within the till and permitted the use of groundwater flow modelling to scope recharge.

The till sequences described in this report are generally very poorly-sorted (the particle size distribution ranges over several orders of magnitude) and therefore they behave as predominantly granular, porous media. It is known that very poorly sorted systems pack efficiently if subject to consolidation, as smaller particles fill the interstices between larger particles and a densely-packed structure results.

Porosity has been found to show very little variability between sites, oxidised tills typically having porosities of between 0.31 and 0.35. Unweathered tills have lower porosities typically 0.22 to 0.28, however the soft, unweathered, high moisture content tills from the Hobs Aerie site are the exception with porosities in the region of 0.34. Wet density is typically in the range 2.04 to 2.18 Mg/m^3, with the lower values coinciding with the lower moisture contents and wet densities, and higher porosities.

Based on triaxial test data laboratory hydraulic conductivity shows very little variation within sites or between sites. Assuming that sample size does not allow the incorporation of fractures then the method is considered to be providing a reliable estimate of the matrix hydraulic conductivity, an average value is 1.57E-10 m/s.

A wide range of field-determined hydraulic conductivity has been found. There is a clear correlation between the state of weathering and the hydraulic conductivity. Weathered tills have

hydraulic conductivity values which are two to three orders of magnitude higher than the corresponding laboratory value, whereas unweathered tills closely approach the laboratory value in most cases. A large body of published literature supports the contention that the field value is reflecting the presence of fractures in the test interval.

Using the data gathered for the Hall Farm site a conceptual model of groundwater flow was developed which identified fracturing as being a key component of the groundwater flow and contaminant transport pathway. The distribution of the anthropogenic contamination associated with a manure pile on the till at Hall Farm was explained in terms of fracturing and, coupled with the corresponding distribution of laboratory and field hydraulic conductivity, it was possible to arrive at a recharge estimate using analytical and numerical modelling techniques.

The principal results of the modelling study were that using reasonable parameter combinations recharge through the till is estimated to be between 29 mm/yr and 40 mm/yr, i.e. between 14.5 and 20% of hydrologically effective rainfall (calculated to be 200mm on bare soil).

In assessing a till as a barrier to contaminant migration or conversely aquifer protection both the physical barrier and chemical barrier properties need to be addressed. Ideally, clay classification methods should be selected solely on the basis of scientific and/or technical criteria and a practical, relatively simple methodology is likely to be easier to implement and be more widely understood than a highly-specialised or overly-sophisticated approach. In terms of hydrogeological classification, particle-size analysis is a crucial method because average particle-size and degree of sorting are primary controls on bulk permeability. Many workers in Quaternary geology also use triangular diagrams of sand/silt/clay to classify lodgement tills because of their matrix-dominant nature. Those samples that plot in sand field of the triangular diagram, or those that contain a large proportion of clasts, are identified as potentially permeable.

Cation exchange capacity (CEC), a good indicator of ion-exchanging or sorbing ability, is an important chemical property of a clay barrier with respect to migrating pollutants. CEC is sensitive to variations in the composition of the clay mineral assemblage, especially smectite-group mineral content. As the clay mineral assemblage of the Lowestoft Till is relatively uniform, CEC values are likely to indirectly measure overall clay mineral content.

The report concludes by identifying the main areas of uncertainty in the current understanding of the hydrogeology of superficial clays and offers suggestions for further work directed at a mapping based approach to the hydrogeological classification of glacigenic sediments. Uncertainty centres on the role of fractures in till contaminant transport processes and their detailed characterisation especially in terms of fracture density, length and aperture. There is no doubt that the presence of fractures in a till sequence is critical in controlling fluid and contaminant movement. It is the

unweathered, less fractured tills which provide the protection to the underlying aquifer and efforts need to be directed to assessing the continuity and thickness of this lithology within an area.

Of particular interest in terms of contaminant transport is the role of anthropogenic organic compounds especially solvents in promoting permeability enhancement. Laboratory studies to examine the effects of chlorinated solvents on Lowestoft till have demonstrated measurable structural changes in the clay minerals. It is believed that these changes could be responsible for enhancing hydraulic conductivity in the field and alter the ranking of a site significantly in terms of the underlying aquifer vulnerability. The data gathered to date and the published literature seem to conflict and further laboratory study is required to resolve this important issue.

A way forward in regionalising the study would be to subdivide the tills into hydrogeological domains using existing borehole records and interpolate data acquired from limited field and laboratory investigations, similar to those used in this study. Areas of low data density would be highlighted during this exercise and could be targeted for follow up study to enhance the existing data base.

1. INTRODUCTION

The following is an account of the main findings of the Environment Agency - British Geological Survey (BGS) co-funded project on the hydrogeological characterisation of superficial clays with special reference to the Lowestoft Till of East Anglia. It is recognised that groundwater quality is at risk from many sources of contamination, including waste disposal, effluent discharge, and diffuse pollution resulting from agricultural practices. The NRA document on "Policy and Protection of Groundwater" (NRA, 1991) identified the need to assess aquifer vulnerability to pollution based on the physical characteristics of the aquifer and the overlying rocks and soils. The presence of extensive drift deposits over much of the U.K. dictates that in many areas superficial clays overly aquifers. Groundwater vulnerability maps currently produced show the extent of drift deposits in relation to the major aquifers, however these deposits are not classified and their thickness is not indicated. Clearly where superficial clays overly major aquifers it is necessary to have more detailed information on clay thickness and its effectiveness as a barrier to pollution movement or its influence on aquifer recharge. The primary objective of this study was to review the hydrogeology of superficial clays and evaluate their influence on water resource management in relation to the NRA Groundwater Protection Policy. The corollary was to examine the effectiveness of superficial clay in providing a barrier to infiltration and hence groundwater pollution.

1.1 Previous Work

In studies of the till sequence inland from Corton in Suffolk, McC.Bridge and Hopson, (1985) suggest that two distinct stages of ice-advance occurred in the area during the Anglian Glacial Stage. An initial 'North Sea' ice advance from the north east was followed by an ice-advance from the west. Subsequent wasting of this later ice-sheet produced an extensive blue-grey chalky till (Lowestoft Till) which drapes the pre-existing topography to form a blanket cover over much of East Anglia. Lunkka, (1994) also suggested that the sandy till which underlies the Lowestoft Till in much of east Norfolk formed beneath ice which advanced from the north east ('Scandinavian' ice), whereas the Lowestoft Till was formed by 'British' ice which advanced from the west in the late Anglian.

Mathers *et al.*, (1987) proposed the term Banham Beds for a distinct suite of clays, silts, sands, gravels and diamictons resting on the Chalk and underlying the Lowestoft Till in an area approximately 10-15 km north-west of Diss in central East Anglia. The Banham Beds were provisionally assigned to the North Sea Drift Formation. The diamicton component was described as a massive, over consolidated lodgement till with a matrix (<2 mm) sand content of 57.5-70%, in contrast to 8.3-31.5% for Lowestoft Till from this region. The sand fraction of the Banham Beds diamicton consists of roughly equal proportions of fine-sand and medium-sand whereas fine-sand was found to predominate in the Lowestoft Till.

A model of glacial stratigraphy proposed by Allen *et al.* (1991) for southern East Anglia invokes a single ice advance during the Anglian Stage producing a series of associated till units. These are equivalent to the Lowestoft Till Group/Lowestoft Till described by other workers. These tills appear to reflect underlying lithologies (clay-rich over Jurassic clays, sandy over pro-glacial sands and gravels and carbonate-rich over chalk). Both lodgement and melt-out facies are represented in the Lowestoft Formation of Suffolk. In west Essex and Hertfordshire, four Anglian till units are recognised by Allen. These represent successive advances by the ice sheet and have been formed predominantly by lodgement processes, although flow, slumped or geliflucted till facies may be present locally.

Whiteman, (1987) proposes a four-fold classification of the Lowestoft Till Group in Essex (Table 1.1). Both Whiteman *op.cit.* and Hopson and Morigi, (1993) suggest that Unit C is the definitive lodgement till type of the Lowestoft Till Group. The common gradational contact between Unit C and Unit D, and the colour of Unit D, led Whiteman to speculate that Unit D is merely the weathered subsurface zone of Unit C. However, the larger clast size and higher chalk content of Unit D, together with the absence of black shale, suggests a difference in genetic origin. Hopson & Morigi note that Unit A and Unit B are laterally variable and often thin.

Mineralogical investigations of the Lowestoft Till Group have previously been carried out by Perrin *et al.*, (1973); Perrin *et al.*, (1979). They investigated the geographical variability of the till by collecting samples from a large number of sites in East Anglia and the east Midlands. In both of these studies, which focused on the mineralogy and particle-size characteristics of the matrix (<2 mm), samples were generally taken from a depth of around two metres.

Perrin *et al.* (1973) found a marked geographical variability in calcium carbonate (chalk) content with mean values ranging from 23% (East Midlands) to 43% (East Anglia). In contrast, the clay mineral assemblage of mica, kaolinite and smectite did not vary significantly and was considered to be consistent with derivation from local Jurassic clays, Gault and Chalk. The <2 mm particle-size distribution data are of limited value since chalk present in the matrix was removed by acid dissolution prior to analysis. The particle-size of the remaining clayey portion of the matrix was found to be very uniform. Perrin *et al.* (1979) confirm the results of the earlier study and provide more detailed information on variability in carbonate content and matrix particle-size.

Some of the earliest investigations into till hydrogeology were conducted with the object of obtaining estimates of groundwater recharge through the drift and the early water balance studies of Ineson and Downing, (1965) for the River Tas catchment in Norfolk were very important in this respect. A number of workers have looked at the composition of till pore waters to provide evidence of fluid transport through tills. Lloyd *et al.*, (1981) discussing the results of pore water chemistry characterisation in a cored borehole from the Stour catchment of southern East Anglia, attributed the presence of a high tritium value (107 TU) at a depth of 11.7 metres to lateral bypass flow through zones of relatively high permeability within the till. Hiscock, (1993) has used hydro chemical evidence to suggest that the boulder clay on interfluve regions inhibits direct recharge to the chalk, but cited the presence of tritium as evidence for a small component of recharge through more permeable material within the bulk of the till. An important contribution to the estimation of recharge rates through till is due to Ross *et al.*, (1989). Based on an analysis of pore fluids extracted at Killingholme, Lincolnshire, it was inferred that groundwater movement is relatively fast, and downwards. Mass balance calculations for chloride and tritium penetration indicated downward vertical velocities of between 0.07 and 0.39 m/yr, consistent with values calculated using Darcy's Law.

Table 1.1 Classification of the Lowestoft Till Group in Essex (Whiteman, 1987).

Unit A
Deformation till. Clasts largely of local origin.

Unit B
?Melt-out till. Sandy, banded till. Local clasts and far-travelled 'exotic' clasts are present.

Unit C
Lodgement till. Compact, structureless, dark grey, silty clay with appreciable small, often striated, chalk clasts and far-travelled 'exotics', including Mesozoic sandstones and black shale. Basal 20-30 cm is often oxidised to an orange-brown colour. ?Unit C subjected to ice-entrained basal transport over a long distance. Unit C is absent if Unit D is less than 3.5 to 4 m thick.

