Engineering Geology of the Quaternary

Dr David Giles*, School of Earth and Environmental Sciences, Burnaby Building,
University of Portsmouth, Burnaby Road, Portsmouth PO1 3QL
dave.giles@port.ac.uk

Mr Chris Martin, BP Exploration Operating Company Ltd, Chertsey Road, Sunbury
on Thames, Middlesex, TW16 7LN
Christopher.Martin@uk.bp.com

Mr Ron Williams, Formerly Mott MacDonald, Mott MacDonald House, 8-10
Sydenham Road, Croydon, CR0 2EE
rew182@btinternet.com

* Corresponding author

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Abstract

Throughout the 50 years of the Quarterly Journal of Engineering Geology and Hydrogeology papers have been published on case studies, site characterization and material geotechnical properties that have been influenced by the climatic and geomorphological environments experienced during the Quaternary. This period of geological time has left a significant legacy for ground engineering and construction projects with a complexity of ground conditions whose interpretation and understanding are crucial for the success of any such schemes. This review presents key papers that mainly focus on the effects of cold climates, both glacial and periglacial, developed during this time. Advances in landsystem description and ground model development published in the journal for these terrains are discussed.

Introduction

The importance of understanding the geological, geomorphological and geotechnical legacy of the Quaternary Period in the development of engineering geological ground models cannot be overstressed yet over the 50 years of the Quarterly Journal of Engineering Geology and Hydrogeology (QJEGH) and Engineering Geology Special Publications (EGSP) published papers, both academic and case histories, have not taken up a significant volume in the journals history. In excess of 150 papers have been published with a *Quaternary Engineering Geology* theme, with significant time gaps between the submissions. This review reflects on papers with a general Quaternary content, considering the early years of the journal, some key seminal papers, the 1989 Engineering Group Conference on Quaternary Engineering Geology and the subsequent EGSP (Forster et al. 1991), the Geological Society Glossop Medal Lectures and the 2017 Geological Society Engineering Group Working Party on Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains (Griffiths & Martin 2017). Notable case studies are also presented highlighting the development of *Quaternary Engineering Geology* throughout the journal's history.

The Early Years

The early years of QJEGH were influenced by two significant ground engineering events; the embankment and slope failures on the A21 bypass scheme at Sevenoaks in Kent (Weeks 1969) (Figure 1) and the embankment failure on the M6 motorway construction at Walton's Wood in Staffordshire (Early & Skempton 1972, 1974). The ground conditions encountered at both these construction projects had been affected by the legacy of a periglacial landsystem. The substantial slope and embankment failures triggered further investigation and research leading to significant advances in the understanding of periglacial slope processes (Weeks 1969; Higginbottom & Fookes 1971), solifluction (Chandler 1970, 1972; Harris 1977), cambering and valley bulging (Higginbottom & Fookes 1971) as well as the development of the concept of residual shear strength (Early & Skempton 1972, 1974). Perhaps for the first time in the engineering geological community there was recognition that these periglacial

phenomena were pervasive and widespread in southern Britain especially on clay-dominated lithologies such as the Weald Clay and Wadhurst Clay amongst others (Weeks 1969).

Figure 1 Trial pit and borehole, Quarry Hill, Tonbridge (Weeks 1969).

Work by Higginbottom and Fookes (1970) developed these themes into the first engineering geological conceptual ground models of these former periglacial environments, detailing a variety of periglacial features and engineering aspects that could be expected to be encountered in such terrains (Figure 2).

Figure 2 Idealised section showing typical field relationships of important periglacial features and deposits (Higginbottom & Fookes 1970).

Significant advances started to be made in the geotechnical characterisation of Quaternary deposits with works on a variety of glaciogenic tills (For example Funnell & Wilkes 1976; Marsland 1977; Eyles & Sladen 1981; Little & Atkinson 1988) and periglacial deposits such as loess (Fookes & Best 1969; Audric & Bouquier 1978). The papers by Kazi and Knill (1969) along with McGown (1971) and McGown and Derbyshire (1977) importantly started to develop the connection between the fundamental glacial processes, environment of deposition and consequent geotechnical properties of these materials. Although this early work has been much advanced, for example in a greater understanding of pre-consolidation pressures, these contributions set the theme for a variety of papers considering genesis and geotechnical behaviour.

