The Chalk revolution – the role of geological mapping for engineering and hazard assessment

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ABSTRACT Since the last Chalk symposium in 1989 in Brighton, our understanding of the UK Chalk has undergone a revolution, not just in terms of the stratigraphical and engineering properties of this enigmatic material, but also in its spatial distribution and variability in 2D and 3D space from geological mapping. The old tripartite Chalk stratigraphy has been replaced with a more detailed stratigraphical scheme with up to nine Formations. The increased stratigraphical precision this brings has revealed far more geological structure and facies variability across the outcrop than previously recognized. Most of the major basin boundary faults, including the Hog's Back, Mere and Pewsey Faults are now known to cut the Chalk sequence. Geological mapping has also provided a wealth of information on associated superficial and mass movement deposits, karst features and hydrogeology.

The role of the engineering geology community in providing data has been a key part of this revolution. High precision site-specific information from ground investigations including the identification of key stratigraphical marker beds in boreholes, quarry and coastal sections is critical in characterizing the Chalk succession. Such point-specific data combined with spatially extensive data derived from geological mapping data enables thickness and facies trends to be identified and allows the prediction of ground conditions over wide areas.

This paper provides insights into our understanding of the facies variability and structure of the Chalk from geological mapping, and how this can benefit the engineering community using specific examples. Also discussed will be what still needs to be done, and to outline new methodologies and techniques to take our spatial understanding of the Chalk to new levels. Advances in technology means that the Chalk is increasingly being visualized in three dimensions through the production of 3D geological models.

1 THE CHALK REVOLUTION

Over the past thirty years, our understanding of the Upper Cretaceous Chalk Group has undergone a revolution, both in terms of its stratigraphy, but also in our knowledge of its spatial distribution and variability in 2D and 3D space. This has been driven in large part by the demand for more detailed information on the properties of the Chalk for numerous engineering schemes and for groundwater management. This requirement for more information led to the initiation of a comprehensive program of geological mapping across the Chalk outcrop by the British Geological Survey which continues today.

The Upper Cretaceous Chalk Group crops out extensively in southern and eastern England, where it varies between about 200 and 560 m in total thickness. It mainly comprises fairly pure fine-grained microporous limestones, although with important variations in clay content, hardness, texture, fossil content and occurrence of flint. These lithological variations influence the engineering and hydrogeological properties of the Chalk (Mortimore et al., 1990; Warren and Mortimore, 2003; Mortimore, 2011) and topographic expression (Aldiss et al., 2012).

However, until the early 1990's geological maps of the English Chalk showed just three divisions: the Lower, Middle and Upper Chalk formations (Figure 1). These were based on the occurrence of two hard marker beds, the 'Chalk Rock' at the base of the Upper Chalk, and the 'Melbourne Rock' at the base of the Middle Chalk. The Lower Chalk was further subdivided into the Grey Chalk and Chalk Marl by the Totternhoe Stone. However, this subdivision was not without its problems. Whilst applicable in the Chilterns and to some extent the Berkshire Downs, the Chalk Rock and the Totternhoe Stone lose their identity away from this area and are not recognizable in Hampshire and the South Downs. Around Brighton, the Middle and Upper Chalk were grouped into a single undivided unit (Young et al., 1988). One of the problems with the tripartite scheme was that each unit lumped together significant lithological complexity, and were so thick that much of the structural resolution was lost.

The first attempts to lithostratigraphically subdivide the Chalk in a more useful way occurred in the

1970s, when the Ulster White Limestone (Fletcher, 1977) and then the Northern Province chalks were subdivided (Wood and Smith 1978). Subsequently, Mortimore (1986) demonstrated that the Chalk Group in the South Downs could be subdivided into many more lithostratigraphical units. Robinson (1986) devised a similar scheme for the North Downs. These lithostratigraphical schemes are far more applicable for engineering and hydrogeological applications.