Unit D
Lodgement till. Up to 6 to 7 m thick. Mottled grey/yellow-brown, either structureless or well-jointed, silty clay, abundant large chalk clasts with exotics including Jurassic and Cretaceous sandstones, limestones and shells. Black shale is absent. ?Unit D subjected to ice-entrained basal transport over a short distance only. Upper 0.5 m often decalcified with tongues of decalcification extending to the base. Redeposited calcium carbonate occurs as nodules.

Klinck *et al.*, (1993) in a review of the readily accessible information on the geology and hydrogeology of superficial clays identified fracturing as a significant contributor to the processes which control groundwater flow through tills. Early work by Williams and Farvolden, (1967) is of interest which suggested that joints (fractures) in till play a major role in controlling groundwater movement. Indeed fracturing in tills is well documented and has been described previously in

In comparison to Hall Farm (and Hobs Aerie), the Uphall Farm sequence is significantly better sorted and particle-size distributions are more strongly coarse-skewed (Figure 3.2). Average clay (<2 μm) content is also higher than for the other two sites.

Average sand/silt/clay content classifies the Uphall Farm sequence as a sandy clayey silt. Clast content (gravel/cobbles) is typically only minor (6.2% av.). Average median and mean values confirm their silty nature. Only limited observations can be made concerning downhole trends due to the small number of samples collected. However, it is possible to divide the sequence into a sandy lower section, a clayey middle section and a silty upper section.

3.1.2 Physico-chemical properties

Down hole profiles of surface area and cation exchange capacity (CEC) show a close positive relationship with clay (<2 μm) content (Figure 3.3). In particular, high surface area values in the Hall Farm sequence correspond to high values for clay content at 6.3m and 8.0m. At Uphall Farm, the highest physico-chemical values obtained correspond with the more clay-rich middle section of the sequence.

3.1.3 Quartz and calcite content

Variations in quartz and calcite content of the fine matrix with depth for the Garboldisham sequences are plotted on Figure 3.4. The combined quartz and calcite content of the majority of samples from the Hall Farm sequence is relatively constant. Clear downhole trends in bulk mineralogy data coincide with the upwards-fining trend in the Hall Farm sequence. Quartz content decreases from 66% to 28% between 12.3 m and 3.7 m, correlating with the decline in the proportion of fine-medium sand and fine-sand. Conversely, calcite content increases from 20% to 50% over an identical depth interval, correlating with an increase in percentage fine-silt and the clay content.

Fine matrix quartz and calcite content also show an antipathetic relationship in the Uphall Farm sequence. Calcite content is highest in both the silty upper section and the sandy lower section, with quartz content being highest in the clayey middle section. An association between calcite and sand content at Uphall Farm suggests that an significant part of the sand fraction consists of chalk. This contrasts with the association between quartz and sand content observed at Hall Farm.

in carbonate content would also be expected where the rockhead is chalk. Sladen & Wrigley (1983) suggest that upwards-fining mainly influences >2mm clast content rather than the particle-size of the <2 mm matrix.

The boundary between till sheets or between two till lithofacies is often marked by an abrupt change in mineralogy and particle-size characteristics. In the past, particle-size has been used to distinguish one till facies from another (Shepps, 1985). Sladen & Wrigley (1983) suggest that individual till lithologies (melt-out tills, lodgement tills) plot within discrete envelopes on triangular sand/silt/clay diagrams. Emphasis has shifted toward lithofacies identification by detailed logging of diamicts using set codes for elements such as lithology, texture and sedimentary structures (Eyles *et al.*, 1983). Distinction between glacial sediments of similar lithofacies, although representing different depositional events, generally requires detailed analysis of physical and/or mineralogical properties. In the Cumbrian lowland, Huddart, (1971) was able to use sand/matrix (S/M) ratios to distinguish lodgement tills of the 'Scottish Readvance' (S/M = 0.6) from those of the Main Glaciation (S/M = 0.2-0.3). These approaches lead naturally to the mapping of glacigenic domains and consequently hydrogeological domains.

Weathering processes

Sladen & Wrigley (1983) divide weathering action affecting lodgement tills into chemical processes caused by oxidation, hydration, and leaching of carbonates and soluble salts and mechanical processes including disintegration and breakdown of particles, change of till structure by fracturing and downward movement of fine particles. Eyles & Sladen (1981) distinguished four weathering zones in the lodgement tills of eastern England (Table 1.2). The extent of each weathering zone varies depending on the nature of the till and factors such as groundwater levels, drainage conditions and vegetation cover. Although oxidation may penetrate to considerable depth, appreciable leaching of primary carbonates is restricted to zone IV.

Eyles and Sladen, (1981) report that carbonate leaching occurred to a depth of one to two metres in weathered lodgement till from Northumberland. Quigley and Ogunbadejo, (1976) report that fine-grained carbonate was leached from the top 1.5m of a Canadian till sequence. Carbonate and iron oxides were subsequently re-precipitated at around five metres depth. Physico-chemical properties (CEC and glycol retention) were also found to be higher within the weathered zone. An engineering geology study of the Lowestoft Till Group at Milton Keynes (Dennes, 1974) noted that weathering of a sandy upper till unit reduced particle size to that of a clayey silt down to a depth of 2.5m. Bell and Forster, (1991) reported that weathering of the Skipsea and Withernsea Tills of

Holderness increased plasticity from a 'low plasticity' category to either 'intermediate plasticity' or 'high plasticity' categories. Plastic Index : Liquid Limit plots showed that weathering effects a diagonal shift along the T-line. This shift is also reported by Sladen & Wrigley (1983). These weathering changes were associated with an increased proportion of kaolinite relative to mica within the clay fraction. Matrix (<2 mm) particle-size was also reported to be more variable in weathered lodgement till.

Table 1.2 A weathering scheme for lodgement tills (Eyles & Sladen, 1981).

Weathering state	Zone	Description
Highly weathered	IV	Oxidised till and surficial material Strong oxidation colours Leaching of primary carbonate High rotten boulder content Prismatic gleyed jointing Increased clay content Increased 'activity'
Moderately weathered	III	Oxidised till Usually dark brown or dark red brown Low rotten boulder content Little leaching of primary carbonate Increased clay content Increased activity
Slightly weathered	II	Oxidation along surfaces of fissures, if present Otherwise as Zone I
Unweathered	I	Unweathered till No oxidation Usually dark grey No rotten boulders No leaching of primary carbonate

1.2 New Data

As an means of achieving the project objectives for the Lowestoft Till referred to in the introductory paragraph detailed studies were carried out at Hall Farm and Uphall Farm in Norfolk and Hobs Aerie in Essex (Figure 1.1). The initial basis for site selection was that the following criteria should be met:

- Mineral Assessment Reports available
- The area is underlain by a class A aquifer
- Drift contact with aquifer within area

Early in the selection process it became evident that all three criteria were unlikely to be satisfied since Mineral Assessment Surveys were generally sited in areas where sub-till, sand and gravel deposits occur. Consequently, it was decided to contrast the area north of the Little Ouse/Waveney valley at Garboldisham, Norfolk, for which a Mineral Assessment Report was available, with the area around Elmdon, Essex where the till was expected to rest directly on the aquifer, but where no Mineral Assessment survey had taken place.

The study involved geological mapping and the use of remote sensing, geophysical surveys, drilling, hydraulic testing, and undisturbed sample acquisition for comprehensive laboratory studies of pore water chemistry, rock properties and mineralogy. This information is reported elsewhere and the reader is referred to the following reports for detail on methodologies, raw data, test analysis and results: Entwisle, (1994); Hopson and Morigi, (1993); Inglethorpe and Bloodworth, (1994); Klinck *et al.*, (1995); Klinck and Wealthall, (1995); O'Connor, (1994). The synthesis of this extensive data set has enabled the recognition of the main controls on fluid transport within the till and permitted the use of groundwater flow modelling to scope recharge.

2. CHARACTERISATION OF LOWESTOFT TILL

2.1 Geological Interpretation

Prior to the selection of drilling sites detailed geological mapping was carried out (Hopson and Morigi, 1993).

2.1.1 Garboldisham Area

This area is 11 km due east of Thetford and is substantially enclosed within a triangle bounded by the B 1111 and B 1114 and a minor country road. In addition to the B 1114, the eastern margin is also marked by a minor southward flowing tributary of the Little Ouse. A low NE-SW ridge founded on Lowestoft Till crosses the eastern half of the survey area. From this ridge the ground falls gently to the west towards a low, westward facing Chalk bluff. This bluff forms the margin of both the area under study and the gently undulating heath and forest landscape characteristic of the Breckland.

Compared to the Elmdon area there are a number of important distinguishing features identified in borehole logs.

- The Glaciofluvial Deposits can be divided into two distinct groups occurring above and below the Lowestoft Till.
- Both the upper and lower deposit are sporadic in occurrence and no discrete sheet like bodies have been identified in this area. To the south, however, the lower group is consistently found at depth.
- The area is covered by a variable thickness of Cover Sand, usually less than one metre thick, it is often intimately mixed with Glaciofluvial Deposits as a result of cryoturbation and pedogenic processes.

The Upper Chalk is exposed locally in a small borrow pits which show white to off-white and well jointed Chalk. The Chalk outcrops to the west of the study area, and is brought to the surface in places by ploughing.

Patches of glacial sand and gravel occur across the study area. The grading of the deposit as a whole is variable ranging from sand to sandy gravel, and from relatively silt free and clay grade material to `very clayey' (20 to 40% fines).

The till within the area is of typical Lowestoft Till aspect. When fresh it is a dark grey, clast rich, silty, over consolidated clay weathering to a yellowish brown mottled clay. For the most part it is concealed beneath a thin blanket of Cover Sand. The thickness of the till as shown by boreholes is variable. While it is commonly about 10 to 15 metres thick over much of the study area a thickness of 35 metres of till resting directly on Chalk has been proved.

The Cover Sand blankets much of the area. In section it is seen to be a mixture between aeolian fine silty sand (true Cover Sand) and a pebbly clayey sand (probably remnant glacial sand and gravel). No unequivocal cryoturbation structures were identified during the survey and the exact mechanism for the mixing of the two deposits is uncertain. It is probably the result of repeated freeze and thaw during several periglacial events since the Anglian, and from pedological processes.

To gain a better understanding of the distribution of the Cover Sand and its three dimensional geometry remote sensing (O'Connor, 1994)) and geophysical techniques were employed at the Hall Farm site. Detailed dipole-dipole apparent resistivity data clearly identified the resistive sand overlying the conductive till, (Busby *et al.*, 1995). Interpretation of the data indicates a northerly trending sand channel with maximum depths of up to two metres. A number of thickenings and shallowing are recognised, Figure 2.1.

The borehole log for the Hall Farm site, Table 2.1, demonstrates the presence of the Cover Sand and a tripartite division of the till. An upper and lower weathered section is clearly identified based on colour alone with a darker grey brown unweathered middle part. A similar feature is seen in the Uphall Farm log, Table 2.2, although the sequence is not as thick. The cores also demonstrate that the weathered tills have well developed fractures, often picked out by the presence of reddish ferruginous coatings compared to the unweathered tills.