The Seminal Papers – Boulton & Paul 1976, Fookes 1991 & Hutchinson 1991

Three papers in the Quarterly Journal of Engineering Geology and Hydrogeology and the EGSP's 50-year history can be considered to have had a significant impact on the development and understanding of the glacial and periglacial landsystem in relation to UK ground engineering. The first such seminal paper was published by Boulton and Paul in 1976 (Boulton & Paul 1976) which considered the influence of glaciogenic processes on the geotechnical properties of glacial soils. The fundamental principles of the transportation of debris within a glacial system, its consequent mode of release and deposition and the subsequent geotechnical properties were presented with examples from contemporary glacial systems. A key geological mantra is the *present is the key to the past*. Boulton and Paul detailed a range of geotechnical properties from glaciogenic soils from modern glaciers and defined what they termed a T-Line on the Plasticity Chart (Figure 3). They suggested that the T-Line owes its position relative to Skempton's A-Line to the difference in grading between glaciogenic tills and sedimentary clays. Although the merit of the T-Line remains under discussion this was an important milestone in the geotechnical characterisation of glaciogenic soils. The importance of till genesis in influencing geotechnical parameters especially with regard to grain-size distribution and its spatial variation, the stress history of the material, the soil mass structure including stratification and fissuring as well as post-depositional processes such as wetting-drying, freezing-thawing, material remoulding and the downward percolation of fines were all further developed. The paper was a reiteration to engineering geology that the understanding of material genesis through modern day analogues was critical in understanding the behavioural legacy of these glaciogenic soils.

Figure 3 Liquid limit / plasticity index plot for tills of known origin at the margins of modern glaciers (Boulton & Paul 1976).

Two papers published in 1991 resulting from the Engineering Group annual conference (discussed later) have also had a profound and long-lasting impact and influence on the development and understanding of the engineering geology of the Quaternary. The paper by Fookes (1991) on what he termed *Quaternary Engineering Geology* set out a framework for the wider understanding of the Quaternary environment with respect to its legacy for engineering geological ground conditions. Macro landsystems or *morphoclimatic regions* (Figure 4) were developed into conceptual ground models for engineering projects. The ideas of climate legacies were outlined with the paper dealing with cold, temperate and hot arid terrains.

Figure 4 World morphoclimatic regions, present climatic zones, simple geomorphology (Fookes 1991, 1997)

As part of the same conference proceedings Hutchinson (1991) contributed a paper dealing with the periglacial environment and slope processes. The full spectrum of the periglacial landsystem with associated processes, deposits and landforms were reviewed with respect to their relict engineering legacy in the UK. Hutchinson spatially delineated the occurrence of these periglacial phenomena and highlighted the lithological connections within the British stratigraphic column to the relict landforms present.

Figure 5 Main types of down-slope shear in clayey periglacial solifluction over a clayey sub-base (Type IIa). Minor, Riedel and other shears, and cross-slope shears are not shown (Hutchinson 1991)

The paper also highlighted the importance of recognising and understanding the engineering significance of relict periglacial shear surfaces that are omnipresent in these landsystems (Figure 5). Hutchinson presented a significant catalogue of periglacial phenomena that the engineering geologist should be aware of when developing conceptual ground models for sites influenced by these former periglacial climatic conditions. This work is a definitive contribution for all engineering geologists operating in such environments with such a periglacial legacy. Key periglacial processes such as solifluction, cambering, superficial valley disturbances (Figure 6), periglacially influenced landsliding, ground ice (including pingos), scour and anomalous depressions in the London Basin, the general influence of permafrost on the ground profiles are discussed in detail with relevant UK examples highlighting classic sites to observe these phenomena.

