British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Engineering Geology of British Rocks and Soils - Lias Group

LAND USE, PLANNING AND DEVELOPMENT PROGRAMME

Internal Report OR/12/032

BRITISH GEOLOGICAL SURVEY

LAND USE, PLANNING AND DEVELOPMENT PROGRAMME

INTERNAL REPORT OR/12/032

Engineering Geology of British Rocks and Soils - Lias Group

P. R. N Hobbs, D. C. Entwisle, K. J. Northmore, M. G. Sumbler, L. D. Jones, S. Kemp, S. Self, M. Barron, J. L. Meakin

Contributor/editor

K. J. Northmore

Keywords

Lias, geology, geotechnics, geohazards, mineralogy, hydrogeology, mudrocks, engineering properties.

Front cover

Top left – Mulgrave Shale Member at Runswick Bay, Norht Yorkshire; Top right – Lias formations at Robin Hood's Bay, North Yorkshire; Bottom – Black Ven Marl Formation at Stonebarrow, Dorset.

Bibliographical reference

HOBBS, P. R. N. ET AL. 2012. Engineering Geology of British Rocks and Soils - Lias Group. *British Geological Survey Internal Report*, OR/12/032. 323pp.

Keyworth, Nottingham British Geological Survey 2012

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the published product of a science-budget research study within the 'Engineering Geology of British Rocks and Soils' project of the British Geological Survey (BGS).

Acknowledgements

A large number of individuals have contributed to this project in terms of work input, expertise and general assistance. Collaborative assistance has also been received from individuals and organisations outwith the BGS. In addition to the collection of data, many individuals have freely given their advice. Many quarry and landowners have kindly provided access and assistance throughout. Engineering consultants and contractors have provided valuable information, and in some cases cores and other samples. Of the many individuals who have contributed to the project we would particularly like to thank the following BGS staff:

Prof. M. Culshaw

A. Forster

Dr. H. Reeves

M. Dobbs

R. Lawley

J. Bouch

L. Nelder

J. McKervey.

Dr. A. Milodowski

B. Cox,

J.W.C. James

Dr. G. K. Lott

Other reports in the series:

Engineering geology of British rocks and soils: **Gault Clay**. (1994) by Forster, A., Hobbs, P. R. N., Cripps, A. C., Entwisle, D. C., Fenwick, S. M. M., Raines, M. R., Hallam, J. R., Jones, L. D., Self, S. J., and Meakin J. L. BGS *Technical Report* No. WN/94/31.

Engineering geology of British rocks and soils: **Mercia Mudstone** (1998) by Hobbs, P.R.N., Hallam, J.R., Forster, A., Entwisle, D.C., Jones, L.D., Cripps, A.C., Northmore, K.J., Self, S.J., & Meakin, J.L. *British Geological Survey, Technical Report* No.WN/98/4.

Engineering geology of British rocks and soils: **Lambeth Group** (2005) by Entwisle, D.C., Hobbs, P.R.N., Northmore, K.J., Jones, L.D., Ellison, R.A., Cripps, A.C., Skipper, J., Self, S.J., & Meakin, J.L. *British Geological Survey, Internal Report* No.IR/05/006.

Contents

FIGURES

TABLES

Summary

The report begins with an introduction and a detailed modern assessment of the geology of the Lias Group in terms of both stratigraphy and lithology. The modern lithostratigraphy is placed in the context of the old, and sometimes more familiar, usage. The next two chapters deal with the mineralogy of a suite of samples collected for the project, and an assessment of the nature and influence of weathering based on a detailed analysis of the Lias dataset held in the BGS National Geotechnical Properties Database. The following chapters cover geohazards associated with the Lias Group, and a brief overview of the wide variety of industrial applications for which the Lias is well known. The geotechnical database forms the basis of the penultimate chapter, geotechnical properties. The contents of the database are analysed, interpreted, presented in graphical form, and discussed in terms of statistical variation and in the light of likely engineering behaviour. The engineering geology of the Lias Group is discussed in the final chapter, borrowing from the preceding chapters. A comprehensive cited reference list and a bibliography are provided. In addition to the large number of technical data provided to BGS, a small data set has been generated by BGS laboratories, particularly in areas where the main database was deficient, and also in connection with associated BGS studies of the swelling and shrinkage properties of the Lias Group.

The individual items of data making up the database are not attributed. However, the contribution of a wide range of consultancies, contractors, authorities, and individuals is acknowledged. It is hoped that this report will provide a source of useful information to a wide range of engineers, planners, scientists, and other interested parties concerned with Lias Group materials.

It should be noted that whilst quantitative technical data are included in this report, these should not be used as a substitute for proper site investigation.

1 INTRODUCTION

Lias is a name, which dates back to some of the oldest works of geology, signifying the earliest of the three sub-divisions of the Jurassic Period; the subsequent ones being the 'dogger' and the 'malm'. William Smith's (and the world's) first geology map of 1799 depicts the outcrop of the Lias to the northwest of Bath (Phillips, 2003). The Lias probably takes its name from the Old French word 'liais' referring to hard *layered* limestone (Webster, 1913). The Lias is characterised by mudstones interlayered with limestones.

In Britain, the Lias Group encompasses an important group of geological materials. It has been the working medium of major engineering projects, industrial exploitation, and scientific research. It comprises those predominantly clay-rich sediments of latest Triassic and Early Jurassic age found in and around the United Kingdom, deposited between 180 and 205 million years ago. The outcrop of the Lias extends in a continuous band from the coast of Dorset in a north-north-easterly direction to Yorkshire, with outlying areas in Somerset and South Wales (Figure 1.1). Significant outcrops are found in the high sea-cliffs on the coasts of Dorset, South Wales, and Yorkshire. This report is the result of an in-depth study of data generated by, and deposited with, the British Geological Survey over many decades. The report describes the geological, lithological, mineralogical and geotechnical features of the major Formations within the Lias Group; each aspect being dealt with in a separate chapter. However, in the geotechnical chapter not all formations are assessed due to lack of data. As a result there tends to be a bias in this chapter towards either clay-rich formations or the clay-rich or sand-rich members of a formation. The processes and effects of weathering are also considered in detail and are dealt with in a separate chapter.

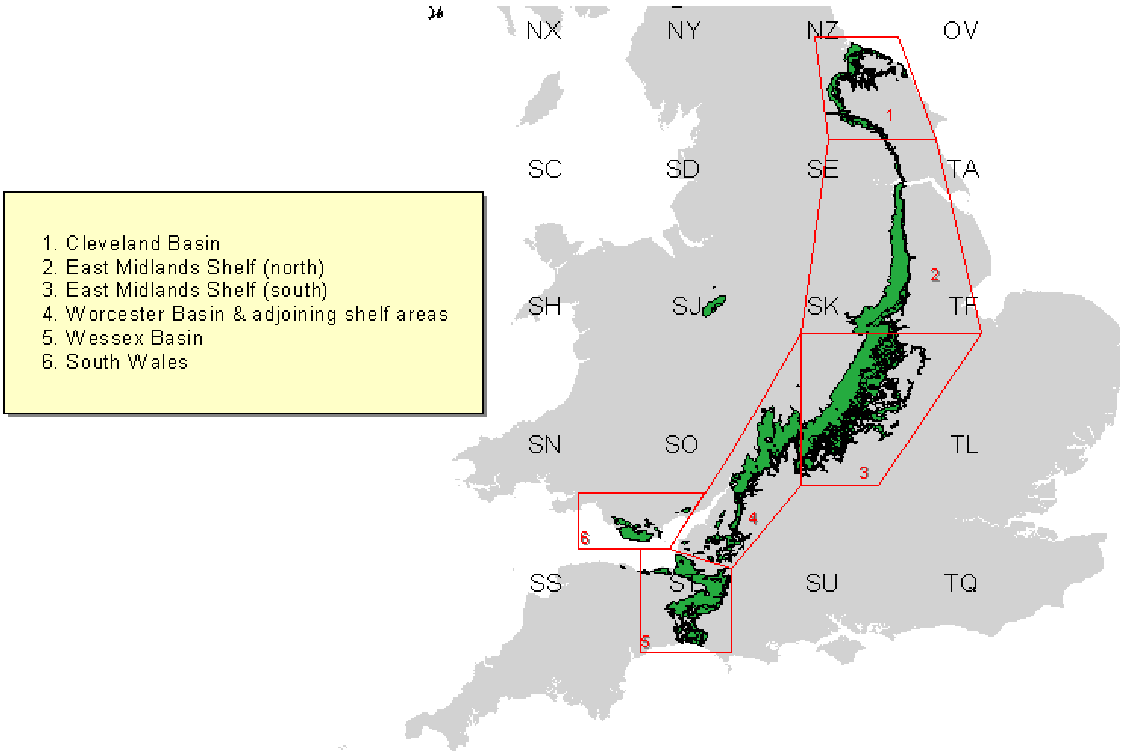


Figure 1.1 Map showing outcrop of Lias Group in England and Wales (green) and database Areas (red)