Table 2.1 Lithological description of the Hall Farm Borehole

Fine, dark, yellowish brown (10YR 4/6), Light brown (10YR 6/2) aeolian SAND, with pebbles and some rootlets.	**Cover Sand**	0 - 2.3
Mottled light grey (10YR 7/1) and brownish yellow (10YR 6/6), silty CLAY with sub rounded, fine to medium gravel sized chalk with some flint, pebble sized chalk, with Sherwood Sandstone, Jurassic limestone and weathered mud rock clasts	**Weathered Till (oxidised)**	2.3 - 7.6
Firm, dark grey (10YR 4/1) or dark brown or brown (10YR 4/3) silty CLAY, with many small gravel sized chalk and some pebble sized chalk. Some ironstone, red chalk, Kimmeridge Clay and coal inclusions. Sub-vertical and sub-horizontal, iron stained fissures	**Unweathered Till (unoxidised)**	7.6 - 14.35
Soft to firm, pale yellow (2.5YR 7/4), light olive brown (2.5YR 5/4) with many sand sized and gravel sized chalk and a pebble sized flint. Possibly gravel at base.	**Weathered Till (oxidised)**	14.35 - 20.29
Chalk	**Chalk**	at 20.29

Table 2.2 Lithological description of the Uphall Farm Borehole

[redacted]	[redacted]	[redacted]
Firm, orange brown to very pale brown (10YR 7/4) sand with some gravel sized flint	**Cover Sand**	0 - 1.4
Mottled olive grey (5Y 4/2) and olive grey (2.5Y 4/4), silty CLAY,sandy in part and gravel and cobble sized chalk with some flint and chalk. Iron stained fissures.	**Weathered Till (oxidised)**	1.4 - 3.5
Firm, dark grey (5Y 4/1) or dark brown or brown (10YR 4/3) silty CLAY, with sand and gravel sized chalk. Sub-vertical and sub-horizontal, iron stained fissures. Shale clasts and mudstone clasts	**Unweathered Till (unoxidised)**	3.5 - 5.35
Mottled silty clay (7.5YR 5/6 to 10YR 5/6), with some layering passing down into olive yellow (2.5YR 6/4) silty CLAY. Iron stained fissures throughout.	**Weathered Till (oxidised)**	5.35 - 7.75
Chalk	**Chalk**	at 7.75

2.1.2 Elmdon Area

The study area is situated in Essex six kilometres west-south-west of Saffron Walden, close to the county boundaries with Hertfordshire to the west and Cambridgeshire to the northwest. The pilot study area covered two square kilometres of a small ridge founded on Lowestoft Till between the B 1039, which follows a minor stream valley, and the headwaters of Wicken Water. Both of these southeastward flowing streams cut down through the till into the Chalk bedrock before their confluence with the River Cam to the east.

The geology of the area illustrates a simple picture of a dissected till plateau underlain by the Upper Chalk (which outcrops on the flanks of the ridge), with deposits of Head in the valley bottoms.

In the district the Upper Chalk is generally described as a soft, white, well jointed chalk with seams of nodular flint. Augering demonstrated that the Chalk at outcrop gives rise to a thin, loamy, calcareous soil, often as little as 20 cm thick, resting on rubbly Chalk. The eroded surface of the Upper Chalk appears to be planar with the possible exception of pre-Anglian solution pipes incorporating Palaeogene deposits or Clay-with-flints; such pipes are usually of limited lateral extent.

The till of the Elmdon area is typical of the Lowestoft Till throughout East Anglia and when fresh is composed of a dark grey, clast rich, silty, over consolidated clay. The clasts are mainly of chalk and flint with some quartz, quartzite and minor amounts of sandstone, black `paper' shale, igneous, metamorphic and limestone rock types together with septarian nodules, and Jurassic and Cretaceous fossil debris. The till weathers to a yellowish brown silty clay with durable rock fragments.

Two minor variants of this general lithology were noted during the initial field survey. First, a highly chalk-rich till found mainly on the southwest side of the ridge overlooking Little Becketts {TL 473 356}. In auger holes this variant proved to be a very pale grey, very hard, exceptionally chalky, silty clay with few other clasts. It gives rise to a highly calcareous, silty, pale greyish brown, loamy soil very similar to that generated on the Chalk outcrop. Its origin is unknown but is thought to be the result of the incorporation of large amounts of chalk into the basal shear zone of the ice sheet.

The second variant, encountered at (or near) the base of the till sequence, was composed of dark reddish brown and orange brown stiff waxy clays and silty clays, finely sandy in part, with fresh nodular flints. Several minor occurrences were noted along the margin of the till overlooking New Farm {TL 481 371}. The basal part of this variant, as seen in auger holes, was often streaked or speckled black as a result of manganese/iron staining. This deposit is thought to be remnant Palaeogene or Clay-with-flints either incorporated into the base of the till sequence or preserved in solution pipes within the Upper Chalk. Head is mapped in both valleys bounding the survey area. These deposits represent a mixed lithology generated by solifluction and hill wash processes from local sources. They are generally dark brown, non-calcareous, structureless, silty, sandy clays with some stones, but where they are directly derived from the Chalk they can contain some chalk pebbles.

Table 2.3 is a summary lithological description of the Hobs Aerie borehole. Once again the tripartite division of till based on weathering and hence colour changes may be made. Two features set this sequence apart from the Norfolk sections:

- The presence of the soft almost unconsolidated layer between 10.5 and 14 metres depth which is believed to be the contact between two separate till sheets, and
- The presence of the clearly defined cryoturbated layer at the base of the till. This layer is believed to have formed in a basal shear layer during glaciation.

Table 2.3 Lithological Description of the Hobs Aerie Borehole.

Top soil	**Cover Sand**	0 - 0.25
Mottled light grey (10YR 5/6 to 10YR 6/4) and light yellowish brown (10YR 6/4), silty CLAY with sub rounded, fine to medium gravel and cobble sized chalk with some flint. Fissured throughout.	**Weathered Till (oxidised)**	0.25 - 4.77
Firm, dark grey (10YR 4/1) or dark brown or brown (10YR 4/3) silty CLAY, with Fe stained chalk. Sub-vertical and sub-horizontal, iron stained fissures less evident below 6.30m	**Unweathered Till (unoxidised)**	4.77 - 10.54
Very wet to soft unconsolidated silty CLAY becoming spongy at (2.5YR 6/1) 12.75m and then becoming firm and pale grey (2.5YR 6/1)	**Unweathered Till (unoxidised)**	10.54 - 14.0
Light olive brown (2.5YR 5/3-5/4) fissured chalky till with fragments of chalk and black shale. Yellowish brown fissure coatings	**Weathered Till (Oxidised)**	14.0 - 19.0
Cryoturbated, mottled clayey silt (10YR 6/3) becoming yellowish brown towards the base	**Weathered Till (Oxidised)**	19.0 - 22.03
Chalk		at 22.03

3. ROCK PROPERTIES

Material was preserved from the cored boreholes for detailed laboratory investigation. The programme was directed at defining the physical characteristics of the till in terms of density, hydraulic conductivity and porosity which are parameters required for any future contaminant transport modelling, and a detailed characterisation in terms of mineralogy, particle size distribution (psd), and cation exchange capacity. The results of these studies are reported in detail by Entwisle, (1994) and Inglethorpe and Bloodworth, (1994). Field hydraulic properties at Hall Farm and Hobs Aerie were determined in order to compare the results of the field and laboratory testing methods. This work is reported in detail by Klinck and Wealthall, (1995).

3.1 Garboldisham (Hall Farm and Uphall Farm Boreholes)

3.1.1 Particle size analysis

Average matrix values of the samples are 26% sand, 41% silt and 33% clay (sandy clayey silt). Clast content (gravel/cobbles) is generally low (average 9.0%). Average mean and median values also fall within the silt-size range. Standard deviation (SD) values indicate that samples are generally classed as 'very poorly sorted' and occasionally as 'extremely poorly-sorted'. Particle-size distributions are typically 'coarse-skewed', indicating enrichment in coarse particles, relative to the ideal normal distribution.

An upwards-fining sequence is apparent in the Hall Farm borehole between 13.0 and 3.6 m where mean particle-size values decrease from 10.9 µm to 2.3 µm and median values decline from 8.0 µm to 2.6 µm (Figure 3.1). The upper part of the borehole appears significantly better sorted than the lower section. The upwards-fining interval is also characterised by a marked decrease in the proportion of fine-medium sand (425-212 µm fraction) and fine-sand (212-63 µm fraction), with a corresponding increase in the percentage of both fine-silt (10-2 µm fraction) and clay (<2 µm fraction).

Hall Farm borehole samples are typically more poorly-sorted than those from Uphall Farm (and Hobs Aerie), especially in the lower section of the borehole. Average sand content is also appreciably higher.

In comparison to Hall Farm (and Hobs Aerie), the Uphall Farm sequence is significantly better sorted and particle-size distributions are more strongly coarse-skewed (Figure 3.2). Average clay (<2 μm) content is also higher than for the other two sites.

Average sand/silt/clay content classifies the Uphall Farm sequence as a sandy clayey silt. Clast content (gravel/cobbles) is typically only minor (6.2% av.). Average median and mean values confirm their silty nature. Only limited observations can be made concerning downhole trends due to the small number of samples collected. However, it is possible to divide the sequence into a sandy lower section, a clayey middle section and a silty upper section.

3.1.2 Physico-chemical properties

Down hole profiles of surface area and cation exchange capacity (CEC) show a close positive relationship with clay (<2 μm) content (Figure 3.3). In particular, high surface area values in the Hall Farm sequence correspond to high values for clay content at 6.3m and 8.0m. At Uphall Farm, the highest physico-chemical values obtained correspond with the more clay-rich middle section of the sequence.

3.1.3 Quartz and calcite content

Variations in quartz and calcite content of the fine matrix with depth for the Garboldisham sequences are plotted on Figure 3.4. The combined quartz and calcite content of the majority of samples from the Hall Farm sequence is relatively constant. Clear downhole trends in bulk mineralogy data coincide with the upwards-fining trend in the Hall Farm sequence. Quartz content decreases from 66% to 28% between 12.3 m and 3.7 m, correlating with the decline in the proportion of fine-medium sand and fine-sand. Conversely, calcite content increases from 20% to 50% over an identical depth interval, correlating with an increase in percentage fine-silt and the clay content.

Fine matrix quartz and calcite content also show an antipathetic relationship in the Uphall Farm sequence. Calcite content is highest in both the silty upper section and the sandy lower section, with quartz content being highest in the clayey middle section. An association between calcite and sand content at Uphall Farm suggests that an significant part of the sand fraction consists of chalk. This contrasts with the association between quartz and sand content observed at Hall Farm.

3.1.4 <2 μm mineralogy

The clay mineral assemblage in the Garboldisham sequences shows very little downhole variation. The assemblage is dominated by kaolinite, with major amounts of illite and smectite. Calcite forms a significant proportion of the <2 μm fraction at these locations. As might be expected, the pattern is similar to that shown by calcite in the whole-rock (Figure 3.4).

3.1.5 Clast lithology

Gravel and coarse sand fractions in the upper seven metres of the Hall Farm sequence are dominated by chalk with subordinate altered iron-rich sandstone. In contrast, the chalk clast content in the deeper part of the sequence (8.00-13.8 m) is lower. This horizon is also marked by the presence of shale and pyrite clasts. The surficial horizon (0.7 m) consists of altered iron-rich sandstone and flint. The clast fraction at 13.7 m is flint-rich. The Hall Farm sequence is typified by the association of bedrock-derived chalk and flint in the gravel fraction and the association of quartz with the coarse sand and coarse-medium sand fractions.