Figure 6 Preliminary classification of superficial valley disturbances in former periglacial areas of Britain (Hutchinson 1991)

The 1989 Engineering Group Conference and Engineering Geology Special Publication

It was 24 years since the first Quarterly Journal of Engineering Geology and Hydrogeology before the significance of the Quaternary to engineering geology was addressed via an Engineering Group Conference. The 25th Annual Conference of the

Engineering Group of the Geological Society at Heriot-Watt University in Edinburgh in September 1989 resulted in the 1991 Engineering Geology Special Publication on Quaternary Engineering Geology (Forster 1991). This work is a significant collection of papers on all aspects of the engineering geology of the Quaternary Period addressing key Quaternary background themes (for example Fookes 1991; Culshaw et al. 1991; Bell 1991a), Quaternary processes (for example Hutchinson 1991; Gostelow et al. 1991; Parks 1991; Spink 1991; Blight 1991), the geotechnics of Quaternary soils (for example Bell 1991b; Bell & Coultard 1991; Bell & Forster 1991; Paul & Jobson 1991; Gregory & Bell 1991; Marsland & Powell), engineering implications (for example Cruden & Tsui 1991; Harris 1991; Hossain & McKinlay 1991; Matheson & Oliphant 1991; Skempton et al. 1991) together with applied mapping of Quaternary terrains (for example Browne & McMillan 1991; Cornwell & McCann 1991). Both cold and temperate Quaternary conditions were discussed with summary papers reporting on the significant points presented (Fannin 1991; Little 1991; Muir-Wood 1991; Nash 1991; Petley 1991; Privett 1991).

The Glossop Medal Lectures

In 1997 the Engineering Group inaugurated the award of the Glossop Medal with the presenting medal winner invited to submit a paper to QJEGH. There have been four Glossop Lectures with a specific Quaternary engineering geology theme, notable Professor Peter Fookes in 1997 (Fookes 1997), Professor John Hutchinson in 2000 (Hutchinson 2001), Professor Denys Brunsden in 2001 (Brunsden 2002) and Professor Martin Culshaw in 2004 (Culshaw 2005). The *Fookes Glossop Lecture* focused on the geological model considering both ground prediction and associated ground performance in an engineering context (Figure 7). The importance of developing conceptual ground models with a specific reference to a variety of Quaternary environments and influences was presented, highlighting the ground conditions that could be expected by engineering geologists resulting from a Quaternary legacy. Highly practical ground models were extensively illustrated to enhance the understanding of the lateral and vertical variability in such relict Quaternary influenced environments.

Figure 7 Common periglacial effects in unglaciated parts of southern Britain (Fookes 1997)

The *Hutchinson Glossop Lecture* further developed these key themes (Hutchinson 2001) of geomorphology and ground models in Quaternary influenced settings. His paper considered the concepts of reading the Quaternary ground legacy resulting from former cold climates, both glacial but more specifically periglacial (See also Hutchinson & Thomas-Betts 1990). The paper presented a series of seminal case studies, which had been key in the understanding, and interpretation of such ground conditions. The concepts of Quaternary Provinces, areas of similar Quaternary influence and experience, were introduced building on previous works (Figure 8).

Figure 8 Quaternary Provinces of southern Britain and sites of landslides considered. The whole coastline is in Province T, except where features associated with earlier Provinces are being exhumed. (Hutchinson 2001)

The Quaternary geomorphological influences were the focus of the *Brunsdan Glossop Lecture* (Brunsdan 2001). He promoted the idea of a *Geo-Team* in order to fully

comprehend the complexities of a glacially and periglacially influenced ground profile (Figure 9). The need for civil engineers, geologists and engineering geologists to engage with Quaternary specialists was emphasised in order to cooperate in the development of ground models for these ground conditions, work building on the previous Fookes ideas.

Figure 9 The arena of work of the Geo-Team. The tasks listed for each discipline are indicative only and not intended to cover every subject. (Brunsden 2002)

The early Glossop Medal lectures and papers firmly established the *Conceptual Ground Model* as a key aspect of predicting ground variability and ground behaviour. The *Culshaw Glossop Lecture* built on these themes considering the attribution of 3D geomodels of the shallow subsurface, the zone most influenced by both Quaternary and anthropogenic processes (Culshaw 2005). The concepts of developing maps for engineering geology of superficial deposits linked to further lithological and geotechnical databases to describe and characterise Quaternary deposits was discussed at a variety of scales (Figure 10). The paper illustrated the potential of the then developing computer-based models for Quaternary ground condition prediction and interpretation.