The Lias Group rocks were deposited in a Mediterranean-like climate in warm, shallow seas. Carbonates were deposited as limestone beds and nodules, particularly in the lower part of the succession, to form the Blue Lias Formation. The Lias Group is very fossiliferous, and ammonites in particular have been used to sub-divide the group into twenty bio-zones. Traditionally, the group has been divided into the Lower, Middle, and Upper Lias, but the succession is better described in terms of the formations, as defined by Cox et al. (1999). Of these, the main clay-bearing formations are the Blue Lias (Ambrose, 2001), Charmouth Mudstone, and Whitby Mudstone Formations. The sole major sand formation is the Bridport Sand, while the Dyrham Formation consists of siltstones and mudstones. Other formations, though much thinner and less well represented in the database, provide topographic features and have been important in terms of industrial exploitation. The Lias Group is best seen in coastal cliff sections in Dorset between Lyme Regis and Bridport, and also in Yorkshire between Robin Hood's Bay and Redcar where large-scale alteration of the landscape has been the legacy of a once thriving alum quarrying, production, and shipping industry (alum was used as a dyeing and tanning fixative). Slopes within the Lias Group have been subject to extensive landsliding and cambering, particularly where overlain by Inferior Oolite limestones, for example in the Cotswolds where both movement processes may be seen within the same valley. Shales within the Lias Group are often highly bituminous and lignitic. Lias Group shales are believed to be the source rock for oil reserves discovered within the Great Oolite at Basingstoke, Hampshire in 1980 (Duff & Smith, 1992). Ironstone bands are also found, for example within the Cleveland Ironstone Formation, and have been exploited for iron ore in the past.

The principal sedimentary basins in which the Lias was deposited are the Wessex, Bristol Channel, Worcester and Cleveland Basins (Figure 2.1). These had developed during the Triassic Period as a result of crustal tension and subsidence. During the succeeding Jurassic Period marine deposition and basin subsidence continued, building up great thicknesses of the Lias Group, with 400 to 500 m in the Wessex, Worcester and Cleveland basins, and some 1300 m near Llanbedr on the margin of the mainly offshore Cardigan Bay Basin, the thickest Lias succession proved in Britain (Woodland, 1971). Because subsidence was less rapid on the inter-basin 'highs' than in the adjoining basins, the successions there are substantially thinner and less complete, with the older parts of the Lias missing. Thus the base of the Lias tends to be younger when traced from the basins onto the highs (e.g. Donovan et al, 1979). The Lias Group is overlain non-sequentially by younger beds throughout southern and eastern England.

The Lias has undergone different amounts of induration and over-consolidation from one basin to another. This is largely determined by the thicknesses of sediment (Jurassic to Quaternary) that may once have overlain a particular site, and the amount of erosion that has subsequently taken place. For example, a maximum previous burial depth of the order of 2 km is indicated for the Cleveland Basin. This has resulted in greater strength ('strong' to 'very strong') and durability overall in the case of the northern Lias mudstones, compared with 'weak' to 'moderately strong' in the south. However, this trend is reversed for plasticity. Merriman & Kemp (1996) indicated burial depths of < 4km based on clay crystallite size. Fresh Lias mudstones tend to be strong and durable but, in common with other Jurassic clay-rich formations, undergo considerable deterioration of most engineering properties following stress relief and weathering (Cripps & Taylor, 1981). Weathering by oxidation, resulting in a colour change from grey to brown, typically extends to depths of about 5 m below ground level. This is accompanied by a significant increase in water content, resulting in altered engineering properties (Chandler, 2000). Shales are inherently weaker and less durable due to the marked anisotropy associated with this lithology.

Weak horizons within the Whitby Mudstone have contributed to the processes of cambering, valley bulging, and landsliding, for example in Northamptonshire, Rutland (e.g. Empingham), and the Cotswold escarpment (e.g. Bredon Hill, Broadway Hill, Leckhampton Hill) where it is overlain by Inferior Oolite limestones. Reworking of Lias mudstones imparts considerable loss of strength and trafficability. This is seen in quarries, particularly within the Charmouth Mudstone, after periods of rain. A good negative correlation has been established between strength and water content (Cripps & Taylor, 1987). Somerset's famous landmark, Glastonbury Tor, is made up of Bridport Sand Formation on Beacon Limestone Formation on Dyrham Formation; the latter also forming Wearyall

Hill west of the Tor. Brent Knoll, adjacent to the M5, also consists of Inferior Oolite overlying Lias Group rocks. These locations have also been subject to recent shallow landslides.

The most impressive exposures of Lias Group rocks can be seen in coastal sections where they are often affected by slope movement processes and/or modified by past industrial activity, for example:

1.1 NORTH YORKSHIRE COAST

The Lias Group rocks occur in the dales of the North York Moors, and intersect the North Yorkshire coast between Redcar and Scalby Bay. The cliffs here are very steep and in places exceed 200 m in height. In areas where the Lias Group rocks are overlain by significant thicknesses of superficial deposits, active coastal landsliding has taken place; for example, at Runswick Bay, Robin Hood’s Bay, Ravenscar, and Filey Bay. For over two hundred years from the mid 17th century a thriving alum quarrying and processing industry existed on the cliff tops between Saltburn and Ravenscar. The alum was taken from the Alum Shale Member of the Whitby Mudstone Formation. This industry has resulted in a distinctly man-made profile to many cliff sections in the area; for example the upper cliffs at Kettleness, Ravenscar, and Sandsend. Kettleness is also famous due to the discoveries, dating back to the 19th century but also very recently, of large marine reptile fossils, such as plesiosaurs, at the former alum workings. The Cleveland iron industry, the largest in Britain in its heyday, had mines and infrastructure dotted across East Cleveland, Rosedale, and Eskdale. On the coast, mining from the Cleveland Ironstone Formation was centred on Skinningrove and Port Mulgrave; at the latter location, the ore was transported from the top of the cliff to a small harbour at the bottom via an inclined tunnel within the cliff (Osborne & Bowden, 2001). A much smaller industry developed, in response to Victorian fashions, to extract ‘jet’ from lenses within the lower part of the Mulgrave Shale Member (Jet Rock).

1.2 WEST DORSET COAST

The Lias Group rocks intersect the coastline between Lyme Regis and WestBay, Dorset and, although not at their thickest here, are well exposed in the cliffs. This scenic stretch of coast is noted for both its abundance of fossils and its extensive and active landslide terrains. Perhaps the best known of the landslides are ‘Black Ven’ and ‘Stonebarrow Hill’, situated to west and east of Charmouth, respectively, and ‘Golden Cap’ further to the east. These are probably the largest coastal landslide features in England, and are also National Trust and World Heritage coastal sites. Black Ven and Stonebarrow have been active in recent times, affecting properties and services in Charmouth and Lyme Regis. The area is also famous for its fossil finds, including large marine reptiles such as ichthyosaurs, dating back to the mid 19th century, which have contributed to the foundation of palaeontology. The cliffs reach a height of 170 m in the central parts of the landslides. There have been many publications dealing with the landslides (Brunsden, 1969; Conway, 1974, Conway, 1976; Brunsden & Jones, 1976; Brunsden & Goudie, 1981; Gibson, 2005).

Whilst not having undergone the levels of industrial exploitation found in North Yorkshire, the West Dorset coast has been influenced by man’s activities. These include the construction of jetties, sea walls, rock-armour, and groynes, ‘quarrying’ of rock and gravel from the shore platform, and beach nourishment (Brunsden & Goudie, 1981). Some of these have had an adverse effect on beach volumes and on slope stability. Due to the prevailing southwesterly winds, the overall direction of sediment transport is to the east, though there have been sustained reversals of this trend. Jetties such as the Cobb at Lyme Regis, interrupt this process and allow depletion of beaches to the east of them. The landslide complexes of West Dorset, in particular Black Ven and Stonebarrow, supply large amounts of material to the shore. Black Ven, which has an estimated landslide volume about double that of Stonebarrow, nevertheless supplies over ten times the annual amount of gravel.

