The Hydrogeological Classification of Superficial Clay:

The hydrogeological characterisation of glacial till and glacio-lacustrine sediments in Shropshire.

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EXECUTIVE SUMMARY

The quantification of recharge to major aquifers, through superficial drift, remains a principal concern for both groundwater resource estimation and when evaluating the protection of such resources from pollutants. This study aims to identify methodologies which can be combined in a framework to provide a classification scheme for superficial clay deposits. It focuses on the properties of lodgement tills, which form the dominant lithology of glacial deposits in the U.K. The development of new methods for investigating such deposits, and subsequently in determining their role in groundwater resource estimation and protection, relies on understanding the major controls on groundwater flow through tills; these include physical properties such as grain size, fissuring and consolidation, in addition to the geochemical and mineralogical properties which retard the migration of solutes.

This report synthesises the results from laboratory and field studies conducted at two sites in Shropshire. The key site selection criteria included that the study area was underlain by a class A aquifer and that there was drift contact with that aquifer. The site at Forton Heath contained till which is present very close to the surface, whilst the till at the Muckleton Moss is overlain by a shallow sand capable of sustaining a perched water table.

The Forton Heath site is characterised by an over-consolidated till which is weathered to a depth of approximately seven metres. Below this depth the till profile is remarkably homogeneous in its physical, mineralogical and geochemical properties. The main control on the hydrogeological properties of the deposits at Forton Heath is the degree of consolidation and the extent of weathering of the till. These mechanisms are, to a large extent, responsible for both the occurrence and frequency of fissuring, and importantly for the ability of fissures to conduct water. The underlying aquifer is protected by a significant thickness of poorly permeable till, however, the capacity for attenuation of solutes may be limited by its relatively low cation exchange capacity (CEC).

In contrast the Muckleton Moss site comprises mainly laminated glacio-lacustrine silts and clays with glacio-fluvial sands. The laminated nature of the sediments imparts considerable anisotropy, this is reflected in the difference observed between field and laboratory hydraulic conductivities which approaches two orders of magnitude. The main controls on the hydrogeological properties of the deposits at Muckleton Moss are the grain size and the anisotropy of the laminated sediments. Prediction of the movement of contaminants from laboratory studies alone would clearly lead to an underestimate in both the rate and the direction of migration. The aquifer may be protected by the glacio-lacustrine sediments but the field derived hydraulic conductivities are several orders of magnitude greater than those observed at

Forton Heath.

The study also provides an estimate of recharge through the till - based on the analysis of data from the Shropshire Groundwater Monitoring Scheme at the Bacon Hall site - of 167 mm per annum. The method used to calculate recharge was based on the Zero Flux Plane (ZPF) method and was constrained by the hydrogeological system and the availability of data both spatially and temporally.

The study has identified a range of methodologies for characterising superficial clay deposits, these include:

- Estimating hydraulic conductivity by a combination of laboratory and field techniques. This ensures that the investigation considers both matrix and fissure flow and, where the anisotropy ratio is high, provides a reliable estimate of both the vertical and horizontal components of hydraulic conductivity;
- The ternary plot is a valuable graphical tool for indicating lithological control on the hydrogeological properties;
- The measurement of CEC provides a rapid method for estimating the clay mineral content and may be used as an indicator of the attenuation/sorption capacity of the clays;
- Determination of pore water chemistry is an essential indicator of the presence of anthropogenic pollutants. However, the fate of such pollutants in complex glacigenic environments requires further study;
- The ZPF method provides a useful tool for the estimation of recharge through the till based on existing historical datasets.

KEYWORDS

Glacial till, hydraulic conductivity, recharge, solute transport.

1. INTRODUCTION

This R&D Technical Report aims to synthesise the results from laboratory and field studies in Shropshire carried out in support of the Hydrogeological Classification of Superficial Clays programme. The project is a co-funded research initiative between the British Geological Survey (BGS) and the Environment Agency. The main objective of this study was to identify methodologies, which may be combined in a framework to provide a classification scheme, to assess the role of superficial clays in groundwater resource estimation and protection.

In a review of glacial landsystems in the UK Eyles *et al* .(1983) concluded that lodgement tills form the dominant lithology. The ability of such deposits to provide an effective barrier to pollutant migration and infiltration to underlying aquifers (NRA, 1991) and the evaluation of their hydrogeological properties remains a principal concern. Understanding the major controls on groundwater flow and solute transport is essential in developing new methods for investigating superficial clays and subsequently in determining their role in the recharge to and protection of groundwater resources. These controls may include physical properties such as grain size, extent of fissuring and the degree of consolidation of a clay, in addition to the geochemical properties which retard the migration of solutes such as cation exchange capacity and the extent of weathering of a clay.

1.1 Previous work

Depositional processes

In a simple model of a lowland lodgement till sequence, both ‘rockhead’ and ‘basal’ elements are recognised. The rockhead refers to the bedrock surface, whereas the basal element usually consists of one or more diamictons emplaced by subglacial lodgement (Paul and Little, 1991). Such lodgement till sequences are invariably poorly-sorted (well-graded). According to Sladen and Wrigley, (1983) the particle-size distribution is determined by various factors including: (1) the type of bedrock; (2) distance from the bedrock source; (3) the proportion and type of reworked sediment incorporated; (4) the degree to which the bedrock source is sealed as deposition progresses and, (5) the extent of post-depositional weathering. Lodgement till is usually matrix dominated with a clast content of <40%. Higher clast contents are rare; in lowland areas these are usually restricted to thin basal zones of deformation till overlying rockhead. McGown and Derbyshire, (1977) suggest that for a lodgement till with a high matrix content (>45%) the matrix acts as a support for the clasts which tend to behave as discrete particles.

Particle-size distributions of matrix dominant lodgement tills are usually represented on sand/silt/clay ternary diagrams. Lodgement tills from North America and the UK tend to plot within a broad diagonal envelope between 15-55% on the silt axis and 65-100% on the sand axis. Matrix particle-size data can also be presented as cumulative plots. Beaumont, (1971) observed a break of slope in cumulative particle-size graphs of tills from east Durham at between 0.2-0.8 mm. He suggested that this marked the point in the size distribution at which constituent particles changed from a predominance of mineral grains to a predominance of rock fragments.

