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# Bromsgrove Aquifer Groundwater Modelling Study: Results from Task 1.1 3D Visualisation and Geological Framework of the Bromsgrove Aquifer

Geology, Geotechnics and Palaeontology Programme

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# Bromsgrove Aquifer Groundwater Modelling Study: Results from Task 1.1 3D Visualisation and Geological Framework of the Bromsgrove Aquifer

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# 1 Introduction

The Bromsgrove Sandstone aquifer is over-abstracted. This has resulted in a long-term fall in groundwater levels, the reduction or loss of baseflow and the derogation of surface water features. To support flows in Battlefield Brook (a BAP site and notable amenity feature in Bromsgrove), Bow Brook (BAP site) and water levels in Hewell Grange Lake (SSSI), four alleviation of low-flow (ALF) boreholes are operated (one by the Environment Agency and three by Severn Trent Water). These ALF boreholes were installed as short term measures, prior to the implementation of a long-term solution to reduce the impacts of groundwater abstraction on surface water features which is under discussion between the water company and the Environment Agency.

In 2001 an existing groundwater model of the Bromsgrove Sandstone aquifer (developed by Birmingham University in 1990) was adopted and updated as part of the Environment Agency Midlands Region Groundwater Modelling Strategy. However, monitoring data collected since 2002 has shown that this groundwater model does not accurately simulate groundwater flows and levels in critical areas. The Bromsgrove aquifer groundwater modelling project aims to develop a new groundwater model that will be used to determine a more optimal groundwater abstraction regime which benefits the surface water environment, with the minimum of overall groundwater abstraction reduction and affordability.

The British Geological Survey (BGS) was contracted to undertake Environment Agency Task 1.1 of the Bromsgrove aquifer groundwater modelling study, namely the production of a three dimensional geological model of the investigation area. The model was specified to cover the outcrop of the Bromsgrove Sandstone Formation, the outcrop of the Clent Formation to the north and the confined Sherwood Sandstone Group to the west. The geographical limits of the area are approximately Droitwich Spa and Astwood Bank in the south (Northing 261550) and Rubery in the north (Northing 279560), Elmley Lovett (Easting 387134) in the west and Redditch (Easting 405456) in the east. The outline of the project area is given in Figure 1. The 3D geological model will be used in a concurrent Task (Task 1.2) to develop the conceptual model of groundwater flow between the principal formations of the Bromsgrove Sandstone aquifer system, as well as providing the geometrical information for building the groundwater model (Task 2).

This report outlines the methods used in the BGS 3D geological visualisation work and provides a brief summary of the stratigraphy, facies relationships and structure of the bedrock geology. Much of the information in the report has not been published before, and results from an extensive reinterpretation of existing borehole lithological descriptions and geophysical logs.

The model integrates information from BGS 1:50000 geological sheets (E167 Dudley, E168 Birmingham, E182 Droitwich and E183 Redditch), borehole descriptions derived from core or cuttings, geophysical logs and NEXTMap digital terrain data. Published information on the regional geological framework was also incorporated into the model (e.g. Old et al., 1991, Old et al. 1987, Powell et al. 2000).

# 2 Source Data and 3D Modelling Information

## 2.1 BOREHOLE DATA

The BGS Single Onshore Borehole Index (SOBI) holds approximately 4700 boreholes for the investigation area (including a variable buffer several kilometres wide). This large dataset was filtered for boreholes greater than 30 m in length due to the fact that the 3D visualisation involved thick (greater than 100 m) bedrock formations. This process removed most of the shallow geotechnical and site investigation boreholes that were unlikely to provide information relevant to the project. Depth filtering reduced the total number of boreholes to 183, and each of these scanned paper records was interrogated for useful geological information (Figure 2).

In total, 60 boreholes contain information that was used to build a 3D geological model, henceforth referred to as the bedrock geology model. This represents a relatively low density of control points, however, to a large extent this was compensated for by the extremely detailed lithological descriptions provided by many of the records. Unusually, many of the deep abstraction boreholes in the Bromsgrove area were cored, and these cores were logged in detail mostly during the 1950s-1980s by Professor L J Wills (University of Birmingham), G Warrington (BGS) and others with an interest in the Permo-Triassic stratigraphy of the area. The majority of these detailed bed-by-bed lithological descriptions have been entered into Oracle database tables as part of this task. No re-examination of core was undertaken as part of this work.