1.3 HEBRIDES

Although not described in detail in this report because of the absence of geotechnical data in the area, Lias Group rocks outcrop at many locations within the Inner Hebrides, including Raasay (Figure 1.2), Skye, and Mull. Here they mainly consist of pale-coloured sandstones and shales. These are frequently faulted, landslipped, and riven and altered by dikes. The Fiurnean Shale, Raasay Ironstone, and Portree Shale Formations (Toarcian, Upper Lias) outcrop in eastern Skye and Raasay. These are frequently obscured by landslides. Layers of jet are found in the soft, micaceous shales of the Portree Shale Formation, and are believed to be equivalent to the Mulgrave Shale Member (Whitby Mudstone Formation) of North Yorkshire. The Scalpa Sandstone (Middle Lias) is found underlying the shales, particularly on Skye and Scalpa, and consists of hard, calcareous, micaceous sandstone with sandy shale layers and doggers (Anderson & Dunham, 1966). This is in turn underlain by the limestones, sandstones, and mudstones of the Breakish Formation. Ironstone has been mined on a small scale from the Raasay Ironstone (Upper Lias) on the isle of Raasay.

Figure 1.2 South-east coast of Raasay (Skye in background) [BGS Photo No. P002828]

2 GEOLOGY

The Lias (or in strict lithostratigraphical terminology the Lias *Group*) comprises those predominantly argillaceous sediments of latest Triassic and Early Jurassic age found in and around the United Kingdom, deposited between about 180 and 205 million years (my) ago. Onshore, the main outcrop of the Lias extends from the coast of Dorset (Lyme Regis to Burton Bradstock) to Yorkshire and Cleveland (Ravenscar to Redcar), with outlying areas in Somerset and South Wales, although parts are concealed beneath Quaternary (drift) deposits (Figure 2.1). Typically the strata dip very gently towards the east or southeast beneath younger beds, and so the Lias is present at depth eastwards (downdip) of the main outcrop other than in the London area (see below). This account will deal principally with these areas but in addition, it should be noted that small drift-covered outliers occur in Cheshire/Shropshire, and near Carlisle in Cumbria, and the Lias also occurs in central Skye and at various localities on the northwest coast of Scotland, and emerges here and there from beneath the Tertiary basalts of Northern Ireland. It also occurs offshore from the mainland outcrops and is also present beneath Cardigan Bay but does not crop out onshore there.

Figure 2.1 Map showing outcrop and subcrop of the Lias Group in England and Wales with depositional basins, axes, and shelves

2.1 TECTONIC SETTING

Over a long period of time during the latest part of the Palaeozoic era, a period of mountain-building (the Variscan Orogeny) produced by continuing movement of the earth's tectonic plates, uplifted the area of crust in what is now northwest Europe such that, by the beginning of the Permian Period (about 290 my), the area of Britain became dry land. During subsequent periods, these orogenic stresses relaxed, but were replaced by tensional forces associated with the beginning of continental rifting and creation of the North Atlantic Ocean basin on the western margins of Britain.

In combination, these effects produced a gradual subsidence of the region and the development of a number of fault-bounded basins (graben), where subsidence proceeded more rapidly than on the adjoining highs. These sedimentary basins are the Wessex, Bristol Channel, Worcester and Cleveland Basins in which great thicknesses of sediments accumulated during the Triassic Period (Sherwood Sandstone and Mercia Mudstone Groups) (Figure 2.1). By Rhaetian times, at the end of the Triassic period (c. 210 my) the sea flooded these basins, depositing the marine mudstone and limestones of the Penarth Group ('Rhaetic'). During the succeeding Jurassic (from c. 205 my) marine deposition continued, building up the Lias Group which typically lies on a somewhat eroded, commonly (trace fossil) bored surface of the Penarth Group. Subsidence continued in the basins, albeit at a reduced rate and with some interruptions, again building up substantial thicknesses of Lias Group sediments; with 400 to 500 m in the Wessex, Worcester and Cleveland basins, and some 1300 m near Llanbedr on the margin of the mainly offshore Cardigan Bay Basin, the thickest Lias succession proved in Britain (Woodland, 1971).

The basins were bordered by structural highs (Figure 2.1), including the small Mendip High, between the Wessex and Worcester basins, and the much more extensive London Platform, to the east. Because subsidence was less rapid on the highs than in the adjoining basins the successions there are substantially thinner and, because the sea lapped onto them progressively, the successions are less complete, with the older parts of the Lias missing. Thus the base of the Lias tends to be markedly diachronous, becoming younger when traced from the basins onto the highs (e.g. Donovan et al, 1979). The highs were not inundated straight away and their interior parts remained land throughout the period of Lias deposition. Thus the London Landmass (i.e. the land area on the London Platform), diminished in size through the Early Jurassic, but some eastern parts probably remained dry land right through the Jurassic as (probably) did upland areas in Cornwall, Wales, Scotland and Ireland. However, the Pennines area was probably submerged early on.

Northwards, the London Platform merges into the East Midlands Shelf, a shallow marine area characterised by a more or less complete Lias succession of moderate thickness (typically 150 to 250 m). The smaller Bristol-Radstock Shelf is rather different, with thin and condensed successions, and could be regarded as the marginal area of the Mendip High. The Market Weighton High (or Axis) at the northern end of the East Midlands Shelf appears to have been an area of reduced subsidence throughout the Jurassic and, moreover, remained a high thereafter, such that Cretaceous rocks, which overlie the Jurassic unconformably throughout most of southern and eastern England, cut out all but the lowest part of the Lias Group there. The Vale of Moreton Axis, to the southwest of the East Midlands Shelf, was formerly perceived to have been an 'axis of uplift' similar to the Market Weighton High, but is now recognised merely as the hinge between the Worcester Basin and London Platform (Sumbler et al. 2000).

The Lias Group is overlain non-sequentially by younger beds throughout southern and eastern England. Erosion prior to deposition of these younger beds cut into the Lias beneath so that the upper part of the succession is incomplete to a greater or lesser degree from place to place. It is most complete, with the youngest Lias beds preserved, in Dorset and Somerset and parts of the Cleveland Basin of Yorkshire. Conversely, the Lias is thinnest and least complete approaching the Market Weighton High and at depth on the interior of the London Platform. In these areas it is progressively overstepped by younger Jurassic and Cretaceous beds until it is cut out altogether.

2.2 SEDIMENTS, STRATIGRAPHY AND NOMENCLATURE

During the early Jurassic, the region that is now Britain lay somewhat closer to the equator than at present, probably at a latitude equivalent to the modern Mediterranean area. Accentuated by the presence of a large northern continental mass, and the lack of a major North Atlantic Ocean at that time, the climate and seas which gradually overwhelmed the region were warm. The seas were shallow; even in the basins, it seems that sedimentation generally kept pace with subsidence so that the water was generally no more than a few tens of metres in depth. Away from the contemporary shorelines, conditions were remarkably uniform over the whole area of deposition so that many beds can be traced across large areas of the country.

Sediments, mainly muds, were washed into the seas by rivers on the adjoining land areas, building up the succession of Lias strata. Much of the succession is more or less calcareous and limestone nodules or beds are developed at many levels most notably at the local base of the succession, having been deposited when the seas were particularly shallow. In some areas these basal beds include pebbly and shelly limestones evidently laid down close to the contemporary shoreline. Sands and silts may represent climatic events, which washed coarser sediments into the sea, and are also associated with two main periods of basin infill and general shallowing (see below).

Life was abundant in the warm shallow sea, and much of the Lias is very fossiliferous, with rich and varied faunas dominated by molluscs, especially bivalves, gastropods, ammonites and belemnites, and with brachiopods also abundant in some beds. Bones of marine reptiles and fish also occur more rarely. For purposes of stratigraphy, the ammonites are the most important fossils of the Lias, providing the basis for chronostratigraphical (age-based) classification, enabling correlation on a worldwide scale. The Lias has been divided up into some twenty zones (and over 50 subzones) based on ammonites (Figure 2.2); a typical ammonite zone represents about 1 to 1.5 million years. Good exposures or cored boreholes are needed to apply ammonite zonation. However, microfossils such as ostracods, foraminifera and dinoflagellate cysts can also be used for zonation, and are particularly useful when dealing with borehole chipping samples. Unfortunately the stratigraphical resolution is, as yet, less precise than the ammonite-based standard.

Stratigraphy is the study of bedded (usually sedimentary) rocks, particularly in terms of their age and correlation with equivalent beds elsewhere. It has many different branches of which some of the most fundamental are:

Lithostratigraphy, the subdivision of the rock succession into units on the basis of its physical characteristics or lithology, and involves the differentiation, delineation, classification and formal definition of such units (Groups, Formations, Members, Beds) and their depiction on geological maps and sections.