During the formation of lodgement till gradational changes in particle-size and mineralogy may occur as a result of depositional processes. For example, the rockhead element often becomes sealed as the basal element accumulates. Thus, an upwards-fining cycle may develop within a single till sheet due to the diminishing input from coarse-grained rockhead. An upwards decrease 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 <u>lithofacies</u> 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.

Weathering processes

Sladen and 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 and Sladen (1981) distinguished four weathering zones in the late Devensian lodgement tills of eastern England (Table 1.1). The weathering scheme is equally applicable to tills in other lowland areas of Britain .

The development of a methodology for the production of superficial clay maps (Boland, 1996) proposed that the vertically continuous clay thickness contour map should include data of the maximum thickness of vertically continuous unweathered clay. For the purpose of map production Zones II to IV are combined into a single weathered zone, and Zone I is considered to represent the unweathered zone.

Table 1.1 A weathering scheme for lodgement tills (Eyles and 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

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 reprecipitated 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 and 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.

The study involved geological characterisation, 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, (1996); Inglethorpe *et al..*, (1996); Macdonald, (1996) and Wealthall *et al..*, (1996). The synthesis of this extensive data set has enabled the recognition of the main controls on fluid transport within the sediment assemblages at the Shropshire sites, and provided an estimate of groundwater recharge through the till.

1.2 Site selection criteria

The initial basis for site selection proposed 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

However, the key selection criterion of the Shropshire study was to identify a site where a major aquifer was overlain by a significant thickness of glacial till.
The study aimed to characterise one site where the till was present at or very close to the surface and to investigate a second site where the till was overlain by a shallow sand capable of sustaining a perched water table.

Two sites were selected based mainly on the evidence of borehole data (Cannell, 1982) provided by the drilling programmes initiated by the Industrial Minerals Assessment Unit (IMAU) of the BGS . The sites selected for study were: Forton Heath {SJ 41 4365 1743} to the north-west of Shrewsbury (Figure 1.1) and Muckleton Moss {SJ 52 5948 2222} near Shawbury, to the south-east of Wem (Figure 1.2).

The bedrock is the Bridgnorth Sandstone Formation of the Sherwood Sandstone Group. It is generally a brownish red sandstone of Triassic age and forms a major aquifer totalling about 180 m in thickness.

The glacial succession in the western part of the Cheshire-Shropshire lowlands results from the advance, coalescence and subsequent uncoupling of the Irish Sea and Welsh ice-sheets (Thomas, 1989) during the late Devensian. During the advance of these two ice sheets a discontinuous sheet of basal till was emplaced by sub-glacial lodgement, the margin of which is marked by a line extending from close to Shrewsbury north-eastwards towards Ellesmere. On retreat the ice sheets uncoupled along this line and compression against bedrock obstructions led to ice stagnation and generated a wide range of sedimentary environments which are characterised by still-stands and ice-front oscillations. The resulting glacigenic form a complex lithostratigraphical unit, the Stockport Formation (Wealthall *et al.* 1996).

The geometry of the individual lithologies displays spatially ordered patterns which may be recognised by their geomorphic characteristics (Thomas, 1989). The systematic mapping of these sediment-landform assemblages would provide a series of glacigenic domains that relate not only to the depositional environment but also to their hydrogeological properties.

The site at Forton Heath is underlain by an overconsolidated lodgement till. Borehole data (Severn-Trent Water Authority borehole at {SJ 4340 1768}) close to the site indicate 39 m of glacial deposits overlying at least 111 m of red sandstone, and an IMAU borehole immediately adjacent to the site penetrated 17.8 m of unbottomed glacial till.

At Muckleton Moss the sequence was mapped by the IMAU (Cannell, 1982) as sand overlying till which in turn rests on the Bridgnorth Sandstone. The following sequence (Table 1.2) was identified from a borehole (SJ 52 SE 57) immediately adjacent to the site:

Table 1.2 Borehole log of SJ 52 SE 57

Geological classification	Lithology	Thickness (m)	Depth (m)
	Soil	0.3	0.3
Glacial Sand and Gravel	Sand, yellowish red	0.5	0.8
Till	Clay, sandy below 6.4 m, bluish grey becoming reddish brown: scattered rounded quartzite pebbles	12.2	13
Bridgnorth Sandstone		1.2+	14.2

2. CHARACTERISATION OF SELECTED GLACIAL DEPOSITS IN SHROPSHIRE

2.1 Geology

The Forton Heath borehole penetrated 21.04 m of lodgement till. The borehole is characterised by the presence of a weathered and cryoturbated till surface which is underlain by a remarkably homogenous unweathered till sequence (Wealthall *et al.*, 1996). A gradational colour change occurs between 3.19 m and 7.40 m depth, below this depth the till is unweathered. Fissuring is present throughout the weathered till but is not evident in the unweathered till. A summary of the geological log is presented in Table 2.1:

A trench was excavated to a depth of 5.05 m adjacent to the borehole site for the purpose of investigating the shallow three dimensional nature of the till (Wealthall *et al.*, 1996). Four distinct lithological units were identified, these are summarised in Table 2.2.

Table 2.1 Summary geological log of the Forton Heath borehole.

Depth (mbgl)	Description
0.00 to 0.08	TOPSOIL
0.08 to 1.30	Fissured and gleyed CLAY with well developed cryoturbation. Strong brown [7.5YR 5/8] mottled grey [N6]
1.30 to 2.93	Cryoturbated mottled pebbly CLAY. Dark yellowish brown [10YR 4/6] mottled light greenish grey [5G 7/1]
2.93 to 7.40	CLAY transitional cryoturbated zone to 3.19. Slight colour change to greyish brown [10YR 5/2].
7.40 to base (21.04)	CLAY, grey [10YR 5/1] to base of borehole

Table 2.2 Summary of the geological log from the trench section at Forton Heath

Unit	Lithological description
Bed D* to 0.70 mbgl	**Head** lying above the localised water table and affected by drying, leaching and other weathering processes
Bed C to 0.72 mbgl	0.02 m thick incipient **iron pan** alteration of the head deposit (Bed B). Probably corresponding to the zone of fluctuation of a localised water table
Bed B to 1.75 mbgl	**Head** deposit derived by the downslope movement (solifluction) of Bed A. Deformation of the regular fissure network into a complex anastomosing network of fissures
Bed A to 5.05 mbgl	An *in situ* unweathered **lodgement till** with a regular network of fissures up to c. 1 mm width. The clast component comprised a suite of mainly Lower Palaeozoic mudstones, sandstones, siltstones and volcanic rocks

* An organic, silty and stony soil was present to a depth of 0.22 mbgl

The presence of Lower Palaeozoic mudstones, shelly sandstones and North Wales volcanics suggest a north-westerly provenance. No stones were recovered in the clast component that were likely to have been derived from the Irish Sea Glaciation. It follows therefore that the till sheet was emplaced beneath a single ice-sheet emanating from North Wales.

