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The 3D Soils Modelling Project – Results, feedback and recommendations of the Brackenhurst site survey 2005

Sustainable Soils Programme

Internal Report IR/06/074

BRITISH GEOLOGICAL SURVEY

SUSTAINABLE SOILS PROGRAMME

INTERNAL REPORT IR/06/074

The 3D Soils Modelling Project – Results, feedback and recommendations of the Brackenhurst site survey 2005

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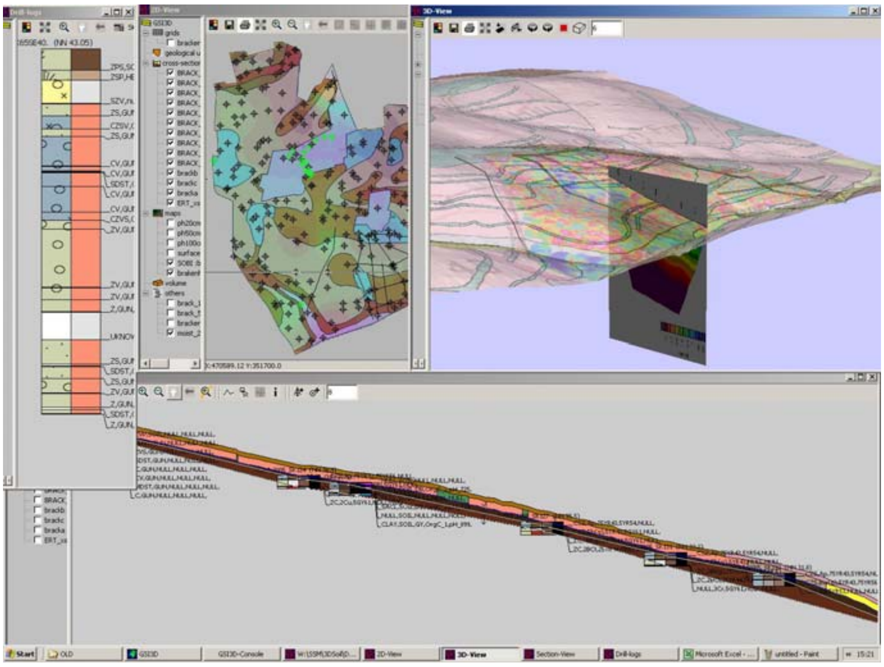

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Bob Palmer (NSRI) giving training to BGS and NSRI employees on the Brackenhurst site in October 2005.

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Summary

This report describes an integrated geoscientific survey at the Brackenhurst College campus of Nottingham Trent University near Southwell Nottinghamshire carried out in 2005. Remote sensing data were integrated with a comprehensive programme of field survey to produce a three dimensional digital model of the near surface, including the geology and soils. The objective of this pilot study was to define the survey and modelling methods that can be successfully applied to a 3D digital soil survey, thereby proposing and recommending a methodology for conducting future surveys elsewhere in the UK.

BGS, as an organisation, has the capacity to conduct all of the surveys and tasks described above. However, as well as considering the contribution of each individual survey, a logistical understanding of how the surveys can interact on the ground has been achieved. For example, it is recommended that the gamma spectrometry survey should be conducted at the same time as the soil sampling to ensure that samples are taken from exactly the same locations and under the same soil moisture conditions. Also the soil geochemistry sampling should be conducted during, or after, the geophysical surveys as the sampling density could be increased in areas of anomalies. Figure 1 illustrates the various survey techniques that were undertaken in this project and outlines the sequence and overlap that we recommend for future surveys. In order to ensure coordination of field activities, we also recommend that an individual is given responsibility for scheduling each individual component survey.

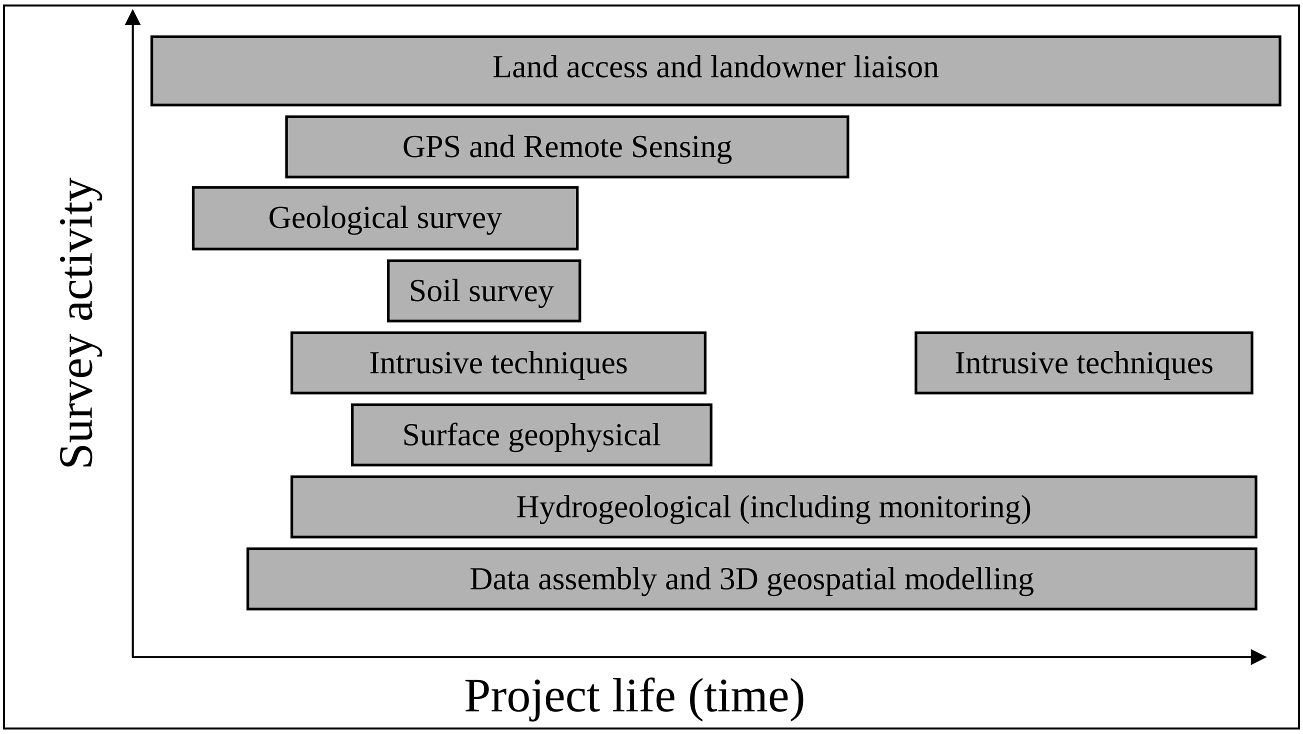


Figure 1 Recommended scheduling of survey activities

It is acknowledged that the recommended BGS survey and modelling workflow starts with compilation of existing/archive data, and gathering/interpreting new data (where available) before a field survey. This is relatively easy to consider and organise even for a multidisciplinary survey when all the data are compiled into a single entity, e.g. a project GIS or GSI3D. In order to keep track of all surveys, and gauge their preliminary results we recommend that raw and processed field data should be captured and added to the GIS as soon as they are acquired, and importantly, that the GSI3D model is constructed as early as possible (even if it is incomplete) so that any gaps in coverage/knowledge etc. can be recognised and filled while field staff are still mobilised. It is anticipated to carry out data processing and 3D visualisation increasingly on-site using the field laboratory.

The construction of 3D models of the near surface environment, such as the one described in this project at the Brackenhurst site have potential in assisting process-related research in both small-scale and landscape projects. The most valuable information 3D models provide are estimates of the different geological units and soil horizons including their extent, volume and position within the study area. On a small scale, this information can be used to help plan the process related research with regard to defining areas of study, particularly those associated with geological interfaces. On larger scale projects the 3D models could be used to generate conceptual models of processes with information such as process rates or properties attached for different geological horizons associated with the process under study.

In addition, the role of some of the surveys undertaken (EM, ERT) at the Brackenhurst site could be of particular importance to understanding processes in the near surface environment. However, these may need to be used in a monitoring capacity instead of a one-time survey. The most important of these are the geophysical surveys that can estimate the position of the water table and the saturated and unsaturated zones. Water and gases such as oxygen are fundamental drivers of physical, chemical and biological processes and frequent monitoring using EM and resitivity surveys could allow annual knowledge of water tables fluctuations, redox reactions and their interactions with geological horizons to be understood in more detail and help explain catchment outputs.

Four main conclusions were derived from the study at Brackenhurst.

1. Despite differences in nomenclatures and methodologies between soil survey and geological surveys we feel it is possible, provided cognisance is taken of the need to use a multidisciplinary approach, to produce fully attributed 3D models of the shallow subsurface.

2. The research has shown that spatial soil horizon modelling can use methods and software developed originally for shallow geological modelling, when soil horizons are stratigraphical. Ongoing studies in other more complex soilscapes at a site specific and catchment scale are being used to test this assumption, including cases where super positional order breaks down.

3. Soil and geology should be seen as a continuum and must be studied and surveyed in an integrated manner, as customer requirements move beyond the traditional boundaries of compartmentalised science.

4. The potential for geophysical methodologies to assist the interpolation and scaling up of models could not be tested at Brackenhurst because of the limited contrast in properties at the site.

The limitations of the Brackenhurst survey have been noted above, therefore, in order to extend the survey capability and methodologies to cover different geological and pedological settings in a systematic manner, future surveys will focus on traverses (also known as catenas) and small catchments covering the major soil-geoscapes of the UK including:

- Lowland periglacial – chalk/clay with flint (e.g. Hampshire Basin)
- Upland/crystalline rocks – valley glaciated and peat (e.g. Scotland, Wales)

- Onshore/estuarine (e.g. Humber, Thames, Mersey or Clyde estuary)
- Riverine terrain and sedimentary rocks (e.g. Trent, Midlands)
- Lowland glaciated (e.g. Vale of York, Cheshire Basin)

1 Introduction

"We know more about the movement of celestial bodies than about the soil underfoot".

Leonardo Da Vinci, circa 1500's

1.1 SUSTAINABLE SOILS PROGRAMME

Soils form an interface between the geosphere, hydrosphere, biosphere and atmosphere, through which nutrients and pollutants travel. In the past, little attention has been given to the protection of soils and to understanding their long-term development and function. In response to recent and currently developing legislation in the EU and the UK (DEFRA, 2004) regulatory agencies and industry (including agriculture) will require data on the sustainability of soils and soil function. Thus there is an increasing need to understand more clearly the coupling of the whole near surface environment to the atmosphere and hydrosphere in support of improving our knowledge of, and ability to predict, the impact of climate change and the environment on human health and ecosystems.

The BGS is currently developing a wide portfolio of data with direct relevance to improving our understanding of soils. These data are held at the UK scale, and are made available to the general public and end user. It is logical that BGS has a scientific objective to improve our understanding of the shallow subsurface as an extension of its traditional survey role. It can call upon 400 professional staff, with a range of expertise in the Environmental and Earth Scientists. BGS is uniquely qualified to work with those involved in Soil Science and Soil Survey to derive data in support of end user needs such as erosion potential maps and groundwater vulnerability assessments, to provide input into the scientific understanding of a variety of soil functions that impinge on the soil – geology interface and to provide solutions to end users such as the Environment Agency, the agricultural sector and forestry industry, and Local Authorities.

This project, which aims to develop the existing Digital Geoscience Spatial Model (DGSM) concepts via 3D and 4D modelling, is one of three projects within the Sustainable Soils Programme. Its objectives for the first year are the consultation of potential collaborators, the identification of potential co-funding opportunities, programme planning and site selection, field surveying, data interpretation, and the production of version 1 of a site specific digital spatial model. The planned work program for the Sustainable Soils Programme 2005-2010 is outlined below:

- Parent Material Mapping of the UK to a scale of 1:50,000 (define the geological component of the interface)
- Develop existing DGSM concepts via 3D and 4D modelling of interface boundaries at a site specific and catchment scale with an emphasis on the collaborative development of exempla sites (requires input in relation to soil profile and properties)
- Provide case specific examples of the relevance of interface processes and properties to subsurface biodiversity, weathering, climate and the sustainability of soil function (requires environmental, ecological, hydrological, microbiological pedological and geochemical input)
- Develop a national approach to assist in the incorporation of geological processes into improving the prediction of the impact of climate change on soil sustainability (requires climate modelling and soil science inputs).

1.2 3-DIMENSIONAL SOILS MODELLING PROJECT

Data gathering and process-based research in the top few metres of the geosphere have traditionally been split between the disciplines of geography, soil science, geology and several sub-disciplines thereof. This has led to different working practices and classifications as well as inconsistent approaches to databasing and modelling.

At a national level this has resulted in the development of significant knowledge gaps and uncertainties that hinder our ability to successfully numerically model environmental processes that traverse this divide (e.g. groundwater recharge and pollutant transport). Figure 2 illustrates the position of this knowledge gap in relation to the different depths of interest and investigation.

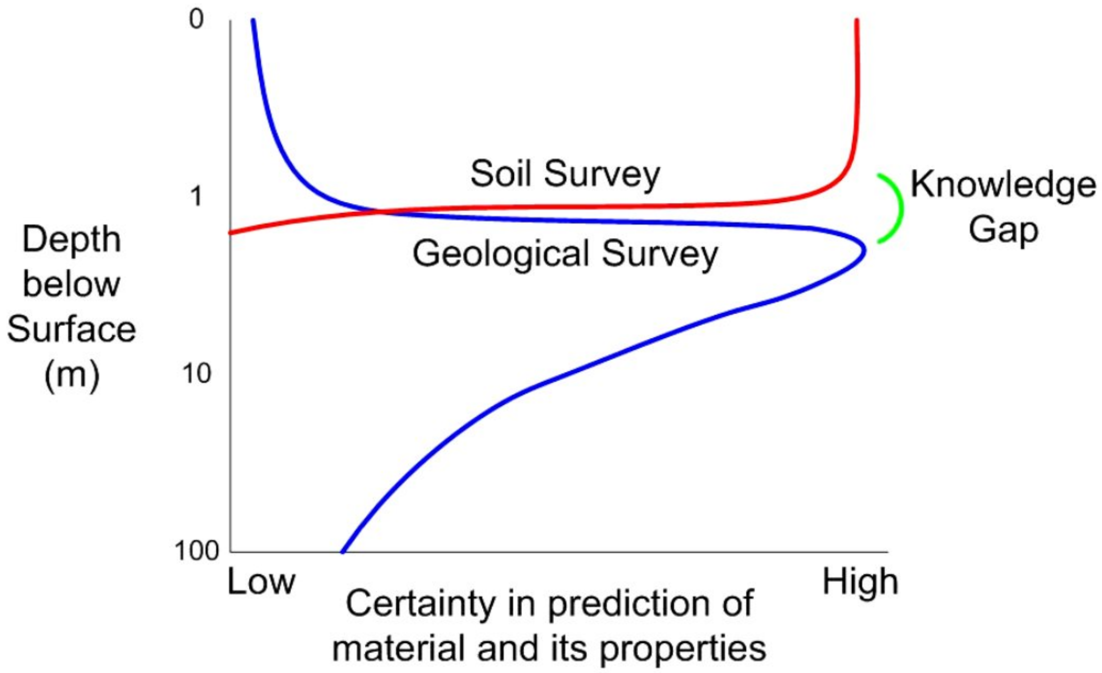


Figure 2 Schematic diagram illustrating variation in the reliability of subsurface information with depth (from Smith et al. 2006)

This project sets out to test and develop the capability and technology to carry out integrated, high detail spatial investigation and modelling of the very shallow subsurface (uppermost 4 metres), across the boundaries of disciplines and their techniques, with the principal aim of closing the knowledge gap described above.

The project draws on previous experiences of 3D geological modelling within BGS, and the testing of the GSI3D methodology described in section 4.2.2.1 forms an important part of the project. Previous modelling described by Grunewald (2006) has employed geostatistical and gridding methods to represent the distribution and geometry of soil horizons. This project will follow the spatial modelling approach as exemplified by, Kessler and Mathers (2004) with user-defined cross-sections utilising a wide range of geoscientific data in the same software environment.

2 Site Overview

The site at Brackenhurst represents the first of a number of site investigations designed to produce and test a series of spatial models covering representative catena's that cover the bulk of UK soilscapes. Being the first site key overarching issues included a relatively low level of spatial complexity, access and landowner support. These issues and others associated with site selection are described in the following sections.

2.1 SITE SELECTION

The main logistical factors and considerations that influenced the choice of site for this study included:

- finding a cooperative land owner or tenant who would grant us permission to access their land for at least one year
- Good vehicle access to and within site
- Size of site approximately 2 square kilometres
- Land Use constrains (hunting, cropping, military)
- Environmental constrains (e.g. source protection zones, protected wildlife, SSSI's)
- proximity to BGS to enable us to make frequent visits;

Main geographical considerations:

- Varying parent material across the site (at least 4 different lithologies)
- Varying topography – traverse concept (e.g. from hill plateau to valley floor, from onshore to estuary)
- Varying hydrogeology (groundwater and/or surface water)
- Varying present and historical land use and land cover.

Other factors:

- Collaboration potential with other BGS or Natural Environment Research Council (NERC) projects
- Collaboration potential with National Soil Research Institute (NSRI) or MACAULAY institute
- Existing and available datasets (e.g. HiRES, LiDAR and climate data) or research

Most of those considerations have been developed during the first year of the project. The main geographical factors had not been a priority during the selection of the first site as the importance was given to a near and well accessible site. The level of complexity of the geology in any prospective site is an important issue. An area of simple or homogeneous geology would make the task of producing the model within one year more achievable. On the other hand an area of such basic geology might not provide a worthwhile model and the resulting methodology might be too simplistic to export to other test sites and catchments. Conversely, an area of complex geology might not be modelled in one year, with obvious knock-on effects for the rest of the Programme. It was agreed to aim for a site with geology that could be modelled in the timeframe provided.

Initially, Agricultural Colleges within a few hours drive from BGS, Keyworth were contacted. The Agricultural College at Brackenhurst Campus, part of Trent University, Nottingham, were quick to reply and extremely interested in our project aims. After a site visit it was agreed to carry out the survey on their land with their full co-operation and access to all parts of the farm. Unfortunately the geology of the area was relatively simple (the whole site is underlain by the Triassic Mercia Mudstone Group), but it was decided that for the first year it was more important to test the various survey methods that could be used.

2.2 SITE LOCATION

The Brackenhurst Campus, Nottingham Trent University, is located just south of Southwell to the east of Nottingham (Figure 3). It is approximately 300 hectares and lies between 20 and 45 metres above sea level. Land use is dominated by pasture, but also with arable crops of peas and wheat.

Precipitation is fairly evenly distributed throughout the year although October and November have consistently been the driest and wettest months respectively and spring is drier than summer. The mean annual rainfall at Brackenhurst is 631 mm, the year on year variation has a standard deviation of 95 mm. The data was supplied by a member of the public.

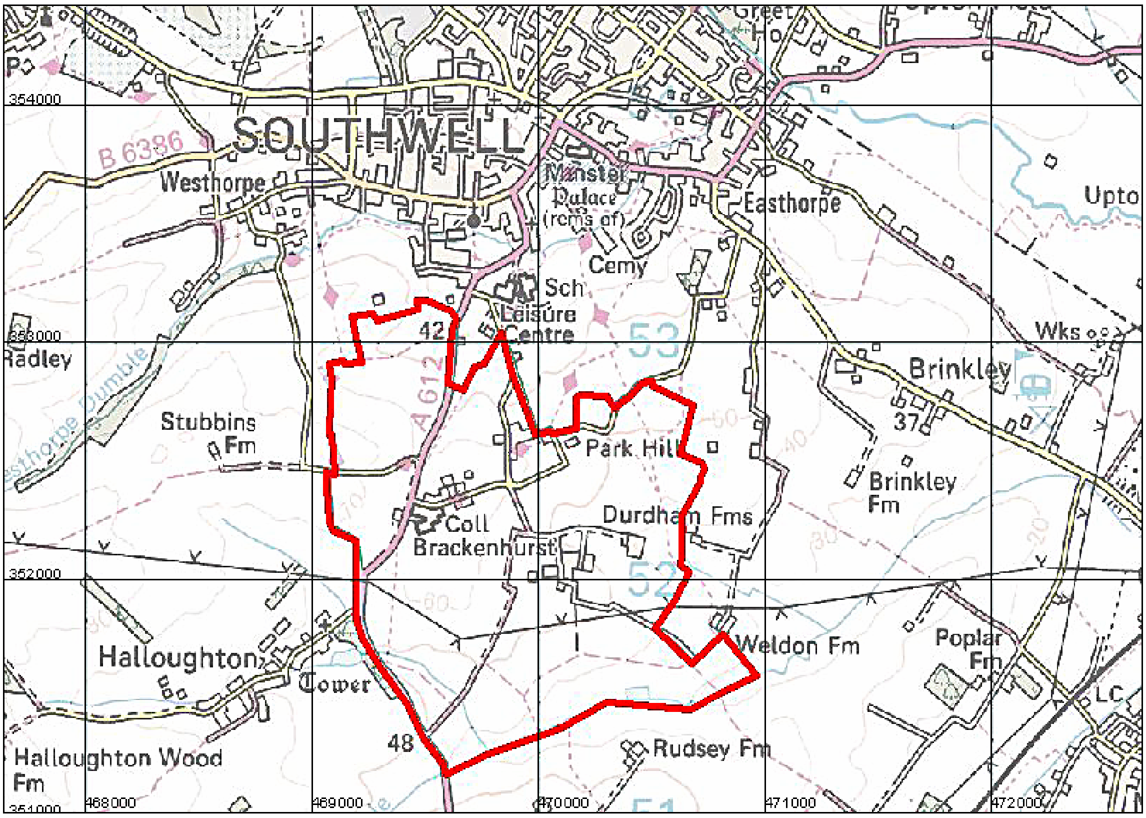


Figure 3: Location of the survey site at Brackenhurst Campus Nottingham Trent University south of Southwell. Coordinates are in metres of the British National Grid.

2.3 GEOLOGY AND SOIL

The site is situated on typical red Triassic mudstones with some interbedded greenish grey silt- and sandstones, so-called skerries. The area has been glaciated but was ice free in the latest glaciation, when the site would have been exposed to periglacial processes such as frost shattering and solifluction, which has resulted in head deposits covering the slopes and valley floors. During the Holocene the lower slopes and valley floors were filled with colluvial deposits. The soils on the site are mainly pelosols, brown earths and surface water gleys on the tops and slopes and some groundwater influenced soils on the valley floors (Palmer, 2006). More detailed descriptions of the geology and soil of the site follow in Section 3.2.

3 Site-specific investigations and methods

The intention was to complete this scoping project in one year, with one field season to mobilise and conduct all the field surveys that were under evaluation. The aim was to combine as many methods and measurements as possible and to determine their contribution to a 3D model of the shallow subsurface. The applied field methods, carried out on the Brackenhurst site are outlined in this section.

The field campaign took place between the months of July and October 2005, with most of the fieldwork carried out from the 22nd August to the 2nd September. The work is outlined below:

- Geological survey
- Drilling and pitting
- Soil survey
- Hydrogeological survey
- Geophysical survey (ground-based gamma spectrometry, electromagnetic mapping electrical resistivity tomography, down hole geophysical logging,)
- Geochemical soil sampling and analysis
- Remote sensing/Terrain analysis

Where necessary, the field surveys made use of BGS's Mobile Environmental Laboratory (MEL) pictured below, which contains chemical analysis instruments such as XRF MiniPal 4 and Niton XLt as well as laptop computers and sample processing equipment.

Figure 4 Mobile Environmental Laboratory at Brackenhurst College

3.1 GPS SURVEY

3.1.1 Aims

A differential Global Positioning System (dGPS) survey network was set up on the site in order to accurately survey the locations of the eight cable percussion, seven sonic boreholes, and additional groundwater well installations. The dGPS also provided positional fixing for the applied geophysical survey grid, and subsequently to provide accurate spot heights for digital terrain analysis.

3.1.2 Methods

The survey used the BGS Leica Geosystems Differential GPS System. The SR530 comprises a 24 channel, dual-frequency receiver with on-board Real Time Kinematic capability. On 11 August 2005, the SR530 reference receiver was installed at a central location within the site (SK470149 351892) and logged for several hours in static mode, which, after post processing, provided an accurate reference location (base station) for subsequent measurements in Real Time Kinematic (RTK) mode. The position of the reference location was marked with a yellow Perma-Mark™ survey pin, to enable it to be reoccupied during subsequent surveys.

All the locations were well within the 8km real time range of the dGPS. The instrument was used to derive point measurements with accuracies in the region of 0.01 m in the horizontal, and 0.02 m in the vertical plane. BGS typically uses this equipment where engineering survey accuracies are required, or where repeat surveys involve deriving the precise movement or change in elevation of specific points. Surveying of borehole locations BH2 & BH6-7 was undertaken during 12 August 2005; boreholes BH1, 3, 4, 5 & 8 during 22 August; and boreholes P9 & S10-16 during 1 September 2005. The receiver setup used for RTK measurement is shown below.

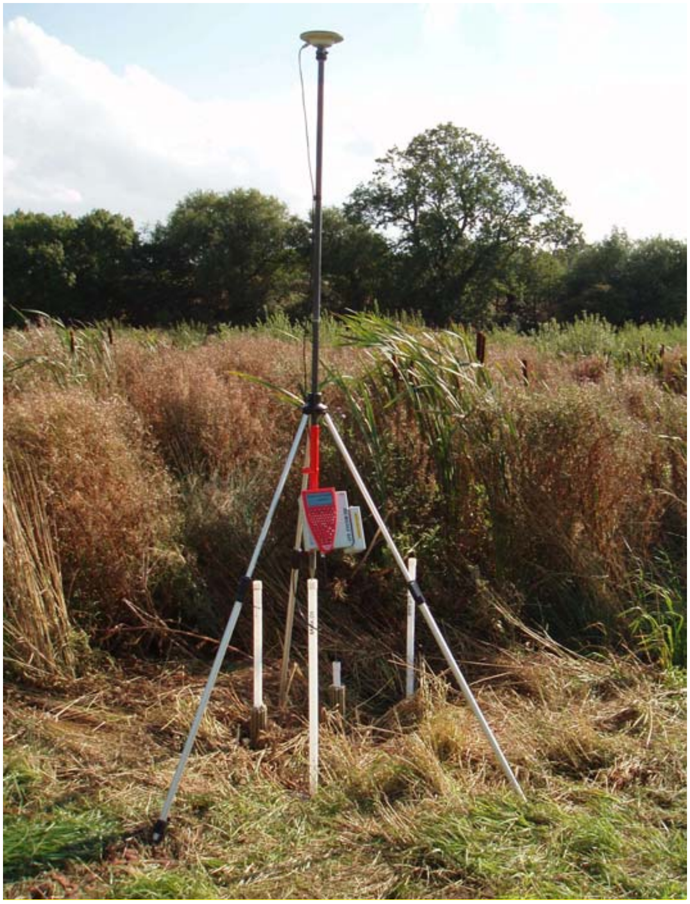


Figure 5 GPS receiver logging location of groundwater well installation

3.1.3 Results

The dGPS survey data are presented Table 1.

Table 1: Borehole locations and altitudes derived from GPS survey

Point ID	Northing	Easting	Ground Surface Altitude (mO.D.)
Reference	351892.08	470149.97	53.90
BH1	351545.36	470828.02	29.72
BH2	352931.59	469845.53	40.26
BH3	351863.40	469213.94	55.04
BH4	351491.51	469629.06	43.05
BH5	351544.76	469699.46	44.44
BH6	352506.24	470129.24	56.43
BH7	351788.71	470498.80	41.48
BH8	352883.56	469234.43	53.77
P9	352417.04	469066.85	71.29
S10	351596.75	470454.08	36.14
S10a	351596.92	470454.35	36.13
S11	351589.92	470454.30	35.74
S12	351573.19	470458.14	35.05
S12a	351573.78	470459.34	35.07
S13	351553.03	470457.77	33.69
S14	351589.24	470454.21	35.71
S15	351589.48	470454.53	35.75
S16	351497.71	470500.30	32.30
S17	351588.98	470453.88	35.66

3.2 GEOLOGICAL SURVEY

3.2.1 Aims

A geological survey of the site was undertaken at 1:10,000 scale to identify suitable locations for trial pits and boreholes. The area was originally surveyed in 1993 to a high standard but it was felt that a rapid revision would be appropriate in light of the specific requirements of this project. While superficial deposits, specifically head, were mapped in 1993, they are mapped in greater detail in the current survey.

3.2.2 Methods

The method followed normal field mapping procedures and involved a walk over the project area. The mapping was undertaken in one day. Observations on the bedrock geology were made based on topographic features that defined the hard beds of green siltstone and sandstone, coupled with observations in the fields of brash (siltstone and sandstone gravel) which occurs prolifically in ploughed fields on and below the topographic features. In general, it was found that the brash extended over a broad area below the topographic features, implying a much greater thickness than would be expected. In some cases this may relate to two or more thin beds of siltstone/sandstone in close proximity forming only one feature; in others it is purely a function of spreading by gravity and ploughing.

The siltstones and sandstones generally form narrow outcrops that follow the topographic features but locally they form well defined dip slopes, for example in the areas immediately east

[697 524] and south-east [699 520] of the college buildings. Limited augering was undertaken, mainly in an attempt to prove the Radcliffe Member, but this horizon was not identified.

The existing map shows five faults. These were checked, where possible, using displacement of the topographic features as the principal method of determination. Two of the faults have been retained on the basis of conclusive evidence of feature displacement, in the south west and east of the district. The latter fault is shown as bifurcating but the easternmost limb has been removed through lack of conclusive evidence. The faults in the extreme north and east have been retained with no evidence found to prove or disprove their presence.

Superficial deposits were shown on the 1993 map but had not been mapped to the same standard as undertaken today. Head deposits occur in six valleys that cross the area. This was mapped on the basis of concave topographic features on either side of the valley close to the bottom and supplemented by augering to prove the nature of the deposit. Alluvium also occurs in two valleys in the south of the area. Here it is defined by a narrow flat area in the valley bottom defined by concave features at the margins. In the same valley, the alluvium is flanked by head deposits defined by a second concave feature higher up the valley side. Augering was undertaken to prove the nature of the deposits and to compare the head and alluvium in this valley.

Observations on the exotic pebble content of the soil were made in all areas of ploughed fields. These are generally remanié pebbles from former glacial deposits that once covered the area but may also include material that has been dumped by landowners. In general, pebbles were very rare and only a very few quartzite pebbles were noted. The areas of superficial deposits (head and alluvium) were also generally free of pebbles. Areas of made ground were also noted, marking the position of shallow former marl or clay pits.

Structure

A number of well-developed dip slopes were noted, formed by the harder beds of green siltstone and fine sandstone. They indicate a gentle dip of around 1º that varies across the site from just south of east around Brackenhurst Farm [701 520] to east-north-east around the area of the cricket ground, to north-east a little to the north [694 527] of the college buildings. The original geological map shows five faults crossing the site.

Bedrock geology

The Brackenhurst site lies entirely on the Triassic Mercia Mudstone Group. The sequence is exclusively in the Gunthorpe Member of the Sidmouth Mudstone Formation. It comprises a sequence of red-brown, blocky and structureless mudstones with common beds of greenish grey, usually dolomitic, fine sandstones and siltstones (‘skerries’). Subordinate lithologies include laminated red and green mudstones and siltstones, which were not recognised in the field but were proved in the boreholes. The Brackenhurst College Southwell No. 9 borehole [69067 52417] proved about 26m of the Gunthorpe Member, with geophysical logs suggesting the base of this members lies at about 29m depth at an OD level of about 43 m. The rocks dip gently at around 1º to the north-east in this area of the site which places the Radcliffe – Gunthorpe boundary some way below the level shown on the original geological map in the extreme north of the site, at an OD level of around 26 m; it was not identified during the resurvey. This member comprises finely laminated red-brown, pink, purple and greenish grey mudstones, siltstones and very fine-grained sandstones and was tentatively identified in one of the shallow boreholes.

In terms of mineralogy the mudstones comprise predominately clay minerals, with subsidiary mica, silt-sized quartz and gypsum. The minor sandstones are much richer in quartz. Evaporite horizons with gypsum, dolomite, anhydrite and even halite may be locally common. The geochemistry is marked generally by high levels of potassium (bound to the clay minerals), magnesium (from dolomite), calcium (from dolomite and gypsum) and sulphate.

Superficial deposits

Superficial deposits of head and alluvium occur in the six main valleys crossing the site. Alluvium is restricted to a narrow belt in the two southern most valleys, consisting of 0.3 m of brown silty clay overlying head. Head also occurs on the lower slopes of these valleys and in four others. The head comprises red-brown silt with very few pebbles and a few clasts of Triassic green siltstone and fine-grained sandstone.

Artificial ground

Artificial ground was recognised in three areas on the site: two areas of fill material were noted around [693 523] and [704 526] comprising mainly pottery, brick, rubble and glass debris. These probably mark the sites of former marl pits that have been backfilled. One area of made ground was mapped, associated with the building site work in the college, running along the northern fringe of the college grounds on the north side of the cricket ground [698 525]. This comprised a 1-2 m high mound of topsoil and rock (red mudstone and green siltstone) debris.

Soils

The soils on the site are mainly pelosols, brown earths and surface water gleys on the tops and slopes and some groundwater influenced soils on the valley floors (Palmer, 2006).

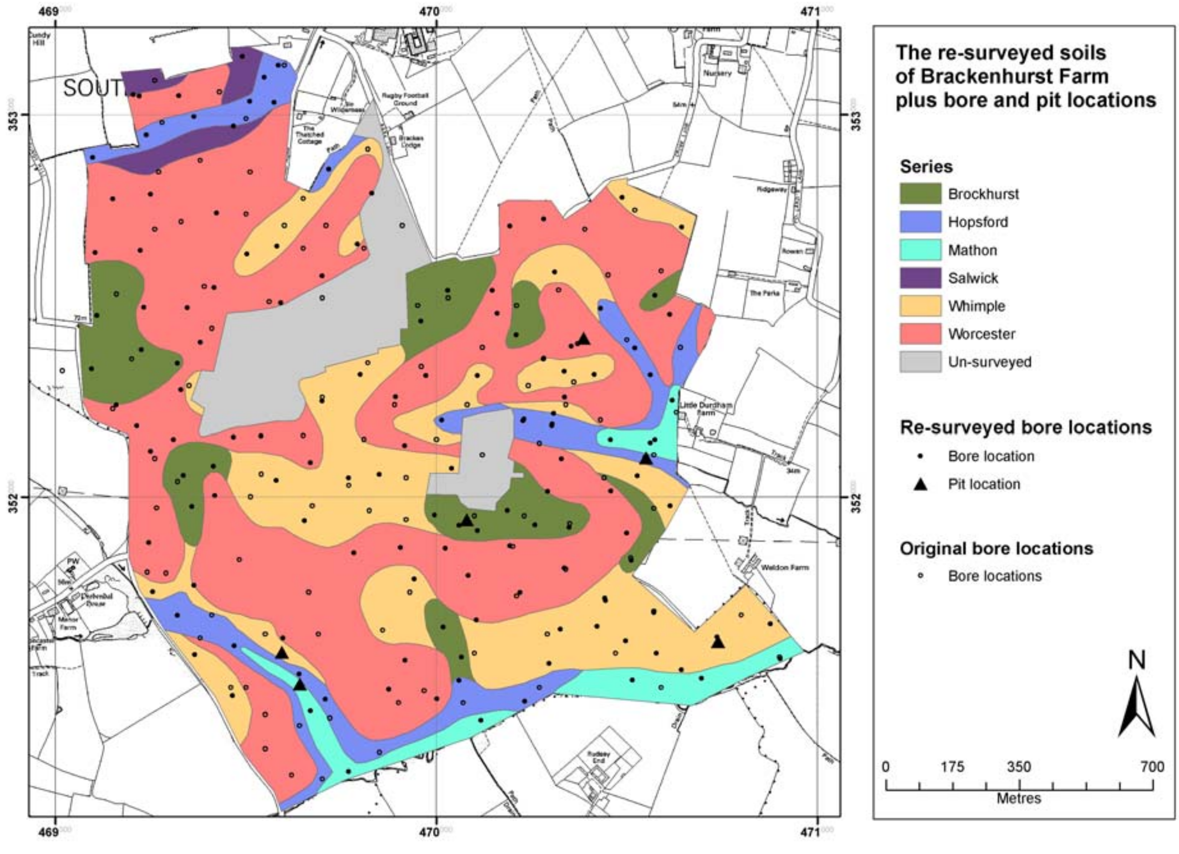


Figure 6 Soil map of the Brackenhurst Campus, Nottingham Trent University (Palmer 2006)

3.2.3 Outputs and Results

The results of the mapping were added to the BGS map database and used in the GIS and modelling packages. The geological map is illustrated below, with the site area outlined in blue.

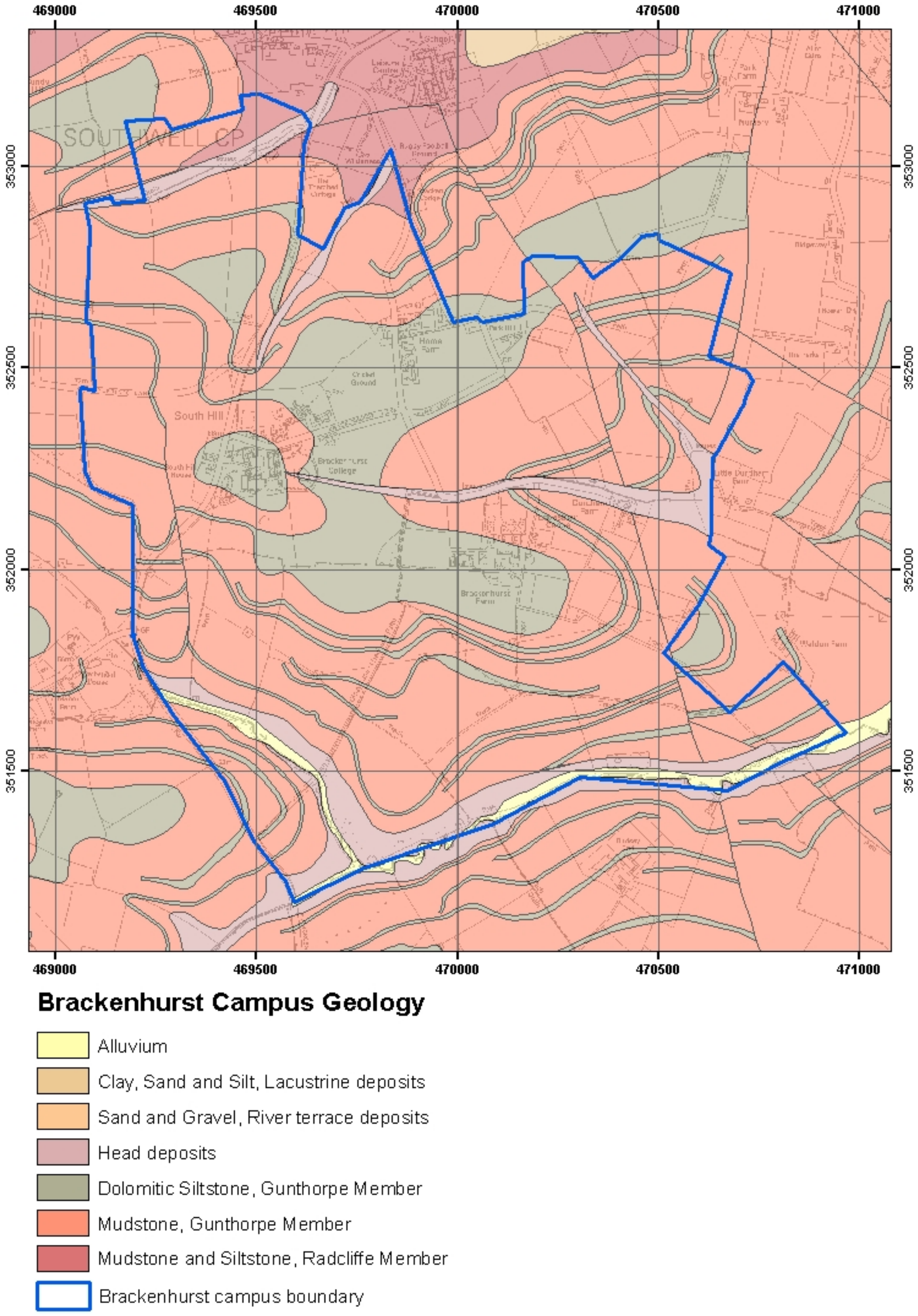


Figure 7: Site geology at Brackenhurst Campus, Nottingham Trent University (DigMap10 BGS)

3.3 INTRUSIVE SITE INVESTIGATION

3.3.1 Aims

An intrusive site investigation was planned in order to acquire samples representative of the soils, superficial deposits and, occasionally, the underlying Gunthorpe Member of the Sidmouth Formation, Mercia Mudstone Group in the Brackenhurst College study area. Three methods of intrusive investigation were used (pitting, cable percussion drilling, sonic core/rotary drilling) in order to allow:

- detailed characterisation of the soil profile;
- characterisation of the geological sequence including ‘skerry’ locations using downhole geophysics;
- high quality, undisturbed core recovery;
- estimation of engineering properties of the mudstones;
- hydrogeological assessment.

The boreholes (cable percussion drilling) and trial pits (excavator) were primarily distributed around the site to investigate a variety of the lithologies in different slope conditions in order to look at the impacts on the soil profile. The sonic rotary borehole was positioned in the northwest of the site to give a complete geological profile for the site, including the position of ‘skerries’ in the mudstones. The sonic core boreholes were positioned for a hydrogeological investigation of a spring in the south of the site. The drilling associated with this method is discussed in Section 3.5.4.

The improved geological understanding, based on the findings of the intrusive investigation, has been used in the construction of the 3D geological model of the study area.

3.3.2 Drilling methodology

A total of eight percussion boreholes, seven sonic core boreholes and one sonic rotary borehole were drilled, and six trial pits were excavated. The location and details of each intrusive site investigation point is illustrated in Figure 8.

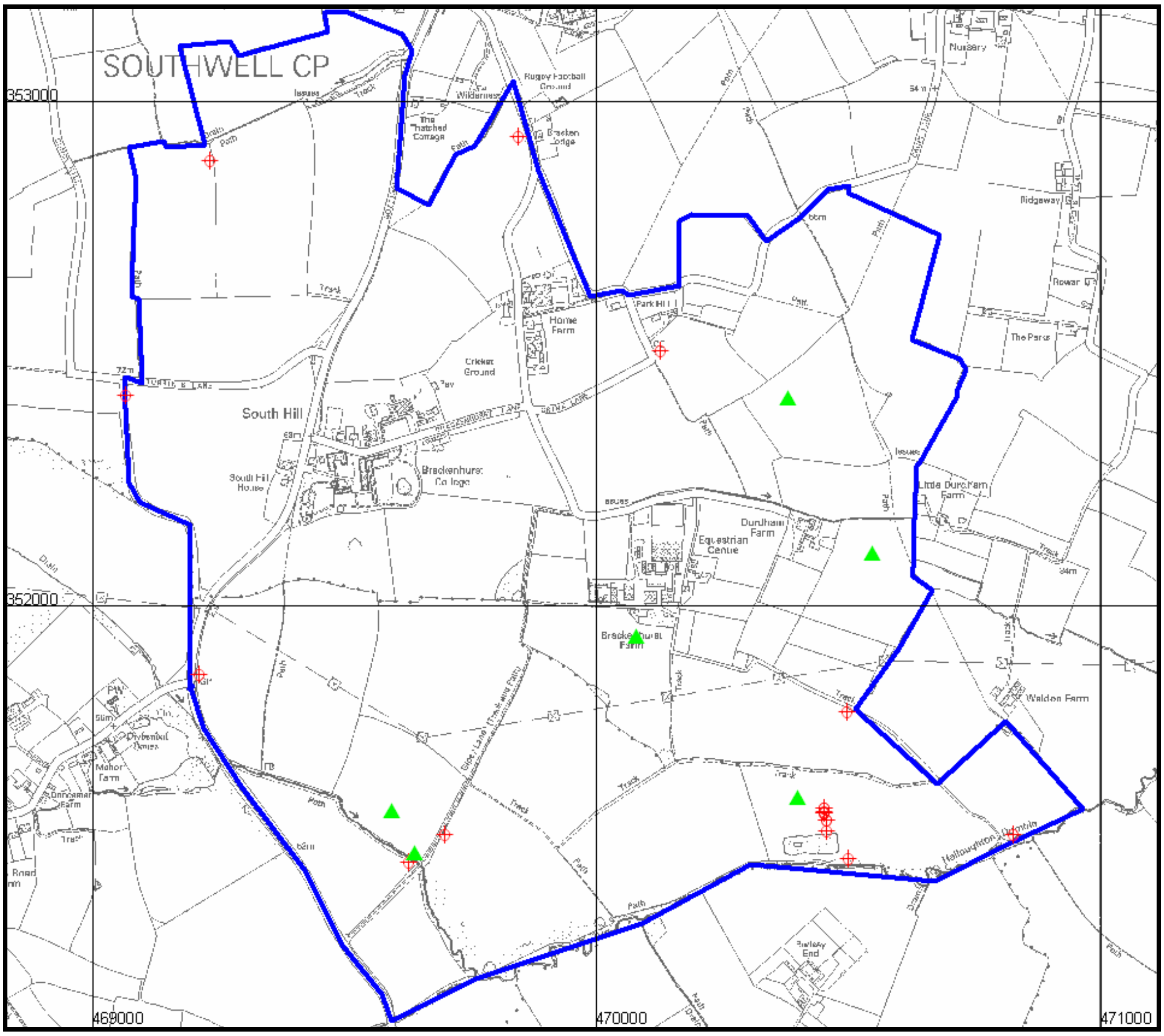


Figure 8 Locations of drilling (red crosses) and trial pitting (green triangles) sites

The eight cable percussive boreholes with a total depth 22.23m of were drilled by Groundwater Monitoring and Drilling Ltd using a Pilcon Wayfarer 1500 rig with continuous U100 core collection. A total of 15.38m of undisturbed core was recovered in 0.46 m long plastic liners that were capped and sealed with tape. Cores were labelled with borehole ID, run number, depth, and way up indicators before being transferred to the BGS for subsequent geological logging. The material in the cutting shoe from each cable percussion sample was bagged, sealed and labelled, as were the bulk samples from borehole 4. The driller’s borehole logs include the number of blows required to take the U100 cores. They are not standard penetration tests values as they are not reported as required by BS1377 part 9 (Anon., 1999) and so can not be used to describe the relative density of the coarse-grained deposits. The very high blow counts, above 100, indicate siltstone and sandstone beds.

The sonic core/rotary boreholes were drilled by Drillcorp using a Sonicbore drill rig. A total of 11.25 m of core was recovered in 1.5 m lengths of 100 mm diameter clear plastic liner, which were capped and tape sealed on site. Each core length was labelled with borehole ID, run number, depth and way up indicators. Cores were transferred to BGS for subsequent geological logging. Six of the sonic core drilled boreholes form the basis of the hydrogeological investigation and are detailed in Section 3.5.4. The one remaining sonic core borehole (S16) was drilled adjacent to a stream in the south of the site to recover potentially saturated/temporally saturated core material and for a downhole geophysical survey.

One rotary sonic borehole was drilled in the northwest of the site using the Sonicbore rig in the rotary mode coupled to an air compressor to give an air flush. The drilling method does not allow detailed geological logging as it only produces chippings recovered at regular (1-2 m) depth intervals. The primary purpose of this borehole was for a downhole geophysical survey of the entire geological sequence that outcrops in the study area.

Table 2: List of boreholes drilled on site with core recovery

Borehole ID	Drill method	Total depth (m)	Core recovery (%)	In-situ testing	Installation	Comment
BH1	Cable percussion	3.36	N/a	SPT??	None	Refilled
BH2	Cable percussion	2.52	N/a		None	Refilled
BH3	Cable percussion	1.82	N/a		None	Refilled
BH4	Cable percussion	6.10	N/a		None	Refilled
BH5	Cable percussion	2.12	N/a		None	Refilled
BH6	Cable percussion	2.12	N/a		None	Refilled
BH7	Cable percussion	1.78	N/a		None	Refilled
BH8	Cable percussion	2.03	N/a		None	Refilled
BH9	Sonic rotary	24.60	N/a		79 mm ID HDPE plain casing to 25.45 m bgl	Downhole geophysics
BH16	Sonic core	3.9			79 mm ID HDPE plain casing to 3.9 m bgl	Downhole geophysics, logged by D.Entwisle

*BH stands for Borehole at Brackenhurst College Southwell

Details of the trial pits excavated during the soil survey by the NSRI are given in (Palmer, 2006). Trial pit logs are shown in Appendix 4.

3.3.3 Core logging and sub-sampling

A total of 17.46 m of undisturbed core was recovered from the cable percussion boreholes and approximately 3.76 m from the sonic core drilling techniques. After returning the core, the liners were cut and cores split in half using the facilities at the National Geoscience Record Centre (NGRC). The core was logged by David Entwisle using BS5930 (Anon., 1999) and by Keith Ambrose using British Geological Survey logging methods. Geological and geotechnical logs for each borehole are given in Appendix 2. Photographs of the core are available on BGS Imagebase database and also in Appendix 3. One half of all core was dried out and stored in the BGS store. The samples can be found via the Borehole Material database. Both can be accessed via the IDA under http://intranet/resources/data/ida/idamain.htm.

3.3.4 SOBI registration and coding in BoGe

Borehole logs for the 8 shallow boreholes, drilled by Andy Dixon and logged by David Entwisle and Keith Ambrose, 2 deeper boreholes, geophysically logged by Ian Wood (Wallingford) and site investigation logs obtained from Nottingham Trent University were scanned and registered in the Single Onshore Borehole Index (SOBI) and subsequently coded in the Borehole Geology (BoGe) facility. Additionally 6 trial pit logs by Robert Palmer (NSRI) were also entered into SOBI and coded in BoGe.

Augerholes from the soil survey carried out by Robert Palmer (NSRI) and G-BASE augerholes are currently managed in their own databases and are listed in the GSI3D borehole index (*.bid) file. This file will be submitted to the Geoscience Large Object Store (GLOS) together with the other 3D model data after the model completion.