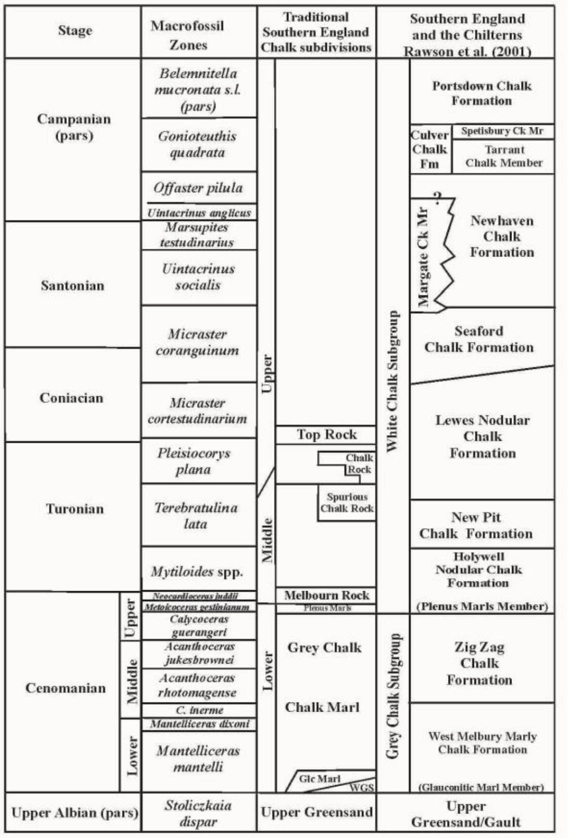

Figure 1. Stratigraphy of the Chalk of southern England and the Chilterns (not to scale) WGS: Warminster Greensand; UGS: Upper Greensand; Glc Marl: Glauconitic Marl; Fm: Formation; Mr: Member; Ck: Chalk.

The revision of the BGS Chichester, Wincanton and Shaftesbury 1:50,000 scale maps in the 1990's provided an opportunity to test the mappability of Mortimore's scheme across southern England. Extensive fieldwork showed that many of the lithological units identified by Mortimore (1986) were associated with distinct topographical features in the landscape and could be mapped accordingly. This led to the adoption of a revised Chalk stratigraphy for the southern Chalk province, based on mapping criteria (Bristow et al. 1997). This was subsequently revised and formalized in 1999 at a meeting of the Stratigraphic Commission of the Geological Society (Rawson et al 2001; Hopson, 2005).

The Chalk is now subdivided into nine formations (Rawson et al 2001; Hopson 2005) which can be mapped consistently across southern England (Figure 1). These formations can be further subdivided into units (members and beds) based on distinct marker horizons, mainly marl seams, sponge beds and flint bands. However, these cannot generally be mapped across unexposed ground, but can be identified in sections and borehole core enabling detailed correlations across wide areas.

2 GEOLOGICAL MAPPING

Field mapping is just one dataset used to compile a geological map. Other datasets used include previous field-slips, reports and memoirs, topographical maps including historical data, peer reviewed papers, fossil collections, remotely sensed data, borehole and section logs, geophysical data and site investigation reports. These are all compiled within a GIS environment to generate the final map. The use of new technology including digital mapping systems, LiDAR and other digital terrain models, and laser scanning of cliff faces and outcrops all contribute to improve the accuracy and resolution of geological maps.

Geological mapping of the Chalk Group south of The Wash is now based on the bulk rock mass character of the individual formations, and determining boundaries between these formations, rather than on tracing marker beds. The recognition of each lithostratigraphical unit is based on a whole rock approach, using all the available evidence including lithology, fossils and topographical expression. The apparently subtle lithological differences between the formations gives rise to observable contrasts in the field that can be mapped consistently across country.

The best evidence is obtained from outcrops such as coastal cliff sections, quarries and road cuttings where the exact stratigraphical horizon can often be identified. However, exposed sections are rare inland,

and many old pits are becoming increasingly degraded. Site investigation data can provide very detailed high resolution records of the geology but is often spatially restricted to individual sites or routes. Aside from pits, cuttings and boreholes, chalk fragments are commonly present in the soil ('brash'), in animal burrows, in fallen tree roots, temporary excavations and tracks/paths. These 'outcrops' often provide good evidence for lithology; the grainy and nodular textures of the Lewes Nodular Chalk and the Holywell Nodular Chalk formations in particular can be easily recognized. Flints with distinctive morphologies that occur at particular horizons (eg tubular and carious flints in the Lewes Nodular Chalk) can also be identified in brash.