Biostratigraphy is the subdivision and correlation of the rock succession based on its contained fossils. Particular [bio] zones may be recognised from the presence of a particular fossil or fossil assemblage.

Chronostratigraphy is the subdivision and classification of the rock succession into [chrono] zones, stages and systems according to its age.

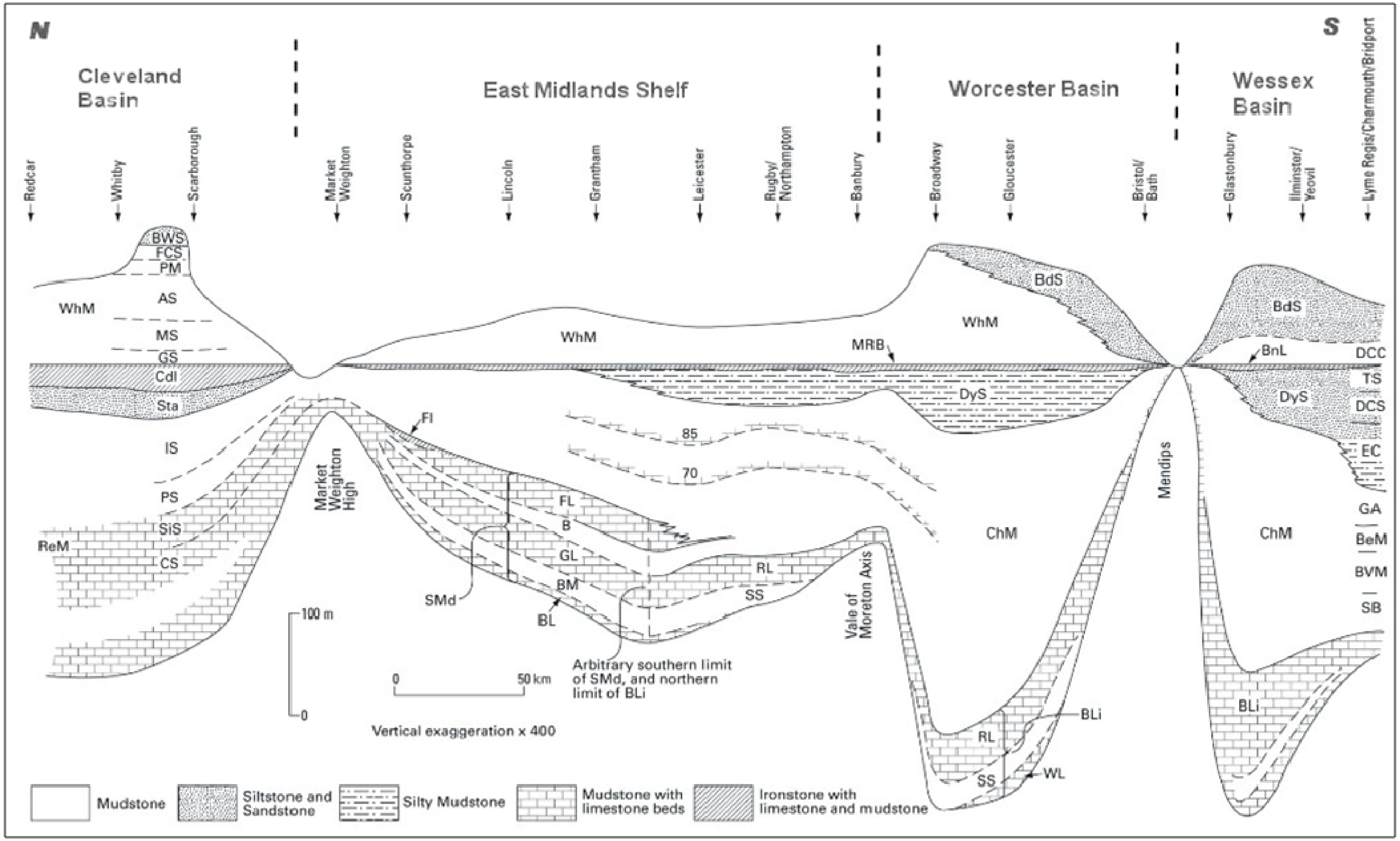


Figure 2.2 Section showing lithostratigraphy and depositional basins (refer to Figure 2.1 for locations and Table 2.2 for abbreviations)

Within the constraints provided by the fossil-based zonation, detailed, bed-by-bed correlation is generally best achieved by detailed comparison of lithological logs of boreholes and sections. For uncored boreholes, downhole gamma ray, sonic and other geophysical logs are valuable tools for correlation, being records of the physical properties of the rocks. Within the Lias, the gamma log essentially reflects the ‘muddiness’ (clay and silt content) of the rocks, and the sonic log measures the hardness of the sediments. Thus mudstones tend to have high gamma counts and low sonic velocities, whilst with limestones and sandstones the converse is true. Even at this basic level, it is often relatively easy to discern the characteristic lithological changes that define the formations and members of the Lias Group.

The rocks of the Lias Group were first studied systematically during the early and middle part of the nineteenth century. They became recognised as a distinct unit of strata, being largely dominated by clays and mudstones, yielding marine fossils, and contrasting with the red Triassic ‘marls’ below and the limestone and sand-dominated Middle Jurassic ‘Oolites’ and ‘Estuarine’ beds above. The Lias was split into a number of units and subunits based initially on lithological character. At the most basic level, it was perceived that the Lias could be divided into three parts, Lower, Middle and Upper Lias. In central England, for example, the succession comprised lower and upper divisions of mudstones separated by a middle division of sandy beds and ironstone. As geology progressed, and greater emphasis was placed on the importance of fossils for correlation, the traditional divisions Lower, Middle and Upper Lias became used variously as litho-, bio- or chronostratigraphical units and, as a result, positioning of their boundaries by different workers has been inconsistent. The same confusion of different disciplines of stratigraphy is inherent in the term ‘Liassic’, generally used in a quasi chronostratigraphic sense as a synonym of Lower Jurassic. Similar problems surround the usage of the numerous other stratigraphical terms, which have been used to describe subdivisions of the Lias Group.

In an attempt to rationalize the plethora of names, and clarify understanding, a revised scheme of lithostratigraphical classification for the Lias Group has recently been developed by the BGS with the support of the Geological Society of London. This scheme (Cox, Sumbler and Ivimey-Cook, 1999), which divides the Lias Group into no more than 12 formations, is followed in this report, and is recommended that all workers should adopt it when describing rocks of the Lias Group. Terms such as Lower, Middle and Upper Lias, and Liassic should no longer be used in formal accounts. It should be noted that it will be some time before the recommended terminology is fully implemented on BGS geological maps.

Dealing with the main depositional areas of the Cleveland Basin, Wessex Basin and Bristol Channel Basin (Somerset and South Wales), Worcester Basin and East Midlands Shelf, the approach adopted is one of unification, emphasising similarities between areas rather than differences, whilst retaining well-established names where possible. The scheme used in these different geographical areas is shown in Table 2.1 and Figure 2.3 and the geographical limits of the various units are shown in Figure 2.2. Table 2.2 lists the current lithostratigraphic terms (in alphabetical order) with their former names or equivalents.