Table 3 below lists SOBI registration codes for each borehole and trial pit existing on site.

Table 3: SOBI registration codes for boreholes and trial pits

Borehole name	SOBI	Comment
Brackenhurst College Southwell 1	SK75SW27	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 2	SK65SE38	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 3	SK65SE39	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 4	SK65SE40	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 5	SK65SE41	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 6	SK75SW34	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 7	SK75SW28	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 8	SK65SE43	Drilled by Andy Dixon (GMD)
Brackenhurst College Southwell 9	SK65SE64	Sonic rotary, geophys. log
Brackenhurst College Southwell 16	SK75SW29	Sonic core, geophys. log
Durdham Farm Soil Pit TP 1	SK75SW30	Robert Palmer, NSRI
Brackenhurst Farm Soil Pit TP 2	SK75SW31	Robert Palmer, NSRI
Durdham Farm Soil Pit TP 3	SK75SW32	Robert Palmer, NSRI
Brackenhurst Farm Soil Pit TP 4	SK75SW33	Robert Palmer, NSRI
Brackenhurst Farm Soil Pit 5	Not in SOBI	Robert Palmer, NSRI
Brackenhurst Farm Soil Pit 6	Not in SOBI	Robert Palmer, NSRI
Brackenhurst College Nottingham Trent University (NTU) BH 1	SK65SE44	By BWB Consulting
Brackenhurst College NTU BH 2	SK65SE45	By BWB Consulting
Brackenhurst College NTU BH 3	SK65SE46	By BWB Consulting
Brackenhurst College NTU BH 4	SK65SE47	By BWB Consulting
Brackenhurst College NTU BH 5	SK65SE48	By BWB Consulting
Brackenhurst College NTU BH 7	SK65SE49	By BWB Consulting
Brackenhurst College NTU TP 1	SK65SE50	By BWB Consulting
Brackenhurst College NTU TP 13	SK65SE51	By BWB Consulting
Brackenhurst College NTU TP 14	SK65SE52	By BWB Consulting
Brackenhurst College NTU TP 15	SK65SE53	By BWB Consulting
Brackenhurst College NTU TP 16	SK65SE54	By BWB Consulting
Brackenhurst College NTU TP 17	SK65SE55	By BWB Consulting
Brackenhurst College NTU TP 18	SK65SE56	By BWB Consulting

Brackenhurst College NTU TP 2	SK65SE57	By BWB Consulting
Brackenhurst College NTU TP 3	SK65SE58	By BWB Consulting
Brackenhurst College NTU TP 4	SK65SE59	By BWB Consulting
Brackenhurst College NTU TP 5	SK65SE60	By BWB Consulting
Brackenhurst College NTU TP 6	SK65SE61	By BWB Consulting
Brackenhurst College NTU TP 7	SK65SE62	By BWB Consulting
Brackenhurst College NTU TP 8	SK65SE63	By BWB Consulting

Figure 9 below, shows an example of the entry system for coding borehole geology. All boreholes and trial pits at the Brackenhurst site were entered to the BGS Corporate Database under BC (Brackenhurst College).

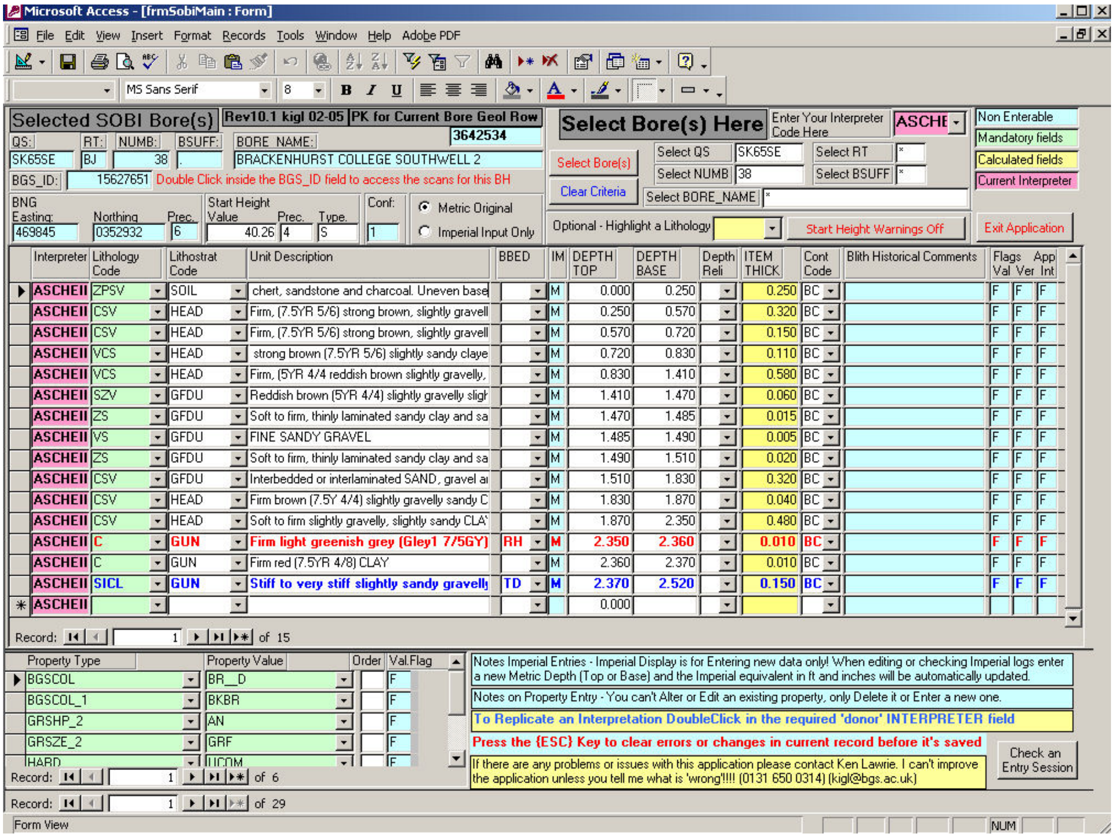


Figure 9: Coding interface of Borehole Geology (BoGe)

NSRI soil texture descriptions had to be converted into BGS standard lithology codes before they could be added to the BGS system. Table 4 lists four NSRI texture descriptions for loam along with their BGS equivalents.

Table 4: Conversion of NSRI loam texture to comparable BGS lithology codes

NSRI texture	BGS Lithology	
Clay loam	CSZ	Silty sandy CLAY
Silty clay loam	CZS	Sandy silty CLAY
Silt loam	ZCS	Sandy clayey SILT
Sandy loam	SCZ	Silty clayey SAND

3.3.5 Discussion and results

The geological map of the area (Figure 7) shows that the Gunthorpe Member of the Sidmouth Mudstone Formation underlies the site. Alluvium is adjacent to the river in the south of the site and Head deposits are in the valleys. A summary of the borehole interpretation, subdivided by deposit, is provided below. The majority of time was spent converting the borehole data into digital format so that it could be input, in combination with the rest of the survey data, into a package such as GSI3D so that a three-dimensional model of the geology and soils could be constructed. The model is discussed in Section 4, 3D Digital Modelling.

3.3.5.1 Topsoil

The topsoil is present in all the boreholes. It is between 0.25 to 0.36 m thick and comprises generally firm, dark grey mottled reddish brown organic clay, or uncompact to compact reddish brown or dark brown organic silt with very closely spaced roots. The mottled parts have the same basic colour and texture as the material below and are likely to be derived from it. Sand to fine gravel-sized manganese oxide concretions are sometimes present. Fine to medium gravel occurs in Topsoil in some of the boreholes. In Borehole 2 it has a manmade component, including brick, chert and charcoal, whereas in Boreholes 3, 5, 6, 7, 8 and 16 the gravel is locally derived, weak to strong siltstone and sandstone. The base of the topsoil undulates or is uneven.

3.3.5.2 Subsoil

A separate subsoil layer from Boreholes 3 and 7 is 0.15 to 0.29 m thick comprising very stiff reddish yellow mottled reddish brown slightly gravelly clay with very closely spaced roots and reddish brown root traces.

3.3.5.3 Coarse Head?

Approximately 0.5 m thick sand deposit beneath the topsoil occur in boreholes 4 and 8. It is red or reddish yellow, slightly gravelly, silty, fine to coarse sand with some sand to fine gravel sized manganese oxide nodules. This may be a coarse Head deposit.

3.3.5.4 Fine Head

Fine Head is present in Boreholes 1, 2 and 16 and varies between 0.59 m thick in borehole 1 to over 1 m thick in boreholes 2 and 16. It is generally soft to firm, brownish red, occasionally mottled light greenish grey, occasionally or slightly gravelly clay. The gravel is usually fine to medium subangular to angular or tabular moderately strong to strong siltstone and fine sandstone. In Borehole 2 the head contains a 0.11 m thick layer of gravel. Manganese oxide nodules and rootlets are sometimes present.

3.3.5.5 Alluvium

Approximately 1.8 m thick layer of Alluvium is present below Head in Borehole 16. The true thickness was difficult to measure, the driller considers that part of this material is infill from above and there was no driller’s log supplied. However, the ‘infill’ is different from the material above. The Alluvium is slightly organic, generally dark greyish brown, brown or dark grey and varies between soft, thinly laminated clay, in the upper few centimetres, to gravelly, very sandy clay and slightly clayey gravelly sand. There are occasional rush or reed stems and roots in the clay and very sandy clay. Clayey or gravelly sand contain occasional to some shell fragments.

3.3.5.6 Colluvium

Borehole 2 contained hill wash or colluvium between 1.47 and 1.83 m deep within Head. It comprised two complex, upward fining sequences. The lower one, about 0.31 m thick, contained approximately 0.29 m thick, of inter bedded or interlaminated sand, fine gravel and soft to firm sandy clay with a sharp basal contact sloped at about 35 º. Above was 20 mm of soft to firm, thinly laminated sandy clay and sandy silt, the laminae being 1 – 2 mm thick. The base of the upper sequence was 20 mm thick; the lower part was a 5 mm thick sandy fine gravel and the upper part, 15 mm thick, was similar to the lower laminated unit.

3.3.5.7 GUNTHORPE MEMBER

All the boreholes encountered the Gunthorpe Member, but the depth of rockhead varied between 0.31 m in borehole 5, and 3.63 m in borehole 2, beneath Topsoil, Head and Alluvium. The thickness encountered varied between 0.27 m in Borehole 16 and 4.78 m in Borehole 4. The majority of the Gunthorpe Member is firm to stiff red, reddish brown, with mottles or thin beds of greenish grey or pale grey clay or compact silt. The strength may increase with depth becoming very stiff or very weak mudstone or moderately weak siltstone. Very closely space fissure were only observed in Borehole 16. The clay and silt may contain siltstone and sandstone gravel derived from weathered siltstone and fine sandstone. Thin to very thin beds of moderately weak to moderately strong red or grey or greenish grey siltstone or moderately strong to strong white or grey, sometimes red, fine sandstone occur throughout. Manganese oxide concretions sometimes occur within a metre of the base of the Topsoil. Calcareous concretions or patches were found in Gunthorpe Member where there was no fine Head above.

3.3.5.8 RADCLIFFE MEMBER

About 0.16 m of the Radcliffe Member was encountered in the bottom of Borehole 2 and comprised firm to very stiff, micaceous, red, slightly sandy gravelly clay/silt.

3.4 REMOTE SENSING / TERRAIN ANALYSIS

3.4.1 Aims

Remote sensing includes both satellite and airborne investigations of the earth’s surface, however the scale of mapping required in this project restricted the imagery to high resolution data acquired from an airborne platform i.e. aerial photography and terrain models that were derived from an airborne radar survey. The aim of these remote sensing / terrain analysis techniques was to provide imagery that is interpreted for geomorphological, geological and general land use information.

3.4.2 Methods

Digital colour aerial photography was acquired with 25 cm ground resolution, photogrammetrically scanned at 20 microns (Figure 10). Ten vertical stereoscopic photographs were required to cover the *ca.* 9 km^2 project area.

Figure 10 25cm resolution orthophotograph of the Brackenhurst site

Hardcopies of the photographs were printed onto stable card for traditional stereoscopic interpretation at the NSRI and by BGS geologists. Unfortunately, the system for digital photogrammetric interpretation was not in place prior to the fieldwork on the Brackenhurst site so feature mapping interpretation was carried out using the hardcopy photographs and mirror stereoscopes.

A Digital Terrain Model (DTM) of the site was extracted from the NEXTMap DTM product generated by Intermap Technologies®. The NEXTMap system is an airborne active side-looking X-band interferometric synthetic aperture radar system that transmits a pulse of energy at an angle to the airborne mounting platform and records the return signal at two parallel radar antennae mounted with a 1m separation. The time between the transmitted and returned signal at each antenna is used to calculate the distance, or range, between the system and the ground as a function of the phase difference between the returned signals. The range is then converted to elevation based on the position of each antenna with respect to the altitude and attitude of the platform. The NEXTMap DTM is a ‘bare earth’ model of surface topography, at a 5m spatial resolution, where elevation values relating to buildings, vegetation and cultural features were digitally removed from the initial Digital Surface Model (DSM) by Intermap using their TerrainFit® software. This dataset represents a georeferenced digital terrain model that is corrected to OD and represents the terrain underlying the filtered features. The vertical accuracy of the DTM is stated as 0.7m-1.0m.

The DTM was assessed to gauge its applicability to soils mapping and modelling in this terrain. Initial visualisation of the DTM suggested that the TerrainFit filtration had removed trees, hedgerows and farm buildings from the original DSM (Figure 11). However, on closer inspection it became apparent that errors had been introduced during the filtration process. Some of the errors may be a result of the position of the trees with respect to the incidence angle of the radar pulse and the slope of the topography (Figure 12), but other peak and trough elevation errors were more subtle and more widely distributed across the study area (Figure 13) and are not easily attributed to any particular feature in the DSM.

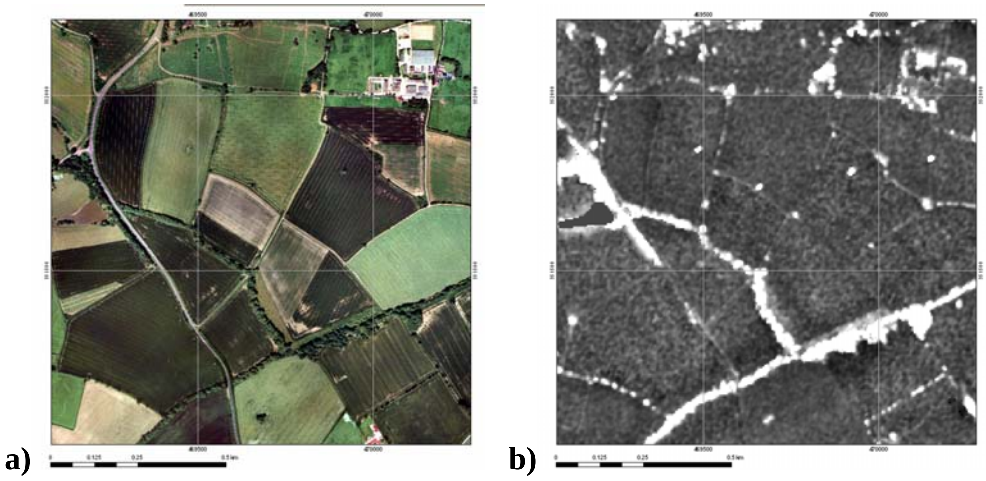


Figure 11: Comparison between a) aerial photograph and b) DSM-DTM difference image, where a high difference between the elevation models appears in white

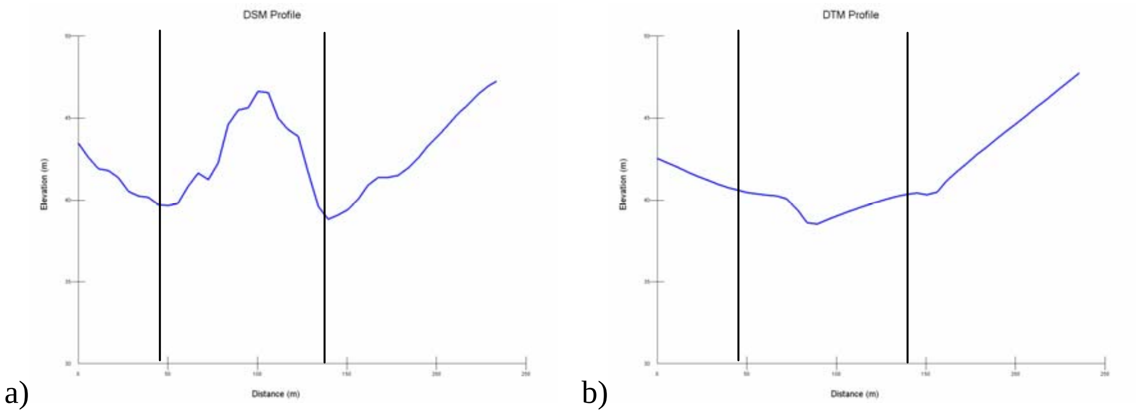


Figure 12: Elevation profile across a hedgerow from the a) DSM and corresponding b) DTM showing offset in the leading edge of the feature and prominent elevation troughs at the edges of the feature

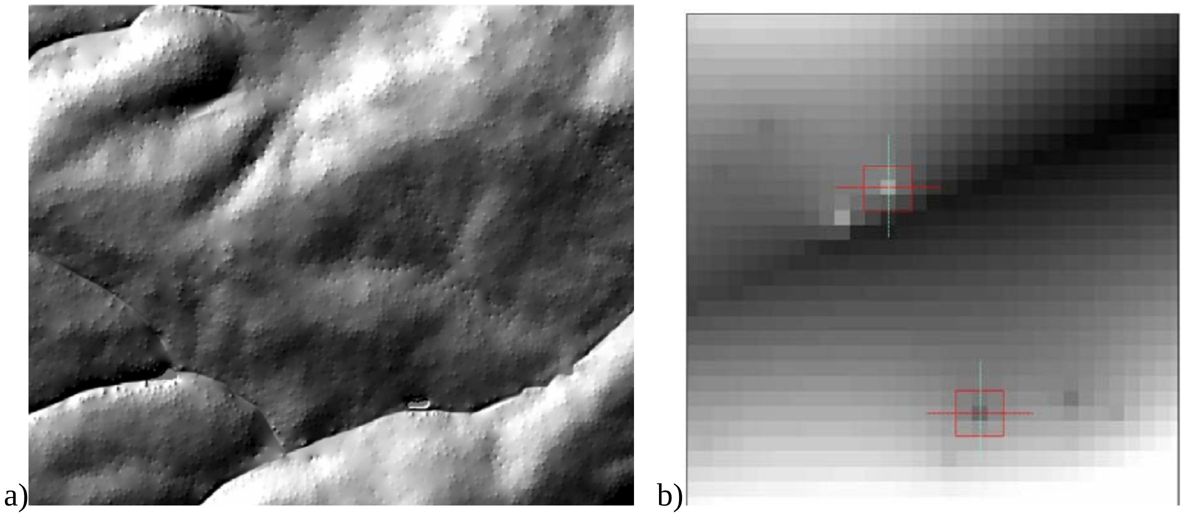


Figure 13: a) Hillshade image revealing pitted appearance of the DTM with b) an example zoom of the peak and trough elevation errors

In order to remove the peak and trough errors from the DTM and provide a more accurate representation of surface topography from which to hang borehole data for 3D soil modelling, a series of digital filtration techniques were applied to the NEXTMap DTM. The techniques adopted were the application of (i) smoothing filters within the ArcGIS environment and (ii) speckle suppression filters within ERDAS Imagine. These are described in Appendix 5.

3.4.2.1 CONCLUSIONS FROM THE DIGITAL NOISE REMOVAL TECHNIQUES

Attempts to remove the peak and trough errors from the DTM through standard digital filtration techniques were unsuccessful. The best results appeared to come from application of the Mean 7x7 smoothing filter, but this also affected the elevation values of the pixels surrounding the error pixel. The Gaussian 7x7 smoothing filter also appeared to reduce the errors without greatly affecting the surrounding elevation values, but errors still remained in the data. It is unlikely that the errors can be removed by increasing the filter matrix in either filtration technique as the spacing between the error pixels is such that a greater filter matrix size would begin to incorporate more than one individual error pixel. The Fourier Transformation has the greatest potential for removal of these high-frequency spatially-widespread errors, but due to time constraints this technique was not applied to completion. Further work will be required in order to generate an accurate surface topographic representation from which to hang borehole data for 3D soil modelling.

3.4.3 Outputs and Results

The outputs from the remote sensing study include digital aerial photography with a pixel size of 25cm in digital stereoscopic and orthophoto format. These data were integrated into the project GIS and were also made available in hardcopy format. The aerial photography provided an informative base that data could be displayed in the GIS, as well as a source for interpreting soil and geological data. The amount of geological information obtained from the aerial photography was less than normally expected due to the low relief of the features and the low variability of the parent material and hydrogeology. Despite this, it is recommended that aerial photography is used in future soil projects due to the valuable information it can provide especially in areas of higher variability of parent material and related soils.

NEXTMap terrain and elevation models were also obtained and processed to remove artefacts before producing derivative raster datasets including shaded relief models. The DTMs and derivatives were used for interpretation and for surface modelling in various software packages. While the resolution of the NEXTMap data is at its limit for a study of this type, and other data such as LiDAR are preferred, a suitable form of DTM/DEM is certainly a prerequisite for any soil project in the future.

3.5 GEOHYDROLOGICAL SURVEY

3.5.1 Regional Setting

The hydrogeology of the East Midlands is dominated by the Sherwood Sandstone Group, which forms the principle aquifer in the region. The Sherwood Sandstone Group is unconfined in a north-south strip running approximately from Nottingham to Darlington with a shallow easterly dip (Smedley and Brewerton, 1997). The Mercia Mudstone Group confines the Sherwood Sandstone aquifer to the east. In the East Midlands, groundwater flow direction in the Sherwood Sandstone aquifer is approximately east to northeast, from the unconfined recharge area towards the confined aquifer, at a shallow hydraulic gradient of approximately 1 in 250 (Edmunds and Smedley, 2000). Piezometric gradients suggest that there may be upward flow from the confined portion of the aquifer through the Mercia Mudstone Group via discontinuities or more permeable horizons (such as “skerries”) (Edmunds and Smedley, 2000). However, it is reported that the River Trent has little or no hydrological interaction with the confined Sherwood Sandstone aquifer (Trowsdale and Lerner, 2003).

Groundwater in the Sherwood Sandstone aquifer progressively ages from recent to late Pleistocene along flow direction under the confining Mercia Mudstone Group (Edmunds et al, 1982). The groundwater chemistry changes along this flow path, becoming progressively more saline.

The Mercia Mudstone Group is dominated by low permeability mudstones and siltstones, however coarser siltstones and sandstones can act as minor groundwater supplies (Brown, 1981). These skerries are generally hydrogeologically independent bodies with lower permeability mudstones above and below. However, discontinuities can allow hydraulic continuity between horizons. The high gypsum content in the Mercia Mudstone Group results in hard groundwater (50 – 2000 mg l^{-1} non-carbonate hardness increasing with depth, and 50 – 450 mg l^{-1} carbonate hardness decreasing with depth).

3.5.2 Site setting

The site owners identified a perennial spring that was feeding a man-made pond in the south of the site. A walkover located the spring source as saturated ground within the field. Groundwater from the spring did not flow at surface, but appeared to be transported down gradient to the pond in the soil zone. The spring source is located on a mapped skerry, and is the presumed immediate source of the groundwater. However, it is uncertain whether the skerry is recharged directly from precipitation, or if a fault approximately 150 m to the east may be feeding the skerry.

3.5.3 Aims

The aims of the hydrogeological survey were three-fold:

1. To identify the effect on soil colour, composition and structure in a permanently or semi-permanently saturated environment (fluviosol/gleysol) and to identify if soil descriptions can be used as an indication of the saturation state;
2. To monitor groundwater heads and gradients (vertical and horizontal) within the spring area over a rising groundwater level period (Autumn to Spring);
3. To identify the inorganic chemical composition of the groundwater in order to try and identify a likely source, and if any identifiable evolution occurs during interflow.

3.5.4 Methods

In order to meet the aims of the hydrogeological survey a Sonicbore drilling rig was used to collect core material and to install piezometers that could be used for groundwater head measurements and sampling.

Three of the boreholes drilled were installed with 25 mm diameter quality well installations. Three additional 25 mm diameter well installations were emplaced using the lost point method. Details of the cored boreholes are given in Table 5 and the installed boreholes in Table 6. Borehole locations are shown in Figure 8. Borehole logs are given in Appendix 2.

Table 5: Cored borehole summary

BH ID	Total depth (m bgl)	Comment
S10	0.76	Disturbed core sample
S10a	0.61	Drilled to refusal
S11	2.43	Water strike at ~ 1.3 m bgl
S12	1.3	Mudstone at ~ 0.6 m bgl
S12a	0.6	
S13	1.65	Mudstone at ~ 0.9 m bgl
S16	3.9	Deep geophysics boreholes

Table 6: Borehole installation details (all installed with 25 mm diameter quality well installations)

BH ID	Location	Ground level (m aOD)	Piezometer bottom depth (m bgl)	Piezometer length (m)	Comment
S11	Spring	35.74	2.0	1.0	Cored
S12a	Interflow 1	35.07	0.6	0.4	Cored
S13	Interflow 2	33.69	1.1	1.0	Cored
S14	Spring	35.71	1.2	0.5	Lost point
S15	Spring	35.75	0.8	0.5	Lost point
S17	Spring	35.66	1.4	0.5	Lost point

3.5.5 Results and discussion

3.5.5.1 SOIL SATURATION INDICATORS

NSRI use the soil wetness class to provide information on the length of time a soil is water logged as shown in Table 7. The wetness classes may be measured using several different methods:

1. quantitative data recorded over a suitable period using dip-well or tensiometers at the site;
2. quantitative data from a similar soil and site elsewhere;
3. interpretation of the observation of soil-water states of many similar soils in different seasons;
4. inference from the morphology and water state of a particular profile at a particular time.

Ideally, the classification should be made using method 1. Assessment by method 4 is speculative and very subjective and should not normally be used to allocate classes II to IV. However, a soil may be allocated to a particular class with varying degrees of confidence using soil morphology, vegetation, water condition and site information at the time of examination only by those with experience of this soil in this situation. Some simple indicators may be used and are indicated in the Table 7 of some of the classes.

Table 7 Wetness class definitions (Hodgson, 1997)

Wetness class	Descriptive term	Duration of waterlogging (in most years)	Indicators
I	Rarely wet (well drained)	Soil profile not wet within 0.7 m of the surface for more than 30 days	Unmottled
II	Seldom wet (Slight seasonal waterlogging)	Soil profile is within 0.7 m of the surface for 31 to 90 days or, if there is no slowly permeable layer within 0.8 m from the surface, it is wet within 0.7 m for more than 90 days, but not wet within 0.4 m from the surface for more than 30 days in most years.	
III	Occasionally wet (Seasonally waterlogged)	Soil profile is wet within 0.7 m of the surface for 91 to 180 days in most years or, if there is no slowly permeable layer within 0.8 m of the surface, it is wet within 0.7 m for more than 180 days, but only wet within 0.4 m of	

		the surface for between 31 and 90 days in most years.	
IV	Commonly wet (Waterlogged for long periods in winter)	Soil profile is wet within 0.7 m of the surface for more than 180 days but not within 0.4 m of the surface for more than 210 days in most years or, if there is no slowly permeable layer within 0.8 m of the surface, it is wet within 0.4 m of the surface for 90-210 days in most years.	
V	Usually wet (Severely waterlogged)	Soil profile is wet within 0.4 m of the surface for 211 to 335 days in most years.	Normally wet within 0.7 m when examined. In lowland Britain are usually confined to basin sites or sites subject to frequent flooding.
VI	Permanently wet (permanently waterlogged)	Soil profile is wet within 0.4 m of the surface for more than 335 days in most years.	Generally has peaty surface, as dead vegetation rots slowly, and typical vegetation of permanently wet soils

Indication of soil wetness, using method 4, requires description of soil morphology, as used in soil surveys, including mottling associated with gleying that indicates periodic waterlogging. The soil series is defined from the morphology of the soil, the parent material and site and may be used to indicate a wetness class (Palmer, 2006, Table 4) and therefore the expected duration of waterlogging. The wetness class for each soils series is shown in Table 8 and the typical characteristics affected by water logging of some of the series are in Table 9.

Gleying occurs in poorly drained soils, which are periodically waterlogged. Gleying is the process of reduction, generally of iron, which becomes more mobile usually with manganese and some other trace elements. The reduction and possible mobilisation of iron often results in grey streaks or mottles and the end point of this is a grey horizon sometimes with ochreous mottling. Gley soils are often split into surface-water and ground water gley from their two main modes of formation.

- Surface-water gley occurs in slowly permeable soils, drainage is restricted by an impermeable layer within the soil so seasonal waterlogging is mainly in the upper horizons in the profile. It is prominently mottled above 0.4 m below the surface. Surface water gley soils include Brockhurst, Clifton and Spetchley Series. Other soils affected to some degree by surface water gleying include Salwick, Worcester and Whimple Series.

- Groundwater gley soils normally develop within or over permeable materials, where the groundwater table approaches the surface, waterlogging the lower part of the profile. They are often found in flat areas. Groundwater gley soils include Dophenby and Fenacre Series. Other soils affected by groundwater include Hopsford and Mathon Series.

Soil profile descriptions (Palmer, 2006) describe the changes in soil morphology for Worcester, Whimple, Brockhurst, Hopsford, Salwick and Mathon Series including mottling associated waterlogging.

Table 8 Wetness class and main characteristics for the soils series identified at Brackenhurst (Palmer, 2006)

Soil Series	Characteristics	Inferred wetness descriptive term	Wetness Class
Clayworth	Slowly permeable, slightly mottled reddish calcareous clays, passing to soft blocky mudstone within 80 cm depth.	slight waterlogging	II
Worcester	Slowly permeable, slightly mottled reddish clays with, passing to soft blocky mudstone within 80 cm depth.	slight waterlogging	II
Wheatley	Well-drained permeable calcareous medium silts over lithoskeletal siltstone at 40 to 80 cm depth, no prominent mottling or greyish colours (gleying) above 40 cm depth.		
Fordoles	Moderately permeable, slightly mottled calcareous medium loams or silts with slight seasonal waterlogging over slowly permeable clays at 40 to 60 cm depth passing to soft blocky mudstone.	slight seasonal waterlogging	II
Hopsford	Deep, moderately permeable, mottled reddish medium loams, slight seasonal waterlogging by groundwater	slight seasonal waterlogging	II
Mathon	Deep, moderately permeable, mottled reddish alluvial medium silts, slight seasonal waterlogging by groundwater.	slight seasonal waterlogging	II
Salwick	Slightly mottled, slightly stony reddish medium loams with a slowly permeable subsoil and slight seasonal waterlogging	slight seasonal waterlogging	II
Whimple	Moderately permeable, slightly mottled medium loams or silts with slight seasonal waterlogging, over slowly permeable reddish clays at 40 to 60 cm depth and passing to soft blocky mudstone at depth	slight seasonal waterlogging	II
Brockhurst	Moderately permeable, ochreous and grey mottles, medium loams or silts with slight seasonal waterlogging, over slowly permeable reddish clays at 40 to 60 cm depth and passing to soft blocky mudstone at depth.	seasonal waterlogging	III
Clifton	Slowly permeable, prominently mottled, seasonally waterlogged slightly stony reddish medium loams	seasonal waterlogging	III
Spetchley	Slowly permeable, prominently mottled, seasonally waterlogged clays passing to soft blocky mudstone at depth.	seasonal waterlogging	III
Dophenby	Deep, moderately permeable, prominently mottled reddish alluvial medium loams, seasonally waterlogged by groundwater.	seasonal waterlogging	III
Fenacre	Deep, moderately permeable, prominently mottled reddish medium loams, seasonally waterlogged by groundwater.	seasonal waterlogging	III

Table 9 Wetness characteristics of some soil series.

Soil Series	Characteristics
Worcester	Slowly permeable subsoil restricting down ward percolation of water causing seasonal water logging in winter and early spring.
Mathon	Moderately permeable upper layer; lower layers affected by fluctuating groundwater during winter and early spring.
Hopsford	Moderately permeable upper layer, lower layers are affected by fluctuating groundwater in winter and early spring.
Salwick	Moderately permeable clay loam upper layers overlying slowly permeable slightly heavier subsoil, which produces slight seasonal surface waterlogging in winter and early spring.
Whimple	Moderately permeable upper layers (to 40-70 cm depth) overlying slowly permeable reddish clayey subsoil.
Brockhurst	Suffer marked surface wetness caused by their slowly permeable subsoil, which severely restrict downward drainage.

3.5.5.2 GROUNDWATER ELEVATION AND GRADIENT

Groundwater elevation was measured in boreholes seven times (approximately every two weeks) between 18 October 2005 and 02 February 2006. The results, adjusted to metres above ordnance datum (m aOD) are given in Table 10 and shown graphically in Figure 14.

Table 10 Measured groundwater elevation in installed boreholes at Brackenhurst

Group	BH ID	Elevation casing (m aOD)	Dipped GW level (m aod)						
			18-Oct-05	1-Nov-05	17-Nov-05	29-Nov-05	19-Dec-05	12-Jan-06	2-Feb-06
Spring	BrackS11	36.65	35.23	35.31	35.32	35.29	35.28	35.31	35.31
	BrackS15	36.53	35.47	35.50	35.52	35.51	35.50	35.50	35.50
	BrackS14	36.08	35.48	35.50	35.52	35.49	35.47	35.40	35.48
	BrackS17	36.49	35.67	35.71	35.70	35.68	35.69	35.67	35.65
Interflow 1	BrackS12a	35.70	34.73	34.77	34.74	34.73	34.65	34.68	34.65
Interflow 2	BrackS13	34.63	33.30	33.30	33.29	33.30	33.29	33.31	33.29

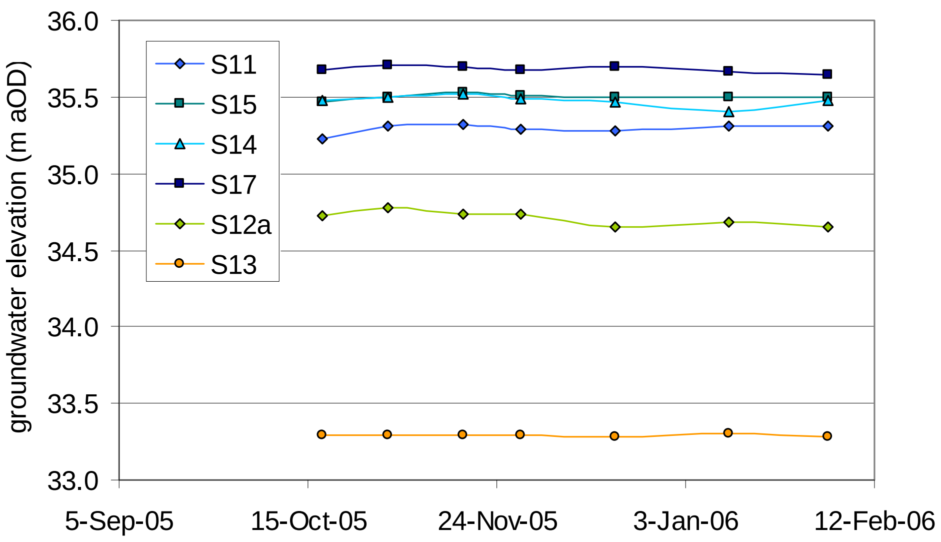


Figure 14 Temporal groundwater elevation change

The groundwater elevation remained constant over the monitoring time period when it was expected to rise. This may be due to the winter period 2005/06 being particularly dry and consequently there was less aquifer recharge than expected. The spring area during the summer drilling was mostly dry with a small flow of water from the spring source. During the winter period this area was saturated with abundant water flow. This indicates that there is a seasonal increase in spring activity, likely to be associated with periods of sustained recharge, but that this did not continue across the winter period due to below average rainfall. Continued monitoring is recommended to better characterise the temporal changes in groundwater elevation. Rainfall was not monitored and this is recommended for any further study.

The cluster of piezometers installed at different vertical positions (S14, S15 and S17) at the spring source was used to measure vertical hydraulic gradients. There is a strong upward vertical gradient between S17 and S14 (Figure 15). The vertical hydraulic gradient is generally shallow and downward between S14 and S15. The monitored spring-head is greatest in the deepest boreholes (i.e. S17 at 1.4 m bgl) and above a depth of 1.2 m bgl (i.e. the piezometer bottom at S14) vertical gradients are generally downwards, possibly due to rainfall recharge. It is likely that groundwater flow is predominantly vertical between S17 and S14 and predominantly horizontal (towards the pond) between S14 and ground surface.

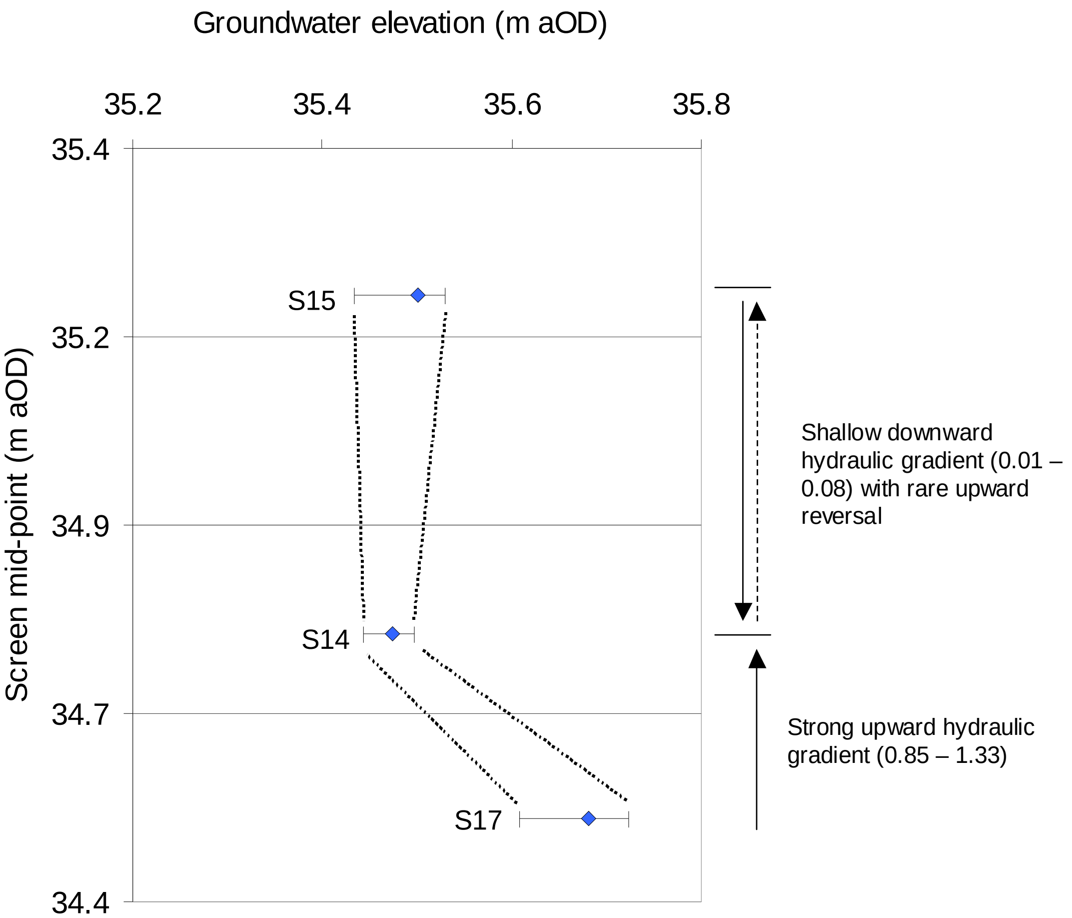


Figure 15 Vertical hydraulic gradient at the spring source between 18 October 2005 and 2 February 2006

Groundwater arising from the spring is likely to be transported as interflow as a reflection of the topography towards the pond. Groundwater elevation monitoring in S11, S12a and S13, positioned in a direct line between the spring and the pond, indicates that there is a decrease in groundwater head in this direction (Figure 16). The water table is positioned approximately 0.4m below ground surface and broadly reflects the ground surface slope.

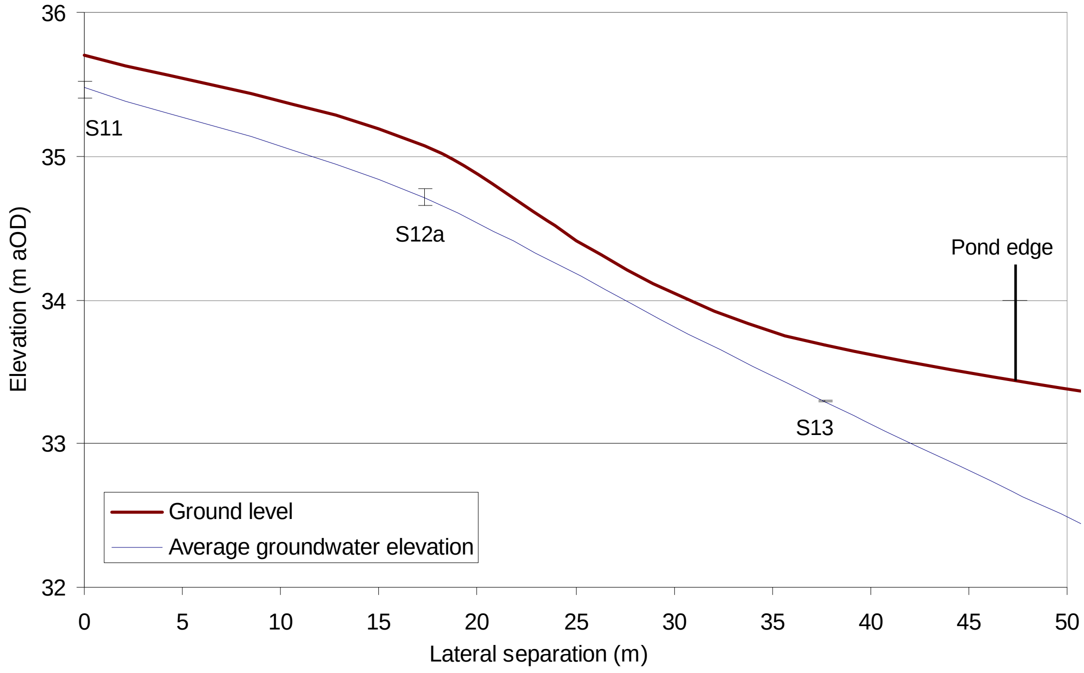


Figure 16 Average groundwater elevation between spring and pond (error bars indicate groundwater elevation range)

3.5.5.3 Groundwater inorganic chemistry

Groundwater samples were collected from boreholes S11 and S17 on the 2nd of February 2006. Boreholes were purged, using an inertial pump, for a minimum of three times the well volume or until the borehole emptied. Sustained purging was possible only in S11 and S17. The remaining installed boreholes (S12a, S13, S14 and S15) rapidly emptied during purging with water levels not recovering in the sampling time. Consequently, groundwater samples were not taken from these boreholes. An additional water sample was taken from the stream down slope of the spring as a background reading for the local surface water chemistry.

Water samples were analysed for a full suite of inorganic determinants by the BGS UKAS accredited laboratories. Dissolved oxygen, pH, conductivity, redox potential and temperature were measured at the time of sampling. The results of the water chemistry analyses are given in Table 11 to Table 13 . Determinand concentrations elevated above the presumed background (stream water) are highlighted and discussed below.

Table 11 Water sample description and field parameters

Sample Code	Sample Description	Field Temp	Field Eh	Field pH	Conductivity	DO_2
		°C	mV		µS cm^{-1}	mg l^{-1}
Stream	clear	8.40	432	8.22	1130	7.86
S11	High suspended solids sulphate odour	8.10	**289**	7.23	**2530**	**9.04**
S17	High suspended solids no odour	12.80	**232**	7.10	**2580**	**3.48**

Table 12 Major cation/anion concentrations and ionic balance for water samples

Sample Code	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Cation Total	Anion Total	Balance
	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	meq l^{-1}	meq l^{-1}	%
Stream	153	64.6	20.2	7.37	459	56.3	170	49.4	14.02	13.46	2.04
S11	**728**	71.1	**94.5**	7.82	409	44.8	**1592**	23.3	46.70	41.50	5.89
S17	**813**	75.2	16.4	6.08	486	45.0	**1559**	23.9	47.81	42.11	6.34

Table 13 Inorganic determinands measured in water samples

Sample Code	TIC	Total Fe	Reduced Fe	Total P	Total S	Reduced S
	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
Stream	85.1	0.071	<0.056	0.239	57.9	0.040
S11	81.4	0.167	0.092	0.318	**648**	0.910
S17	91.1	0.061	<0.056	0.014	**642**	0.600

Sample Code	NO_2^-	HPO_4^{2-}	F^-	Si	Ba	Sr	Mn	NH_4^+
	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
Stream	0.032	<0.100	0.238	3.27	0.098	0.439	0.018	0.060
S11	0.033	<0.100	0.208	4.20	0.035	**7.13**	1.44	0.260
S17	0.064	<0.100	0.389	4.07	0.026	**7.85**	0.208	0.110

Sample Code	Co	Ni	Cu	Zn	Cr	Mo	Cd	Li
	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
Stream	<0.002	<0.001	<0.002	0.002	<0.002	<0.015	<0.002	<0.025
S11	<0.002	<0.001	<0.002	0.005	0.002	<0.015	<0.002	0.048
S17	<0.002	<0.001	<0.002	0.006	<0.002	<0.015	<0.002	0.059

The principal cations and anions (Table 12) for each water sample are displayed graphically in Figure 17 and Figure 18. Both the stream water sample and groundwater samples contain similar concentrations of sodium, potassium, magnesium and have similar alkalinities (HCO_3^-). However, there is significantly more calcium and sulphate in groundwater samples compared to stream water samples. Elevated concentrations of these determinants can be due to dissolution of gypsum as shown below:

$$CaSO_4 \, . \, 2H_2O \quad \Leftrightarrow \quad Ca^{2+} + SO_4^{2-} + 2H_2O$$

Gypsum dissolution is likely to be the source of calcium and sulphate in the groundwater samples, as approximately equivalent concentrations of calcium and sulphate were measured (Figure 19). Gypsum is common in the Mercia Mudstone Group and is abundant in the type section of the Gunthorpe Formation at Gunthorpe Bridge, Nottingham. Gypsum can occur as finely disseminated crystals in pores, cement, nodules or veins or as massive deposits up to two metres thick (Hobbs *et al.* 1998).

Elevated concentrations of strontium, relative to stream water, were identified in the groundwater samples at approximately 7 mg l^{-1}. Celestite (strontium sulphate) is a likely source for the strontium as it is present in small quantities as disseminated crystals or small nodules in the more gypsiferous parts of the Mercia Mudstone Group (Hobbs, *et al.*, 1998).

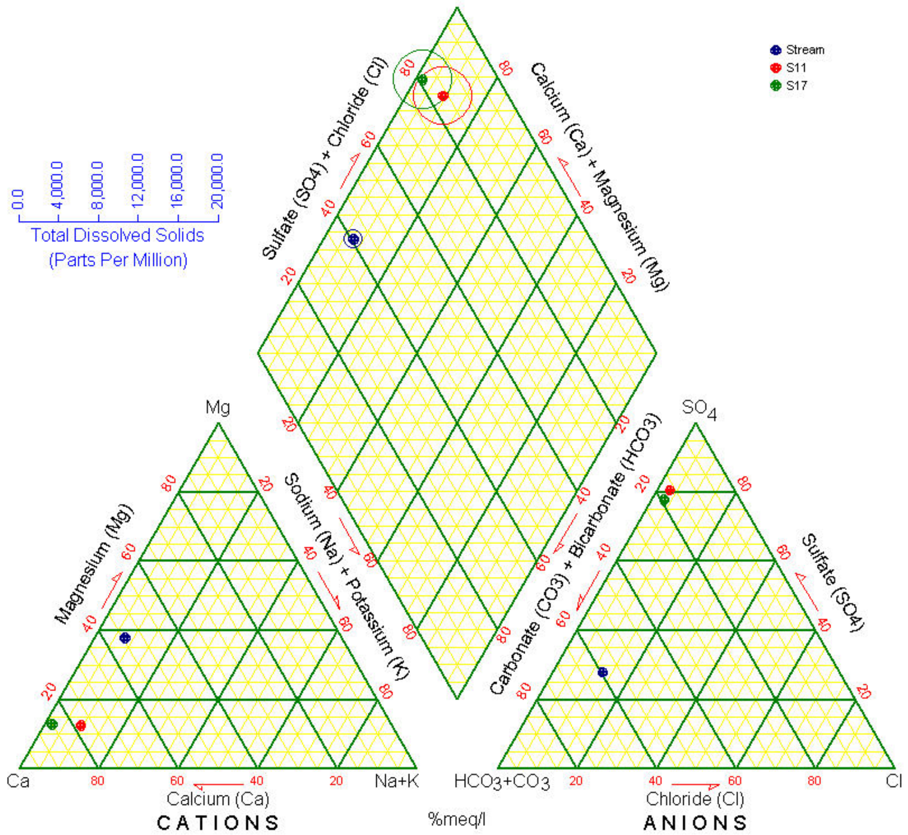


Figure 17 Piper diagram comparing the basic water chemistry for stream and groundwater samples

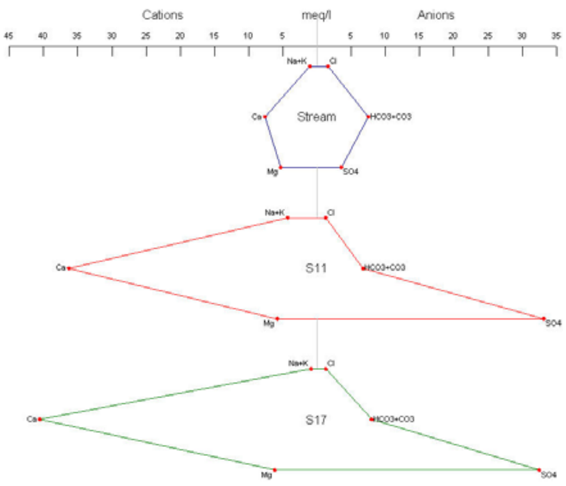


Figure 18 Stiff plot comparing the basic water chemistry for stream and groundwater samples

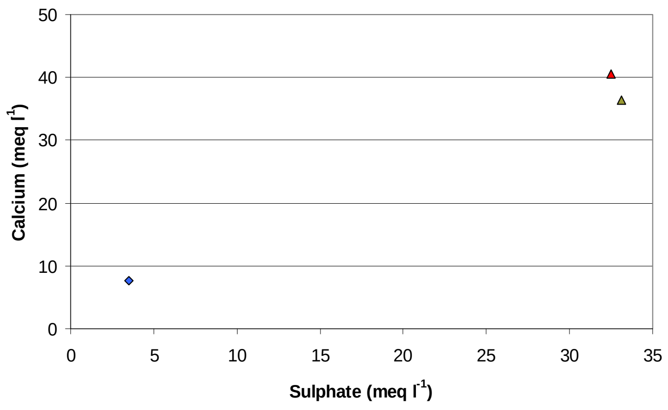


Figure 19 Calcium and sulphate levels in the groundwater

3.6 SURFACE GEOPHYSICAL SURVEYS

3.6.1 Aims

In general, the application of surface geophysical techniques to the characterisation of soils may provide the following types of information:

- mapping information (distribution and lateral extent of parameters that may be derived from interpreted geophysical data, e.g. soil types, surface geology, moisture content, crop yields),
- structural information (e.g. position and thickness of geological deposits and soil horizons, depth of water table),
- quantitative data (derivation of pedological/geological/hydrological/engineering properties from geophysical data) and
- spatial (1D, 2D, 3D) and spatio-temporal (4D through permanent monitoring) digital models.