The sequence at Muckleton Moss is in complete contrast to the Forton Heath succession, it contains little till and is dominated by rapidly alternating laminated clay and silts from 1.59 m depth. A silty sand was observed at the base of the sequence, below 6.58 m depth. A summary of the geological log is presented in Table 2.3. This succession is in contrast to the log described by Cannel (1982) who proposed a sequence comprising sand overlying till which in turn rested directly on Bridgnorth Sandstone.

Table 2.3 Summary geological log of the Muckleton Moss borehole

Depth (mbgl)	Description
0.00 to 0.54	TOPSOIL. Very dark brown [7.5YR 2.5/3], humic silty sand
0.54 to 1.21	Variable brown [7.5YR 5/3] clean SAND with clay layers
1.21 to 1.41	Greyish brown to dark brown [7.5YR 3/3] CLAY with pale blue grey gleyed streaks with pebbles (TILL)
1.41 to 1.59	Brown medium well sorted sand with irregular clay lenses (1-2 cm thick)
1.59 to base (6.58)	Well laminated silty CLAY. Separates along fine silty layers in core with banding picked out by rapid alternation of grey [7.5YR 5/1] and brown [7.5YR 4/3] clay. Sandy layer (2 cm thickness) at 5.3 m.

It is suggested that the sandy horizons with clay lenses and the presence of a thin till may represent a retreating ice-marginal sequence. Whereas the underlying laminated clays and silts were deposited as glacio-lacustrine sediments in an ice-dammed proglacial lake.

2.2 Mineralogy

The laboratory mineralogical studies were based around a methodology which was rationalised in earlier studies (Inglethorpe and Bloodworth, 1994). The following description summarises the results of this study (Inglethorpe, 1996) by contrasting the mineralogical properties of both field sites for each laboratory method:

2.2.1 Particle size analysis

The Forton Heath sediments are remarkably homogenous throughout the borehole sequence and comprise very poorly sorted silts and clays with both a mean and median grain size between 3.9 µm and 7.8 µm (very fine silt) with a coarse to strongly coarse-skewed distribution.

However, at Muckleton Moss the particle size distribution is lithology dependent. In the laminated clays and silts, between 2.5 and 6.5 m depth, the sediments mainly comprise very poorly sorted clays and silts with both a mean and median gain size below 3.9 µm (clay) with a distribution that varies from fine-skewed at 2.5 m depth to strongly coarse skewed at 6.5 m depth. In contrast the extremely poorly sorted, strongly fine-skewed sand below 6.5 m depth is much coarser with a mean grain size of between 31 µm and 63 µm (coarse silt) and a median grain size which is greater than 63µm (sand).

The sediments at Muckleton Moss may be classified as silty clays and clay silts (Figure 2.1) and are generally more variable and more finer grained than the uniformly distributed clay silts of Forton Heath. The samples from the Forton Heath site fall within the Sladen and Wrigley (1983) envelope for lodgement tills (Figure 2.2). The sample of silty sand from the base of the Muckleton moss sequence plots within the range of samples of Wolverhampton Till and provides further evidence of a locally derived input to the sediments.

2.2.2 Clast lithological analysis

The clast (>2 mm) composition of the Forton Heath borehole is dominated (>85 %) by dark grey mudstones and grey micaceous sandstones. Less prevalent lithologies include greywackes, vein quartz, calcite and gypsum. It is suggested that the majority of the clasts have a westerly to north-westerly provenance of Lower Palaeozoic age.
At Muckleton Moss dark grey and light grey silty mudstones form less than 60 % of the clast content. Locally derived material forms a major component of the remaining clasts and includes red and purple sandstones, yellow sandstones, coal and shell fragments.

2.2.3 Clay mineralogy

X-ray diffraction (XRD) analysis of the clay-sized material (<2 µm) at Forton Heath identified a highly uniform profile characterised by an illite, chlorite assemblage. Whereas the XRD analysis for the Muckleton Moss samples indicate an illite, chlorite, kaolinite and smectite assemblage.

The variability in clay mineralogy at the two sites reflects the origins of the two sediment types. Both sites comprise sediments deposited by ice-sheets emanating from North Wales. However, at Muckleton Moss the clay mineralogy reflects an additional input of locally derived material which is considered to be typical of Permo-Triassic sediments.

2.2.4 Cation exchange capacity (CEC) and specific surface area

The Forton Heath sediments show little variation with depth for CEC and specific surface area. The CEC is less than 15 meq/100 g and the specific surface area less than 80 m^2/g. The low values of CEC reflect the absence of smectite in the clay mineral assemblage at Forton Heath.

At Muckleton Moss CEC and specific surface area are well correlated and strongly lithology dependent. The CEC ranges between 7.5 and 16.5 meq/100 g whilst specific surface area is between 65 and 130 m^2/g in the laminated clays and silts decreasing to 45 m^2/g in the sand at 7.1 m depth.

The mineralogical studies indicate poorly sorted sediments with properties diagnostic of their provenance. When compared to the deposits at Forton Heath the Muckleton Moss sediments are generally finer grained and possess a higher specific surface area and CEC which results from the increased presence of clay minerals including illite, chlorite, kaolinite and smectite. It follows, therefore, that the CEC provides an indirect measure of the overall clay mineral content. The ability of a clay to retard the migration of solutes is dependent on its CEC or sorbing ability (Bath, 1983), therefore the CEC also provides a useful indicator of the performance of a clay in protecting the underlying aquifer from solutes migrating down profile.

2.3 Hydrogeology

The fully cored boreholes were used to measure *in situ* hydraulic properties, whilst the core samples provided material for detailed laboratory characterisation. The laboratory programme aimed to define the physical characteristics of the sediments by selecting properties which would provide data for groundwater flow and contaminant transport modelling; these included measurement of density, moisture content, porosity and hydraulic conductivity.