These small outcrops also regularly yield fossils. Macro and microfossils can help determine the stratigraphical position of chalk fragments found in soil or tree roots. For example, the co-occurrence of *Platyceramus* and *Volviceramus* fragments, both of which commonly weather out in material ploughed up in fields indicate a level approximately coincident with the Seven Sisters Flint in the lower part of the Seaford Chalk Formation. Similarly, the occurrence of *Uintacrinus socialis* and oyster fragments associated with a break of slope and a change in lithology enabled the base of the Newhaven Chalk to be mapped across large parts of Hampshire. Trying to map out formation boundaries from quarry sections, boreholes or fossil localities alone ignores a huge amount of potential data and may lead to erroneous structural interpretations (Farrant et al., 2012).

Topographical features, particularly breaks of slope, are often associated with changes in underlying lithology (Aldiss et al., 2012). Where features are corroborated by lithological and palaeontological evidence, they can be used to help map formation boundaries. Similarly, particular types of landscape morphology are associated with certain formations; the Seaford Chalk for example, gives rise to very characteristic convex rolling slopes whilst the New Pit and Newhaven Chalk formations are often associated with steep scarp slopes. It should be noted that features by themselves are not used to map the chalk, but act as a useful guide to the underlying geology.

Using this approach, is often possible to identify sub-formational markers/units in the Chalk, even when they are not exposed in quarries or pits. The Stockbridge Rock Member, a very hard porcellanous chalkstone near the top of the Seaford Chalk was identified and mapped across Hampshire almost entirely from copious field brash. Similarly, hard sponge beds and glauconite stained hardgrounds often weather out in the brash and can sometimes be mapped locally. With experience, it is possible to infer intra-formational level from a combination of lithology, fossil evidence and topographical expression.

Mapping the modern chalk stratigraphy has led to a step change in the resolution of geological structure. The traditional Lower, Middle and Upper Chalk units were too thick to resolve any but the largest faults. The higher resolution offered by the new Chalk formations mean that much smaller faults, often down to 10 m of throw or less can be identified. Recent mapping has proved that many of the major inversion structures in southern England do not stop at the base of the Cretaceous as previously thought (Chadwick, 1986) but instead cut the Chalk and Palaeogene strata (Figure 2). These include the Mere Fault west of Salisbury major faults along the Hog's Back in Surrey and on the Isle of Wight, and the Flamborough-Howardian Hills fault zone in the Yorkshire Wolds. Similarly, previously unrecognized fold structures can now be identified.

The high resolution Chalk stratigraphy has been successfully mapped across much of southern Britain, including most of the Chalk outcrop in the Hampshire Basin (Figure 3) and the South Downs. Work continues in the Chilterns, the North Downs, and the Yorkshire Wolds.

3 APPLICATION TO ENGINERING GEOLOGY

As the new stratigraphy is based on lithology, it can be readily translated into engineering properties such as strength or fracture style. Thus modern BGS maps (freely available online via the BGS Open Geoscience website: http://www.bgs.ac.uk/opengeoscience/) provides significant benefits for engineering geologists, enabling the prediction of ground conditions over wide areas. The combination of detailed site-specific information from ground investigations and spatially extensive data derived from geological mapping can provide a far more robust ground model than relying on site investigation data alone. This is particularly the case for geological features such as faults or geological structure where evidence beyond the immediate project site may impact on engineering activity within the site. This can aid site characterization, improve engineering classification and provide a more robust evidence base for decision making on construction methods/specifications and the design of earthworks, machinery and equipment.