BGS held no geophysical logs for the investigation area. However, a selection of logs were provided by the Environment Agency/Severn Trent Water at varying scales from 1:200, 375, 750, 800, 1000, 1250 and 2000. Logs of three observation boreholes (Sanders Park (EA Observation Borehole Reference No. 0349), New Road Deep (0577) and Wildmoor (1914)) were supplied digitally and were plotted from Recall software. Considerable effort was expended in trying to source the original digital files for the remaining boreholes, however, these proved unobtainable. A selection of the remaining paper records were therefore scanned and digitised so they could be rescaled and plotted using WellCAD and Gocad.

| Borehole | Type* | EA OBH ref | EASTING | NORTHING | TD | Drill year |
|---|---|---|---|---|---|---|
| Hewell Grange | ALF | | 400920 | 269430 | 147.8 | 2005 |
| Battlefield Brook SP | ALF | | 394800 | 270500 | 100 | 1991 |
| Wildmoor No1 | PWS | | 395490 | 275180 | 263.3 | 1953 |
| Wildmoor No2 | PWS | | 395450 | 275190 | 264.4 | 1954 |
| Wildmoor | OBH | 1914 | 395961 | 274641 | 26.9 | 2004 |
| Washingstocks No1 | PWS | | 395930 | 273240 | 192.3 | 1899 |
| Washingstocks No2 | PWS | | 395800 | 273190 | 91.4 | 1900 |
| Washingstocks No3 | PWS | | 395930 | 273220 | 191.1 | 1924 |
| Webheath No1 | PWS | | 400980 | 266930 | 390.8 | 1970 |
| Webheath No2 | PWS | | 400800 | 266900 | 222.8 | 1974 |
| Webheath No3 | PWS | | 401180 | 266890 | 396.2 | 1972 |
| Burcot No1 | PWS | | 398470 | 271610 | 194.2 | 1938 |
| Burcot No2 | PWS | | 398480 | 271630 | 122.5 | 1894 |
| Sugarbrook No1 | PWS | | 396020 | 268150 | 288.0 | 1963 |
| Sugarbrook No2 | PWS | | 396100 | 268210 | 281.9 | 1965 |
| Sugarbrook No3 | PWS | | 396190 | 268160 | 398.4 | 1970 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sugarbrook No4 | PWS | | 396100 | 268070 | 375.2 | 1969 |
| Brockhill No1 | PWS | | 400100 | 270160 | 186.5 | 1942 |
| Brockhill No2 | PWS | | 400180 | 270140 | 186.5 | 1942 |
| New Road Deep | OBH | 0577 | 396290 | 270260 | 147.5 | 1993 |
| Sanders Park | OBH | 0349 | 395310 | 270770 | 150 | pre1978 |

* PWS = public water supply, ALF = Alleviation of low flow, OBH = observation borehole

Table 1 List of boreholes with geophysical logs

## 2.2 BEDROCK GEOLOGY LINEWORK

The extent of each modelled unit was initially constrained by existing geological mapping, as represented by BGS DiGMapGB-50. This 1:50 000 scale dataset provides a 2D representation of the bedrock geology (members, formations, groups and faults) either at surface or beneath superficial and artificial deposits. For modelling purposes, the DiGMapGB-50 geological linework was simplified to reduce node density and attributed with an elevation value using the NEXTMap terrain model.

It is important to note that while the modelled outcrop traces provided by the surfaces generally conform to the mapped outcrop traces as shown on BGS 1:50 000 scale maps, they are not an exact match:

1. In some areas the outcrop trace has been considerably simplified to streamline the modelling, for example in the structurally complex area to the east of the Lickey Hills (Block E on Figure 5). In this area, there is insufficient borehole control to justify an attempt to convert the many small outcrop polygons into 3D surfaces.
2. Mapping of the Droitwich (182) sheet is considerably older than all other areas and may not be as accurate and detailed as other geological map data used in this syudy.
3. Outcrop traces represent the intersection of a geological surface with the terrain model surface (which approximates to the geological horizon at ground surface). The outcrop trace can therefore vary depending on the type and resolution of the terrain model that is used. The geological map was constructed using a different terrain model (OS contours) to that used in the modelling (NEXTMap DTM downgraded to 50 m cell size and converted to a TIN in Gocad). Geological linework projected vertically onto a different terrain model than that used in the original mapping invariably produces an extremely irregular (in the Z dimension) and unlikely cropline.
4. In this study, the Gocad 3D modelling application has been given considerable freedom to generate a synthetic outcrop trace by using only widely-spaced (>1 km) outcrop control points and then clipping (eroding) the geological surface with the terrain surface. This removes some of the difficulties created by mapped outcrop polylines which do not sit realistically on the terrain model. Observing the similarities and differences between the modelled and observed outcrop traces can also provide a useful means of validating the surface (e.g. highlighting a missed structure) or indeed indicating where the original geological linework may require modification.