2.3.1 Laboratory studies

The measurement of hydraulic conductivity was performed on core samples recovered from the rotary drilling programme . In order to allow a comparison between the laboratory tests and field derived values the samples were selected from the core at depths which corresponded to the piezometer response zones.

The test methods selected for this study (Entwisle, 1996) were;

- A one-dimensional isotropic triaxial consolidation (oedometer) test suitable for low hydraulic conductivities and involving two stages of consolidation (50 % and 90% consolidation) which consequently provided two values for hydraulic conductivity (k_{50} and k_{90}).

- A constant flow rate triaxial test which is considered ideal for heterogeneous materials that usually have low, but variable, hydraulic conductivities. Again two values of hydraulic conductivity are determined, however, in this method the first value is derived from the consolidation stage (similar to the oedometer test) and the second value is obtained from a constant flow rate test.

Moisture content and density were also determined for all samples tested.

Both laboratory methods used to determine hydraulic conductivity are configured with a geometry which provides an estimate of the vertical component of flow. The triaxial cell provides the most representative value of hydraulic conductivity due to both the larger sample volume and the capacity to conduct flow through tests. However, the availability of well documented oedometer data allows comparison with many other studies.

The results from the following test methods have been selected as they provide the most relevant physical properties:

- Moisture content which provides an indication of the saturation state of the core sample;
- Dry and bulk density which may be used to estimate the degree of compaction and saturation;
- Hydraulic conductivity which provides an estimate of the matrix flow properties.

Forton Heath

The samples from the till at Forton Heath are described for each test method, a summary of the results is presented in Table 2.4 below (hydraulic conductivity data is reported here for constant flow rate triaxial tests (k_f)).

Table 2.4 A summary of the results of the laboratory testing for the Forton Heath site

Test type	Minimum	Maximum	Mean (arithmetic)
Moisture content (%)	16.8	20.3	18.6
Bulk Density (kg/m^3)	1970	2167	2081
Dry Density (kg/m^3)	1659	1827	1751
Hydraulic conductivity, k_f (ms^{-1})	1.0x10^{-10}	3.5x10^{-9}	-

The moisture content varied between 16.8 - 20.3 % in cycles of slightly higher and lower moisture content but with a general trend of decreasing moisture content with depth . Both the bulk and dry density were fairly uniform with depth with an average value of 2081 and 1751 kg/m^3 respectively.

The hydraulic conductivity (k_f) of most samples had a range of values between 1x10^{-10} and 4 x10^{-10} ms^{-1}. The only exception being the sample at 1.4 m depth where the hydraulic conductivity is considered to be enhanced by alteration of the till by fissuring and weathering, resulting in a k_f of 3.5x10^{-9} ms^{-1}. The values are plotted against estimated *in situ* depth in Figure 2.3.

When the hydraulic conductivity data (k_f) was plotted against porosity the bulk of the values demonstrate a reduction of hydraulic conductivity with decreasing porosity.

Muckleton Moss

The results from the Muckleton Moss site reflect the variability in physical properties due to the heterogeneity of the glacial outwash and glacio-lacustrine deposits. The laboratory methods tested only the finer grained low permeability sediments and estimates from the oedometer were of vertical hydraulic conductivity.

A summary of the results are presented in Table 2.5 below (hydraulic conductivity data is reported here for oedometer consolidation tests (k_{90})).

Table 2.5 A summary of the results of the laboratory testing for the Muckleton Moss site

Test type	Minimum	Maximum	Mean (arithmetic)
Moisture content (%)	16.1	45.0	32.9
Bulk Density (kg/m^3)	1778	1927	1834
Dry Density (kg/m^3)	1230	1472	1330
Hydraulic conductivity, k_{90} (ms^{-1})	1.6x10^{-10}	6.0x10^{-10}	-

The moisture content varied between 30.6 - 45.0 % except in the sands close to the surface in borehole where the moisture content approached 16 %. The highest values of moisture content occur in the laminated glacio-lacustrine deposits. The bulk and dry densities showed little variability with depth, except for a peak in both densities at 4.8 m depth, with average values of 1834 and 1330 kg/m^3.

The estimated *in situ* hydraulic conductivity (k_{90}) of most samples had a range of values between 6x10^{-11} and 6 x10^{-10} ms^{-1}. A trend of decreasing hydraulic conductivity with depth is observed in the glacio-lacustrine sediments. The values are plotted against estimated *in situ* depth in Figure 2.4.

The test apparatus provides a methodology for testing low permeability samples. Results are not available for the sandy horizons both at the top and the base of the laminated silts and clays. Additionally the geometry of the test apparatus and the method of sampling results in a value for the vertical component of hydraulic conductivity.

Porosity was calculated from the voids ratio (Entwisle, 1996) for each consolidation phase. At Forton Heath the hydraulic conductivity is positively correlated with porosity, therefore the lowest values of porosity are associated with the lowest hydraulic conductivites. It follows that, in these relatively homogenous deposits, the consolidation state is the primary control on the hydraulic conductivity. Whereas at Muckleton Moss the hydraulic conductivity is inversely correlated with porosity. This suggests that the main control on hydraulic conductivity is the grain size distribution, in particular the variation due to the relative proportions of clay sized material, where the highest clay content samples will have the lowest hydraulic conductivity. The reader is referred to Entwisle (1996) for further description of the testing methodology and discussion of results.

2.3.2 Field hydraulic testing

In addition to the continuously cored boreholes a number of auger-flight boreholes were drilled at each site and completed with standpipe piezometers. The boreholes were completed with the aim of undertaking hydraulic tests in low to very low hydraulic conductivity formations. This required the design of completions which were carefully sealed and of low compliance, full details of which are given in Wealthall *et al.* (1996).

In situ hydraulic tests in over-consolidated clays are prone to excessive testing durations (Daniel, 1989). At values of hydraulic conductivity less than 1×10^{-9} ms^{-1} tests in open piezometers maybe of several days duration, whereas at values in excess of 1×10^{-9} ms^{-1} tests in open piezometers are typically completed in a few hours. The testing programme proceeded using slug tests (Cooper *et al.*, 1967) in open piezometers where recovery was achieved in a reasonable time period and switched to a pressure pulse test (Bredehoeft and Papadopulos, 1980; Neuzil, 1982) in a shut-in piezometer for the low to very low hydraulic conductivity completions. The values of field derived hydraulic conductivity in this study are considered to represent a reliable estimate of the horizontal, radial component of permeability (K_h). A full description of the testing methodology and a discussion of results is provided by Wealthall *et al.* (1996).