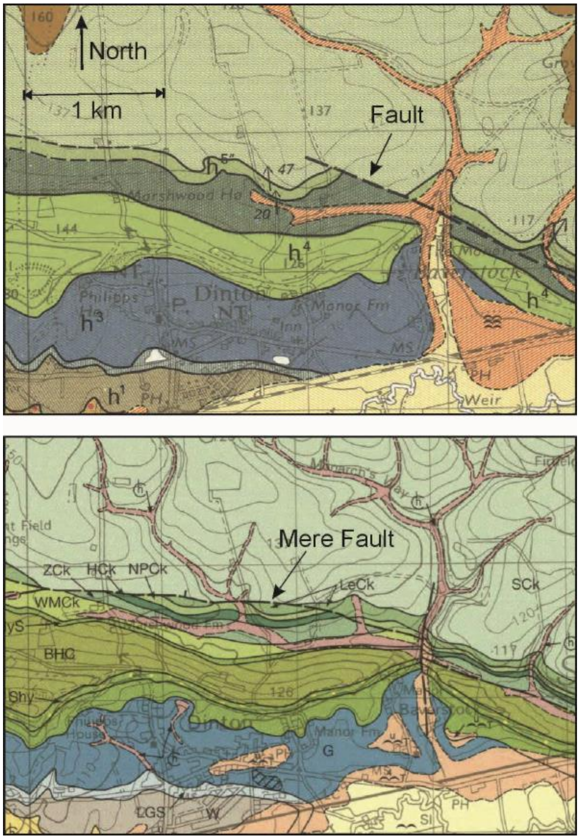

Figure 2. Geological map of the Dinton area near Salisbury. Upper map is based on the old chalk stratigraphy (published 1976). Although a fault is identified it is not well defined. The lower map is following remapping in 2005. The structure of the Mere Fault and its westward extension is clearly shown by the Chalk formations. Note also that the Upper Greensand (h4) is also subdivided into three units, thus improving stratigraphical resolution.

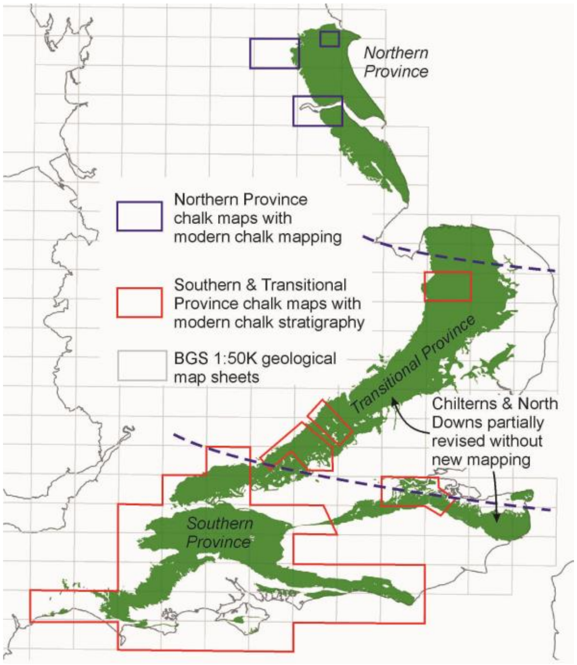

Figure 3. Area of the English chalk outcrop updated with modern Chalk lithostratigraphy. Parts of the North Downs and the Chilterns have been revised based on desk studies.

As well as providing baseline data, geological maps are increasingly used to generate a wide range of derived and applied products, including maps of potential hazards such as landslides and dissolution features (Figure 4), engineering properties and natural resources. The higher resolution afforded by the more detailed Chalk stratigraphy means that engineering properties and potential hazards can be mapped out in much greater detail, for example by identifying horizons or zones where karst features may be present (Figure 5), fault zones where weathered or destructured chalk may occur, or where particularly thick, numerous or continuous flint bands may prove problematic for tunneling. As mass fracture proprieties vary with lithology, the stability of excavations, cuttings and cliffs can be anticipated at an early stage. Similarly, the behavior of material in transport and as an engineering fill can be assessed.

