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3-D Rock Mass Characterization in the Urban Environment

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BRITISH GEOLOGICAL SURVEY

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3-D Rock Mass Characterization in the Urban Environment

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3-D Rock Mass Characterization in the Urban Environment

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Introduction

The objectives of this project, one of three generic research sub-projects, of the **Urban Geosciences Programme** (UGP), were to establish

- *a methodology for the identification and collection of 3-D rock mass property data to enable subsequent 3-D modelling of the subsurface* in urban areas.
- *to provide clear guidance to current and future project managers and team members in urban areas on the key date types necessary for successful project outcomes.*

The driving force behind the project is the increasing importance to the BGS of multidisciplinary studies, particularly in urban areas, involving the use of computer-based modelling in 3-D, to produce a better understanding of the surface and subsurface geological framework of the UK landmass.

Urban areas – *'Geographically the programme will be constrained within the limits of the built and areas undergoing urbanization, the adjacent hinterland, including green belts and coastal and nearshore areas of the United Kingdom.'*
For the purposes of this report a working definition of the term **'rock mass'** is all strata underlying natural and artificial (man-made) superficial deposits (Northmore 2000).

The principal datasets relevant to the rock mass were considered to be *hydrogeological, lithological, mineralogical, geochemical, geotechnical, geophysical* and *structural.* In order make an assessment of data sources within each of these areas, the project team was selected to cover all of the specializations mentioned above. Further team members were added on the basis of their past and present involvement in multidisciplinary projects using some aspects of 3-D Modelling. Other BGS staff involved in 3-D Modelling projects within BGS, were also consulted to obtain their views on the likely future needs and direction of such work programmes. Individual reports, produced for this project, are referred to in the text and are held in files named as Appenices onv:eh/uggh/urban/3D Rock Mass/.

A further adjunct to the remit was to ensure that any recommendations defined by the project could be totally integrated within the developing BGS **Digital Geoscientific Spatial Model (DGSM).**

The report covers information about the modelling of the 3D rock mass, identified urban issues that the principal earth science datasets need to address, the potential data sources , and the lBGS datasets that are currently available.

Project team members:-

Project leader Graham Lott (BGS Keyworth)	*Geotechnical Characterization* Kevin Northmore (BGS Keyworth) Steve Rogers
Hydrogeological characterization John Bloomfield; Nick Robins (BGS Wallingford)	*Geochemical characterization* Dick Nicholson (BGS Keyworth)
Geophysical Log Characterization/IT Advisor Chris Evans (BGS Keyworth)	Applied Experience (NIREX) Steve Rogers (formerly BGS Keyworth)
Remote Sensing Stuart Marsh Colm Jordan (BGS Keyworth);	*DGSM compliance* Ian Smith (BGS Keyworth)
Geophysics methodology John Busby (BGS Keyworth)	*Others consulted* H. Johnson, M. Akhurst, A. McMillan (BGS Edinburgh) M. Shaw, S. Dumpleton, G. Kirby , B. Hatton, D. Bridge, A. Humpage, T.R. Lister, Robert Cuss (BGS Keyworth)

1. Information Technology - 3-D 'modelling practice' in the BGS

Currently the concept of **'3-D Modelling'** within the BGS is not clearly defined. It appears to *mean different things to different people* and therefore to take a number of forms. Projects described as having a 3-D Modelling component so far completed in the BGS, have had widely different objectives and have consequently been carried out using a range of different software/hardware packages. This is simply because each of the packages currently available in BGS only appears to offer the power and flexibility to deal with one type of data e.g. seismic profiles (*Landmark*), mineralogical modelling data (*Vulcan*), subsurface contouring (*Earthvision*).

All of the packages are flexible enough to use 're-constituted' data subsets derived from SQL queries on BGS's *Oracle* tables; new datasets held in *Access;* or *Excel* spreadsheets, .csv files etc. without significant problems. Current software packages, however, cannot as yet draw data directly from the existing BGS main datasets held in *Oracle*, however, new software packages do offer this option.

In order to focus on the types of data required for the any future 3-D geological modelling projects it was considered necessary to undertake a brief review of the current status of such work within the BGS.

1.1 GIS (Arcview and Map Info) 2-D-Modelling/Visualization

The BGS, as part of its developing GIS capabilities, now has strong credentials in the presentation of its geological datasets in 2-D form.. The Geographic Information Systems (GIS) developed in the last 10yrs, already in widespread use within the BGS, were initially designed to **manage** and **present** or **visualize** spatial data in two dimensions. This has proved highly successful and BGS geological data can be displayed as on-screen digital maps, principally as points, lines or polygons, from ground level outcrops into the deep sub-surface.

In order to accomplish this the attached data table requires each data point to be geo-referenced by the provision of an **x y** location. The data routinely acquired by the BGS, for the UK area in particular, is perfectly suited to incorporation into such 2-D digital systems as all such data points are located using the **British National Grid** co-ordinates system onshore, and a **UTM Grid** for the offshore area. The only serious problem that has arisen is in the merging of data from the two areas to provide a seamless database. This is because each co-ordinate system has developed historically using different map projections. 2-D GIS software packages such as ***Arcview*** and ***Map Info*** allow moderately sophisticated contouring of a surface between data points, providing a good density of data are available. However, they are not yet powerful enough to produce, for example the highly effective **shaded relief** maps commonly used by BGS (BGS-developed COLMAP software) to display gravity and magnetics data, in pseudo 3-D relief, without recourse to other more powerful software gridding packages e.g. ***Earthvision.***

1.2 3-D Modelling - software packages

- *Vertical Mapper (MapInfo)* (e.g. Locus Project; Permo-Triassic Project, Bridge *et al* 1999) In projects of this type, data are reconstituted in Excel Spreadsheets for import into MapInfo and then contoured in the Vertical Mapper (or Earthvision) add-in. This produces a 'first pass' visualization of surfaces rather than a true 3-D Model.
- *Earthvision, Vulcan, Landmark and GoCad* – More sophisticated packages currently still being evaluated principally include these three software/hardware systems. GoCad -BGS has only undertaken preliminary investigations of this relatively new software package. Projects that have been completed using Vulcan are listed in Table 1 below.