The choice of techniques and survey methodologies will depend on the specific objectives pursued at a given site. At Brackenhurst College, the main aim was to carry out a scoping exercise and determine which types of geophysical data could best inform and support the spatial and process modelling of the very shallow subsurface (uppermost 4 metres). It was envisaged that a rapid geophysical mapping capability should be developed, which would provide both (1) high-resolution, georeferenced data at the centimetre scale and (2) efficient areal coverage at farm (and ultimately catchment) scale.

3.6.2 Method review

An in-depth review of the application of geophysical methods to soil science was not feasible due to the breadth of the subject and the lack of resources at this early stage of the project. However, drawing upon BGS experience in shallow geophysics, the following techniques were identified as suitable candidates for 3D soil characterisation:

- Ground-based gamma spectrometry
- DC electrical mapping
- Electromagnetic mapping
- Electrical tomography (e.g. ERT, IPT, SPT, SIP, ALERT)
- Ground penetrating radar (GPR)
- Geophysical/geotechnical probing (penetrometer suite)
- Downhole geophysical logging

This list is not exclusive and other techniques may be considered once further objectives have been identified. The applicability of all geophysical methods is constrained by

- Site conditions (topography, surface roughness, vegetation)
- Availability and cost of equipment (BGS-owned or rental?)
- Staff requirements (how many people, what qualifications/training?)
- Timings (seasonal variations, surveys simultaneous to other activities?)

One possible classification divides geophysical techniques (and survey strategies) into those suitable for mapping large areas and those suitable for localised (point) investigation. Whilst electrical and EM mapping, electrical tomography, radiometry and GPR tend to belong to the former category, intrusive probing and logging naturally tend to provide sparser data. Detailed areal coverage of a site with the latter techniques is therefore likely to require increased amounts of time and effort, so there is a need to prioritise the most effective methods depending on time and budget constraints.

Constraints

Geophysical data collection could not be comprehensive and only elementary coverage with very few techniques was possible during Year 1 due to limited resources. It was decided to employ BGS-owned equipment in the first instance and make use of inexpensive resources wherever possible (e.g. low-cost software, student labour).

Long-term strategy

A more strategic issue is linked to the question of whether geophysical data should be acquired on a regular basis, e.g. by a permanently installed sensor system. Such data could help monitor soil functioning with time, changes in land-use, biodegradation and organic-chemical reactions and could contribute to an improved understanding of soil processes, particularly soil-water interactions. BGS Automated time-Lapse Electrical Resistivity Tomography (ALERT) technology would be ideally suited for this purpose. Alternatively, most of the techniques described above can be deployed periodically to provide manual 4D monitoring. The relatively high cost of repeat manual surveys would have to be balanced against the investment in permanent sensor arrays.

3.6.3 Gamma spectrometry

3.6.3.1 BACKGROUND AND REGIONAL CONTEXT

Gamma spectrometry can be widely used in geological mapping, mineral exploration, regolith studies and soil surveying. Gamma ray spectrometric mapping applications typically rely on the type of integrated approach possible within the 3D soils modeling project; mineralogical and geochemical studies of rocks and soils play a fundamental role in corroborating the interpretation of gamma ray spectrometry surveys, as they provide insight in the mode of occurrence of the radioelements and their petrogenetic or pedogenetic associations (IAEA, 2003). On the other hand, geochemical and mineralogical studies often have a sparser distribution than the coverage obtained by gamma spectrometry surveying such that once a relationship is established between the gamma spectrometry signal and for example, soil geochemical data, the gamma spectrometry information can be used to infill areas where other data is missing. Gamma ray data can also be interpreted in combination with other geophysical and remotely sensed data such as magnetic and electromagnetic data, satellite images and digital elevation models.

Gamma Spectrometry provides a direct measurement of radioactive elements at the surface of the earth with only a limited depth of penetration, typically <30 cm. Potassium, uranium, thorium and total count are recorded in regions of interest (ROI) of the gamma-ray spectrum but the full 256 channel gamma-ray spectrum is recorded, should interest in other energy peaks arise. Recording the whole energy spectrum also allows the use of noise-reducing post-processing techniques, such as NASVD (Noise-Adjusted Singular Value Decomposition) and MNF (Minimum Noise Fraction).

Uranium and thorium are not directly measured, instead the equivalent uranium (eU) value is determined from the ^{214}Bi gamma peak and an equivalent thorium (eTh) value is determined from the ^{208}Tl gamma peak (^{214}Bi and ^{208}Tl being decay products of U and Th)) with potassium being measured directly from the ^{40}K gamma peak.

Gamma spectrometry can be carried out as an airborne method, or on foot. The airborne method provides systematic coverage of large areas whereas the ground-based method greatly improves the resolution of data obtained. The High resolution airborne Resource and Environmental Survey (HiRES-1) of onshore UK conducted by BGS in collaboration with World Geoscience (UK) Ltd. (WGL) in 1998 acquired airborne gamma spectrometry data over a large area of central England, including the Brackenhurst area (Peart *et al*., 2004). Figure 20-Figure 22 show HiRES-1 potassium, uranium and thorium for the region around Brackenhurst. A good correlation to bedrock geology is displayed, particularly picking out the differing geochemical signatures of the Sherwood Sandstone Group and the Mercia Mudstone Group. A high degree of small-scale spatial variation in uranium is apparent from the texture of the gridded image (Figure 21), relative to the potassium and thorium images. This is probably due to the inherent 'noisiness' of the uranium data.

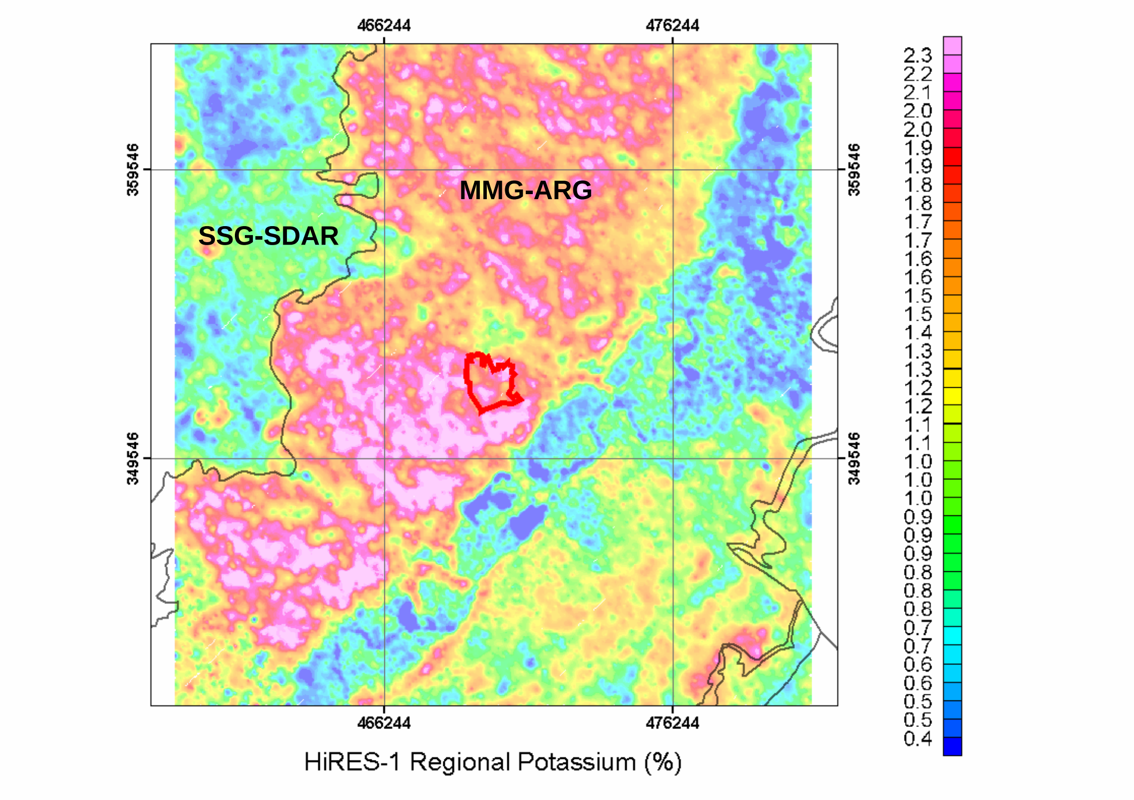


Figure 20 HiRES-1 regional potassium (K%) surrounding the Brackenhurst site (outlined in red). (SSG-SDAR: Sherwood Sandstone Group-Sandstone and Argillaceous Rocks; MMG-ARG: Mercia Mudstone Group- Argillaceous Rocks).

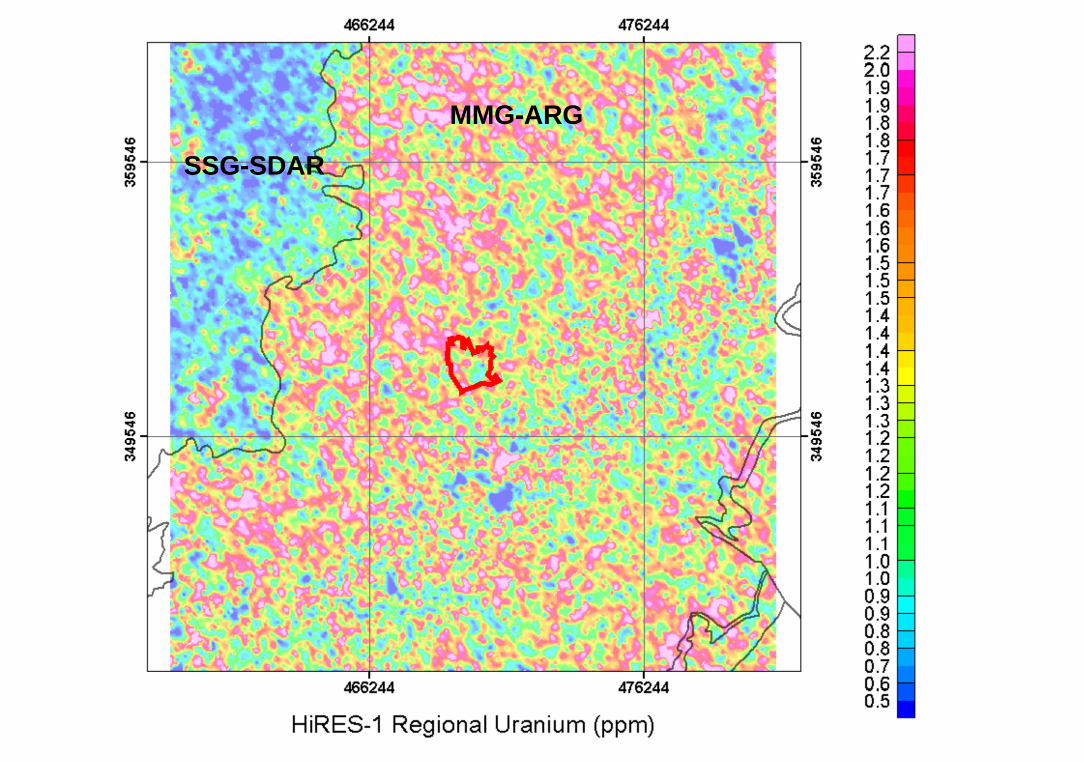


Figure 21 HiRES-1 regional uranium (eU, ppm) surrounding the Brackenhurst site (outlined in red). (SSG-SDAR: Sherwood Sandstone Group-Sandstone and Argillaceous Rocks; MMG-ARG: Mercia Mudstone Group- Argillaceous Rocks).

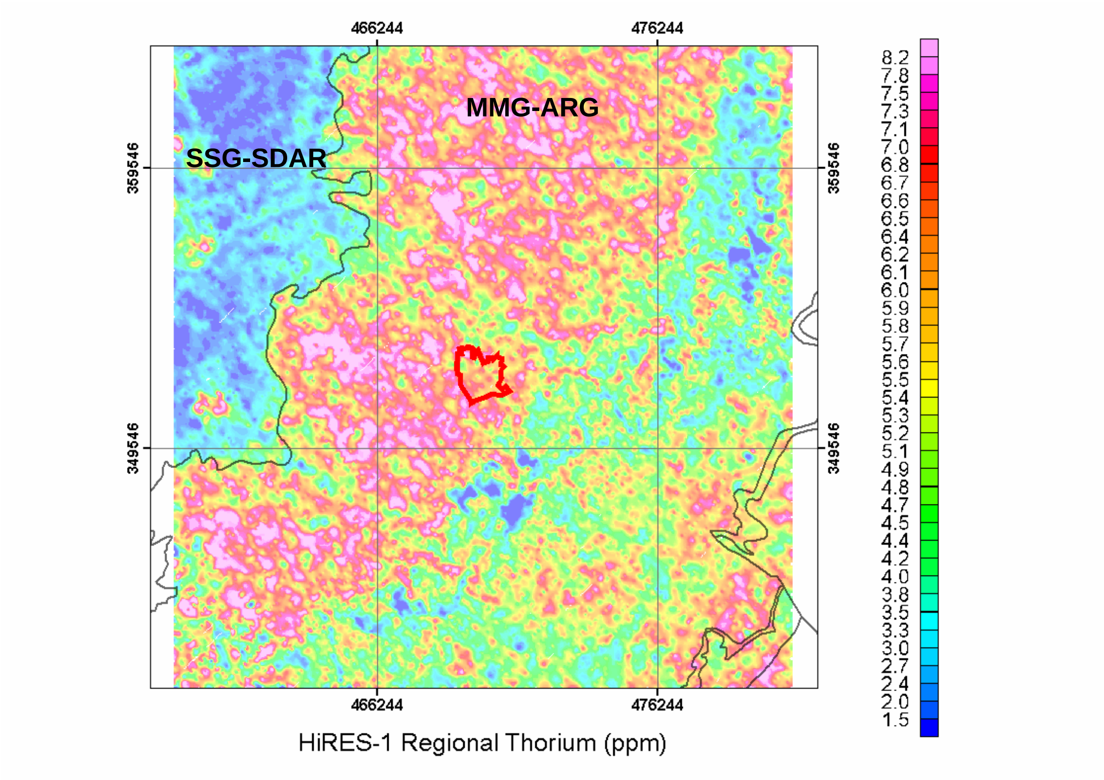


Figure 22 HiRES-1 regional thorium (eTh, ppm) surrounding the Brackenhurst site (outlined in red). (SSG-SDAR: Sherwood Sandstone Group-Sandstone and Argillaceous Rocks; MMG-ARG: Mercia Mudstone Group- Argillaceous Rocks).

3.6.3.2 GROUND-BASED GAMMA SPECTROMETRY METHOD

In order to carry out the ground-based gamma spectrometry survey at the Brackenhurst College site, an Exploranium GR-320 gamma spectrometer with a 76 x 76 mm NaI (Tl) detector was mounted in a backpack at an approximate height of 1m. At this height the instrument detects gamma rays from an area within approximately a 10-meter radius (Atomic Energy Commission, USA, 1972). Potassium, uranium, thorium and total count were recorded as the operator walked slowly over the ground (Figure 23).

The GR-320 NaI (Tl) detector was energy-stabilised with a small ^{133}Ba source. The energy calibration, Full Width Half Maximum (FWHM) of the ^{133}Ba peak and system gain were tested at the start and end of each day, and are monitored during data collection, to show the equipment is functioning correctly.

The detector was calibrated on the BGS radiometric calibration pads prior to, and after fieldwork. There are four concrete calibration pads; one with a known concentration of each of potassium, uranium and thorium and one ‘blank’ pad which allows the background contribution from the concrete to be subtracted. After a spectrum is collected on each pad, stripping ratios are calculated which remove the influence of other radionuclides from each ROI therefore leaving only net counts of potassium, uranium and thorium in their specific ROI. As the concentrations of each nuclide in the pads are known, the sensitivity can be calculated. This is counts per second in the K window, per percent potassium, and counts per second in the eU and eTh windows per ppm uranium and thorium, respectively.

An allowance for geometry correction must also be made, as the calibrations pads do not represent an infinite source. Therefore, a geometric correction factor for each nuclide is applied in the Explore™ software during data processing (factors given in Grasty *et al.*, 1991). The background of the instrument itself must also be subtracted. This is measured by recording a spectrum over a large water body from a boat. The stripping ratios, the sensitivity, the geometric conversion factor and the instrument background are all taken into account during data processing in the Explore software (Grasty *et al.*, 1991).

Positional information was collected in British National Grid via a GPS and merged with the gamma spectra through a ‘Husky’ palm-top computer (Figure 23). A line spacing of 20m was used for the majority of the south of the Brackenhurst site (Figure 24). In addition, in an effort to further integrate techniques, data was acquired alongside the electromagnetic (EM) data acquisition using a line spacing of 5m (Figure 24). During this data acquisition a differential GPS was used to provide more accurate positional information. The positional information from the differential GPS was not merged with the gamma spectrometry data in real time; the two data streams were merged back in the office.

Data were collected over 5 s intervals and converted into ground concentrations of K, eU and eTh. In addition, to improve counting statistics and hence data precision, 45 s moving sums were calculated and converted to concentrations. This reduces noise and should give more coherent images.

Figure 23 Ground based gamma spectrometry equipment; an Exploranium GR-320 NaI detector mounted in a backpack, connected to a Garmin GPS and a Husky palm-top computer.

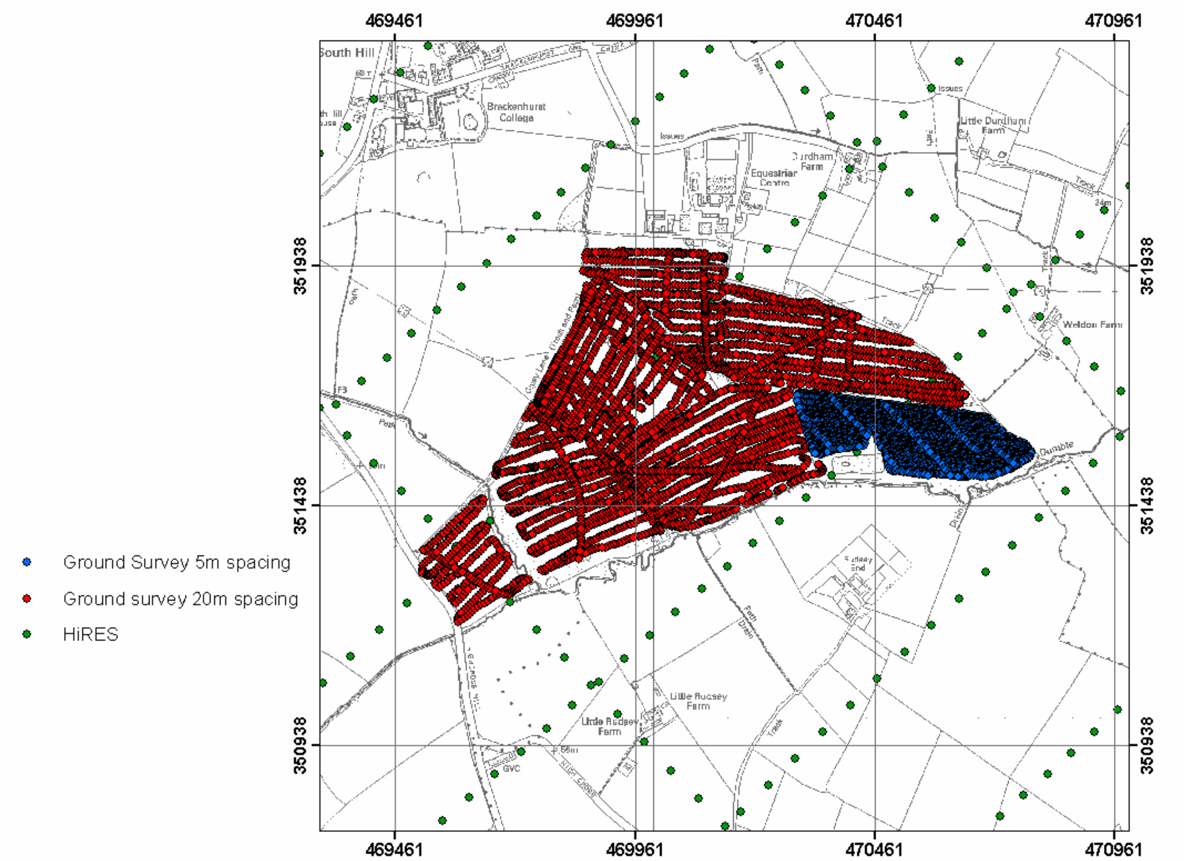


Figure 24 Sample density of the ground-based and airborne (HiRES-1) gamma spectrometry surveys over the Brackenhurst site.

3.6.3.3 Results and Recommendations

As the ground-based gamma spectrometry survey was carried out over a small and relatively uniform area, the data obtained shows short-scale variability (over a few hundred metres), with little in the way of large scale trends. In its present state, the ground-based data from the

Brackenhurst site would be of limited use to the construction of a 3D model. Had the survey been done over an area of contrasting bedrock/ superficial geology and soil, and therefore over an area with a larger range of K, U and Th values, a better distinction would have been seen, as demonstrated over the region by the HiRES-1 survey (Figure 20 - Figure 22).

Results

Summary statistics of K, eU and eTh are shown in Table 14. Preliminary gridded maps of calibrated K, eU and eTh data (based on the 45s moving sums) are displayed in Figure 25 - Figure 27. The level of small-scale variation makes it difficult to delineate the site into areas with similar textures and spatial distributions of the three elements (even when employing clustering techniques) but the 45s moving sum data did reduce the degree of very small scale variation compared to the 5s results and provide greater data coherence. Further techniques outlined in the recommendations could have been applied to the data to help draw out interpretations and conclusions, if resources had allowed.

Some features in the data coincide with different fields surveyed on different days. These may reflect changes in land use and soil moisture content, which could relate to weather conditions as well as the nature of the near surface soil. Areas of lower K and eTh, and less obviously eU (Figure 25 - Figure 27) may reflect wet soil on the day of the survey. Higher K and eTh seem to be associated with areas of dolomitic siltstone in the Gunthorpe Member, in the northern part of the surveyed area, and parts of the head deposits in the south. They therefore seem to equate to the Brockhurst and parts of the Worcester and Hopsford soil series. Higher eU may also follow the head and some siltstone bands. The higher eU values encountered along the southern section of the survey area may correspond to alluvium and head deposits and thus to the Mathon and Hopsford soil series.

The relationship between K measured by continuous gamma spectrometry and K measured by XRF in soil samples was difficult to define, as there were too few soil samples that fell in areas where gamma spectrometry was carried out. XRF analysis of soil sample has been shown in previous studies to correlate well with *in situ* gamma spectrometry measurements (e.g. Emery *et al*., 2006). The gamma spectrometry measurements would typically be made in exactly the same location as the soil sampling over a 5 or 10-minute period, as opposed to the 5-second measurements taken during the continuous monitoring at Brackenhurst. In future site surveys of this type the gamma spectrometry survey should be carried out at the same time as the soil sampling to ensure samples can be taken from exactly the same location, and under the same soil moisture conditions.

Table 14 Summary statistics of K, eU and eTh measured by ground-based gamma spectrometry (45s moving sum data)

	K	**eU**	**eTh**
Measurement Units	%	ppm	ppm
Mean	1.94	1.95	6.53
Standard Error	0.00	0.01	0.01
Standard Deviation	0.25	0.70	1.26
Skewness	-0.72	-0.03	0.10
Range	2.64	6.18	10.05
Minimum	0.29	-1.19	0.96
Maximum	2.92	4.98	11.01
Count	8014	8014	8014

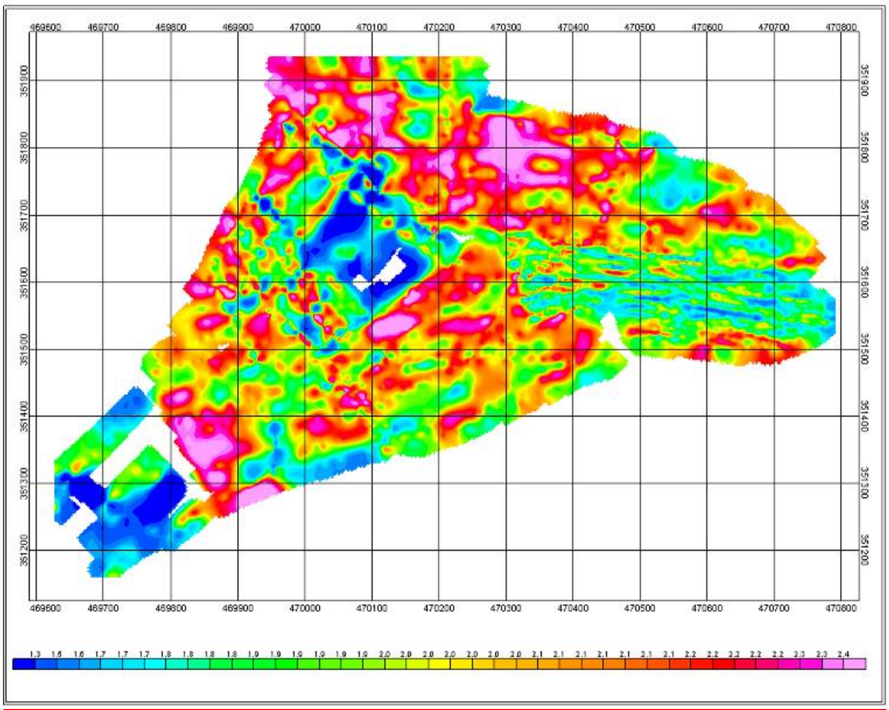


Figure 25 Preliminary ground-based gamma spectrometry gridded map of K (%) using 45s moving sum data

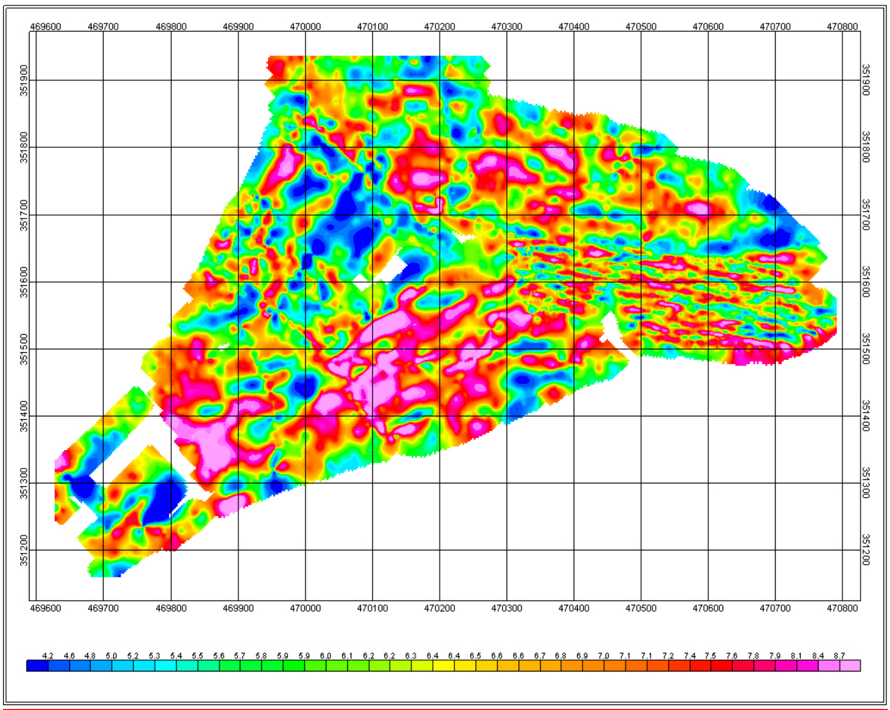


Figure 26 Preliminary ground -based gamma spectrometry gridded map of Th (ppm) using 45s moving sum data

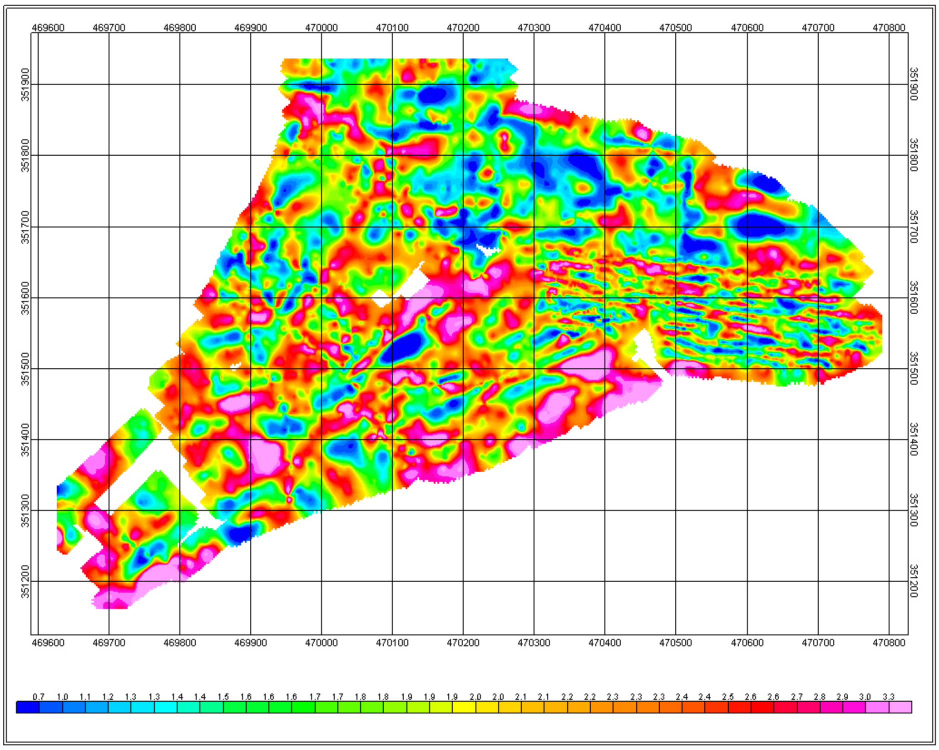


Figure 27 Preliminary ground -based gamma spectrometry gridded map of U (ppm) using 45s moving sum data

Recommendations

The outcomes of the ground-based gamma spectrometry survey at Brackenhurst were severely limited by a lack of staff availability. The interpretation of the gamma spectrometry data and integration with other data sets was unfortunately minimal. For gamma spectrometry to fulfil its potential, interpretation has to go beyond gridding and mapping data. The following steps are recommended in future surveys to enhance data quality, make fuller use of the data and to improve the outputs:

- Use of larger portable or vehicle-mounted detectors (which were not available for the Brackenhurst survey) to improve count rates. Ideally data should be collected in as short a time as possible during dry and stable weather conditions
- Further data processing including using noise adjustment techniques (NASVD and MNF) and or possibly averaging of spectra (although this will reduce the resolution);
- Spectral shape analysis;
- Integration with other data sets or techniques (geochemical soil analysis, geological mapping, soil mapping, EM, soil moisture etc);
- Edge detection and clustering techniques to delineate areas within the gamma spectrometry data with similar textures and spatial distributions;
- Further correlation with HiRES-1 airborne gamma spectrometry data.

In addition, further analyses that could be considered in order to improve knowledge on the spatial distribution of gamma emitting nuclides at Brackenhurst include:

- *In situ* gamma spectrometry traverses (static counts) across areas of interest;
- Laboratory or down borehole gamma spectrometry (Laboratory analysis would be carried out on a high-purity germanium detector and so information would be acquired on other gamma emitting nuclides in addition to potassium, uranium and thorium).

Conclusion and applicability for future surveys

More time and skills need to be invested in this technique for it to attain its potential and for the technique to provide useful input to 3D soil models. As the Brackenhurst survey was carried out over a small and relatively uniform area, the data obtained is variable at the small scale, with trends being hard to identify. Therefore, with the present capability, ground-based gamma spectrometry may not be a suitable technique over a similarly uniform site. However, with more processing and interpretation, and if future surveys were carried out over a larger or a more varied area, this technique could yield important information on potassium, uranium and thorium, and the spatial distribution of soil boundaries.

Although radiometric data relates only to the top 30 cm or so in solid rock, in lower density materials, such as peat, it would perhaps extend to a maximum of a few metres in dry conditions. For saturated peat, with a water content of up to 90 %, around 90 % of the gamma rays would come from the top 1 m. Where the material in the near surface layer is derived from that at greater depth then the technique also has an effectively greater penetration.

3.6.4 DC electrical mapping

One of the geophysical techniques most commonly applied to soil characterisation is electrical mapping, particularly the areal measurement of electrical resistivity. This can be carried out manually with portable instruments (e.g. RM-15 resistivity meter, often employed in the Channel 4 *Time Team* programme) or, more efficiently, with mobile multi-sensor arrays. Resistivity mapping at multiple depths of investigation is likely to have the highest potential for quantitative interpretation in a soils context because the variation of physical properties with depth can be taken into account and 3D property distributions can be generated. Two viable measurement systems that are currently available are the BGS Capacitive Resistivity Imaging (CRI) system (Figure 28) and the French Automatic Resistivity Profiling© (ARP) system developed by Geocarta (Figure 29). Five separate depths of investigation could be measured simultaneously with CRI and three with the ARP, ranging from approximately 0.5 to 3m.

The BGS CRI system is based on a non-contacting measurement with capacitive plates and is mainly designed for use on pavements or even surfaces with little vegetation. It is available at minimal cost to the project. The device is pulled by a Land Rover, can navigate with real-time kinematic GPS, has onboard computing facilities and can acquire a resistivity value every 5-10cm. Thus, using a 5m inter-profile spacing, up to 40,000 resistivity measurements per hectare and per depth of investigation may be recorded.

The ARP system is based on the use of spiked metallic wheels as sensors and is therefore probably the most suitable for surveys on farmland, rough ground and ploughed fields. The device is pulled by a quad bike, navigates with differential GPS, has onboard computing facilities and acquires a resistivity value every 20 cm. The ARP system surveying services are exclusively provided by a single contractor in France.

Figure 28 The BGS CRI system

Figure 29 The Geocarta ARP© system (source: www.geocarta.net)

3.6.4.1 Recommendations

Limited resources during Year 1 of the project meant that DC electrical mapping could not be employed at Brackenhurst College. However, for Year 2 and certainly for the longer term, a dedicated capability for rapid geophysical soil mapping is likely to be required.

Besides traditional techniques available at BGS, it is recommended that the applicability of the BGS CRI system for this purpose be reviewed. Although originally designed for surveying on smooth surfaces, it is currently the only viable mobile non-inductive resistivity mapping system in the UK and has significant potential for further development. A small amount of funding may be required to adapt the system (hardware and software) specifically to a soils context. It is also recommended to evaluate the possibility of contracting Geocarta to carry out an Automatic Resistivity Profiling (ARP) demonstration survey. This will provide an electrical mapping capability in rough terrain, including ploughed fields.

3.6.5 Electromagnetic mapping

The spatial distribution of electrical properties can also be determined by electromagnetic (EM) mapping, where electrical conductivity is measured by EM induction in pairs of coils. Depth discrimination with EM mapping is often limited; however boom lengths and coil orientations can be varied to provide a wider range of depths. Drawbacks of the technique are the sensitivity near metallic objects such as fences, gates and services and a higher degree of complexity of interpretation and modelling procedures. Available instruments for shallow prospecting are for example EM-38, EM-31 and DualEM. The latter system is owned by BGS. It can provide conductivity data with nominal depths of investigation of 1 and 3m (2m boom) as well as 2 and 6m (4m boom). Equipment designed for shallower depth penetration (EM-38) would have to be purchased or rented.

For the site survey at Brackenhurst College, it was decided to utilise the BGS DualEM system for areal conductivity mapping. Due to time limitations and the considerable size of the area of interest, it soon became clear that conventional EM survey procedures would be unsuitable for rapid soil characterisation. It was therefore decided to develop a mobile surveying capability using the DualEM instrument in combination with GPS navigation and automated data acquisition.

3.6.5.1 Development of a mobile EM mapping platform

Traditionally the DualEM instrument is used in manual mode where an operator carries the boom from one survey station to another, manually triggering a measurement or marking a fiducial on the survey profile by pressing a button on the system console. Measurements can be carried out manually or automatically at a constant sampling rate of up to 2Hz. Although data can be stored on the instrument for post-survey download and processing, the actual survey procedure is time-consuming, particularly if survey poles and tape measures have to be used to mark out a survey grid.

A system has therefore been devised that makes use of a specific mode of operation of the DualEM instrument, where a permanent data stream with a constant sampling rate is provided via the serial interface in a standardised ASCII format. The system is based around a laptop running specialised software to record this data stream simultaneously with a second one containing real-time positional data provided by a suitable GPS receiver (Leica Geosystems SR530 owned by BGS). The DualEM sensor boom together with the laptop, battery, GPS receiver and antenna were mounted on a survey trolley for improved mobility, physical stability and ergonomics (Figure 30). The trolley-mounted solution also represents a Health & Safety improvement as the DualEM instrument is relatively heavy when carried for a long time in the field.

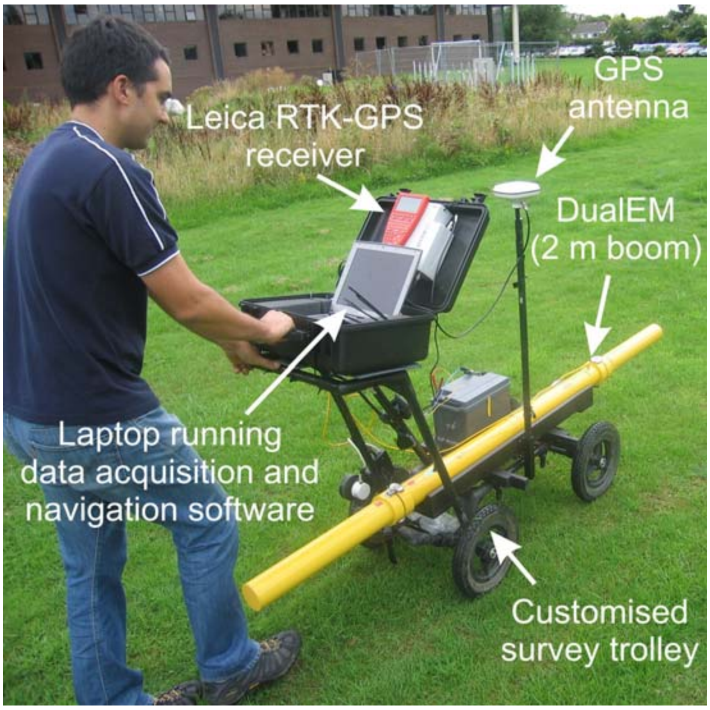


Figure 30 Mobile EM mapping platform

The software (Personal Navigator III) allows the use of basic GIS data (shapefiles) and enables the user to define features such as survey lines or grids, marker points and site boundaries. This information can be displayed in conjunction with raster graphics, for example aerial photography, and a plot of incoming data currently measured by the EM sensors (Figure 31).

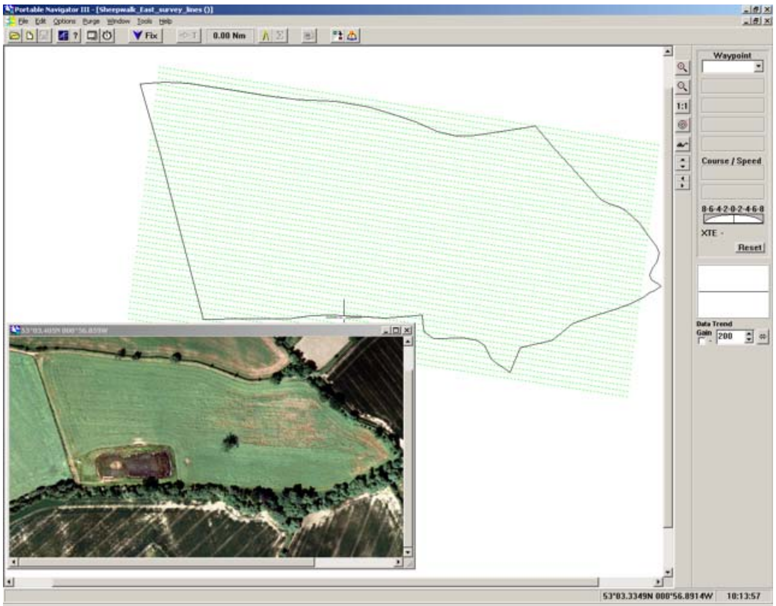


Figure 31 Screenshot of the Personal Navigator software used for automated data aquisition and real-time navigation

Surveys can be carried out in the following fashion:

1) The user plans and designs a survey in the office using desktop GIS;

2) GIS data are uploaded onto the survey PC, which displays the current position as well as tracking data;

3) the user starts the system and pushes the survey trolley along predefined survey lines, while monitoring progress on the PC screen;

4) after the survey is complete, data can be processed directly on the laptop PC (gridding, filtering, visualisation).

3.6.5.2 EM MAPPING SURVEY AT SHEEPWALK EAST

An EM mapping survey was carried out at the Brackenhurst site in order to evaluate the new system. A field known as “Sheepwalk East” in the southeastern corner of the Brackenhurst estate was chosen as a suitable location for this survey, which took place on the 22nd and 23rd of August 2005 and lasted a total of approximately 12 hours. The field is approximately 400m E-W by 170m N-S, a total area of around 7ha.

A Leica Geosystems SR530 receiver was set up in the northwestern corner of Sheepwalk East to act as a GPS base station for real-time kinematic surveying (cf. Figure 5). Communication with the roving trolley-mounted receiver was established via a radio modem link. In-phase and quadrature data for the DualEM-2 configuration (2m boom length) were collected at the maximum sampling rate of 2Hz on a total of 28 parallel survey lines with an inter-line spacing of 5m. The DualEM instrument is designed for low-induction-number operation (operating frequency 9kHz) and contains two independent coil configurations (one horizontal co-planar HCP and one perpendicular PRP), so that a total of four separate parameters could be recorded simultaneously.

Figure 32 shows the system in field operation as well as the GPS track of the occupied profiles. Following the survey, data were grouped into profiles and uploaded to the Geosoft Oasis Montaj software package, where quality checks, coordinate transforms and further processing were performed. Of the four parameters recorded, only PRP and HCP conductivities were used initially due to time limitations and because in-phase data appeared to contain significantly less useable information on this particular site.

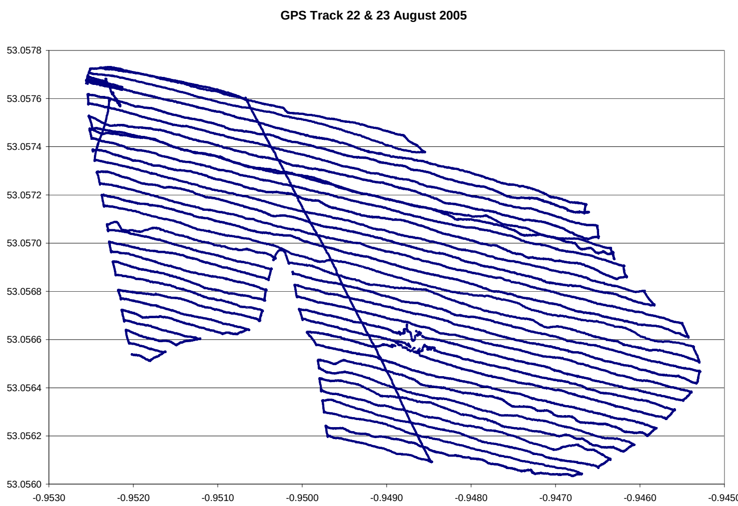


Figure 32 Shallow EM mapping survey at Sheepwalk East. System in field operation (left) and GPS track of EM coverage (right; coordinates shown are WGS84)

The conductivity data were subjected to moderate low-pass filtering and gridded using a bi-directional algorithm. Some empirical levelling had to be carried out to correct for obvious tracking errors in the raw data. Preliminary results obtained from this processing sequence are shown in Figure 33 (PRP conductivities) and Figure 34 (HCP conductivities).

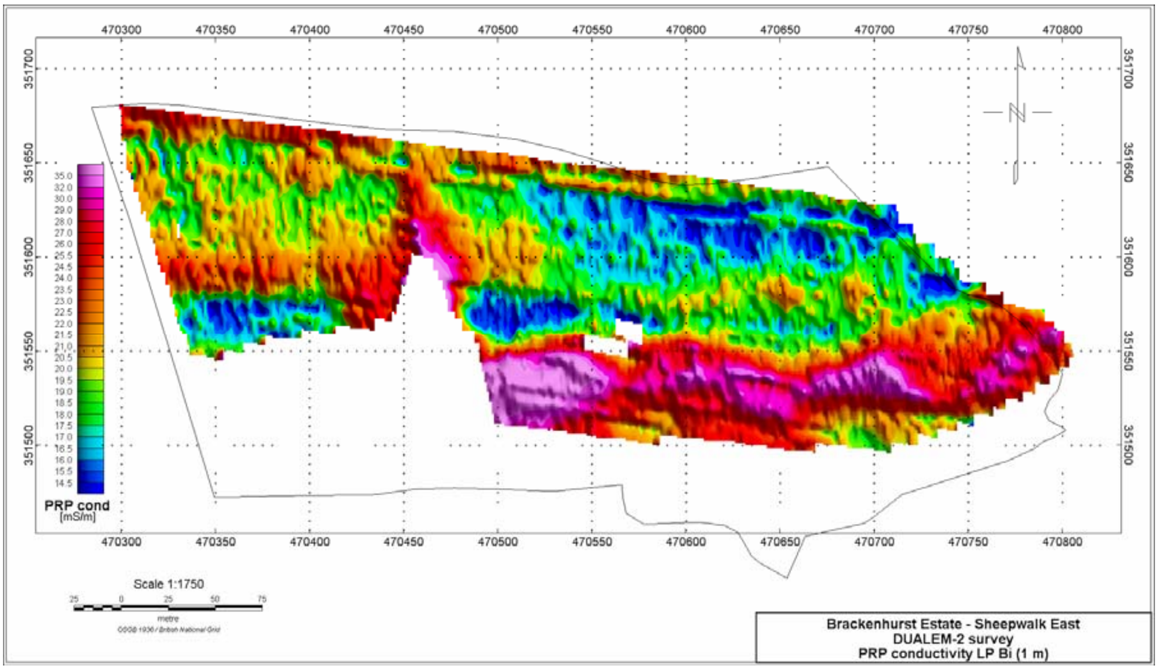


Figure 33 Preliminary results of EM mapping survey: DualEM-2 PRP conductivity after low-pass filtering and bi-directional gridding; nominal depth of investigation 1m

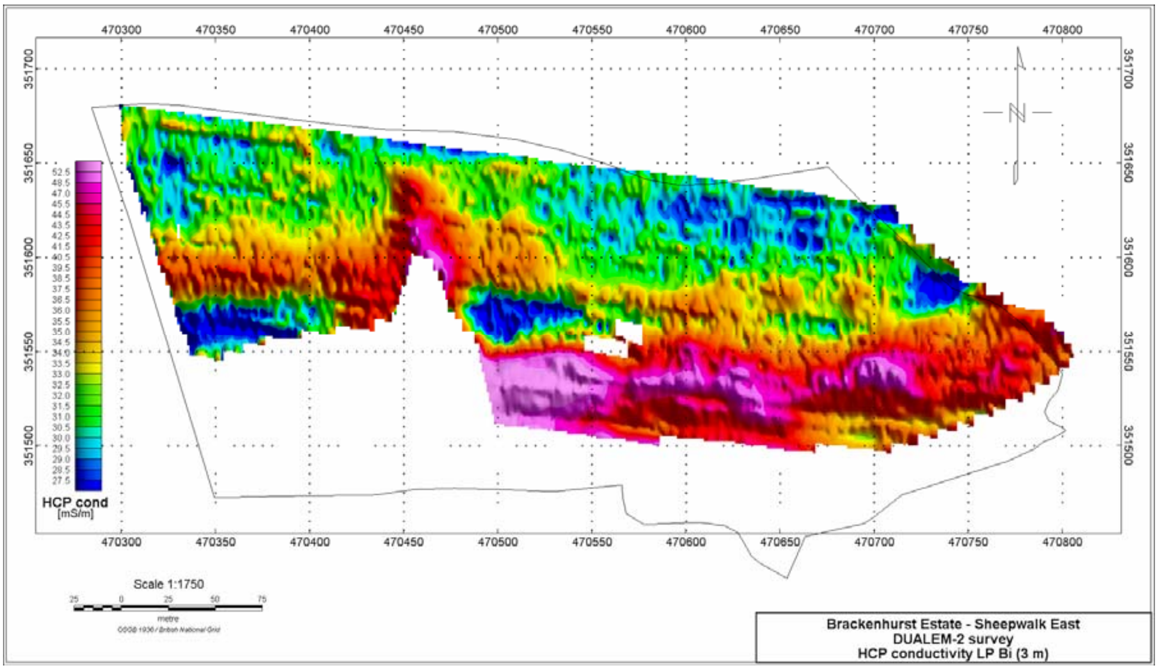


Figure 34 Preliminary results of EM mapping survey: DualEM-2 HCP conductivity after low-pass filtering and bi-directional gridding; nominal depth of investigation 3m

3.6.5.3 RESULTS

Interpretation of soil electrical conductivity (or resistivity) data can make use of the fact that the bulk apparent electrical conductivity EC_a measured by electromagnetic methods is a function of the soil physical and chemical properties, primarily soil salinity, saturation, water content and bulk density (e.g., Corwin and Lesch, 2003). Saturation and density are closely related to clay content. ECa is therefore an important parameter for the spatial characterisation of soilscapes; knowledge of its volumetric distribution may facilitate the understanding of soil-water-vegetation relationships. However, the individual effect and relative contribution of these parameters to the overall bulk conductivity is difficult to quantify without tight constraints on geological and hydraulic conditions or the availability of complementary laboratory/in situ data to calibrate the electrical measurements.