Chalk and flint clasts are present throughout the Uphall Farm sequence. Erratic clasts (particularly shale) are most common in the middle part of the sequence, whilst altered iron-rich sandstone is present without shale in the deeper part of the sequence. The presence of pyrite is restricted to a layer at four metres.

3.1.6 Moisture content, porosity and density

Hall Farm moisture content results and depth profiles are shown in Figure 3.5, most of the samples came from depths between 2.4 m to 21.0m. There is an indication of increasing moisture content with depth for the top half metre of the tested section. The lower moisture contents of the upper samples may be due to the close vicinity of the cover sand above and seasonal drying. Below this contact zone there is a reduction of moisture content from about 19% to 12.3% into the unoxidised tills which coincides with increasing stiffness and less weathering. This is also indicated by the colour changing from mainly yellow brown and greyish brown to dark grey brown. Higher moisture content samples from 14.5 m and below are associated with a change to pale brown, buff material which is again oxidised. A range of porosities were encountered ranging from 0.253 for the stiffer unweathered tills to around 0.3 for the oxidised tills.

The density data reflect, to some extent, the change from soft or firm to firm or stiff samples. Most of the samples had similar bulk density of between 2.063 Mg/m^3 to 2.270 Mg/m^3 with an average of 2.143 Mg/m^3 and a dry density of between 1.746 Mg/m^3 to 1.87 Mg/m^3 with an average of 1.843 Mg/m^3.

At Uphall Farm the uppermost sandy loam had a moisture content of 15.4% dropping to 11.9% in the firm sand below. Below this, most of the samples were clay or clayey. The moisture content of the clay varied between 17.1% and 22.5%. Porosity was in the range determined for the Hall Farm site with unweathered tills having a lower value than weathered tills (0.22 compared to 0.31).

The bulk density ranged from 1.976 Mg/m^3 to 2.045 Mg/m^3 and the dry densities varied from 1.624 Mg/m^3 to 1.802 Mg/m^3 reflecting the changes in moisture content.

3.1.7 Laboratory hydraulic conductivity

The tests included a standard one dimensional consolidation test carried out in an oedometer. This test is used regularly in civil engineering for foundation design and is also used as an indirect method of calculating hydraulic conductivity. A direct method of hydraulic conductivity testing, the consolidated constant flow test, was also carried out.

The oedometer hydraulic conductivity for most samples from the Hall Farm borehole varied between about 3.9×10^{-10} m/s and 3×10^{-9} m/s at low stresses (less than 100 kPa) to between 3.3×10^{-11} m/s to 8×10^{-11} m/s at the maximum stress, 1832 kPa. At low stresses the difference between the lowest and the highest value was about one order of magnitude whereas at higher stresses it was about half an order of magnitude. There was a trend of decreasing hydraulic conductivity with increasing stress.

The result of four oedometer tests results on the Uphall Farm borehole samples varied between 2.1×10^{-10} m/s and 3.9×10^{-9} m/s at low stresses to about 8.5×10^{-12} m/s to 1.9×10^{-10} m/s at 1832 kPa.

The triaxial consolidation results from the Hall Farm samples gave results ranging from 1.7×10^{-10} m/s to 7.2×10^{-10} m/s at 70 kPa and 6.3×10^{-11} m/s to 9.1×10^{-10} m/s at 200 kPa. The constant rate test results varied between 8.0×10^{-11} m/s to 3.8×10^{-10} m/s at the lowest mean effective stress and 2.9 x 10^{-11} m/s to 1.3 x 10^{-10} m/s at the highest mean effective stress. The results of the testing have been recalculated to *in situ* stress and are summarised in Table 3.1.

Table 3.1 Laboratory determined *in situ* hydraulic conductivity (Hall Farm)

3.74 (O)	4.0 x 10^{-10}
3.80(T)	7.5 x 10^{-11}
5.37(T)	2.1 x 10^{-10}
5.82 (O)	1.2 x 10^{-9}
6.82 (O)	1.0 x1 0^{-9}
7.00(T)	1.9 x 10^{-10}
8.05 (O)	6.0 x 10^{-10}
8.22(T)	1.2 x 10^{-10}
9.55(T)	1.2 x 10^{-10}
9.73 (O)	8.3 x 10^{-10}
12.61 (O)	7.2 x 10^{-10}
12.8(T)	7.0 x 10^{-11}

3.1.8 Field hydraulic testing results

Field hydraulic conductivity tests were conducted in standpipe piezometers and a specially constructed 50mm multi screen completion using the standard falling head test and pulse tests. The results for the Hall Farm site are tabulated in Table 3.2. Unlike Hobs Aerie (see below) there is no well defined trend with depth. Rather the pattern which emerges is one of higher hydraulic conductivity in the oxidised tills and lower hydraulic conductivity in the unoxidised tills. Values for the oxidised tills range over two orders of magnitude from approximately 1x10^{-6} to 1x10^{-8}m/s. For the unoxidised till the range is from 1x10^{-8} to 1x10^{-11}m/s. The Hall Farm unoxidised till values correspond to the range of Lloyd, (1983) for matrix rich, unweathered tills; the values for the oxidised tills quoted above span Lloyd's *op. cit.* fractured and weathered categories.

Two values of hydraulic conductivity were determined for the cover sand busing an infiltrometer. A value of 1.31×10^{-6}m/s was determined at the surface and 2.46×10^{-5} m/s at a depth of 0.45m which, in terms of range, are consistent with the slug test results GFH/3 and GFH/2 in Table 3.1. A constant flow triaxial test on the core material gave results in the range 2 to 3×10^{-6} m/s.

Table 3.2 Results of Field Hydraulic Testing at Hall Farm

HF1U	Standpipe	**16.1**	6.77E-8(s)
HF1L	Standpipe	**20.62**	1.22E-06(s)
HF2-1	Multiscreen	**2.61**	6.37E-09(p)
HF2-2	Multiscreen	**4.1**	6.21E-09(p)
HF2-3	Multiscreen	**5.57**	4.47E-07(s)
HF2-4	Multiscreen	**7.04**	3.37E-07(s)
HF2-5	Multiscreen	**8.49**	8.25E-11(p)
HF2-6	Multiscreen	**9.99**	2.19E-09(p)
HF2-7	Multiscreen	**11.43**	1.17E-11(p)
HF2-8	Multiscreen	**12.92**	9.29E-09(p)
HF3U	Standpipe	**12.7**	8.03E-08(p)
HF3L	Standpipe	**14.3**	1.45E-08(p)
GFT/5	Standpipe	**2.01**	3.48E-5(s)
GFH/4	Standpipe	**2.35**	2.71E-6(p)
GFH/3	Standpipe	**4.26**	1.73E-7(p)
GFH/2	Standpipe	**6.19**	3.79E-8(p)

Notes: (s) refers to slug test result and (p) refers to pulse test result

The depth refers to the mid-point of the response zone

3.2 Hobs Aerie borehole

3.2.1 Particle size analysis

In comparison to the Garboldisham sequences, the Hobs Aerie borehole samples are more fine-grained with low average median and mean values. The matrix tends to be less sandy and more silty than the other sites. Average values classify this sequence as a sandy clayey silt with a low (10%) clast content. Average mean and median values are within the silt-size range. Samples can almost exclusively be described as 'very poorly-sorted' on the basis of average standard deviation values. Particle-size distributions are generally 'near symmetrical' in the lower section, but tend towards 'coarse skewed' in the upper section indicating an enrichment in coarse particles.

The most significant pattern in particle-size values for Hobs Aerie is an upwards coarsening trend (from 18.1 to 6.5 m) which is characterised by an increase in the medium-fine and fine sand fractions at the expense of both coarse-silt and fine-silt fractions (Figure 3.6). The trend leads to the development of a distinct sandy horizon at 6.5 m. Upwards coarsening is confirmed by the upwards drift of median and mean indicators between 18.1 and 6.5 m; the sequence also tends to become increasingly poorly-sorted from base to top. Clay (<2 μm) fraction values are relatively uniform throughout the sequence.

3.2.2 Physico-chemical properties

Downhole profiles from Hobs Aerie showing variation in specific surface area and CEC are similar and, as in the case of the Garboldisham sequences, appear to broadly reflect changes in clay content.

3.2.3 Quartz and calcite content

On the basis of the calcite content of the fine matrix, the sequence at Hobs Aerie can be divided into two distinct sections with a discontinuity at 10.5 - 13.5 m (Figure 3.7). The lower part of the sequence (13.5 -18.1 m) is relatively fine-grained and is characterised by a high calcite content (58-80%) whereas the upper part is more coarse-grained (0.7-10.5 m) and is typified by appreciably lower levels of calcite (28-49%). The association between mineralogy and particle size observed in the Hall Farm sequence also applies at Hobs Aerie. An example of this relationship is the sandy horizon at 6.5 m which is characterised by high quartz and low calcite content.

3.2.4 <2 μm mineralogy

The relative proportions of clay mineral species present in the <2 μm fraction from the Hobs Aerie borehole show very little variation. The clay assemblage is almost identical to that at Garboldisham; kaolinite predominates, with major illite and smectite. Calcite forms a significant component of the <2 μm fraction of the Hobs Aerie sequence. In contrast to the clay mineral assemblage, relative proportions of calcite in the <2 μm fraction shows considerable variation. The very high whole-rock calcite content of the till in the lower part of the Hobs Aerie borehole is reflected in calcite contents in the <2 μm fraction of around 50%, which contrast strongly with values of around 20% <2 μm calcite in the upper part of the sequence.

3.2.5 Clast lithology

In contrast to Hall Farm, both shale and sandstone clasts are present throughout the sequence at Hobs Aerie. Erratics are particularly concentrated in the interval between 9.3 and 10.5 m. Pyrite is commonly present below a depth of 4.8 m. A predominantly flinty clast lithology was observed at 16.7 m. Iron-stained chalk clasts were also identified at 4.8 m.

3.2.6 Petrography

Petrographic analysis was carried out on two polished thin-sections cut from an undisturbed monolith sample of fissured till collected at a depth of six metres from a trench dug at Hobs Aerie. The aims of the petrographic analysis was to examine the nature of fissuring (previously observed in the pit and core material) on the microscopic scale, and also to examine the general microfabric of the till and relate this information to observations made elsewhere in this report regarding the physical properties and mineralogy of the till sequences at Elmdon and Garboldisham.

Till microfabric was examined by reflected light microscopy, backscattered electron imaging (BSEM) and element mapping by electron micro probe analysis (EMPA). Well-rounded fossiliferous chalk clasts are common, together with smaller, angular flint clasts. Clasts of other lithologies such as sandstones and siltstones are also present, along with relatively large fragments of derived fossil material, though these components are much less common than chalk and flint. The clasts are set in a chaotic matrix composed of sand-, silt- and clay-grade calcite, quartz and clay minerals, together with abundant fossil material which appears to be derived from the chalk clasts. The high levels of calcite in the matrix are revealed by the EMPA element maps showing Ca- and

Si-distribution and concentration (Figure 3.8). These data support evidence from XRD analysis indicating abundant calcite in the <2 μm fraction.

Micro-scale fissuring is evident and using conventional optical microscopy, natural fissures can be distinguished from those induced during section manufacture by their iron oxide coating which is visible when viewed with crossed polars (Figure 3.9). Unfortunately, this method of identifying fissures is only effective at relatively high magnification where the field of view is extremely restricted. BSEM images give very high-quality textural and mineralogical information over a wide field of view. Fissure systems are readily visible using this imaging technique and some can be seen cutting through chalk clasts.