Forton Heath

Due to the low hydraulic conductivities encountered at the Forton Heath site and in order to complete the testing programme in a reasonable timescale each piezometer was tested using the pressure pulse test. The results are presented in Table 2.6 and plotted as a depth profile in Figure 2.3.

The pattern which emerges is one of decreasing hydraulic conductivity with depth in the weathered, oxidised till and one of increasing hydraulic conductivity with depth below an inflection point at 9.74 m depth in the unweathered, unoxidised till.

The decreasing hydraulic conductivity with depth at the base of the weathered till is possibly in response to the closure of fissures due to compression of the till by the overriding ice sheet. Below this depth the influence of the overriding till sheet is less significant and the hydraulic conductivity is seen to increase with depth towards the base of the profile. It should be noted, however, that the range of hydraulic conductivity is less than one order of magnitude across the entire till profile. The values span 3.90×10^{-10} ms^{-1} to 1.16×10^{-9} ms^{-1} and correspond to the range of Lloyd, (1983) for both matrix rich, unweathered tills, and matrix rich, weathered tills.

Muckleton Moss

In contrast to Forton Heath, the relatively high hydraulic conductivities at Muckleton Moss allowed testing of the piezometers using the slug test methodology. The results are tabulated in Table 2.4 and plotted as a depth profile in Figure 2.4.

Although the values of hydraulic conductivity range over approximately two orders of magnitude most results fall between c. 1×10^{-8} ms^{-1} and 1×10^{-7} ms^{-1}. The maxima of 6.07×10^{-7} ms^{-1} at 7.14 m depth represents a relatively permeable sandy horizon.

The range of hydraulic conductivities observed at Muckleton Moss are two to three orders of magnitude greater than those at Forton Heath due to the presence of highly anisotopic laminated silts and clays and glacio-fluvial sands. The anisotropic nature of these sediments suggests that the main control on water movement will be lateral.

It should be noted that the field test measures the horizontal (radial) component of hydraulic conductivity whereas the configuration of the laboratory test results in a value of vertical hydraulic conductivity. In highly anisotropic deposits the data represented by field hydraulic testing are therefore an upper limit of hydraulic conductivity, whereas those determined by the laboratory test provide an estimate of the minimum value of hydraulic conductivity.

Table 2.6 Hydraulic conductivity values determined at Forton Heath

BH	Depth	K (ms^{-1})
FH1	20.77	$1.29x10^{-9}$
FH2	19.75	$1.19x10^{-9}$
FH3	18.82	$1.06x10^{-9}$
FH4	17.81	$9.12x10^{-10}$
FH6	15.72	$4.58x10^{-10}$
FH7	14.72	$5.51x10^{-10}$
FH8	13.72	$5.69x10^{-10}$
FH9	12.73	$4.72x10^{-10}$
FH10	11.73	$8.77x10^{-10}$
FH11	10.76	$2.90x10^{-10}$
FH12	9.74	$1.97x10^{-10}$
FH13	8.73	$3.45x10^{-10}$
FH14	7.74	$5.56x10^{-10}$
FH15	6.76	$6.46x10^{-10}$
FH16	5.75	$4.95x10^{-10}$
FH17	4.75	$5.21x10^{-10}$
FH18	3.77	$1.16x10^{-9}$

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

Table 2.7 Hydraulic conductivity values determined at Muckleton Moss

BH	Depth	K (ms^{-1})
MM1	12.03	$7.85x10^{-8}$
MM3	7.14	$6.07x10^{-7}$
MM4	7.18	$1.02x10^{-8}$
MM5	6.01	$4.12x10^{-9}$
MM6	5.24	$1.93x10^{-8}$
MM7	3.88	$7.42x10^{-9}$
MM8	3.00	$5.41x10^{-8}$
MM9	6.55	$1.95x10^{-8}$

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

2.3.3 Soil moisture studies

Estimates of groundwater recharge (MacDonald, 1996) were made using soil moisture and soil water potential data from the Shropshire Groundwater Scheme for the Bacon Hall site. The methodology used to calculate groundwater recharge relies on the presence of a zero flux plane (ZFP). The ZFP is the point at which the soil water potential gradient changes from negative to positive, that is where water moving upwards towards plant roots can be separated from water moving downwards. The changes in moisture content below the ZFP define the drainage moving downwards to the water table. Hence an estimate of groundwater recharge is made without the use of meteorological data. When the ZFP is not present an unsaturated zone moisture balance method was used to estimate groundwater recharge. This method is based on data for soil moisture, rainfall and evapotranspiration, and assumes negligible soil moisture deficit.

A period which encompassed one full recharge cycle, defined as the period between October 1989 and November 1990, was used to estimate groundwater recharge. The total recharge for this period was 167 mm which is equivalent to 28.8 % of the rainfall during that period.

The method used to calculate recharge is sensitive to the location of the ZFP. The thickness of the unsaturated zone was small in relation to the measurement interval of the tensiometer and neutron probe array. Difficulty in locating the exact position of the ZFP was experienced, particularly where small variations in pressure were recorded from a number of tensiometer readings. Additionally, the presence of a perched water table in the soil moisture profile indicates the potential for lateral movement of groundwater. This lateral movement would tend to reduce the estimate of recharge. However, the value for recharge does appear reasonable and compares well with estimates of recharge through sandy till by other authors (Johansson 1987, 1988).

2.4 Hydrochemistry

Major element and trace element chemistry was determined from pore waters extracted from sections of the core. Pore water extraction was usually attempted on core corresponding to the depth of piezometer installation.

The following discussion considers solute transport, with special reference to nitrate and chloride - which are considered to have arisen anthropogenically, as an indicator of the potential for groundwater flow through the glacial deposits.