1. 3-dimensional modelling of the Foss Barite Orebody, Scotland. DTI Technology Access project Norton, J. & Colman T. 1999
2. An evaluation of the Letham Opencast Coal prospect – Midland Valley of Scotland (Commercial in Confidence)
3. The combined use of PIMA and VULCAN technology for mineral deposit evaluation based of their application to the Parys Mountain Mine, Anglesey. DTI Technology Access Project.
4. An evaluation of the Ishim River gold prospect – Northern Kazakhstan (Commercial in Confidence)
5. Structural modelling of the Base of Crag and Top of Chalk surfaces – Woodbridge and Felixstowe sheet remapping.
6. Simple structural modelling of the 'Watford' borehole data, Crediton Trough for Crediton Minerals plc (Commercial in Confidence)
7. Mineral Resources and International Nature Conservation designations in Dorset – 3-D modelling of the main ball clay surfaces of the county
8. Melton Mowbray sheet remapping – structural contouring several geological units and rockhead over two standards mapped by myself.
9. Modelling of the Clontibret and Cononish gold prospects for the E.C.-funded CRAFT ORE_SHOOTS project.
10. The South Downs aquifer – visualization and modelling Jones, H. Dance, L. and Dumpleton, S.

Table 1. Use of Vulcan in BGS projects

A review of 3-D modelling in geology can be seen at http://intranet/3-D/integrate/isevframes.htm

- *3-D Simulation modelling - mathematical modelling* –(v:/eh/uggh/urban/3D Rock Mass/Appendix 1)

The basis of simulation modelling is to build a realisation or representation of a phenomenon that is not real, yet possesses the same spatial properties as the real process. This enables complex environments to be modelled that allow a range of scenarios to be applied in order to optimise the solution. A common example of simulation is used in the oil industry where the complexity and heterogeneity of the hydrocarbon reservoir is simulated, allowing a number of technical options such as future well sites, pumping levels etc to be tested against the simulated reservoir.

There is little doubt that BGS has a requirement for all of these different 3-D systems and should continue to investigate their use and support them until such time as they are superseded by the **DGSM** .

3D Modelling is an area that will need considerable commitment and support, both financial and in the form of sufficient suitably trained staff, if the BGS is to achieve its aims in this area, particularly with regard to the DGSM.

2. 3-D Rock Mass Characterization – urban issues

3-D Rock Mass Characterization may be defined as *"the graphical characterization of three-dimensionally defined geological units in terms of their physical, mechanical and chemical properties."* Even the most sophisticated and powerful modelling packages now being used, however, are very selective in the types of data that they can manipulate and even then still require a massive simplification of the datasets available. Such characterization of the rock mass in 3-D is intended to take the 2-D graphical visualization of BGS 'surfaces' data a significant step forward by introducing a third dimension to the datasets. Visualization and manipulation of the data in 3-D, it is envisaged, should substantially improve scientific understanding of geological problems.

In order to understand which data types would be of most use in characterizing the subsurface rock mass in UK urban areas, it was first necessary to determine which geologically related issues most commonly occur in such areas. Members of the project team contributed a list of known problems within their own areas of *expertise (lithological, mineralogical hydrogeological, geochemical, geophysical, geotechnical and structural)* which are presented in the following sections.

2.1 Hydrogeological issues in urban areas – (v:/eh/uggh/urban/3D Rock Mass/Appendix 2)

In urban areas where abstraction of groundwater is of great importance, and therefore most evident, both the quality and quantity of the water available is under threat from a wide variety of sources. Most of these threats are ***anthropogenic*** and may lie both within and outside the urban development area.

*2.1.1 Groundwater **quantity** is threatened by*

- rising groundwater levels resulting from declining industrial demands creates major problems for underground structures with significant cost implications.
- seasonal changes in demand, particularly in tourist dependent areas - these require the management of groundwater abstraction
- to maintain low flow streams, rivers and wetland areas
- to minimise saline intrusion
- to provide a sustainable resource for the future
- to assess the impact of global climatic change on future water resources – sea level rise

*2.1.2 Groundwater **quality** is threatened by contamination from*

- groundwater rebound in abandoned mines - Acid Mine Drainage (AMD)
- rising ground waters in former brownfield sites contaminated by industrial spoil heaps
- unmonitored landfill sites - historic
- redevelopment of former brown-field sites – historic contamination from non-aqueous phase liquids (NAPL's - dense (DNAPL's) and light (LNAPL's) varieties) and heavy metals
- saline intrusion by over abstraction

2.2 Geochemical issues – (v:/eh/uggh/urban/3D Rock Mass/Appendix 3)

Principally man-made contamination

2.2.1 Pollutants from industrial wastes including:-

- aluminium smelting, blast furnace slag, brick, glass and china clay works, coal burning, electroplating, fertiliser production, fluorspar processing, metal and coal mining, non-ferrous metal production, pulverized fuel ash (PFA), quarry wastes, town gas manufacture etc.

2.2.2 Inorganic pollutants

- natural pollutants – radon, potentially harmful element (PHE's) concentrations associated with particular rock groups e.g. As, Cd, Cu, Pb and Zn
- landfill and other leachates
- inorganics *metals and metalloids* (Ar, Cd, Cr, Cu, Fl, Pb, Hg, Ni, Zn) acids and alkalis from spoil heaps *non-metals* – nitrates, boron, cyanide, fluoride and sulphur

2.2.3 Organic pollutants

- natural - methane, carbon dioxide and oil seeps
- anthropogenic:-hydrocarbon spillage from fuels, lubricants chemical feedstocks

chlorinated hydrocarbons – PCB's, pesticides, phenols, industrial solvents/degreasants

2.3 *Geophysical issues* (v:/eh/uggh/urban/3D Rock Mass/Appendix 4)

Geophysical methods are applied routinely in many earth science investigations where the remotely sensed data add greatly to the direct data obtained from mapping and boreholes. Instrument and interpretation advances have also lead to new applications for geophysics in monitoring changes with time. However, many traditional geophysical techniques have been difficult to apply in the urban setting, particularly in highly built-up areas.

2.3.1 Geophysical methodologies

Geophysical methods use physical fields that are either natural or are generated by a transmitter. When mapping the geology, the alterations to these physical fields (termed anomalies) generated by changes in the geology are usually small. It is therefore important that other sources of anomalies, particularly those due to man made sources do not interfere with those due to the geology. For this to be the case they must be either smaller or at a distinctly different frequency so that their effect can be removed. In some cases the target is not the geology, but the man made source of the anomaly. Examples are locating buried pipes or electrical cables and mapping metallic waste within landfill sites.