The conductivity maps produced by the EM mapping survey at Brackenhurst College are of good overall quality. However, both PRP and HCP datasets are still visibly affected by the directionality of the survey, resulting in some residual levelling errors and high-frequency undulation in cross-profile direction. Although these effects are controllable and could be mitigated by further processing, it would be advisable to investigate fundamental data quality aspects of the technique in a separate study, particularly if quantitative interpretation at small scales is expected to be of greater relevance in future surveys.

In qualitative terms, the PRP and HCP maps both appear to contain useful information about the spatial variability of the soils at Sheepwalk East. Both show a distinct transition from very conductive ground along the valley bottom at the southern site boundary towards more resistive ground upslope. The highest conductivities (red/pink colours) are observed to the east of the large pond and associated wetland in the south-western corner of Sheepwalk East. A further distinct conductivity high is associated with the wet ground surrounding the spring described in Section 3.5.2. These higher conductivities appear to be largely controlled by soil moisture.

A banded zone of low conductivities (blue colours, corresponding to resistive ground) appears at the centre of both maps, striking approximately E-W and following the curvature of the valley. This zone corresponds roughly to a mapped skerry and may possibly be an expression of the less conductive, coarser silt- and sandstone compared to the mudstone above and below, which contain greater proportion of clay.

The overall range of conductivity values is 14 mS/m < EC_a <36 mS/m for PRP and 27 mS/m < EC_a < 53 mS/m for HCP, indicating that the ground is becoming increasingly conductive with depth. This is consistent with the observation of shallow water tables on site (Section 3.5), indicating that the nominal depth of investigation of the deeper configuration (HCP) lies within the saturated zone.

3.6.5.4 RECOMMENDATIONS

Electromagnetic mapping at the Brackenhurst site provided useful information despite the experimental nature of the survey platform and the sub-optimal character of the grid layout. The conductivity maps showed spatial variability which correlated well with the re-mapped geology and other data. Quantitative interpretation of the conductivity datasets was minimal. The following recommendations should enable future users to improve the survey strategy and to make fuller use of EM mapping data:

- Smaller coil spacings (e.g. EM-38) should be employed to provide additional coverage at shallower depths;
- Additional options for further automation and greater survey efficiency should be investigated – for example the use of vehicles (system towed by quad bike, see www.turftraxgms.com/scanning.htm);

- The effects of different survey grid layouts on the resulting maps should be studied – a smaller ratio of profile spacing versus in-line sampling distance may be more adequate;
- A "Best Practice" procedure for obtaining real-time kinematic GPS data with the Leica SR530 receivers should be established and documented;
- Quantitative interpretation of the EM data should be attempted through calibration with intrusive and other geophysical and geotechnical data;
- Further correlation with other data sets should be performed (geochemical soil analysis, geological mapping, soil mapping, soil moisture etc).

3.6.6 Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) is an increasingly popular geophysical technique that is applicable to soil characterisation and allows the generation of tomographic images of the subsurface, thus enabling detailed structural evaluation and the quantification of hydraulic and geotechnical parameters that are related to electrical properties. Interpretation can be 2D, 3D and also 4D (for time-lapse measurements).

ERT surveys require the installation of multiple electrodes, which makes large-scale mapping surveys less practicable, but they are highly suitable for local reconnaissance, the evaluation of complex geological structures and the resolution of property variations with depth. ERT is minimally invasive and is therefore also useful in areas where intrusive investigation (drilling, augering) would be difficult or impossible.

It was decided to carry out a demonstration survey at the Brackenhurst site in order to evaluate the potential of ERT for the spatial characterisation of soils.

3.6.6.1 2D ERT SURVEY AT SHEEPWALK WEST

A field known as "Sheepwalk West" at the southern boundary of the Brackenhurst estate was chosen as a suitable location for this survey, which took place on 25 August 2005 and lasted approximately 5 hours.

A total of 64 stainless steel electrodes were installed at 5m separations on a linear profile running approximately N-S in the direction of the main track leading from the College towards Sheepwalk West (Figure 35). The start of the profile (x = 0m) was at the bottom of the slope near the stream, in immediate vicinity of the field boundary. The profile continued uphill through the main access gate and along the main track towards the College. The total profile length was 315 m. The survey design was not optimised with regard to obtaining maximum spatial resolution in the top few metres of ground, but represented a compromise between resolution and distance covered in a short period of time.

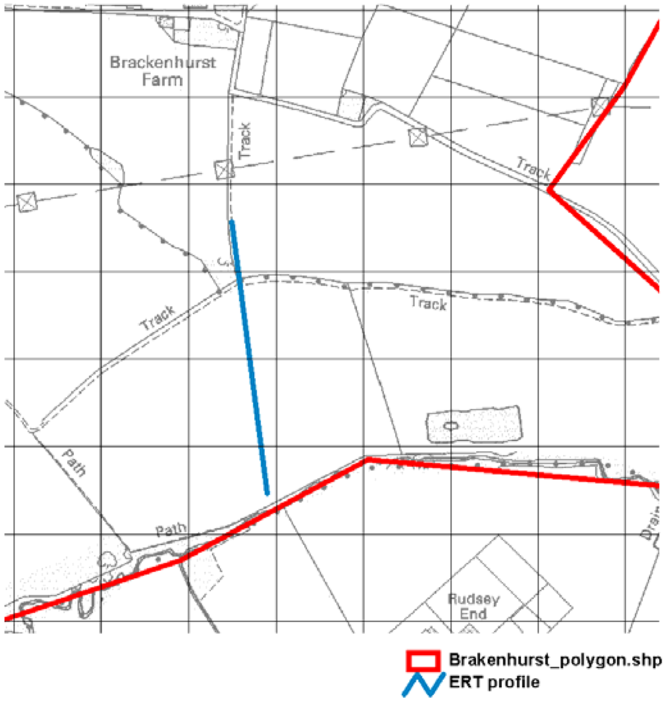


Figure 35 Location of 2D ERT profile on Sheepwalk West

An AGI SuperSting R8 resistivity meter was employed to perform a set of automated multi-channel measurements based on a modified Wenner array configuration, resulting in a dataset with nearly 2,800 data points. Data processing comprised basic quality checks and various screening stages, followed by 2D least-squares smoothness-constrained inversion. Simplified topography was included in the inverse model, which uses a cell width of 2.5m and contains 14 layers (Figure 36). Preliminary inversion results are shown in Figure 37.

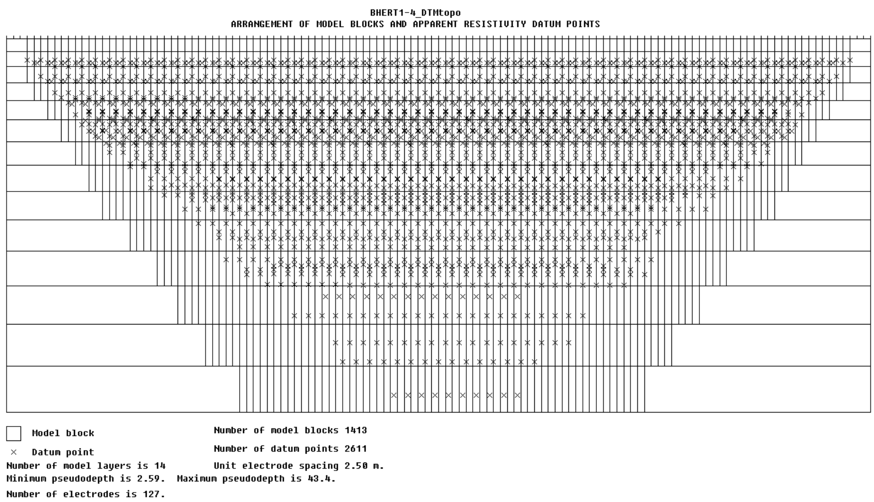


Figure 36 Discretisation of 2D resistivity model and distribution of measured data points

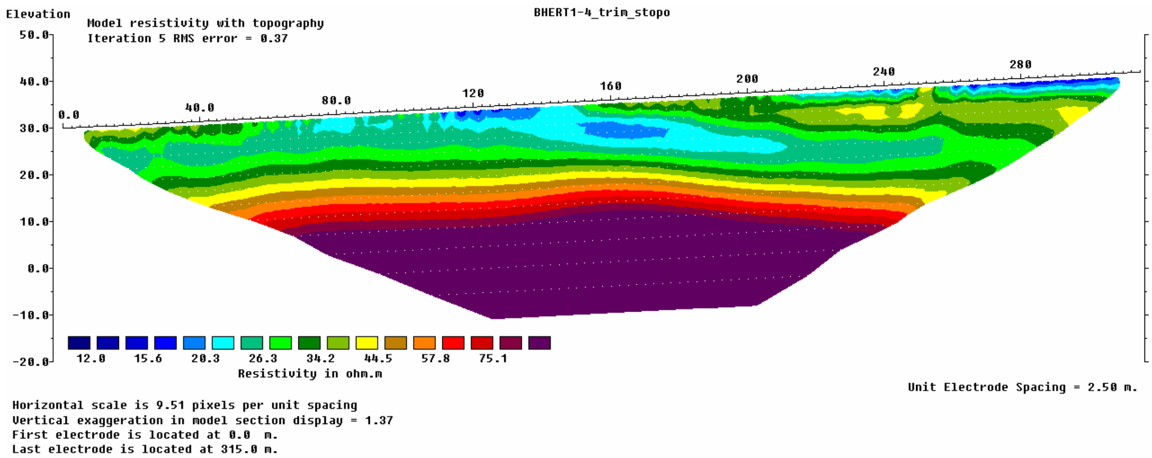


Figure 37 Preliminary results of the ERT survey at Sheepwalk West; inverted 2D resistivity model with simplified topography

3.6.6.2 RESULTS

The ERT demonstration survey produced a dataset of very good quality. Standard screening procedures with relatively tight error thresholds did not remove any data from the original set. The inversion was halted after five iterations, resulting in a Root-Mean-Square (RMS) error between modelled values and measured data of 0.37%.

The resulting inverse model (Figure 37) displays a wide range of resistivity values (14 – 280 Ωm) and significant structural variation in the top 15m below ground level, reflecting the complexity of the soilscape and shallow geology at the Sheepwalk West hillside. The shallow part of the model is characterised by banded zones with similar bulk properties that are gently dipping northwards. A prominent band of conductive material (15 – 25 Ωm) dominates the near surface at the centre of the profile. This is likely to be the mudstone bedrock (Gunthorpe Member). Further upslope, this band is overlain by a band of higher resistivity (25 – 50 Ωm), which may be associated with one or several skerries, i.e. bands of relatively coarser, silty or sandy material with lower clay content. A conductive surface layer is observed in the northernmost part of the profile (x > 210 m), it is only interrupted by the resistive expression of the boundary track (x = 257.5 m) that is crossed by the ERT line. In accordance with the surface geological map, this surface layer is likely to be associated with clay-rich soils derived from the Gunthorpe Member. A resistive surface layer at the bottom of the slope (x < 60 m) is likely to reflect the head deposits found in that area. The base of the ERT model is electrically uniform and significantly more resistive than the near-surface material (> 50 Ωm at depths greater than 15 m below ground level).

A georeferenced bitmap of the ERT model was uploaded to GSI3D (cf. Section 4.1.4) for spatial integration with the 3D soil model and related datasets. A preliminary qualitative interpretation was carried out by visual correlation with the re-mapped geology. Detailed quantitative interpretation of the inverse resistivity model requires calibration with intrusive data, for example samples obtained in auger holes, downhole electrical logs or penetrometer tests. Lack of time meant that this was not attempted with the Brackenhurst dataset. Important factors in this context are parameters such as clay content, moisture content and saturation levels, as they all affect the bulk resistivities determined by ERT.

3.6.6.3 RECOMMENDATIONS

Despite its preliminary character and non-optimised survey design, the ERT survey at Brackenhurst provided useful information about the spatial structure of the soilscapes at Sheepwalk West. The provision of geophysical property distributions in the form of vertical cross-sections proved to be an intuitive aid for spatial modelling. Due to lack of time, quantitative interpretation of the resistivity data was minimal, but this should be possible on the basis of ground truth information available in this area following the intrusive investigations. The following recommendations should enable future users to improve the survey strategy and to make fuller use of ERT data:

- Smaller electrode spacings to enhance near-surface resolution;
- Acquisition of longer profiles to study soil evolution and variations over greater distances;
- Quantitative interpretation (e.g. separation of matrix and pore water properties) through calibration with intrusive and other geophysical and geotechnical data;
- Integration with other data sets or techniques (geochemical soil analysis, geological mapping, soil mapping, EM, soil moisture etc);

3.6.7 Ground Penetrating Radar

Another technique that may be employed to characterise the soils is Ground Penetrating Radar (GPR). BGS owns a range of GPR instruments (Noggin 250, Pulse Ekko 100). The technique operates by recording the reflection of pulsed EM data, and hence is of particular interest when the objective is to image discreet interfaces. GPR data provide visually attractive models of the subsurface, but quantitative evaluation and parameter extraction is more difficult and time-consuming. One drawback is that the radar signal is attenuated in electrically conductive environments, hence GPR tends to be less suitable for clays and other conductive materials.

GPR trials were conducted at the Brackenhurst site using the Noggin 250 system. Data were recorded on selected profiles on Sheepwalk East, but the results showed high attenuation of the GPR signal even at very short travel times. This is thought to be due to high clay content in the soils at Brackenhurst. No further processing was performed.

3.6.8 Penetrometer tests

Penetrometer tests provide a simple means of obtaining intrusive data to calibrate the results of surface-only geophysical techniques. The BGS probe suite is manually driven and includes mechanical resistance, electrical resistance and volumetric moisture content measurements. It is available at minimal cost to the project. Tests were carried out at the Brackenhurst site during which a small number of moisture content profiles were obtained in the Sheepwalk East field (Figure 38). Ground conditions at Brackenhurst were found to be unsuitable to justify a more extensive study with the manually driven probes, but future surveys may benefit from this methodology.

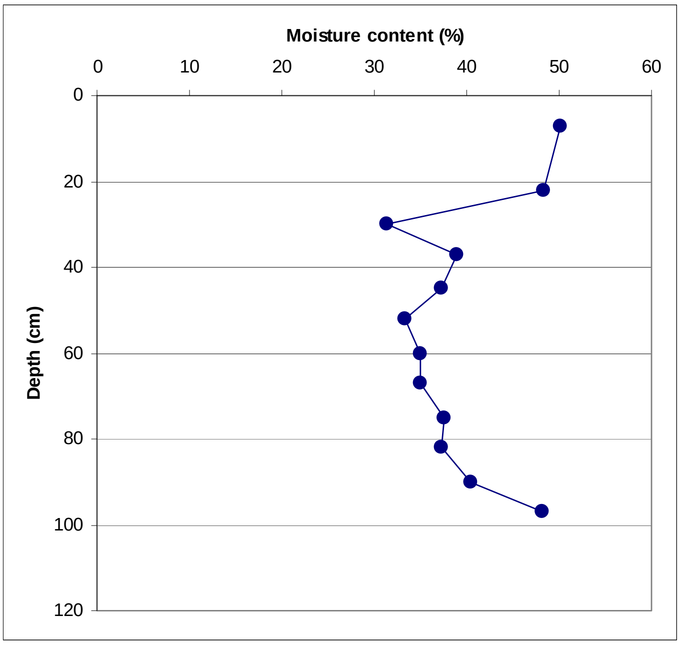


Figure 38 Example of a moisture content profile determined by a penetrometer test

3.7 DOWNHOLE GEOPHYSICS

3.7.1 Aims

The BGS internal downhole geophysical logging service was commissioned to log the deep borehole at Stubbins Lane and one of the shallow boreholes in the Sheepwalk East field. The aim was to establish the relevance of the method to the investigation of lithological and stratigraphic variations in these logs and to include the results in the 3D modelling exercise.

3.7.2 Methods

3.7.2.1 Geophysical logging

Geophysical logs were run by BGS in Stubbins Lane Brackenhurst 9 Borehole (SOBI: SK65SE64) on 1 September 2005. The borehole was fully lined with 57 mm ID plastic casing and was dry. The logging datum was the top of the plastic pipe at ground level.

The depth on logging was 25.3 m and the calliper / natural gamma ray, induction conductivity and high-sensitivity gamma ray measurements were recorded using the BGS Robertson Geologging PCL2 logger. The log measurements were acquired every 1cm and were processed using VIEWLOG software.

Shallow borehole Brackenhurst 16 Borehole (SOBI: SK75SW29) was also logged, with the log datum at the top of the plastic casing (at ground level). The hole was 3.8 m deep and dry. The same log measurements were made as at No.9 above. The induction log showed high conductivity in the top 0.8 m, but this was due to the proximity of the logging vehicle. The log data was processed using VIEWLOG software and results are shown in Figure 39 and Figure 40.

3.7.2.2 Gamma ray logging

Natural gamma ray logs reflect the concentration of three radioactive elements (^{40}K, ^{237}U and Th), present in minerals within the rock materials penetrated by drilling. Because finer-grained layers i.e. siltstones, mudstones and clays have larger grain specific surface areas, natural processes tend to concentrate the gamma activity in the finer fractions where they are absorbed on the grain surfaces. Thus finer–grained material, in this case the mudstones, display higher gamma ray activity and plot to the right of track 1 (HSGR, NGAM curves Figure 39) and the relatively coarser siltstone layers, i.e. the skerries plot to the left of the track reflecting their lower gamma activity. In borehole 9, gamma activity > 120 API, counts/second, (American Petroleum Institute unit), appears to indicate mudstones, and values < 120 reflect siltstone.

3.7.3 Outputs and Results

3.7.3.1 BRACKENHURST COLLEGE BH 9

Two gamma ray logs were run in BH9. The HSGR probe has the detector near the base of the probe and therefore records most of the drilled section. The NGAM probe is 3.45 m in length and its detector is 1.56 m up from its base and therefore cannot record the bottom 1.5 m. The position of the sensor and the length of the probe are important when logging shallow holes.

The induction conductivity log displayed in track 2 reflects the electrical conductivity of the layers penetrated downhole induced by the passage of an electromagnetic field generated by an emitter coil in the probe. The signal is proportional to the ground conductivity and the plot in track 2 shows the ground conductivity increasing (finer-grained, more conductive) to the right. In general form it is approximately parallel to the gamma ray log, reflecting the grainsize control of properties, but in detail the relationship breaks down in some intervals. The thick mudstone above 8 m depth is the highest conductivity (75 mS/m) and this may be a reflection not only of its thickness but possibly a higher moisture content. Where there are skerries with thin mudstones, the induction conductivity log alongside the skerries may be a mirror-image of the gamma ray log (e.g. 11 to12 m, 14 to14.5 m, 16 to 17 m).

The induction resistivity curve displayed in track 5 is derived from the induction COND measurements, and generally in freshwater saturated sediments, gamma ray-resistivity profiles are often an approximate mirror-image relationship reflecting the grainsize. In BH9, the two logs show a mirror-image relationship below 12 m depth but above are generally parallel. Below 12 m the induction resistivity is generally higher, and the lower resistivity above that depth may reflect an increased moisture content.

The resistivity profile suggests that there is probably a siltstone or coarser material layer from 21.6-25 m depth that is moderate gamma ray. The lithology column shown on the log figures is interpreted from study of the core and the geophysical logs (see Figure 39).

3.7.3.2 BRACKENHURST COLLEGE BH 16

Brackenhurst College BH16 was 3.84 m depth and was logged with the HSGR gamma ray probe, as the NGAM probe was too long. Figure 40 identifies predominantly clay (>120 cps) from 0 to 1.9 m overlying a lower gamma ray unit (mean (105 cps) alongside sandy layers of the alluvium from 1.9 to 3.3 m depth. Below 3.3 m the gamma signal increases towards the bottom of the hole reflecting the ‘gravelly clay’ (3.5—3.63 m) and Mercia Mudstone below.

The induction conductivity log in track 4 shows sharply increasing formation conductivity above 0.8 m which is due to the presence of the logging vehicle. The induction log curve shows the clay above 1.9 m is relatively high resistivity (track 5) except below 1.5 m depth where reducing conditions and perhaps greater moisture content lowers the resistivity.

Below 1.9 m the induction resistivity increases alongside the indicated coarser sandy unit of the ‘Old Alluvium’ to 3.15 m depth below which the resistivity falls against the siltstone and clay units. The presence of ‘peat’ reported in the lithology description (Figure 40) can dramatically lower the gamma-ray activity recorded, and might be responsible for the lower gamma ray recorded from 2.7-3.0 m depth, though it should be noted that only fragments of peat were reported, rather than actual ‘layers’.

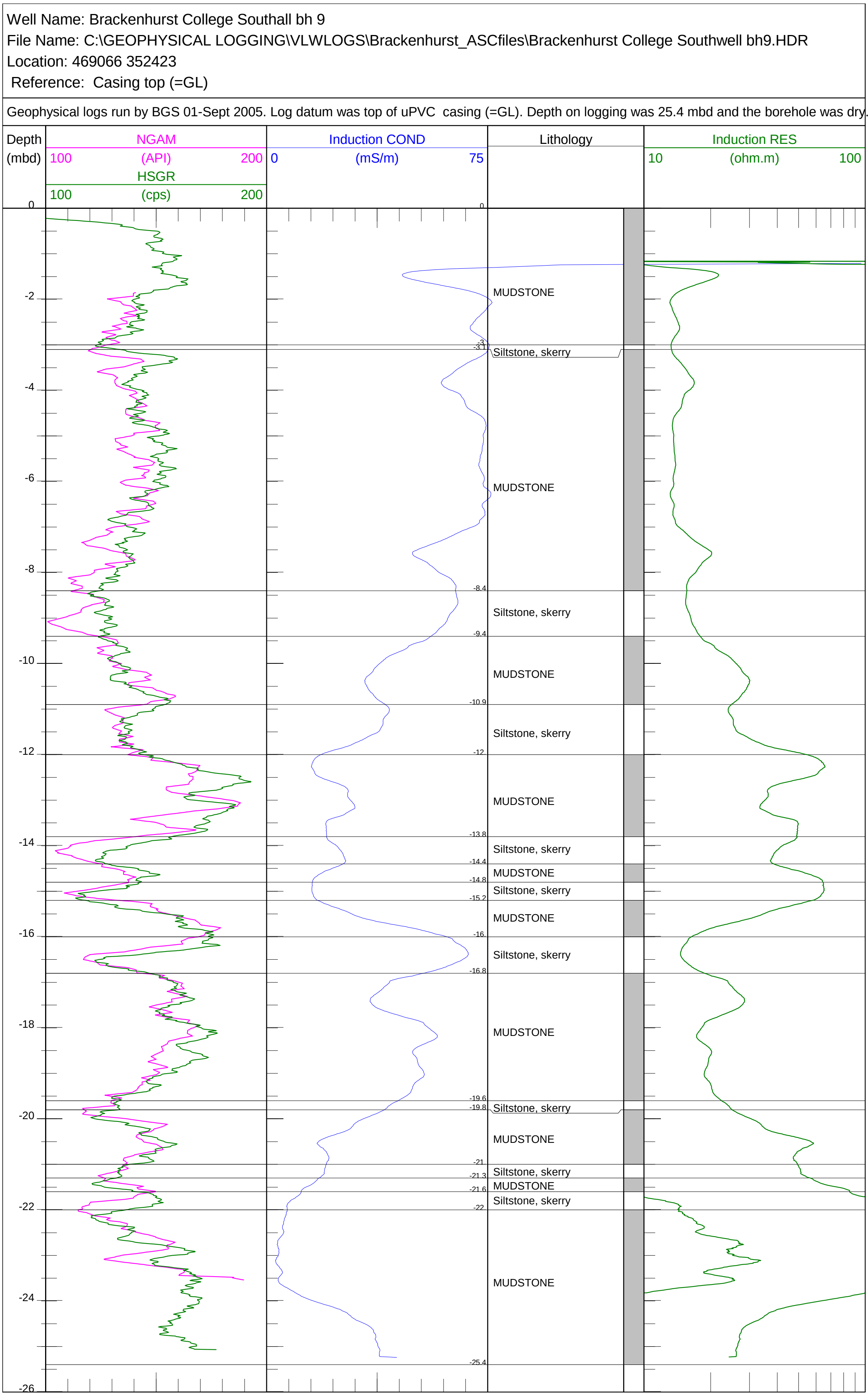


Figure 39 Brackenhurst BH 9 Geophysical Log

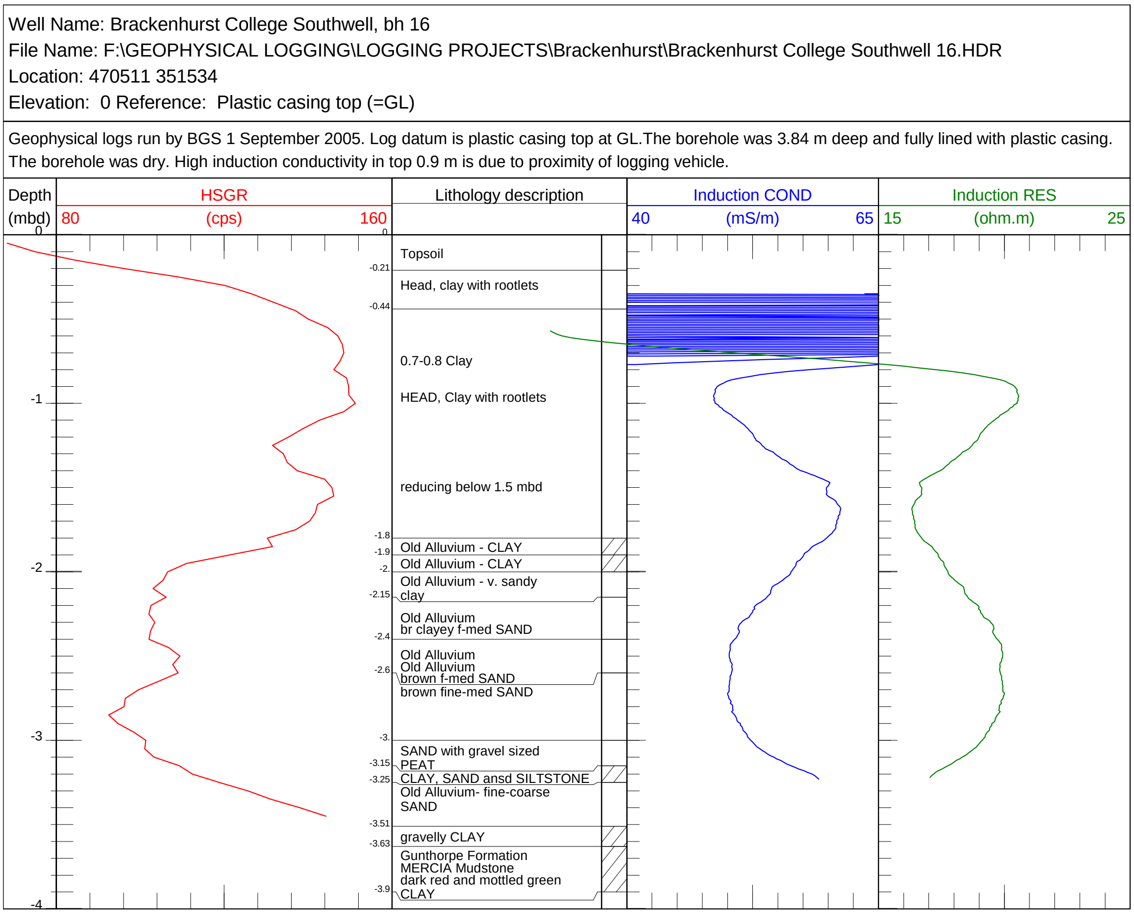


Figure 40 Brackenhurst BH16 Geophysical Log

3.8 GEOCHEMICAL SOIL SAMPLING

The aim of the geochemical sampling campaign within the 3D Soil modelling project was to provide information on the major and trace element concentrations and their distribution in surface and sub-surface soils over the site. Another aim was to test whether preparing and analysing samples onsite using the Mobile Environmental Laboratory (MEL) equipped with mobile XRFs would be efficient and accurate.

3.8.1 Sampling methods

Soil samples were collected at three different depths (0.20 m, 0.50 m and 1 m) at 32 sites, which encompassed the whole of Brackenhurst College (Figure 41). After sample collection the soil was prepared and analysed using portable XRFS methods in the MEL.

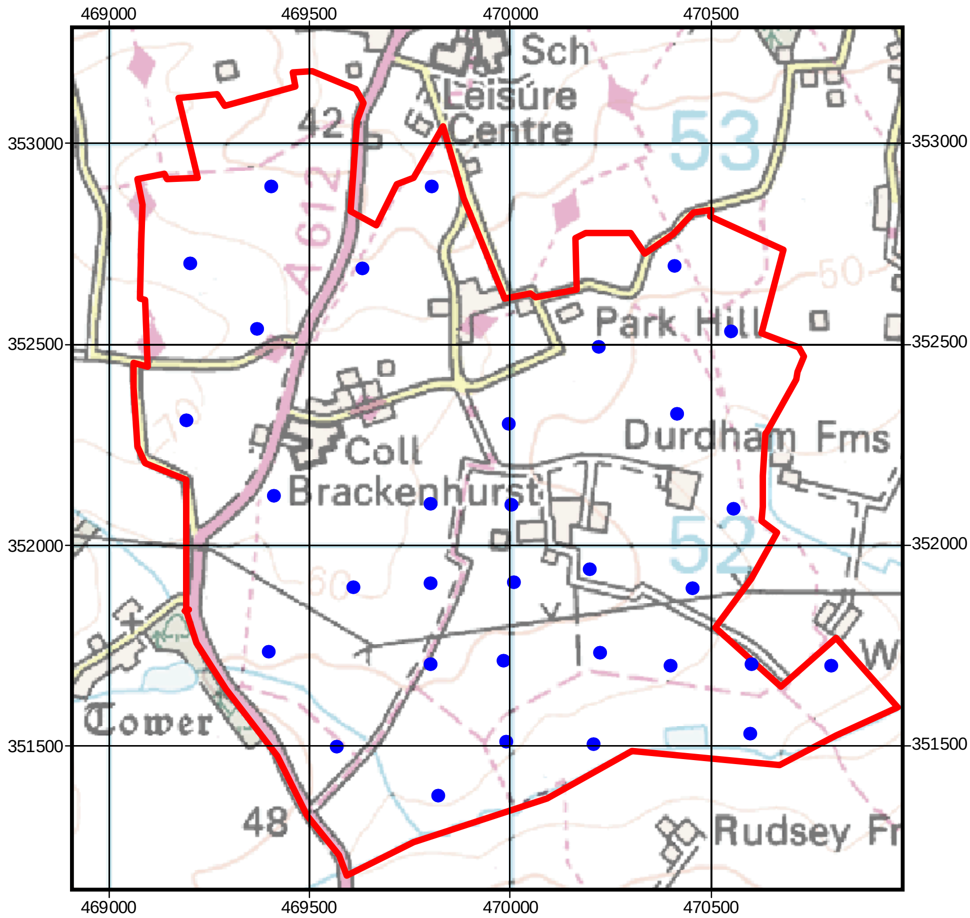


Figure 41 Soil sample locations (blue dots) within the Brackenhurst College Estate

The soil sampling and sample preparation was carried out by BGS staff and volunteer students (Paul Donald and Nina Mistry) from the 25th August to the 2nd September 2005. Leian Grimsley and Mark Ingham provided analytical support, which included a hand held X-ray Fluorescence Spectrometer (XRFS) and a bench top XRFS which was housed in MEL. Soil pH was measured using a pH meter.

Soil samples were taken using a hand held extendable soil auger at depths of 0. 2m, 0.5 m and 1 m (Figure 42). Occasionally stronger beds (bedrock) were reached at <1 m, and when these could not be penetrated by the auger, samples were taken as deep as possible and the depth recorded on a field sheet. The Brackenhurst site was divided into a 200 m^2 grid with the intention of sampling as close to the centre of each one of the grid squares as possible. The sampling commenced to the south east of the site (Sheepwalk East Field), but it soon became apparent that there would not be enough time to complete the sampling at such a high density. Therefore the sample sites are spaced approximately every 400 m^2 to the north of the site, and built-up areas were avoided. This resulted in a total of 32 sample sites, making a total of 96 samples. At every site the sample was taken by a 5-point composite sampling method using a 10m x 10m grid (Figure 43).

Figure 42 Soil augering in a wheat field at Brackenhurst site

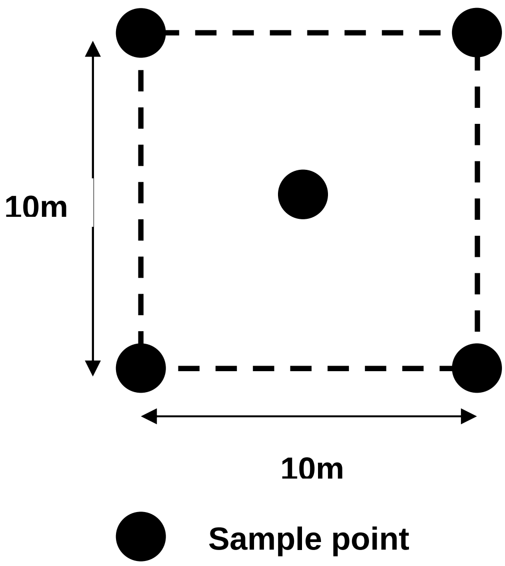


Figure 43 Soil sampling 5 point composite

Additionally a small (ca. 200g) soil sample from the surface auger hole (<20 cm) was collected and later tested for soil moisture content at BGS Keyworth.

3.8.2 Sample preparation and analysis

Sample preparation was carried underneath the awning attached to MEL in an effort to minimise exposure to dust, following the flow chart outlined in Figure 44. The trace element analysis was carried out inside MEL using two XRF spectrometers (a hand held and a bench top).

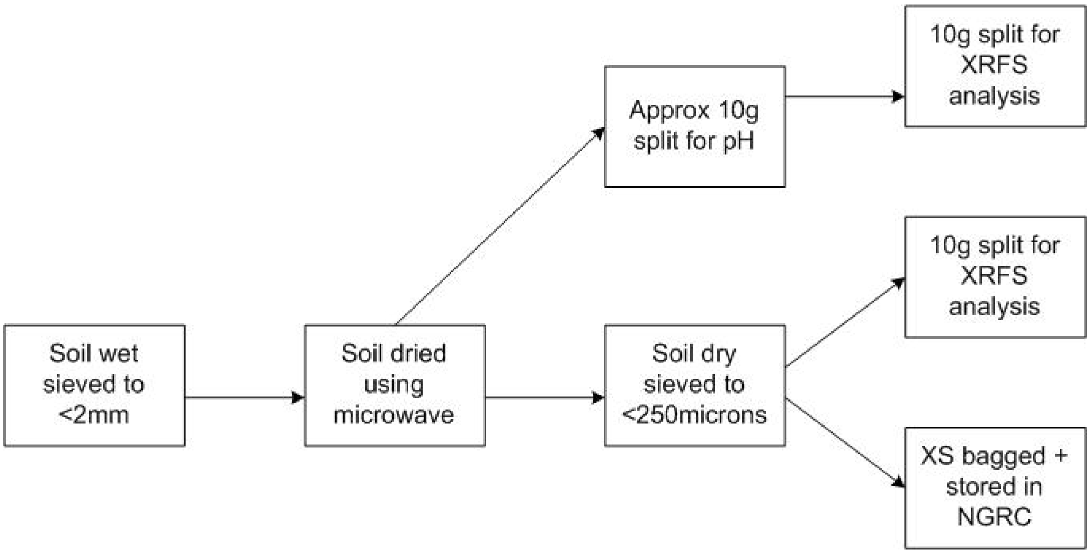


Figure 44 Sample preparation flow chart

For health and safety reasons a 1-metre exclusion zone was enforced whilst the machines were in use and only qualified analysts operated the machines. Each < 2 mm wet sample was tested by the handheld Niton XLt while the dried < 250 microns samples were analysed by the bench top MiniPal 4 (Figure 45). The samples were sieved to <250 µm rather than the standard <2 mm as this is the size fraction needed for the portable and bench top XRFS analysis. Excess <2 mm fractions of the samples were saved and prepared in the Keyworth Sample Preparation Facility for analysis by XRFS on the Keyworth site.

All soil samples were also submitted to the BGS laboratories at Keyworth and analysed with WD-XRF for the following:

Major elements: CaO, Fe_2O_3, K_2O, MnO and TiO_2.

Trace elements: Ag , As, Ba, Bi, Br, Ce , Cd, Cl, Co, Cr, Cs, Cu, Ga, Ge, Hf, I, In, La, Mo, Nb, Nd, Ni, Pb, Rb, S, Sb, Sc, Se, Sm, Sn, Sr, Ta, Te, Th, Tl, U, V, W, Y, Yb, Zn and Zr.

Figure 45 Inside MEL showing the analytical XRF instruments MiniPal 4 (left) and Niton XLt (right)

Soil pH measurements were carried out on site on microwave-dried soil in the second laboratory using the distilled water slurry method. 10 g of <2 mm soil in a solid-solution-ratio of 1:2.5 was added to 25 ml of deionised water and then stirred for 5 minutes. After settling for another 15 minutes a pH electrode was immersed into the suspension. Once the pH meter stabilised a reading was taken.

The same samples were also analysed by the laboratories at Keyworth to ensure the quality of the measured pH data. The method was the same as in the field except that samples were dried at ~35°C rather than drying with a microwave. Two duplicate samples were collected within the 96 samples to establish the validity of variation between samples collected and for purposes of error monitoring, as outlined in Johnson (2005).

3.8.3 Sample site information

Site and sample information were recorded onto G-BASE soil field cards (version 2005.1) while the soil samples were collected (Figure 46). The data were subsequently transferred into a digital field database that holds the grid reference, sample depth below surface, date of sampling, collector's initials, land use, site contamination and soil description, which includes colour, texture, moisture and organic content and the clast lithology. Additionally, more detailed comments were also made, e.g. how observed contamination or soil properties varied within the holes of the composite sample. Further details of protocols for recording field data and the applied codes can be found in the internal report IR/05/097 (Johnson, 2005, G-BASE Field Procedures Manual).

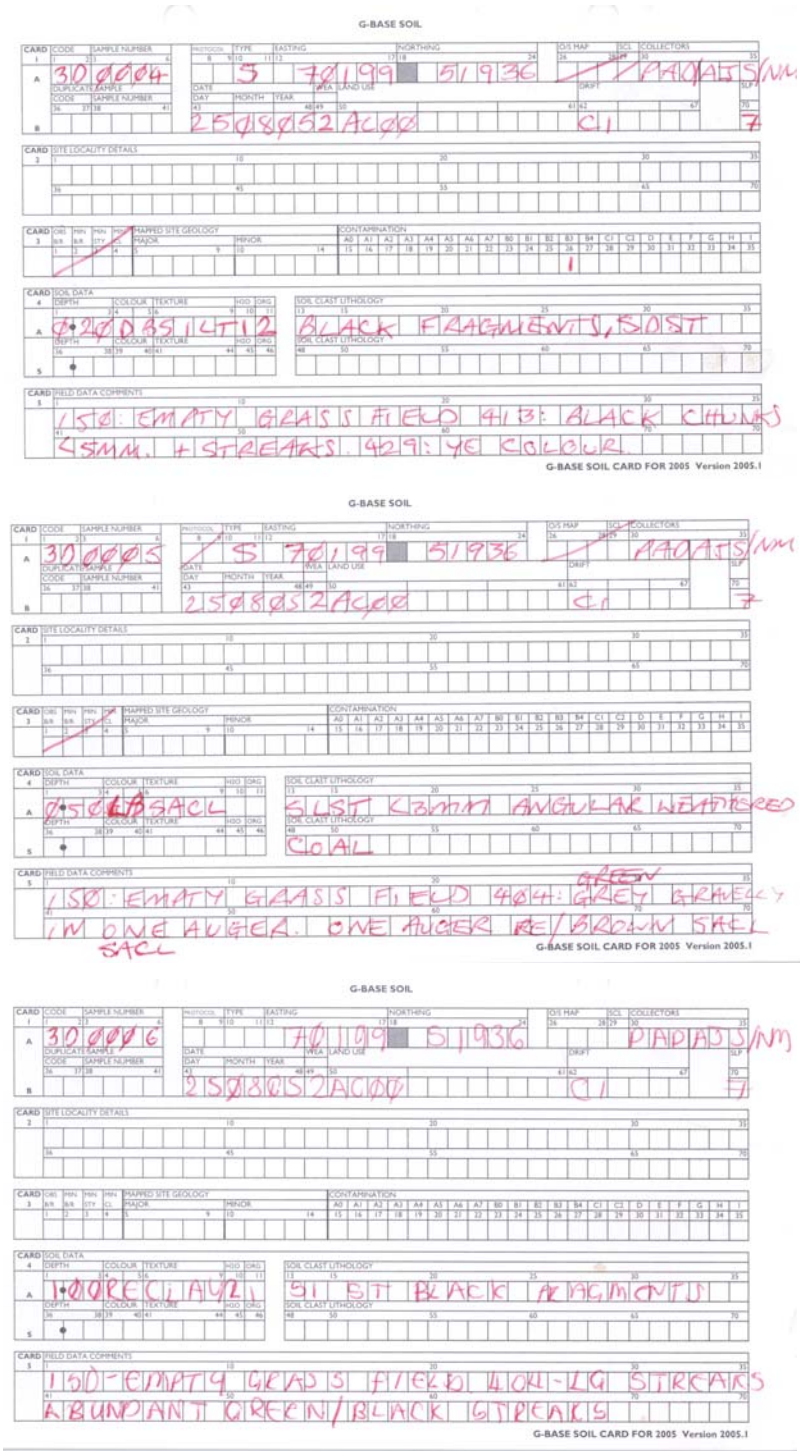


Figure 46 Example of field cards for Brackenhurst geochemical survey

3.8.4 Soil Geochemistry

A total of 96 soil samples were collected and analysed at the Brackenhurst site. The samples were analysed on site with the MiniPal bench top XRF, samples were also submitted to the BGS laboratories, Keyworth, for the more comprehensive WD-XRF analysis. Results from latter analysis are presented in this report. Data comparison of the two XRFS methods for the surface soils only are presented in Appendix 1 providing an indication of the accuracy, precision and reliability of using a portable method. Additionally soil pH was tested for all soil samples and moisture contents for surface soils (see Section 3.8.5).

A selection of 8 analytes, out of a total of 36, were chosen to describe the geochemistry of the soil profile (down to 1m). Table 15 lists the selection, including oxides of Fe, K, Ca, Ti and Mn and three trace metals Rb, Sr and Zr. Rb, Sr and Zr were chosen for further interpretation as they reflect the geochemistry of the underlying Mercia Mudstone Group. The table lists the minimum, maximum, median and mean values at sample depths of 0.2, 0.5 and 1.0 m for each selected element. It should be noted that the 1.0 m depth also includes samples that did not reach this, but the deepest auger hole was recorded on the field sheet.

Table 15 Summary of analytical statistics

Sample depth (m)		K_2O wt %	CaO wt %	TiO_2 wt%	MnO wt%	Fe_2O_3 wt %	Rb mg/kg	Sr mg/kg	Zr mg/kg
0.2	Min	3.23	0.33	0.53	0.05	2.91	91	47	154
	Max	4.85	10.5	0.77	0.15	4.76	118	68	447
	Median	4.14	1.11	0.69	0.08	3.91	106	51	309
	Mean	4.15	1.95	0.69	0.08	3.90	106	53	314
0.5	Min	3.53	0.22	0.54	0.04	2.80	88	18	153
	Max	8.69	8.69	0.80	0.18	5.68	128	35	471
	Median	4.11	1.88	0.68	0.08	4.30	112	27	278
	Mean	4.18	2.96	0.69	0.08	4.25	110	27	284
1.0*	Min	3.00	0.25	0.51	0.05	2.76	81	45	109
	Max	5.24	11.63	0.81	0.14	6.92	139	87	480
	Median	3.96	6.70	0.66	0.09	4.36	107	60	204
	Mean	4.01	5.62	0.66	0.08	4.42	109	60	231

*a small number of samples were collected at 0.85 to 0.95 m depth due to penetration of parent material.

CaO levels are low for most of the surface soils, although it is noticeable that the CaO median level increases with depth, by up to a factor of 6, between surface soils at 20 cm and the deepest sample at 100cm (see Figure 47) where the horizontal lines represent the median and the black round symbols denote the mean. Higher Ca levels in peri-urban areas are common as concrete, cement and plaster dust are distributed throughout the urban environment and in rural soils, the application of lime as a soil conditioner can cause anomalies. As images of the CaO distribution in soils of the Humber Trent Geochemistry atlas shows, CaO levels have a range widely over the Mercia Mudstone Group (BGS, 2007). The increase of CaO with depth observed in these soils could be related to the presence of gypsum within the Gunthorpe Member skerries.

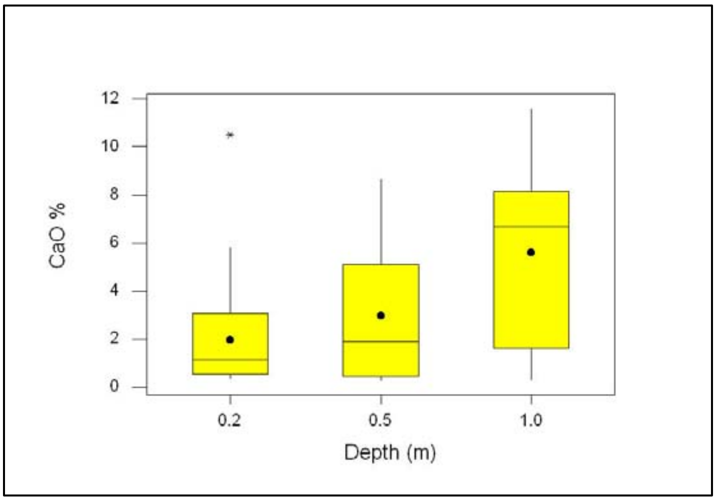


Figure 47 Box and whisker plot for CaO (%)

Figure 48 shows that Fe_2O_3 is relatively uniform throughout the vertical soil profile, although there is a slight increase in concentration with depth. K_2O content on the other hand shows a slight decrease in concentration with depth (Figure 49) and the median values of all 3 depths are higher than the regional median of 1.88% (BGS, 2007) reflecting the high clay content of the Mercia Mudstone Group.

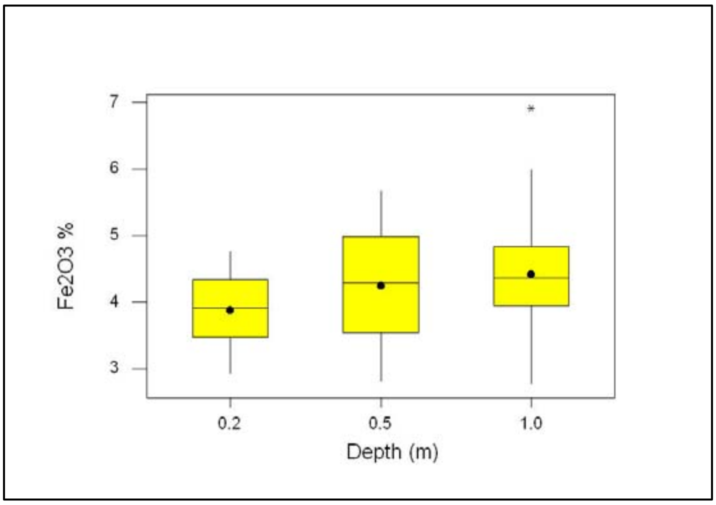


Figure 48 Box and whisker plot for Fe_2O_3 (%)

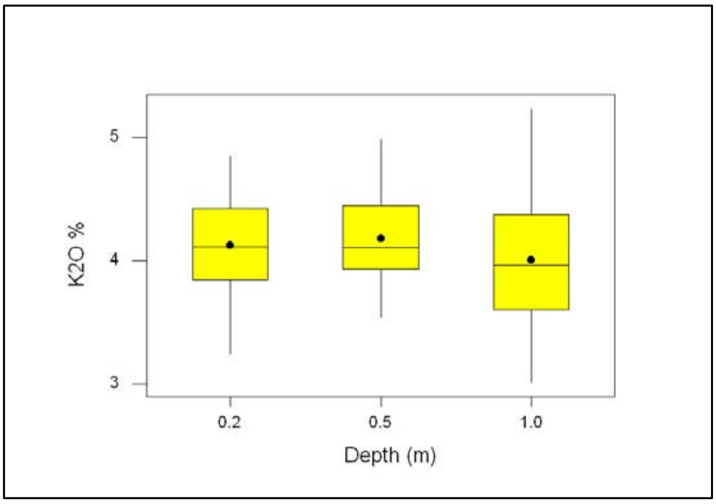


Figure 49 Box and whisker plot for K_2O (%)

TiO_2 and MnO (Figure 50 and Figure 51 respectively) do not show any significant variation with depth and are consistent with the regional medians which are for TiO_2 0.68% (surface) and 0.74% (profile) and for MnO 0.08% (surface) and 0.104% (profile).