The most effective method of viewing micro-scale fissuring over a relatively wide field of view was found to be mapping iron distribution and concentration using EMPA. An area approximately one square centimetre was mapped (Figure 3.10). A low-sinuosity fissure system can clearly be seen linking and extending beyond two chalk clasts in the plane of the section. Iron oxide appears to concentrate at the clast/matrix contact in those clasts linked by fissures. Other fissures are highly-sinuous and show clear gradients in iron concentration which decrease from the walls of the fissures out into the matrix.

3.2.7 Moisture content, porosity and density

The moisture content ranged between 16% to 23.8%, the softer clays found towards the base of the sequence tending to have the higher moisture contents. The higher moisture contents were also reflected in a higher porosity of between 0.342 and 0.356. The upper weathered tills had porosities within the range of the Hall farm site of 0.316.

The bulk density is fairly constant to about 7.3 m with an average value of 2.046 Mg/m^3. The higher moisture content, soft or soft to firm samples of the lower part of the borehole have lower densities of about 1.93 Mg/m^3.

3.2.8 Laboratory Hydraulic Conductivity

The oedometer results from Hobs Aerie varied between 3.6 x 10^{-8} m/s and 1.4 x 10^{-10} m/s at low stresses to between 2.8 x 10^{-10} m/s and 2.0 x 10^{-11} m/s at the maximum stress. The lowest values of hydraulic conductivity coincide with the softer clays while the higher values are associated with the weathered tills.

The oedometer data shows that the till from Hobs Aerie tends to have higher hydraulic conductivity than Hall Farm and Uphall Farm.

The hydraulic conductivity determined by the triaxial consolidation tests varied between 5.8 x 10^{-11} m/s and 8.4 x 10^{-9} m/s at 70 kPa and 5.6 x 10^{-11} m/s and 3.2 x 10^{-9} m/s at 200 kPa. The constant flow rate tests gave results from 1.6 x 10^{-10} m/s and 3.8 x 10^{-9} m/s at the lowest mean effective stress and 8.6 x 10^{-10} m/s to 2.7 x 10^{-11} m/s at the highest mean effective stress. The results of the testing, recalculated to *in situ* stress are shown in Table 3.3.

Table 3.3 Laboratory determined *in situ* hydraulic conductivity (Hobs Aerie)

3.09	2.0 x 10^{-8} (O)
3.09	3.0 x 10^{-9} (T)
4.82	4.4 x 10^{-9} (O)
6.16	1.5 x 10^{-8} (O)
7.02	4.5 x 10^{-9} (O)
7.33	7.0 x 10^{-10} (T)
9.61	4.2 x 10^{-11} (T)
9.82	1.3 x 10^{-9} (O)
12.14	9.0 x 10^{-10} (O)
12.5	4.5 x10^{-10} (T)
13.22	1.0 x 10^{-9} (O)
16.21	1.5 x10^{-9} (O)
18.33	1.0 x 10^{-10} (O)
18.38	3.0x10^{-11} (T)

(T) Triaxial test, (O) Oedometer test

3.2.9 Field hydraulic conductivity

A total of twelve completions were installed at Hobs Aerie, one of which was a multiscreen device. The deepest piezometer was installed in the chalk and could not be tested because of unsaturated conditions. Similarly the upper two screens of the multi screen device were also unsaturated. The results of the hydraulic testing are tabulated below, Table 3.4. The table shows that piezometers HA7 to HA10 were installed to approximately the same depth, but with different types of c ompletions. HA7 is a driven piezometer whereas the remaining completions had different diameters and screen lengths. The driven piezometer gave a lower value of hydraulic conductivity than the piezometers completed with gravel packs, and this is attributed to smearing of the clay during emplacement. Figure 3.11 is a plot of hydraulic conductivity against surface area of the response zone. Although the data set is not comprehensive there appears to be a trend of increasing hydraulic conductivity with surface area which is attributed to an increasing number of fractures per unit of surface area exposed to the test zone.

Figure 3.12 indicates that there is a general trend of decreasing hydraulic conductivity with depth and overall a range in the hydraulic conductivity of over three orders of magnitude. There are no clear relationships between weathering and hydraulic conductivity or depth and hydraulic conductivity. The upper till sequence tends to have higher hydraulic conductivity than the lower till sequence with a quite well defined inflection at the level of the unconsolidated zone.

3.3 Discussion

The Garboldisham and Elmdon sequences are poorly-sorted and matrix-dominant throughout, both properties typical of lowland lodgement tills. Matrix content is generally >84%,and clast content is <16%. On ternary sand/silt/clay diagrams (Figures) samples from all three sites plot within the lodgement till envelope proposed by Sladen and Wrigley, (1983). In terms of lithology, both bedrock-derived and reworked sediment are present. Generally, gravel/cobble fractions consist of bedrock-derived chalk and flint clasts. Bedrock-derived chalk is also present as fine-silt and clay-grade rock flour within the matrix. This is consistent with the results of Perrin *et al.*, (1973) who noted chalk coccoliths and coccolith debris of 6-7 μm size. Typically, reworked quartz dominates the sand fraction. Clay minerals derived from chalk bedrock and reworked sediment are concentrated within the <2 μm fraction.

Table 3.4 Hydraulic conductivity values determined at the Hob's Aerie Site

HA3	Standpipe	9.69	6.62E-09(s)
HA4U	Standpipe	14.89	5.55E-09(s)
HA4L	Standpipe	17.73	4.65E-09(s)
HA5U	Standpipe	13.22	1.80E-08(s)
HA5L	Standpipe	16.14	6.33E-08(s)
HA6U	Standpipe	10.78	1.93E-08(s)
HA6L	Standpipe	12.18	7.64E-09(s)
HA7	Drive-in	9.64	2.13E-08(p)
HA8	Standpipe	9.68	1.07E-08(s)
HA9	Standpipe	9.57	5.76E-07(p)
HA9	Standpipe	9.57	1.24E-08(s)
HA10	Standpipe	9.37	1.76E-07(s)
HA11-3	Multi screen	4.78	3.31E-09(p)
HA11-4	Multi screen	6.25	1.61E-07(p)
HA11-5	Multi screen	7.7	1.02E-07(s)
HA11-6	Multi screen	9.32	5.20E-07(s)

Notes: (s) refers to slug test result and (p) refers to pulse test result
The depth refers to the mid-point of the response zone

The sequence at Hall Farm is weathered to a depth of 8.5 m which might be expected to cause significant leaching of the fine-silt and clay-grade chalk, especially towards the top of the sequence. Instead, calcite content gives a reverse trend showing an increase from the base to the top of the borehole. The high levels of calcite in the fine-textured upper section (1.7-6.4m) cannot be attributed to re-precipitated carbonate as there is no obvious zone of leached till above this and the uppermost section (0.7-1.7m) consists of the cover sand which is low in carbonate. These observations indicate that weathering is unlikely to be responsible for the major changes in particle-size and carbonate mineralogy within the sequence. It is likely that oxidation and not decalcification is the principal weathering process operating. In this respect, the presence of pyrite clasts below 8.0 m may be a good indicator of the limit of the weathering front.

The upwards fining observed at Hall Farm has been noted within a single till unit elsewhere in the Lowestoft Formation. The Stortford Till member, a unit of the Lowestoft Formation in west Essex and Hertfordshire, is 12 m thick at its stratotype and exhibits progressive vertical changes very similar to those noted at Hall Farm. Sand content decreases upwards from 18.0 to 9.2% and, conversely, carbonate content (of+1 to -2.5 phi fraction) increases upwards from 43.5 to 90.5% Allen *et al.*, (1991). An interpretation of this upwards-fining was not provided, but it may relate to the process of rockhead 'sealing'.

The data are consistent with the stratigraphy for the Lowestoft Till Group proposed by Whiteman (1987) and utilised by Hopson and Morigi, (1993). On this basis, the Hall Farm sequence is composed of Unit C (9.7-13.8 m) overlain by Unit D (1.7-6.4 m). Whiteman, (1987) indicated that a gradational boundary between Unit C and Unit D (6.4-9.7 m) is common. The higher chalk content and the absence of shale clasts in Unit D suggests a different provenance for this unit rather than it being a weathered analogue of unit C.

Textural and stratigraphic relationships at Uphall Farm are broadly similar to the thicker sequence at Hall Farm. However, there are significant differences between the two sites. The contact between the upper and lower sections at Uphall Farm is abrupt (i.e. an upwards-fining trend is absent). Also, the downhole trends for carbonate and quartz content do not correspond. Iron-stained chalk clasts at 5.3 m suggest water movement, possibly within the underlying coarse-textured basal zone.

The kaolin/ illite/ smectite clay mineral assemblage present in the two sequences are similar to that observed elsewhere in the Lowestoft Till (Perrin *et al.*, 1973). This assemblage appears to reflect that found in the Chalk and older, more argillaceous formations outcropping further west. The Lower Chalk of eastern England contains a similar assemblage of kaolinite, illite and smectite

(Jeans, 1968). This clay assemblage together with quartz and minor amounts of other minerals may be present as 'insoluble residue' in concentrations of up to 30% in the Lower Chalk (Young, 1965). Kaolinite is generally absent from the Middle and Upper Chalk (Jeans, 1968), and the overall clay content of these formations is much reduced compared to the Lower Chalk (Young, 1965). Ice-movement from the west would entrain significant amounts of kaolinite-bearing Lower Chalk as well as argillaceous material from formations such as the Gault, Oxford and Kimmeridge Clays in east and central England. Progressive alteration of clay mineral assemblages as a result of weathering has been noted in tills from East Yorkshire (Madgett and Catt, 1978) and the mid-west of the United States (William, 1966). However, the lack of variation in the assemblage present in the till sequences at Garboldisham suggests that the influence of weathering processes on the clay minerals has been relatively modest.

The <2 µm fraction in the upper part of the Hall Farm sequence contains large amounts of calcite (30-65%). These data show that the 'clay' grade (<2 µm) fraction in much of this till sequence is dominated by rock flour (principally calcite, with minor quartz), rather than by clay minerals. The presence of large amounts of <2 µm calcite-dominated rock flour in this till reflects the major input of material from the chalk.

The abrupt discontinuity in bulk mineralogy within the Hobs Aerie sequence suggests that two distinct till units are present. The relatively low carbonate content of the coarser-textured upper section is unlikely to result from leaching during weathering. The presence of pyrite clasts at 4.8 m and below may indicate the position of the weathering - oxidation front.

The high carbonate content of the very fine textured lower section (58-80%) is unusual. Perrin *et al.* (1979) indicate that values of 35-40% for Lowestoft Till matrix are more typical of southern East Anglia. However, in central East Anglia, some distance to the north-east of the Hobs Aerie site, values of 53-70% carbonate are noted. The chalk-rich facies of the Lowestoft Till, the Marly Drift Formation, is thought to be confined mainly to the northern margins of East Anglia (Lunkka, 1994). Perrin *et al.* (1979) distinguished a fine-textured chalky facies within the Lowestoft Till, the Calcethorpe-Marly facies, but its geographical association is with the Chalk of Lincolnshire and north Norfolk.