## 2.3 MODELLING WORKFLOW

The bedrock geology model was constructed using GSI3D and Gocad 3D visualisation software. These applications facilitate the construction of faulted geological surfaces based on a combination of mapped geological linework, subsurface picks from borehole descriptions/geophysics and manually-inserted phantom points that are used to constrain the surface in a geologically reasonable way. Figure 3 shows the workflow that was used to generate the surfaces:

1. Lithological and lithostratigraphical information from paper borehole records was entered into Oracle database tables.
2. Borehole records, geological maps and a terrain model (NEXTMap 50) were loaded into GSI3D and a grid of cross-sections was generated. The building of cross-sections provides stratigraphic control on the generation of phantom points between the relatively widely-spaced borehole control points. Each cross-section polyline was attributed with a formation name.
3. The XYZ coordinates of cross-section polylines were exported from GSI3D to Gocad. In Gocad a mesh with a predefined triangle size was created and then deformed using Discrete Smooth Interpolation (DSI) to best-fit the points set for each surface. A triangle size of 1 km was considered sufficient given the relative sparseness of borehole control points and the apparent absence of folding with a wavelength of less than 1 km in the Permo-Triassic cover. The triangulated surfaces were pre-cut with simplified fault traces prior to DSI to build in the effects of faulting. Faults were modelled as simple, continuous vertical planes. In reality it is likely that the faults are inclined and composed of multiple offset segments. This is a pragmatic simplification given that the bedrock geology model will provide the geometric framework for a groundwater model.
4. Geophysical log data were loaded into Gocad and then both the surfaces and the log correlations were evaluated. Faults which did not appear necessary were removed. The dip and azimuth of modelled surfaces were checked against outcrop measurements derived from BGS maps and memoirs.
5. Insight gained from the 3D visualisation often resulted in a need to adjust borehole interpretations and the derived cross-sections. Several iterative loops of borehole interpretation, section building and surface construction were required to generate the final bedrock geology model. The latest version of the bedrock geology model may be subject to further (re)interpretation as new data become available, and the inherent uncertainties in building subsurface geological models should be taken into account when using this model.

# 3 Geology of the Bedrock Units

## 3.1 STRATIGRAPHY

Table 2 shows the five main stratigraphic intervals covered by the study. No single borehole within the area penetrates the complete stratigraphical range of these formations, and their precise thicknesses is in most cases uncertain. Full details on the historical evolution of these lithostratigraphical terms can be found elsewhere (e.g. Warrington, 1970; Warrington et al. 1980).

| | | | |
|---|---|---|---|
| Triassic | Mercia Mudstone Group | | Mudstones, thin sandstones and gypsum, includes the Droitwich Halite Member in the Worcester Basin |
| | Sherwood Sandstone | Bromsgrove Sandstone Formation | Conglomerates at base fining upwards to sandstones and mudstones |
| | | Wildmoor Sandstone Formation | Friable sandstones and thin mudstones |

| | | | |
|---|---|---|---|
| | Group | Kidderminster Formation | Conglomerates with sandy matrix fining upward to sandstone |
| Lower Permian? | Clent Formation | | Breccias with clayey matrix |

Table 2 Stratigraphy of the Bromsgrove aquifer block

### 3.1.1 Clent Formation

The Clent Formation typically comprises poorly sorted breccia with angular and subangular fine-grained volcanic clasts set in a reddish brown mudstone matrix. These breccias range up to 150 m in thickness and commonly lie marginal to present basinal areas. Within the investigation area, they are only mapped on the western slope of the Lickey/Clent Hills (Figure 5). They appear to pre-date the development of Permo-Triassic extensional basins and have been interpreted as Late Carboniferous/Early Permian alluvial fan deposits (Powell et al. 2000).

### 3.1.2 Kidderminster Formation

The Kidderminster Formation comprises a succession of fluvial conglomerates and sandstones formerly known as the 'Bunter Pebble Beds'. The base of the Kidderminster Formation is generally a clast to matrix-supported conglomerate with pebbles of grey-brown quartzite, vein quartz and rare chert, rhyolite and tuff. The conglomerate beds show a range of internal structures including poorly developed horizontal stratification, and planar and trough cross stratification. Beds of conglomerate interfinger with sandstones, pebbly sandstones and red-brown micaceous mudstones. The thickest known sequence of the formation is 166.7 m in the Kempsey Borehole (Whitaker, 1980) sited a little to the south of the study area. The characteristic high sonic velocity of the basal Kidderminster Formation probably results from extensive carbonate and/or silica cementation. Palaeozoic limestone clasts within the conglomerate could have acted as a local source of carbonate. In the upper part of the formation, the proportion of conglomerate decreases and it is dominated by red-brown, fine- to coarse-grained, slightly micaeous sandstones in which pebbles are dispersed or form discrete lenses or channel lags.

