Geology of London, UK

Katherine R. Royse[1], Mike de Freitas[2,3], William G. Burgess[4], John Cosgrove[5], Richard C. Ghail[3], Phil Gibbard[6], Chris King[7], Ursula Lawrence[8], Rory N. Mortimore[9], Hugh Owen[10], Jackie Skipper [11,]

1. British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK. krro@bgs.ac.uk 2. Imperial College London SW72AZ, UK & *First Steps Ltd*, Unit 17 Hurlingham Studios, London SW6 3PA, UK. 3. Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK. 4. Department of Geological Sciences, University College London, WC1E 6BT, UK. 5. Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK. 6. Cambridge Quaternary, Department of Geography, University of Cambridge CB2 3EN, UK. 7. 16A Park Road, Bridport, Dorset 8. Crossrail Ltd. 25 Canada Square, Canary Wharf, London, E14 5LQ, UK. 9. University of Brighton & ChalkRock Ltd, 32 Prince Edwards Road, Lewes, BN7 1BE, UK. 10. Department of Palaeontology, The Natural History Museum, Cromwell Road, London SW7 5BD, UK. 11. Geotechnical Consulting Group (GCG), 52A Cromwell Road, London SW7 5BE, UK.

Abstract

The population of London is around 7 million. The infrastructure to support this makes London one of the most intensively investigated areas of upper crust. however construction work in London continues to reveal the presence of unexpected ground conditions. These have been discovered in isolation and often recorded with no further work to explain them. There is a scientific, industrial and commercial need to refine the geological framework for London and its surrounding area. This paper reviews the geological setting of London as it is understood at present, and outlines the issues that current research is attempting to resolve.

Keywords: London Basin, Forum, Atlas, 3D-models, Review, Faulting, stratigraphy, structure hydrogeology, planning, development

1. Introduction

This paper reviews the geological framework for London and its surrounding area. It highlights the complex nature of London's geology and the possible implications for current and future development. Within this review article the London Basin's boundaries are defined by the limit of the Chalk outcrop (Sumbler 1996). The Basin is described by Sumbler (1996), as a broad, gentle synclinal fold (Fig. 1); although its seaward extension is not shown, the structure continues out into the North Sea (King 2006). The term 'London Basin' was first used on the maps of William Smith (1815, 1817) and George Bellas Greenough (1820) to describe the sediments that make up the geology of London (Sheppard 1917). The outcrop limits of the Chalk were fundamental in defining the original limits of this "basin". However, to understand London's geology, it is necessary to go beyond these present-day geographical limits. It is really only in the later stages of geological history that the idea of a London-centred geology can be considered helpful.

The British Geological Survey commenced detailed geological mapping of the London Basin in 1861 and soon realised that the correlation of strata across and beneath London was not always as straightforward as it at first appeared (Whitaker 1875). For example, the substantial and isolated Chalk outcrop at Windsor in the west occurs 5 km south-east of the main Chalk outcrop near Maidenhead. There are smaller but largely unexplained Chalk structures mapped in the east by Wooldridge (1923, 1926) and Wooldridge and Linton (1939). However in 1947 the Basin was still presented by the British Geological Survey as a simple unfaulted downwarp on undifferentiated basement (Sherlock 1947).

Boreholes drilled in the London Basin for oil, coal and gas have proved the extent of a Palaeozoic basement, the London Platform, of folded Silurian and foreland Devonian rocks at depths of ~ 300m in central London (Sumbler 1996). Upon these Palaeozoic rocks are found remnants of strata of Jurassic age, which are themselves covered unconformably by strata of Early Cretaceous age (table 1). The Gault is the earliest preserved formation to cover the whole area. The London Platform (Fig. 2) is considered to extend to the Worcestershire Basin in the west, to the East Midlands Shelf in the north, to the southern North Sea graben in the east, and to the Weald Basin in the south (Sumbler 1996). This Platform forms the western part of the London-Brabant massif (Lee *et al.* 1993). The southern boundary of the Platform and its Western boundary are fault controlled. The faulted southern boundary has been referred to as the “Variscan Front”, a tectonic line extending from the Bristol Channel to cross southern England to the Strait of Dover.

The late Variscan pattern of faulting in the Platform had a profound effect on the subsequent location and development of Mesozoic and Cenozoic tectonic structures, because tectonic stresses associated with the rotation of Africa and the opening of the Atlantic reactivated Variscan block faulting. At the Jurassic-Cretaceous boundary, faulting which produced the proto-Weald basin was reactivated, causing major uplift of the platform and the subsequent erosion not only of the Jurassic sediments previously deposited on it but also the Palaeozoic core upon which they rest. The products of this erosion were redeposited in the Weald and Hampshire Basins during the Early Cretaceous, initially as the freshwater Wealden Group and subsequently as the marine Lower Greensand. The Lower Greensand is present widely below the Gault in borings in the London Platform, but is essentially of Late Aptian and Early Albian age. Later, the Gault sea covered the Platform, depositing deeper water clays.

The geological structure of the Cretaceous and Paleogene strata which overlie this basement has in the past been considered 'relatively simple' (Ellison *et al.* 2004); for example, despite the accumulated indirect evidence for brittle structures in the basin, only two faults are shown on the current geological maps for the region: the Wimbledon-Streatham fault and the Greenwich fault (Fig. 3). There is, however, a growing body of direct evidence, particularly from recent deeper engineering projects, such as the Channel Tunnel Rail Link, Thames Water Ring Main (Newman 2009), Crossrail and the Docklands Light Railway, which demonstrate that there is much more faulting in London and that the structure of London is more complex (Royse, 2010). One aspect of the tectonic history that is of overriding significance to the geological development of the London Basin, and consequently to the application of London's geology to engineering and water supply, is the location of a broad tectonic boundary running approximately east to west beneath the London Basin (Fig. 4). It originates from movements in the Variscan orogeny during and after the Carboniferous and is likely to have been reactivated periodically ever since as a line of crustal weakness.

The Upper Cretaceous Chalk Group is present at subcrop throughout London and comes to the surface along its southern margin (the North Downs) and its northwest margin (the Chiltern Hills); elsewhere it occurs locally at or close to the surface, e.g. along the Greenwich and Purfleet anticlines in East London and also within the Chislehurst 'horst'. The Chalk of the London Basin is typically a fine grained white limestone made largely from organically precipitated aragonite (Hancock 1975), in contrast to the largely clastic formations below and above it, and represents a period of very high sea-levels. Of the nine Chalk formations defined for mapping in southern England (Bristow *et al.*, 1997), six are present in the London Basin (Fig. 5). These are distinguished by the presence or absence of marl and flint bands, their physical properties including density and porosity and by their colour. However, it is important to appreciate that in the London area the total thickness of the Chalk preserved is only between 170 and 210 m and it generally thins from west to east; the succession within the London Basin is relatively thin compared to that of the more complete Hampshire–Dieppe Basin where younger formations are preserved and the Chalk is over 400 m thick (Ellison *et al.* 2004). Thus, a substantial history of late and post-Cretaceous uplift and erosion is recorded in the London region.

Overlying the Chalk is the oldest Paleogene deposit, the Thanet Sand Formation. This consists of a coarsening upwards succession of fine grained, clean grey sand. The formation reaches a maximum thickness of about 30 m. Above the Thanet Sand Formation lies the Lambeth Group, consisting of the Upnor, the Woolwich and the Reading Formations. The Lambeth Group is between 20 and 30 m thick in London and has a highly variable lithology, containing differing proportions of sands, silts, clays and gravels. Overlying the Lambeth Group are the Eocene sediments of the Thames Group which consist of the Harwich and London Clay Formations. The Harwich (formerly known as the Blackheath or Oldhaven Beds) contain predominantly sand and pebble beds up to 4 m thick. Above this is approximately 90 to 130 m of the London Clay Formation, a sequence of grey to blue grey, often bioturbated, silty clay. Quaternary deposits are encountered throughout the London Basin and these include evidence of ancient river systems and the development of the present-day River Thames. Deposits include alluvium, peat, brickearth and river terrace deposits, for example the Kempton Park, Taplow and Shepperton Gravels.