Although not explicitly detailing with the engineering geology of the Quaternary several other Glossop Medal winners have made reference to Quaternary themes, for example de Freitas (2009) and Griffiths (2014).

Figure 10 Superficial Deposit thickness variation across part of the River Thames. Note the thinning (blue) associated with modern scouring along the current river channel. (Culshaw 2005)

Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains – Working Party Report and Engineering Geology Special Publication

In 2011 the Engineering Group of the Geological Society convened a Forum meeting on *Quaternary Engineering Geology*. A consequence of this event was the establishment of a Working Party with a remit to produce an Engineering Geology Special Publication considering the engineering geological and geomorphological aspects of glaciated and periglaciated terrains (Figure 11).

Figure 11 Geological Society Periglacial and Glacial Engineering Geology Working Party members (Left to right: Dr Sven Lukas, Prof. Julian Murton, Prof. David Norbury, Prof. Martin Culshaw, Prof. David Evans, Prof. Jim Griffiths, Ms Anna Morley, Prof. Mike Winter, Dr David Giles, Dr Mike de Freitas, Mr Chris Martin)

This Working Party report was subsequently published in 2017 (Griffiths & Martin 2017) as a set of chapters written by leading academics and engineering geology professionals (Figure 12). The book focused on the ground conditions associated with former Quaternary periglacial and glacial environments and their deposits from an engineering geological viewpoint. Coverage was given to modern processes and environments that gave rise to these materials but did not consider or define the geographic extent of these former environments around the world. The papers concentrated on developing ground models that would be applicable to support the engineering geological practitioner working in these terrains.

Figure 12 Engineering Geology Special Publication Number 28 (Griffiths & Martin 2017)

The EGSP had a British Isles focus drawing on multiple case studies from the annals of the Quarterly Journal to illustrate the nature and complexity of these relict terrains (Griffiths & Giles 2017). As with many Quaternary papers published over the 50 years of the journal only the legacy of cold glacials were considered, not the warmer interglacial stages. A key approach of the EGSP was to develop an extensive visual glossary of the deposits, structures (both macro and micro) and landforms that could be encountered in these former glacial and periglacial areas (Giles et al. 2017). A landsystems approach was adopted in order to provide the necessary building blocks to develop appropriate ground models for the engineering geologist and proposed construction project. Guidance was provided (Figure 13) on how to approach the development of such ground models for cold climate Quaternary terrains (Martin et al. 2017).

Figure 13 Flow chart for risk evaluation in relict periglacial and glacial environments (Martin et al. 2017)

In many of the previous QJEGH papers over the 50-year period of its publication there have been various attempts to define glacial tills. Terms such as *boulder clay*, *lodgement till* along with simply *till* have previously been widely used. In these more formal times with the requirement for highly detailed and specific materials description as defined by the Eurocodes and BS 5930 a major recommendation of the Working Party through the Special Publication was for a reclassification of glacial till for engineering purposes. The report specifies 4 principal glaciogenic materials that could be consistently recognised and logged by engineering geologists in the field, namely subglacial traction till, glaciotectonite, supraglacial mass flow diamicton / glaciogenic debris flow deposit and melt-out till were defined. These glaciogenic deposits were described in terms of their origin, mode of deposition and engineering properties.

Notable Case Studies

In the early years of the journal it was customary for practising engineering geologists to write up and publish case study material from their work projects. Sadly this practice has demised in recent years. Table 1 lists some notable such case studies published in the journal which present *Quaternary Engineering Geology* themes. These papers have mainly considered UK sites and provide to this day a valuable desk study resource. Table 2 lists significant published papers where the geotechnical properties of glacial and periglacial deposits have been reported.

Concluding Comments

Figure 14 The complexity of the ice-marginal environment. Modern day ice margin Skaftafellsjökull proglacial lake and moraines (Giles et al. 2017)

The relict Quaternary environment presents the engineering geologist and geomorphologist with a terrain that is inherently complex with a super position of processes that have led to a lateral and vertical variability of ground and groundwater conditions. Figure 14 demonstrates a modern example of such a complex terrain.