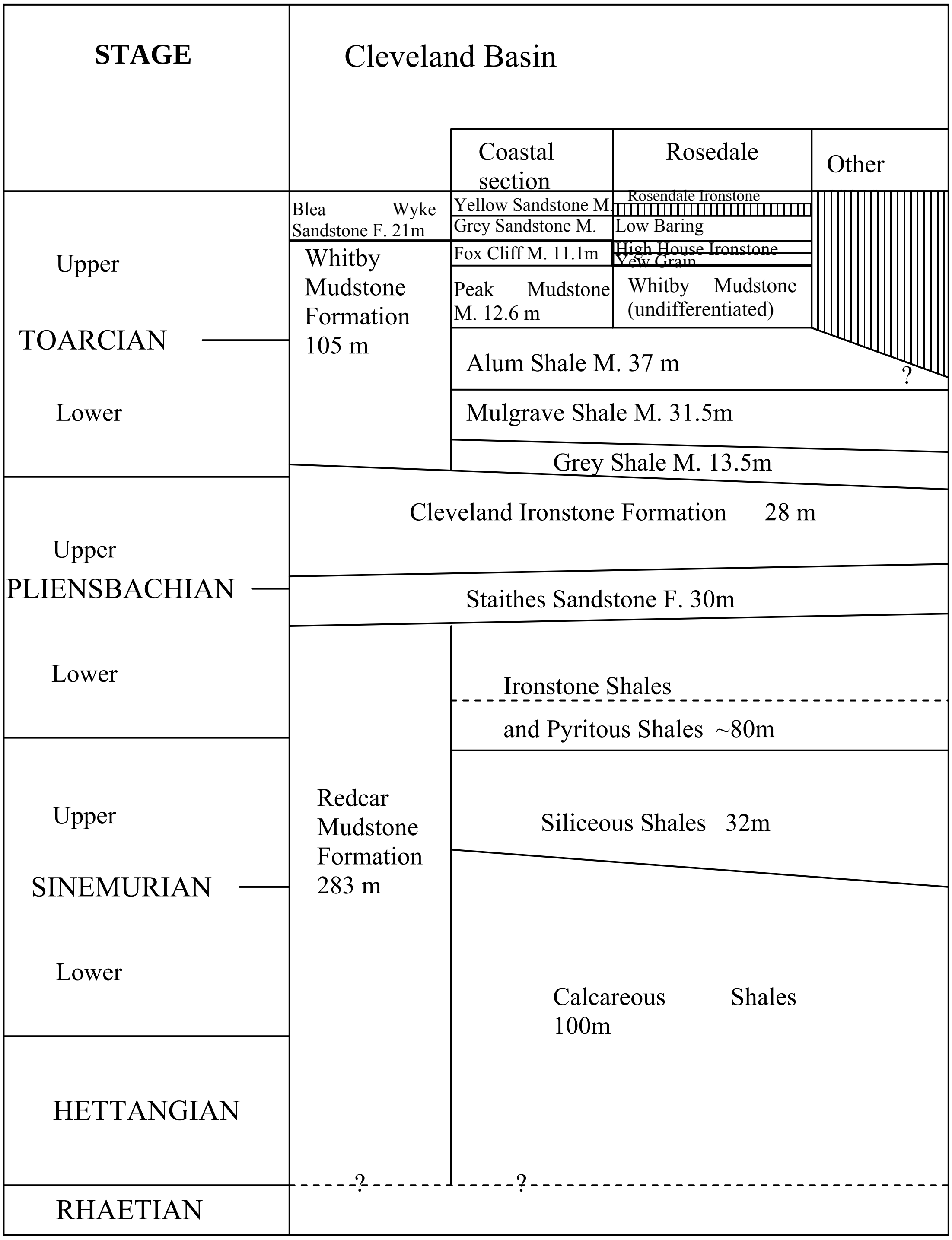


Figure 2.3 Lias stages, formations and members showing regional variations.

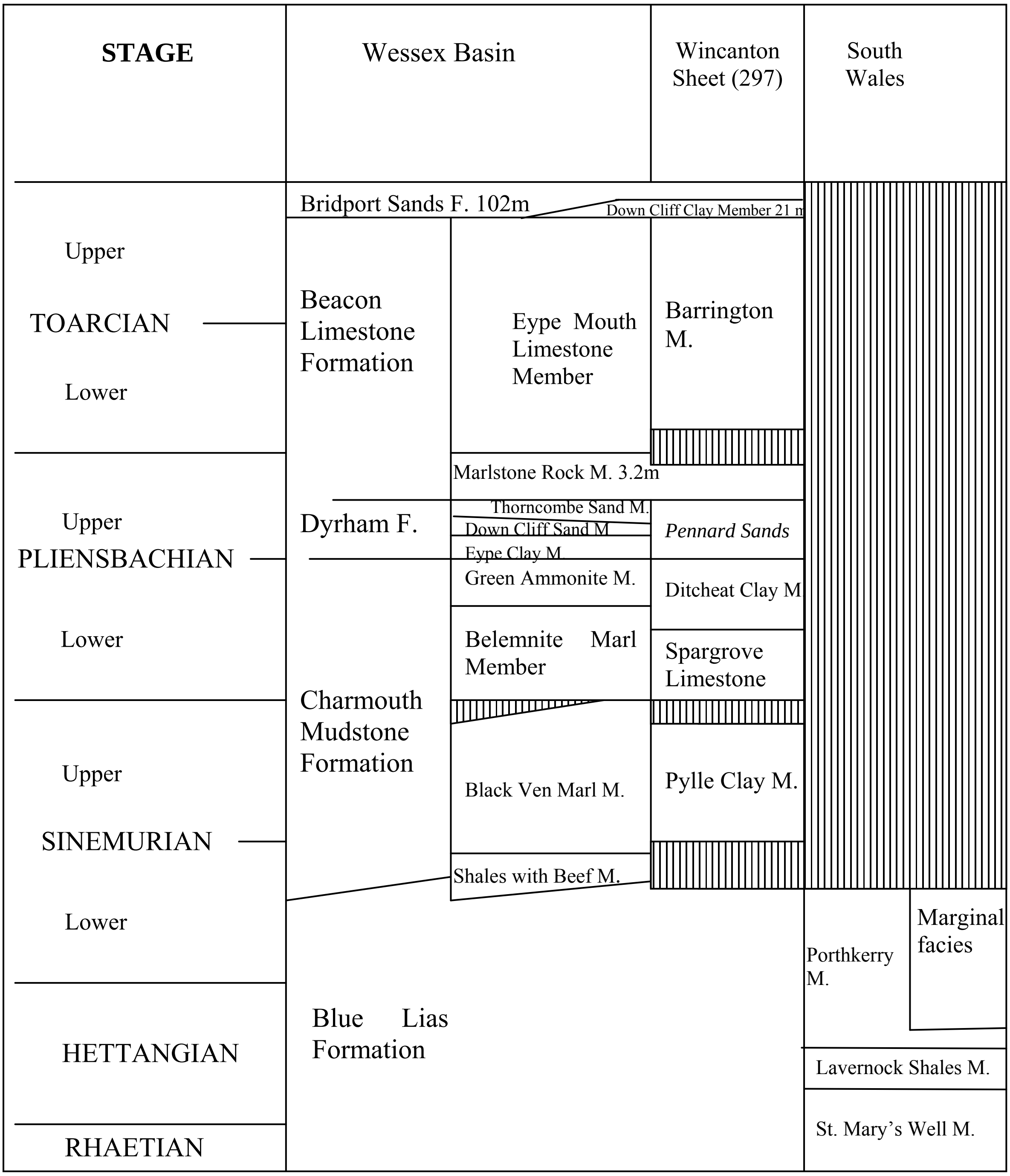


Figure 2.3 (contd.) Lias stages, formations and members showing regional variations.