One aspect of the post-Cretaceous succession in the London region that is not widely appreciated is the considerable period during which no record of deposition exists. Comparison with the successions of similar age in the Hampshire Basin demonstrates that approximately 50 Ma of deposition is missing from the successions that lie above the Chalk. It is likely that periods of uplift are the cause for these absences and this will be discussed further in the paper. Recent and extensive investigations for engineering excavations in the London region have provided considerable quantities of high quality geological data causing some long established concepts concerning the continuity and extent of sedimentation to be revisited. Currently, work is being undertaken by the London Basin Forum to synthesise, summarise and present an updated version of the geology in a Geological Atlas of the London Basin. The London Basin Forum is a collaborative project, with goescientists from industry, academia and government whose sole aim is to develop an up-dated regional framework within which data from local ground investigations can be interpreted.

To explain the need for such work, selected details from the geological history of London will now be reviewed which illustrate major issues and anomalies within the region. The structure of the London Basin will then be described as understood at present, followed by a review of the implications a better understanding of the geology of the London Basin will have on major engineering projects and long term groundwater management strategies. The paper concludes by describing how technologies such as GIS and 3D modelling are changing the way geological, geotechnical and hydrogeological datasets of the sort available for London are presented and interpreted.

2. Pre-Gault and Gault sedimentary formations

The mudstones of the Gault Formation are the first sedimentary unit to cover the whole of the London Basin. These mudstones were deposited following a period of intense tectonic activity related to the opening of the northern Atlantic Ocean (Sumbler 1996). This was followed throughout the Aptian and Albian by periods of erosion, subsidence and sea level rise, which eventually led to the establishment of shallow marine conditions across the whole of the London basin (Table 2).

The mudstones are transgressive across a terrain of eroded Jurassic, Wealden and Lower Greensand sediments and, at the core of the Platform, rest directly on Palaeozoic rocks. In much of the area to the north, in East Anglia, the Gault is underlain immediately by the Carstone Formation, essentially of latest Early Albian and early Middle Albian age (e.g. Gallois & Morter 1982, Gallois 1994, Owen 1995). To the west, the Carstone Formation is itself underlain in places by the Late Aptian Woburn Sands Formation. In the southern bounding area of the Platform, the Gault is separated from the eroded Jurassic surface by the Lower Greensand Group. Further south, beyond the southern bounding faults of the London Platform, limited areas of Atherfield Clay and Hythe Beds Formations overlie Wealden sediments, which are the product of the early Cretaceous erosion of the Jurassic upland terrain.

Such was the scene at the start of the Gault. A fascinating aspect of the research currently under way for the Geological Atlas of the London Basin is the extent to which a re-interpretation of known deposits against a background of a faulted basement will permit a better understanding of how the basin developed at this time. If that is possible, then some of the anomalous conditions found within the London area may be amenable to rational explanation and indeed prediction. With that in mind, aspects of the overlying succession, i.e. the cover, will be reviewed.

The stratigraphy of the Lower and Upper Gault and contiguous Upper Greensand in south east England has been described in some detail by Owen (1971a, b, 1976, 1996) and its subcrop succession in central East Anglia by Gallois & Morter (1982), the latter being used extensively in the British Geological Survey Memoirs of the region. The evidence indicates that the Lower Gault originally covered the whole Platform area. However, it is absent over much of northern and western Greater London and Essex, where it was removed as a result of uplift from renewed faulting along older lineations of Variscan and Jurassic–Cretaceous boundary age (Ellison 2004, Owen 1971, Sumbler 1996). This faulting phase and subsequent erosion can be dated as earliest Late Albian (*Dipoloceras cristatum* Zone) age (Owen 1971a, b).

The sedimentary character of the Upper Gault is essentially one of more marly mudstones deposited in deeper water than those of the Lower Gault and replaced progressively from the south west by the arenaceous Upper Greensand facies. The Upper Greensand underlies the Chalk over much of the southern area of the Platform from the Thames axis southward with an eastern termination in west Kent (Owen 1996). Continued tectonic activity in the mid-Late Albian Stage (*Callihoplites auritus* Subzone) produced minor graben structures found preserved in the Fetcham Mill area of Surrey (Gray 1965), near Sevenoaks (Owen 1996) and in the Folkestone area of Kent. Gault Formation~~s~~ sedimentation terminated with the Early Cenomanian transgression, although earliest Cenomanian sediments of Upper Greensand facies are locally present in south Essex and Surrey (Sumbler 1996).

3. The Chalk

For many, the Chalk remains divided at its Formation level as Lower, Middle and Upper, but these divisions are of limited value to both pure and applied geology and attention is now given to the relatively recent development of new Formation divisions. This has meant returning to first principles. First, a stratigraphy has been constructed from the many cored boreholes, particularly in east London. From these boreholes, marker beds have been identified that provide reliable horizons for correlation (Mortimore *et al.*, 2011). Most of the marker beds identified through east London are also beds present in the main basinal areas for the Chalk to the south and west. Some of the marker beds, including the main marl seams, have been occluded where major hardgrounds coalesce to form rock bands such as the Chalk Rock and Top Rock of the Chiltern Hills and the Dover Chalk Rock of the North Downs in Kent.

Marker beds are being correlated with borehole geophysical wire-line logs to extend the stratigraphy into areas where no cored boreholes exist. By combining the wire-line logs with cored boreholes and field sections, maps of thickness, lithology and lateral variation are being developed as part of the research that should be published by the London Basin Forum in a Geological Atlas of the London Basin. In addition, the differential uplift and erosion of the Chalk in different parts of the Basin prior to commencement of the Thanet Sand Formation is being mapped from the age of the topmost Chalk.

The main outcomes from these recent and detailed stratigraphical studies of the Chalk in London are an ability to:

- (i) Locate faults and fault zones previously unidentified
- (ii) Identify the age of the Chalk immediately beneath the sub-Paleogene surface
- (iii) Interpret geophysical borehole logs and seismic sections.

These studies are thus providing a new understanding of the relationship between the tectonic structure and chalk sedimentation (Mortimore *et al.* 2011). The advantage of having a consistent lithostratigraphic interpretation to use when interpreting ground investigations throughout London is an ability to:

1) Identify the presence of major fault complexes displacing the Chalk
2) Distinguish where lateral variations observed within chalk sediments across the Basin are related to syn-depositional reactivation of folds and faults
3) Appreciate that styles and frequency of fracturing are stratigraphically significant as stratabound fracture sets, (Fig. 6) and that these fracture styles relate to syn-depositional phases occurring within tectonic pulses in the Late Cretaceous
4) Categorise fractures in the Chalk which are primarily related to tectonic stresses and recognise that these are usually preserved best in Chalk which is buried beneath thick Paleogene deposits and protected from the effects of Quaternary weathering processes
5) Predict the position of particular and sometimes troublesome layers, such as bands of large flints within the Lewes Nodular Chalk and Seaford Chalk formations
6) Recognise stratigraphic control of index properties such as intact dry density and porosity, and, to a lesser extent, unconfined compressive strength
7) Understand that groundwater flow is partly controlled by lithology with flow horizons occurring along sub-horizontal features such as sheet-flints and marl seams.

From these it will be appreciated that four of the seven developments provide insights into the behaviour of the basement during periods of important tectonism within Europe, and indeed the “featureless and uniform” chalk may yield some of the best evidence for reconstructing the history of the London region.

The remaining three developments have practical implications for applied geology. As engineering projects go deeper than ever before beneath London, the more often they are constructed in the Chalk, particularly tunnels (Mortimore *et al.* 2011). Projects such as the Channel Tunnel Rail Link, Docklands Light Railway, Crossrail, Thames Water Ring Main and the Thames Tideway Tunnel scheme**s** have or will be encountering Chalk. Consequently, there needs to be a good understanding of important elements of the Chalk affecting construction in terms of alignment and ground conditions, including the size and frequency of flints and flint bands and other lithological features such as hard-grounds and marl seams, which might affect ground stiffness, permeability and groundwater flow horizons. Equally important to engineering is the degree to which tectonics and weathering have influenced rock mass fracture characteristics (fracture openness, persistence, frequency, style, fill) and material strength as a function of density (Lord *et al.*, 2002). Features of the material, such as these and of the rock mass, are combined to assess potential engineering behaviour.

This research and its contribution to applied geology through projects of the sort mentioned above illustrate the need for a conceptual ground model in which all boreholes are correlated; in this way, project alignments in both the horizontal and vertical planes can be planned and the impact of subsequent changes assessed in terms of ground conditions and ground response. Such models would incorporate groundwater behaviour; however, the evaluation of groundwater resources in the Chalk aquifer requires its own conceptual model (Buss and Daily 2009; Royse *et al.* 2010, Fig. 7).