The junction with the overlying Wildmoor Sandstone Formation is transitional and is drawn conventionally at the point above which the sequence becomes pebble free (Figure 7). However, the recognition of a strong geophysical marker (high gamma-ray zone) toward the base of the Wildmoor Sandstone in the Wildmoor No. 2, Wildmoor (1914), Burcot No. 4 and Brockhill No. 1 boreholes (Figure 8) shows that the highest pebble bed can occur at different stratigraphical levels in different areas. A more reliable criterion would appear to the first downhole appearance of conglomerates which is generally associated with an increase in resistivity (Figure 7). This may be up to 65 m below the first appearance of pebbles, as in the case of the Wildmoor No. 2 Borehole. In the model, the Kidderminster Formation/Wildmoor Sandstone contact has been taken at the first downhole appearance of pebbles in the Wildmoor No. 2 Borehole which in this borehole coincides with a gradual change toward a more uniformly high sonic velocity. A comparable level has been picked in other boreholes using (1) the known thickness between this level and the overlying high gamma marker in the Wildmoor Sandstone and (2) limited geophysical log correlation (this would be the preferred method but more work is required to acquire, digitise and interpret all of the geophysical logs).

### 3.1.3 Wildmoor Sandstone Formation

The Wildmoor Sandstone Formation (formerly known as the 'Upper Mottled Sandstone') comprises reddish brown, very fine to fine-grained, micaeous sandstones. The base of the formation is generally gradational with upper sandstones of the Kidderminster Formation. The upper boundary is a sharp erosional disconformity with the Bromsgrove Sandstone. The formation is 284.7 m thick in the Worcester Basin (Kempsey Borehole, to the south of the study area; Whittaker, 1980). The sandstones range from friable to moderately well cemented, with a dolomitic to patchily calcareous cement. Sedimentary structures include cross-lamination and low-angle trough and planar cross-bedding. Sandstone beds are commonly separated by thin, but laterally persistent, mudstone beds. The formation is generally interpreted as fluvial in this region, but it may also contain an aeolian component.

An important outcome of this study is the recognition of the strong geophysical marker (high gamma-ray zone) approximately 100 m above the base of the formation, as described in Section 3.1.2 above (also Figure 8). Lithological records are often unclear (largely due to extensive core loss of the friable sandstones), but this 25-30 m thick interval appears to correspond to a zone of clayey sandstones.

### 3.1.4 Bromsgrove Sandstone FORMATION

The Bromsgrove Sandstone Formation, formerly known as the 'Lower Keuper Sandstone', is the youngest formation in the Sherwood Sandstone Group. The formation rests sharply on the Wildmoor Sandstone and passes gradationally upwards into the Mercia Mudstone Group. The Bromsgrove Sandstone is lithologically distinct from the Wildmoor Sandstone Formation, the most conspicuous feature being the reappearance of conglomerates in the lower part of the formation, the incoming of fresh K-feldspar as a detrital mineral component (Warrington, 1970), and a greater incidence of thin mudstone beds. The erosion surface at the base of the Bromsgrove Sandstone, the Hardegsden Disconformity, has long been recognised as a key unconformity in UK Triassic stratigraphy.

The formation reaches a maximum thickness of 493.8 m in the Worcester Basin (Kempsey Borehole, to the south of the study area; Whittaker, 1980) and thins to the north and east where it is typically 50-100 m thick. The formation is lithologically variable and includes conglomerates, cross-bedded sandstones, siltstones and claystones deposited in a predominantly fluvial environment. Fining up cycles are common. It has traditionally been subdivided into three units, namely the 'Basement Beds', 'Building Stones', and 'Waterstones', which have been formalised as the Burcot, Finstall and Sugarbrook members (Old et al., 1991). The Sugarbrook Member is laterally equivalent to the Tarporley Siltstone Formation of the Mercia Mudstone Group elsewhere in the UK. The interbedding of sandstones and mudstones throughout the formation results in a characteristic serrated gamma-ray profile, with a progressive increase in value as the Bromsgrove Sandstone fines upwards into the Mercia Mudstone Group.

Sugarbrook No. 3 Borehole is the key reference borehole, having spudded into the Mercia Mudstone Group and thoroughly lithofacies-logged. The gamma ray log correlates well with the adjacent Sugarbrook No. 4 Borehole (Figure 9). The recognition of internal stratigraphical markers or zones in the Bromsgrove Sandstone was an important finding of this study, as it was previously uncertain whether any boreholes at other locations in the Bromsgrove area actually prove the contact between the Bromsgrove Sandstone and the Wildmoor Sandstone. Structural markers independent from this boundary were required. Figure 9 shows how the stratigraphy has been subdivided into three zones.