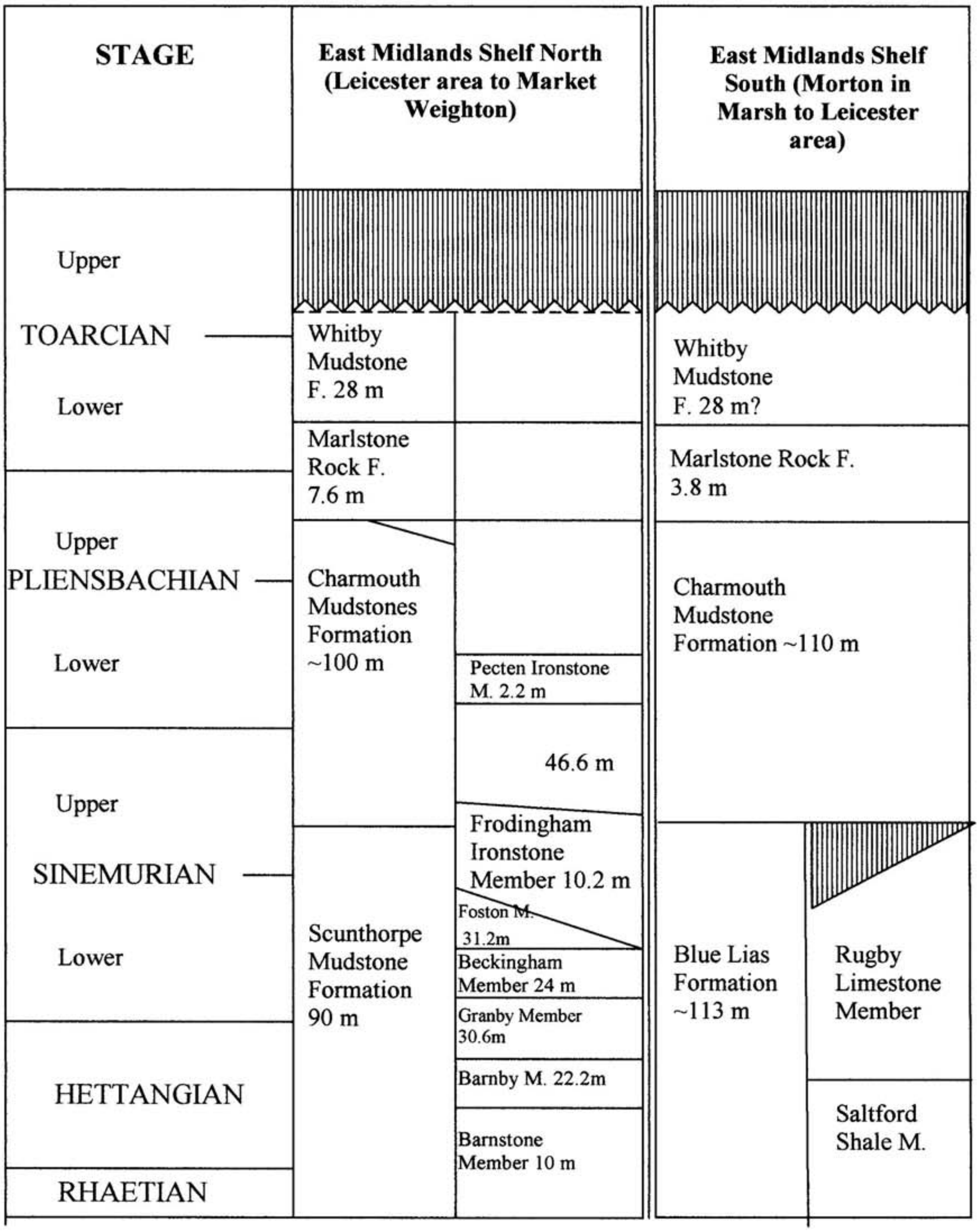


Figure 2.3 (contd.) Lias stages, formations and members showing regional variations.

Table 2.1 Table 2.1 Lias Group 1:50 000 geological maps, thicknesses of Lias Formations.

Cleveland Basin

Map number	Map Name	Redcar Mudstone Formation m	Staithes Sandstone Formation m	Cleveland Ironstone Formation m	Whitby Mudstone Formation m	Blea Wyke Sandstone Formation m
35 + 44	Whitby and Scarborough	151	16.4 to 19.7	29.5 to 32.8	65.6 to 82	39.4 to 65.6
42	Northallerton	230	20 to 26	Up to 15	Up to 60	
52	Thirsk	Up to 200	20 to 25	9 to 13	40 to 43	
62	Harrogate	Up to 200	20	10	15 to 20	

Wessex Basin including Somerset and South Wales

Map number	Map Name	Blue Lias Formation	Charmouth Mudstone Formation m	Dyrham Formation m	Beacon Limestone Formation m	Bridport Sand Formation m
262	Bridgend	>146	--	--	--	--
263	Cardiff	Up to ~ 103	--	--	--	--
281	Frome	0 to 10?	Up to 46?	?	0 to 3	0 to 3
295	Taunton and Quantocks	100	100	--	--	--
296	Wincanton	23.8 to 52.3	~60 to 105?	5 to 40	1 to 6	0 to 83?
312	Yeovil	6.7 to 8.2	34.5 to 46	15 to 120	0.6 to 8.2	38 to 91
313	Shaftesbury	52 to 146	106 to 226	112 to 116	?	88 to 180
327	Tavistock		93 to 114	58.8 to 123	0 to 2	55 to 91
328	Dorchester	95 to 207	116 to 241	35 to 125	1 to 2	48 to 122?

East Midlands Shelf

Map number	Map Name	Scunthorpe Mudstone Formation m	Blue Lias Formation	Charmouth Mudstone Formation m	Brant Formation m	Dyrham Formation m	Marlstone Rock Formation m	Whitby Mudstone Formation m
80 + 89	Kingston upon Hull	45 to 90		35 to 100	35 to 85		1.9 to 7.6	10.6 to 28
90 + 91	Grimsby	45 to 90			70 to 79		3 to 11	13 to 38
126	Nottingham	28	--	--	--	--	--	--
127	Grantham	113 to 128			103 to 118	12 to 19	2.5 to 7.3	38 to 60
142	Melton Mowbray	124 to 136		110 to 130		15 to 25	1 to 5	55
171	Kettering		0 to 32	150 to 178		6 to 12	0 to 1	49 to 58
184	Warwick		24 to 35.3	150 to 170		21 to 26	2.5 to 4	Up to 38
185	Northampton					17 to 31	1 to 3	47 to 60
199	Worcester		Up to 85	Up to 250		Up to 60	0 to 6	Up to 105
200	Stratford-upon-Avon		6 to 85	61 to ~305		46 to 61	3 to 6.1	13 to 103?
201	Banbury		7.5 to 17	75 to 110		12 to 42	1.2 to 7.5	15 to 47
202	Towcester					12.5 to 16.7	0.3 to 3.3	14.8 to 49.2
216	Tewkesbury		96	225		60	Up to 5	Up to 76
218	Chipping Norton		0 to 11.2			7.5 to 30	0.3 to 7.6	7.5 to 60

Worcester and Severn Basin

Map number	Map Name	Blue Lias Formation	Charmouth Mudstone Formation m	Dyrham Formation m	Marlstone Rock Formation m	Whitby Mudstone Formation m	Bridport Sand Formation m
217	Moreton-in-Marsh	10 to 75	130 to ~290	15 to 60	0 to 6	25 to >110	0 to
235	Cirencester	8.7 to 57.8	120.6 to 284	15 to 54	0 to 5	9.6 to 98	7.8 to 75
236	Whitney	?	60 to 140	10 to 30	0 to 5		4 to 16
251	Malmesbury	2 to 14	61 to 122	21 to 46	Up to 6.7	0 to 4.6	30 to 80?
264	Bristol	17 to 20	up to 122	Up to 9	Beacon Limestone Formation 1.4 m	Up to 23	

Table 2.2 Lias Group lithostratigraphic terms and former names NOTE: where alternative abbreviations exist those used in cross-section (Figure 2.4) are shown in italics

Current lithostratigraphic term	Former name
Alum Shale Member (AS)	Alum Shale Series/Formation, Hard Shales+Main Alum Shales+Cement Shales
Barnby Member (BM)	Angulatum/Angulata Clays, Barnby Clays
Barnstone Member (*BL*)(Bst)	Strensham Series, Hydraulic Limestone (Series)
Barrington Member (BARB)	Barrington Beds, Upper Lias Limestone
Beacon Limestone Formation (BnL)	Junction Bed+Marlstone (Rock Bed)
Beckingham Member (*B*)(Bkg)	Bucklandi Clays
Belemnite Marl Member (BeM)	Belemnite Marls/Beds, Stonebarrow Beds
Black Ven Marl Member (BVM)	Black Ven Beds/Marls, Black Marls [part]
Blea Wyke Sandstone Formation (BWS)	Blue Wick Sands, Blea Wick Sands/Beds/Series, Upper Lias (part)
Blue Lias Formation (BLi)	Blue Lias, Lyme Regis Beds, Hydraulic Limestones, Blue Lias Formation, marginal facies, White and Blue Lias [part]
Broadford Beds Formation (BfB)	Upper & Lower Broadford Beds
Bridport Sand Formation (BdS)	Bridport Sands, Midford Sands, Cotswold/Cotteswold Sands, Yeovil Sands, Upper Lias Sands
Calcareous Shale Member (*CS*)	Calcareous Shales
Charmouth Mudstone Formation (ChM)	Blue Marl, Lower Lias (Clay)(Formation), Brant Mudstone (Formation), Coleby Mudstone Formation (part), Pylle Clay Mbr+Spargrove Limestone Mbr+Ditcheat Clay Mbr
Cleveland Ironstone Formation (CdI)	Kettleness Beds, (Cleveland) Ironstone Series
Ditcheat Clay Member (DICL)	Lower Lias Marls (upper part), Belemnitiferous and Micaceous Marls (upper part)
Down Cliff Clay Member (DCC)	Down Cliff Clay
Down Cliff Sand Member (DCS)	Laminated Beds
Dyrham Formation (DyS)	Middle Lias Clays/Silts/Silts and Clays/Sandy Beds/Sands and Silts/Marls, Dyrham Silts, Dyrham Siltstone Formation, Pennard Sands (Member)
Eype Clay Member (EC)	Blue Clays, Eype Clay, Margaritatus Marls, Micaceous Beds, includes Three Tiers (Sandstone)
Eype Mouth Limestone Member	Junction Bed