4. Lower Paleogene

The tectonic activity recorded in Chalk times was followed by a period of erosion and quiescence that, by the start of the Paleogene, placed London on the edge of a sedimentary basin incorporating a large proportion of the North Sea and probably extending as far east as Poland (Ellison *et al.* 2004). In this marginal position, Paleogene deposits were laid down during a period of repeated transgressions and regressions driven by global sea-level changes and or by tectonics (Knox 1996).

The oldest Formation is that of the Thanet Sands, with outcrops occurring in southeast London and northern Kent. The formation sits unconformably on the eroded Upper Chalk surface (Knox 1996). The Thanet Sand Formation in London is largely unfossiliferous and therefore we must still resolve how it correlates with the five lithological units identified using foraminifera assemblages by Hayes (1956) in the Thanet Sands in Kent. The basal unit, known as the Bullhead Beds, consists of up to 0.5m of clayey, glauconitic silt or fine sand with abundant, relatively unrolled (hence like 'bulls' heads'), up to cobble-sized chalk-derived flints. The bulk of the formation as seen in the greater London area is a coarsening upward sequence of dominantly fine to medium grained glauconitic sand which can be silty or clayey in places (up to 30m in thickness on the eastern side of the basin, Ellison *et al.* 2004). Leaching of heavy mineral suites at the top of the Thanet Sand Formation has been interpreted as evidence of uplift and emergence (Morton 1982).

The succeeding Lambeth Group, although relatively thin (10 to 20 m in central London), lithology is highly variable both laterally and vertically and consists of three Formations (Table 3; after Ellison, 1983, Ellison *et al.*, 1994, Ellison *et al.*, 2004). Skipper (1999) proposed a sequence stratigraphical interpretation which demonstrated that the Group had been deposited in three depositional sequences. This interpretation was used in Page and Skipper (2000) to invoke a predictive model and descriptive lithological stratigraphy (Table 3) which is now widely used.

The Group is a complex sedimentary assemblage that was deposited in shallow marine, estuarine, lagoonal, and fluvial to terrestrial environments, the result of what has traditionally been considered as eustatically controlled marine transgressions (Knox 1996, Ellison *et al.* 2004). The shallow marine to estuarine Upnor Formation, deposited over a wide area of SE England, is succeeded by the lower part of the Reading Formation, which consists of terrestrial, pedogenically altered (colour mottled) and fluvial sediments. The upper surface of the lower Reading Formation is described as the Mid-Lambeth Hiatus (Page and Skipper 2000), a useful marker horizon corresponding to an omission surface marking a basin wide fall in sea-level (Collinson et al 2003).

In the London area the lower part of the Reading Formation is succeeded by the Woolwich Formation, consisting of the brackish marine Lower Shelly Clays (grey laminated clay, with occasional silts and sands and abundant layers of shells) and the Laminated Beds (thinly laminated clay-silt and silt-sand, with frequent organic remains and occasional shell beds). These sediments thin rapidly westwards across London and are succeeded by the upper Reading Formation (mottled clays, silts and sands with the rare deep sand channel deposits). In the far west of the London Basin, the lower Reading Formation is succeeded directly by the upper Reading Formation; both lower and upper Reading Formations thin eastwards across the London area (Ellison et al 2004).

In south London (and rarely in east London), the upper Reading Formation sediments are succeeded by the upper part of the Woolwich Formation - the Upper Shelly Clays. Although in east London these manifest as similar sediments to the Lower Shelly Clays, in south London these sediments consist of up to 2.5m of firm to very stiff firm organic clays and silts and laminated dark grey shelly clays and silts and mudstones. The *Paludina* Limestone and Oyster Limestone occur within this unit and each comprise up to 250mm of moderately strong rock, the former having a freshwater monospecific fauna and the latter having an estuarine fauna (Dewey and Bromehead 1921, Ellison et al 2004).

One of the most interesting aspects about the Lambeth Group is its ability, as a rapidly changing and colourful sequence of sediments, to show fault movements (Fig. 8) which are much more difficult to identify in most other sediments in the London basin. This unique attribute enhances the importance of this otherwise thin and seemingly enigmatic group of sediments to the London Basin Forum project. Ground investigations carried out for major engineering projects across London such as Crossrail and the Thames Tideway project provide evidence that faulting, possibly syn-sedimentary, played a significant part in controlling the distribution of the Lambeth Group. This implies that the variability of environments of deposition in the group is not just eustatically controlled.

As part of the work of the London Basin Forum project, the British Geological Survey utilised 1400 recent digital site investigation borehole logs to review and modify the original lithofacies maps produced for the Lambeth Group by Ellison *et al.* (1994). The modified lithofacies maps have been compared with structures within the London area, as revealed by recent 3D geological modelling work (Fig. 9, Ford *et al.* 2010). It is hoped that future work aimed at producing a 3D geological model for the Lambeth Group under London will provide a clearer understanding of the structural controls on the distribution of sediments within this group.

5. The Thames Group

The Thames Group marks a return to marine conditions throughout the region, driven by pulsed global sea-level rise, with the coastline shifting far westwards from the present limits of the London

Basin. It was preceded by an episode of uplift and erosion, with its initial sediments, included in the Blackheath Formation and the overlying Harwich Formation, deposited disconformably on the Lambeth Group. The Blackheath Formation includes estuarine pebble-gravels and sands, filling deep channels incised into the Lambeth Group and underlying sediments. The Harwich Formation comprises mainly thin glauconitic sands and sandy glauconitic clays. All these units have discontinuous distributions. Although often thin, they have great significance for engineering projects, particularly tunnelling, due to their often highly permeable lithology and the development of hard calcareous concretions at several levels. These features have caused significant problems in some recent construction projects, and detailed mapping of individual units is currently under way as part of the London Basin Forum project (Fig. 10).

Overlying the Harwich Formation is the London Clay Formation, probably the most well known of all the Formations in the London Basin and having a significant influence on the development of London’s infrastructure. Its presence beneath much of central London, and its relatively homogeneous nature makes it a near perfect tunnelling medium, thus facilitating the development of the London Underground. The London Clay Formation, as its name suggests, is predominantly a bioturbated clay with silty and sandy clay intervals, with a maximum thickness of 130 m (Ellison *et al.* 2004).

It has long been acknowledged that the upper part of the London Clay is more sandy than the lower part (Whitaker 1866), but early attempts to subdivide it were held back by a lack of exposure and the relatively monotonous lithology. However, King (1981) used a combination of biostratigraphy and lithological variation, and the identification of marine flooding events, to define five divisions (A to E) which have in general been found to be laterally and vertically consistent throughout the London Basin (Fig. 11). Improvements to this detailed understanding of the succession have been made from boreholes drilled throughout the London Basin**,** most significantly the stratigraphic boreholes drilled as part of the BGS mapping programme in the London area and Essex (Bristow, 1982; Lake *et al.* 1986; Ellison *et al.* 2004).

The youngest Eocene sediments in the London Basin, the Bracklesham Group are predominantly sands, with some thinner clay units, largely removed by subsequent uplift and erosion, but preserved mainly west of London, forming the higher hills of Surrey and Berkshire. In north London these cap the hills of Highgate and Hampstead Heath. These are a complex series of sediments deposited in shallow marine and marginal marine environments, part of a formerly much more extensive sheet covering much of SE England.

6. Quaternary

By this time, the London Basin, as it would be recognised now, had been established for probably 20Ma. The long history of weathering and erosion commenced, with the ice ages dominating events by the magnitude of the changes associated with them. These changes were not just erosional and depositional; glaciers of considerable thickness moved across the country to the north of the Basin imposing transient loads to the ground, causing the crust to deform. Those deformations would probably have been accommodated in the "basement" by movements on various faults. Much happened in the Quaternary but for the purposes of this review, the materials of two environments are considered: weathering producing Clay-with-Flints and deposition, most notably of river terraces.

Quaternary deposits formed in the London Basin over a period spanning approximately the last 1.65 Ma. They provide evidence of an ancient river system, a precursor to the River Thames, glaciations of Anglian age in the north of the district, and the development of the present River Thames valley. Understanding Quaternary history is difficult because of the complex and discontinuous nature of the sediments and the incompleteness of the stratigraphical record, and this is particularly so in the London Basin where considerable anthropological disturbance also occurs.