The Hobs Aerie sequence is probably best interpreted using the scheme set out by Whiteman (1987). The very fine textured lower section (13.5-18.1 m) corresponds closely to the pale grey chalky basal till observed during the field survey. Hopson and Morigi (1993) suggested that this unit formed by the incorporation of large amounts of chalk bedrock within the basal shear zone of the icesheet. It probably corresponds to Whiteman's Unit A deformation till. The upper section at

Hobs Aerie (0.7-10.5 m) is interpreted as the definitive Unit C - lodgement till of Whiteman (1987) and the characteristic shale clasts are present throughout.

The lack of variability in the clay mineral assemblage observed at the Hall Farm and Uphall Farm sites is also evident at Hobs Aerie. This means that similar inferences can probably be drawn regarding the origin of the clay mineral assemblage and effects of weathering. Calcite-dominated rock flour again forms a significant component of the <2 μm fraction of samples taken from the Hob's Aerie sequence. In contrast to the clay mineral assemblage, the relative proportions of calcite and quartz in the <2 μm fraction show considerable variation which is related to the amount of these minerals in the whole-rock. The very high whole-rock calcite content of the till in the lower part of the Hobs Aerie borehole is reflected in calcite contents in the <2 μm fraction of around 50%, which contrasts with values of around 20% <2 μm calcite in the upper part of the sequence.

The limited petrographic observations carried out on one sample taken from the Hobs Aerie sequence confirm other field and laboratory evidence that this material is a typical matrix-supported lodgement till. Under the scheme for the description and environmental interpretation of glacigenic sequences devised by Eyles *et al.*, (1983), this material can be classed as a massive, matrix supported diamict. The microfabric of this sample clearly supports observations made from particle-size distribution data which indicate that the tills from both Hobs Aerie and Garboldisham sites are very or extremely poorly-sorted. Variations in clast shapes reflect the relative resistance of the different lithologies to frictional interparticulate contact in the basal debris-bearing zone of the glacier which deposited the lodgement till (Boulton and Paul, 1976).

The fissure morphology evident in the Hobs Aerie till is complex. Clasts appear to be critical in controlling fissure propagation, with gaps between larger clasts frequently bridged by fissures. Chalk clast/matrix contacts are clearly a common pathway for fluid movement in this material. The highly-sinuous fissures appear to be independent of the clasts, although this may be because they mostly lay outside the plane of the section examined.

The results of the laboratory hydraulic testing show that the oedometer values and the triaxial values are usually within an order of magnitude of each other. Hydraulic conductivity trends can be inferred from the oedometer test and this method used as a sample selection aid for subsequent triaxial tests. The *in situ* hydraulic conductivity can be estimated for the three test methods employed given that the increase in effective stress is about 10 kPa/m. The results are plotted for Hall Farm and Hobs Aerie in Figure 3.14 and 3.15. There appears to be no pattern of laboratory determined hydraulic conductivity with depth. The field hydraulic conductivity is given for comparison and the difference in the results is attributed to absence of fracturing in the laboratory sized samples. Furthermore the reduction in the field hydraulic conductivity in the Hall Farm samples is seen to correspond very closely with the position of the unweathered till in the sequence. This range of two orders of magnitude difference between field and laboratory values of hydraulic conductivity is attributed to a scale effect. The consensus is that laboratory sized samples taken for oedometers and triaxial cells are only sampling the till matrix, whereas piezometers, with their larger response zones, are sampling matrix and fractures. The implication of this interpretation in the case of Hall Farm is that the weathered till is more fractured than the unweathered till. There is no clear pattern of hydraulic conductivity for the Hobs Aerie site. The laboratory values tend to be higher than the Garboldisham samples and may reflect the incorporation of fractures into the samples.

4 HYDROCHEMISTRY

Major element and trace element chemistry was determined from pore waters extracted from sections of the core. Pore water extraction, using the squeezing method described by Ross *et al.*, (1989), was usually attempted on core corresponding to the depth of piezometer installation.

4.1 Hall Farm Pore Water Chemistry

The conditions at the Hall Farm site differ from the other two sites investigated in that the borehole array was drilled in a cultivated field and within a few metres of a manure pile used for fertilizer. The very high levels of nitrate, ammonium, TOC and chloride in the pore water, and in the cover sand, perched-water table are attributed to leachate infiltration from the manure pile. A partial leachate analysis is presented in Table 4.1 for a sample collected at the base of the manure pile.

The high values of TOC, NH_4, NO_3 and HCO_3 are to be expected from a manure leachate; the high chloride is also consistent with a manure source. Of interest are the heavy metal concentrations which are believed to be derived from animal feed supplements.

Pore water profiles with depth are presented in Figures 4.1 and 4.2. The nitrate concentration is highest in the cover sand and decreases in the oxidised till remaining more or less constant to the un-oxidised till contact where the concentration drops off almost to zero. The nitrate concentration then increases in the lower oxidised till returning to almost zero in the chalk. It is interesting that the chalk ground water concentration at this site is of the order of 60 mg/l. This would seem to indicate that there is little transfer of nitrate from the ground water into the chalk matrix. The sodium and chloride profile of Figure 4.2 shows a comparable trend to the nitrate, higher concentrations of the ions are found in the weathered till and decrease in the un-oxidised till. Although the sodium profile does not match the chloride profile exactly the trend is similar and the difference is possibly due to sodium ion exchange with clay minerals.

Table 4.1 Analysis of Manure Pile Leachate, Hall Farm

pH	**8.09**
K	**1804**
HCO_3	**5832**
Na	**152**
Cl	**574**
SO_4	**341**
TOC	**1450**
NH_4	**299**
NO_3	**1300**
Ba	**0.062**
Cu	**0.85**
Zn	**1.48**

The pore water profile for nitrate indicates that the oxidised tills have higher pore water concentrations compared to unoxidised tills. Taking into account the sodium and chloride profiles and the distribution of hydraulic conductivity in the section it is apparent that concentration drops off with decreasing hydraulic conductivity, Figure 4.3. The explanation for this is that the oxidised tills are more fractured than the unoxidised tills and hence present a higher surface area for matrix diffusion of the nitrate and chloride through fracture surfaces. The rise in concentration of the anthropogenic contaminants in the basal oxidised till may be explained by a similar mechanism, or alternatively by-pass flow of the unweathered till, via a permeable pathway, may be invoked. Clearly the unoxidised till is providing the aquifer protection in this instance.

Copper concentration is rapidly reduced to below detection limit within about three metres of the surface while zinc and barium behave erratically with no clear pattern emerging.

4.2 Uphall Farm Pore Water Chemistry

The Uphall Farm borehole was sited in a pasture within a small depression. No nearby source of anthropogenic contamination was recorded and the nitrate levels in the pore water were probably due to animal and rainfall input. Figure 4.4 is the nitrate pore water profile with depth and it is evident that the concentration is rapidly declining. Like the Hall Farm site the basal oxidised till has an elevated concentration of nitrate compared to the unoxidised till. It would appear that in the absence of a continuous nitrate source term the oxidised and weathered clay can protect the aquifer from nitrate contamination.

4.3 Hobs Aerie Pore Water Chemistry

This site was drilled in a pasture where, once again, the only input of nitrate probably derives from animals and rainfall. Figure 4.5 indicates that, like the Uphall Farm site, the nitrate concentration declines with depth with a clear cut-off corresponding to the top of the unconsolidated clay layer at about 10 metres.

According to Parker *et al.*, (1987) the nitrogen in grazed grassland systems is taken in by animals and mostly recycled as excreta. The local deposition of excreta is capable of causing an excess of nitrate beyond the capacity of the vegetation to absorb it and the balance can be leached into the till profile. Within the till profile denitrification is thought to be responsible for decreasing nitrate concentration with depth.

5 RECHARGE THROUGH THE TILL

The study of recharge and runoff and their influence on the threat to groundwater is on the agenda for groundwater research, Grey *et al.*, (1995). In East Anglia the chalk aquifer is covered by a variable sequence of glacial drift which includes not only sands and gravels, but also large expanses of till. While recognising that recharge through till needs to be quantified in order to be able to effectively manage groundwater resources, the pollution potential of this recharge is an issue which needs to be addressed too. A commonly held view of the till is that it is impermeable, inhibits recharge, and provides a measure of protection to the underlying aquifer. Hiscock, (1993) has used hydrochemical evidence to suggest that the boulder clay on interfluve regions inhibits direct recharge to the chalk, but cited the presence of tritium as evidence for a small component of recharge through more permeable material within the bulk of the till.

Early work by Ineson and Downing, (1965) using a water balance approach for the River Tas catchment in Norfolk arrived at an estimate of infiltration through the boulder clay of five inches per annum (127 mm/yr) for the period 1957-61, and an average of four inches per annum (102mm/yr). For the Stour catchment similar calculations suggested a recharge of 1.4 inches per annum (35 mm/yr) through the boulder clay. Jackson and Rushton, (1987) assessed the recharge component to the chalk through the boulder clay for the Gipping catchment to be at least 36 mm/yr (0.1 mm/d). Subsequent to numerical modelling of the catchment this estimate was reduced to 24 mm/yr which represented 71% of the total recharge for 1973 and 48% for 1982. Clearly recharge through the till is a significant proportion of the total recharge.

5.1 A conceptual model of groundwater flow for the Hall Farm site

Daily rainfall and potential evaporation data for East Harling, three kilometres north of Hall Farm, were obtained from the Meteorological Office Rainfall and Evaporation Calculation System (MORECS). Data for 1986 were chosen as this was considered to be an average rainfall year. The total rainfall was 613.3 mm and using an algorithm given by Lerner *et al.*, (1990) for the Penman-Grindley model of soil moisture budgeting a hydrologically effective rainfall (HER) of 200 mm was calculated. A root constant and wilting point of 25 mm, i.e. bare soil was assumed. The HER is the amount of rainfall that is available for recharge.

The conceptual model of the Hall Farm site may be summarised as follows and is based on information presented in the preceding sections:

- The cover sand supports a perched water table above the till which, due to point sources, such as manure piles, can maintain diffuse pollution plumes.
- The till sequence can be subdivided into three distinct units, an upper and lower weathered oxidised layer, and an intermediate unweathered, unoxidised layer.
- Fracture density is higher in the weathered tills compared to the unweathered tills.
- The matrix hydraulic conductivity of weathered and unweathered till is 1.1×10^{-10} m/s.
- The field hydraulic conductivity of weathered till can take a range of values from 4.47×10^{-7} to 6.37×10^{-9} m/s.
- The geometric mean, field hydraulic conductivity of unweathered till is taken to be 3.74×10^{-10} m/s with a range from 1.17×10^{-11} to 8.03×10^{-8} m/s.
- The vertical hydraulic conductivity of the cover sand is 2.46×10^{-5} m/s.
- Fracture flow is the dominant transport mechanism of anthropogenic pollutants and presumably also groundwater.
- The HER is 200 mm.

The features of the conceptual model are shown schematically in Figure 5.1.

5.2 Modelling Studies - Analytical

Klinck *et al.*, (1995) examined two mathematical models of the above conceptualisation. The first was an analytical solution of a drain - leakage model (Figure 5.2) which subdivided the sequence into three layers and made the following assumptions:

Layer 1 (Cover Sand)

A perched water table remains in this layer.

Lateral flow is negligible and there is negligible head loss during downward flow through the layer, i.e. the permeability is relatively high.