Some geophysical methods, notably **magnetic** (anomalies in the Earth's natural magnetic field) and **electromagnetic** - **EM** (secondary magnetic anomalies generated by any electrically conductive object) techniques can be difficult to apply in the urban environment because of interference from ferromagnetic sources including vehicles, buildings, fences, street signs, cables etc open areas. Electrical cables generate large secondary EM fields. **Direct Current Resistivity (DCR)** methods, which require electrical (galvanic) contact with the ground usually via a metallic stake, are obviously hampered by asphalt, concrete etc coverings.

However, developments in equipment design and methodologies have produced other geophysical techniques that are relatively successful in built-up urban settings. These include

- *Ground penetrating radar* (GPR) – an EM technique which can operate through asphalt and concrete with a depth range of 2-20m
- *Microgravity* – measurement of changes in the earth's gravitational field to detect near surface lateral density changes. The technique is particularly useful for the detection of cavities and sub-vertical faults where rock units of contrasting density are juxtaposed
- *Capacity coupled resistivity* – can be used in areas where galvanic contact with the ground cannot be made. An array of sensors can be towed over the ground enabling a profile of the subsurface resistivity to be acquired.
- *Seismic methods* – these techniques have been traditionally difficult to apply in urban areas because of vibration interference to the seismic signals and also because of impulsive seismic sources, such as weight drops or sledgehammers, which cause obvious damage to coated surfaces. However, a new portable vibrator system can now be used as a source in high frequency seismic reflection surveys and which can independently discriminate noise from signal using an energy density low enough to avoid destructive damage (Ghose et al. 1998).

2.4 Geotechnical issues – natural and anthropogenic (McMillan et al, 2001; v:/eh/uggh/urban/3D Rock Mass/Appendix 5*)*

Urban areas are subject to intensive development including the construction of buildings and their associated infrastructure of roads, rail links and general services.

2.4.1 'Rockhead' the soil/rock interface - the validity and definition of the term

- depth and nature of 'engineering rockhead' surface (soil/ rock interface) *
- depth and nature of 'geological rockhead' surface (presence of glacial channels, pits etc)
- depth and nature of weathered surface
- clay heave

2.4.2 Surface and subsurface stability

Ground stability is affected by:-

- faults, joints and fractures
- natural cavities
- mine workings
- made ground

* Currently enquiries to the BGS, in most major urban areas, are principally concerned with supplying geological information for the near surface succession (<50m depth). Defining the term **rockhead** is therefore a fundamental concern for modelling of the rock mass in the subsurface. There is no clear agreement within the geological world in general for a single definition of this term. Each area of expertise tends to favour its own definition.

- geological mappers take the boundary between unconsolidated superficial sediments and bedrock as rockhead
- rockhead in the unconsolidated successions e.g. London basins is pragmatically taken at the geological boundary between the Quaternary and Tertiary sequences.
- engineering geologists are more concerned with the boundary between weathered (weakly consolidated) 'engineering soil' and unweathered (indurated) rock surface
- ? of what relevance is the term rockhead to the hydrogeologist?
- should we accept one of these existing terms, redefine rock head or coin a new term and avoid more confusion?

3. Potential data sources for urban areas

3.1 Digital Elevation Models (DEM) – (McMillan et al, 2001; v:/eh/uggh/urban/3D Rock Mass/Appendix 6*)*

Essential to the development of subsurface models in the BGS is an acceptable, corporate **DEM** of ground surface i.e. its precise location in vertical space. This is because:-

- BGS must project its 2-D digital geological maps into 3-D, by draping them onto a DEM to review the linework
- when creating a subsurface contour map it is essential to know the elevation of the upper surface where drilling (or auguring) was initiated.

Three alternatives appear to be available to the BGS with regard to obtaining a DEM

- development in-house of a DEM from available OS topographic data

- development of DEM in-house by digital photogrammetric techniques – do we have sufficient relevant expertise?
- purchase from a third party – currently this seems to be the most cost effective approach and a variety of sources are available and are being investigated.

3.2 Digmap coverage

Completion of the digital geological line coverage and attribution for both the onshore and offshore areas is an essential requirement for future subsurface mapping and 3-D digital modelling projects.
1:250K complete
1:50K *to be completed 2001*
1:10K *underway*

3.2 Stratigraphic databases

A fundamental requirement for geological modelling in the subsurface of the UK is the development of a framework of geo-referenced (**xy & z** co-ordinates) stratigraphic data points. Currently, such subsurface stratigraphic data are held in a variety of largely unrelated project-based databases across the BGS. Most were developed for single projects and then insufficiently resourced to be maintained after the end of the project. There appears to be no clearly defined route for absorbing these isolated datasets into BGS's main digital data archive. Such databases are often stratigraphically restricted in the range of data they contain. In contrast the BGS deep geology *Stratigraphic Database* is far and away the most accessible and effective source of subsurface geological data, at present containing location data for 13592 onshore and offshore wells and 34,353 comprehensive stratigraphic entries for 7038 selected wells.
The BGS needs to prioritise funding for the databasing of subsurface stratigraphic data abstracted from existing borehole records to provide the geological framework for further progress in 3-D modelling

3.4. Geological and geologically related datasets (Solid Geology)

Underpinning the following sections is the need for the BGS to provide corporate guidance and regular training to scientific staff in general, on the accurate and consistent recording of different data types from outcrop, excavations, boreholes and the subsurface in general. Corporate guidelines showing the methodologies necessary for the collection of all types of data need to be devised (where necessary), introduced, formalised, kept up-to-date and **widely circulated** to all scientific staff.

3.4. 1 Data collection in the field

Very little, if any of the geological or geologically-related data currently collected by BGS field workers is routinely data-based either in the field or back at the office. An exception is the **G-Base** programme that already routinely uses laptops for data entry in the field. At present the only digital data input of geological field data taking place is the recording of page header location data in the *Field Notebook Index* database. Geological and related data are recorded in field notebooks subjectively and in a free text format and not currently databased.