Clay-with-Flints

Clay-with-Flints was originally described as *'stiff brown and red unctuous clay with large unworn flints and at the base a few inches of black clay with black coated flints'* (Hull and Whitaker, 1861). It outcrops on the Chalk plateaux around the edges of the London Basin, between the Chalk scarp and the main outcrop of the Paleogene. It is a very extensive deposit, covering an area of the Basin, as defined by the limits of the Chalk outcrop, at least as great as that of the fluvial deposits. Paleogene deposits extend from their main outcrop to merge into Clay-with-Flints. The maps of the British Geological Survey record exposures of Chalk between the Clay-with-Flints and other deposits, both periglacial and fluvial (Fig. 12). This apparent gap arises because the Survey's mapping convention is not to show deposits less than 1 m in thickness; thus the thin veneer of Quaternary deposits overlying much of the Chalk outcrop is unrecorded.

Clay-with-Flints is currently defined as an *in situ* residual soil derived from the Paleogene and the Chalk; it is underlain by intact Chalk. Remnants of weathered Chalk are confined to the clays immediately overlying the Chalk (Klinck *et al.* 1998) and consist predominantly of flint nodules along with a small percentage of clay and siliceous fossils. Pedological processes generated by infiltrating ground water redistribute the clay fractions within the soil profile. The smectite clays, in particular, are concentrated immediately above the Chalk surface, possibly carried in suspension. The concentration of smectite clays is reflected in the variation of the engineering properties of the deposits with depth, especially by their ability to take up water, as seen in their liquid limit, which increases towards the surface of intact Chalk.

The location and orientation of faults and joints in the Chalk is reflected by the distribution of the Clay-with-Flints seen in dry valleys that dissect the Chalk outcrop. Many dry valleys follow the major directions of brittle fracture associated with deformation within the London Basin, usually the direction of tension parallel to dip and one of the conjugate shear directions, unless the outcrop has been modified by local drainage patterns. Detailed mapping of the Paleocene clay-with-flints has revealed that the Paleogene deposits on which they are found are preserved within secondary flexures within the Chalk surface. For example, the 1: 50,000 scale Chatham Sheet (British Geological Survey 1972) shows that the Paleogene deposits are associated with asymmetric folds running down and along the dip slope of the Chalk.

The Clay-with-Flints should be differentiated from the adjacent Quaternary deposits with which they are often and confusingly associated, by their different fabric and content, as these reflect their methods of formation. Much Valley Gravel, for example, consists of original Clay-with-Flints that has moved into dry valleys by periglacial slope processes and in so doing, has been mixed with materials that have also moved down-slope, having been originally derived from Paleogene deposits and the Chalk.

River Deposits

The Thames system is the largest drainage basin in Britain. For convenience, it can be divided into three regions reflecting bedrock and river form, and referred to here as the Upper, Middle and Lower Thames. The Middle and Lower Thames occupy the London Basin. At this point the Thames is a broadly west to east aligned stream axial to the Basin, with tributaries entering from both the northern and southern margins (Fig. 13). In the extreme east, a large estuary occurs where the river and its drowned tributary valleys enter the North Sea. The deposits of the Thames and its tributaries occur from the tops of the highest hills on the Basin margin (180 m OD) to below sea level in the Thames Estuary (Fig. 13). The earliest Thames deposits, the so-called Pebble Gravel Formation, represent a fragmentary series of gravels composed predominantly of local materials, particularly flint. They postdate marine sands that are also found at up to 180 m OD on the margins of the London Basin, the occurrence of which indicate relative uplift of the western end of the Basin during the Pleistocene (Gibbard *et al.*, 1988, Mathers and Zalasiewicz 1988). The Pebble Gravels therefore represent the Thames and tributaries established immediately following regression of the sea in the Early Pleistocene (Wooldridge and Linton 1955).

A profound change in gravel lithology is present in the next youngest units, which form a series of terrace remnants that are characterised by their content of rocks exotic to the present Thames catchment. These units can be traced from the Upper Thames, where they are aligned parallel to the modern Thames tributary, the Evenlode, downstream through the Middle Thames Valley. Here they diverge from the modern course and pass through Hertfordshire, parallel the shallow Vale of St Albans and enter East Anglia where they form a terrace-like system, mostly buried beneath tills of the Anglian glaciation (Hey, 1980, Rose *et al.*, 1999, Whiteman and Rose, 1992).

Glaciation in the Anglian overrode the drainage system of east and central England, damming the Thames and its southbank tributaries north of London. This resulted in the river adopting a new course through London (Gibbard, 1994, Gibbard, 1985, Bridgland, 1988). Subsequent evolution of the Thames system has been marked by the cyclic development of a sequence of gravel and sand aggradations under periglacial climates during the Middle and Late Pleistocene. These aggradational members show a marked reduction in exotic material with time, accompanied by an equivalent increase in local lithologies as the deposits get younger.

The Thames Valley also includes many important interglacial fossiliferous sequences that provide both stratigraphical control and palaeo-environmental evidence. East of London, the valley was invaded repeatedly by the sea, so that, as today, a substantial estuary developed during periods of high eustatic sea level (interglacials). Submergence of the valley system has meant that offshore from south east Essex, a drowned course of the Thames and its tributaries occurs aligned towards the east and south east (Bridgland 1988; Bridgland *et al.* 1995). Upstream in the estuary, a thick wedge of Flandrian (Holocene) marsh and mud sediments accumulated (Devoy 1979). The current subdivisions are largely based on morphological evidence, however the focus is now moving towards one based substantially on geological sequences and their three-dimensional relationships. This change reflects the explosion of developments in Quaternary science in general. Today, the outcomes of this approach are in a phase of consolidation and although substantial changes are still possible, they are less likely now than some 20 years ago. However, much remains to be elucidated, particularly in terms of dating and finer stratigraphical resolution of the unfossiliferous parts of the sequences.

Of the problems remaining, the most obvious is the disagreement over the stratigraphical status of individual terrace aggradations. In the following section the lithostratigraphical approach of Gibbard (Gibbard, 1985, Gibbard *et al.*, 1988, Gibbard, 1994) has been adopted. In this system, individual sediment bodies are assigned *member* status, because this is thought to be the most appropriate hierarchical level; it is compatible with neighboring areas and with other unit classifications. The term *formation* has been used to refer collectively to members with broadly unified lithological characteristics. This is contrary to Bridgland (1994; 1988) who considers that terrace aggradations should be assigned formation status. Likewise, Bridgland favours *group* status for some of the formations defined below. Bridgland considers this necessary, because the complexity of the Pleistocene sequence requires the use of all available hierarchical levels (Bridgland, personal communication). The term Group has also been used by (Whiteman and Rose, 1992) to refer collectively to deposits previously termed Kesgrave Formation (Eastern Essex, note 1). However, some consider this term is too large scale for use in Pleistocene stratigraphy, by comparison of group status units in other parts of the geological column, and so no units of this rank have so far been adopted. More problematic is the means by which chronostratigraphical correlation of individual temperate character deposits is achieved both between sites and between the conventional terrestrial and ocean isotope stages. Conflicting results have arisen from the application of conventional biostratigraphical techniques, particularly palynology, and geochronology, particularly amino-acid racemisation. This has led to the Thames' sequence being subdivided chronostratigraphically using systems that stress different elements of the sequence (*cf*. Gibbard 1985, 1994; Bridgland 1994).

7. **Geological Structures in London**

In regional terms, London is located within the western area of the Anglo-Brabant Massif, north of the “Variscan front” and east of the Mesozoic North Sea rift system (Erratt *et al.*, 1999; Ellison *et al.*, 2004). Traditionally, the geology in London has been considered to be ‘relatively simple’ (Ellison *et* *al.*, 2004). However, observations and data collected from recent site investigations suggest that, in reality, the structure of the London Basin is more complex (e.g., Newton 2009; Skipper *et al*. 2009). The Chalk was deposited syntectonically over faulted basement blocks and it is these faults (Mortimer *et al*. 1997; Mortimer 2011) that controlled both its lithology and thickness. Modern alluvial deposits of the river Thames reveal multiple structurally controlled off-sets and flow patterns (de Freitas 2009), implying that fault movements in London have occurred throughout the Cretaceous and Tertiary periods and remain modestly active at the present day.