The storage is relatively high and characterized by a storage coefficient.

The layer is consider to recharge at a spatially uniform but temporally variable rate $R(t)$. It is be further assumed that the recharge is periodic with period θ; so $R(t+\theta)=R(t)$.

Layer 2 (weathered till)

Weathered layer which remains fully saturated and is bound by two parallel drains at distance $2L$ apart which are maintained at constant head H_D.

Horizontal flow to the drains characterized by transmissivity T. The transmissivity is calculated assuming that all of the Cover Sand and a fraction, f, of the oxidised till layer make a contribution:

(1)

$$T = b_{sand}K_{sand} + fb_{ox.till}K_{ox.till}$$

Storage is assumed negligible.

Layer 3

Low permeability unweathered layer incorporating a fraction of the weathered layer which remains saturated to its base and through which flow is essentially vertical and the basal weathered layer.

Vertical hydraulic conductivity K_v and thickness b. Storage is assumed negligible so the layer is hydraulically characterized by the single combined parameter K_v/b. The parameter combines a fraction $(1\text{-}f)$ of the oxidised till with the unoxidised till. It is calculated from the weighted harmonic mean:

(2)

$$\frac{K_v}{b} = \left(\frac{(1-f)b_{ox.till}}{K_{ox.till}} + \frac{b_{unox.till}}{K_{unox.till}} \right)^{-1}$$

Although it is tempting to make f equal to the fractional penetration of the drains into the oxidised till, a much larger value may be appropriate.

Layer 4

This is an unconfined chalk aquifer layer of much higher permeability than layer 3. Water seeping out of the saturated layer 3 percolates through the upper regions of layer 4 to a water table.

At the top of this layer there is a uniform pressure (atmospheric pressure) which, given the elevation of the layer interface, is equivalent to a fixed head H_A at the base of layer 3.

The reader is referred to Klinck *et al.*, (1995) for details of the derivation of the governing equations and their solution. The results of applying the model may be summarised as follows:

- The percentage of recharge was insensitive to a one order of magnitude change in the hydraulic conductivity of the oxidised till from $4.47\text{x}10^{-8}$ to $4.47\text{x}10^{-7}$ m/s. Recharge changed from 15.72% HER to 15.53% HER.
- Assuming a two metre thick cover sand then reasonable values of *f* where considered to be 0.1 and 0.2 which gave values of recharge of 15.09% and 14.65% respectively.
- The percentage of recharge was very sensitive to the hydraulic conductivity of the unoxidised till reducing by an order of magnitude for a corresponding order of magnitude decrease in hydraulic conductivity.
- In all of the above simulations overland flow did not occur. This is consistent with field information to the effect that surface water does not develop at this site during high rainfall events.
- Using reasonable parameter combinations recharge through the till is estimated to be between 29 mm/yr and 31 mm/yr at the Hall Farm site.

5.3 Modelling Studies - Numerical

The second approach to modelling adopted was numerical and the computer code FRACTRAN (Sudicky and McLaren, 1992) was implemented to take into account fracturing in the till. The model was based on the conceptual model previously described. In addition some input regarding fracture spacing and fracture aperture was required. The vertical fractures were assumed to be more closely spaced in the oxidised layers than in the unoxidised layer giving rise to a greater vertical hydraulic conductivity. Thus the oxidised layers are given fractures spaced at intervals of 0.3 m with apertures of 24 μm to give an average vertical conductivity of $3.8\text{x}10^{-8}$ m/s. This spacing is consistent with field observations. The spacing of fractures in the unoxidised layer is set at 11.5 m and their apertures are set to 17 μm to give an average vertical conductivity of 3.8×10^{-10} m/s. The sand layer is assumed to be a porous medium with a hydraulic conductivity of 2×10^{-5} m/s. The calculations were also performed with the apertures of fractures in the unoxidised layer increased to 24 μm. This raises the average vertical hydraulic conductivity of this layer to 10^{-9} m/s, and shows the sensitivity of the system to this parameter.

Groundwater head contours and logarithmically scaled flow vectors are shown in Figure 5.3. It is found that most of the rainfall runs off through the sand layer to the drain on the right hand boundary. The main head gradients are found in the unoxidised clay layer. Flows in the oxidised clay layers are found to be strongly focused on the sparse fractures in the unoxidised layer, especially in the case examined in which fractures in all three layers align.

Figure 5.4 shows the distribution of the recharge across the bottom boundary of the model. Integrating this profile and dividing by its length gives an average recharge rate to the aquifer of about 28 mm/yr or 14% of the incident recharge. However, the recharge is strongly concentrated within about 1m of the locations of the main fractures in the unoxidised clay. The central fracture on the section, which connects through all three clay layers, is found to be associated with about 35% of the total recharge, whilst the other two fractures in the unoxidised clay together contribute about 45%. The remaining 20% is uniformly distributed across the section. When the larger aperture fractures are used in the unoxidised layer the overall average recharge rate increases to about 38 mm/yr, nearly 20% of the incident recharge.

The influence of the degree of alignment between fractures in the oxidised and unoxidised layers on recharge was examined by performing additional calculations in which this was varied. These calculations were all performed using the smaller aperture fractures for the unoxidised layer, so that the rates of recharge to the aquifer should be compared to the value of 28 mm/yr previously determined. When all three fractures in the unoxidised layer are aligned with those in the oxidised layers the average recharge to the aquifer rises to about 35 mm/yr. When all three fractures are offset to fall mid-way between oxidised layer fractures (ie with the maximum possible mis-alignment) the average recharge to the aquifer falls to about 23 mm/yr. Finally, when fractures in the unoxidised layer are aligned with those in the upper oxidised layer but are all mis-aligned with those in the lower layer an average recharge rate to the aquifer of about 26 mm/yr is obtained.

6. CONCLUSIONS

This section is an attempt to summarise the influences of physical and mineralogical characteristics of the till sequences on their hydrogeological and geotechnical properties, and the likely effectiveness of tills as natural clay barriers to aquifer contamination.

Ideally, a clay barrier should consist of anisometric clay particles arranged in parallel, face-to-face contact to form a strongly-oriented platey fabric (Weiss, 1989). Pore size in such an aligned clay mineral fabric is small, being similar to the thickness of individual clay crystals. However, the fabric of tills is very different from that of an ideal clay barrier. Weiss (1989) states that isometric mineral particles such as quartz will disrupt the oriented clay mineral fabric creating a more open structure and larger voids with resulting increase in permeability. The review by Bath, (1993) of clays as hydraulic and chemical barriers classes till as a poorly-sorted and heterogeneous lithology in which advective transport processes predominate over diffusive flow.

The average quartz plus calcite content in the till sequences in this study is 79-87% and (by subtraction) average clay mineral content is 13-21% only. The proportion of isometric particles (quartz and calcite) therefore exceeds the proportion of anisometric particles (clay minerals), and the till matrix is mostly granular in texture. The till sequences described in this report are generally very poorly-sorted (the particle size distribution ranges over several orders of magnitude) and therefore will behave as predominantly granular, porous media. However, Paul and Little, (1991) indicate that lodgement tills are typically over consolidated with a high packing density. Subglacial sediments are subject to consolidation from the combined pressure of the overlying glacier and the pressure of melt-water beneath the ice sheet (Boulton and Paul, 1976). It is known that very poorly sorted systems pack efficiently if subject to consolidation, as smaller particles fill the interstices between larger particles and a densely-packed structure results. Petrographic observations on a sample from Hobs Aerie confirm the presence of such a densely-packed structure. On this basis, a simple mineralogical model of the matrix of the tills is proposed:

The matrix consists of three principal elements:

(1) sand-sized, isometric, non-deformable quartz particles;
(2) silt-sized, approximately isometric, non-competent chalk coccoliths and coccolith fragments;
(3) clay-sized, anisometric, plastically-deformable clay mineral particles and 'rock flour'.

The fabric is granular in nature due to the high proportion (>79%) of isometric non-clay minerals. As the lodgement till is typified both by very poor sorting and over consolidation, a densely-packed fabric is present. Clay mineral particles are plastic and deform during consolidation tending to 'wrap' around larger isometric particles and clay particle size rock flour in-fills the void space causing pore-throat blocking.

Porosity has been found to show very little variability between sites, oxidised tills typically having porosities of between 0.31 and 0.35. Unweathered tills have lower porosities typically 0.22 to 0.28, however the soft, unweathered, high moisture content tills from the Hobs Aerie site are the exception with porosities in the region of 0.34. Wet density is typically in the range 2.04 to 2.18 Mg/m^3, with the lower values coinciding with the lower moisture contents and wet densities, and higher porosities.

The laboratory hydraulic conductivity again shows very little variation within sites or between sites if the triaxial data is considered. Based on the assumption that sample size does not allow the incorporation of fractures then the method is considered to be providing a reliable estimate of the matrix hydraulic conductivity. An average matrix hydraulic conductivity derived for the three sites is 1.57E-10 m/s.

A wide range of field-determined hydraulic conductivity has been found. There is a clear correlation between the state of weathering and the hydraulic conductivity. Weathered tills have hydraulic conductivity values which are two to three orders of magnitude higher than the corresponding laboratory value, whereas unweathered tills closely approach the laboratory value in most cases. There is a large body of published literature, alluded to previously, which supports the contention that the field value is reflecting the presence of fractures in the test interval. The inference is that the larger test zone associated with field testing is sampling more fractures. Experiments to test this hypothesis were conducted at the Hobs Aerie site and involved installing a number of piezometers to the same depth and within one metre of each other, but with different diameters and length of gravel packs, and consequently different test zone surface areas. The results suggest that a correlation does indeed exist between test zone surface area and hence fracture density and hydraulic conductivity. However, it was not possible to establish an optimum piezometer test zone geometry from this limited experimental data set.

Using the data gathered for the Hall Farm site a conceptual model of groundwater flow was developed which identified fracturing as being a key component of the groundwater flow and contaminant transport pathway. The distribution of the anthropogenic contamination associated with a manure pile on the till at Hall Farm was explained in terms of fracturing and, coupled with the corresponding distribution of laboratory and field hydraulic conductivity, it was possible to arrive at a recharge estimate using analytical and numerical modelling techniques.

The principal results of the modelling study were :-

- Using reasonable parameter combinations recharge through the till is estimated to be between 29 mm/yr and 40 mm/yr, i.e. between 14.5 and 20% of hydrologically effective rainfall (calculated to be 200mm on bare soil).

- The percentage of recharge is very sensitive to the hydraulic conductivity of the unoxidised till, reducing by an order of magnitude for a corresponding order of magnitude decrease in hydraulic conductivity.

- Overland flow did not occur in any simulations and is consistent with field information to the effect that surface water does not develop at this site during high rainfall events. Rapid lateral transfer to field drains through the Cover Sand seems to occur.

- The vertical conductivity of the unoxidised layer is determined by the frequency and transmissivity of sparse fractures.

- The rate of recharge is also strongly influenced by the connectivity between fractures in the oxidised and unoxidised layers.

To assess the applicability of the modelling approach on a more widespread basis requires father scoping studies. Although the analytical model was developed for the Hall Farm site, it is transferable to other 4-layer sites where the cover sand is present. The semi-analytical FRACTRAN model is not constrained in the same way and can be set up on a site specific basis. Clearly there is some uncertainty regarding the magnitude of hydraulic conductivity to be used in any assessment of contaminant migration or recharge and this uncertainty does affect the model output. Effort should be directed towards reducing this as much as possible in any proposed future study. It is important that a clearer understanding of the nature of fracturing in the tills is acquired, not only in a genetic sense, but also in terms of *in situ* physical character.