Foston Member (*FL*)(Fst)	approximates to Ferruginous Limestone Series
Fox Cliff Siltstone Member (FCS)	Striatulus Shales
Frodingham Ironstone Member (FI)	Frodingham Ironstone
Granby Member (*GL*)(Gby)	Granby Limestones
Green Ammonite Member (GA)	Green Ammonite Beds, Wear Cliff Beds
Grey Sandstone Member	Grey Beds/Sands
Grey Shale Member (*GS*)	Grey Shales Series/Formation
Ironstone Shale Member (*IS*)	Ironstone Shales
Kettleness Member	Kettleness Beds
Lavernock Shale Member	Lavernock Shales, Lavernock Shale Formation
Marlstone Rock Formation (MRB)	Marlstone, Marlstone Rock, Marlstone Rock Bed
Marlstone Rock Member [of Beacon Lst Fm.] (*MRWB*)	Marlstone, Marlstone Rock
Mulgrave Shale Member (MS)	Jet Rock Series/Beds/Formation/Member, Jet Shales+Bituminous Shales
Pabba Shales	Pabba Beds
Peak Mudstone Member (*PM*)	Peak Shales
Penny Nab Member	*none*
Porthkerry Member (*PO*)	Porthkerry Formation
Portree Shale Formation (Pee)	Portree Shale
Pylle Clay Member (PYC)	Lower Lias Marls, Lower Lias Shales
Pyritous Shale Member (*PS*)	Pyritous Shales
Raasay Ironstone Formation (RASI)	*none*
Redcar Mudstone Formation (ReM)	Lower Lias
Rugby Limestone Member (*RL*)(RLs)	Blue Lias, Lima Beds, Plagiostoma Beds
Saltford Shale Member (*SS*)(SaSh)	Angulata Beds, Psiloceras Shales, Planorbis Beds (approx.), Lower Lias Clays (part), clays beneath Blue Lias
Scalpay Sandstone Formation (SCS)	Scalpa Sandstone Formation

Scunthorpe Mudstone Formation (SMd)	approximates to Hydraulic Limestones, Angulata Clays, Granby Limestones, Bucklandi Clays and Ferruginous Limestone Series/Frodingham Ironstone
Shales-with-Beef Member (SB)	Black Marl [part]
Siliceous Shale Member (SiS)	Siliceous Shales
St Mary's Well Bay Member	St Mary's Well Bay Formation
Staithes Sandstone Formation (Sta)	Staithes Beds/Formation, Marlstone Series, Sandy and Micaceous Beds, Sandy Series, Cleveland Sand Formation
Thorncombe Sand Member (TS)	Thorncombe Sands
Whitby Mudstone Formation (WhM)	Upper Lias (Clays/Clay Formation)
Wilmcote Limestone Member (*WL*)(Wct)	combinations of Ostrea Beds, Pre-Planorbis Beds, Saurian Beds and Insect Beds
Yellow Sandstone Member	Yellow Beds/Sands

2.2.1 Cleveland Basin

The succession in the Cleveland Basin is well displayed on the coast between Ravenscar, at the southern end of Robin Hood’s Bay, and Redcar. It is classified in terms of the units traditionally recognised in these cliff sections:

Blea Wyke Sandstone Formation

Whitby Mudstone Formation

Cleveland Ironstone Formation

Staithes Sandstone Formation

Redcar Mudstone Formation

Strictly, this nomenclature should be applied as far south as Market Weighton [SE 87 41] but in some contexts it may prove more convenient to take the southern limit a few kilometres farther north, at National Grid Line ^{4}50 or at the closely corresponding southern edge of BGS 1:50000 Sheets 63 and 64.

2.2.1.1 Redcar Mudstone Formation

The Redcar Mudstone constitutes the ‘Lower Lias’ in the Cleveland Basin. The upper c. 150 m, making up the greater part of the formation, is exposed at Robin Hood’s Bay [NZ 9505 to NZ 9702] (Hesselbo and Jenkyns, 1995), which constitutes the type section. Some beds lower in the succession, although not the basal part of the formation, can be seen on the foreshore at Redcar, Cleveland [NZ 60 24].

The Redcar Mudstone is typically about 225 to 250 m thick in the coastal area, and up to 280 m or more at depth inland, but thins to the west, being only 194 m in the Felixkirk borehole [SE 4835 8576] near Thirsk. The succession also thins dramatically southwards to the margin of the Cleveland Basin (Figure 2.1 and Figure 2.2) with perhaps only 30 or 40 m of strata at Market Weighton, although the thin succession there is partly due to the absence of the top part of the succession beneath the Cretaceous unconformity.

The Redcar Mudstone comprises grey, fossiliferous, fissile mudstones and siltstones with subordinate thin beds of limestone at some levels, and sporadic nodules of argillaceous limestone throughout.

The succession has been divided into several parts based on the excellent coastal sections. Approximately the lower half is assigned to the **Calcareous Shale Member**. It comprises mudstones with numerous thin beds of more or less shelly, argillaceous limestone, which tend to become more sandy up-sequence. Boreholes show that these limestones are particularly frequent and well developed in the lowest, poorly exposed part, forming a unit analogous to the Barnstone Member and Blue Lias elsewhere in England and Wales. Above, the **Siliceous Shale Member**, about 30 m thick on the coast, comprises silty mudstones with intercalations of strong calcareous siltstone and sandstone, often shelly, which represent storm-winnowed deposits. The topmost part of the Redcar Mudstone has been divided into the **Pyritous Shale Member** (c. 28 m), made up of mudstones with pyritic burrows and fossils, and the **Ironstone Shale Member** (c. 62 m) comprising mudstones with hard sideritic ironstone nodules. However, it is doubtful that these two units could be readily separated inland from their lithological characteristics alone. In the upper part of this succession, silty layers herald the transition to the succeeding Staithes Sandstone Formation.

2.2.1.2 Staithes Sandstone Formation

This unit is well exposed in the cliffs of its type section at Staithes Harbour (Howarth, 1955; Hesselbo and Jenkyns, 1995) and also between Robin Hood's Bay and Hawsker Bottoms ([NZ 960 065] to [NZ 955 071]). In these sections it is about 26 m thick, and thicknesses of between about 24 and 30 m are recorded elsewhere in the Cleveland Basin, though it may be a little thicker in places, whilst thinning markedly to the south (Figure 2.1 and Figure 2.2). It comprises more or less argillaceous silty sandstone with some units of non-argillaceous fine-grained laminated sandstone, particularly in the middle and upper parts, and shows many types of bedding structures illustrating deposition in a shallow marine environment. The lower boundary lies within a transition from the underlying mudstones of Redcar Mudstone Formation; but for consistency is defined at base of 'Oyster Bed', a fossiliferous calcareous and ferruginous sandstone packed with fossil shells (including *Gryphaea*), which persists throughout the Cleveland Basin. The top is marked by a rapid transition to mudstones of the Cleveland Ironstone Formation.

Sands and silts are also developed at this level in the Lias elsewhere in England, and these strata indicate a widespread shallowing event, as the sedimentary basins became filled.

2.2.1.3 Cleveland Ironstone Formation

The Cleveland Ironstone is well displayed at its type section on the coast near Staithes ([NZ 788 189] to [NZ 794 183]) (Howarth, 1955; 1973; Hesselbo and Jenkyns, 1995) and also at Hawsker Bottoms [NZ 953 073] and Kettle Ness [NZ 832 161]. About 29 m thick at Staithes, it generally falls within the range 20 to 35 m throughout the Cleveland Basin, though it thins markedly towards the margins to west and south, being only a few metres thick near Thirsk. This thinning is a result of a more condensed sequence with some parts absent, notably one near the top which separates the **Penny Nab Member** from the succeeding **Kettleness Member** (Howard, 1985). Whilst dominated by mudstone, argillaceous siltstone and silty sandstone, it characteristically contains beds of siderite and berthierine-rich, often somewhat nodular, ooidal ironstone which occurs at the tops of sedimentary rhythms. Where the succession is fully developed, there are six named ironstone bands, typically 0.3 to 1 m thick, the thickest and most persistent being the 'Main Seam' close to the top of the formation (in the Kettleness Member). The ironstone bands are best developed in the Guisborough-Loftus area near Middlesbrough, where they form up to 20 per cent of the thickness of the formation and once formed the basis of a thriving iron and steel industry (refer to section 4.5). There, the Main Seam, where not removed by mining, locally exceeds 3 m in thickness.

The base of the formation is clearly marked by a rapid downward transition from shaly mudstone with scattered sideritic nodules to the siltstone or sandstone of the Staithes Sandstone Formation. The top is similarly readily apparent, being taken at the top of the highest ironstone bed or nodule band, which is succeeded by grey mudstone of the Whitby Mudstone Formation.