Because the majority of bedrock is buried beneath thick Quaternary deposits related to the development of the River Thames (Royse 2010) and/or the built environment of London, the nature and extent of faulting within London has been difficult to determine, but significant structural information can be inferred from an understanding of the structural controls imposed by these past tectonic events. We therefore need to consider each event in turn, identifying the brittle structures created by each event and the effects that subsequent tectonic events had on these structures. Three important events dominate the brittle structures found in the basement:

- The orogenies that formed Pangaea (Devonian - Carboniferous);
- The break up of Pangaea (Jurassic — Cretaceous);
- The Alpine Orogeny (Cretaceous — Tertiary).

Deformation within NW Europe has been dominantly compressional in the last 50 Ma, a consequence of the Late Cretaceous collision between Africa and Europe that led to the formation of the Alpine orogenic belt. These compressive stresses have been transferred through the Variscan basement that underlies NW Europe. This basement is cut by major fracture zones: the Silurian NE–SW fractures of the Caledonian orogeny and the later E–W and NW–SE trending end-Carboniferous fractures of the Variscan orogeny. London lies at the boundary between these two major basement fracture sets (Fig. 14), on the southern margin of the Midland Craton (part of the Anglo-Brabant Massif), a stable Proterozoic crustal block that separates the Variscan fractures to the south and Caledonian fractures to the north. Variscan structures therefore provide the dominant structural control on the geology of London.

London lies immediately to the north of the Variscan Front (VF in Fig. 14), the origin and nature of which are still debated (Shackleton 1984). In Pembrokeshire, South Wales, the basement rocks and their structures also crop out just north of the Variscan Front to reveal an approximately E-W trending Variscan fold/thrust belt, a tectonic regime compatible with their marginal position with respect to the main orogenic belt to the south. These folds and faults are now displaced by NW-SE trending wrench faults (Fig. 15) that are also related to the Variscan collision.

This superposition of two fault regimes is predictable. A fold/thrust belt is characterised by the minimum principal stress being vertical, but as the belt develops, the overburden stress increases until it becomes the intermediate principal stress, a regime that results in wrench tectonics. These wrench faults, together with the ~E-W trending thrust faults, divide the basement into multiple blocks of different sizes. The response of these blocks to later tectonic stresses during the break-up of Pangea and the Alpine orogeny is critical to understanding the depositional environments of, and structures developed within, the basin sediments.

During the Cretaceous in London, nominally N–S crustal extension was focussed along the E–W fractures of these basement blocks, causing individual blocks to subside in an irregular pattern of horsts and grabens into which the Chalk was deposited. The fractured boundaries of these blocks propagated into the overlying Chalk and now control the movement of groundwater in the Chalk aquifer, causing the observed grid-like pattern of drawdown and recharge.

8. The impact of geology on ground engineering in London

The intensity of development in London, coupled with its legacy of contaminated ground, vulnerability to rising sea level and size of population, all drive the need for establishing a geological model upon which planners, developers, engineers and insurers can rely. Examples of the geologically based problems to be solved are described below and illustrate the continuing need for such studies and the research currently being directed by the London Basin Forum.

Two aspects of geology that play a major role in the development of London are the success to which ground engineering can be accomplished in the sediments of the London Clay Formation and the management of the water resources of the Thames valley. These developments have been achieved as a consequence of long and continued research into the hydrogeology of the Chalk aquifer and the geology and mechanics of the London Clay Formation, through which many sections of the London Underground and utilities have been bored and in which major foundations have been sited.

In addition, all the studies to date in this recent phase of research show that the Formations in London have been affected by the reactivation of faults at depth, and this has significant implications for ground engineering. A major concern will be that faulting has divided the basin into compartments which have been able to move by different amounts vertically, relative to each other. It appears that neither the London Clay nor the aquifers beneath it can be relied on to have lateral continuity.

Much engineering has been completed within the London Clay Formation and as a consequence considerable banks of data have been accumulated in company and public records. A similar situation exists for the hydrology of the Chalk and water supplies derived from it. The value of such data for geotechnical engineering is considerable, because the subject relies so heavily on experience; however, the value of that experience depends on the confidence with which it can be used. That confidence is eroded if the data from one location cannot be used at another, because the body from which it comes is not laterally continuous between the two. Differences from place to place in a continuum can be explained as gradual change but that need not be so in a discontinuum; here, an abrupt change is expected, as can occur across faults. Thus the question arises, *"Is the London Basin divided into compartments by faults?"*

There are many lines of evidence relevant to answering this question; figure 16 illustrates some of the near-vertical structures known in the London Basin and should be compared with figure 17, which illustrates other possible locations based on the positions of tributaries of the Thames. At the very least, geotechnical engineering has good reason to consider the likely presence of faulting within the London Basin (de Freitas 2009; Mortimore *et al.* 2011). The sudden change in conditions which faults can create for sub-surface work, as revealed by the recent discovery of faulting at Plaistow (Fig. 18, Newman 2008), and 3D modelling of the Chalk (Fig. 7 Royse 2010) for the new hydrogeological model for the Chalk under London, are examples of what could be a widespread phenomenon.

The implications of faulting for ground engineering are many. Data banks of geotechnical properties for the Basin (Hight *et al.* 2001), need to be used with care, as differences may reflect more than just local variations in lithology. The fault zones themselves may be thin in the clays but broader in gravels and quite wide in the Chalk, where their internal structure could be more permeable than their margins, especially if the latter have been reduced by displacement to a putty-like consistency. Such faults could divide the Chalk into compartments, yet may also be able to support a flow regime of their own if hydraulically insulated by their boundaries. The difficulties of dewatering three sites in Docklands, situated above the Chalk in an area where faulting in the Chalk is known, are recorded by Linney and Withers (1998). Although Linney and Withers (1998) did not consider faulting at the time to be a contributory factor, the fact that each site behaved quite differently, even though they were separated by a little over one kilometre, suggests that faulting had played a part.

The sedimentological history of a Formation influences how the ground will respond to engineering and can influence the geotechnical risk of working within it. However, the ability to assess accurately the impact of the ground conditions depends on the quality of the ground investigation, which is itself influenced by the geology (Clayton *et al.* 1995). Ground investigations can introduce two sources of risk to a project: incomplete data, generated by either the sampling regime or result from drilling losses, and erroneous data. These contribute to the third and biggest ground risk, that of incorrectly interpreted data. Drilling losses are commonly experienced when harder materials occur within comparatively softer materials, and this can be a constant problem in the London Basin. A typical example is core loss due to pebble beds or concretions in clays, e.g., “claystones” in London Clay and flints in Chalk, and in pebble beds as found in the Harwich Formation, Lambeth Group and River Terrace Deposits.

The research carried out within the London Basin Forum has benefited from data generated by several large engineering projects that have procured high quality round investigations with detailed logging, closely spaced boreholes, sampling and testing to generate detailed profiles of both the geology and the engineering properties of considerable tracts of ground. The data from these profiles is used to model and predict ground movement in response to engineering work, and so link geological history to accurate models of ground conditions and reliable predictions of engineering performance.

The dewatering performance on the Jubilee Line was found to be influenced by the vertical variation in the permeability of the Chalk due to the (i) distribution of fissures, (ii) variation of infill on fissures and (iii) the presence of marl bands (Withers 1996). Large engineering projects through the Chalk (e.g., CTRL and Crossrail) have encountered consistent properties associated with each of the Chalk Formations. Research on the engineering properties of Chalk has demonstrated a clear link with the diagenetic history, especially on compressibility and stiffness (Clayton 1983). The Seaford Chalk which underlies much of London contains steeply dipping joint sets with consistent trends. The underlying Lewes Nodular Chalk contains inclined fractures which become more vertical and irregular as the Seaford Chalk is approached (Warren and Mortimore 2003). Detailed lithostratigraphic logging has picked up many new faults which produce higher and more irregular groundwater flows. Similarly, the flints vary in size and character systematically through the lithology. They can form considerable obstructions to ground investigations, cause excessive wear to tunnelling equipment and have significant impact on rubber-tyred plant on the surface. Tabular sheet flints can significantly affect groundwater flows and frustrate dewatering if not accounted for (Lord *et al.* 2002). However, they are very difficult to recover during ground investigations and can often only be inferred from a zone of core loss.