In assessing a till as a barrier to contaminant migration or conversely aquifer protection both the physical barrier and chemical barrier properties need to be addressed. For instance is the hydraulic conductivity low enough to provide sufficiently long transport times to the underlying aquifer and are the physico-chemical properties adequate to ensure sufficient attenuation of any contaminant so that it does not pose a risk on arrival at the aquifer. Ideally, clay classification methods should be selected solely on the basis of scientific and/or technical criteria and a practical, relatively simple methodology is likely to be easier to implement and be more widely understood than a highly-specialised or overly-sophisticated approach.

In terms of hydrogeological classification, particle-size analysis is a critical method as average particle-size and degree of sorting are primary controls on bulk permeability. The relative proportions of sand silt and clay can be determined relatively rapidly by BS1377: 1990 as used in geotechnical site investigation work. Many workers in Quaternary geology also use triangular diagrams of sand/silt/clay to classify lodgement tills because of their matrix-dominant nature. Those samples that plot in the bottom-left, sand field of the triangular diagram, or those that contain a large proportion of clasts, are identified as potentially permeable.

Cation exchange capacity (CEC) is a good indicator of ion-exchanging or sorbing ability which according to Bath, (1993) is a critical chemical property of a clay barrier with respect to migrating pollutants. CEC is sensitive to variations in the composition of the clay mineral assemblage, especially smectite-group mineral content (Taylor, 1985). As the clay mineral assemblage of the Lowestoft Till is relatively uniform, CEC values are likely to indirectly measure overall clay mineral content.

The impermeability of a clay barrier may be affected adversely by the nature of both organic and inorganic compounds (Bath, 1993). The effect of acid leachates on permeability will be determined to a large extent by the pH buffering capacity of the clay. In the till sequences similar to those investigated in this study, carbonate (calcite) content of the matrix will be the principal control on this property. Determination of matrix carbonate content is a relatively simple procedure which will give a quantitative indication of the buffering capacity of the clay.

Laboratory studies to examine the effects of chlorinated solvents on Lowestoft till (Holmes, 1995) have demonstrated measurable structural changes in the clay minerals. It is believed that these changes could be responsible for enhancing hydraulic conductivity in the field and alter the ranking of a site significantly in terms of the underlying aquifer vulnerability. More work needs to be done on this topic given the previous widespread manufacture and disposal of these compounds on till covered areas.

Justifiably this study can be described as having been comprehensive, but with the very important qualification that it has been of very limited geographical extent. Not withstanding this some very important information has been accumulated and a number of techniques developed and employed.

However, the following questions need to be addressed:

1. ***"How transferable are the results of the project on a regional scale?"***
This question is probably the most difficult to answer because it is not known how representative these sites are of the regional till sheet.

2. ***"What are the principal areas of uncertainty identified that make this transfer difficult?"***
Current uncertainty centres on the role of fractures in till contaminant transport processes and their detailed characterisation especially in terms of fracture density, length and aperture. The regional variability of the till is not well understood at the present and the possible influence of this on fracturing. There is no doubt that the presence of fractures in a till sequence is critical in controlling fluid and contaminant movement. It is the unweathered, less fractured tills which provide the protection to the underlying aquifer and efforts need to be directed to assessing the continuity and thickness of this lithology within an area.

3. ***"Which areas of work need to be progressed to increase our confidence in the data acquired?"***
In central Essex, two till lithofacies are recognised within the Lowestoft till: the upper Great Waltham Till, a dull yellowish-brown to dark grey mostly massive chalk-rich sandy clayey silt, and the lower Newney Green Till, a brown banded silty clayey sand becoming moderately chalky upwards. In contrast, in west Essex up to four till units are recognised (Allen *et al.*, 1991): the Westmill Till (fine-textured, yellowish-brown, chalky); the Ugley Till (fine-sand in texture, dark grey, chalky); the Stortford Till (texture variable, dark grey to yellow-brown, chalk content variable), and the Ware Till (coarse-textured, dark-grey to yellow brown, low chalk content). A way forward in regionalising the study might be to characterise each of these till units independently along similar lines to those adopted in this study and extrapolate the results over a larger area where geological control is available. This would be an expensive approach. Less costly would be to subdivide the tills into hydrogeological domains using existing borehole records and interpolate data acquired from limited field and laboratory investigations, similar to those used in this study. Areas of low data density would be highlighted during this exercise and could be targeted for follow up study to enhance the existing data base. Of particular interest in terms of contaminant transport is the role of anthropogenic organic compounds especially solvents in promoting permeability enhancement. The data gathered to date and the published literature seem to conflict and further laboratory study is required to resolve this important issue.

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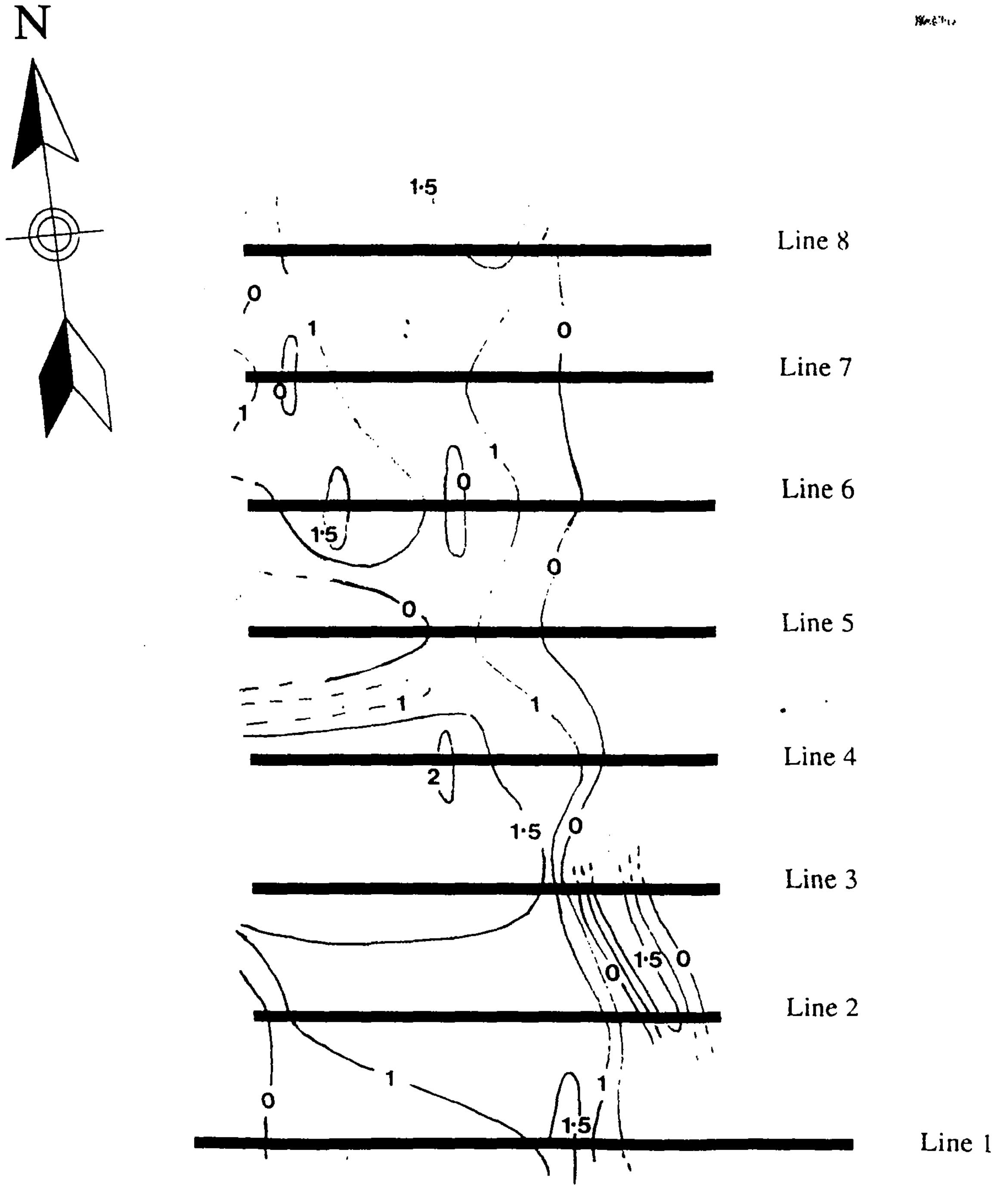

Figure 2.1 Contour plot of the depth to the base of the surface sand layer over the detailed apparent resistivity grid. Depths are in metres.

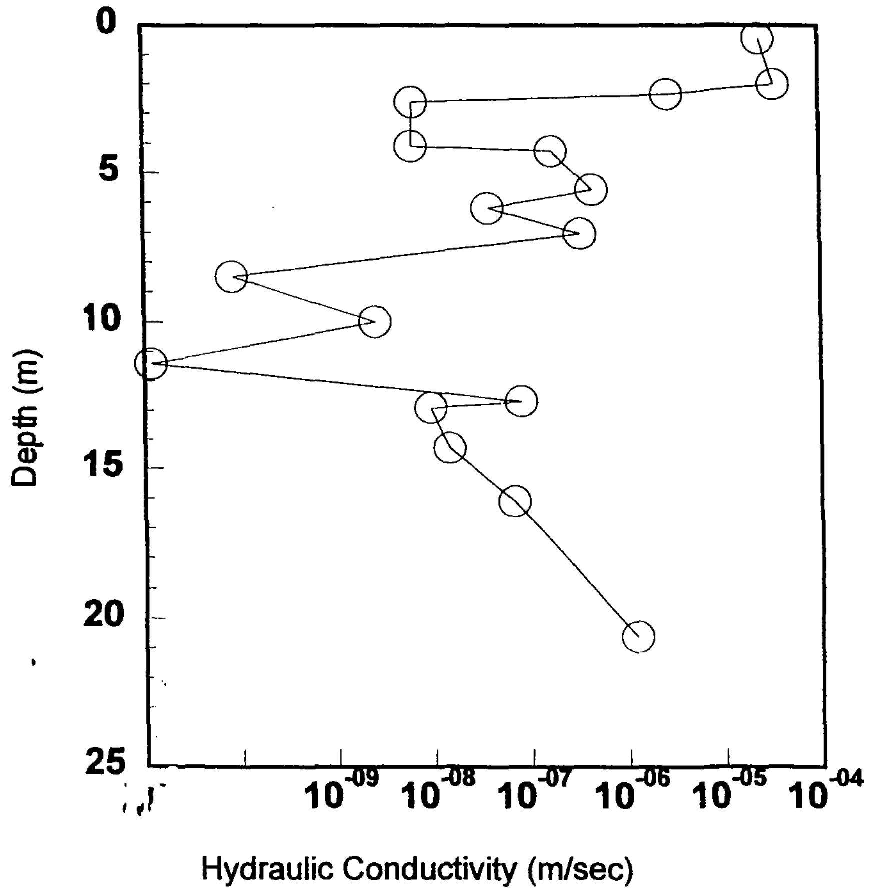

Figure 3.12 Hydraulic conductivity profile for Hall Farm