The range of information available for a given field site may be extensive for example:

- lithological descriptions – BGS recommended rock classification reports are now available for *Igneous* Research Report 99-06, *Sedimentary* RR 99-03 and *Metamorphic* RR 99-02 rock types – http://kwnts10.nkw.ac.uk/reports/rcs.htm
- mineralogical descriptions – framework and accessory mineralogy, cementation, clay types, reactive or soluble minerals
- mineral deposits – mines, ore bodies, quarries, pits
- biostratigraphical data – macrofossil occurrences etc
- fluid content or flow data – natural springs, water table levels, hydrocarbon etc
- geochemical analytical data
- environmental pollutants
- porosity/permeability data – primary intergranular, secondary dissolution - cavities, vugs etc
- geotechnical data – *see section 3.4 and* v:/eh/uggh/urban/3D Rock Mass/Appendix 5
- natural radioactivity levels
- made ground, subsidence indicators etc
- interpretative datasets may be important for some 3-D modelling projects e.g. sedimentary environment/facies classification schemes (see Holmes *et al* 2000b)

It should be noted that outside the field mapping staff there is no general requirement for BGS staff to record field data, other than locational data, in a standardized format.

There is no BGS-wide issue of the standard 'field mappers notebook', the format of which includes some guidance as to classification schemes and was at least in part designed with a view to future databasing and archiving requirements.

There are no corporate written guidelines on how or what parameters should be recorded from an outcrop or borehole site or even when logging a borehole core or describing a rock/sediment sample.

For example grain-size analysis is carried out in several parts of the BGS but no recommended corporate classification scheme for such work is in place. Also there are no guidelines prioritizing the types of data that should be collected at any site, urban or otherwise.

3.5 Geotechnical data (v:/eh/uggh/urban/3D Rock Mass/Appendix 5)

Standard descriptive schemes and terminology for the descriptions of rocks and soils are given in **BS5930:1999** ***(Code of practice for site investigations)*** which is *the* standard and which must be followed for all engineering site investigation work *in the commercial arena*. The descriptive methodology presented in BS5930 enables the *material* and *mass* characteristics to be fully described. For rocks, *strength, weathering effects* and *discontinuities* are particularly important characteristics governing engineering properties and mass behaviour. The BS5930 descriptive scheme pays much more attention to these characteristics than is generally done in 'normal' geological descriptions. The quality of the observed sample or exposure is reflected in the level of detail in the description. Therefore, it is useful to note what the description is based on (e.g. core, natural outcrop, excavation) and to additionally note any doubts as to how representative or reliable the description might be etc.

Geotechnical parameters normally recorded should include:-

- weathering characteristics
- particle size analysis
- rock density,
- discontinuities - bedding planes, joints and faults – size, spacing orientation, aperture, connectivity, RQD value,
- porosity,
- permeability
- saturation/pore pressure measurements,
- a measure of rock strength (UCS, Schmidt hammer. point load),
- elastic and shear moduli,
- in situ stress
- sulphate test

It should be clearly stated whether this BS code is the corporate standard in BGS for recording geotechnical parameters of the rock mass.

3.6 Hydrogeological data

The collection of hydrochemical and physical property data for the minor and major aquifers of England and Wales is already well established at BGS Wallingford. The following parameters are routinely recorded where possible.

3.6.1 Hydrogeochemical characteristics

- Baseline pore water chemistry
- Mineralogy and rock chemistry
- Gas chemistry in unsaturated zone
- Hydrogeochemical and microbiological controls on contaminant attenuation

3.6.2 Physical properties

- 3-D distribution of groundwater head
- Transmissivity or hydraulic conductivity in 3-D
- Storage coefficient
- Specific yield
- Matrix permeability and bulk porosity distributions
- Matrix pore-throat size distribution
- Matrix diffusion coefficient

The form and areal extent of the ***Wellmaster/Aquifer Properties*** databases are summarised in two recently published reports by Allen *et al.* 1997 and Jones *et al* 2000.

3.7 Geochemical data

The collection of either **organic** or **inorganic** geochemical data for a given area is usually governed by the demands of the project. However, there are some basic geochemical analyses that should be carried out as a minimum requirement for any site visited. Such analyses will provide essential background data in order to assess whether further more detailed study is required and where the focus (organic or inorganic) of such extra work should take place. Guidelines for standardizing the collection and analysis of **rock samples** were proposed in Haslam & Plant, 1990. Guidelines for the collection of **soil samples** for geochemical analysis in urban areas are given in Flight *et al*, 1998.

When assessing a 'new' site, use of some simple tests are usually necessary to gain basic information on soil chemistry. Soil colour is important, as are soil pH and organic content. The colour of a soil is usually observed as soon as possible after taking a sample and soil pH can be carried out either in the field or in a field laboratory.

The mobility of trace elements is often governed by the amount of organic component, and whilst this is best quantified by measuring the **total organic carbon (TOC)** content, a determination of **loss on ignition** at $450^{o}C$ will often suffice. This method has limitations but is routinely employed by geochemists on the Urban G-Base Programme. The TOC content may also help to indicate contamination by organic species such as hydrocarbons.

More detailed analysis is carried out in the laboratory by techniques such as **X-ray Fluorescence Spectrometry (XRF)**, which is used to determination the **major** and **trace** elements content of solid geological materials. Namely MgO, P_2O_5, K_2O, CaO, TiO_2, MnO, Fe_2O_3, V, Cr, Co, Ba, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Pb, Bi, Th, U, Ag, Cd, Sn, Sb, Cs, La and Ce. The technique is relatively rapid, does not require samples to be dissolved, and analytical detection limits less than 1ppm for many elements are achievable using modern instrumentation.

The determination of **organic** species is more complex, and usually requires the organic component to be extracted using a suitable solvent prior to determination by chromatography.

Provision of in-house standards and guidance to project managers and teams on the organic and inorganic geochemical parameters are needed to deal with the wide range of problems identified in *Section 2.2* above.