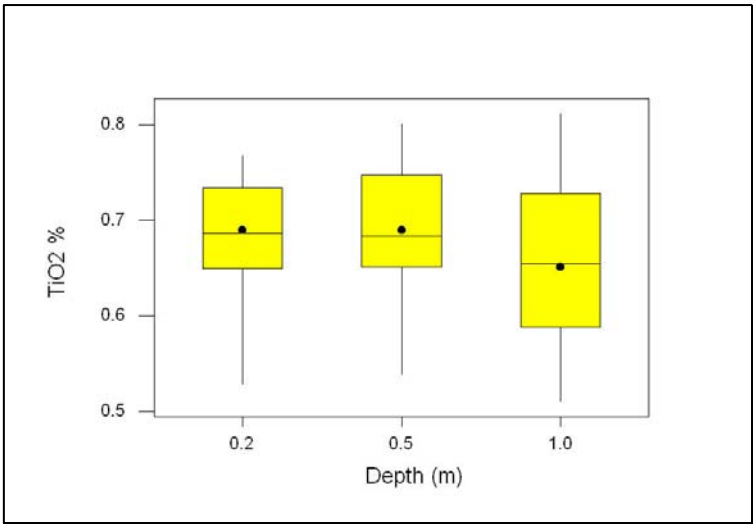


Figure 50 Box and whisker plot for TiO2 (%)

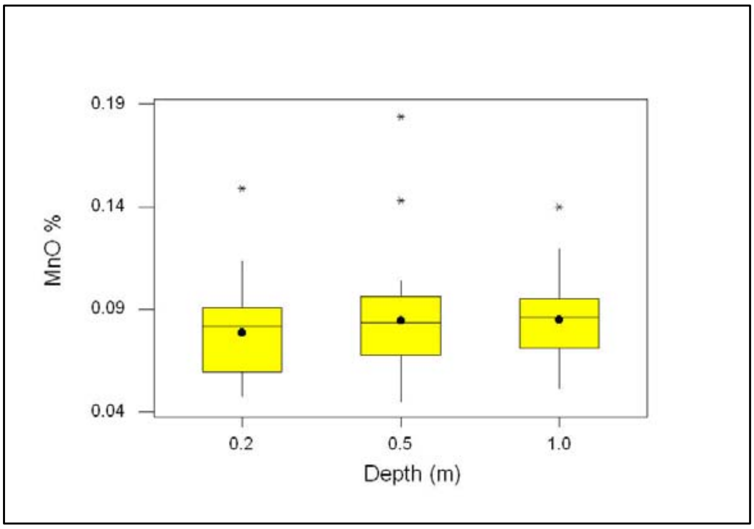


Figure 51 Box and whisker plot for MnO (%)

The median values for Rb are higher than the regional median of 65 mg/kg and 74 mg/kg for surface and profile soils respectively (BGS, 2007). This may be due to the strong affinity of Rb with clay minerals found within the Mercia Mudstone Group. There is no correlation with Rb concentration and depth (Figure 52).

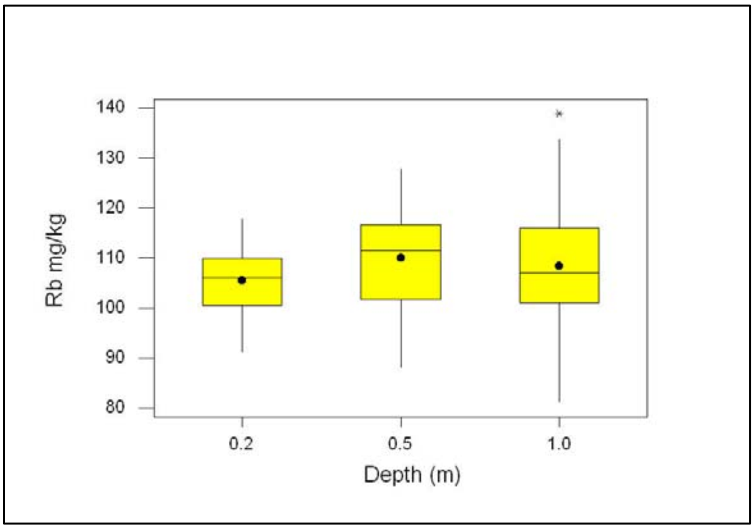


Figure 52 Box and whisker plot for Rb (mg/kg)

Sr levels show no particular pattern within the profile (Figure 53). The median values at each depth are below the regional median of 66 mg/kg (surface soils) and 75 mg/kg (profile soils). Sr is closely associated with sulphates; therefore the presence of gypsum within the siltstone skerries would suggest that higher levels of Sr could have been expected. Gypsum is often removed by groundwater in the near surface zone (Hobbs, 1998), which could explain why the values for Sr are lower, although the CaO concentrations would seem to contradict this.

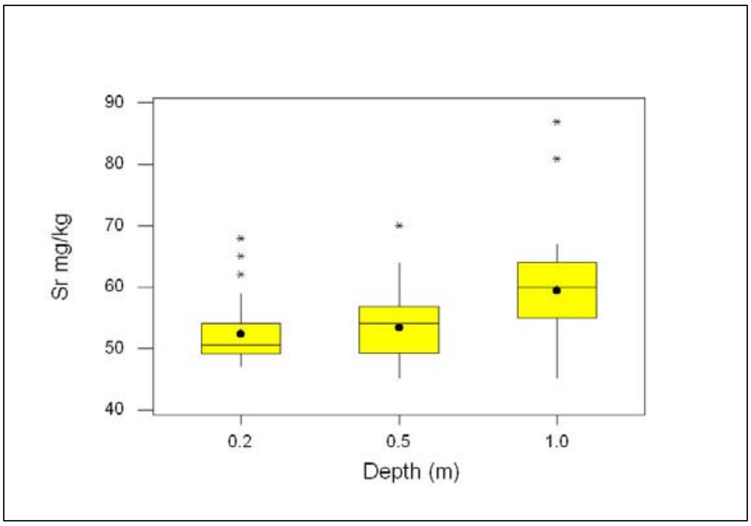


Figure 53 Box and whisker plot for Sr (mg/kg)

The Zr data shows a significant decrease of concentration with depth (Figure 54). The Mercia Mudstone Group tends to have around average concentrations of Zr, so the elevated levels in the near surface would have to come from another source.

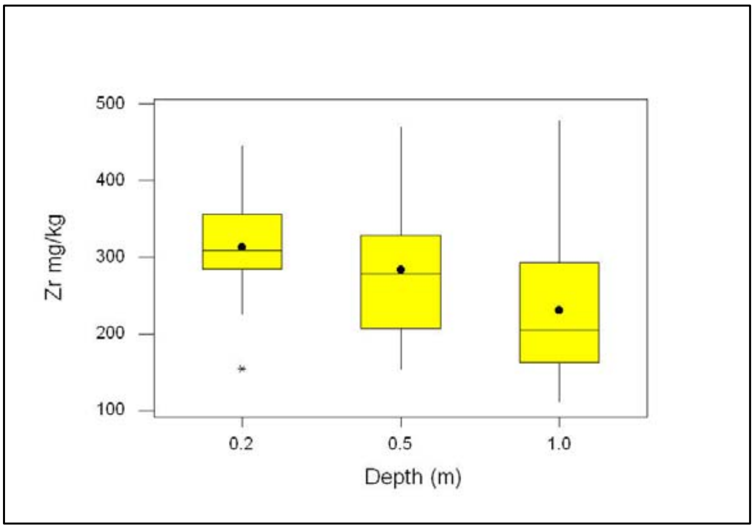


Figure 54 Box and whisker plot for Zr (mg/kg)

When looking at this in more detail (Figure 55) it can clearly be observed that the higher values for Zr can be linked to the superficial deposits of alluvium and head in the area. Zr is a residual element and will congregate on the surface as it is a reasonably heavy element (i.e. it will not be removed as easily by weathering). It is also one of the less mobile elements and will therefore not easily be leached into the soil profile.

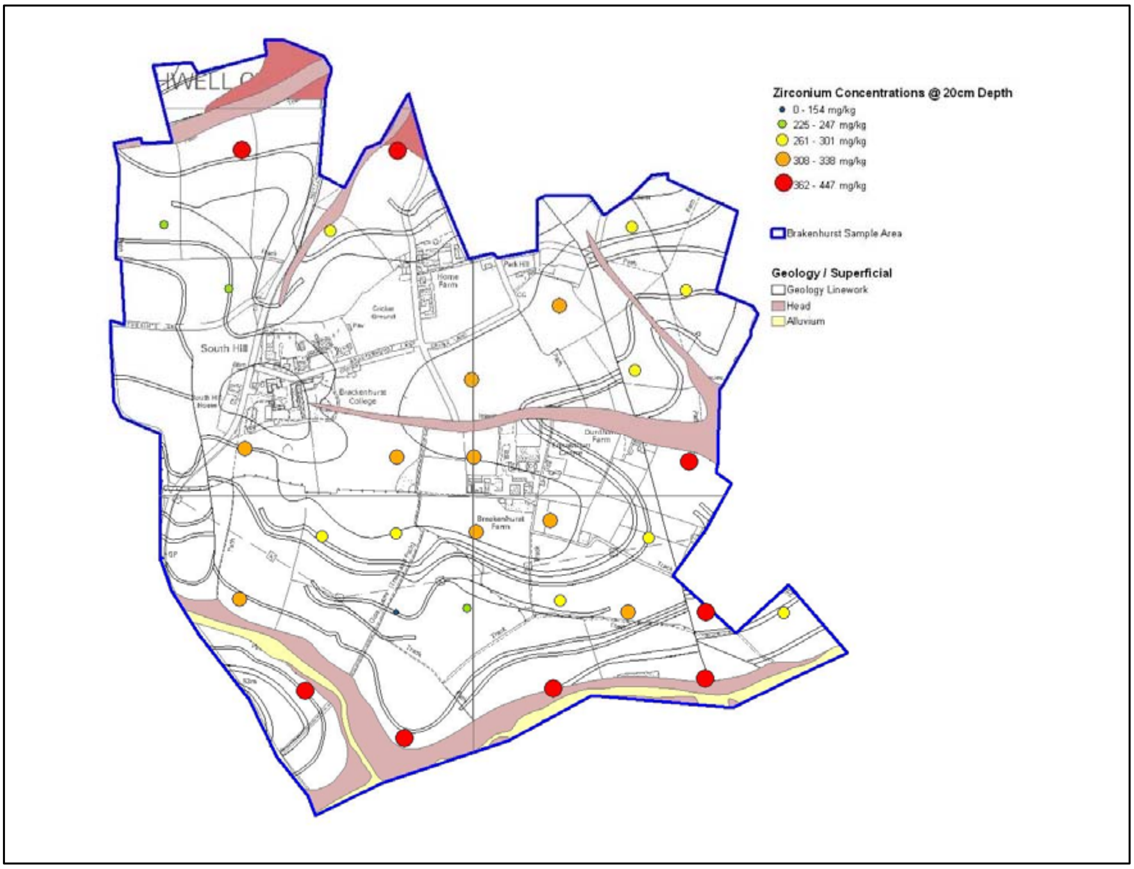


Figure 55 Zr (mg/kg) shows high concentrations within close proximity to superficial deposits

3.8.5 Soil pH and Moisture

A 10 g fraction of each soil sample (2 mm) was analysed for soil pH, using the distilled water slurry method. The analysis was carried out both in the mobile laboratory and at the laboratories in Keyworth. The test results of the pH analysis on site correlated with the Keyworth Laboratories very well, although a small percentage of the results did vary up to 1 pH unit, which given this is a logarithmic scale represents a significant difference. The variation is thought to be due to the way that the samples were dried on site. The microwave method dries the samples at an extremely high temperature, which could have altered the soil pH. Therefore, it was decided to use the more reliable test results from the laboratories. The pH values varied from 4.7 for sample 3D67 at 0.20 m to pH 9.0 for sample 3D15 at 1.00 m. A complete table of pH values for each soil sample is attached in Appendix 1.

Table 16 gives the summary statistics for pH values over the Brackenhurst site in the three sampling depths of 20 cm, 50 cm and 100 cm below surface. The results show a trend of a significant increase of the pH with depth, resulting in neutral to basic pH values (>7.5) at 100 cm. This increase in pH may be attributed to the presence of dolomitic siltstones within the mudstone. Mercia Mudstone also has a tendency to become more acidic when weathered, which could explain the lower pH values at the surface.

Table 16 pH statistics for the Brackenhurst Site

Depth	pH min	pH max	pH median	pH mean
20 cm	4.7	8.2	7.8	7.2
50 cm	5.8	8.7	8.1	7.8
100 cm (or max penetration)	7.9	9.0	8.5	8.5

An additional sub-sample of the topsoil was collected to test for moisture content during the soil sampling campaign from 25th August to the 2nd September. This was thought to be valuable information especially for geophysical surveys. The samples were collected within 5 consecutive days, during which the weather conditions were warm and dry.

The moisture content was determined by weighing approximately 1g of soil straight from the field, drying at ~35°C for 24 hours and reweighing and calculating the percentage difference. The results are expressed as percentage weight loss. **Table 17** presents the summary statistics for this data.

Table 17 Surface soil summary statistics for moisture content

Depth	Moisture min %	Moisture max %	Moisture median %	Moisture mean %
20 cm	12.72	32.40	22.50	21.98

The variability of the moisture content throughout the Brackenhurst site is shown in Figure 56. The wettest areas are indicated by a deep navy blue colour, e.g. in the valley bottom by the pond to the southeast.

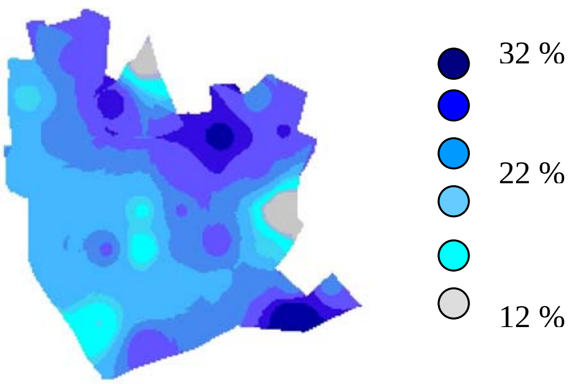


Figure 56 Moisture content of topsoil (5 – 20cm) over Brackenhurst Campus

3.8.6 Recommendations

- Geochemical data of, for example, K_2O and CaO etc. can help to identify clay-rich or Ca-rich soil horizons. If geochemical sampling is carried out in future surveys it should be attempted to relate the data to other survey techniques such as gamma spectrometry.
- Moisture measurements should be undertaken at the same time as the geophysical surveys, as it can aid data interpretation.
- Soil geochemical sampling should be carried out either during or after geophysical surveys as sample density could be increased in areas of interest, e.g. anomalies.
- Collection of soil information such as texture, organic content etc. should be continued.
- Observation of depth below surface of the A-horizon should be recorded.

- Observation of depth from transition/change from soil to parent material or drift should be noted.
- Samplers should be equipped with drift/geology maps.

3.8.7 Conclusions

It should be noted that the geochemical sampling was conducted as a trial to establish whether chemical data would assist in the production of the near surface 3 D model.

Unfortunately, the spatial and vertical variations in the geochemistry of the Mercia Mudstone Group that were recorded using the adopted sampling configuration do not have a distinct signature and could not be used when constructing the model. There are noticeable differences in concentration at depth for some elements, which could be of use when trying to distinguish between soil horizons. It may be helpful to carry out a geochemical survey on a more varied soil-geoscape, and tailoring the chemical analysis to the underlying parent material. It could then be possible to determine whether the data would be helpful in constructing the 3D model.

It also became apparent that other data collected in conjunction with the geochemical sampling (but not presented in this section) was useful when constructing the 3D model. These were soil property details, such as texture, colour and moisture content, and these will be sampled and analysed for in future surveys.

3.9 SOIL SURVEY

3.9.1 Aims

NSRI were invited to collaborate in this Brackenhurst site research by supplying soil science expertise. This section describes the soil mapping that was undertaken to produce a 1:10,000 scale soil map (Palmer, 2006).

3.9.2 Methods

During the collation of extant datasets related to the site, interrogation of the NSRI commercial contracts database identified a soil map at 1:10,000 scale prepared for the former Brackenhurst College in 1987. Subsequently, 94 auger bore record cards (RUFFS) were found within the NSRI paper archive dating from the survey in December 1987. These RUFF cards had not been processed and, therefore, were not stored in LandIS (Land Information System – NSRI's national soil database).

Following a review of the available data, and in the absence of any original field maps, a re-survey of the site was undertaken at approximately 40 bores per square kilometre to check the validity and composition of the soil map units identified on the 1987 map. The soil survey methods used at Brackenhurst are those described in Palmer (1982) p.33 from a detailed survey in Worcestershire, which incorporated a similar suite of soils on the Mercia Mudstone Group. A short description of the soil classification used by NSRI is also given in this Soil Survey Record. A breakdown of key tasks undertaken by NSRI during this project is given in the Table below.

Table 18: NSRI key tasks during the 3D soils project in 2005/2006 (Palmer, 2006)

<table>
<tr><th>Research packages</th><th>Timescale</th><th>Specifics / location</th></tr>
<tr><td>1. Collaboration with BGS staff in the planning and optimum scheduling of work</td><td>End September 2005</td><td>Office based discussions mainly at Keyworth</td></tr>
<tr><td>2. Review of existing data with BGS staff and develop field strategy.</td><td>End August 2005</td><td>At Silsoe, York and Keyworth as required</td></tr>
<tr><td rowspan="6">3. Site survey at Brackenhurst according to the experimental strategy defined jointly with BGS in 2 above.
Soil sampling and training for NSRI and BGS staff.
Includes field demonstration and discussion of salient points that will form basis of the final strategy.</td><td rowspan="6">End December 2005</td><td>Initial site meeting</td></tr>
<tr><td>Basic survey (approx 100 bores to base of soil layers)</td></tr>
<tr><td>Training element – up to 3 junior NSRI staff and 3 BGS staff</td></tr>
<tr><td>Pits and samples (5 pits) – surveyor</td></tr>
<tr><td>Training element as above</td></tr>
<tr><td>Sample cataloguing and soil record card input to LandIS.</td></tr>
<tr><td rowspan="3">4. Sample analysis
Assuming 5 horizons per pit – 25 in total
At Silsoe</td><td rowspan="3">End January 2006</td><td>Particle size analysis (5 fractions),
pH, OC and CEC</td></tr>
<tr><td>Water retention curve (triplicate tins) plus bulk density</td></tr>
<tr><td>Residual dithionate ext Fe% & Carbonate</td></tr>
</table>

5. Collaboration to define optimum strategies for future studies, including planning and scheduling surveys for 2006-07 and input to project report	End February 2006	Protocols for future work Variations to protocols for specific landscapes (Keyworth and York as required)

All observations were recorded on RUFF cards and these were digitised and input to LandIS. The original 94 RUFF cards from the 1987 survey have also been digitised and both sets of data are stored in Excel worksheets. One worksheet incorporates the site information from each observation and a second worksheet contains information on the various horizons (layers) of the soil profile described at each site.

Two separate two-day soil mapping training courses were held for mixed groups of staff from the BGS and NSRI. A typical range of soils across the farm were described during these two sessions and geomorphological relationships between soil series were demonstrated. A further training day for each group covered the description of soil profiles in trial pits. The profile descriptions resulting from these days and the results of subsequent laboratory analysis are given in the Appendices.

3.9.3 Outputs and results

Outputs of the re-survey at Brackenhurst Campus are a soil map, soil series description, and trial pit descriptions including soil property analyses. The results of the soil survey, carried out by R. C. Palmer were documented in an NSRI report (Palmer, 2006), which includes background data, methodologies, results, a soil description and some interpretation. A brief summary of the results and findings of the soil survey report are presented here.

Figure 57 below shows the resurveyed 1:10,000 scale soil map. The map identifies six soil series: the Mathon, Hopsford and Salwick Series occur on head and alluvial deposits and more commonly, soils of the Worcester, Whimple and Brockhurst Series appear on the Mercia Mudstone Group. The soils found at Brackenhurst occur widely on Mercia Mudstone Group deposits elsewhere in the Midlands and South West England. Small areas are also found in Wales and Northern England. On the National Soil Map these soils are included within the Worcester (431), Whimple 1 (572d), Whimple 2 (572e), Whimple 3 (572f) and Brockhurst (711b) soil associations. The density of soil observations made across the farm is greater than typical in 1:10,000 scale soil surveys and the higher observation density has allowed better definition of boundaries between soil series, but the extra bores have not led to the identification of more soil series (Palmer, 2006). Description of trial pits, marked on the soil map, which were dug during the soil survey training course are included in the Appendices.

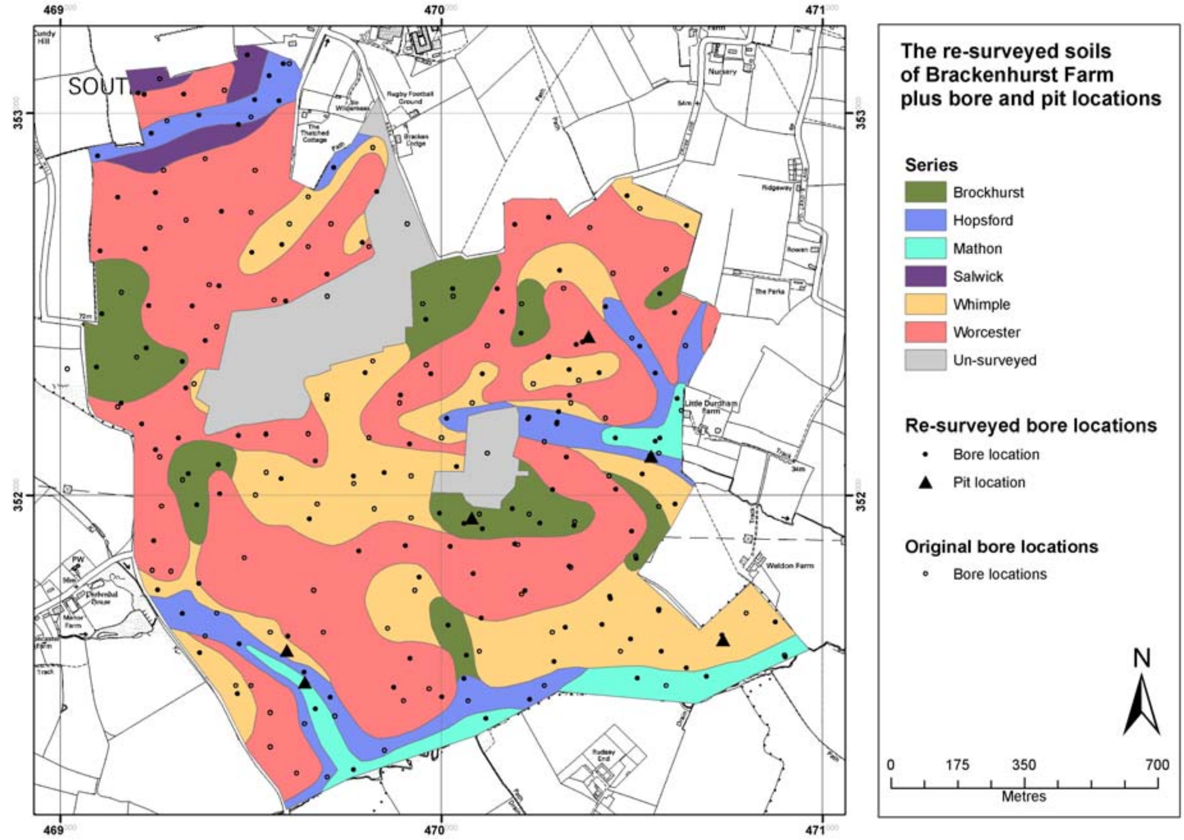


Figure 57 Soil map of Brackenhurst Campus, Nottingham Trent University (Palmer, 2006)

3.9.4 Soil description

Soils of the Worcester Series are reddish brown clayey soils, widespread on sloping ground across the whole farm. Topsoils are generally clayey but locally are heavy clay loam in texture and pass abruptly downwards with an increase in clay content and decrease in organic matter to reddish brown silty clay or clay subsoils which frequently contain greenish grey streaks and patches often associated with thin bands of weathered siltstone. Subsoils are often slightly calcareous, reflecting the carbonate content of the underlying Mercia Mudstone, but topsoils can be moderately acid unless regularly limed.

Soils of the Whimple Series have moderately permeable clay loam or sandy clay loam upper layers (to 40-70 cm depth) overlying slowly permeable reddish clayey subsoils. They occur either on gently sloping interfluve sites or on shallow concave lower valley sides or along narrow valley bottoms. They differ from the similar Worcester series by the presence of thin moderately permeable clay loam upper layers; their much shorter period of seasonal waterlogged differentiates them from the otherwise similar Brockhurst series. As is the case with the Worcester and Brockhurst series they are developed in reddish slowly permeable Mercia Mudstone Group soils. Because clay is encountered at deeper depth than is the case with the Worcester series, Whimple soils are generally more responsive to under drainage although care has to be taken when the clay interface occurs at or around drain depth.

The Soils of Brockhurst Series are physically very similar to the Whimple series but because they occur on level interfluves or in valley bottoms they suffer marked surface wetness caused by their slowly permeable subsoils, which severely restrict downward drainage. The level sites preclude lateral water movement through moderately permeable upper layers. Clay subsoils usually occur between about 40 and 60 cm depth. Prominent ochreous and grey mottling in upper layers provides evidence of the seasonal surface wetness that is typical of these soils.

Hopsford soils are deep moderately permeable and developed in Head deposits, which fill the shallow valleys across the farm and form concave slopes flanking the main areas of river alluvium. Upper horizons are clay loam or occasionally sandy silt loam passing down to clay loam or sandy clay loam subsoils at depth. Lower layers are affected by fluctuating groundwater in winter and early spring.

Small areas of Salwick series have been mapped in the north of the farm, generally in low-lying concave footslope sites. They usually form a narrow transitional unit between the Hopsford series downslope and the Worcester series upslope. Locally these soils are too narrow in extent to map separately as demonstrated around the profile pit site near Gypsy Lane. Salwick soils are developed in thick loamy reddish brown Head and till deposits and have moderately permeable clay loam upper layers overlying slowly permeable slightly heavier subsoils. The slow subsoil permeability produces slight seasonal surface waterlogging in winter and early spring, which limits their suitability for spring-sown crops. In many respects Salwick soils behave in a similar manner to Whimple series.

Soils of the Mathon Series are deep moderately permeable soils and developed in reddish silty riverine alluvium, which forms thin strips along the Helloughton Dumble and its tributaries. They are stoneless and silty clay loam in texture throughout and lower layers are affected by fluctuating groundwater during winter and early spring months. On the farm these soils are either under permanent grass or wildlife amenity land adjacent to the stream. When adequately underdrained they form the most flexible land on the farm and are well or moderately well suited to all common arable crops (Palmer, 2006).

3.9.5 Recommendations

- Soil studies provide information on the presence and duration of waterlogging within 1m depth and this is a key addition to standard geological information. These data should be incorporated into future 3D modelling if these models are to fully integrate soil science and geology and then used for applications of soil data (leaching risk, corrosion potential, crop suitability - all require soil water info).
- Deeper augering should be conducted if the parent material in the soil profile has not appeared at depth of 1.2 m confirming the depth of the “C” horizon or top of parent material is important.
- The relevant NSRI soil texture classes were converted into BGS Lex-Rock classes for this project, and this will be necessary for any similar surveys in the future. A translation table for all NSRI data should be produced.
- Physical soil analysis (bulk density etc.) is necessary for the construction of the 3D model as changes can directly affect direction and speed of water movement in soils.
- Photographic documentation of trial pits/profiles should be stored in the Geoscience Imagebase.

4 3D Digital Modelling

The aim of the 3D digital modelling exercise was to combine data of different file formats and geoscientific disciplines into one 3D model. This would enable scientists to create an integrated geological and detailed soil model for the Brackenhurst site which could be used for further analysis, such as groundwater vulnerability assessments or hydrogeological pathways studies (Kessler et al, 2005), as well as to aid our knowledge of the shallow subsurface and produce a graphical output that would help demonstrate our understanding to the public.

The visualisation and 3D modelling of the project was carried out in the GSI3D software. The GSI3D methodology was developed by Hans-Georg Sobisch (INSIGHT Geological Software Systems) originally in collaboration with the Lower Saxony Geological Survey in Germany and later with the BGS acting as a testbed for accelerated development. The methodology is documented in Hinze et al (1999), Sobisch (2000) and Kessler et al. (2004).

In principle GSI3D combines Digital Terrain Model, geological surface linework and downhole borehole data to enable the scientist to construct regularly spaced intersecting cross sections by correlating boreholes and the outcrops-subcrops of units to produce geological fence diagrams (Figure 58 a-c). Mathematically interpolating between the nodes along these sections (and the outcrop/subcrop limits of the units) produces a solid model. This is built from a series of stacked triangulated objects, each corresponding to one of the geological units present (Figure 58 d-e).

After model has been computed, it is ready for interrogation and analysis (Figure 58 f-h). Originally the software was developed for use in geological modelling, but its use is extending into the modelling and visualisation of man made ground and archaeology, and in this project to soil horizons.

Figure 59 shows the user interface of the software with some of the key datasets loaded from the Brackenhurst site.

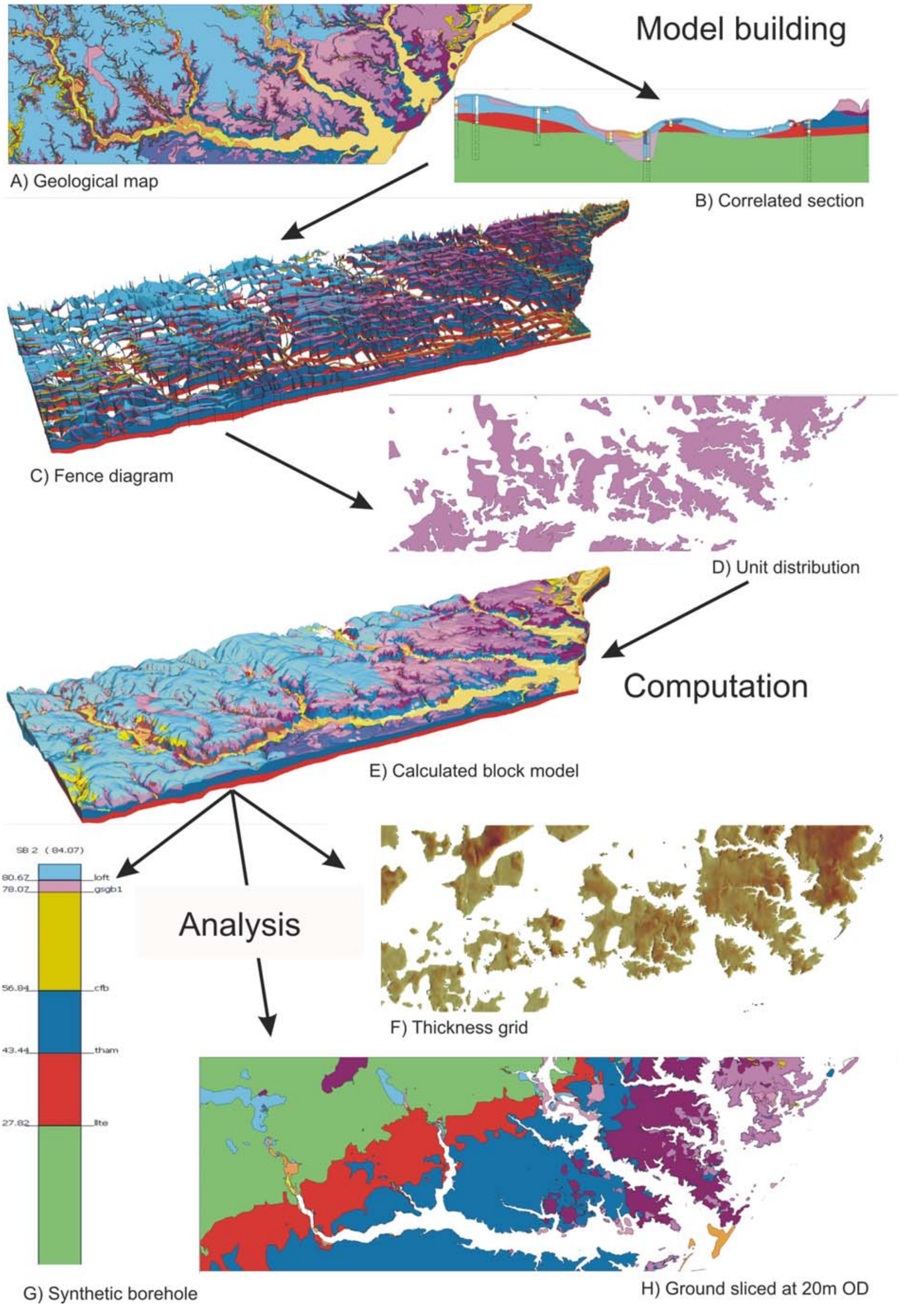


Figure 58 The model building workflow (A-E) in GSI3D and example analytical outputs (F-H) that can be derived from a 3D geospatial model. The model shown comprises some 1200 sq km of the Sudbury-Ipswich-Felixstowe area of southern East Anglia.

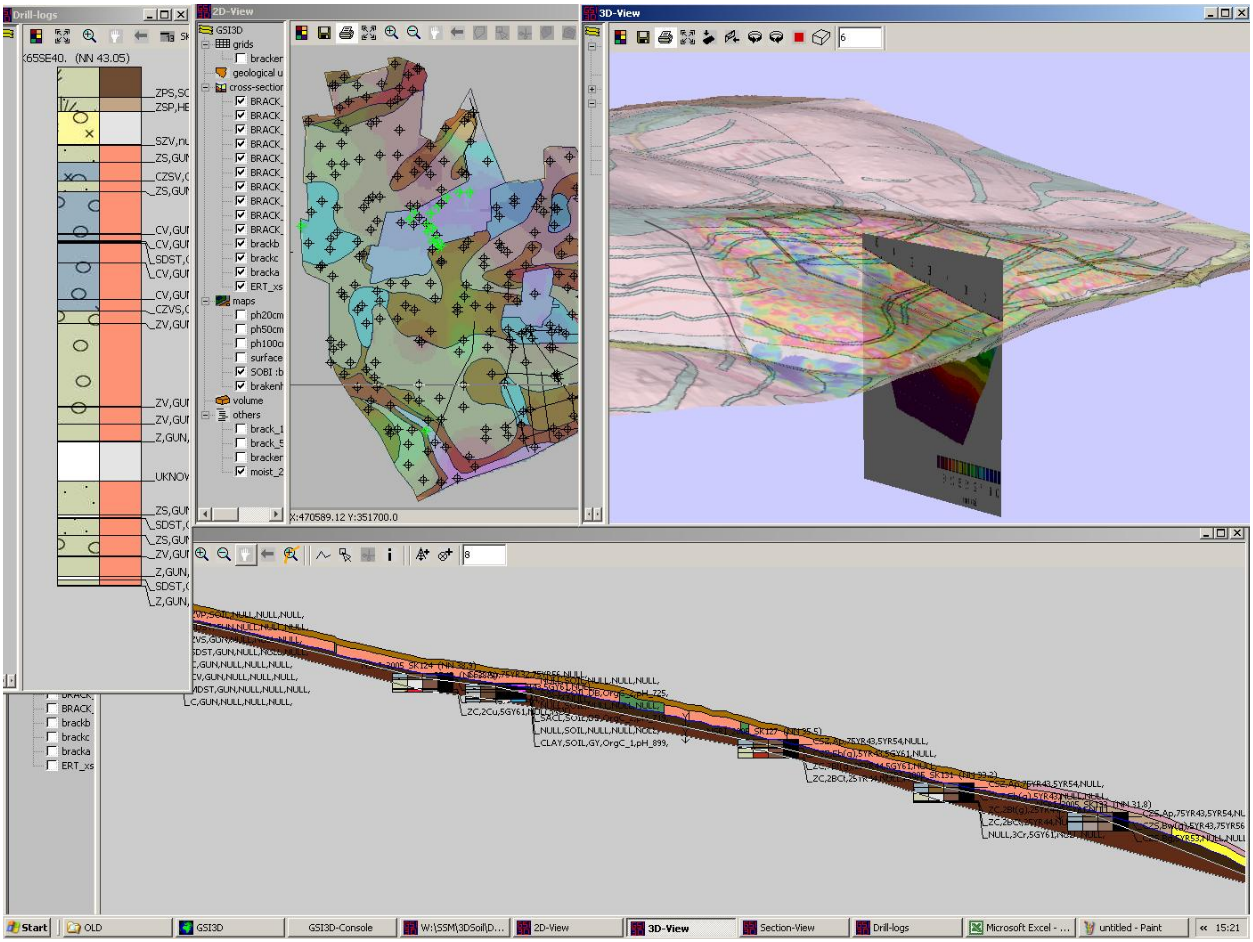


Figure 59 Key datasets assembled in GSI3D, displaying borehole viewer (left), 2D window (centre top), 3D viewer (top right) and cross-section window (bottom).

4.1 DATASETS

4.1.1 Borehole and auger data

The bespoke BGS DGSM data portal was used to extract digital borehole data from the corporate SOBI and BoGe databases into two tab separated ASCII files (*.bid and *.blg). NSRI auger data and geochemical sample points were subsequently entered manually into the *.bid and *.blg files.

The *.bid file is the borehole index data file, containing an ID, x, and y data to define each borehole location, and the start (collar) height relative to OD. The *.blg file is the borehole log file, with information on the depth to base of each of the identified units i.e. it is the down hole log file. This can be geological information from BoGe or any other down hole database organised in tab separated columns. The log must be ‘complete’ from the surface downwards and not intermittent; intervals of core loss are coded as absent data not left blank.

The borehole index file (*.bid) needs to be prepared with the following structure

Table 19: Example of structure of the *.bid file

Unique Borehole ID	Easting	Northing	Start Height
SE64SW23.	123456	123456	11.22
3D96	123477	123477	8.67

A total of 36 borehole / trial pit entries were retrieved from the DGSM Data Portal v2.0 and 274 augerholes entered manually into the data file. No start heights existed for the NSRI and geochemical data sets as they were not recorded during the survey. These boreholes were attached to the DTM within GSI3D for modelling.

The borehole log file (*.blg) needs to be prepared with the following structure

Table 20 Example of structure of the *.blg file

Unique Borehole ID	Depth to base of Unit from start height (in metres)	Lithostrat. Code (Lexicon)	Lithology Code (RCS)	Other codes	More codes
SE64SW23.	1.23	ALV	CZ	ABC	DEF
SE64SW23.	4.56	LGFG	SV	ABC	DEF
SE64SW23.	7.89	LOFT	CSZV	ABC	DEF

The corresponding borehole log file contains down hole information of borehole geology, NSRI soil data and geochemical field data. A trimmed *.blg file was created for the modelling consisting of texture or lithology in column 0, stratigraphy or horizon in column 1, colour in column 2 and colour or organic content in column 3.

4.1.2 Generalised Vertical Section (GVS)

The GVS file is a tab separated ASCII text file; (*.gvs) and forms the backbone of the GSI3D project. It is produced by the modeller, evolving throughout the project and finally containing all units in their correct and unique super-positional order. The order itself defines the ‘model stack’ that is calculated to make the 3D geological map. This can be a lithostratigraphical order or, in this case a detailed model, of soil horizons. The *.gvs file included an order of soil horizons and a lithostratigraphical order. Table 21 below shows the essential elements of the GVS file.

Table 21 Example of structure of a *.gvs file

Name	id	Stratigraphy	Lithology	Genesis	Free text
Dtm_site	0	DTM	DTM		NEXTMap DTM for the site
Alv	10	ALV	CZ	Fluv	Overbank...
Lgfg	20	LGFG	SV	glac_fluv	Sheet sands...
Ap	20	SOIL	Ap	Mixed or ploughed surface mineral horizon	
Bt	270	SOIL	Bt	Horizon with translocated silicate, clay	
C	320	SOIL	C	Unconsolidated horizon that retains rock structure	

4.1.3 Legend (GLEG) file

The legend file is used to assign colours and textures to the map polygons, borehole sticks, sections, and envelopes and is created as an ASCII tab separated text file; (*.gleg).

Table 22 Example of structure of a *.gleg file

LEG_ID	Description	Red	Green	Blue	Transparency	Texture link
ALV	Sandy, clayey …	55	66	77	255	TEXTURES/gravel.jpg

LEG_ID	This column contains the codes corresponding to the entries in the GVS files (Stratigraphy, Lithology, Genesis, etc.) and the codes used in borehole log descriptions
Description	Free text description of the unit
Red	Red value (0-255)
Green	Green value (0-255)
Blue	Blue value (0-255)
Transparency	Pre-set transparency (0-255) (0 = transparent; 255 = full colour)
Texture link	This field contains the path to the Folder containing the texture JPGs

All new down hole data entries gathered in the course of this integrated site survey were assigned an RGB code in addition to the common lithology and texture codes. The data sets for which a colour description had to be created are listed below:

- NSRI augerhole data including horizon codes, Munsell colour codes for soil matrix and mottling
- Soil series (RGB colours recommended by R.C. Palmer)
- Moisture and pH values of geochemical soil samples
- Munsell colours have been converted into RGB codes

4.1.4 Sections and slices

Images of vertical sections and horizontal slices of geophysical and radiometric data as well as gridded geochemical data were imported as *.gxml files into GSI3D for visualisation.

Sections must have the X/Y/Z coordinates of the lower left and upper right image corner pixel and slices/maps must be geo-registered with a tfw world file (e.g. using ESRI), which can be re-named to jpgw file for use in GSI3D.

Some geophysical and geochemical measurements were taken at a specific depth below surface. To display maps at the representing depth, a new DTM was calculated and reduced by the required depth. Horizontal slice of geochemical images were hung on reduced DTMs of 0.2, 0.5 and 1 metre and geophysical slices at 1 and 3 metres depth.

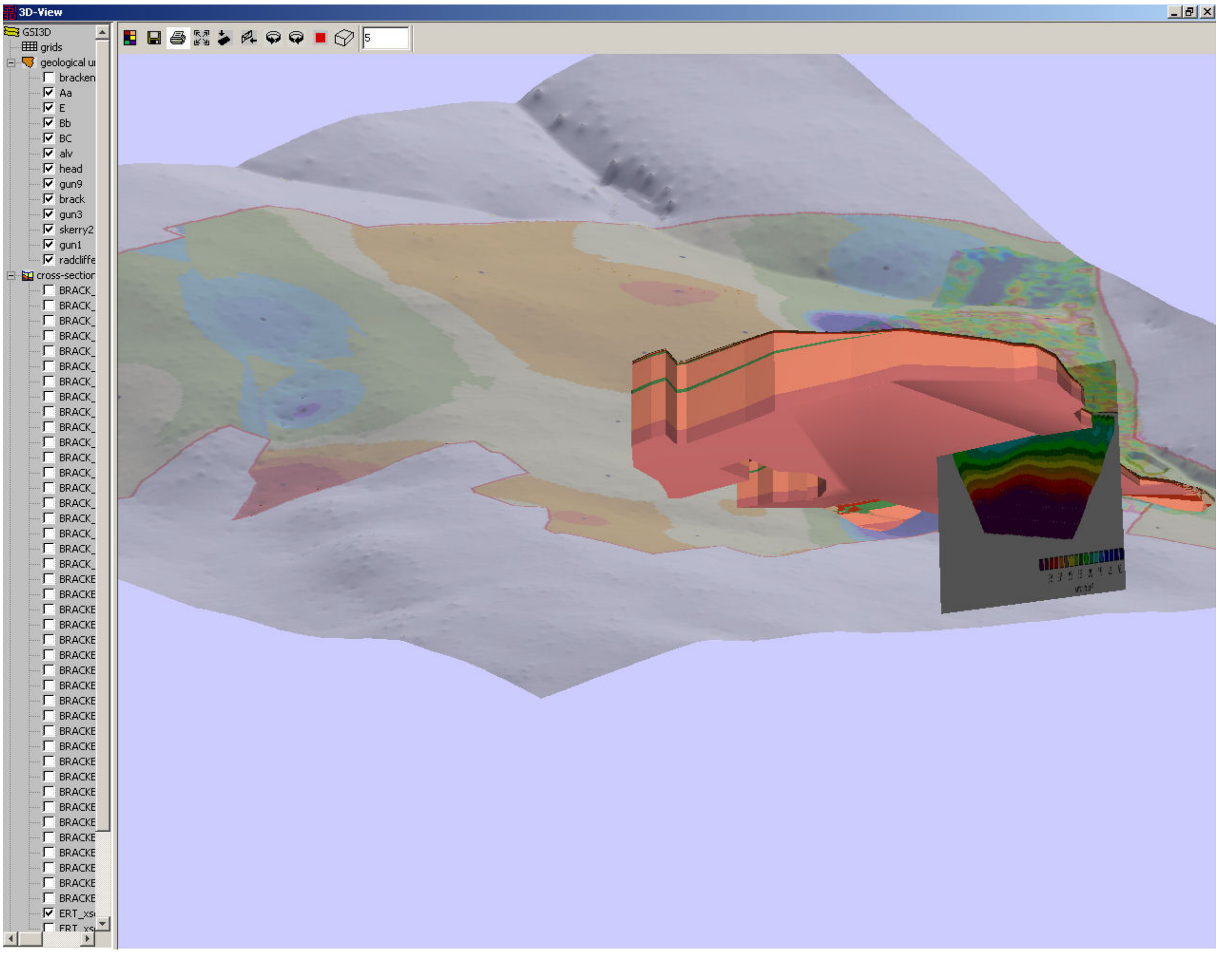


Figure 60 View from below the 3D model showing geochemical and geophysical slices and sections

4.1.5 Other data sets

Other datasets used included the geological and soil maps, which were in the ESRI shape file format.

4.2 3D GEOSPATIAL MODEL

4.2.1 Detailed soil modelling

A detailed soil horizon model was calculated for approximately a quarter of the project area in order to gain experience in modelling the shallow surface. The geological model was correlated for the whole site.

The soil model was constructed by correlation of soil horizons. Sections were drawn using auger hole sticks recorded by NSRI and GBASE surveys. In addition to the horizon description of each auger hole, down hole information also included depths, colour and texture descriptions. This information was extremely valuable for successful correlations.

Four horizons were correlated in the sections:

i. the “A” horizon, an organic mostly ploughed top soil horizon;

ii. an “E” horizon, indicating eluvial processes, such as downward translocation of clay minerals and sesqui-oxides;

iii. a “B” horizon, a subsoil horizon showing pedogenetic processes;

iv. a “BC” horizon, which is transitional in character, appearing between the “B” horizon and the mostly weathered parent material.

The “B” horizon shows a wide range of different characteristics due to pedogenetic processes across the site, but was combined into one subsoil horizon for modelling purposes. A total of 23 sections were correlated for the subsurface soil model in an area of approximately 900 by 800 metres, with average section spacing of 100 metres (Figure 61).

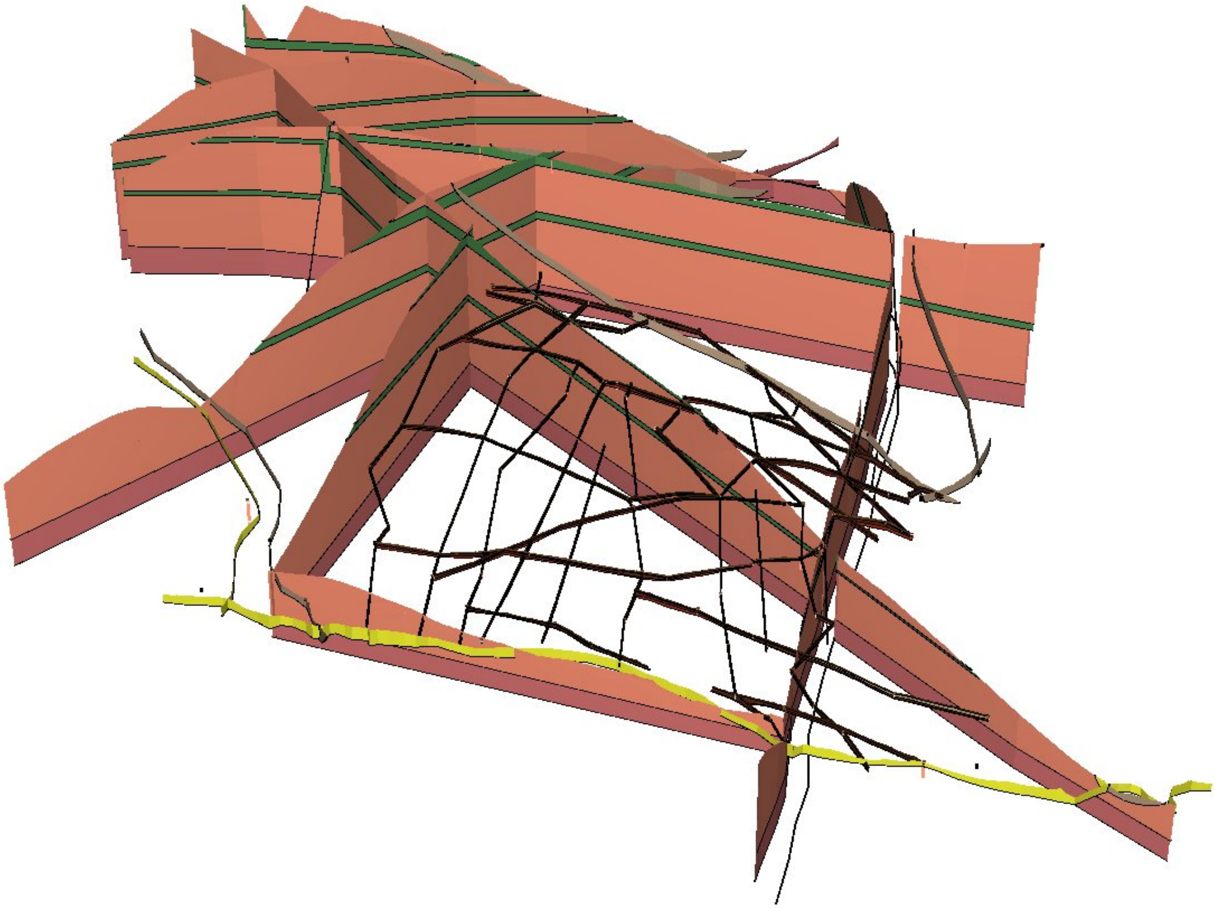


Figure 61 Correlated soil and geological sections in GSI3D

The soil horizon modelling was strongly aligned to the terrain morphology. Thickening or thinning of soil horizons is closely related to slope angle, aspect and form of the relief and also depended on the modeller’s experience in understanding soil forming processes.