The lower zone (broadly equilvalent to the Burcot Member) consists of conglomerates, pebbly sandstones and mudstones with common early-diagenetic carbonate nodules (calcrete). As might be expected in a fluvial environment with switching channel belts, pebbly sandstones and conglomerates can occur at different stratigraphical levels in different locations. A consequence of this is that the downward transition from pebbly lithologies into sandstones may have been incorrectly interpreted as a Bromsgrove-Wildmoor boundary in some previous borehole interpretations.

The upper zone comprises mainly sandstones and mudstones with rare calcrete but locally common plant remains including equisetalean pteridophytes and coniferalean gymnosperms (Old et al. 1991). This part of the formation has been largely eroded from the Washingstocks-

Whitford Public Water Supply (PWS) area, and thickens southward from Sanders Park toward Sugarbrook PWS Borehole (Figure 9).

There is some evidence from gamma-ray logs and lithological descriptions that a (generally) loosely-bounded 50 m thick central zone of more abundant and thicker mudstones separates the upper plant-rich sandstones from the lower calcrete-rich pebbly sandstones. This interval occurs at a depth of approximately 200-250 m in the Sugarbrook PWS Boreholes and can be traced up-dip to Washingstocks PWS Borehole where, in this case, a sharply-defined high-gamma ray/muddy zone occurs near the top of the borehole at 20-70 m downhole depth (Figure 9).

The general two/three-fold division of the Bromsgrove Sandstone can be extended to other areas in the Bromsgrove region, such as along a section line from Ombersley Park, Westwood and Chaddlesley Corbett to the north and west of Sugarbrook PWS, through to Webheath PWS and eastwards across the Lickey Fault (Figure 10). Many faults and fractures are recorded in the Webheath cores, and parts of the upper plant-rich sandstones may be faulted out in these boreholes.

### 3.1.5 Mercia Mudstone Group

The Mercia Mudstone Group (MMG) is composed predominantly of red, blocky mudstones and siltstones with subordinate laminated, green and grey beds. Thin beds of greenish grey, dolomitic siltstone and sandstone (often termed ‘skerries’) occur at intervals throughout.. The group exceeds 500 m thick in the deeper basins of the Midlands; the Stratford seismic reflectin profile suggested thicknesses in excess of 1000m adjacent to the Inkberrow Fault on the margin of the Worcester Basin in the western part of the study area. Within the Mercia Mudstone, the Arden Sandstone Formation forms a prominent marker horizon, which is up to 11 m thick. Gypsum is common throughout the group, occurring is small primary nodules and secondary veins. At least one prominent bed of gypsum occurs near the top of the group. Halite is also developed, with local thick (150 m) halite-bearing units in the northern part of the Worcester Graben at Droitwich (Figure 11). This is the lateral equivalent of the Arden Sandstone. The distribution of the Droitwich Halite Member is not shown on the geological map of this area, but is well-known from a line of brine-producing boreholes between Droitwich and Stoke Prior Salt Works (Poole and Williams, 1980), and from subsidence features at the surface. The south-eastern dip of the halite across the Shernal Green Fault has been modelled using information from the ICI Saleway Borehole. There is no control on the presence or location of the halite adjacent to the Western Boundary/Lickey Fault (Figure 11). The modelled form of the halite in this area is based only on the concept that the distribution of the Droitwich Halite is controlled by the fault-bounded basin. Evidence from mapping in the Worcester area shows the limits of the Droitwich Halite are fault controlled on it’s western margin and the Inkebrrow Fault is the eastern limit (Barclay et al., 1997).

## 3.2 GEOLOGICAL STRUCTURE

The project area covers the northern part of the Worcester Graben in the west, the southern extent of the South Staffordshire Coalfield in the north and the western part of the Knowle Basin in the east. The South Staffordshire Coalfield is bounded to the west by a series of north-north-west-trending, down-west faults forming the eastern margin of the Worcester Graben. These faults merge with the north-south trending Inkberrow Fault, where the Lower Jurassic crops out near the southern margin of the area as shown in Figure 4.