3.8 Geophysical data

Geophysical techniques that may be of importance in urban areas include downhole Geophysical Log suites and Electro-Magnetic, Resistivity, Seismic and Gravity surveys (see *section 2.3.1* and v:/eh/uggh/urban/3D Rock Mass/Appendix 4)

3.8.1 Wireline logs data

A typical generic log suite should include the following logs to provide maximum information on both rock and fluid properties

- Gamma Ray – natural radioactivity, lithological determinations
- Caliper – hole conditions, validity of tool response
- Sonic – seismic calibration, lithological determination

- Resistivity/conductivity (Shallow, Deep, Microresistivity) - rock fluid evaluation
- Formation Microscanner/Micro-imager (FMS/FMI)– local and regional structural data, fractures, faults
- Neutron – fluid evaluation, porosity/permeability
- Density – bulk density rock and fluids
- Spontaneous Potential - formation water resistivity
- Temperature log – hole and formation conditions (mud measurement)
- Geochemical Logging – formation evaluation
- Nuclear Magnetic Resonance (NMR) – permeabilty measurement

This suite would need modification depending on the objectives of the project. Calibration of such logs to aid interpretation of their responses is an area where BGS stratigraphic datasets are invaluable.

Image logs such as the *Borehole Televiewer*, *Formation Microscanner* and the *Makivision - Downhole Video Camera* for assessing for example discontinuities / fractures in chalk aquifers, are becoming increasingly important in evaluating some rock formations.

3.8.3 Geophysical surveys (v:/eh/uggh/urban/3D Rock Mass/Appendix 4),

These techniques can provide surface and shallow subsurface information on a number of themes.

- *Microgravity* – recognition of cavities (within the top 10m), faults, areas of made ground, areas of subsidence and landslips
- *Ground Penetrating Radar* (GPR)- mapping of lithostratigraphic boundaries, fractures, made ground, foundations etc: Water table levels
- *Seismic* – velocity calibration with rock lithology
- *Capacity Coupled Resistivity* (CCR)– cavities, made ground, faults, water quality

The BGS has an in-house capability for EM work and is currently bidding to purchase Microgravity equipment. The CCR technique is currently under development by BGS. Seismic data acquisition is not an area in which BGS has an in-house capability and in general expertise and equipment would need to be hired-in.

3.8.3 Deep Seismic, etc

- Refraction seismic data is digitally available for both the UK area.
  BGS is the designated holder of the *British Coal* seismic collection for UK onshore area.
  Lynx Information Systems Ltd hold UK onshore seismic datasets http://www.lynxinfo.co.uk/
- Gravity and magnetics airborne survey data for the whole of the UK (onshore) are held by BGS

3.8.4. High Resolution Airborne Survey data

- High Resolution airborne surveys in which radiometric and electromagnetic data are recorded have been flown over a number of test sites, including some urban areas, sites in the UK e.g. Newbury. However, the full potential of the system needs further evaluation, particularly for larger urban developments, to assess the affects of the 'noise' from the built environment on the survey data.

3.9 Structural data

The standardisation of the collection and storage in digital form of structural geological data (dip/plunge, strike/azimuth etc) has been recently addressed by Holmes *et al* (2000) who have proposed a corporate data model for BGS. They recognise 4 structural data classes that should be recorded:

- point observations (**xy** and **z** located where possible)
- planar structures- bedding, joint planes, veins etc
- linear structures – glacial striae, fold axes, ripple marks, structural lineaments etc
- composite data – referring to larger structures inferred from other data sources fold and fault types

3.10 Remotely Sensed Imagery - (v:/eh/uggh/urban/3D Rock Mass/Appendix 6)

3.10.1 Aerial photographs & Landsat Thematic Mapping (TM)

The BGS has long used high resolution aerial photographs to facilitate its mapping programmes. Such photographic coverage, available in the UK since the 1930's will remain an important historic resource for comparative studies in developing urban areas. Currently, however, the advantages of using the ever improving higher ground resolution achievable using the infrared techniques of Landsat Satellite Imagery make them an essential part of any future Urban Mapping programme. The European Commission project CORINE, as far back as 1985, successfully interpreted such data to recognise the following themes in urban areas

3.10.2 Urban fabric

- Continuous urban fabric
- Discontinuous urban fabric

3.10.3 Industrial commercial and transport units

- Industrial or commercial units
- Road and rail networks and associated land
- Port areas
- Airports

3.10.4 Mine, dump and construction sites

- Mineral extraction sites
- Dump sites
- Construction sites

3.10.5 Artificial, non-agricultural vegetated areas

- Green urban areas
- Sport and leisure facilities.

Currently high spatial resolution commercial satellites (e.g. IKONOS) offer stereoscopic imagery to 1 metre resolution, at a significant price, for the whole of the UK.

4. In-house corporate digital datasets

For urban areas two aspects of in-house data sources are important. *'A major problem currently being faced by the BGS through its GEOIDS project is locating and accessing its datasets because BGS holds a vast wealth of data. Much of the information is difficult to access as it is neither effectively catalogued nor curated, and it is in diverse formats, ranging from hand written archives to digital maps. BGS staff spend considerable periods locating and processing data. Staff and (worse) external customers may never be aware that potentially relevant data exist.'*

BGS-GEOIDS – http//kwnts10.nkw.ac.uk/geoids/docs/BGS-geoIDS.doc

The BGS-GEOIDS project is currently developing, among other items, a particularly relevant facility the **Discovery Metadata Search Page** (accessible via the BGS Intranet) that assists users in identifying what data are available for a current area using a *keyword* and *locational* search system.

The data acquired by the BGS ranges from on-going, Science Budget regional surveys, acquisitions in response to legislative demands, commercial commissions, voluntary private sector donations and opportunistic acquisitions. Continued careful validation of data quality in all, but particularly older, datasets is essential and particularly relevant for example to Geochemical Data where sampling, preparation and analytical techniques have changed substantially over the years.

There is considerable overlap in the data requirements for some of the existing BGS databases e.g. Borehole location and stratigraphic surfaces data are held in several different local or project-linked databases. It is essential, for example, that the current project to rationalise borehole locational data throughout the BGS is funded to completion to avoid inconsistencies and duplication of effort.

4.1 Geological

- *stratigraphic*

BGS Rock Lexicon http://kwnts10.nkw.ac.uk/lexicon/lexquery.htm	**BGS Keyworth** Lithostratigraphic datasets
BGS Rock Lexicon http://kwnts10.nkw.ac.uk/lexicon/lexquery.htm	**BGS Keyworth** Chronostratigraphic datasets
Biostratigraphic data	**BGS Keyworth** Digital data only on collecting site locations. Hardcopy reports and project-based digital datasets only – no index currently available.
BGS Biostratigraphic Collections Database	**BGS Keyworth** (under development) Macrofossil and microfossil stratigraphic collections – onshore and offshore UK

Stratigraphic Surface Database	**BGS Keyworth** Contains onshore and offshore downhole stratigraphic well data (underway)

- *borehole datasets*
  A current, on-going priority for BGS is the merging of the varied datasets that contain borehole location data in order to define a unique reference number for each borehole site.