Soil series polygons of the soil map were used mainly for the E horizon envelope construction.

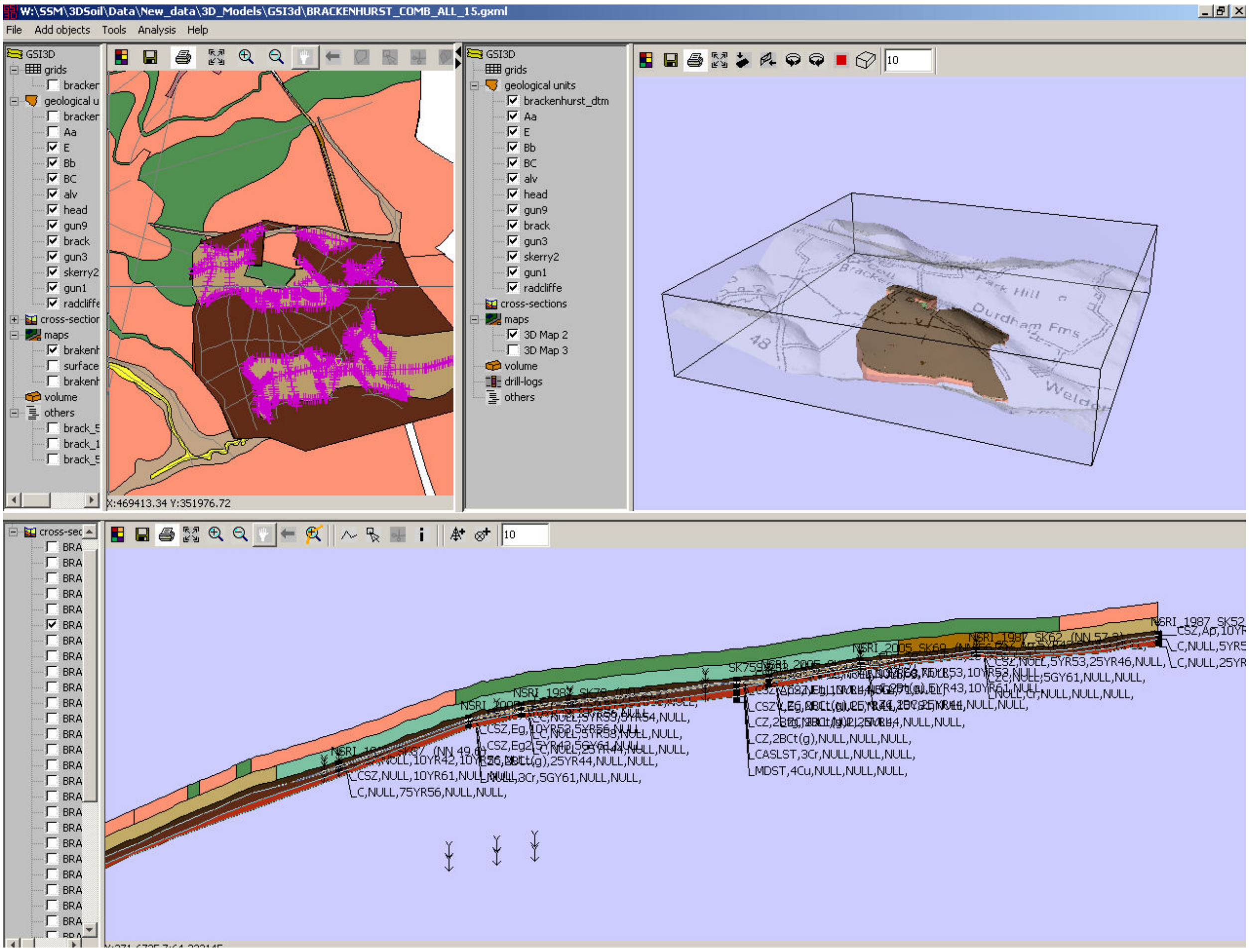


Figure 62 Calculation of the detailed soil horizon model in GSI3D, showing the 2D-View (top left), the 3D-View (top right) and the section window at the bottom

During the analysis of the triangulated and gridded volume model "holes" appeared in the top horizon where lower horizons were visible,. This problem was due to spacing of correlation sections in those areas. Therefore five helper sections were lain across the problem areas.

4.2.2 Geological modelling

The underlying Mercia Mudstone Group comprises of an interbedded sequence of mudstone, siltstone and fine silty sandstone referred to as skerries. In places, these skerries form distinctive flat features in the landscape. Further details are provided in Section 2.3.2.

In the Brackenhurst site a number of north-south, east-west and northwest-southeast trending normal faults have been interpreted with displacements typically less than 5 m. The objective of the bedrock modelling task was to produce a 3D model of the main bedrock units in the area and to show their displacement as a result of normal faulting.

4.2.2.1 Methodology

GSI3D modelling software was used to attempt to build the 3D model. GSI3D was developed to build models in the shallow sub-surface, including simple dipping or folded strata. It has not been designed to model faults as discrete objects or to easily model even simple faulted strata. Part of the aim of building a 3D model in the Brackenhurst site was to investigate different techniques for modelling faulted strata using the existing GSI3D functionality. For a full description of the GSI3D modelling methodology refer to Kessler et al. (2004). The GSI3D methodology relies on the use of existing datasets to constrain the 3D model. For modelling bedrock at Brackenhurst, data from only one borehole (SK65SE\64) was available.

4.2.2.2 3-D Modelling Section Construction

Four main cross-sections were constructed. The revised digital geological outcrop linework was used as the main dataset to tie the geological correlation lines to. Two were drawn parallel to the interpreted dip of the rocks and two were drawn approximately perpendicular to it. This ensured that the true thickness of the strata would be modelled. In some places it proved difficult to rationalise the mapped outcrop lines with the correlated sections, which assumed a constant and low angle dip (1°) without interpreting complex structure. It is more likely that the mapped outcrop was different to that shown when the high resolution DTM (NEXTMap) was used for modelling.

Helper sections were constructed to aid modelling of thin superficial deposits that comprised Head and Alluvium.

Two alternative ways of correlating cross sections in faulted bedrock were investigated. Firstly, full correlation across fault planes where the base of the unit is correlated at a steep angle across the fault (Figure 63). This produced cross sections that would be suitable for printing and display but they are not geologically correct as the beds across a fault are off set. In addition, different thicknesses of units cannot be correlated in the same way as the cumulative effect would be to "overlap" correlation lines.

Instead of correlating a steep angle, beds could be correlated vertically. This was attempted and again produced sections suitable for printing, but the calculation of the model would not honour the nodes. If beds were correlated vertically in this manner, only the uppermost node on the correlation for a given unit would be used in the calculation of the model. Other nodes vertically below it would be in exactly the same geographic (x,y) position but would have different elevation (z) values. In these cases the lower nodes would be ignored in the calculation.

The second method attempted was to stop correlation lines at the interpreted location of a fault and only show the extent of the base of the bed in the footwall and hanging wall of the fault (Figure 64). The horizontal correlation can then be continued at a different elevation, corresponding to the interpreted throw on the fault. Consequently, each correlation has gaps in it corresponding to the displacement along the fault. This is geologically correct but produces sections that are unsuitable for printing and publication as colour from older units "bleeds" through younger ones.

The second option was chosen as being the most likely to produce a geologically reasonable model.

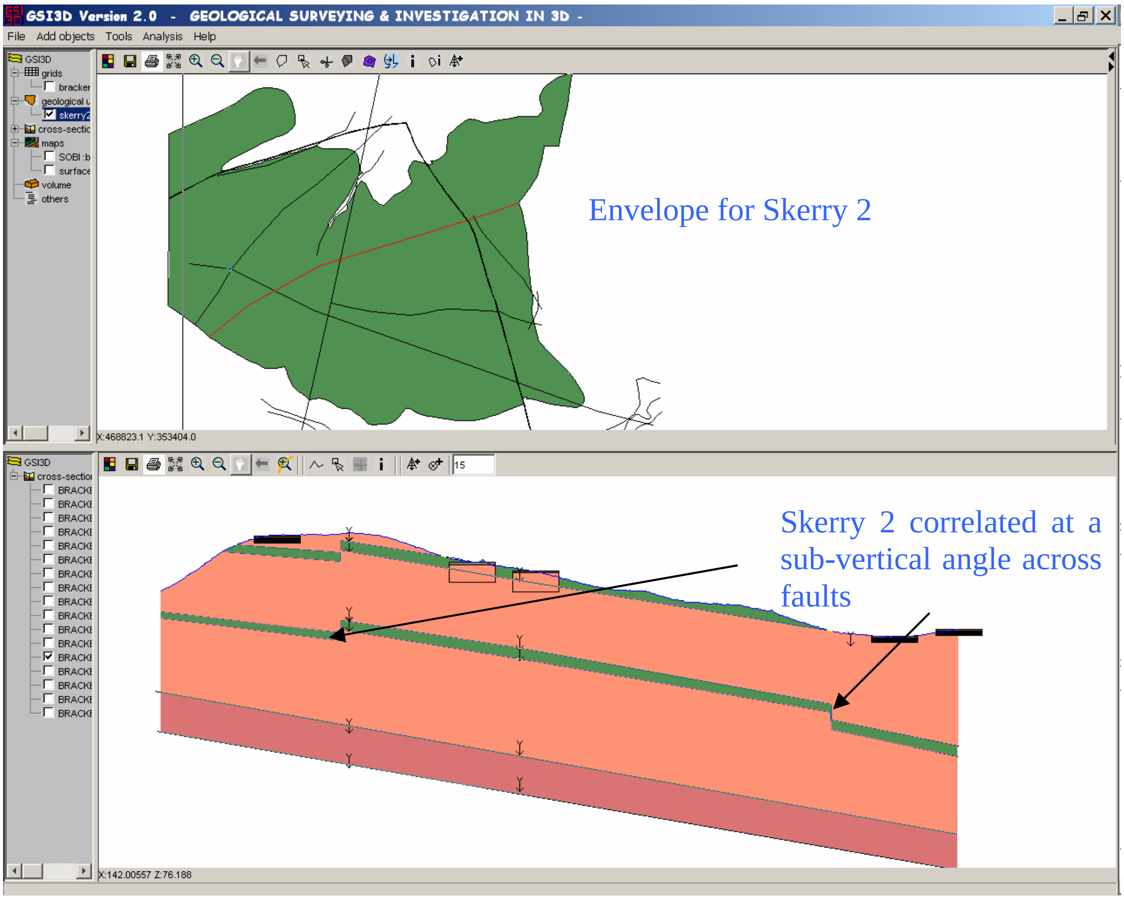


Figure 63 Bedrock Correlation Option 1 - correlation of bedrock units across faults as a continuous unbroken line

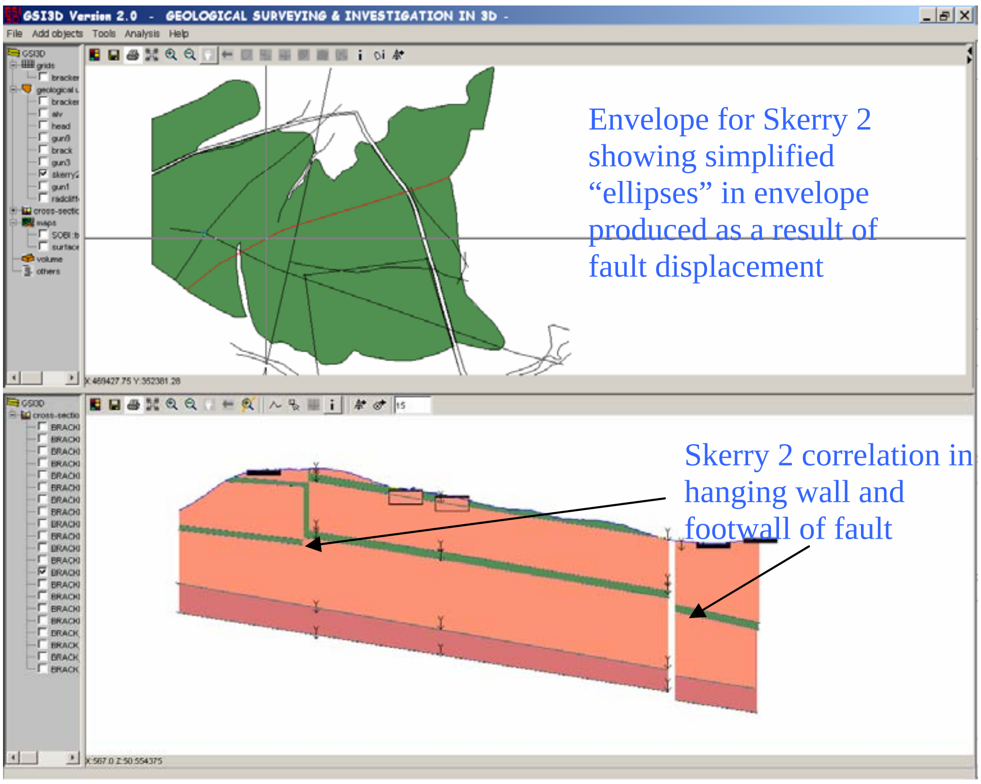


Figure 64 Bedrock Correlation Option 2 - correlation of bedrock units stops in fault footwell and hanging wall. The amount of horizontal displacement shown by the correlation lines is proprtional to the throw of the fault.

4.2.2.3 DETAILED AREA

A sub-set of the 3D bedrock model was constructed for the area coinciding with that calculated for the soil modelling (Section 4.2.1). In this area four helper sections were constructed around the perimeter of the area and bedrock correlation on section BRACKENHURST_EW1 were used to build them. The approximate dip of the main geological units was reflected in these correlations.

4.2.2.4 CORRELATED BEDROCK UNITS

Initially, all bedrock units were correlated. The correlations were tied to the outcrop of each unit where possible. In some areas however, it was not possible to tie the mapped outcrop of a unit to that proved in boreholes and the interpreted dip. Given this complexity, a selected number of units were correlated. The name and lithology (in parentheses) of the main correlated units are: Gun9 (Mudstone), Brack (Sandy Siltstone), Gun3 (Mudstone), Skerry2 (Sandy Siltstone), Gun1 (Mudstone), Radcliffe (Mudstone and Siltstone).

4.2.2.5 ENVELOPE CONSTRUCTION

Envelopes were constructed for each unit based on their outcrop distribution and their interpreted sub-surface distribution. Envelopes constructed for units correlated in this way must show a representative displacement ellipse to reflect the displacement across a fault.

4.2.2.6 RESULTS

It was only possible to construct a complete model in the detailed area using GSI3D. It proved extremely difficult to build a faulted 3-D model for the area as a whole. It may have been possible to refine the model using at least two helper sections along the strike of the faults; one along the footwall of the fault and another representing the hanging wall. Using helper sections, each unit could then be tied to a position in the hanging wall and footwall. The resulting model would show the displaced beds would not show the faults as discrete objects themselves.

GSI3D can be used for simple, dipping or folded strata. This was achieved in the detailed area (Figure 65 and Figure 66) where it was combined with the shallow soils model. The production of a faulted bedrock model, within a geological succession of alternating thick and thin units is difficult as GSI3D did not allow for modelling faults as discrete objects. It would be possible to use the method for correlating units as a continuous line across faults for units of relatively equal thickness to produce a 3D model but the envelopes would not show any offset produced by the fault. It was not possible to use this method in the Brackenhurst site because the units were of unequal thickness, therefore two or more correlation lines would have to overlap exactly.

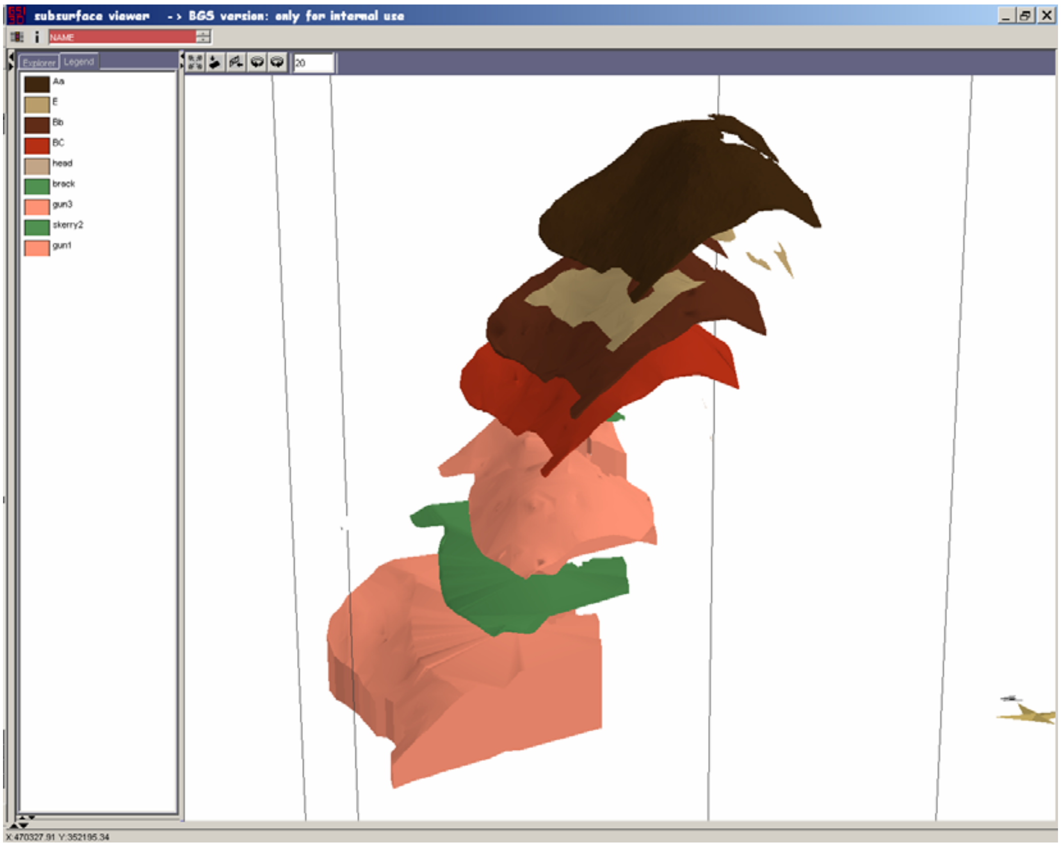


Figure 65 Exploded view of the detailed bedrock geology and soil model (900 by 800 m) in the Subsurface Viewer ™ – a standalone software for viewing and analysing geospatial models

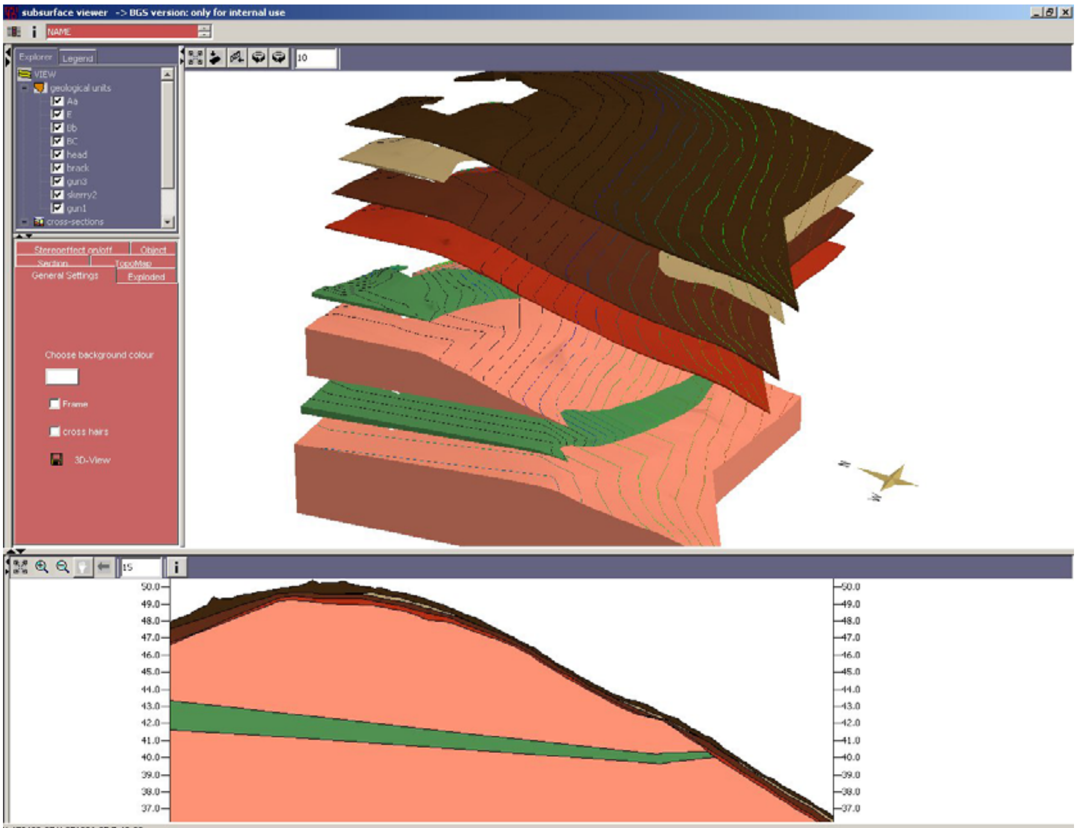


Figure 66 Screen shot of subsurface viewer showing contoured and exploded soil/geology horizons and a synthetic section through the model at the bottom.

4.5 Recommendations

- Individual airphotos and other rasters or grids imported into the model should not exceed 10 Mb as this can severely reduce processing speed.
- GSI3D allows only one unique code/ID to exist. Problems appeared during modelling session as codes A, B and C did appear in *.gvs and *.gleg files twice. They either stand for horizons of the NSRI data or indicate a Lithostratigraphy code. For this reason the newer NSRI IDs got changed to Aa, Bb and Cc.
- A single downhole database for geotechnical, soil and geological data with unique identifiers would be advantageous.
- Some corporate databases for (non GBASE) geochemical sample data, radiometric data and shallow geophysics need to be created for incorporation into the model.
- When correlating thin soil horizons, errors in the DTM (see section 3.4) should not be carried into the subsurface. The base of the first horizon should be drawn as if the error does not exist – this will lead to an exaggerated thickness of the first horizon at that point. – a high quality, clean DTM (bare earth model) will be necessary when creating accurate horizon volumes.
- Because of the higher spatial accuracy needed when correlating soil compared to geological horizons, a lot of nodes are required along correlation lines. Some planned software development could be to place a preset node spacing along a given line and the inclusion of preset templates (flat horizons, valley shape etc) in GSI3D
- The most important downhole data fields used in modelling in this particular soilscape were: Lithology/texture, Stratigraphy/soil horizon and Colour. Soil pH and moisture content were rarely used in the model construction.
- It is not possible at present to produce a faulted bedrock model using GSI3D alone. Correlation points could be exported to GoCad for example. It would require much more time to draw helper sections and treat each faulted domain as a discrete area, rather than trying to model the area as a whole. Even then the model would be mainly built on helper sections and envelopes rather than any meaningful correlations.
- Soil Horizons are seen as a continuum of the geological stratigraphy, whereas they actually crosscut the near surface geology. As the GVS file is set up, soil horizons will cut out the geological units during model calculation. In section, both horizons crosscutting the Geology can be displayed, but this is not yet possible in the calculated 3D model. Soil and geology must be correlated/modelled at the same time in one project file
- For a better visualisation of the model, it should be considered to use a brighter and greater variety of colours for soil horizons. At the moment the model contains similar but more realistic brown tones.

5 Conclusion and Recommendations

The scientific drive behind this project was to develop and apply a methodology to carry out integrated, high detail spatial and process modelling of the very shallow subsurface, which would help BGS to increase our understanding of the air-soil-geology interface and interactions within and between soils, the superficial/bedrock geology and the entire geosphere. This was the first multidisciplinary survey of its type in BGS, and it gained international recognition through presentation and publication (Smith *et al*., 2006). One of the main outcomes of this project is a comprehensive review of BGS's near surface investigative capabilities, while the project also introduced a soil surveying training course to BGS and has invested in development of survey and modelling hardware and software.

A key objective was to integrate the results of the individual surveys by interpretating and modeling the data in one 3D software environment. Whereas all datasets where successfully gathered, loaded and displayed in their true location in three dimensions, not all datasets were used in the modelling process. This is partly due to the limited variability in the geological and pedological setting of the site and because some of the data did not provide sufficient detail and resolution at the desired depth of investigation. Furthermore, the aim to have all data available in "real time" and to use the 3D geospatial model to aid the survey planning was not fulfilled and this will be a priority in future surveys.

This 3D Soils Project was ambitious in its aims and timescale, even though a small (approx 300 hectares) area of land was chosen to develop and test the methodology. While the site met all of the requirements, a number of issues came to light during the project:

- Despite the small size of the study area, the resources could not stretch to conducting or completing some of the high resolution surveys that the team had hoped to trial, e.g. DC electrical mapping, 3D modeling.
- The simplicity of the geology was a source of debate when the project began, and while the homogeneous geology made some surveys easier to conduct and analyse, the lack of contrast meant that the data from the ground-based gamma spectrometry, for example, could not contribute in these circumstances. Bearing that in mind, the survey techniques used at Brackenhurst should be assessed in relation to the geology in order to understand if they would be applicable in complex or other relatively simple geological terrains.
- The subdued geomorphology meant that many of the landforms / landscape features were not visible on NEXTMap. However this is true for the geomorphology of many UK terrains and the style and scale of landforms must be taken into account when choosing which DTMs / DEMs or other remotely sensed datasets to use in any project.

5.1 SURVEY REVIEW AND RECOMMENDATIONS

Bearing in mind the three points above, each of the various surveys and tasks are briefly assessed here in terms of their contribution to the 3D Soils model, and recommendations on their use in future surveys are provided.

1. **GPS** surveys are becoming routine in BGS, and this technique was used to successfully locate the boreholes and additional groundwater well installations. The real-time kinematic mode of operation (RTK-GPS) was found to be essential for geophysical mapping at the high resolutions required. The RTK-GPS technique with an average

locational error of 0.01 m in the horizontal, and 0.02 m in the vertical plane is recommended for future 3D soil modelling surveys.

2. The **geological survey** consisted primarily of a one-day walk-over survey to update the existing 1993 mapping. The geology was mapped, and proposed locations for trial pits and boreholes were identified. It is recommended that a new survey, such as this, should be conducted whenever updated linework is required (especially of superficial geology). It is recommended that the geological survey leads to the construction of the 3D model as soon as possible, before the multidisciplinary site survey commences. It is recommended that the MIDAS field entry system is used in future studies within the SIGMA Workflow.

3. **Intrusive site investigation** includes drilling (cable percussion and sonic core / rotary) and trial pitting. This is conducted to get representative samples of soils, superficial deposits, and underlying bedrock geology. The boreholes and augers supplied useful data for the 3D digital model. This technique is recommended for use in future projects where information of this type is required.

   The newly acquired Dando Terrier rig should be used before sub-contracting drilling at higher cost.

   Drill/trial pit locations and borehole names should be agreed by all survey teams at the time of drilling/digging and should be positioned in accordance with geophysical survey lines.

4. **Remote sensing** (including satellite and airborne sensors that record spectral properties as well as elevation data) is recognised as a ‘baseline’ dataset and forms part of most survey projects where funds and/or imagery is available. NEXTMap data can be used in this sub-catchment scale of mapping, but artefacts mean that a higher resolution dataset (such as LiDAR) should be used where available. Aerial photography was useful for interpreting soils/geology/geomorphology and as backdrops for data in the GIS and 3D modelling package, and therefore it is recommended in future studies.

5. The **geohydrological** investigation successfully monitored the groundwater heads and gradients in the spring area and found that the elevation remained constant when it was expected to rise, probably because of the particularly dry winter. The water table was found to lie approximately 0.4 m below ground surface, broadly reflecting the ground surface slope. The inorganic chemical composition indicated that the source of the groundwater is the Mercia Mudstone Group. Finally, this survey attempted to identify if the soil descriptions can be used as an indicator of the saturation state. The aims of this survey were met, and it is recommended that a geohydrological investigation is included in other surveys.

   Data on water table and soil moisture has been identified by several survey teams as vital for the overall project and more emphasis should be placed on geohydrological monitoring and modelling.

6. **Surface geophysical** surveys were carried out to determine which types of geophysical data could best inform and support the spatial and process modelling of the very shallow subsurface.

   - ***Gamma spectrometry*** was already available through the HiRES project but this provided regional information too coarse for this project. A ground-based survey was conducted but the results were of limited use due to the homogeneous bedrock geology and the limited resources available to process the data. This type of survey can yield useful results where scale and near-surface / subsurface conditions are appropriate, so it is recommended to conduct a similar survey in the next project area (if the geology is suitably varied) but to allocate more time for processing. Furthermore, the addition of *in situ* gamma spectrometry should be considered to increase the possible exploitation of the data.

- The technique of ***Electromagnetic mapping*** was chosen in order to determine the spatial distribution of ground conductivity in the very shallow subsurface. The resulting conductivity maps showed good correlation with the mapped geology; this was in accordance with expectations as water and clay content are likely to exert primary control over the electrical conductivity in the near surface. Utilising the existing BGS DualEM instrument, a GPS-enabled mobile surveying capability was developed for rapid conductivity mapping in order to achieve dense areal coverage. This worked well in principle for surveys at site scale, however surveys at farm or catchment scale will remain time-consuming and require significant staff effort. Also, with existing equipment only two depths of investigation can be covered simultaneously.

- Better vertical resolution and more advanced depth discrimination would require multi-frequency EM equipment (cf. HiRES airborne EM) or multi-depth electrical mapping surveys. In this context it is recommended that ***DC electrical mapping*** be trialled in the near future to evaluate the use of the technique as an alternative to electromagnetic mapping. Recently developed DC mapping instrumentation would offer highly efficient data acquisition and a larger range of depths of investigation, which may ultimately allow more accurate volumetric interpretation and the generation of 3D property models of the shallow subsurface.

- ***Electric resistivity tomography*** was performed as a demonstration survey to evaluate its potential to spatially characterise soils and underlying geology. Using a relatively coarse electrode spacing of 5 m, a 2D cross-section was obtained which showed very good correlation with the mapped surface geology and indicated the spatial extent and subsurface orientation of the mapped formations, particularly the skerries and head deposits. It is recommended that ERT should be applied to future survey areas of this project. Shorter electrode spacings should be used to survey the very near surface. ‘Roll-along’ surveys should be conducted to obtain longer ERT profiles covering the transition between different soilscapes and geological/hydrological domains. Quantitative interpretation should be attempted using representative information from intrusive sampling (e.g. auger holes, trial pits). It is also recommended that automated time-lapse ERT be considered in the future for capturing variation of soil properties with time (e.g. water content) and monitoring soil evolution and processes such as soil-water interaction.

- A ***Ground Penetrating Radar*** survey using the Noggin 250 system showed high attenuation of the signal even at very short travel times at selected profiles of the Sheepwalk East field. This is probably due to the high clay content, so the technique was discontinued. While deemed unsuccessful at this site, it can and should be trialled at future sites where clay content is lower.

There are no corporate data stores for some of the above surface geophysical survey data, this may need to be addressed in the Information Management Programme.

7. **Downhole geophysics.** For future logging in shallow boreholes it is recommended that the hole is drilled 1 to 2 m deeper than the bottom rock unit of interest to allow the probe sensors to fully traverse it.

   Subsequent to the logging survey of the two boreholes at Brackenhurst, BGS acquired a new logger with dual induction resistivity probe (L = 1.69 m) where the shallow reading curve provides a more detailed vertical resolution than that obtained with the older single sensor equipment. In addition a spectral gamma ray probe (L = 0.90 m) is also available. To deploy these probes the casing and any open hole section should be 75 mm ID minimum, preferably 100 mm ID to allow adequate clearance, so this should be borne in mind during future drilling exercises if these techniques are required. Alternatively use could be made of the recently updated core logging facility at BGS Keyworth.

8. The aim of the **Geochemical** sampling programme was to contribute information on major and trace element concentrations and their distribution in surface and sub-surface soils over the site, as well as including an evaluation of the efficiency and accuracy of on-site use of the facilities in MEL to prepare and analyse samples.

   - Ninety-six samples were collected, and analysis showed a correlation between ***pH*** and both the Gunthorpe Member (which contains gypsum) and the location of buildings. ***Soil moisture*** was linked to topography, with the highest moisture values recorded in the valley bottom by the pond to the south-east. ***Calcium*** levels were seen to increase six-fold from 20 to 100cm from the surface, which could be explained by the gypsum content of the Gunthorpe Member.

   - The on site pH test results correlated with the Keyworth laboratories very well, although a small percentage of the results did vary by up to 1 pH unit. This variation is thought to be due to the way that the samples were microwave-dried on site, but this theory should be investigated, and it should be decided if a 1 pH unit difference is acceptable. Also a comparison of MiniPal data showed that results from on-site analysis are reliable, but it is recommended to test MiniPal with samples collected from various parent materials.

   - Recommendations from the geochemical sampling include that it should be more integrated with other surveys, especially geophysical. Furthermore, more detail should be recorded including texture and colour (using Munsell charts) and additional features should be recorded including the depth of observation below surface of the A-horizon, and the depth of transition/change from soil to parent material or drift.

   - At least one entire augerhole should be logged per sampling site. If possible, unweathered parent material should be proven at base.

9. The **Soil Survey** was done by staff of the NSRI and presented in digital map and report form (including trial pit logs) to BGS. This was the most expensive single outlay in the project but it is expected that the training provided by NSRI to BGS staff will mean that some of this type of survey can be conducted in future by BGS staff, thereby reducing costs.

10. **Data assembly and 3D modelling.** The ultimate aim of the project was to combine the geological and soil survey into one single workflow, using joint methodologies and dictionaries leading to an integrated 3D soil/geology model.

- In order for the survey and modelling processes to be truly integrated real time it is vital that data are collected digitally to a common reference grid and nomenclature and that data can be exported quickly and accurately into common formats for GIS (ESRI) and 3D modelling software (GSI3D & GoCad).

- It is recommended to construct the geological and soil horizon model in one process and start modelling earlier in the project. It would be advantageous if the modelling could be carried out on site, informing all surveys of the emerging 3D picture.

- The challenge is to model cross-cutting soil horizons and integrate surfaces such as the water table. This will be possible due to further development of the software towards modelling faulted, overthrusted and overturned geological units.

- Complex faulting is currently beyond the scope of GSI3D. It is recommended either to expand the functionality of GSI3D or carry out this type of work in GoCad until the GSI3D bedrock development project delivers the first working prototype.

11. Site access

- Due to the intensive fieldwork in this project it was vital to the success that the landowner and local residents were fully aware of the activity and its purpose. Contracts about liability and access must be drawn up between BGS and landowners, with full risk assessments in place.

- It is also recommended that this contract covers the possibility of land rental and/or compensation payments to the farmers to enable digging of large trial pits and the installation of long term monitoring sites.

- A full site search for services must be carried out (BT, Electricity, Gas, Water/Sewage). The plans should be registered and loaded in to the Project GIS.

- It is recommended to have a dedicated task in the project to clear access with landowners, oversee general survey logistics, carry out the service search and maintain public relations with landowners, residents and local businesses.

The Brackenhurst survey was a multidisciplinary and logistical challenge that included nine survey types, followed by integrated 3D digital modelling. The main conclusions drawn from the experience are:

1. It is possible to produce fully attributed 3D models with an associated XML database. There are differences in nomenclature and methodologies between soil and geological surveys but these can be overcome as long as cognisance is taken of the need to use a multidisciplinary approach.
2. Methods and software originally developed for the shallow geological environment can be used in soil modelling when soil horizons follow a unique super positional order.
3. Soil and geology are a continuum and must be surveyed and studied in an integrated manner.
4. One of the reasons Brackenhurst was chosen for this scoping study was its low geological and pedological complexity. However, the limited contrast in these properties meant that some surveys could not be fully tested.

The conclusions and recommendations derived from this study and documented in this report are being applied to a follow-up project at Shelford, also near Keyworth. The soil and geology at Shelford are more varied than Brackenhurst, allowing for additional testing of many of the techniques. Furthermore, new techniques are being added such as automatic monitoring of hydrogeological properties, rapid geophysical imaging, and the use of interferometry to detect millimetric changes in elevation over time. The results from Shelford will be published in due course.

Appendix 1 Geochemical sampling

Table of sample site locations

Sample number	Easting	Northing	Depth below surface	Sample number	Easting	Northing	Depth below surface
1	470224	351729	0.2	50	469203	352699	0.2
2	470224	351729	0.5	51	469203	352699	0.5
3	470224	351729	1	52	469203	352699	1
4	470199	351936	0.2	53	469404	352892	0.2
5	470199	351936	0.5	54	469404	352892	0.5
6	470199	351936	1	55	469404	352892	1
7	470453	351890	0.2	56	469822	351374	0.2
8	470453	351890	0.5	57	469822	351374	0.5
9	470453	351890	1	58	469822	351374	1
10	470400	351699	0.2	59	469567	351497	0.2
11	470400	351699	0.5	60	469567	351497	0.5
12	470400	351699	0.95	61	469567	351497	1
13	470600	351700	0.2	62	469398	351732	0.2
14	470600	351700	0.5	63	469398	351732	0.5
15	470600	351700	1	64	469610	351894	0.2
16	470801	351698	0.2	65	469610	351894	0.5
17	470801	351698	0.5	66	469610	351894	1
18	470801	351698	1	67	469802	352100	0.2
19	470599	351529	0.2	68	469802	352100	0.5
20	470599	351529	0.5	69	469802	352100	1
21	470599	351529	1	70	469410	352121	0.2
22	470207	351503	0.2	71	469410	352121	0.5
23	470207	351503	0.5	72	469410	352121	1
24	470207	351503	1	73	469631	352685	0.2
25	469989	351509	0.2	74	469631	352685	0.5
26	469989	351509	0.5	75	469631	352685	1
27	469989	351509	1	76	469804	352891	0.2
28	470002	352099	0.2	77	469804	352891	0.5
29	470002	352099	0.5	78	469804	352891	1
30	470002	352099	0.95	79	469996	352300	0.2
31	470008	351906	0.2	80	469996	352300	0.5
32	470008	351906	0.5	81	469996	352300	1
33	470008	351906	0.85	82	470558	352087	0.2
34	469801	351902	0.2	83	470558	352087	0.5
35	469801	351902	0.5	84	470558	352087	1
36	469801	351902	1	85	470417	352324	0.2
37	469801	351700	0.2	86	470417	352324	0.5
38	469801	351700	0.5	87	470417	352324	0.85

39	469801	351700	1	*88*	470549	352530	0.2
40	469985	351710	0.2	*89*	470549	352530	0.5
41	469985	351710	0.5	*90*	470549	352530	0.8
42	469985	351710	1	*91*	470409	352693	0.2
43	469195	352310	0.2	*92*	470409	352693	0.5
44	469195	352310	0.5	*93*	470409	352693	0.95
46	469195	352310	1	*94*	470222	352492	0.2
47	469370	352535	0.2	*95*	470222	352492	0.5
48	469370	352535	0.5	*96*	470222	352492	1
49	469370	352535	1				

Table of pH values

Sample ID	East	North	Depth [m]	pH Field	pH Lab	Sample ID	East	North	Depth [m]	pH Field	pH Lab
3D0001	470224	351729	0.20	7.97	8.09	3D0048	469370	352535	0.50	8.39	8.41
3D0002	470224	351729	0.50	8.14	8.46	3D0049	469370	352535	1.00	8.36	8.61
3D0003	470224	351729	1.00	8.49	8.76	3D0050	469203	352699	0.20	8.08	8.11
3D0004	470199	351936	0.20	5.55	5.61	3D0051	469203	352699	0.50	8.16	8.57
3D0005	470199	351936	0.50	6.81	6.81	3D0052	469203	352699	1.00	8.24	8.78
3D0006	470199	351936	1.00	6.73	7.85	3D0053	469404	352892	0.20	7.76	7.82
3D0007	470453	351890	0.20	7.58	7.87	3D0054	469404	352892	0.50	7.48	8.10
3D0007	470453	351890	0.20	7.69	7.91	3D0055	469404	352892	1.00	6.87	8.37
3D0008	470453	351890	0.50	7.08	8.66	3D0056	469822	351374	0.20	6.65	6.92
3D0009	470453	351890	1.00	7.36	8.86	3D0057	469822	351374	0.50	6.34	7.36
3D0010	470400	351699	0.20	8.04	8.21	3D0058	469822	351374	1.00	7.95	8.29
3D0011	470400	351699	0.50	8.02	8.70	3D0059	469567	351497	0.20	6.45	6.39
3D0012	470400	351699	0.95	8.03	8.75	3D0060	469567	351497	0.50	6.52	6.52
3D0013	470600	351700	0.20	7.07	N/A	3D0061	469567	351497	1.00	7.32	8.29
3D0014	470600	351700	0.50	7	N/A	3D0062	469398	351732	0.20	7.97	8.16
3D0015	470600	351700	1.00	8.59	8.99	3D0063	469398	351732	0.50	8.58	8.46
3D0016	470801	351698	0.20	6.89	7.66	3D0064	469610	351894	0.20	7.88	7.99
3D0017	470801	351698	0.50	7.72	8.20	3D0065	469610	351894	0.50	8.27	8.42
3D0018	470801	351698	1.00	8.17	8.55	3D0066	469610	351894	1.00	8.42	8.48
3D0019	470599	351529	0.20	7.41	7.98	3D0067	469802	352100	0.20	5.24	4.68
3D0020	470599	351529	0.50	7.21	8.08	3D0068	469802	352100	0.50	6.34	7.00
3D0021	470599	351529	1.00	7.36	8.17	3D0069	469802	352100	1.00	7.77	8.49
3D0022	470207	351503	0.20	5.88	7.10	3D0070	469410	352121	0.20	5.37	5.05
3D0023	470207	351503	0.50	6.91	7.23	3D0071	469410	352121	0.50	7.42	7.86
3D0024	470207	351503	1.00	7.63	8.20	3D0072	469410	352121	1.00	8.68	8.63
3D0025	470207	351503	0.20	7.51	7.82	3D0073	469631	352685	0.20	8	7.85
3D0026	470207	351503	0.50	7.64	7.85	3D0074	469631	352685	0.50	8.25	8.22
3D0027	470207	351503	0.75	7.66	8.32	3D0075	469631	352685	1.00	8.65	8.63
3D0028	470002	352099	0.20	6.93	7.35	3D0076	469804	352891	0.20	7.76	5.16
3D0029	470002	352099	0.50	8.31	8.35	3D0077	469804	352891	0.50	4.99	5.84
3D0030	470002	352099	0.95	8.75	8.64	3D0078	469804	352891	1.00	5.5	8.19
3D0031	470008	351906	0.20	6.32	6.43	3D0079	469996	352300	0.20	7.78	7.81

3D0032	470008	351906	0.50	6.38	6.42	3D0080	469996	352300	0.50	8.41	8.49
3D0033	470008	351906	0.85	8.14	8.32	3D0081	469996	352300	1.00	8.6	8.71
3D0034	469801	351902	0.20	6.24	6.33	3D0082	470558	352087	0.20	5.48	5.22
3D0035	469801	351902	0.50	6.76	7.33	3D0083	470558	352087	0.50	6.67	7.27
3D0036	469801	351902	1.00	8.09	8.42	3D0084	470558	352087	1.00	8.32	8.35
3D0037	469801	351700	0.20	8.22	8.19	3D0085	470417	352324	0.20	7.87	8.00
3D0038	469801	351700	0.50	8.53	8.46	3D0086	470417	352324	0.50	8.07	8.27
3D0039	469801	351700	1.00	8.61	8.85	3D0087	470417	352324	0.85	8.62	8.68
3D0040	469985	351710	0.20	8.06	7.93	3D0088	470549	352530	0.20	7.99	7.91
3D0041	469985	351710	0.50	8.09	8.14	3D0089	470549	352530	0.50	8.55	8.36
3D0042	469985	351710	1.00	8.04	8.35	3D0090	470549	352530	0.80	8.63	8.53
3D0043	469195	352310	0.20	5.29	5.76	3D0091	470409	352693	0.20	8.36	8.15
3D0044	469195	352310	0.50	6.85	6.93	3D0092	470409	352693	0.50	8.67	8.54
3D0045	469195	352310	0.50	6.92	6.94	3D0093	470409	352693	0.95	8.62	8.71
3D0045	469195	352310	0.50	6.96	6.94	3D0094	470222	352492	0.20	6.68	6.79
3D0046	469195	352310	1.00	8.15	8.14	3D0095	470222	352492	0.50	7.68	8.18
3D0047	469370	352535	0.20	8.36	8.08	3D0096	470222	352492	1.00	8	8.51

Appendix 2 Borehole logs

Borehole	**Brackenhurst College Southwell, 1**			**Logged by**
NGR	**470828E**	**351545N**		**David Entwisle**
Datum level mOD		**29.72**		

Depth top	Depth Base	Thickness	Description	Lithostratigraphy
0	0.31	0.31	Firm, dark grey (7.5YR 4/1) organic CLAY with firm fine to medium gravel sized reddish brown clay, Undulating contact. TOPSOIL	TOPSOIL
0.31	0.9	0.59	Firm, brownish red (7.5YR 4/1) CLAY with dark brown or black fine rounded gravel concretions of manganese and occasional vertical light greenish grey (Gley1 8/5G) streaks (gley) associated with the roots.	
0.9	1.62	0.72	Firm, weak red (5YR 5/2) CLAY with dark brown or black fine rounded gravel concretions of manganese and occasional vertical light greenish grey (Gley1 8/5G) gley streaks associated with the roots.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
1.62	1.76	0.14	Firm, weak red (5YR 5/2) CLAY with dark brown or black fine very weak rounded gravel concretions or sand of manganese and occasional vertical light greenish grey (Gley1 8/5G) gley streaks.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
1.76	2.2	0.44	Firm, weak red (5YR 5/2) CLAY with dark brown or black fine very weak rounded gravel concretions or sand of manganese and occasional vertical light greenish grey (Gley1 8/5G) mudstone streaks.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
2.2	2.9	0.7	Core lost or badly disturbed. Probably - Firm, weak red (5YR 5/2) CLAY with dark brown or black fine very weak rounded gravel concretions or sand of manganese and occasional vertical light greenish grey (Gley1 8/5G) gley streaks.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
2.9	3.12	0.22	Moderately pale greenish grey (Gley1 8/5G) strong fine SANDSTONE with some slightly clayey sand and a few firm light greenish grey (Gley1 8/5G) gravel-sized clay litho relicts.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
3.12	3.25	0.13	(Soft) finely laminated reddish brown (2.5YR 4/4) CLAY with a few light greenish grey (G1 8/10GY) horizontal and vertical steaks.	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP

3.25	3.27	0.02	Light greenish grey (Gley2 7/5BG), very clayey fine SAND	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP
3.27	3.36	0.09	Very weak to moderately weak, thickly laminated to thinly bedded light greenish grey (Gley2 7/5BG) fine SANDSTONE	GUNTHORPE MEMBER, SIDMOUTH MUDSTONE FORMATION, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 1**			**Logged by**
NGR	**470828E**	**351545N**		**Keith Ambrose**
Datum level mOD		**29.72**		
Depth top	**Depth Base**	**Thickness**	**Description**	**Lithostratigraphy**
0.00	0.30	0.30	TOPSOIL	
0.30	1.16	0.86	Clay, red-brown, with common small dark grey Mn 'nodules'/clasts up to 5 mm diameter, small dark grey flecks, clast at 0.36 m, 3 mm in diameter,	HEAD?
1.16	1.46	0.30	Missing core	
1.46	1.61	0.15	Clay, red-brown, with common small dark grey 'nodules'/clasts up to 5 mm diameter, small dark grey flecks, with manganese oxide nodules.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.61	1.76	0.15	Clay, red-brown, silty, pale greenish grey, gleying.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.20	2.80	0.60	Disturbed core (Dark brown and grey organic clay).	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.80	3.10	0.30	Sandstone, pale greenish grey, fine grained, highly fragmented. Angled basal contact.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.10	3.27	0.17	Clay, red brown, silty, soft, common pale greenish grey gleying imparting sub-horizontal fabric more common in basal 3 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.27	3.36	0.09	Sandstone, pale greenish grey, fine grained, fragmented.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 2**			**Logged by**
NGR	**469845E**	**352932N**		**David Entwisle**
Datum level mOD		**40.26**		
Depth top	**Depth Base**	**Thickness**	**Description**	**Lithostratigraphy**
0	0.25	0.25	Uncompact mottled (7.5YR 3/3) dark brown with some (7.5YR 5/6) strong brown patches slightly gravely slightly sandy organic SILT. Gravel fine angular of brick, chert, sandstone and charcoal. Uneven base. TOPSOIL.	TOPSOIL
0.25	0.57	0.32	Firm, (7.5YR 5/6) strong brown, slightly gravely, sandy CLAY, with occasional infilled root holes (7.5YR 3/3) dark brown, some sandy pockets. Gravel mostly fine with a little medium, sub angular to angular moderately strong white siltstone/sandstone. HEAD	HEAD
0.57	0.72	0.15	Firm, (7.5YR 5/6) strong brown, slightly gravely, sandy CLAY, with occasional infilled root holes (7.5YR 3/3) dark brown, some sandy pockets. Gravel mostly fine with a little fine to medium, sub angular to angular moderately strong white siltstone/sandstone and fine manganese oxide nodules. HEAD	HEAD
0.72	0.83	0.11	Strong brown (7.5YR 5/6) slightly sandy clayey sub rounded to sub angular fine to medium GRAVEL. Gravel moderately strong to strong siltstone and fine sandstone. HEAD.	HEAD
0.83	1.41	0.58	Firm, (5YR 4/4 reddish brown slightly gravely, very sandy CLAY. Gravel fine to occasionally medium of siltstone and fine-grained sandstone. HEAD	HEAD
1.41	1.47	0.06	Reddish brown (5YR 4/4) slightly gravely slightly silty medium to coarse SAND. Gravel is very weak yellow (10YR 7/8) medium-sized.	GLACIOFLUVIAL OR HILL WASH
1.47	1.485	0.015	Soft to firm, thinly laminated sandy clay and sandy SILT. Laminations about 1- 2 mm thick.L	GLACIOFLUVIAL OR HILL WASH
1.485	1.49	0.005	Fine sandy GRAVEL	GLACIOFLUVIAL OR HILL WASH
1.49	1.51	0.02	Soft to firm, thinly laminated sandy clay and sandy SILT. Laminations about 1- 2 mm thick.	GLACIOFLUVIAL OR HILL WASH

1.51	1.76 to 1.83		Interbedded or interlaminated SAND, gravel and sandy CLAY. 2-4 cycles of fining up sequences. Contact sharp sloping at ~35 deg	GLACIOFLUVIAL OR HILL WASH
1.76 to 1.83	1.82		Firm brown (7.5Y 4/4) slightly gravely sandy CLAY. Gravel fine of siltstone and fine sandstone HEAD.	HEAD
1.87	2.35	0.48	Soft to firm slightly gravely, slightly sandy CLAY. Gravel sub rounded to sub angular fine siltstone and fine sandstone. HEAD	HEAD
2.35	2.36	0.01	Firm light greenish grey (Gley1 7/5GY) CLAY	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.36	2.37	0.01	Firm red (7.5YR 4/8) CLAY	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.37	2.52	0.15	Stiff to very stiff slightly sandy gravely CLAY/SILT	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 2**			**Logged by**
NGR	**469845E**	**352932N**		**Keith Ambrose**
Datum level mOD		**40.26**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0	0.2	0.20	TOPSOIL. Undulating base	
0.2	0.69	0.49	Clay, red-brown, silty to sandy, some more sandy pockets	HEAD
0.69	0.84	0.15	Sand. Red-brown, fine-grained, clayey, passing rapidly at 0.73 m gravel, poorly sorted clasts few mms up to 3 cm of siltstone, fine grained sandstone stained dark brown with manganese oxide, tabular and sub rounded.	HEAD
0.84	0.99	0.15	Sand red-brown, fine-grained with coarser grains, clayey, some greenish grey gleying few sub-rounded, fine-grained; Mn impregnated sandstone clasts clasts up to 2 cm (skerry), passing rapidly to very sandy clay, as above.	HEAD
0.99	1.19	0.20	Core loss.	
1.19	1.27	0.08	Sand. Red-brown, fine-grained, clayey, passing rapidly at 0.73 m gravel, poorly sorted clasts few mms up to 3 cm of siltstone, fine grained sandstone stained dark brown with manganese oxide, tabular and sub rounded.	HEAD?