Engineering geologists deal with the legacy of Quaternary environments. These highly problematic terrains lend themselves to a landsystems approach in the development of ground models and risk registers. They are engineering environments where the multidisciplinary approach advocated by Brunsdon (2002) and the domain mapping and landsystem approach as illustrated by McMillan et al. (2000) are highly advisable. Quaternary science, geography, geomorphology, hydrogeology, hydrology, geophysics, geotechnical engineering along with the more fundamental aspects of geology such as the present is the key to the past and, as is being seen on the Crossrail project archaeology, all have a role to play in understanding the complexity of these terrains and solving engineering problems within them.

THE QJEGH and EGSP have made a tremendous contribution to this discipline over their 50 years and the impact on the published papers on the understanding of what Fookes termed *Quaternary Engineering Geology* should not be understated.

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Table 1 Selected case studies published with an engineering geology of the Quaternary theme.

Reference	Case Study Theme	Location
Banks et al. 2015	Anomalous buried hollows.	London, UK
Barker & Harker 1984	Location of buried tunnel-valleys using geophysical techniques.	Stour, Essex, UK
Berry 1979	Late Quaternary scour-hollows and related features.	London, UK
Chandler 1972	Periglacial mudslides and solifluction shears in low angled clay slopes.	Vestspitzbergen, Norway
Chandler 1970	Solifluction on low-angled clay slopes.	Northamptonshire, UK
Clark et al. 1979	Geotechnical aspects of a dry dock construction in potential quick clays.	Portavadie, UK
Croot & Griffiths 2001	Engineering geological significance of relict periglacial activity.	South and East Devon, UK
Early & Skempton 1974	Slope failures during construction of M6 motorway.	Walton's Wood, Staffordshire, UK
Fletcher & Nicholls 1984	Buried tunnels and valleys.	Orwell estuary, Suffolk, UK
Fookes & Best 1969	Consolidation characteristics of periglacial metastable soils.	East Kent, UK
Gostelow et al. 1991	Late and postglacial slope development.	Ironbridge, Shropshire, UK
Gregory & Bell 1991	Geotechnical properties of Quaternary sediments.	Belfast, Ireland
Harris 1977	Engineering properties, groundwater conditions, and the nature of soil movement on a solifluction slope.	Okstindan Mountains, Norway
Hawkins & Privett 1981	Building site on cambered ground.	Radstock, Avon, UK
Hutchinson et al. 1973	Landslides in periglacially disturbed Etruria Marl.	Bury Hill, Staffordshire, UK
McGown et al. 1974	Fissure patterns and slope failures in till.	Hurlford, Ayrshire, UK
Nichol 2001	Geo-engineering along the A55.	North Wales, UK
Phipps 2002	Engineering geological constraints for highways schemes.	Kinnegad to Athlone, Ireland
Skempton et al. 1991	Solifluction shears.	Carsington, Derbyshire, UK
Skipper et al. 2005	Engineering geology and characterization of till deposits.	Dublin, Ireland
Spink 1991	Periglacial discontinuities in Eocene clays.	Denham, Buckinghamshire, UK
Toms et al. 2016	Investigation of structure and geology of drift-filled hollows.	Battersea, London, UK
Weeks 1969	Stability of natural slopes as affected by periglacial activity.	South east England, UK
Younger 1989	Devensian periglacial influences on the development of spatially variable permeability in the Chalk.	South east England, UK

Table 2 Significant papers published considering the geotechnical properties of Quaternary deposits.