2.4.1 Forton Heath Pore Water Chemistry

The nitrate concentration (Figure 2.5) is highest in the weathered oxidised till and decreases in the unweathered, unoxidised till where the concentration drops off to almost zero. The Forton Heath borehole was sited in pasture land at the edge of a disused runway, no nearby source of anthropogenic contamination was recorded and the nitrate levels in the pore water are probably due to animal and rainfall input. 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. A recent study by Robertson *et al.* (1996) identified a close association in the depletion of nitrate with an abrupt increase in the porewater sulphate concentration. In this study it was proposed that reduced sulphur compounds, present in the unweathered sediment, act as electron donors for microbial degradation of the nitrate. At the Forton Heath site a comparison of the NO_3 and SO_4 profiles (Figure 2.5) suggests that a similar mechanism may be occurring, thus indicating that intrinsic bioremediation is responsible for the decreasing nitrate concentration with depth.

The chloride concentration (Figure 2.6) declines to a minima in the oxidised till and then increases with depth to the base of the borehole reaching a concentration of 541 mg/l. The elevated concentrations of chloride in the profile may result from salt used for de-icing of the adjacent runway. Sodium and chloride follow similar trends across the profile, except at the base where ion-exchange may be depleting sodium, and close to the surface in the weathered till where leaching may be lowering the chloride concentration.

All of the major cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) are observed (Figure 2.7) to increase in concentration with depth across the weathered zone. Little variation is evident in the porewater concentrations below the weathered/unweathered contact, with the exception of magnesium which decreases in concentration with depth possibly as a result of cation exchange with clay minerals. Inglethorpe (1996) identified a remarkably homogenous suite of samples which show little variation with depth with respect to both the bulk mineralogical properties and the particle size distribution. For these reasons it is suggested that the decrease in concentration of the major cations close to the surface results from the apparent dilution of solutes due to leaching in the weathered zone.

Correlation of porewater concentrations of calcium, sulphate and strontium (Figure 2.7) suggests the formation of gypsum throughout the profile. The equilibrium constant for gypsum is given by Hem (1985):

$$\frac{[CaSO_4^0]}{[Ca^{2-}][SO_4^{2-}]} = 10^{2.31}$$

And implies that solutions containing 10^{-2} to 10^{-3} moles/litre (equivalent to a concentration of 1000 - 100 mg/l) of SO_4^{2-} will contain significant amounts of the ion pair $CaSO_4$. The range concentration of SO_4^{2-} in the Forton Heath profile varies between 367 mg/l and 3110 mg/l , therefore formation of significant amounts of gypsum is a favourable reaction. The concentrations of calcium, sulphate and strontium are lower in the weathered till horizon which suggests depletion of solutes due to leaching.

2.4.2 Muckleton Moss Pore Water Chemistry

The Muckleton Moss borehole was sited at the edge of a bridleway adjacent to pasture land, no nearby source of anthropogenic contamination was recorded and the nitrate levels in the pore water are probably due to animal and rainfall input. The nitrate concentration (Figure 2.8) is highest in the glacio-fluvial sands and clays and decreases with depth in the laminated clays and silts where the concentration drops off to almost zero. The mechanism describing the decrease of nitrate concentration with depth cannot be attributed solely to an increase in the pore water sulphate concentration (Robertson *et al.*, 1996), as observed at Forton Heath. The variable lithological sequence at Muckleton Moss may exert considerable influence on the concentrations of nitrate with depth.

The sulphate concentration (Figure 2.8) is highest in the glacio-fluvial deposits and is attenuated rapidly with depth to <50 mg/l in the laminated clays and silts. The sulphate profile shows a similar trend to that of nitrate and it is suggested that the decreasing sulphate concentration may result from a number of mechanisms. These include:

i) the original mineralogical composition of the differing lithologies;
ii) the reduction of sulphate to sulphide;
iii) as a function of decreasing hydraulic conductivity, from the overlying glacio-fluvial sediments to the glacio-lacustrine clays and silts, hence lower matrix diffusion.

The chloride concentration (Figure 2.9) increases to a maxima (58 mg/l) in the sand with clay layers then decreases with depth to the base of the borehole. The decreasing concentration with depth may result from either lower matrix diffusion in the lower permeability laminated clays and silts or as a result of dilution from groundwaters in the underlying, more permeable horizons. The major cations (Ca, Mg and Na) show a comparable trend (Figure 2.9) to that of the conservative species, chloride.

3. DISCUSSION OF RESULTS

This section aims to summarise the main controls on the movement of groundwater through contrasting glacial deposits at the Forton Heath and Muckleton Moss borehole sites.

Forton Heath

The lithological log of the Forton Heath site describes an over-consolidated glacial till which is cryoturbated and weathered to a depth of approximately seven metres. Below this depth the till profile is remarkably homogenous in its mineralogical, geochemical and physical properties.

The *in situ* and laboratory derived hydraulic conductivities are generally within one order of magnitude. The hydraulic conductivity, measured in the piezometers, decreases at the base of the weathered zone in response to the closure of fissures due to compression of the till by the overriding ice sheet, the minimum value of hydraulic conductivity at this point approaches that measured in the laboratory at an equivalent depth. This suggests that the *in situ* test represents mainly matrix flow with little contribution from the fissure component. Laboratory derived hydraulic conductivity from approximately two metres depth are one order of magnitude greater than those measured in the rest of the borehole. The weathering, cryoturbation and degree of consolidation clearly exert a control on the rate of movement of water through the uppermost section of the profile. This is reflected by the porewater chemistry where the concentrations of many of the solutes are depleted due to leaching .

In summary, the main control on the hydrogeological properties of the deposits at Forton Heath is the degree of consolidation and the extent of weathering of the till. These mechanisms are, to a large extent, responsible for both the occurrence and frequency of fissuring, and importantly for the ability of fissures to conduct water.

Muckleton Moss

In contrast the deposits at Muckleton Moss comprise mainly laminated glacio-lacustrine silts and clays with glacio-fluvial sands. The laminated nature of the sediments imparts considerable anisotropy which is reflected in the difference between field and laboratory derived hydraulic conductivity. The *in situ* test provides an estimate of the horizontal component of hydraulic conductivity and is largely a measure of the coarser grained sediments in the laminated clay/silt sequence. However, the laboratory test measures the vertical component of hydraulic conductivity and at Muckleton Moss is observed to be approximately two orders of magnitude lower than the *in situ* test conducted at an equivalent depth. Studies of fluvial deltaic silty-clay sediments from the Texas Gulf coast (Capuano and Jan, 1996) recorded measurements of vertical hydraulic conductivity from core samples which were two to four orders of magnitude lower than values for *in situ* horizontal hydraulic conductivity. Additionally the hydraulic conductivity of the glaciofluvial sands, at the base of the laminated clays and silts, was observed to be at least one order of magnitude greater than the overlying sediments.