1.27	1.39 to 1.43	0.15 to 0.16	Clay, very sandy	HEAD?
1.39 to 1.43	1.44 to 1.45	0.02 to 0.05	Sand, red brown, fine- to medium- grained, clean, some manganese staining, poorly sorted.	HEAD?
1.44 to 1.45	1.47 to 1.49	0.03 to 0.04	Clay, red brown sandy, finely laminated, thin layer of skerry fine gravel grade	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.47 to 1.49	1.52	0.03 to 0.05	Sand, red-brown, clayey, a few tabular sub-rounded skerry (fine grained sandstone and siltstone) clasts less than 1 cm in diameter.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.52	1.62	0.10	Core loss	
1.62	1.72	0.10	Clay, red brown, laminated	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.72 to 1.74	1.76 to 1.84	0.04 to 0.10	Sand, red brown, clayey, clasts. Mn nodules becoming common to 5 mm upwards fining) mudstone rip-up clasts	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.76 to 1.84	1.84 to 1.91	0.07 to 0.08	Sand, red-brown, clayey, scattered tabular, sub rounded clasts of skerry and red mudstone; slightly more gravely at base; clasts less than 1 cm in diameter.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.84 to 1.91	2.05	0.14 to 0.21	Clay, brown, silty to sandy with some medium to coarse sand grains; fine gravel clasts of greenish grey fine-grained sandstone; clast of weathered red-brown mudstone, 5 cm in diameter (platy); some manganese nodules.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.05	2.12	0.07	Core loss	
2.12	2.29 to 2.37	0.17 to 0.25	Clay red brown very silty varying to silt very micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.35	2.36	0.01	Clay, greenish grey with sand laminae, micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.36	2.37	0.01	Clay brick red, silty, laminated, micaceous.	?RADCLIFFE MEMBER
2.37	2.78	0.41	SILTSTONE, greenish grey, some red mottled at top; micaceous	?RADCLIFFE MEMBER

Borehole	**Brackenhurst College Southwell, 3**			**Logged by**
NGR	**469213E**	**351863N**		**David Entwisle**
Datum level mOD	**55.04**			
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0	0.27	0.27	Compact reddish brown (2.5YR 4/4) sandy gravely organic SILT, with closely to extremely closely spaced roots. Gravel of sub angular to rounded fine to medium white fine sandstone and some stiff red (10YR 4/8) stiff gravel sized stiff clay clasts and some dark brown or black coarse sand to fine gravel concretions of manganese oxide.	TOPSOIL
0.27	0.56	0.29	Very stiff reddish yellow (5YR 6/6) mottled reddish brown (2.5YR 5/4) slightly gravely CLAY with very closely spaced roots, Gravel of moderately strong to strong subangular to sub rounded fine sandstone and some dark brown to black fine grained nodules. Some reddish brown (2.5YR 4/4) root traces	
0.56	0.72	0.16	Generally strong, weak at top, white (5Y 5/1), sometimes black stained fine SANDSTONE, with some as fine to coarse gravel in very stiff dark yellowish brown (10YR 4/6) clay matrix, some dark brown and black manganese oxide concretions in the clay.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.72	0.92	0.2	Stiff to very stiff mostly light red (2.5YR 6/6) multicoloured dark yellowish brown (10YR 4/6), reddish brown (2.5YR 5/4) sandy gravely CLAY with about 40% fine to medium gravel sized thinly bedded very weak litho relicts. Gravel strong fine to medium strong fine sandstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.92	1.02	0.1	Stiff to very stiff thinly laminated multicoloured dark yellowish brown (10YR 4/6) reddish brown (2.5YR 5/4) dark greyish brown (10YR 4/2) light yellowish brown (2.5YR 6/4) pale yellow (2.5YR 7/3) CLAY with some very weak red elongate siltstone and mudstone and some sand sized calcium carbonate clasts.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

1.02	1.45	0.43	Moderately strong white (10R 8/1) and red (10R 5/6) fine SANDSTONE and SILSTONE with calcareous very stiff thinly laminated red (10R 4/6) clay and very weak elongate fine to medium gravel sized mudstone clasts. Some of the sandstone disturbed in the upper part.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.45	1.48	0.03	Firm, thinly laminated mottled red (10R 4/6) dark yellowish brown (10YR 7/3) CLAY calcareous with occasional dark brown or black sand or fine gravel sized concretions of manganese dioxide.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.48	1.52	0.04	Moderately strong pale greenish grey fine SANDSTONE, and yellowish brown (10YR 5/6) very silty fine SAND with firm clay beds ~ 5 mm thick to gravely silty fine sand.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.52	1.59	0.07	Light grey (5Y 7/2) SILT	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.59	1.75	0.16	Weak light grey SILSTONE with some weak yellowish red (5Y 4/6) MUDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.75	1.82	0.07	Strong light grey (5Y 7/1) SILTSTONE	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 3**			**Logged by**
NGR	**469213E**	**351863N**		**Keith Ambrose**
Datum level mOD		**55.04**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0	0.25	0.25	TOPSOIL with Fragments of skerry	
0.25	0.55 to 0.57	0.30 to 0.32	SUBSOIL. Reddish brown with fragments of skerry with Mn nodules. Undulating base.	
0.55 to 0.57	0.72 to 0.78	0.15 to 0.33	SANDSTONE, pale greenish grey fine grained some inclusions red mudstone, disturbed and cryoturbated	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

0.72 to 0.78	0.83 to 0.87	0.09 to 0.11	CLAY, red with a few fine-grained sandstone fragments.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.83 to 0.87	0.92	0.05 to 0.09	SANDSTONE, disturbed. Calcareous layer at base	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.92	1.12	0.2	CLAY, red brown, laminated, common pale calcareous patches. Becomes very silty downwards. Some green mottling below 2.06 m. Lamination shows paler silt laminae, some brick red laminae.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.12	1.43	0.31	SILTSTONE, red brown with irregular greenish grey mottling; disturbed; layers of fine grained sandstone (greenish grey). Poorly defined lamination visible in parts e.g. below 1.34 m. Some impersistent clay laminae, predominantly greenish grey in basal 0.5 cm - laminated with some fine-grained sandstone laminae. Micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.43	1.48	0.05	CLAY, red brown lamination defined by paler and greyish grey mottling; some very silty parts. Micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.48	1.52	0.04	SANDSTONE, pale greenish grey, fine grained; irregular red clay laminae (5 mm). Micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell 4**			**Logged by**
NGR	**469629E**	**351491N**		**David Entwisle**
Datum level mOD		**43.05**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.36	0.36	Compact mottled dark reddish grey (2.5YR 3/1) and reddish yellow (5YR 6/6) and black (10YR 2/1) large root channel slightly sandy organic SILT extremely closely spaced roots. Base undulating. TOPSOIL	TOPSOIL
0.36	0.53	0.17	Compact reddish yellow (7.5YR 6/6) slightly organic sandy SILT with extremely closely spaced roots.	HEAD?

0.53	0.92	0.39	Dense, reddish yellow (5YR 6/8) slightly gravely silty, fine to coarse SAND with some dark brown or black rounded fine gravel sized nodules of manganese dioxide and dark reddish grey (2.5YR 3/1) root channels in the upper part. Gravel strong white (5Y 5/1) fine sandstone mostly in the upper part. Base undulating.	
0.92	1.12	0.20	Compact mottled brown (7.5YR 4/4) and (7.5YR 5/3) slightly sandy SILT with some dark brown or black fine gravel-sized manganese oxide nodules in upper part rare in the lower part.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.12	1.34	0.22	Firm or compact brown (10YR 5/3) fine sandy CLAY/SILT slightly gravely in lower third. Gravel very weak sub rounded sub rounded fine sandstone sometime with sand outer layer. Base irregular.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.34	1.47	0.13	Compact brown (10YR 5/3) with a little mottled very pale brown (10R 7/4) sandy SILT with thin band of very weak greenish grey siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.47	1.97	0.50	Firm thinly laminated red (10YR 4/4) mottled with a little light greenish grey (Gley 2 7/10G) slightly gravely CLAY. Gravel of very weak red siltstone and moderately strong to strong white fine sandstone. Occasional dark brown or black coarse sand and fine gravel sized nodules of manganese oxide.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.97	2.05	0.08	Firm red (10R 5/6) slightly calcareous slightly gravely CLAY. Gravel generally strong sometimes weak white (10YR 5/1) and light red (2.5YR 7/6) fine to medium sandstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.05	2.07	0.02	Strong white (10YR 5/1) fine SANDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.07	2.30	0.23	Firm red (10R 5/6) slightly gravely CLAY. Gravel generally strong sometimes weak white (10YR 5/1) and light red (2.5YR 7/6) fine to medium sandstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.30	2.73	0.43	Firm thinly laminated red (10YR 4/4) mottled with a little light greenish grey (Gley 2 7/10G) slightly gravely CLAY. Gravel of very weak red siltstone and moderately strong to strong white fine sandstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

2.73	2.87	0.14	Firm or compact red (10R 4/4) sandy slightly gravely CLAY/SILT. Gravel weak fine- to medium-sized siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.87	3.02	0.15	Compact, light grey (5Y 7/1) slightly gravely SILT. Gravel moderately strong light grey (5Y 7/1) tabular fine- to coarse-sized siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.10	4.00	0.90	Compact, mottled light grey (5Y 7/1) and reddish brown (5YR 5/4) slightly gravely SILT. Gravel moderately thinly laminated strong light grey (5Y 7/1) tabular fine- to medium-sized siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
4.00	4.20	0.20	Compact, mottled light grey (5Y 7/1) and reddish brown (5YR 5/4) slightly gravely SILT. Gravel moderately thinly laminated strong light grey (5Y 7/1) tabular fine- to medium-sized siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
4.20	4.40	0.20	Compact red (2.5YR 4/6) SILT.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
4.40	4.86	0.46	CORE LOST	
4.86	5.26	0.40	Thinly laminated mostly red (2.5YR 4/6) mottled light grey (5Y 7/1) slightly sandy SILT.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.26	5.30	0.04	Moderately strong to strong light red (10R 6/6) fine SANDSTONE and stiff weak red (10R 4/4) slightly sandy CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.30	5.50	0.20	Red (2.5YR 4/6) mottled pale red (2.5YR 7/2) fine sandy SILT	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.50	5.63	0.13	CORE LOST	
5.63	5.75	0.12	Red (2.5YR 4/6) and grey gravely SILT. Gravel generally fine to medium moderately strong greenish grey sub angular fine sandstone and weak siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.75	5.98	0.23	Firm becoming stiff or compact Interlaminated to thinly interbedded grey green (Gley 1 8/5G) CLAY and SILT, silt predominates.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.81	5.85	0.04	Weak light grey (5Y 7/1) fine-grained SANDSTONE/SILTSTONE and compact light grey (5Y 7/1) SILT.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.98	6.03	0.05	Strong grey fine SANDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

6.03	6.10	0.07	Compact and very stiff interlaminated mottled red and grey SILT and CLAY. Gravel of pale grey siltstone lithorelicts in the grey silt beds.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell 4**			**Logged by**
NGR	**469629E**	**351491N**		**Keith Ambrose**
Datum level mOD		**43.05**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.40	0.40	TOPSOIL	
0.40	0.46	0.06	PASSAGE	
0.49	0.59	0.10	SAND, brown fine to coarse silty.	HEAD?
0.59	0.92	0.33	SAND, orange brown, fine to coarse, Mn nodules common to 0.72, scattered below becoming clayey below 0.84 and browner	HEAD?
0.92	1.32	0.40	SILT, brown, clayey, micaceous	
1.32	1.40	0.08	SAND greenish brown fine to coarse grained, very clayey, micaceous; a few ochreous and red particles; clasts of grey green fine grained sandstone at base	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.40	1.47	0.07	SANDSTONE, greenish grey fine grained very fragmented some red mottling.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.47	2.05	0.58	CLAY, red brown less silty than above micaceous; silty in part; 5 mm clast of red brown fine grained sandstone at 1.90 m. Common fragments of greenish grey siltstone below 1.95 m, A few green spots and black MN spots to 1.87 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.05	2.07	0.02	SILTSTONE greenish grey; incomplete core.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.21	2.28	0.07	CLAY, red brown with common fragments of greenish grey siltstone and fine-grained sandstone. Disturbed.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.28	2.44	0.16	CLAY, red brown micaceous. Fragment of satin spar (gypsum) at 2.30 m, some green mottling.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

2.44	2.75 to 2.82	0.31 to 38	CLAY, red brown micaceous with 2 cm lens of greenish grey fine grained sandstone 2.75 - 2.79 m. Undulating base.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.78 to 2.82	3.02	0.20 to 0.24	SANDSTONE, greenish grey, fine sandstone fragments some red clayey particles.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.02	3.36	0.34	CORE LOSS	
3.36	3.80	0.44	SILT red brown clayey; micaceous; fragments of green siltstone and fine-grained sandstone; very silty.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.80	5.25	1.45	CLAY, red brown clayey; micaceous; fragments of green siltstone and fine-grained sandstone; silty patches, very soft.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.25	5.75	0.50	CLAY, red brown clayey; micaceous; silty patches, very soft.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
5.75	6.03	0.28	CLAY, greenish grey interlaminated with siltstone and fine-grained sandstone. Thin to thickly laminated.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
6.03	6.10	0.07	CLAY red brown, thickly laminated with greenish grey fine grained sandstone; some lenticular ?	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 5**			**Logged by**
NGR	**469699E**	**351544N**		**Keith Ambrose**
Datum level mOD		**44.44**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.31	0.31	TOPSOIL	
0.31	0.41	0.10	CLAY, red brown silty, some small (few mm) skerry clasts; green mottling large clasts (6 cm) at top	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.41	0.46	0.05	SAND, very fine grained clayey; micaceous; green mottling; a few small (few mm) skerry clasts	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.46	0.53	0.07	CORE LOSS	

0.53	0.78	0.25	CLAY, red brown silty to very silty, micaceous, green mottling; some Mn nodules; pale slightly calcareous patches; thinly laminated with more and less silty lenses.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.78	0.90	0.12	SAND and SANDSTONE, greenish grey; fine grained; some red mottling; more red mudstone to base.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.90	0.99	0.09	CLAY, red brown, green mottled, laminated.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.99	1.30	0.31	CORE LOSS	
1.30	1.52	0.22	CLAY, red brown, locally more silty; very weakly laminated; a few Mn nodules; irregular green mottling as streaks cutting bedding or nodular shaped.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.52	1.58	0.06	CORE LOSS	
1.58	1.75	0.17	CLAY red brown; slightly micaceous, common green mottling.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.75	1.88	0.13	SANDSTONE; pale greenish grey fine to very fine grained;silty clay in top 1 - 2 cm; red muddy layers and mottling; silt for basal 6 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.88	1.97	0.09	CLAY, red brown; green mottling impersistent layer of calcareous nodules (soft) at 1.92 m (soil horizon).	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.97	2.12	0.15	CLAY, greenish grey with small (1 cm) siltstone lithorelicts; some fine to very fine grained sandstone; 1 cm layer of red clay at base.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 5**			**Logged by**
NGR	**469699E**	**351544N**		**David Entwisle**
Datum level mOD		**44.44**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.30	0.30	Compact dark reddish grey (2.5YR 4/1) slightly sandy gravely organic SILT. Gravel fine sub angular to sub rounded fine moderately strong light grey (5YR 7/1) sandstone and weak to moderately weak grey (5YR 7/1) siltstone and firm to stiff red (10R 5/6) clay clasts which are more common in lower part. TOPSOIL.	TOPSOIL

0.30	0.59	0.29	Firm to stiff closely fissured (2.5YR 4/6) CLAY with very thin beds (<1 cm) (2.5YR 6/6) gravel. Gravel moderately strong fine white sandstone rounded sandy calcareous nodules and a few dark brown to black manganese oxide flecks.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.59	0.60 to 0.64	0.01 to 0.05	Moderately weak pale red (2.5YR 7/2) and light reddish brown (2.5YR 7/3) SILTSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.60 to 0.64	0.80	0.16 to 0.20	Firm to stiff thinly bedded to thickly laminate slightly gravely CLAY. Gravel of moderately weak to moderately strong mottled dark red (2.5YR 3/6) and red (2.5YR 4/6) siltstone and fine sandstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.80	0.90	0.10	Moderately strong greenish grey (GLEY2 7/5BG) mottled weak red (10R 4/4) silty fine SANDSTONE and fine SAND thinly bedded with stiff weak red (10R 4/4) clay.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.90	1.75	0.85	Firm to stiff thinly laminated predominantly red (10R 4/4) with some (Gley 2 7/5BG) CLAY. Less laminated and less mottling in lower part.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.75	1.87	0.12	Moderately strong silty fine SANDSTONE thinly bedded with stiff weak red (10R 4/4) clay. At base very weak light greenish grey (Gley2 7/5BG) siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.87	2.03	0.16	Stiff thinly laminated mottled red (10YR 4/6) and some light grey (10R 7/1) CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.03	2.12	0.09	Firm greenish grey slightly gravely CLAY becoming compact gravely SILT. Gravel weak light grey (10R 7/1) grey mottled pale red (10R 6/6) in middle of siltstone and weak silty fine sandstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 6**			**Logged by**
NGR	**470129E**	**352506N**		**Keith Ambrose**
Datum level mOD		**56.43**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.35	0.35	TOPSOIL, irregular base	TOPSOIL

0.35	0.65	0.30	CLAY, red brown; paler calcareous, patches, Manganese oxide nodules. Undulating base.	
0.65	0.87	0.22	CLAY, red brown; slightly micaceous; common calcareous patches, Mn nodules, sandy to basal 9 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.87	0.99	0.12	CLAY, red brown, greenish grey in top 1 cm weakly laminated, paler calcareous patches; Mn nodules to 0.97 m. Well laminated - thin to thick below 1.16 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.99	1.16	0.17	LOST CORE	
1.16	1.50	0.34	Paler and darker laminae; brick red laminae; green laminae; predominantly green 1.16 - 1.22 m with fine sandy laminae; some irregular green mottling. Calcareous patches 1.40 - 1.46 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.50	1.54	0.04	SILT and SILTSTONE; green	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.54	1.59	0.05	CLAY, red and green clay thick laminae to 1.59 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.59	1.61	0.02	Green silt and siltstone to 1.61 m	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.61	1.64		CLAY, red to 1.64 m;	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.64	1.72	0.08	CLAY silty red with green mottling and green siltstone patches to 1.72 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.72	1.73	0.01	Red clay to 1.73	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.73	1.76	0.03	Red silty Clay to 1.76 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

1.76	1.79	0.03	Green silt and siltstone to 1.79 m.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.79	1.88	0.09	CLAY, silty; red brown 1.79 - 1.88 m with green streaks thicker ones are siltstone; some mica.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.88	1.94	0.06	SILTSTONE green, rubbley and red mottled in top 2 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.94	1.97	0.03	MUDSTONE, red brown, micaceous	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.97	1.99	0.02	SANDSTONE, green, fine grained	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.99	2.05	0.06	CLAY, very silty, red brown, slightly micaceous to 2.05	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.05	2.12	0.07	SILT, Yellowish red (5YR 5/6) and light grey (2.5Y 7/2).	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 6**			**Logged by**
NGR	**470129E**	**352506N**		**David Entwisle**
Datum level mOD		**56.43**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.20	0.20	Compact brown (7.5YR 5/3) slightly sandy slightly gravely organic SILT. Gravel strong fine to medium fine-grained sandstone.	TOPSOIL
0.20	0.35	0.15	Compact mottled brown (7.5YR 5/3) strong brown (7.5YR 4/6) slightly sandy slightly gravely slightly organic SILT. Gravel strong fine to medium fine-grained sandstone.	TOPSOIL

0.35	0.65	0.30	Firm to stiff red brown CLAY, red brown; paler calcareous, patches, manganese oxide nodules. Undulating base.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.65	0.87	0.22	Firm to stiff weak red (10R 4/4) slightly micaceous CLAY with coarse sand or fine gravel-sized manganese oxide nodules and calcareous patches. Becomes slightly sandy in lower 9 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.87	0.99	0.12	Firm to stiff thinly laminated weak red (10R 4/47) in top 1 cm CLAY, top light greenish grey (Gley2 7/10BG) with white calcareous patches and to fine gravel sized manganese oxide nodules.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.99	1.07	0.08	Stiff (2.5YR 4/4) CLAY becoming compact SILT towards base	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.07	1.16	0.09	LOST CORE	
1.16	1.39	0.23	Firm thinly laminated with closely spaced red (10R 4/4) dark red (10R 3/6) vertical grey (Gley2 8/10BG) CLAY with sand to fine gravel sized calcareous nodules.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.39	1.46	0.07	Stiff multicoloured red (10R 4/8) reddish grey (10R 5/1 and 5YR 6/1) weak red (10R 5/3 and 10R 4/3) CLAY with calcareous nodules	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.46	1.52	0.06	Stiff multicoloured red (10R 4/8) reddish grey (10R 5/1 and 5YR 6/1) weak red (10R 5/3 and 10R 4/3) CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.59	1.61	0.02	Compact greenish grey SILT and about 40% weak greenish grey SILTSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.61	1.64	0.03	Firm very thinly laminated mottled red (10R 4/4) and grey (Gley2 8/10BG) CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.64	1.70	0.06	Stiff to hard or compact very thinly laminated mottled red (10R 4/4) and light greenish grey (Gley2 8/10BG) CLAY/SILT with ~40% very weak to weak light greenish grey (Gley2 8/10BG) SILTSTONE	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.70	1.73	0.03	Stiff to hard or compact very thinly laminated mottled red (10R 4/4) and light greenish grey (Gley2 8/10BG) CLAY/SILT with ~20% very weak red (10R 4/4) mudstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

1.73	1.76	0.03	Stiff weak red (10YR 4/4) CLAY	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.76	1.79	0.03	Compact light greenish grey (GLEY2 7/5BG) SILT and weak SILTSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.79	1.88	0.09	Stiff weak red (10R 4/4) with pale green streaks (GLEY1 7/5G) slightly gravely CLAY. Gravel of moderately strong thin tabular siltstone. Slightly micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.88	1.94	0.06	Moderately strong light greenish grey (Gley2 7/10BG) SILTSTONE recovered as medium gravel. Weak red (10R 4/4) in top 2 cm.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.94	1.97	0.03	Weak red (10R 4/4) micaceous MUDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.97	1.99	0.02	Moderately strong to strong light greenish grey (Gley1 7/5G) fine grained SANDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.99	2.03	0.04	Stiff, weak red (10R 4/4) slightly micaceous CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.03	2.08	0.05	Stiff or compact very silty, light red (10R 6/4), slightly micaceous CLAY/SILT.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
2.08	2.12	0.04	Compact yellowish red (5YR 5/6) and light grey (2.5Y 7/2) SILT.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 7**			**Logged by**
NGR	**470499E**	**351789N**		**Keith Ambrose**
Datum level mOD		**41.48**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.29 to 0.35	0.29 to 0.35	TOPSOIL	TOPSOIL
0.29 to 0.35	0.50	0.15 to 0.21	SUBSOIL; angular to sub rounded fragments of green siltstone and fine-grained sandstone in a brown clay matrix with Mn nodules; some red (clay) mottling.	
0.50	0.72	0.22	SILTSTONE or SANDSTONE, fine	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

0.72	0.81	0.09	SILTSTONE laminated to 0.73 m, on green clay with calcareous nodules at 0.76 m; mainly red to 0.78 m; green to 0.81 m with fragmented SILTSTONE layer at top. Irregular undulating base.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.81	1.63	0.82	CLAY, red brown with green (gleying?) sub vertical from top to base; scattered Mn nodules becoming less common downwards common pale calcareous patches. A few small mudstone litho relicts.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.63	1.71	0.08	MUDSTONE, red brown; slightly micaceous.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.71	1.78	0.07	SILTSTONE, light grey.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 7**			**Logged by**
NGR	**470499E**	**351789N**		**David Entwisle**
Datum level mOD		**41.48**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.33	0.33	Uncompact gravely organic gravely SILT with extremely closely spaced roots and some dark brown or black manganese dioxide nodules. Gravel mostly moderately weak to moderately strong fine-grained sandstone. TOPSOIL	TOPSOIL
0.33	0.35	0.02	Moderately light grey (2.5YR 7/1) strong fine-grained SANDSTONE.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.35	0.50	0.15	Compact light brown (7.5YR 6/4 and 7.5YR 5/4) slightly sandy slightly gravely SILT. Gravel strong grey and red angular to tabular and red stiff fine to medium clay litho relicts	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.50	0.74	0.24	Moderately strong closely jointed light grey (2.5YR 7/2) fine SANDSTONE	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
0.74	0.80	0.06	Stiff mottled grey (Gley1 6/N) and red (10R 4/6) CLAY with strong <3 mm thick fine sandstone. Irregular base	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

0.80	1.64	0.84	Stiff red (10R 4/6) mottled greenish grey (Gley1 6/5G) slightly gravely CLAY. Gravel moderately weak to moderately strong	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.64	1.68	0.04	Very weak closely fissured red (10R 4/6) MUDSTONE	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.68	1.78	0.10	Very stiff light grey CLAY and moderately weak light grey (2.5YR 7/2) SILTSTONE	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Borehole	**Brackenhurst College Southwell, 8**			**Logged by**
NGR	**469234E**	**352884N**		**Keith Ambrose**
Datum level mOD		**53.77**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.44 to 0.49	0.44 to 0.49	TOPSOIL	TOPSOIL
0.49	1.00	0.51	Sand, red brown, fine coarse grained, clayey; common fragments of green siltstone and fine grained sandstone - sub angular generally less than 1 cm or 2 cm; Mn nodules.	
1.00	1.17 to 1.18	0.17 to 0.18	Sandstone, greenish grey, fine grained fragments - irregular patches of red and green clay; more clayey to base	
1.17 to 1.18	1.47	0.30 to 0.31	Clay, red brown, clasts fine grained sandstone in top 2 cm.	
1.47	1.50	0.03	Siltstone, greenish grey.	
1.53	1.70	0.17	Clay, red brown; a few green patches common to some.	
1.70	1.78	0.08	Sandstone, very fine grained; greenish grey fragmented; some green clay. Irregular base.	
1.78	2.03	0.25	Clay, red brown silty. Below 1.80 m green sandy patches; 1 cm layer of greenish grey fine-grained sandstone layer, 1.94 to 1.96 (irregular top) red clay with a few green patches to base.	

Borehole	**Brackenhurst College Southwell, 8**			**Logged by**
NGR	**469234E**	**352884N**		**David Entwisle**
Datum level mOD		**53.77**		
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.44 to 0.49	0.44 to 0.49	Compact brown (7.5YR 5/3) slightly sandy gravely organic SILT with very closely spaced roots. Gravel weak to strong fine sandstone with few fine rounded gravel-sized more common below 0.20 m. Diffuse irregular base.	TOPSOIL
0.44 to 0.49	1.00	0.51 to 0.54	Probably dense, red (2.5YR 5/6) slightly gravely silty fine to medium with some coarse SAND with some dark brown or black patches and sand to fine gravel-sized manganese oxide nodules. Gravel very weak to strong light grey (10R 7/1) fine to medium sub rounded to sub angular or tabular fine sandstone.	
1.00	1.25	0.25	Very weak to strong reddish brown (2.5 YR 4/4) and white (2.5YR 8/1) interbedded SANDSTONE and firm CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.25	1.70	0.45	Firm to stiff thinly laminated red (10R 4/8) and a little light grey (10R 7/1) CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.70	1.74	0.04	Compact grey (5YR 6/1) sometimes mottled red (10YR 4/6) slightly gravely SILT. Gravel weak tabular fine to medium siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.74	1.83	0.09	Firm to stiff laminated red (2.5YR 4/6) mottled grey (5YR 7/2) slightly gravely CLAY. Gravel very weak fine to medium tabular light grey (10R 7/1) siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.83	1.85	0.02	Moderately strong light grey (5YR 7/2) SANDSTONE with about 20% compact grey (5YR 6/1) SILT	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
1.85	2.03	0.18	Stiff thinly laminated red (2.5YR 4/6) CLAY with 1 - 3 cm thick beds of compact light grey (5YR 7/2) gravely silt. Gravel fine to medium weak to moderately strong fine-grained sandstone and siltstone.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

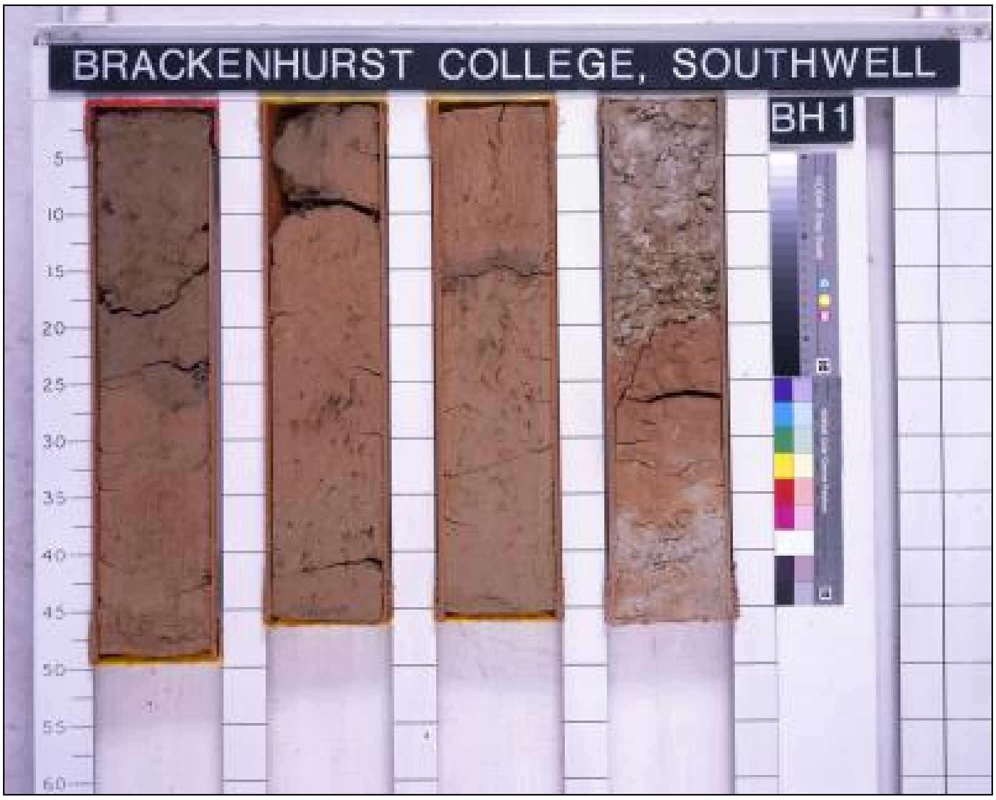
Borehole	**Brackenhurst College Southwell, 9**			**Logged by**
NGR	**469067E**	**352417N**		**Keith Ambrose**
Datum level mOD		**73.1**		**Sonic rotary borehole,**
				logged from geophysics and chippings only

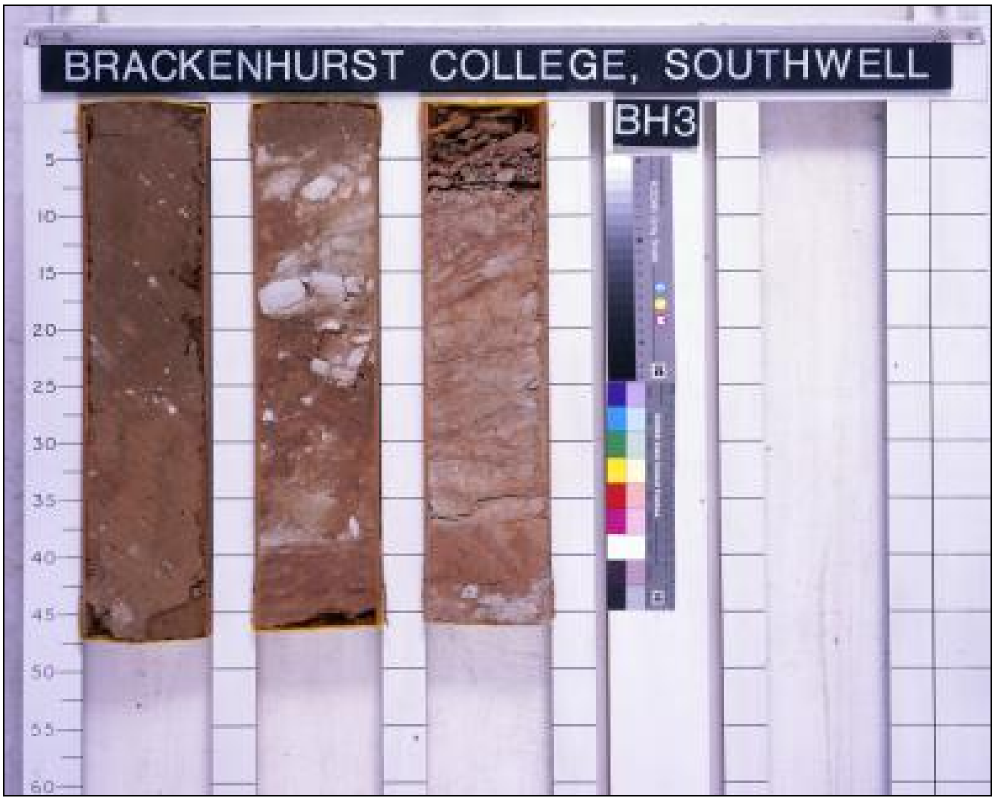
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	3.00	3.00	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.00	3.10	0.10	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
3.10	8.40	5.30	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
8.40	9.40	1.00	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
9.40	10.90	1.50	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
10.90	12.00	1.10	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
12.00	13.80	1.80	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
13.80	14.40	0.60	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
14.40	14.80	0.40	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
14.80	15.20	0.40	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
15.20	16.00	0.80	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
16.00	16.80	0.80	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
16.80	19.60	2.80	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
19.60	19.80	0.20	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
19.80	21.00	1.20	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
21.00	21.30	0.30	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
21.30	21.60	0.30	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
21.60	22.00	0.40	Siltstone, skerry	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP
22.00	25.70	3.70	Mudstone	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

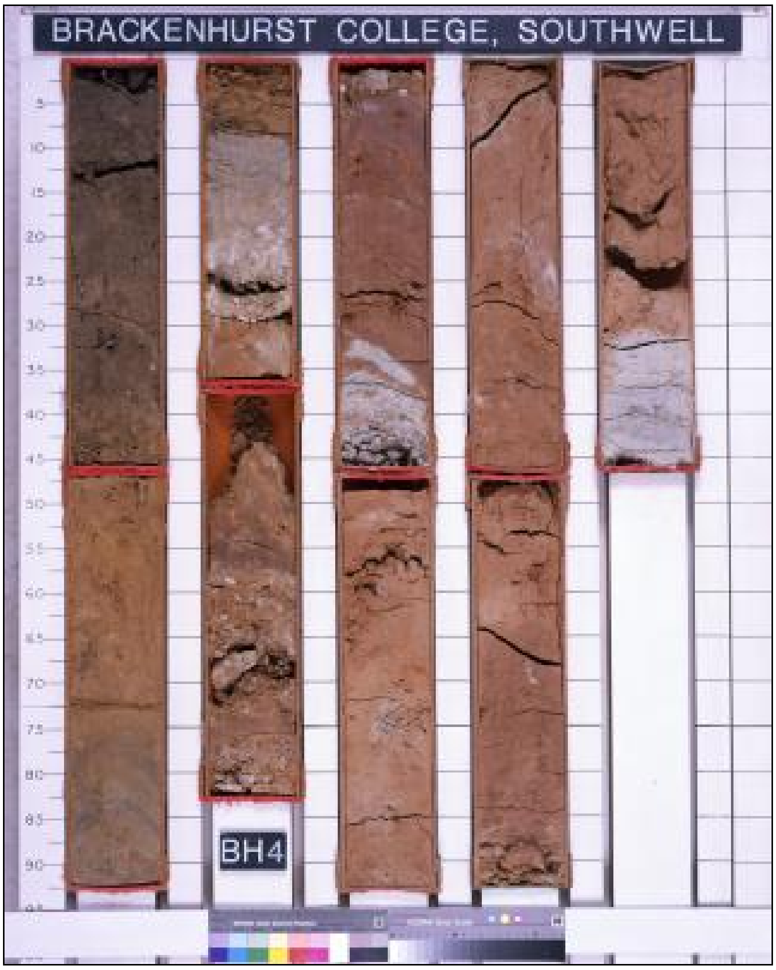
Borehole	**Brackenhurst College Southwell, 16**			**Logged by**
NGR	**470500.3E**	**351497.7N**		**David Entwisle**
Datum level mOD		**32.34**		**Sonic rotary borehole**
Depth top, m	**Depth Base, m**	**Thickness, m**	**Description**	**Lithostratigraphy**
0.00	0.21	0.21	Stiff, dark brown (7.5yr 3/2), with some medium gravel sized reddish brown (2.5 YR 5/4) increasing downward, very closely spaced roots and rootlets, occasionally gravelly, slightly sandy CLAY. Gravel is angular, medium sandstone. Base is undulating.	TOPSOIL
0.21	0.44	0.23	Stiff, reddish brown (5YR 4/3) occasionally mottled reddish brown (2.5YR 3/1), very closely spaced rootlets, CLAY with some sand sized black manganese concretions.	HEAD
0.44	1.80	1.36	Soft to firm, reddish brown (5YR 4/3), occasionally mottled (2.5 YR 3/1) and multicoloured occasional increasing to some with depth vertical grey (5GY) sometime with yellowish red (5YR 5/6), occasional very closely spaced to closely spaced rootlets to 1.50 m reducing below, occasion to common black mostly sand sized manganese concretions but between 0.70 to 0.80 m common, fine gravel-sized, CLAY	HEAD
1.80	1.90	0.10	Soft, thinly laminated, dark greyish brown (10YR 4/2), slightly organic CLAY with very closely space reed or rush stems and roots.	Old Alluvium
1.90	2.00	0.10	Soft, dark greyish brown (10YR 4/2), occasionally gravel, slightly organic CLAY with very closely space reed or rush stems and roots. Gravel is grey subrounded and fine.	Old Alluvium
2.00	2.15	0.15	Soft, brown (7.5YR 4/2), slightly organic, occasional gravel, occasional shell fragments, very sandy CLAY. Sand fine to medium, gravel fine, shell fragments fine gravel size.	Old Alluvium
2.15	2.40	0.25	Brown (7.5YR 4/2), Occasional to some shell fragments, slightly gravelly, slightly clayey, fine to medium, occasional coarse, SAND. Gravel grey, (7.5YR 5/1) sub angular to sub rounded siltstone (skerry).	Old Alluvium

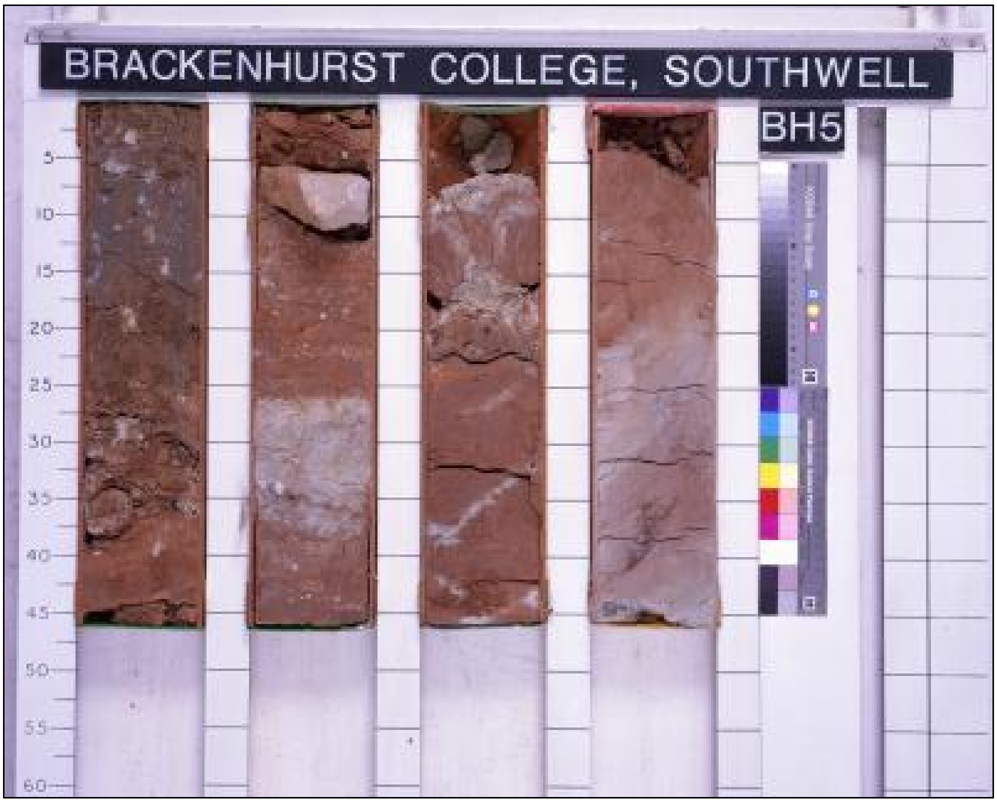
2.40	2.60	0.20	Brown (7.5YR 4/2), Occasional to some shell fragments, slightly gravelly, very clayey, fine to medium, occasional coarse, SAND. Gravel grey, (7.5YR 5/1) sub angular to sub rounded siltstone (skerry).	Old Alluvium
2.60	3.00	0.40	Brown (7.5YR 4/2), Occasional to some shell fragments, slightly gravelly, slightly clayey, fine to medium, occasional coarse, SAND. Gravel grey, (7.5YR 5/1) sub angular to sub rounded siltstone (skerry).	Old Alluvium
3.00	3.15	0.15	Dark grey (55YR 4/1), Occasional to some shell fragments, slightly organic, slightly clayey, gravelly fine to medium, occasional coarse, SAND with gravel-sized peat mostly at top of interval. Gravel weak to strong grey, (7.5YR 5/1), subangular or flat, fine to medium, sub angular or flat siltstone and siltstone (skerry).	Old Alluvium
3.15	3.25	0.10	Soft, dark grey (5YR 4/1), slightly organic, slightly gravelly sandy CLAY with occasionally reed stem. Sand fine to medium, gravel weak dark grey (5YR 4/1) angular to tabular siltstone.	Old Alluvium
3.25	3.51	0.26	Dark grey or dark greyish brown, occasional shell fragments, slightly organic, clayey gravelly fine to coarse SAND. Gravel weak angular or tabular	Old Alluvium
3.51	3.63	0.12	Soft to firm, dark reddish brown (5YR 3/4) gravelly CLAY. Gravel, grey (2.5YR 5/1) medium to coarse, subangular to subrounded, moderately strong to strong sandstone.	Old Alluvium
3.63	3.90	0.27	Firm to stiff, very closely fissured, sometimes thinly laminated, dark red (2.5YR 3 /4 or 4/4) sometimes mottled greenish grey (10GY 6/1) CLAY.	GUNTHORPE MEMBER, MERCIA MUDSTONE GROUP

Appendix 3 Core photographs

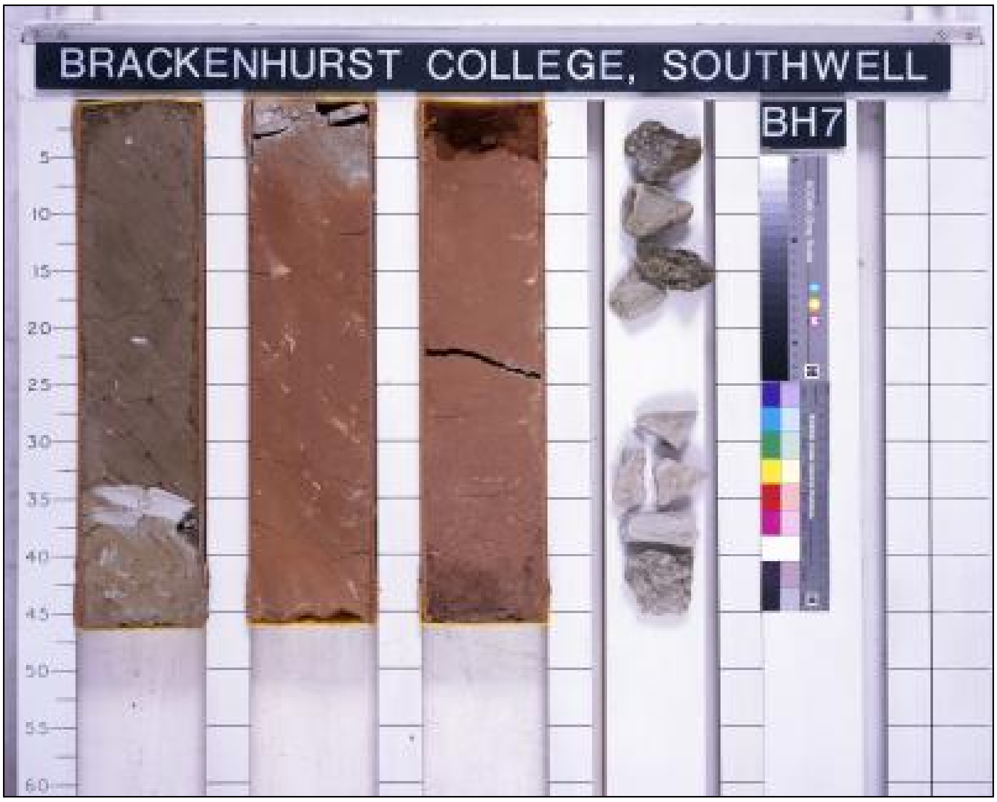



BRACKENHURST COLLEGE, SOUTHWELL
BH3


BRACKENHURST COLLEGE, SOUTHWELL
BH4


BRACKENHURST COLLEGE, SOUTHWELL
BH5


BRACKENHURST COLLEGE, SOUTHWELL
BH6


BRACKENHURST COLLEGE, SOUTHWELL
BH7
5
10
15
20
25
30
35
40
45
50
55
60


BRACKENHURST COLLEGE, SOUTHWELL
BH8
5
10
15
20
25
30
35
40
45
50
55
60


3.00m
3.90m
3.00m
1.50m
1.50m
0.44m
0.00m
0.44m
Brackenhurst College
Southwell 16
0.00 – 3.90 m

Appendix 4 NSRI trial pit logs

Trial pit name: Brackenhurst College Soil pit 1

Representative profile description

Site description

Profile no.:	SK75/0424; **Worcester series**
Location:	Durdham Farm, Brackenhurst, Notts (grid ref. 470382 352414)
Described by:	R C Palmer (field training NSRI; Jack Hannam, Tim Farewell and BGS; Sarah Brown, Andi Tigh, Dave Entwistle)
Date:	2nd November 2005
Weather:	Relatively dry summer followed by recent autumn rains and heavy overnight rain; profile not yet at field capacity
Elevation:	48.9 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Upper valley side
Micro relief:	Stubble field with flattened surface and occasional wheelings (<5 cm deep)
Slope and aspect:	Gently sloping (2.5^0) ESE (110^0)
Soil erosion:	None
Flooding:	None
Rock outcrops:	None
Land use:	Arable: wheat stubble
Sampling unit:	JCB pit 4 m long, 1.5 m wide and 1.38 m deep.

Horizons:

0-27 cm Ap

Dark reddish brown (5YR 3/2) stoneless silty clay loam (20% C; 50% S); few medium red (2.5YR 4/4) mottles; moist; moderately developed coarse subangular blocky peds; medium packing density; slightly porous; moderately weak soil strength; moderately sticky, very plastic; few very fine fibrous roots; earthworms active; few very fine fibrous roots; sharp smooth boundary.

27-48 cm Bt(g)

Dark reddish brown (2.5YR 3/4) very slightly stony silty clay (45% C, 55% Z); stones small subangular tabular siltstones; few fine distinct light greenish grey (10GY 7/1) mottles; moist; structureless massive; high packing density; very slightly porous; very firm soil strength; very sticky, very plastic; few very fine fibrous roots; common very fine and extremely fine ferri-manganiferous concretions; gradual smooth boundary.