The Thanet Sand Formation, being shallow marine in origin, consists of fine grained sand which initially appears to be fairly uniform in character. However, particle size distribution tests in the Thanet Sand show a coarsening up sequence. This has caused problems for vertical dewatering at several shaft sites along the Jubilee Line Extension. Care has to be taken with filter design so as to retain the fines in the lower sections but not unduly restrict flow in the upper sections. This variation in fines content is not readily apparent from samples. It was by careful profiling of grain size and downhole geophysics that the increase in fines was clearly demonstrated (Withers 1996). It was also noted that the ability to profile the increasing fines content with depth is affected by difficulties in the recovery of representative samples (Linney and Withers 1998). Cable percussion drilling in granular deposits below the water table consistently struggles to retain the finer fractions of samples. This can affect permeability values derived from correlations based on grain size, a problem not just confined to the Thanet Sand.

The intense variability of the Lambeth Group gives rise to complex and challenging ground conditions for civil engineering works encountering it (Page and Skipper 2000). A better understanding of these deposits is critical for many current and future civil engineering projects, e.g., the Jubilee Line Extension (Bailey *et al.*, 1999) the Channel Tunnel Rail Link (Dyke and Glover 2007) and the development of the Crossrail network (Heath 2001); therefore widespread acceptance of training in its stratigraphy and logging techniques (Skipper 2008) is rapidly effecting an improvement in the understanding of this Group. The Lambeth Group contains sand channels reflecting the original tidal mudflats environment. These granular bodies can produce irregular groundwater flows when encountered particularly in tunnels and deep excavations, leading to instability at the tunnel face. The most famous case history of Lambeth Group instability is the construction of the Thames Tunnel by Brunel from Rotherhithe to Wapping (Hight *et al.* 2004). The initial ground investigation appeared to show significant thickness of clay. However, borings ahead of the face demonstrated that the clay was not continuous. There were many incidents during excavation of running sand and silt in the Laminated Beds. The most serious events caused the collapse of the overlying Upper Mottled Beds and inundation by river water. One collapse event was sufficient to irreparably damage the tunnelling shield. The collapses and inundations caused delays and resulted in the tunnel taking almost 20 years to complete.

Each of the lithological units within the London Clay has specific geotechnical properties of relevance to engineering within the Formation. In addition, the presence of silt and sand partings, claystones, concretions, pyrite and selenite have an influence on the behaviour of the London Clay and the design of structures within it. For instance, pyrite reacts with oxygen and water to produce acidic groundwater and a variety of minerals which have a larger volume than the original pyrite causing heave. The acidic groundwater can also attack cast iron and concrete structures in both tunnelling and highways environments (Hight *et al.* 2004). This is not just a problem with London geology, as it has been encountered in black shales especially where they were used as engineering fill above the water table (Steward and Cripps, 1983). It is therefore essential that in ground investigations the lithological units are clearly differentiated. Once this is achieved, it is then possible to start to make predictions as to how the ground might respond during major engineering works such as tunnelling. This type of study has been developed during recent major engineering projects and continues to be refined. One of the earliest engineering failures in the London area, the Highgate tunnel collapse of 1812, was the result of failure to appreciate that the London Clay was not quite as suitable for tunnelling as at lower levels in central London!

Drift deposits are not without their problems; for example, engineers have struggled with identifying, quantifying, describing and classifying Clay-with-Flints as a material, because of the apparently random distribution of flints within it. Sampling and testing regimes have often been conducted largely out of context of local geology, and this together with a reliance on traditional interpretation methods has resulted in the engineering parameters being poorly defined and unintentionally attributed to materials of different geological origin. Clay-with-Flints creates problems in engineering work for two other reasons: first, the finer fraction may have Atterberg limit values which are outside the specification for earthworks, and second, its highly irregular boundary with the underlying Chalk causes difficulty both for estimating earthwork volumes and for mixing materials from separate earthwork classes. Much remains to be known of this enigmatic material.

The thickness of drift deposits, e.g. river terrace deposits, is known to vary considerably within London (Berry 1979). Some of the largest “anomalies” have been described as filling “Scour features” or “Drift Hollows” and are associated with-an unexpected change in ground conditions where “host” strata such as the Chalk or the London Clay are eroded and replaced by collapsible granular materials with high=groundwater flows (Ellison et al 2004). They have been encountered in foundation excavations and in tunnelling projects both during the ground investigations and subsequent tunnelling, for example, for the Victoria Line (Berry 1979). The most famous example is the scour feature encountered as part of the investigation and construction of the Blackwall Tunnels. This feature was sufficiently large to have eroded through the London Clay and into the underlying Lambeth Group. Hutchinson (1980) has suggested that many of these features could have originated as pingos.

9. Hydrogeology

The Upper Cretaceous – lower Tertiary stratigraphic sequence of the London Basin hosts the regionally important Chalk aquifer, which as an unconfined aquifer forms the northern and southern flanks of the basin and becomes confined by the London Clay across the central regions. In places, the Chalk aquifer is overlain by sands of the Lower Paleogene, with the Chalk and Lower London Tertiary sequences together forming a hydraulically connected, layered aquifer system. In London, Quaternary-recent terrace gravels of the River Thames, overlying the London Clay, form a discrete shallow aquifer whose water table is much disturbed by near surface activity, the engineering of shallow drainage schemes, and by leakage from and to a multitude of service pipes (Gray and Foster, 1972; Price and Reed 1989; Price 2004). Locally, in the vicinity of the structures at Greenwich and at the sites of discrete solution/collapse structures of disputed origin (Berry 1979; Hutchinson 1980), direct contact between the Chalk aquifer and the shallow aquifer is established, which provides discrete routes for recharge (and potentially for contamination) of the aquifer at points throughout the confined region.

The earliest groundwater-sourced water supply for London from the Chalk aquifer was provided via an aqueduct, the ‘New River’, engineered at the beginning of the 17th Century to convey water by gravity from a Chalk spring on the northern limb of the Basin at Chadwell in Hertfordshire to Islington in north London (Ward 2003). Boreholes in the Chalk aquifer situated directly at the points of demand in London contributed substantially to water supply from the middle of the 19th century, when the construction of deep wells and extensive adits in the Chalk became possible through the development of steam-powered drilling rigs and lifting machines. Excessive groundwater abstraction from central London between the mid-19th century and the mid-20th century led to the decline of the potentiometric surface of the Chalk aquifer by close to 100 m, the transition from confined to unconfined aquifer conditions occurring over much of central London, and under-drainage leading to partial dewatering of the London Clay. Minimum water levels were reached between 1950 and 1970, by which time large-scale expansion of the public water supply system based on surface water treatment and storage had led to abandonment of most private boreholes in the urban centre and the onset of water level recovery of the Chalk aquifer.

Groundwater conditions across the central regions of the Chalk aquifer in the London Basin have been substantially modified by this history of excessive groundwater abstraction across the capital. Regional potentiometric recovery since the 1970s has had deleterious consequences for groundwater quality, and potentially adverse implications for the stability of deep foundations engineered in the London Clay and underlying formations. It has also provided the impetus for development by Thames Water Utilities Ltd of one of the largest schemes in Europe for management of aquifer storage to augment groundwater recharge.

The strategic importance of the Chalk aquifer of London led to it becoming the focus for some of the earliest quantitative hydrogeological studies and analyses of regional groundwater flow in the UK. These studies, broadly accepted as demonstrating geological control on hydrogeological structure and response to pumping, included:

- The first use of groundwater contours in a regional map of water levels (Joseph Lucas 1874)
- The first analyses of spatial variability of aquifer transmissivity in the Chalk, related to geomorphological context (Ineson, 1962) and of the scale of karst development associated with acidic recharge from focussed surface run-off (Harold 1937)
- Recognition of individual solution/collapse or pingo structures providing isolated routes for recharge and/or contamination of the aquifer throughout the confined region (Berry 1979; Hutchinson 1980)

- The first regional descriptions of groundwater chemical trends (Ineson and Downing, 1963)
- The first regional mapping of groundwater O and H isotopes (Water Resources Board 1972; Downing *et al.* 1979), indicating groundwater flow patterns and residence times
- The first application of C isotopes to groundwater dating in the context of a regional groundwater flow system (Water Resources Board 1972; Smith *et al.* 1976)
- The first measurements of groundwater tritium as an indicator of recent groundwater recharge and of rapid flow routes (Water Resources Board 1972; Mather and Gray 1973).