The main controls on the hydrogeological properties of the deposits at Muckleton Moss are the grain size and the anisotropy of the laminated sediments. Prediction of the movement of contaminants from laboratory studies alone would clearly lead to an underestimate in both the rate and the direction of migration.

4. CONCLUSIONS

Two field sites in Shropshire have been studied and the results provide a valuable contrast between the intrinsic properties of individual glacigenic domains. Data from the Shropshire Groundwater Monitoring Scheme have been analysed to provide an estimate of groundwater recharge to the till.

The key results of the project are summarised by reference to each site as follows:

Forton Heath (Till site)

- Laboratory and field hydraulic conductivity results are very similar and within one order of magnitude. This reflects the remarkable homogeneity of the till and suggests that fissure flow is not the main control of groundwater movement through the till at the Forton Heath site but it is the degree of consolidation and the extent of weathering;
- The particle size distribution is also very uniform and is concordant with the Sladen & Wrigley envelope for lodgement tills;
- Analysis of the clast content and clay mineralogy suggests an ice sheet with a North Wales provenance;
- CEC values are low (between 8 and 13 meq/100g). This reflects the absence of smectite in the clay mineral assemblage;
- The hydrochemistry identified attenuation of nitrate below the weathered zone by microbially mediated processes, but a chloride front resulting from historical de-icing of the adjacent runway suggests that some solutes are migrating down profile;
- The underlying aquifer is protected by a significant thickness of poorly permeable till, however, the CEC is lower than other clays (for example the clay-with-flints) and the capacity for attenuation of solutes may be limited.

Muckleton Moss (Glacio-lacustrine site)

- The variability in field derived hydraulic conductivity is a function of the lithology, where the dominant control is the fabric;

- The variability observed between laboratory and field derived hydraulic conductivity is due to the anisotropy of the laminated glacio-lacustrine sediments, this will result in a flow regime which promotes lateral movement of groundwater;
- A different clay mineral assemblage to that observed at Forton Heath reflects a more locally derived input to the sediments. This is assumed to be from the Triassic sediments;
- The CEC is generally higher than in the Forton Heath samples, this results from the presence of smectite in the Muckleton Moss sequence;
- The aquifer may be protected by the glacio-lacustrine deposits at Muckleton Moss but the field derived hydraulic conductivity is several orders of magnitude greater than that at Forton Heath.

Bacon Hall (Till site)

- Data from the Shropshire Groundwater Scheme monitoring network at Bacon Hall has provided an estimate of recharge through the till using a simple zero flux plane method;
- The value of groundwater recharge is 167 mm for one full recharge cycle, which is 28.8% of the annual rainfall;
- However, during the analysis doubts were raised about the method used to calculate recharge. The accuracy of the estimate was constrained by the hydrogeological system at the site and the interval at which data was available, both in time and depth.

This study has identified a range of methodologies for characterising the properties of superficial clays. Those methodologies that contribute most are listed below:

1 Laboratory methods for the determination of hydraulic conductivity are limited by the scale of the measurement and as such provide an indication of matrix properties. Whereas the radius of influence of field derived hydraulic conductivity includes both a matrix and fissure component and is generally a more representative estimate of hydraulic conductivity.

2 A combination of field and laboratory methods for the determination of hydraulic

conductivity are important particularly if the anisotropy ratio is high, e.g. at Muckleton Moss. When constructing groundwater flow and contaminant transport models reliable estimates of both the vertical and horizontal component of hydraulic conductivity are required.

3 The ternary plot is a valuable tool for indicating lithological control on the hydrogeological properties.

4 Measurement of CEC provides a rapid method for estimating clay mineral content and surface area. It provides an indicator of the attenuation/sorption capacity of the sediments.

5 Density provides an indicator of the degree of consolidation and moisture content of the degree of saturation.

6 Determination of pore water chemistry is an essential indicator of presence of anthropogenic contamination. However, in the absence of readily identifiable point source pollution (e.g. manure stockpiles) the use of isotopes should be considered. Additionally, the role of reduced sulphur compounds, such as pyrite, in the depletion of nitrate should be given further consideration.

Many of the methodologies listed above are low technology solutions which are easily applied to borehole investigations in till sequences. When combined with a fuller understanding of the depositional environments a framework for the classification of superficial clays may be developed which will aid the estimation of recharge, and provide an indication of the degree of protection provided by such deposits.