The main consequence for the hydrogeology is that there are two considerably varying geological sequences. The sequence within the Worcester Graben includes a very thick Bridgnorth Sandstone, Kidderminster, Wildmoor Sandstone, Bromsgrove Sandstone formations and Mercia Mudstone Group, as proved in the Kempsey Borehole (Whittaker, 1980) and the Stratford seismic reflection profile (Chadwick, 1985). To the east of the Inkberrow-Lickey Fault line, a thinner sequence probably overlies a basement high (Lickey Ridge), comprising thin or absent Wildmoor Sandstone, with Kidderminster Formation unconformably overlying Carboniferous to Permian breccias (Clent Formation). These breccias may have been reached in the deepened Burcot No 3 Borehole, although there is a possibility that these sandy breccias represent a locally-derived facies of the Kidderminster Formation. It is probable that the Clent Formation does not occur in the basin and the Bridgnorth Sandstone does not occur on the high. However, there is no seismic reflection data within the project area to confirm this. The Stratford seismic reflection profile was acquired primarily to resolve this relationship between the Worcester Graben, Lickey Ridge and Knowle Basin, but was sited some distance to the south (Chadwick, 1985).

For the purposes of 3D visualisation, the stratigraphy and structure has been simplified into six main structural blocks (shown as A-F on Figure 5)

A. To the west of the Western Boundary Fault and Lickey Fault systems, a Wildmoor Sandstone Formation to Jurassic sequence dips at around 5 degrees to the south-east. Although not shown on the BGS Droitwich 1:50000 map sheet, the Mercia Mudstone Group includes the Droitwich Halite Member which crops as a zone of ‘wet rockhead’ (i.e., salt is dissolved at shallow depths) between Droitwich and Stoke Prior and is intersected at depth in the south under a Jurassic and Triassic cover by the Saleway Borehole.

B. Bromsgrove is located on a lozenge-shaped, fault-bounded block composed of Bromsgrove Sandstone dipping gently (<5 degrees) to the south-west beneath a cover of Mercia Mudstone. The western margin of the block is formed by the Western Boundary Fault which probably drops the top of the Bromsgrove Sandstone by around 200 m on its western side (Figure 6), although there is very limited borehole control on this estimate. The Lickey Fault forms the eastern margin of the block. In the northern part of Block B the Lickey Fault downthrows Bromsgrove Sandstone against Wildmoor Sandstone, and in the south, Mercia Mudstone against Bromsgrove Sandstone.

C. The older Permo-Triassic formations (Clent Formation, Kidderminster Formation and Wildmoor Sandstone) form a broadly conformable package which dips southwest off the western slope of the Lickey and Clent Hills. These formations have the steepest dip in the area of up to 10 degrees. Together with older rocks that include the Ordovician Lickey Quartzite Formation, these Permo-Triassic strata form the footwall of the Lickey Fault (Figure 6).

D. Block D, which is penetrated by the Webheath PWS boreholes, is a narrow, triangular sliver of Bromsgrove Sandstone which dips 5 degrees to the south-east beneath a cover of Mercia Mudstone. The block is a horst, bounded on the west by the Lickey Fault and on the east by the Longbridge Fault. The Longbridge Fault downthrows the base of the Mercia Mudstone to the east by around 200 m.

E. This is a relatively steeply dipping (approximately 10 degrees) Kidderminster Formation to Mercia Mudstone succession faulted against the eastern slope of the Lickey Hills and bounded to the east by the Longbridge Fault. The 1:50000 map sheet shows a structurally complex, faulted outcrop pattern here which is greatly simplified in the bedrock geology model.

F. This is a large area of Mercia Mudstone on the eastern, downthrown side of the north-south trending Longbridge Fault. The Bromsgrove Sandstone aquifer is concealed by around 200 m of Mercia Mudstone and is approximately half the thickness of equivalent strata west of the Lickey High.

This structural subdivision is also shown in the surfaces of the bedrock geology model (Figure 5).

# 4 Conclusions and Recommendations

The bedrock geology modelling process integrates a range of 2D and 3D geological information to produce an interpretation of the subsurface geology of the project area. Every effort has been made to ensure that the bedrock geology model is consistent with this information and the conceptual geological model for the project area. However, this bedrock geology model represents one interpretation of the available data, and it is important to recognise that other equally valid interpretations may be possible. Groundwater modelling within the Bromsgrove aquifer may highlight areas where the bedrock geology model requires modification.

Some stratigraphical observations and correlations in the report are new and would benefit from more lithological and particularly geophysical log correlation. This should be undertaken if it becomes apparent during the groundwater modelling phase, that the internal stratigraphy of the Bromsgrove Sandstone and Wildmoor Sandstone formations is influencing the storage and movement of groundwater.