The 'rising groundwater levels' of the Chalk aquifer (Marsh and Davies 1983), more properly the 'potentiometric recovery' (and the associated pore water pressure recovery of the London Clay) have been of interest, and concern, to the present day, with implications for groundwater quality in the aquifer and the bearing strength at the depths of building foundations in the London Clay and the formations of the Lambeth Group and Thanet Sands.

The original contributions by the Water Resources Board, (1974) had been targeted at establishing the scope for 'artificial recharge' i.e. for strategic management/augmentation of storage in the Chalk aquifer beneath London. This was predicated on some of the earliest experiments in 'artificial recharge' (Boniface 1959; Hawnt *et al.* 1981; Flavin and Joseph 1983). It underpinned development during the 1990s of the largest operational scheme in the UK for the augmentation and management of groundwater/aquifer storage (the North London Artificial Recharge Scheme (NLARS) – O'Shea *et al.*, 1995; O'Shea and Sage 1999). The success of NLARS led to additional applications of 'artificial storage' south of the river Thames – South London Artificial recharge Scheme (SLARS), (Environment Agency 2010).

Knowledge and understanding of the aquifer acquired through these fundamental investigations has been applied to predict the hydraulic and hydrochemical response of the aquifer to recovery from the hydraulic minimum established under stressed conditions by the late 1960s/1970s. These predictions have been based on:

- Long-term regional monitoring of the aquifer potentiometric recovery and groundwater quality (e.g., Environmental Agency annual reports)

- Development of numerical groundwater flow models (Wilkinson 1985; Simpson *et al.* 1989; Lucas and Robinson 1995; Mott MacDonald 2000), used for guiding the control of London's rising water levels by strategically positioned groundwater abstraction boreholes
- Investigation of the hydrochemical implications of the rising groundwater levels for groundwater (artificial recharge) management schemes (Kinniburgh *et al.* 1994; Mühlherr *et al.* 1998) and engineered structures (Rainey and Rosenbaum 1989)
- Basin-wide determination of hydrochemical characteristics, including trace constituents, dissolved gases, environmental and radiogenic isotopes (Dennis *et al.*, 1997; Elliot *et al.* 1999)

The detailed monitoring of Chalk aquifer groundwater levels, and the requirements for improved calibration of the groundwater models, have indicated grid-like patterns in piezometric recovery and aquifer transmissivity, suggesting structural control not recognised in the early basin-wide studies. The emerging recognition of this possible structural control provides a basis for refining hydrogeological models of the basin (Buss and Daily 2009) and a context within which observations made during geotechnical site investigations at sites of faults and other structures may profitably be interpreted. These new insights offer the prospect of a more detailed understanding of the styles of hydraulic functioning of fault structures (*i.e.* the nature of internal hydraulic boundaries within the London basin), the stratigraphical distribution of hydraulically active fractures, and the relative significance and the origins of deep solution enhancement.

9. The Use of 2D and 3D modelling techniques in understanding the geology of the London Basin

If sound decisions are to be made, then organisations involved in planning and development need access to all relevant geo-environmental information (Royse *et al.* 2009). New and developing technologies allow geoscientists to present and communicate their information more effectively, especially to users of geology, many of whom are not geologists (e.g. planners, developers, financiers, insurers, engineers, Local Government officers etc), so enabling development strategies, from regional to local, to include geoscientific information at an appropriate level for their purpose.

The application of geoscience has two major problems to overcome. Firstly, the geological map; although an excellent way of recording several sets of 2D information on a flat surface, it requires a significant amount of expert knowledge to interpret its meaning. For the non-geoscientist, the geological map presents a confusing array of colours and lines, which have little relevance to the users' everyday working lives (Royse *et al.* 2008). Secondly, through changes in planning policy; these have caused a significant change in the users of geoscience information. Culshaw (2003) suggested that academic users were no longer the majority users of geoscientific information, but those working in the land-use planning sector; and as a consequence, geoscientists have to change the way their data is presented and visualised.

Turner (2003) indicated that generic products (of which the traditional geological map is a classic example) are often insufficient to meet the needs of a specific user group such as planners, suggesting instead that geoscientists should also produce customised products. However, before the geoscientist can produce such outputs, three questions must be considered:

1. What geoscientific information do planners and developers need?
2. What types of geoscience data are required to meet these needs?
3. Why are geoscientific data not always fully utilised?

Urban areas require geological resources for construction and maintenance (Marker, 1998). They also require geological data to ensure that sterilisation of resources or contaminative activities close to vulnerable aquifers do not occur. With these views firmly in mind, several authors such as: Brook & Marker (1987), Marker (1998), Bell & Culshaw (1998), Smith & Ellison (1999), Howland (2000), and Paul *et al.* (2002) have suggested the types of geoscientific data planners and developers require:

- Lithostratigraphical geology (at site, area and regional scale)
- Geomorphology
- The nature and use of ground materials
- The availability and quality of water
- The susceptibility of aquifers to pollution
- Natural and anthropogenic geohazards
- The engineering behaviour of the ground
- Land that may be contaminated
- Identification of development potential (constraints on and resources for development).

Two key advances have enabled geoscientists to change the way they present data to planners and developers (Royse *et al.* 2008). Firstly, the availability of geoscientific data in computer-readable (i.e.

digital) form (Bowie 2005; Jackson 2004) and secondly, advances in GIS and 3D modelling software which allow geoscientists to take account of the 3rd dimension and in the future the 4th dimension (time). It is now possible to view and manipulate 3D models on a standard desktop computer and, more importantly, the model can be updated quickly and easily when new data become available. These are major steps forward from previous 3D urban modelling systems (Strange *et al.* 1998) which required a significant amount of specialist computer knowledge and access to large computing capabilities.

In essence, the 3D geological model provides either a framework within which or a platform on which the integration and visualisation of data from many different sub-disciplines can be achieved. This allows the model to portray some of the natural heterogeneity of real geological systems (Culshaw 2005). The level of geological detail contained within the models will always be dependent on the amount and quality of the digital data available (Royse *et al.* 2010). Using this technology, a start can be made with predicting not only the type of rocks and soils that lie beneath the surface of London (Fig. 19), but also their physical and mechanical properties. For example, foundation conditions can be assessed by evaluating the ground at depth. In West Thurrock (Fig. 20), at 2m below the surface, nearly half the area is underlain by soils whose compressibility falls within the 'high to very high' category. At 5m below surface, only a small proportion of the same area contains highly compressible soils. Such data can be used in many ways, from predicting how long settlement might take, to choosing where to build. Robins *et al.* (2005) suggested that the 3D geological model could be improved, if it is combined with hydrogeological data, the two independent sources of data being used to complement and to check each other.

In this way, the 3D geological model can be used to show variations in hydrogeological properties for identifying the presence and location of high permeability units at depth. The 3D geological model constructed this way provides a means for assessing the potential hydrogeological performance of any lithological sequence modelled (Fig. 21). Thus it could be used to define either areas of likely recharge and discharge and to evaluate potential pollution pathways. If groundwater level data are added, the relationship between the potentiometric surfaces, geological units and the land surface can also be visualised (Royse *et al.* 2009). In summary, 3D attributed geological models are transforming the way geological maps are made and produced and changing the way groundwater modelling and ground investigations are carried out (Buss and Daily 2009). In the future, it is probable that ground investigations will become more focused on areas where either the engineering and hydrogeological behaviour is known to be anomalous or data is sparse (Culshaw, 2005).

A demonstration of this work will be the development of a new geological Atlas of the London basin by the London Basin Forum. Its task will be to distil the information now available for the London region and to synthesise it, in order to produce an holistic approach to the Basin, integrating its tectonic development, its record of sedimentation and its long history of uplift, weathering and erosion. This will be done using maps, sections, cartoons, 3D drawings and photographs.

Its data base will be integrated with that of the British Geological Survey, in a format that can be used by geologists, hydrogeologists, geotechnical and environmental engineers, and others involved with private industry and public works. In this way, the Atlas will become a geological basis for guiding local and national Government decisions concerning planning and development. To facilitate this, the text for the Atlas will address three levels of readership: geologists, users of geologists (mainly engineers) and users of geology (mainly planners and local government). In this respect, the Atlas is intended to be a key resource for science, industry and government.