Reference	Geotechnical Properties, Glaciogenic & Periglacial Material	Location
Audric & Bouquier 1976	Collapsing behaviour of some loess soils.	Normandy, France
Barton et al. 1991	In situ density and shearing resistance of plateau gravels.	Hampshire Basin, UK
Bell & Coultard 1991	The Tees laminated clay.	North East England, UK
Bell et al. 2003	Metastability of gull-fill materials.	Allington, Kent, UK
Bell & Forster 1991	Till geotechnical properties.	Holderness, UK
Bell 1991b	Till geotechnical properties.	Norfolk, UK
Cotecchia & Chandler 1995	Geotechnical properties of Quaternary clays.	Pappadai Valley, Taranto, Italy
Denness 1974	Engineering aspects of chalky till.	Milton Keynes, UK
Eyles & Sladen 1981	Stratigraphy and geotechnical properties of weathered till.	Northumberland, UK
Farrell et al. 1995	Till genesis and geotechnical properties.	Dublin, Ireland
Fookes & Best 1969	Consolidation characteristics of periglacial metastable soils.	East Kent, UK
Funnell & Wilkes 1976	Engineering characteristics of Quaternary sediments.	East Anglia, UK
Gregory & Bell 1991	Geotechnical properties of Quaternary sediments.	Belfast, Ireland
Hossain 1992	Permeability of fissured tills	Scotland
Hughes et al. 1998	Glacial succession and geotechnical properties of Quaternary sediments.	Northern England, UK
Kazi & Knill 1969	Sedimentation and geotechnical properties of till deposits.	Cromer, Norfolk, UK
Kidson & Heyworth 1976	Characterisation of Quaternary sediments.	Somerset Levels, UK
Little & Atkinson 1988	Geological and engineering characteristics of tills.	St Albans, Hertfordshire, UK
Marsland & Powell 1991	Field and laboratory investigations of tills.	Garston, Hertfordshire, UK
Matheson & Oliphant 1991	Till suitability and acceptability for earthworking.	Scotland
McGown & Miller 1984	Stratigraphy and properties of alluvium.	Clyde Basin, UK
Northmore et al. 1996	Engineering properties and behaviour of brickearth.	South Essex, UK
Paul & Jobson 1991	Geotechnical properties of soft clays.	Witch Ground Basin, central North Sea, UK
Skipper et al. 2005	Engineering geology and characterization of till deposits.	Dublin, Ireland
Winter 2004	Acceptability of glacial tills for earthworks	Scotland
Zourmpakis et al. 2006	Loess collapse field trial.	Kent, England, UK

Figure 1 Trial pit and borehole, Quarry Hill, Tonbridge (Weeks 1969).

Figure 2 Idealised section showing typical field relationships of important periglacial features and deposits (Higginbottom & Fookes 1970).

Figure 3 Liquid limit / plasticity index plot for tills of known origin at the margins of modern glaciers (Boulton & Paul 1976).

Figure 4 World morphoclimatic regions, present climatic zones, simple geomorphology (Fookes 1991, 1997).

Figure 5 Main types of down-slope shear in clayey periglacial solifluction over a clayey sub-base (Type IIa). Minor, Riedel and other shears, and cross-slope shears are not shown (Hutchinson 1991).

Figure 6 Preliminary classification of superficial valley disturbances in former periglacial areas of Britain (Hutchinson 1991).

Figure 7 Common periglacial effects in unglaciated parts of southern Britain (Fookes 1997).

Figure 8 Quaternary Provinces of southern Britain and sites of landslides considered. The whole coastline is in Province T, except where features associated with earlier Provinces are being exhumed. (Hutchinson 2001).

Figure 9 The arena of work of the Geo-Team. The tasks listed for each discipline are indicative only and not intended to cover every subject. (Brunsden 2002).

Figure 10 Superficial Deposit thickness variation across part of the River Thames. Note the thinning (blue) associated with modern scouring along the current river channel. (Culshaw 2005).

Figure 11 Geological Society Periglacial and Glacial Engineering Geology Working Party members (Left to right: Dr Sven Lukas, Prof. Julian Murton, Prof. David Norbury, Prof. Martin Culshaw, Prof. David Evans, Prof. Jim Griffiths, Ms Anna Morley, Prof. Mike Winter, Dr David Giles, Dr Mike de Freitas, Mr Chris Martin).

Figure 12 Engineering Geology Special Publication Number 28 (Griffiths & Martin 2017).

Figure 13 Flow chart for risk evaluation in relict periglacial and glacial environments (Martin et al. 2017).

Figure 14 The complexity of the ice-marginal environment. Modern day ice margin Skaftafellsjokull proglacial lake and moraines (Giles et al. 2017).