48-92 cm Btg

Reddish brown (2.5YR 4/4) very slightly stony silty clay (48% C, 45% S); stones small subangular tabular siltstones; many coarse distinct light greenish grey (10GY 7/1) and common coarse distinct weak red to reddish brown (2.5YR 5/3) mottles; moist; structureless massive; high packing density; very slightly porous; very firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; few very fine and extremely fine ferri-manganiferous concretions; slightly calcareous; clear smooth boundary.

92-138 cm BC(g)

Dark reddish brown (2.5YR 3/4) moderately stony silty clay loam (35% C, 60% Z); stones mainly rotting greenish grey (5GY 6/1) siltstones in distinct horizontal bands (skerry bands in situ?) and locally containing large hard tabular blocks; common coarse distinct reddish brown (5YR 4/4) mottles; moist; weak fine angular blocky rock structure; high packing density, very slightly porous; very firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; common very fine and extremely fine ferri-manganiferous concretions; slightly calcareous; clear wavy boundary.

At 138 cm Cr

Greenish grey (5GY 6/1) hard bedded slightly calcareous siltstone (skerry).

Sample depths (cm):

Bulk bag samples	Comment	Water release tins	Comment
0-27		3-8	
27-48		29-34	
48-92		48-53	
92-138			No tins from this layer

Trial pit name: Brackenhurst College Soil pit 2

Representative profile description

Site description

Profile no.:	SK75/0416; **Whimple series**
Location:	Brackenhurst Farm, Brackenhurst, Notts (grid ref. 470400 351620) field south of Weldon Farm
Described by:	R C Palmer (field training NSRI; Helen Cooke and Julia Duzant and BGS; Andreas Scheib, Louise Ander and Russell Lawley
Date:	7th November 2005
Weather:	Relatively dry summer followed by recent autumn rains and heavy overnight rain; profile not yet at field capacity
Elevation:	39.2 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Valley side
Micro relief:	None
Slope and aspect:	Gentle (2.5^0) at SSE (155^0)
Soil erosion:	None
Flooding:	None
Rock outcrops:	None
Land use:	Permanent grass
Sampling unit:	JCB pit 4 m long, 1.5 m wide and 1.40 m deep.

Horizons

0-30 cm Ap

Dark reddish brown (5YR 3/4) very slightly stony clay loam (25% C; 25% S); stones very small subangular tabular siltstones; few very fine distinct red (2.5YR 4/6) mottles; moist; strongly developed medium subangular blocky peds; medium packing density; moderately porous; moderately weak soil strength; moderately sticky, very plastic; many very fine fibrous roots, some well rotted material (turf mat?) at 25 cm depth; earthworms very active; few fine to extremely fine ferri-manganiferous concretions; sharp irregular boundary.

30-39 cm Eb(g)

Yellowish red (5YR 4/6) very slightly stony clay loam (27% C; 40% S); stones very small subangular tabular siltstones and one flint; few very fine brownish yellow (10YR 6/6) mottles; moist; moderately developed fine and medium prismatic peds; moderate packing density; moderately porous; moderately firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; sharp wavy boundary.

39-74 cm 2Btg

Dark red (2.5YR 3/6) stoneless clay loam (27% C, 20 S); few faint very fine sharp pale brown (10YR 6/3) mottles; moist; weakly developed coarse prismatic peds; moderate packing density; moderately porous; moderately strong soil strength; moderately sticky, very plastic; few very fine fibrous roots; few coarse vertical earthworm channels coated with dark reddish brown (5YR 3/4) topsoil material; few extremely fine ferri-manganiferous concretions; sharp irregular boundary. [texture should be ZC??]

74-123 cm 3BC

Grey to light grey (5YR 6/1) moderately stony silty clay loam (30% C, 55% Z); stones very small to very large mainly weathering siltstones; many prominent fine sharp brown (7.5YR 5/4) mottles; moist at top of layer and wet at base with water weeping into pit; structureless massive, though some horizontal rock structures remain (rotting skerry band); high packing density, very slightly porous; moderately weak soil strength; slightly sticky, very plastic; few very fine fibrous roots; few extremely fine ferri-manganiferous concretions; sharp smooth boundary.

123-140 4Cu

Reddish brown (5YR 4/4) very slightly stony silty clay (40% C, 55% Z); stones grey to light grey (5YR 6/1) rotting siltstones; common fine reddish brown (5YR 5/4) mottles; moist; moderately developed fine angular blocky rock structure; high packing density, very slightly porous; moderately firm soil strength; moderately sticky, very plastic; sharp smooth boundary.

At 140 5Cr

Greenish grey (5GY 6/1) hard slightly calcareous siltstone.

Sample depths (cm):

Bulk bag samples	labels	Water release tins	Comment
0-30	8-13	8-13	1A, 1B, 1C
30-39	36-41	36-41	2A, 2B, 2C
39-74	54-59	54-59	3A, 3B, 3C
74-123	95-100		
123-140	122-127		

Trial pit name: Brackenhurst College Soil pit 3

Representative profile description

Site description

Profile no.:	SK75/0621; **Hopsford series**
Location:	Durdham Farm, Brackenhurst, Notts (grid ref. 470550 352105); large field east of farm buildings
Described by:	R C Palmer (field training NSRI; Jack Hannam, Tim Farewell and BGS; Sarah Brown, Andi Tigh, Dave Entwistle)
Date:	2nd November 2005
Weather:	Relatively dry summer followed by recent autumn rains and heavy overnight rain; profile not yet at field capacity
Elevation:	38.4 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Concave footslope approximately 10 m above alluvial flat
Micro relief:	Ridge and furrow running WNW-ESE – amplitude 35 cm across 6.5 m spaced crests
Slope and aspect:	Gently sloping (2.5^0) NE (45^0)
Soil erosion:	None
Flooding:	None
Rock outcrops:	None
Land use:	Permanent grassland, heavily poached near gate and feeders (on alluvial soils) but not near pit
Sampling unit:	JCB pit 4 m long, 1.5 m wide and 1.52 m deep.

Horizons:

0-20 cm Ah

Dark reddish brown (5YR 3/3) stoneless clay loam (20% C; 50% S); moist; strongly developed coarse granular peds; medium packing density; moderately porous; moderately weak soil strength; very weak soil strength; slightly sticky, very plastic; many very fine fibrous roots; earthworms and earwigs active; gradual smooth boundary.

20-45 cm Bw(g)

Brown to dark brown (7.5YR 4/4) very slightly stony clay loam; stones small to medium subangular tabular siltstones; common fine distinct reddish yellow (7.5YR 6/6) mottles; moist; moderately developed coarse subangular blocky peds breaking to fine and very fine; medium packing density; moderately porous; weak ped strength; slightly sticky, moderately plastic; common very fine fibrous roots; earthworms active; gradual smooth boundary.

45-61 cm Bg

Brown to dark brown (7.5YR 4/4) slightly stony clay loam (24% C, 45% S); stones medium and small subangular tabular siltstones; common coarse distinct yellowish red (5YR 5/8) and common fine distinct dark reddish grey (5YR 4/2) mottles; moist; moderately developed coarse subangular blocky peds breaking to fine and medium; medium packing density, moderately porous; weak soil and ped strength; slightly sticky, moderately plastic; few very fine fibrous roots mainly along coarse vertical earthworm channels coated with dark reddish brown (5YR 3/3) topsoil material; earthworms active; common very fine and extremely fine ferri-manganiferous concretions; sharp wavy boundary.

61-115 cm Bg2

Dark reddish brown (2.5YR 3/4) slightly stony silty clay (40% C, 50% Z) with patches of sandy clay loam (25% C, 55% S) occupying approximately 25% of upper part of horizon, with these inclusions becoming sandier below 85 cm depth; stones as above; common, prominent fine light greenish grey (5GY 7/1) and common, distinct, fine yellowish red (5YR 4/6) mottles; moist, very moist at base; moderately developed very coarse prismatic peds with slightly greyed ped faces; medium packing density, slightly to moderately porous; moderately strong ped strength; slightly sticky, slightly plastic; few very fine fibrous roots; common very fine and extremely fine ferri-manganiferous concretions; clear wavy boundary.

115-138 cm 2BC(g)

Reddish brown (2.5YR 4/4) moderately stony silty clay; stones medium subangular tabular siltstones; common, distinct, fine reddish brown (2.5YR 4/3) mottles and many coarse to fine light greenish grey (10Y 7/1) patches associated with weathered skerry and mudstone; moist; strongly developed fine and very fine angular blocky rock structure; high packing density, very slightly porous; moderately weak soil strength, moderately firm ped strength; slightly sticky, very plastic; very slightly calcareous.

Sample depths (cm):

Bulk bag samples	Comment	Water release tins	Comment
0-20		5-10	
20-45		29-34	
45-61		51-56	
61-84	84-115 layer found on close inspection to be similar to 61-84	??-??	No depth recorded on tin
115-130		118-123	

Trial pit name: Brackenhurst College Soil pit 4

Representative profile description

Site description

Profile no.:	SK75/0119; **Brockhurst series**
Location:	Brackenhurst Farm, Brackenhurst, Notts (grid ref. 470080 351940); field immediately south of farm house
Described by:	R C Palmer (field training NSRI; Helen Cooke and Julia Duzant and BGS; Andreas Scheib, Louise Ander and Russell Lawley
Date:	7th November 2005
Weather:	Relatively dry summer followed by recent autumn rains and heavy overnight rain; profile not yet at field capacity
Elevation:	55.4 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Level interfluve
Micro relief:	Stubble field with flattened surface and occasional wheelings (<5 cm deep)
Slope and aspect:	Level (<1^0) E (98^0)
Soil erosion:	None
Flooding:	None
Rock outcrops:	None
Land use:	Arable: weed and grass infested cereal stubble
Sampling unit:	JCB pit 4 m long, 1.5 m wide and 1.80 m deep.

Horizons:

0-16 cm Ap1

Dark reddish brown (5YR 3/3) very slightly stony clay loam (25% C; 30% S); stones medium to very small subangular tabular siltstones and rounded quartzites; moist; moderately developed medium to coarse subangular blocky fragments; medium packing density; moderately porous; moderately weak soil and ped strength; moderately sticky, very plastic; common very fine fibrous roots with layer of well rotted stubble at base of horizon; earthworms active; sharp wavy boundary.

16-32 cm Ap2

Dark reddish brown (5YR 3/3) stoneless clay loam (25% C; 30% S); moist; weakly developed coarse prismatic fragments, locally structureless massive; high packing density; slightly porous; moderately firm soil strength; moderately sticky, very plastic; common very fine fibrous roots; sharp wavy boundary.

32-42 cm Eg

Brown to dark brown (7.5YR 4/4) very slightly stony clay loam (25% C, 35% S); stones small subangular tabular siltstones and subrounded Carboniferous siltstones and sandstones; many very fine distinct diffuse strong brown (7.5YR 4/6) and common very fine faint diffuse dark red (2.5YR 3/6) mottles; moist; weakly developed coarse prismatic peds; high packing density; slightly porous; moderately weak ped strength; moderately sticky, very plastic; few very fine fibrous roots concentrated down common coarse vertical earthworm channels coated with dark reddish brown (5YR 3/3) topsoil material; few fine to extremely fine ferri-manganiferous concretions; sharp smooth boundary.

42-77 cm 2Btg

Dark reddish brown (2.5YR 3/4) stoneless silty clay (40% C, 60% Z); common fine distinct reddish brown (5YR 4/3), few very fine distinct light yellowish brown (10YR 6/4) mottles with a discontinuous horizontal dark greenish grey (5GY 5/1) layer of silty clay (parent material colours) up to 3 cm thick;

moist; weakly developed coarse angular blocky peds; high packing density, very slightly porous; very firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; few extremely fine ferri-manganiferous concretions; gradual wavy boundary.

77-130 2BCt(g)

Red (2.5YR 4/6) with generally horizontal bands (up to 7 cm thick) of grey (5Y 6/1) stoneless silty clay (40% C, 60% Z); moist; weakly developed coarse prismatic peds; high packing density, very slightly porous; very firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; few fine to extremely fine ferri-manganiferous concretions; matrix non-calcareous but grey (5Y 6/1) bands patchily slightly calcareous; gradual smooth boundary.

130-140 3Cr

Greenish grey (5GY 6/1) soft weathering slightly calcareous siltstone band with common reddish brown (2.5YR 4/4) patches of soft mudstone.

140-180 4Cu

Reddish brown (2.5YR 4/4) mudstone; common fine and very fine dusky red (10R ¾) and brownish yellow (10YR 6/6) mottles; many light grey (5Y 7/1) patches of soft siltstone and mudstone; fine angular blocky rock structure; slightly calcareous.

Sample depths (cm):

Bulk bag samples	Comment	Water release tins	Comment
0-16	Labelled 6-11	6-11	1A, 1B, 1C
16-32	Labelled 19-24	19-24	2A, 2B, 2C
32-42	Labelled 33-38	33-38	3A, 3B, 3C
42-77	Labelled 52-57	52-57	4A, 4B, 4C
77-130	Labelled 80-85	80-85	5A, 5B, 5C

Trial pit name: Brackenhurst Farm College Soil pit 5

Representative profile description

Site description

Profile no.:	SK65/9616 **Salwick series**
Location:	Brackenhurst Farm, Brackenhurst, Notts (grid ref. 469595 351593) field west of Gypsy Lane but north of tributary to Helloughton Dumble
Described by:	R C Palmer
Date:	17th November 2005
Weather:	Relatively dry summer followed by autumn rains but dry and frosty prior to sampling; profile not yet at field capacity
Elevation:	45.6 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Lower valley side
Micro relief:	None
Slope and aspect:	Gentle (1^o) at SSW (210^o)
Soil erosion:	None
Flooding:	None
Rock outcrops:	None
Land use:	Arable; cereal stubble
Sampling unit:	JCB pit 4m long, 1.5m wide and 1.42m deep.

Horizons

0-28 cm Ap

Dark reddish brown to reddish brown (5YR 4/3) slightly stony clay loam; stones medium to very small subangular tabular siltstones plus small and very small rounded quartzites; moist; weakly developed medium to fine subangular blocky fragments; medium packing density; moderately porous; moderately weak soil strength; moderately sticky, moderately plastic; common very fine fibrous roots; earthworms active; abrupt smooth boundary.

28-57 cm Eb(g)

Dark reddish brown to reddish brown (4YR 4/3) slightly stony sandy silt loam; stones as above; few distinct fine strong brown (7.5YR 5/6) sharp mottles; moist; weakly developed medium angular blocky peds with reddish brown (5YR5/4) faces; medium packing density; moderately porous; moderately firm soil strength; moderately sticky, moderately plastic; few very fine fibrous roots; few fine ferri-manganiferous concretions; clear smooth boundary.

57-84 cm 2Bt(g)

Reddish brown (5YR 5/4) moderately stony silty clay to silty clay loam; stones small to very large angular tabular siltstones, frequently soft and weathering though locally hard; common distinct fine yellowish red (5YR 5/6) and few faint dark reddish brown (5YR 3/4) clear mottles; moist; moderately developed medium angular blocky peds with reddish brown (5YR 5/3) faces; high packing density; slightly porous; very firm soil strength; moderately sticky, very plastic; few very fine fibrous roots; few coarse vertical earthworm channels coated with dark reddish brown (5YR 4/3) topsoil material; few fine ferri-manganiferous concretions; clear smooth boundary.

84-142 cm 2Bt(g)2

Dark reddish brown (2.5YR 3/4) with streaks of greenish grey (5GY 6/1) slightly stony silty clay loam; stones medium to large angular tabular siltstones, mix of soft and hard but all greenish grey (5GY 6/1) in colour; common distinct brown (7.5YR 5/4) fine sharp mottles; moist; weakly developed very coarse prismatic peds but locally structureless massive; high packing density, very slightly porous; moderately strong soil strength; very sticky, very plastic; few very fine fibrous roots.

Analyses

Horizon	**Ap**	**Eb(g)**	**2Bt(g)**	**2Bt(g)2**
Depth (cm)	0-28	28-57	57-84	84-142

Sand				
Coarse 600 µm-2 mm %	3.2	4.8	1.3	1.3
Medium 200-600 µm %	7.4	8.7	1.3	1.2
Fine 100-200 µm %	5.3	4.9	1.2	0.6
Very fine 60-100 µm %	6.5	8.1	2.9	0.9
Silt 2-60µm %	53.7	55.9	70.5	63.2
Clay <2µm %	23.9	17.7	22.9	32.9
Organic carbon %	1.5	1.3	N.D.	N.D.
CEC (me/100g)	9.0	4.1	8.6	7.7
pH in CaCl2 (1:2.5)	6.7	6.3	7.2	6.9
pH in water (1:2.5)	7.2	7.2	7.6	7.4
CaCO3 equiv (g/kg)	63.4	95.0	96.4	53.1
Bulk density $g.cm^{-3}$				
Total pore space %vol				
Available water %vol				
Air capacity %vol				
Retained water capacity %vol				
Packing density $g.cm^{-3}$				

Trial pit name: Brackenhurst Farm College Soil pit 6

Representative profile description

Site description

Profile no.:	SK65/9615 **Mathon series**
Location:	Brackenhurst Farm, Brackenhurst, Notts (grid ref. 469642 351509) field west of Gypsy Lane but north of tributary to Helloughton Dumble
Described by:	R C Palmer
Date:	17th November 2005
Weather:	Relatively dry summer followed by autumn rains but dry and frosty prior to sampling; profile not yet at field capacity
Elevation:	43.05 m O.D.
Regional relief:	Gently undulating Mercia Mudstone outcrop
Local relief:	Valley floor
Micro relief:	None
Slope and aspect:	Level
Soil erosion:	None
Flooding:	No evidence of recent flooding; stream incised and 5 m below level of floodplain
Rock outcrops:	None
Land use:	Permanent grass strip at edge of arable with cereal stubble
Sampling unit:	JCB pit 4 m long, 1.5 m wide and 1.20 m deep.

Horizons

0-38 cm Ah

Dark brown to reddish brown (7.5YR 3/2) stoneless silty clay loam; moist; strongly developed medium subangular blocky peds; medium packing density; moderately porous; moderately firm soil strength; moderately weak ped strength; moderately sticky, very plastic; common very fine fibrous and few fine fleshy roots; earthworms active; few fine ferri-manganiferous concretions; abrupt smooth boundary.

38-60 cm Bw(g)

Reddish brown to dark reddish brown (5YR 4/3) stoneless silty clay loam; moist; moderately developed medium prismatic peds with reddish brown (5YR5/4) faces; medium packing density; moderately porous; moderately firm soil and ped strength; slightly sticky, very plastic; few very fine fibrous roots; earthworms active and common vertical earthworm channels coated with Dark brown to reddish brown (7.5YR 3/2) topsoil material; few fine ferri-manganiferous concretions; gradual smooth boundary.

60-120 cm Bwg

Reddish brown (5YR 5/4) stoneless silty clay loam; common distinct yellowish red (5YR 5/6) fine sharp mottles; moist; moderately developed medium prismatic peds with reddish grey (5YR 5/2) faces; medium packing density; moderately porous; moderately firm soil strength; moderately sticky, very plastic; common very fine fibrous roots; earthworms active and few coarse vertical channels coated with dark brown to reddish brown (7.5YR 3/2) topsoil material; common fine ferri-manganiferous concretions; clear smooth boundary.

Analyses

Horizon	**Ah**	**Bw(g)**	**Bg**
Depth (cm)	0-38	38-60	60-120

Sand			
Coarse 600 µm-2 mm %	0.4	0.1	0.4
Medium 200-600 µm %	2.9	0.3	4.9
Fine 100-200 µm %	1.9	0.7	3.5
Very fine 60-100 µm %	4.5	4.1	10.6
Silt 2-60µm %	64.0	72.8	62.1
Clay <2µm %	26.4	22.0	18.5
Organic carbon %	2.2	0.7	N.D.
CEC (me/100g)	11.5	9.2	5.3
pH in CaCl2 (1:2.5)	5.9	6.4	6.4
pH in water (1:2.5)	6.7	7.2	7.3
CaCO3 equiv (g/kg)	0.0	86.3	47.0
Bulk density g.cm^{-3}			
Total pore space %vol			
Available water %vol			
Air capacity %vol			
Retained water capacity %vol			
Packing density g.cm^{-3}			

Appendix 5 DTM Digital Noise Removal Techniques

Mean Smoothing Filtration

The Mean filter replaces the central pixel in the filter matrix with a value determined as the mean of all the pixel values occurring within the filter matrix. A series of 3x3, 5x5 and 7x7 Mean filters were applied to the DTM. The results appeared identical on initial visualisation (Figure 67). The elevation profile extracted across an example peak and trough error showed that these errors were suppressed with increasing filter size (Figure 68) with a progressive smoothing evident on hillshade images generated for the filtered products (Figure 69). When an extended elevation profile was compared with that from the original DTM, the filtered elevation values did not appear to be dramatically altered, but some of the peak and trough features appeared to be widened, which is not wholly unexpected (Figure 70).

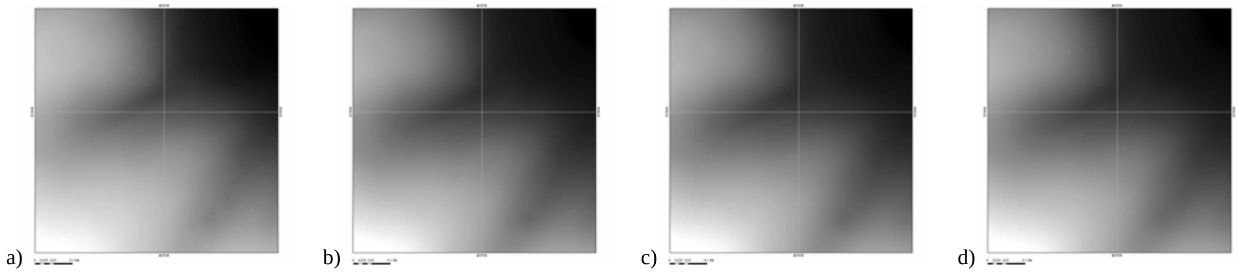


Figure 67: Comparison of a) DTM with Mean b) 3x3, c) 5x5 and d) 7x7 filtration

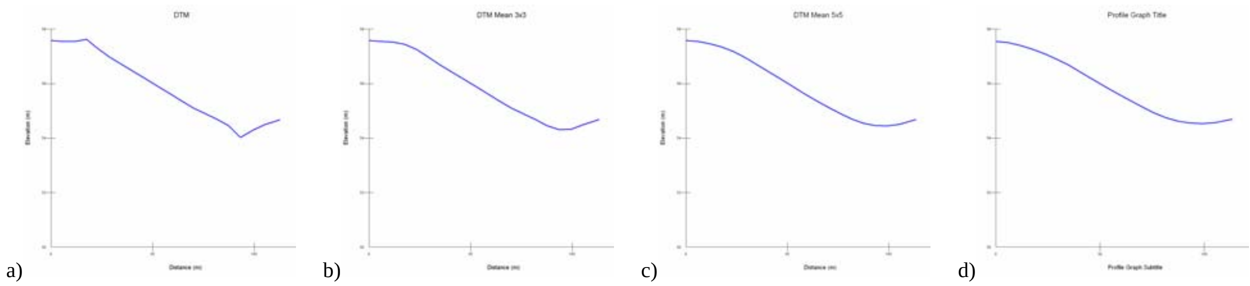


Figure 68: Elevation profiles extracted over an example peak and trough error from a) DTM and Mean b) 3x3, c) 5x5 and d) 7x7 filtration

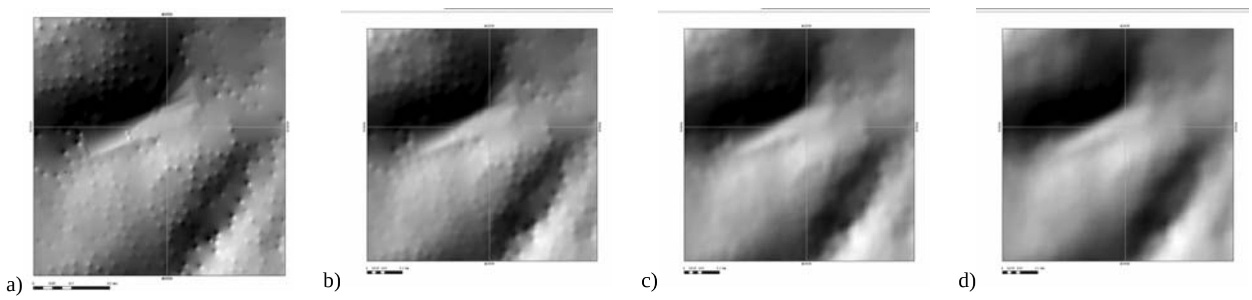


Figure 69: Hillshade images of a) DTM and Mean b) 3x3, c) 5x5 to d) 7x7 filtration

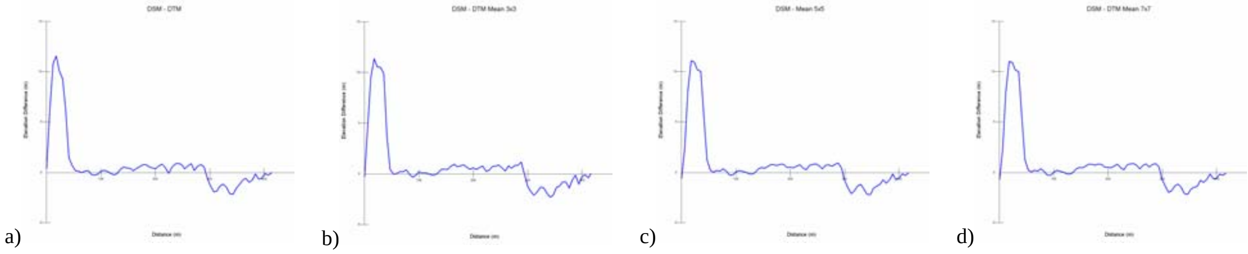


Figure 70: The difference in elevation between the DSM and a) DTM and Mean b) 3x3, c) 5x5 and d) 7x7 filtration

Median Smoothing Filtration

The Median filter replaces the central pixel in the filter matrix with a value determined as the median of all the pixel values occurring within the filter matrix. A series of 3x3, 5x5 and 7x7 Median filters were applied to the DTM. As for the Mean filtration, the results appeared identical on initial visualisation (Figure 71) and again the same peak and trough errors were suppressed with increasing filter size on the extracted elevation profiles (Figure 72). The hillshade images again showed a smoothing of the errors with increased filter size (Figure 73), but the hillshade images also showed the introduction of a terrace effect with increased filter size.

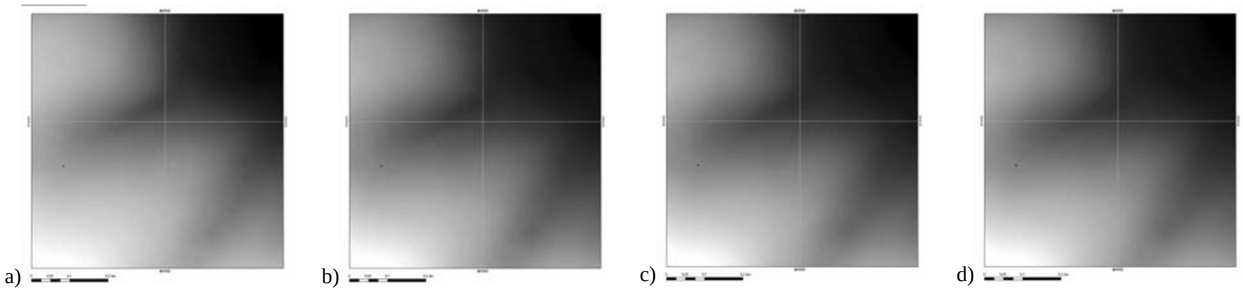


Figure 71: Comparison of a) DTM with Median b) 3x3, c) 5x5 and d) 7x7 filtration

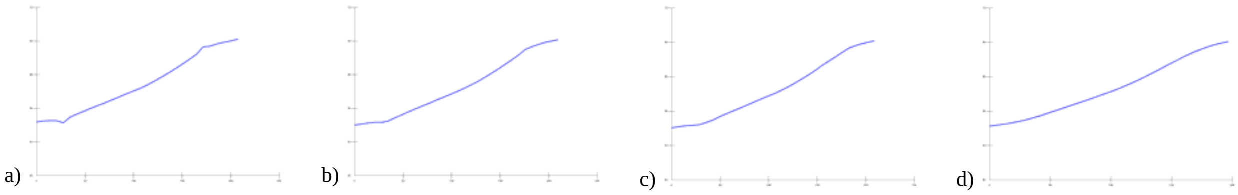


Figure 72: Elevation profiles extracted over an example trough and peak error from a) DTM and Median b) 3x3, c) 5x5 and d) 7x7 filtration

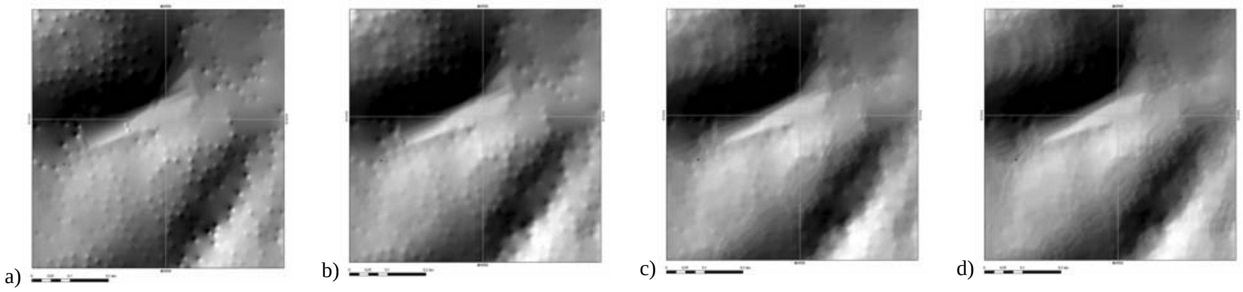


Figure 73: Hillshade images of a) DTM and Median b) 3x3, c) 5x5 to d) 7x7 filtration

Gaussian Smoothing Filtration

The Gaussian filter replaces the central pixel in the filter matrix with a value determined from the Gaussian distribution of all the pixel values occurring within the filter matrix. A series of 3x3, 5x5 and

7x7 Gaussian low pass filters were applied to the DTM (Figure 74). As for both the Mean and Median filtration, the results appeared identical on initial visualisation (Figure 75) with suppression of the peak and trough errors on increasing filter size (Figure 76) and a progressive smoothing of the errors on the associated hillshade images (Figure 77). Although the Gaussian filtration appears to have reduced the prominence of the errors, they are still clearly evident.

a)

0.0007	0.0256	0.0007
0.0256	0.8948	0.0256
0.0007	0.0256	0.0007

b)

0	0.0007	0.0024	0.0007	0
0.0007	0.0314	0.1131	0.0314	0.0007
0.0024	0.1131	0.4067	0.1131	0.0024
0.0007	0.0314	0.01131	0.0314	0.0007
0	0.0007	0.0024	0.0007	0

c)

0	0	0.0003	0.0006	0.0003	0	0
0	0.0011	0.0079	0.0153	0.0079	0.0011	0
0.0003	0.0079	0.0563	0.1082	0.0563	0.0079	0.0003
0.0006	0.0153	0.1082	0.2079	0.1082	0.0153	0.0006
0.0003	0.0079	0.0563	0.1082	0.0563	0.0079	0.0003
0	0.011	0.0079	0.0153	0.0079	0.0011	0
0	0	0.0003	0.0006	0.0003	0	0

Figure 74: Gaussian a) 3x3, b) 5x5 and c) 7x7 filters

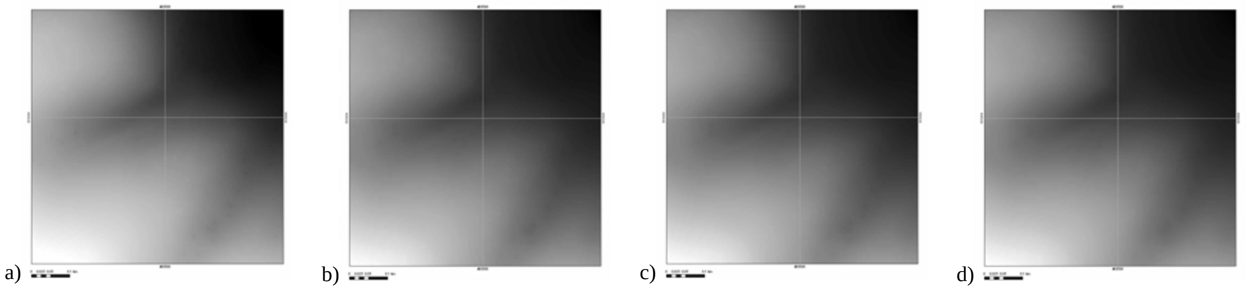


Figure 75: Comparison of a) DTM with Gaussian b) 3x3, c) 5x5 and c) 7x7 filtration

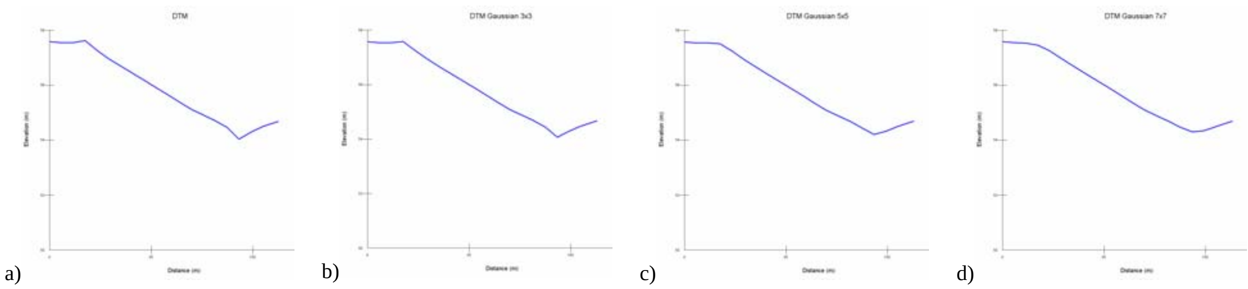


Figure 76: Elevation profiles extracted over an example peak and trough error from a) DTM and Gaussian b) 3x3, c) 5x5 and d) 7x7 filtration

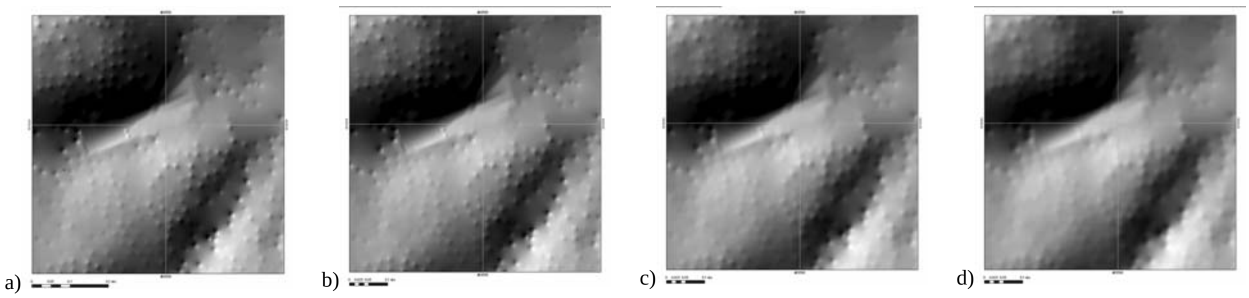


Figure 77: Hillshade images of a) DTM and Gaussian b) 3x3, c) 5x5 and d) 7x7 filtration

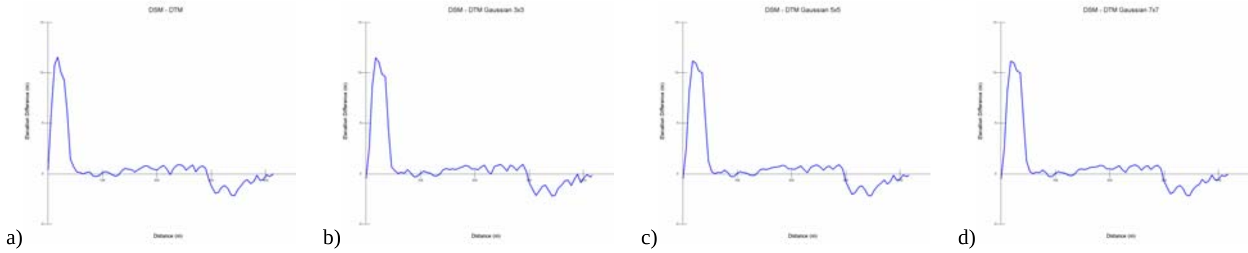


Figure 78: The difference in elevation between the DSM and a) DTM and Gaussian low pass b) 3x3, c) 5x5 and d) 7x7 filtration

Lee-Sigma Speckle Suppression

The peak and trough errors in the DTM are similar in appearance to speckle, a term commonly used in the interpretation of radar data to signify noise. Speckle suppression filters determine whether the digital value of the central pixel in the filter matrix is a representative function of the sampling distribution around that pixel, representing a pixel of similar characteristics, or whether the pixel is not representative and is likely to be corrupted by speckle noise (Xiao, *et al*¸ 2003).

The Lee-Sigma filter is an adaptive filter that preserves the detail and removes noise from an image, based on the sigma probability of the Gaussian distribution of the noise. A series of 3x3, 5x5 and 7x7 Lee-Sigma filters were applied to the DTM. The results appeared similar for the filtered images (Figure 79) but the area as a whole appeared to have higher elevation values than the original DTM as represented by a lighter image. The elevation profile extracted across example peak and trough errors showed that the errors were suppressed with increasing filter size (Figure 80) and there was a progressive smoothing observed on the associated hillshade images (Figure 81). However, when the elevation values were compared with the original data it was evident that there was an increase of up to a few metres in filtered elevation (Figure 82).

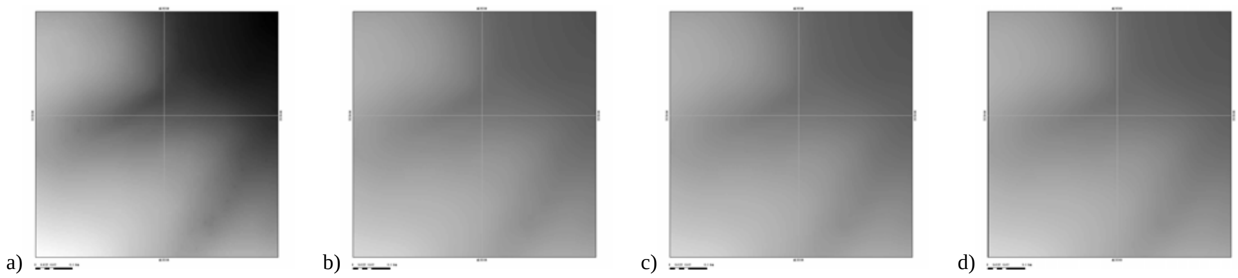


Figure 79: Comparison of a) the original DTM with results of the Lee-Sigma b) 3x3, c) 5x5 and d) 7x7 filtration

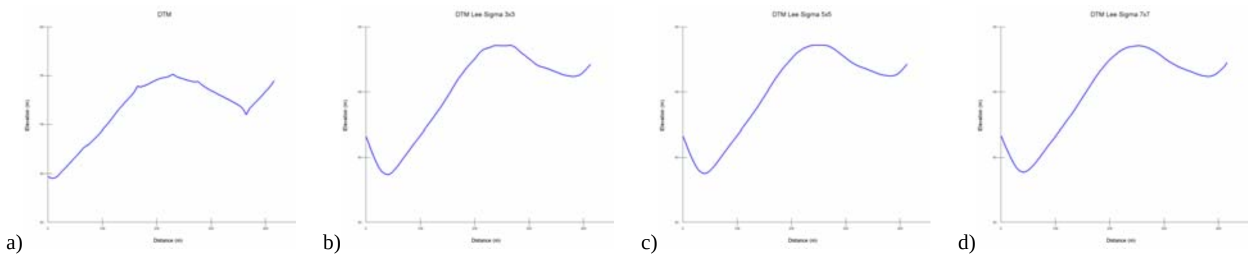


Figure 80: Elevation profiles extracted over a transect through trough and peak errors from a) the original DTM and results of the Lee-Sigma b) 3x3, c) 5x5 and d) 7x7 filtration

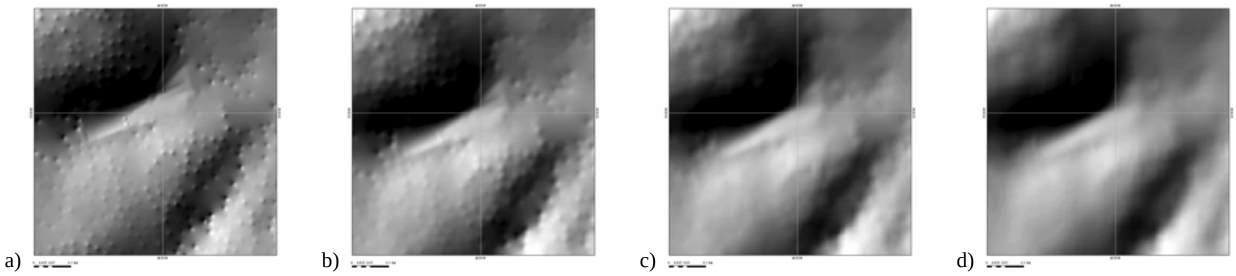


Figure 81: Hillshade images of a) the original DTM and on application of the Lee Sigma b) 3x3, c) 5x5 and d) 7x7 filtration showing gradual filtration of the errors

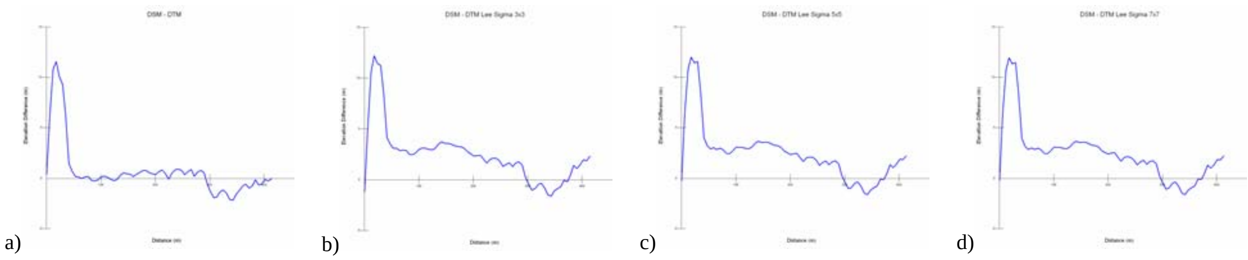


Figure 82: The difference in elevation between the DSM and a) the original DTM and the Lee-Sigma b) 3x3, c) 5x5 and d) 7x7 filtration

Fourier Transformation

A Fourier Transformation essentially breaks down a single band image into its scale components as sinusoidal waves of varying amplitudes, frequencies and directions, converting the normal spatial-domain representation of the image (x, y) into its frequency-domain representation. On the application of the Forward Fourier Transformation, the phase and amplitude components of the image data are determined where low-frequency noise would be expected to appear at the outer edges of the amplitude image and could be removed by running an Inverse Fourier Transformation, recombining the phase image with the amplitude image where the noise had been masked out. When the Forward Fourier Transformation was applied to the NEXTMap DTM, the amplitude image was incredibly complex with a more uniform frequency distribution than initially expected. This may have been due to the high frequency and wide spatial distribution of the peak and trough errors. Due to the time constraints of the study, removal of the noise from the amplitude image could not be performed and as a result the Fourier Transformation was not performed.

Glossary

BOGE	The BGS borehole geology database
CEH	Centre for Ecology and Hydrology http://www.ceh.ac.uk
DGSM	Digital Geoscience Spatial Model, a 5 year research project directed at methods and standards development for 3 dimensional modelling in BGS
DTM	Digital Terrain Model
GIS	Geographical Information System, holding georeferenced spatial data
GPR	Ground Penetrating Radar
IDA	Intranet Data Access – A BGS internal webpage giving form based access to BGS corporate databases
MIDAS	Mobile Integrated Data Acquisition System, developed by BGS to provide a capability for digital field data collection
NSRI	National Soil Resources Institute, part of Cranfield University (prev. Soil Survey of England and Wales) http://www.silsoe.cranfield.ac.uk/nsri/
SIGMA	System for Integrated Geoscience Mapping
SOBI	Single Onshore Borehole Index

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

Anon. 1990. Methods of test for soils for civil engineering purposes. Part 9, *In situ* tests. *British Standards Institution, London.*

Anon. 1990. Code of practice for site investigation. BS5930. *British Standards Institution, London.*

Atomic Energy Commission. United States Of America. 1972. In situ Ge(Li) and NaI(TI) gamma-ray spectrometry. *Health and safety laboratory publication, New York*. Report number: HASL-258.

BRITISH GEOLOGICAL SURVEY. 2007. *Regional geochemistry of Humber-Trent: stream water, stream sediment and soil.* British Geological Survey, Keyworth, Nottingham, NG12 5GG.

BROWN, G. M. 1981. *Hydrogeological map of the Northern East Midlands.* Cook, Hammond and Kell Ltd

CORWIN, D. L., AND LESCH, S. M. 2003. Application of Soil Electrical Conductivity to Precision Agriculture: Theory, Principles and Guidelines. *Agronomy Journal*, 95 (3), 455 – 471.

DEFRA 2004. *The first soil action plan for England 2004-2006. Department for the Environment, Food and Rural Affairs,* London, UK.

EDMUNDS, W. M., SMEDLEY, P. L. 2000. Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. *Applied Geochemistry*. 15. 737 – 752.

EDMUNDS, W. M., BATH, A. H., MILES, D. L. 1982. Hydrochemical evolution of the East Midlands Triassic sandstone aquifer, England. *Geochemica et Cosmochimica Acta*. 46. 2069 – 2081.

EMERY, C., DAVIS, J. R., HODGKINSON, E., JONES, D.G. 2006. Airborne and ground-based radiometric investigation of colliery spoil near Shirebrook, the English Midlands. *British Geological Survey* Internal Report IR/05/059. 60pp.

GRASTY, R L, HOLMAN, P B AND BLANCHARD, Y B. 1991. *Transportable calibration pads for ground and airborne gamma-ray spectrometers*. Geological Survey of Canada, 1991.

GRUNWALD, S. 2006. Three-dimensional Reconstruction and Scientific Visualisation of Soil-Landscapes. 373-392. In: Grunwald S. (ed.) *Environmental Soil-Landscape Modelling*, 488pp.

HINZE, C., SOBISCH, H-G & VOSS, H-H. 1999. Spatial modelling in Geology and its practical use. *Mathematische Geologie,* 4, pp. 51-60.

HODGSON, J.M. (1997). Soil Survey field handbook. *Soil Survey Technical Monograph No. 5*. NSRI, Silsoe.

HOBBS, P. R. N., HALLAM, J. R., FORSTER, A., ENTWISLE, D. C., JONES, L. D., CRIPPS, A. C., NORTHMORE, K. J., SELF, S. J., MEAKIN, J. L. 1998. Engineering geology of British rocks and soils. Mudstones of the Mercia Mudstone Group. *British Geological Survey* Technical Report, WN/98/4.

JOHNSON, C C 2005. 2005 G-BASE field procedures manual. *British Geological Survey* Internal Report Series, No.IR/05/097.

KESSLER, H. MATHERS, S J. SOBISCH, H-G. 2004. GSI3D - The software and methodology to build near-surface 3-D geological models. *British Geological Survey* Internal Report IR/04/029, 96pp.

KESSLER, H. MATHERS, S J. 2004. Maps to Models. *Geoscientist*, 14/10, pp. 4-6.

http://www.bgs.ac.uk/news/press/mapstomodels.html

KESSLER, H. et al. 2005. 3D geoscience models and their delivery to customers: In: Three-dimensional geologic mapping for groundwater applications, Workshop extended abstracts, Salt Lake City, Utah, 15 October 2005. Geological Survey of Canada, 2005. p. 39-42.

http://www.isgs.uiuc.edu/3DWorkshop/2005workshop/kessler2005.pdf

PALMER, R.C. 1982. Soils in Hereford and Worcester I: Sheet SO85 and 95 (Worcester). *Soil Survey Record No. 76.*

PALMER, R.C. 2006. The soils of Nottingham Trent University farm at Brackenhurst, Nottinghamshire. NSRI unpublished research report no. YE20006E for the British Geological Survey.

PEART, R J, CUSS R J, BEAMISH, D, JONES, D G. 2004. The High Resolution Airborne Resource and Environmental Survey- (Phase 1) (HiRES-1): background, data processing and dissemination and future prospects. British Geological Survey, IR/03/112.

SMEDLEY, P. L., BREWERTON, L. J. 1997. The natural (baseline) quality of groundwaters in England and Wales. Part 2: The Triassic Sherwood Sandstone of the East Midlands and South Yorkshire. British Geological Survey Technical Report WD/97/52.

SMITH, B, KESSLER, H, SCHEIB, A J, BROWN, S E.; PALMER, R.C.; KURAS, O.; SCHEIB, C. & JORDAN, C.J. 2006. Digital soil mapping and monitoring at a local scale: In: Second Global Workshop on Digital Soil Mapping for regions and countries with sparse soil data infrastructures [by Brazilian National Soil Research Centre. Rio : Brazilian National Soil Research Centre, 2006.

SOBISCH, H-G. 2000. Ein digitales raeumliches Modell des Quartaers der GK25 Blatt 3508 Nordhorn auf der Basis vernetzter Profilschnitte. Shaker Verlag, Aachen.

TROWSDALE, S. A., LERNER, D. N. 2003. Implications of flow patterns in the sandstone aquifer beneath the mature conurbations of Nottingham (UK) for source protection. *Quarterly Journal of Engineering Geology and Hydrogeology*. 36. 197 – 206.

XIAO, J., LI, J. & MOODY, A. 2003. A detail-preserving and flexible adaptive filter for speckle suppression in SAR imagery. International Journal of Remote Sensing. 24. 2451-2465.