Case histories will be presented that illustrate the practical consequences of geological controls on sedimentation and tectonics. These cases are drawn mainly from the construction industry but also include important examples from water supply, groundwater control and hydrogeology. Planning aspects are also to be considered, now that geo-data can be interrogated across the region, e.g. the propensity for swelling and shrinking of sediments beneath foundations and the incidence of insurance claims for structural damage resulting from these movements.

Such a resource is also of relevance to basic geological research, the region being a very well-documented example of the control that basement tectonics can exert upon sedimentation, stratigraphy, material properties, natural resources and neotectonics. The Atlas will not attempt to cover every aspect of the region’s geology but will concentrate on areas where high quality data exist to illustrate the various aspects of geological control on materials and their properties, and to provide the appropriate interpretation of geological data.

A framework for interpretation is one of the major contributions the Atlas will make for its users; those who work in London are usually not short of data; quite the reverse, the problem for many is too much data and no way of knowing how best to interpret it. The Atlas will provide a basis for placing the data from local sites, even large local sites such as Crossrail, into a regional framework. In this way, features of London's geology that have up until now tended to be "anomalous" may become predictable and the severity of the consequences of encountering them unexpectedly much reduced.

9. Summary and conclusions

There is as yet an untold history of the geology of the London Basin. Throughout the formation of its constituent strata, there is repeated evidence of tectonism, either by displacing strata that was once continuous, or by controlling rates and quantities of deposition, or by influencing the facies developed, or by subsidence, uplift and erosion, even up to the present day. There is much still to be learnt, but much can be achieved by using data already at hand and enabling one database to be compared with another over a common geographical area. This is the work of the London Basin Forum and the intended outcome of the Geological Atlas of the London Basin. Basic geological investigations are underway to re-evaluate the geological history recorded by the Gault and the Chalk, the Formations of the Paleogene and the Quaternary, and to compare this geology through time over the region of the basin, to reveal the existence and likely form of controlling structures at depth.

This basic research is therefore in sympathy with the pressures on urban space, above and below ground, as developers will need to make better use of the subsurface. In London, competing uses for underground space is requiring major new engineering projects to go deeper, thus associating themselves with higher stresses in geological formations whose strength is not easily able to carry them. Geological history, both sedimentological and structural, dominates the response of the ground and can influence geotechnical risk to a considerable degree. However, from the outset it should be stated that the ability to assess accurately the impact of ground conditions depends on the quality of the ground investigation. It has been said that you pay for a quality ground investigation whether you procure one or not (Terzaghi 1943). Ground investigations do not inevitably reduce risk; they can introduce risk by supplying incomplete or erroneous data. These contribute to the third and biggest ground risk, i.e. incorrectly interpreted data. The challenge is now on to bring together locally held geodata sets so that the data are properly archived, collated and made publicly available.

The current failure to share ground investigation geodata and knowledge about anomalous ground conditions in London has prevented the geological model for the Basin from evolving and therefore failed to reduce the risk to engineering projects of unforeseen ground conditions. The current model oversimplifies the geological structure of the region (Royse 2010). If nothing is done to improve this model, it will continue to result in unrealistic ground models and unreliable predictions (Wycisk *et al.* 2009). This is a situation that has already proved costly in terms of project overruns and is a continuing health and safety risk. An additional issue resulting in a failure to share geodata is that, currently, every major engineering project has to recreate a significant proportion of geodata, adding to the cost of each project (Hack 2009). It is important to realise that the value in having geoscientific information is not in the possession of it, but in its amalgamation and interpretation. It is only when all geo-information is collected together that a realistic model can be generated. Data, even when collected and presented, as in 3D models, still has to be interpreted, and it is clear that London lacks a sound basis for the interpretation of its geological data; hence the anomalies and unexpected situations. Here the synthesis of geological evolution in place and time provided by the Atlas throughout what is now the London Basin offers a framework within which data can be interpreted.

With current advances in the ability of Geographical Information Systems (GIS) and 3D modelling technology to handle large datasets on nothing more than a regular desktop PC, coupled with a basis for their interpretation, at least for London, a revolution has occurred in the way geo-environmental information can be viewed, manipulated and interpreted. This is enabling the construction of the 'next generation' of geological models for London that will provide a platform for integrating and visualising data from many different sub-disciplines, so allowing a model to portray some of the natural heterogeneity of real geological systems. As with all geological models, the users must understand the limitations of the data on which they base their assessments. This is becoming more critical as technological improvements are allowing geoscientists to introduce a far greater level of realism into their models.

As this paper has shown, the accuracy of these new models will not only be dependent on the density and quality of the data input, but also on the theoretical understanding of the underlying geology. A good example of this is in the understanding of the impact of faulting on geotechnical properties of rocks and soils within the Basin. It is apparent from this paper, that re-evaluation of geological data from ground investigations (both new and old) is proving that faults are not only more numerous than previously thought, but have had a significant impact on the development and deposition of sediments within the Basin. With the amount and complexity of future engineering work planned in the London Basin, such as the tunnels for Crossrail, scheduled for 2010 – 2017, Thames Tideway, scheduled for 2012 – 2020, (Tunnels & Tunnelling International 2007), and the cable tunnels for National Grid, scheduled for 2009 – 2016 (Tunnels & Tunnelling 2008), the presence or absence of faulting is becoming an ever more significant issue for which a new geological model is urgently required.

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Figures

Figure 1: Geological sketch map of the London Basin. Based on Sumbler (1996, fig 1).

Figure 2: Mesozoic structural setting (Sumbler 1996, fig. 8). Sumbler notes that the Southern and western boundaries of the London Platform are defined by basement faults but the northern and eastern boundary with the East midlands Shelf and North Sea Basin are gradational and arbitrary.

Figure 3: Geological cross-section across the region showing the ‘relatively simple’ geological structure of region as previously proposed by Sumbler (1996). Section based on Sumbler (1996, fig 2).

Figure 4: Colour-shaded Bouguer gravity relief map showing location of a broad tectonic boundary running east-west beneath the London Basin (dashed white line) From Ellison et al (2004). OS data ©Crown Copyright. All rights reserved. BGS 100017897 / 2009

Figure 5: Detailed lithostratigraphy of Chalk in London from Ellison *et al.* (2004).

Figure 6: Major persistent primary joints (many sheet-flint filled) and fault orientations in the Seaford Chalk Formation, Northfleet Quarries, north Kent. Adapted from Mortimore *et al.* 2011.

Figure 7: 3D model of Chalk Group under London (Royse, 2010). OS data & Crown Copyright. All rights reserved. BGS 100017897/2011

Figure 8: Photograph of a Thames Water rotary core from the Stoke Newington area (north London) showing lower Woolwich Formation (Laminated Beds) faulted against upper Reading Formation (Upper Mottled Clay).

Figure 9: Distribution of A) the Lower Mottled Clay of the Reading Formation (brown); B) the Lower Shelly Clay of the Woolwich Formation (green); overlain on monochrome shaded relief map of the base of the Paleogene adapted from Ford *et al.* (2010).

Figure 10: Distribution of the Blackheath Formation in London: a provisional version (2007), already modified by later information. The River Thames is shown in grey.

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Figure 19: 3D geological model of the Thames Gateway Development Zone from Stratford in the west to Canvey Island in the east (Royse et al 2008). Areas of peat (brown) are revealed beneath deposits of alluvium (yellow), river terrace deposits (orange) and anthropogenic deposits (grey). Bedrock is composed of Paleogene deposits (orange, blue and pink) underlain by Chalk (green).

Figure 20: 3D block model of the engineering geological classification of the area between Dartford and Thurrock (Royse *et al.* 2009).

Figure 21: Exploded volume model illustrating the Environment Agency's Water Framework Directive aquifer classification scheme for the East End of London (adapted from Royse *et al.* 2009)

Table 1: Summary of the geological strata of the London Basin from Ellison et al 2004 with Chalk Group thickness updated from Royse et al 2010

Table 2: Pre-Cenomanian stratal representation, depositional/erosional phases, principal events and distribution of sediments on the London Platform. Presumed extent of Middle (Callovian) and Late Jurassic sediments based on their development in regions adjacent to the Platform.

Table 3: Paleogene, after King (1981) and Page and Skipper (2000).