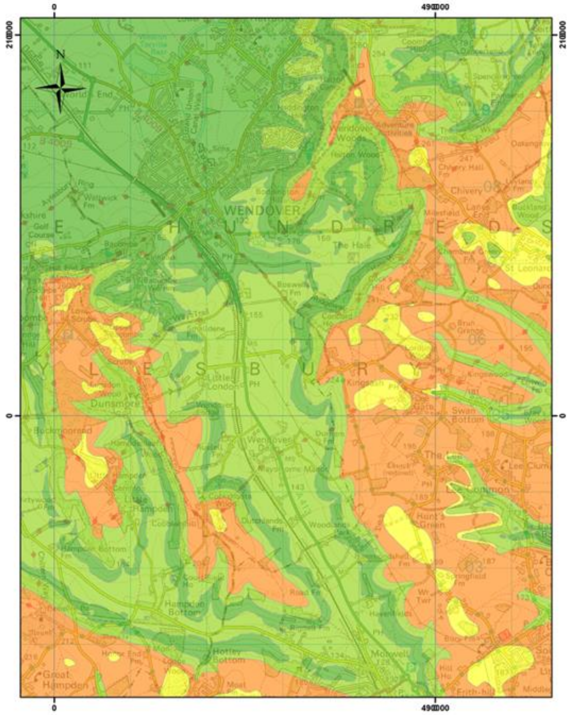

Figure 4. Derived map showing the potential for soluble rock hazards in the Chilterns. Orange represents areas with greater susceptibility to dissolution, leading to the generation of sinkholes, dissolution pipes and an irregular rock-head. Dark green indicates low susceptibility.

Figure 5. Karst dissolution features developed on the Severn Sisters Flint in the lower part of the Seaford Chalk Formation, Dieppe, northern France.

2D MAPS TO 3D MODELS

Increasingly, the detailed lithostratigraphy is being used to construct high resolution 3D geological models of the Chalk, enabling engineering geological ground conditions to be visualized in 3D space. These models can be interrogated through the use of synthetic boreholes, sections and slices (Kessler et al., 2009; Woods et al this volume) and 3D PDF's. Data derived from these models such as isopachytes or surfaces can be exported into other proprietary software, or visualization packages such as Geovisonary^{TM}. These models enable users to visualize and predict not only the type of rocks in the shallow subsurface, but also their engineering and hydrogeological properties. They can be used to assist in the recognition and identification of problematic ground conditions; as a tool to aid the planning process; to help locate ground investigations and to ensure that the most economical and valuable information is obtained from ground surveys. The models also enable regional trends in thickness and facies variations to be visualised along with structural features such as fault and fold axes.

Compared to the cost of invasive site investigation, geological mapping and 3D modelling is relatively cheap, has the potential to save time and money, and can be used for other purposes such as groundwater modelling, which may impact on engineering schemes.

Detailed mapping and 3D geological modelling has been used in several recent high profile engineering projects. Geological mapping, aided by high resolution macro- and micro-biostratigraphy, coupled with site investigation data for the proposed A303 Stonehenge tunnel enabled the spatial extent of the thickest phosphatic chalk sequence in Europe to be delineated (Mortimore et al, 2017). Similarly, geological mapping along the High Speed 2 (HS2) rail corridor through the Chilterns enabled the construction of detailed 3D geological models of the route. This has highlighted zones of potential faulting and areas where there is a high potential for karst dissolution features (Figure 4) and problematic ground conditions.

Moreover, modern technology means that these 3D models are no longer static objects. They can be updated as and when new data is obtained to create a dynamic ground model. The use of 3D models in this way can promote a cycle of risk reduction through the implementation of geotechnical risk management tools. This approach was used successfully during the construction of Farringdon station in the lithologically variable Palaeogene Lambeth Group on the new Elizabeth Line (formerly Crossrail) in central London (Aldiss et al., 2012).

However, as with geological maps, the accuracy and resolution of 3D models depends on the quantity and quality of 3D data. Having readily available, high quality borehole data with detailed logs is an essential pre-requisite for a robust model.

CONCLUSIONS

The application of a high resolution stratigraphy has revolutionized our understanding of the Chalk Group. The benefits of this more detailed geological understanding has been facilitated by detailed geological mapping of the Chalk outcrop across southern England, and increasingly through the production of detailed 3D geological models. New technology and datasets continue to help improve the accuracy of maps and models. The use of the Chalk stratigraphy in maps and 3D models means that site investigations can become more targeted, concentrating on areas where the engineering or hydrogeological behaviour is known to be complex, saving time and money.

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