Borehole/well location databases for review see Rowley 2000 @ http://kwnts10.nkw.ac.uk/info_services/info_mangmt/ubi/design.htm	**BGS Keyworth** SOBI (onshore). Wellmaster (Wallingford). DEAL (Digital Energy Atlas & Library) website – *currently holding only offshore data but likely to include onshore data in near future.* http://www.ukdeal.co.uk BGS Offshore Samples. Scottish Groundwater.
Borehole core and sample data	**BGS Keyworth and Edinburgh** All borehole and sample data held by BGS.

- *mineralogical datasets* – the BGS does not routinely assess the mineralogy of rock units on a stratigraphic basis either in the surface outcrops or in subsurface units. For example, we cannot provide even a basic summary of the likely regional mineralogical variations in the Sherwood Sandstone Group for the whole of the UK without considerable staff effort. This could become a much more serious omission if advances in remotely sensed geological techniques continue where calibration or ground-truthing of outcrop data is required.

BRITPITS	**BGS Keyworth** Industrial Minerals database (locational data for UK mineral extraction sites, active and historic quarries , mines and pits only)
BRITROCKS	**BGS Keyworth** Mineralgical/Petrological database. Locational data and basic descriptive fields for hand specimen and thin section collections.
Mineralogical analyses	**BGS Keyworth** Hardcopy report and project-

	based digital datasets only e.g NIREX, Moroccan Project etc
BGS Petrological analyses	**BGS Keyworth and Edinburgh** Hardcopy reports and project-based datasets only e.g. Morocco. No index currently available.
British Coal petrological dataset	**BGS Keyworth** UK coal and associated lithologies as rock thin sections - cataloguing underway

regional mapping datasets **DigMap**	**BGS Keyworth** 1:10K; 1:50K; 1:250K 1:625K geological mapping and associated structure contour, isopach, isochron maps etc
BGS Applied Geological Mapping Projects completed Aberdeen Airdrie - Coatbridge Aldridge-Brownhills Bathgate Black Country Bournemouth-Poole Bradford Bridgend Brierley Hill, Dudley Bristol Chacewater, Cornwall Coventry Cramlington-Killingworth Crosby-Bootle-Aintree Dearham and Gilcrux, West Cumbria Deeside Dunfermaline - Fife Edinburgh SE Exeter Fareham & Havant Falkirk-Grangemouth Fife-Cowdenbeath Fife-Kirkcaldy Garforth-Castleford-Pontefract Glasgow Glenrothes Great Broughton-Lamplugh, Cumbria Greenock Hamilton Hamilton-Wishaw Leeds Livingston Motherwell Morpeth-Bedlington-Ashington Newcastle Nottingham Peterhead Plymouth Ponteland-Morpeth SevernLevels	**BGS** **Monro, S.K. and Hull, J.H.** **BGS Keyworth (see Smith & Ellison 1996)** Thematic mapping showing Data points Ground significantly affected by human activities. Thematic maps: Drift (Superficial) Geology (Solid (Bedrock) Geology. Engineering geology Geomorphology/Topography Constraints on land use – stability, industrial use etc Resources – Industrial minerals + hydrogeology **BGS Edinburgh (Browne etal. 1986)**

Southampton South East Leeds South Humberside South West Essex St Helens Stoke-on-Trent Torbay West Wiltshire and South East Avon Wigan Wishaw Workington and Maryport Wrexham	

- miscellaneous datasets

British Coal	**BGS Keyworth** **NGDC** Main dataset now held by BGS on behalf of the **Coal Authority** (mine shaft, mine plans, borehole and stratigraphic data)
Site Investigation datasets etc	**BGS Keyworth** **NGDC** assorted hardcopy datasets e.g.
BGS Mineral Resource Surveys (Harris 1995) (current and historic datsets)	including:- Sand and Gravel Limestone Dolomite Sandstone Ironstone Ganister Aggregates Building Stone Brick Clay Metamorphic slate Gypsum etc

4.2 Hydrogeological

- groundwater related datasets –

WELLMASTER	**BGS Wallingford** SOBI equivalent for hydrogeological well data – largely locational datasets
Aquifer Properties Database: Major and minor aquifers	**BGS Wallingford and Edinburgh** contains data on:-

	rock porosity rock permeability pumping test data core analysis data anisotropy diffusivity diffusion co-efficient dispersion engineering geology parameters unsaturated flow parameters

4.3 Geotechnical

There is an increasing need for characteristic values, or ranges of characteristic values, for UK rock and soil formations e.g. strength, deformation etc to be readily available to the civil engineering community. Such data are generally an essential prerequisite before any surface excavation is carried out. BGS is in a unique position to provide this information for many urban areas in the UK. To date, geotechnical data held in this database are largely restricted at present to those pertaining to the *Gault Clay*, *Mercia Mudstone Group*, the *Lambeth Group* and south-east Essex deposits. Other geotechnical datasets relating to the 'thematic mapping' projects of south-west Essex, Stoke, Wrexham, Leeds etc (see listing above) are also accessible (although created in an earlier database structure). With the exception of the 'thematic databases', relatively little data on superficial deposits are currently held in the geotechnical database as priority consideration is given to inputting data relevant to the particular 'solid' formations earmarked for study under the 'Engineering Geology of UK Rocks & Soils project'. This problem needs to be addressed, perhaps, for example, by a parallel urban geotechnical databasing programme.

An industry standard for the collection of geotechnical data in digital form already exists and set up by the **Association of Geotechnical and Geo-environmental Specialists (AGS).** Digital data in AGS format is already being acquired by the BGS. It is essential that BGS's urban geotechnical database, which is currently being developed and populated, is compatible with the digital AGS format.