# References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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# Appendix 1 Borehole Stratigraphy

Boreholes in the table contain a stratigraphical contact. Boreholes not in the table which are contained within one unit are: Fairfield No.1, Meadow Farm = WRS; Fockbury Mill, New Road Shallow, Burcott Lane, Tardebigge, Hewell Grange ALF/OBH = BMS. Z is depth in metres above or below ordnance datum. MD is measured downhole depth. HGZ in the MarkerName column stands for High Gamma Zone and represents an informal muddier subdivision of the formation that is prefixed. Dip and azimuth represent the dip and direction of dip of the surface in the borehole.

| WellName | X | Y | Z | MD | MarkerName | Dip | Azimuth |
|---|---|---|---|---|---|---|---|
| Battlefield_Brook_SP | 394800 | 270500 | 29.0 | 59.0 | 5_2_BMS_HGZ_TOP | 2.6 | 137.2 |
| Brockhill_No1 | 400100 | 270160 | 98.1 | 36.5 | 6_1_WRS_HGZ_TOP | 2.5 | 225.6 |
| Brockhill_No1 | 400100 | 270160 | 76.6 | 57.9 | 6_2_WRS_HGZ_BASE | 2.5 | 225.6 |
| Brockhill_No1 | 400100 | 270160 | 13.0 | 121.6 | 6_WRS | 2.5 | 225.6 |
| Brockhill_No2 | 400180 | 270140 | 100.5 | 32.8 | 6_1_WRS_HGZ_TOP | 3.1 | 307.5 |
| Brockhill_No2 | 400180 | 270140 | 79.1 | 54.3 | 6_2_WRS_HGZ_BASE | 3.1 | 308.1 |
| Brockhill_No2 | 400180 | 270140 | 15.4 | 117.9 | 6_WRS | 2.9 | 303.9 |
| Burcot_No1 | 398470 | 271610 | 81.5 | 50.2 | 6_1_WRS_HGZ_TOP | 10.0 | 236.7 |
| Burcot_No1 | 398470 | 271610 | 54.1 | 77.6 | 6_2_WRS_HGZ_BASE | 9.9 | 236.6 |
| Burcot_No1 | 398470 | 271610 | 2.0 | 129.7 | 6_WRS | 9.9 | 236.6 |
| Burcot_No2 | 398480 | 271630 | 84.7 | 47.0 | 6_1_WRS_HGZ_TOP | 6.9 | 234.3 |
| Burcot_No2 | 398480 | 271630 | 57.3 | 74.5 | 6_2_WRS_HGZ_BASE | 6.9 | 234.3 |
| Burcot_No3 | 398470 | 271710 | 89.4 | 44.1 | 6_1_WRS_HGZ_TOP | 6.9 | 234.3 |
| Burcot_No3 | 398470 | 271710 | 61.9 | 71.6 | 6_2_WRS_HGZ_BASE | 6.9 | 234.3 |
| Burcot_No3 | 398470 | 271710 | 9.9 | 123.6 | 6_WRS | 6.9 | 234.3 |
| Burcot_No3 | 398470 | 271710 | -96.2 | 229.7 | 7_KDM | 5.4 | 234.2 |
| Burcot_No4 | 398460 | 271720 | 89.1 | 42.6 | 6_1_WRS_HGZ_TOP | 6.9 | 234.3 |
| Burcot_No4 | 398460 | 271720 | 61.7 | 70.1 | 6_2_WRS_HGZ_BASE | 6.9 | 234.3 |
| Burcot_No4 | 398460 | 271720 | 9.6 | 122.1 | 6_WRS | 6.9 | 234.3 |
| Catshill | 395760 | 273850 | 113.3 | 8.1 | 5_2_BMS_HGZ_TOP | 1.4 | 158.8 |
| Fairfield_No2 | 395650 | 275670 | 132.6 | 14.0 | 6_2_WRS_HGZ_BASE | 8.3 | 233.9 |
| Meadow_Farm | 395680 | 274800 | 62.3 | 70.2 | 6_1_WRS_HGZ_TOP | 8.8 | 216.3 |
| Meadow_Farm | 395680 | 274800 | 40.8 | 91.7 | 6_2_WRS_HGZ_BASE | 7.7 | 220.7 |
| Meadow_Farm | 395680 | 274800 | -13.8 | 146.2 | 6_WRS | 6.2 | 230.7 |
| New_Road_Deep | 396290 | 270260 | -25.4 | 107.9 | 5_2_BMS_HGZ_TOP | 3.4 | 142.5 |