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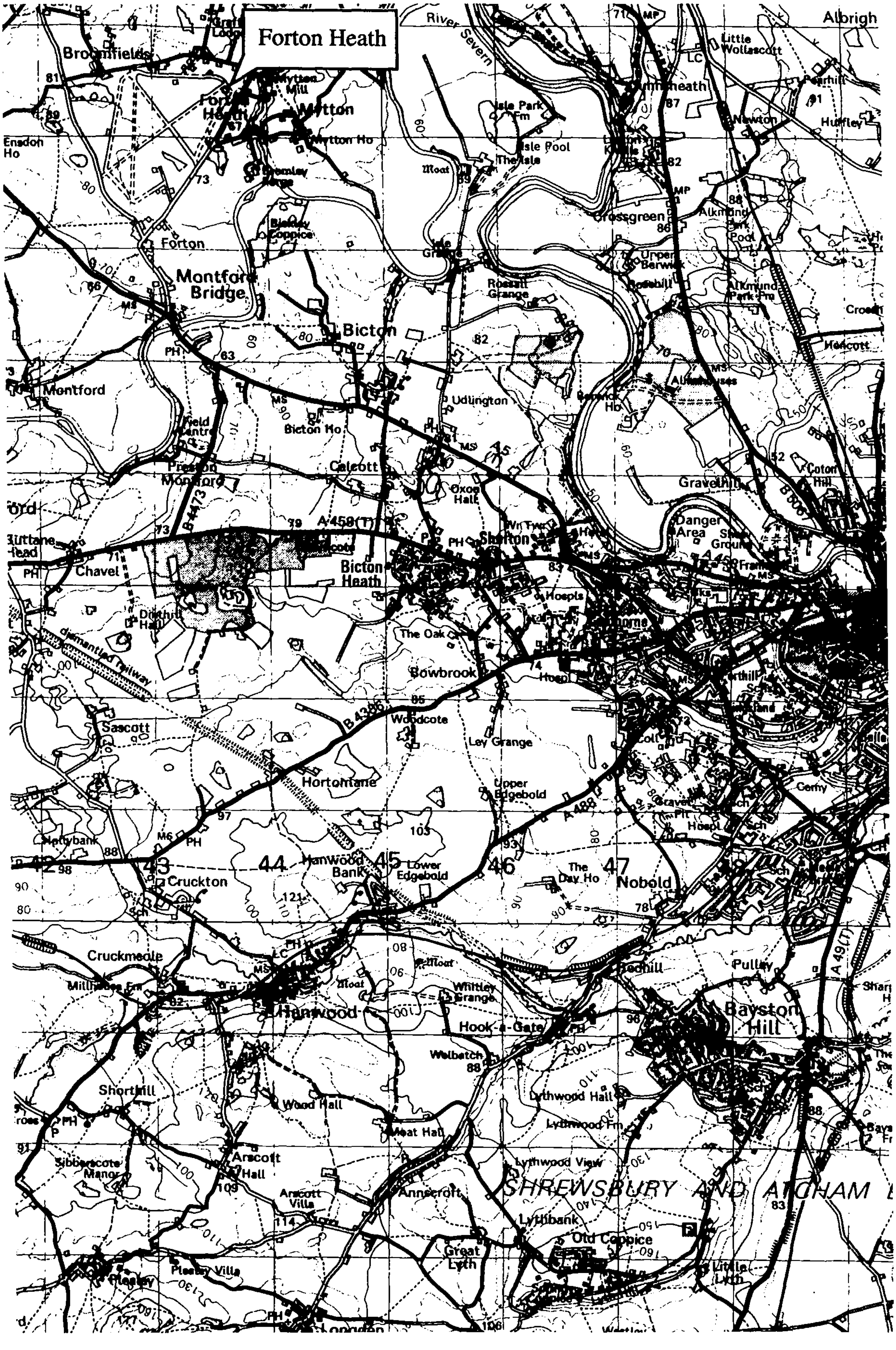

Figure 1.1 Forton Heath site location map

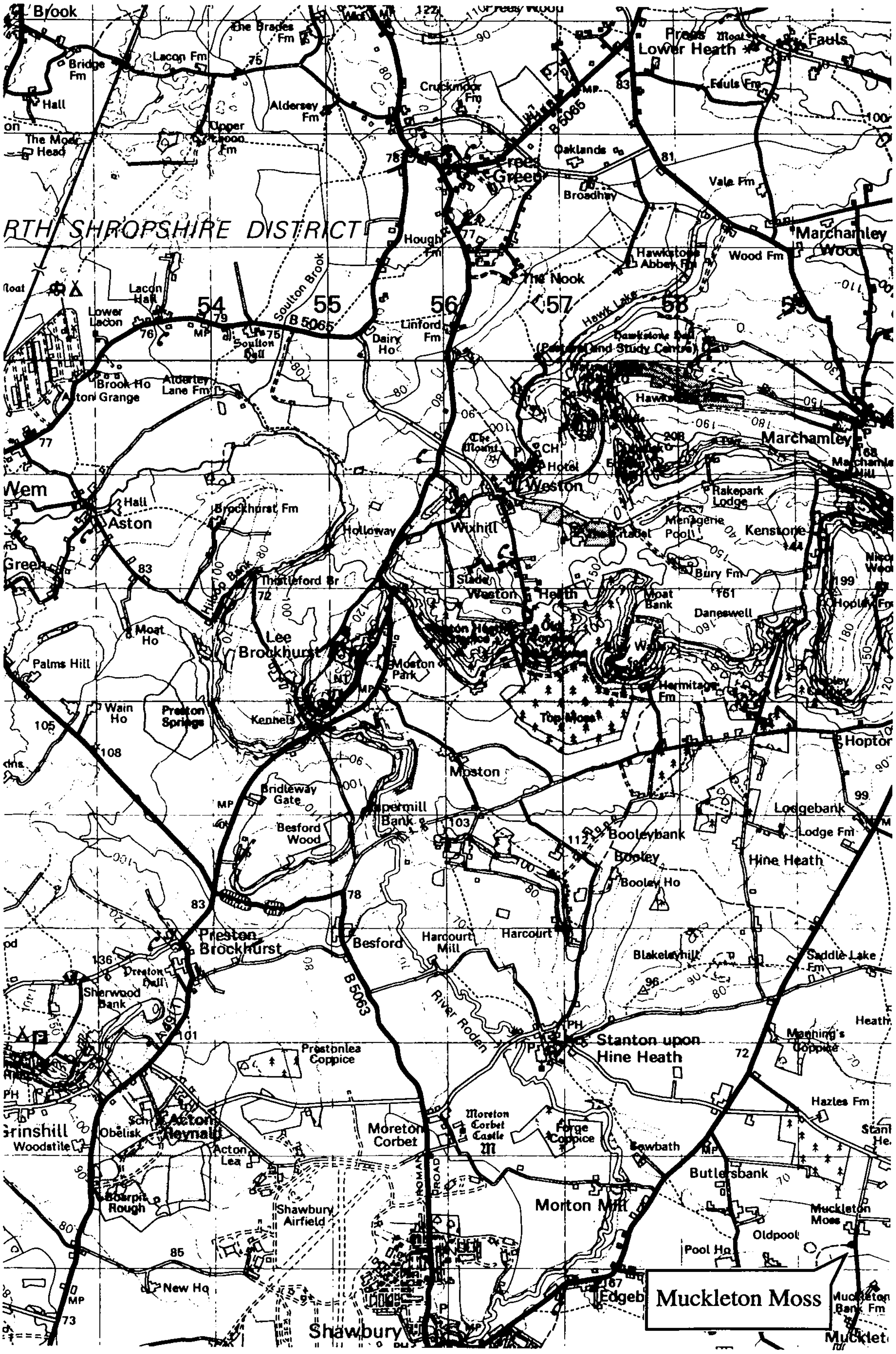

Figure 1.2 Muckleton Moss site location map