Geotechnical Rock Properties database	**BGS Keyworth** active - under development

4.4 Geochemical

G-BASE **REGIONAL BASELINE DATA** – stream sampling **URBAN BASELINE DATA** - systematic sampling of urban areas based on the collection of surface and profile samples at 4 samples per square kilometre.	**BGS Keyworth** mineral exploration surveys – *stream data* (Colman & Cooper 2000) – UK-wide coverage (ongoing for Central and Southern England) *Urban areas* already covered:- Cardiff Corby

	Coventry (underway) Derby Doncaster Hull Leicester Lincoln Mansfield Northampton (underway) Nottingham Peterborough Sheffield Scunthorpe Stoke on Trent Swansea Telford Wolverhampton York
Rock Geochemistry database	**BGS Keyworth** Limited subsurface data for all rock groups (Haslam & Plant 1990). Other data project-based hardcopy.
Geochemical analytical results	**BGS Keyworth** Not routinely data-based centrally in the past. Project-based datasets only

4.5 Geophysical

WELLOG (WELLOG #3 under development)	**BGS Keyworth** Digital geophysical log suites – onshore and offshore. Mixture of BGS and Commercial data
SEISMIC NETWORK and MAGNETIC DATA	**BGS Edinburgh** Seismic (earthquake), gravity and geomagnetic data
HiRES-1	14000 sq. km of the Midlands area Some smaller project –based datasets e.g. Newbury
Geophysical surveys (EM, CCR etc)	Some project based and development survey data

4.6 *Structural*

STRUCTURAL DATABASE	**BGS Edinburgh** proposed only (Holmes *et al.* 2000)

5. External datasets

Extensive datasets may be available from other organisations e.g. DTI, British Coal/Coal Authority. BGS should continue to actively monitor the situation and be ready to act decisively to acquire such new data.
5.1 Potential data sources include:

- Government departments
  DTI
  DETR
  other **NERC** and Research Council component bodies
  EA Environment Agency
  HO Hydrographic Office
  BRE Building Research Establishment (geotechnical datasets)
- Local Authorities
- Universities
- Private sector companies
- Oil Companies
- Mineral companies
- Water Authorities
- the Civil Engineering Industry

6. Training

Regular courses should be provided to explain and up-date staff on the corporate standards of data collection required by the BGS.
The increasing importance of GIS-based projects in current and future BGS programmes places increasing demands on the BGS's limited IT manpower resources. Adequate general IT training of all staff and training on project-specific GIS-based modelling software should be underwritten as a vital part of future programme and staff development plans.

7. Conclusions

This report collates the contributions received through project team members, based on their own and other colleagues experiences. It identifies the most important geological/geologically related issues likely to occur in UK urban areas and the essential datasets needed to deal with any problems arising.

As the project has developed it has become increasingly evident that under the new matrix there is some overlap of effort between several on-going projects, under the different programme managers, following similar themes. One such example is the current **Midland Valley Project,** which is already addressing some of the potential data-related problems associated with Rock Mass Characterization identified in this report. It would be advantageous if these efforts were properly co-ordinated / focussed in any future development of the Urban Geoscience Programme. The **CILOR** programme which is about to get underway is also addressing accessing data sources highlighted in this report.

Towards the end of this project's deliberations the publication of the report by the **Programme Development Group** set out a series of 4 overall strategic aims for future work in the BGS programme (Walton & Lee 2000). Two of these aims in particular are directly relevant to the remit of the current project.

- *To reinforce the position of the BGS as the main provider to the public and private sectors of definitive information on the geology of the surface and* ***subsurface*** *of the UK landmass.*
- *To improve the understanding of geological structure, stratigraphy and process using a multidisciplinary research-based survey approach to meeting user and strategic needs for geological information*

Clearly, in order to fulfil these commitments, the BGS must continue to develop and expand its expertise in the field of computer-based 3-D geological studies. This should be facilitated by closely monitoring software and hardware developments and by ensuring that its existing datasets and any future data acquisition programmes, provide data in a standardized, 'future-proofed' form that will allow direct import of such data with the minimum of editing. In-house guidelines for identifying, acquiring and formatting essential 3-D Rock Mass datasets are, therefore, a prerequisite for further progress in this area.

A number of key issues face the BGS in the area of 3D Rock Mass Characterization

- Geological and geologically related issues affecting the subsurface, particularly beneath urban developments, can be broadly divided into natural and man-made, or at least man-induced, problems. A great variety of problems can be identified from past enquiries concerned with urban subsurface areas of the UK. As a result there can be little doubt that data parameters that the BGS has in the past routinely recorded and made available, will need to be considerably broadened in scope if we are to continue to provide a useful service for our existing customers and to interest new clients.
- It is unlikely that the BGS currently has sufficient manpower and expertise to deal with the creation and maintenance of complex (i.e. stacked) 3-D Datasets for all the urban areas of the UK. BGS should, therefore, continue to be selective over which datasets it needs to acquire for such projects.
- The BGS should establish a small advisory group of staff with up-to-date and relevant experience, who can advise Project Managers on the way to tackle new Urban Projects that will increasingly involve modelling the rock mass in 3-D.
- BGS should focus its efforts on developing a 3-D geological framework for the UK around which other geologically related parameters can be modelled for specific areas such as urban centres. *Essential to this aim is the development of a fully populated stratigraphic database.*
- An immediate problem that needs to be addressed is BGS's ability to handle any expansion in data validation, acquisition and data type with its present staff levels and expertise. The question arises as to whether there are sufficient staff available

to be reassigned to any substantial new urban 3-D programme, without severe disruption to existing Science Budget/CR projects? The *Locus* GIS required *c*.6 man years of effort to reach its current state. The man years involved in producing the *NIREX* 3-D models, which are still currently probably the most sophisticated in the UK, needed massive investment in manpower, hardware and funding. Consequently, BGS needs to monitor and maintain the right level and range of core staff expertise to support a move into the more specialized field of 3-D modelling, initially at least with modest objectives.

- The BGS must continue to look for innovative ways of interpreting and presenting its datasets in anticipation of the changing future demands of the customer/client base.
- Experience from the existing **Locus** and **Algi** 2-D+ GIS projects, suggests that while there is already a substantial market for 2-D data, in the form of digital geological subsurface contour maps, borehole prognoses and 2-D cross sections. It is not yet as clear that a similar demand exists for 3-D datasets. Currently the few 3-D software modelling packages available to BGS are highly specialized requiring high specification computer systems etc. Can data manipulations carried out in these packages be exported to ARCVIEW or MAPINFO which are becoming the accepted platforms for 3D visualization in many organizations. If not then BGS may need to recognise that the market for 3-D Modelling may lie with a few larger clients for some years to come.