| Sanders_Park_OBH | 395310 | 270770 | 25.3 | 59.5 | 5_2_BMS_HGZ_TOP | 2.5 | 149.0 |
| Sugarbrook_No1 | 396020 | 268150 | 52.0 | 16.9 | 4_MMG_LOWER | 3.9 | 169.5 |
| Sugarbrook_No1 | 396020 | 268150 | -123.7 | 192.6 | 5_2_BMS_HGZ_TOP | 4.1 | 160.8 |
| Sugarbrook_No1 | 396020 | 268150 | -168.9 | 237.8 | 5_1_BMS_HGZ_BASE | 4.0 | 162.9 |
| Sugarbrook_No2 | 396100 | 268210 | 54.7 | 15.1 | 4_MMG_LOWER | 3.3 | 167.7 |
| Sugarbrook_No2 | 396100 | 268210 | -121.5 | 191.3 | 5_2_BMS_HGZ_TOP | 4.1 | 160.8 |
| Sugarbrook_No2 | 396100 | 268210 | -166.6 | 236.4 | 5_1_BMS_HGZ_BASE | 4.0 | 162.9 |
| Sugarbrook_No3 | 396190 | 268160 | 50.7 | 22.5 | 4_MMG_LOWER | 3.5 | 175.9 |
| Sugarbrook_No3 | 396190 | 268160 | -125.3 | 198.5 | 5_2_BMS_HGZ_TOP | 3.3 | 177.7 |
| Sugarbrook_No3 | 396190 | 268160 | -170.3 | 243.4 | 5_1_BMS_HGZ_BASE | 3.3 | 177.7 |
| Sugarbrook_No4 | 396100 | 268070 | 45.6 | 24.8 | 4_MMG_LOWER | 3.5 | 175.9 |
| Sugarbrook_No4 | 396100 | 268070 | -130.3 | 200.7 | 5_2_BMS_HGZ_TOP | 3.3 | 177.7 |
| Sugarbrook_No4 | 396100 | 268070 | -175.2 | 245.6 | 5_1_BMS_HGZ_BASE | 3.3 | 177.7 |
| Washingstocks_No1 | 395930 | 273240 | 93.4 | 22.4 | 5_2_BMS_HGZ_TOP | 1.7 | 153.9 |
| Washingstocks_No1 | 395930 | 273240 | 49.1 | 66.7 | 5_1_BMS_HGZ_BASE | 1.7 | 153.9 |
| Washingstocks_No2 | 395800 | 273190 | 93.8 | 17.9 | 5_2_BMS_HGZ_TOP | 1.7 | 153.9 |
| Washingstocks_No2 | 395800 | 273190 | 49.5 | 62.2 | 5_1_BMS_HGZ_BASE | 1.7 | 153.9 |
| Washingstocks_No3 | 395930 | 273220 | 92.9 | 22.3 | 5_2_BMS_HGZ_TOP | 1.7 | 153.9 |
| Washingstocks_No3 | 395930 | 273220 | 48.6 | 66.6 | 5_1_BMS_HGZ_BASE | 1.7 | 153.9 |
| Webheath | 400930 | 266870 | 77.9 | 35.1 | 4_MMG_LOWER | 3.1 | 281.4 |
| Webheath_No1 | 400980 | 266930 | 79.9 | 33.2 | 4_MMG_LOWER | 3.4 | 266.8 |
| Webheath_No1 | 400980 | 266930 | -253.6 | 366.7 | 5_BMS | 3.7 | 241.3 |
| Webheath_No2 | 400800 | 267000 | 71.2 | 50.0 | 4_MMG_LOWER | 2.3 | 294.8 |
| Webheath_No3 | 401180 | 266890 | -243.6 | 365.5 | 5_BMS | 3.7 | 241.3 |
| Whitford | 394410 | 270690 | 49.0 | 41.8 | 5_2_BMS_HGZ_TOP | 2.9 | 135.9 |
| Whitford | 394410 | 270690 | -11.3 | 102.1 | 5_1_BMS_HGZ_BASE | 3.1 | 137.1 |
| Wildmoor | 395961 | 274641 | 104.5 | 20.5 | 6_1_WRS_HGZ_TOP | 19.5 | 244.4 |
| Wildmoor_No1 | 395490 | 275180 | 110.9 | 28.3 | 6_1_WRS_HGZ_TOP | 9.6 | 181.0 |
| Wildmoor_No1 | 395490 | 275180 | 79.9 | 59.4 | 6_2_WRS_HGZ_BASE | 8.8 | 185.8 |
| Wildmoor_No1 | 395490 | 275180 | -3.6 | 142.8 | 6_WRS | 6.2 | 230.6 |
| Wildmoor_No2 | 395450 | 275190 | 108.7 | 30.5 | 6_1_WRS_HGZ_TOP | 7.2 | 262.3 |
| Wildmoor_No2 | 395450 | 275190 | 77.4 | 61.9 | 6_2_WRS_HGZ_BASE | 7.2 | 262.3 |
| Wildmoor_No2 | 395450 | 275190 | -7.5 | 146.8 | 6_WRS | 7.2 | 262.3 |

# Appendix 2 Figures as Separate PDF file

## The following figures are bundled in the pdf file which accompanies this report.