7. References

Appleton, J.D., Hooker, P.J. and Smith, N.J. 1995. Methane, carbon dioxide and oil seeps from natural sources and mining areas: characteristics, extent and relevance to planning and development in Great Britain. British Geological Survey. *Technical Report. WP/95/1*

Appleton, J.D. and Ball, T.K. 1995. Radon and background radioactivity from natural sources: characteristics, extent and relevance to planning and development in Great Britain. British Geological Survey. *Technical Report WP/95/2.*

Appleton, J.D. 1995. Potentially harmful elements from natural sources and mining areas: characteristics, extent and relevance to planning and development in Great Britain. British Geological Survey. Technical Report *WP/95/3*

Allen, D.J, Brewerton, L.M, Coleby, L M, Gibbs, B R, Lewis, M A, MacDonald, A M, Wagstaff, S J, and Williams, A T 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report WD/97/34 Environment Agency R & D Publication 8.*

Bridge, D. M^C. Bowden, A, & Barnett, A 1999. Report on a 3-D Modelling Study of the Permo-Triassic succession of South Nottinghamshire and Derbyshire. *BGS Technical Report WA/99/54.*

Browne, M.A.E., Forsyth, I.H. and McMillan, A.A. 1986. Glasgow, a case study in urban geology. Journal of the Geological Society of London, 143, pp. 509-520.

Chilton, J. et al 1997. *Groundwater in the Urban Environment.* A.A. Balkema/Rotterdam/Brookfield

Coleman, T.B. & Cooper 2000. Exploration for metalliferous and related minerals in Britain: a guide. (1st & 2nd editions 1990/2000)

Dumpleton,S, Robins, N.S, Walker, J.A and Merrin, P.D. 2000. Minewater rebound in south Nottinghamshire: Risk evaluation using 3-D visualization and predictive modelling. BGS Technical Report.

Flight, D. M. A. and Lister, T.R. 1998. GBASE Field Procedures Manual (Version 1.0).Technical Report WP/98/5. British Geological Survey, Nottingham. (CURRENTLY UNDER REVISION)

Forster, A., Arrick, A.., Culshaw, M.G. and Johnston, M. (eds) 1995. A geological background for planning and development in Wigan. Vols. 1 & 2. British Geological Survey *Technical Report* WN/95/3 *(see also others in this series for Bradford, Coventry, Nottingham, Black Country etc).*

Ghose, R., Nijhof, V., Brouwer, J., Matsubara, Y., Kaida, Y., and Takahashi, T., 1998. Shallow to very shallow, high-resolution reflection seismic using a portable vibrator system. *Geophysics*, **63**, 1295-1309.

Gillespie, M.R. & Styles, M.T. 1999. BGS Rock Classification Scheme. Vol. 1. Classification of Igneous Rocks. RR 99-06.

Grey, D. R.C. Kinninurgh, D.G, Barker, J.A. & Bloomfield, J.P. 1995. Groundwater in the UK: A strategic study. Issues and Research Needs. Groundwater Forum Report FR/GF 1.

Haslam, H.W. & Plant, J.A. 1990. Rock Geochemistry: Guidelines for the acquisition and interpretation of lithogeochemical data - Sedimentary rocks. British Geological Survey *Technical Report WP/90/1.*

Harris, P.M. 1995. The UK Minerals Industry. (Keyworth Nottingham: British Geological Survey).

Hallsworth, C.H. & Knox, R.W.O'B. 1999. BGS Rock Classification Scheme. Vol. 3. Classification of Sediments and sedimentary rocks. *RR 99-06.*

Hillier, J., Chapman, G. E. & Highley, D.E. 2000. United Kingdom Minerals Yearbook 1999. (Keyworth, Nottingham: British Geological Survey).

Holmes, K.A., Sowerbutts, A. A, and Thomas, C. 2000. A BGS Structural database: User Requirement. British Geological Survey Technical Report WA/00/46.

Holmes, K.A., Sowerbutts A.A and Johnson, H. 2000b. A BGS Sedimentary Environments Database User Requirement. British Geological Survey Technical Report WA/00/06

Hooker, P.J. & Bannon, M.P. 1993. Methane: its occurrence and hazards in construction. CIRIA Report 130 1993.

Jones, H. K, Morris, B.L, Cheney, C.S, Brewerton, L.J, Merrin, P.D, Lewis, M.A, MacDonald, A.M, Coleby, L.M, Talbot, J.C, McKenzie, A.A, Bird, M.J, Cunningham, J, and Robinson, V.K. 2000. The physical properties of minor aquifers in England and wales. British Geological Survey Technical Report, WD/00/4 234pp. Environment Agency R&D Publication 68.

Jones, H.K. , Morris, B.L. Cheney etc 2000. The physical properties of minor aquifers in England and Wales. British Geological Survey, Technical Report WD/00/4

Klinck, B. 2000. Transport and fate of heavy minerals and other pollution from mines – 3-D Tomographic Imaging Schemes.

Munro, S.K. and Hull, J.H.. 1986. Environmental Geology in Britain. In. Bender, F. (ed) pp. 107-124. Geo-Resources and the Environment. proceedings of the Fourth International Symposium, Hannover 1985,Stuttgart

Robins, N.S. 1990. *Hydrogeology of Scotland. (London: HMSO for the British Geological Survey).*

Robertson, S. 1999. BGS Rock Classification Scheme. Vol. 2. Classification of metamorphic rocks. RR 99-02.

Smith, A, and Ellison, R.A. 1999. Applied geological maps for planning and development. *Quarterly Journal Engineering Geology.* **32**. *May Supplement*

Appendix 1

Parallel research programmes in BGS

Urban Geoscience Programme – Superficial Deposits Characterization project – A. McMillan

Engineering Geology of UK Rocks and Soils - K. Northmore

Development of integrated methods for characterising faults and fractures in reservoirs and aquifers – A Milodowski

Rock mass, fracture modelling and fluid flow – S.Rogers (*see **Appendix 1***)

Pollution and Waste Management & Extraction Industries Impacts Programme- B. Smith

Groundwater Systems & Water Quality – I N. Gale

CILOR – J. Welsby

3-D Modelling in BGS

Norton, J. & Colman T. 1999. 3-D Visualization of the Foss Barite Mine, Aberfeldy.