2.2.1.4 Whitby Mudstone Formation

The Whitby Mudstone, essentially the 'Upper Lias clays' of previous accounts, is well exposed in the cliffs between Hawsker Bottoms [NZ 951 077] and Whitby Harbour [NZ 901 114], which constitutes its type section (Howarth, 1962, 1973, 1992). There it is about 115 m thick, but it thins to the west being about 40 m near Thirsk, principally due to the loss of the upper part by erosion beneath the succeeding Middle Jurassic beds. Southwards, towards Market Weighton, it is cut out altogether beneath the Cretaceous unconformity (Figure 2.1 and Figure 2.2).

The Whitby Mudstone is composed of medium and dark grey fossiliferous mudstone and siltstone, which at some levels is shaly and somewhat bituminous. It also includes thin siltstone or silty mudstone beds and hard nodules of argillaceous limestone are very common at some horizons. Both the base and top of the formation are marked by strong lithological changes, to the Cleveland Ironstone below and (generally) sandstones above. The Whitby Mudstone of the coast has been divided into five members. The **Grey Shale Membe**r at the base, about 15 m thick comprises silty, micaceous mudstones with bands of sideritic ironstone nodules. The succeeding **Mulgrave Shale Member**, about 32 m, is made up of finely laminated, bituminous and pyritic shales (see front cover photo). The lower c. 7 m constitutes the Jet Rock, which is particularly rich in organic material, and includes very hard pyritic limestone nodules. Near the top of the Jet Rock, lenses of jet were formerly mined for making jewellery and ornaments (refer to section 4.6). Jet is essentially a black, lustrous, high-grade lignite, representing fossilised driftwood. Above the Mulgrave Shale, the **Alum Shale Member** comprises about 37 m of medium grey, relatively blocky or poorly laminated silty mudstone with sporadic limestone and ironstone nodules. The middle part of the member, the ‘Main Alum Shales’ is particularly low in calcium carbonate and partly for this reason proved suitable for the manufacture of alum (a potassium aluminium sulphate), and was extensively worked for this purpose until the late nineteenth century (refer to section 4.2). The topmost part of the formation comprises about 13 m of highly micaceous silty mudstone (**Peak Mudstone Member**) succeeded by 11 m of argillaceous siltstone and silty mudstone (**Fox Cliff Siltstone Member**). These beds are of rather restricted occurrence; over much of the Cleveland Basin they are cut out beneath younger strata.

2.2.1.5 BLEA WYKE SANDSTONE FORMATION

The Blea Wyke Sandstone, forming the youngest part of the Lias Group, is exposed only at the type section Blea Wyke Point [NZ 991 015], near Ravenscar (Knox, 1984; Hesselbo and Jenkyns, 1995), and is present only in the vicinity of this locality, elsewhere being cut out beneath the Middle Jurassic beds. It comprises 18 – 21 m of fine-grained, micaceous sandstones. The succession is divisible into two parts, representing two coarsening upward cycles. The lower **Grey Sandstone Member** is markedly banded, and generally somewhat argillaceous, and the succeeding **Yellow Sandstone Member** is more massive, and generally better sorted.

2.2.2 Wessex Basin and Bristol Channel Basin

The entire Lias succession is well exposed on the Dorset coast between Lyme Regis and Burton Bradstock (Callomon and Cope, 1995; Hesselbo and Jenkyns, 1995). As now classified (Cox et al., 1999) it comprises:

Bridport Sand Formation

Beacon Limestone Formation

Dyrham Formation

Charmouth Mudstone Formation

Blue Lias Formation

Inland from the Dorset coast, data (particularly cored boreholes) are limited. Whilst there is no doubt that the formational framework remains valid, details of the succession, and the degree of lateral persistence of the members recognised on the coast is not entirely clear, whilst other members have been recognised in some areas (e.g. Bristow and Westhead, 1993).

2.2.2.1 BLUE LIAS FORMATION

The Blue Lias is perhaps the best known, though not the most typical, part of the Lias Group, having been visited by generations of geologists at Lyme Regis [SY 320 908 to SY 333 914] (Lang, 1924; Hallam, 1960; Hesselbo and Jenkyns, 1995; Callomon and Cope, 1995), though its type area is between Bath and Bristol in Somerset (Torrens and Getty, 1980). At Lyme Regis, the formation is about 25 m thick, and comprises thin (typically 0.10 m to 0.30 m) beds of argillaceous fine-grained limestones (‘cementstones’) interbedded with mudstones and silty mudstones, in beds of generally slightly greater thickness (Figure 2.4). The limestones make up about 40 per cent of the succession. In fact, viewed regionally, the Blue Lias at Lyme Regis is thin and condensed, as it thickens substantially northwards, probably being some 90 to 130 m inland and is typically developed on the coast east of Watchet, Somerset [ST 080 436 to ST 220 470] (Whittaker and Green, 1983; Warrington and Ivimey-Cook, 1995), where it is about 145 m thick. There, although more individual limestone beds are present, they are of comparable thickness with those in Dorset, whilst intervening mudstones are typically thicker, such that overall, limestone makes up a much smaller proportion of the total succession (perhaps only 20 per cent). Throughout the region, the top of the Blue Lias (i.e. the base of Charmouth Mudstone Formation) is marked by an upward decrease in abundance of limestone beds, sometimes associated with marked decrease in their individual thickness and lateral persistence. Particularly in more expanded successions, the level at which to take the boundary is somewhat arbitrary; guidelines intended to achieve some consistence are given by Cox et al. (1999).

Figure 2.4 Blue Lias Formation at Ware Cliff, Lyme Regis

On the opposite side of the Bristol Channel, about 150m of Blue Lias are represented in Glamorgan, and well exposed on the coast (Waters and Lawrence, 1987; Wilson et al., 1990; Warrington and Ivimey-Cook, 1995) where it is the only part of the Lias preserved (Figure 2.5). The Glamorgan Blue Lias laps onto a massif of Carboniferous Limestone and older rocks, which during Early Jurassic times, formed islands in the Lias sea, which were progressively submerged and buried by sediment. The near-shore location is reflected in the relatively high proportion of limestone in the succession; overall, about 50 per cent. The succession is readily divisible into three members, directly equivalent to those developed in the Worcester Basin and East Midlands Shelf. The basal **St Mary's Well Bay Member** comprises c. 20 m of limestone and mudstone in approximately equal proportions. Above, some 9 to 12 m of shaly mudstone with very subordinate nodular limestones is known as the **Lavernock Shale Member**. The succeeding **Porthkerry Member**, of which about 120 m are preserved, is much like the St Mary's Well Bay Member, but includes some unusually thick limestones (over 1 m) albeit with thin mudstone partings. Locally the limestones are secondarily silicified, with the development of chert nodules and bodies. Close to the 'islands' of older rocks, a near-shore marginal facies of the Blue Lias is developed (the Sutton Stone and Southerndown Beds). This comprises massive or rubbly, often shelly and conglomeratic limestones and, as might be expected, is highly diachronous.

Figure 2.5 View from Trwyn y Witch to Nash Point, Glamorgan Heritage Coast Blue Lias Formation (Porthkerry, Lavernock Shales, & Shelly Limestone Members) (Note: folds & faults on wave-cut platform), C. James 11/07/01

2.2.2.2 Charmouth Mudstone Formation

The Charmouth Mudstone is essentially equivalent to the Lower Lias clay of many earlier accounts, that is the 'Lower Lias' excluding the Blue Lias. At the Dorset coast type section (between Seven Rock Point [SY 327 909] and Golden Cap [SY 407 922]) it is about 136 m thick, but thickens substantially inland to perhaps as much as 290 m, and with c 235 m proved at Brent Knoll near Burnham on Sea, Somerset. The Charmouth Mudstone comprises mudstones of various types ranging from dark grey laminated mudstone to generally paler grey blocky mudstone. It contains sporadic, nodular limestone beds and nodule bands, and at many levels, particularly in the upper part, phosphatic or sideritic nodules and silty and finely sandy beds.

The Charmouth Mudstone of the Dorset coast has been divided into four members. Whilst these can be recognised inland on the basis of geophysical borehole log correlation (e.g. Whittaker et al., 1985) they have never been mapped at the surface and it is doubtful that they could be reliably identified on the basis of lithologies alone. The basal c. 36 m comprises dark shaly laminated mudstone with a few very thin limestone bands and is known as the **Shales-with-Beef Member**. Characteristically it contains lenticles of fibrous crystalline calcite (the 'beef' of the name). Although generally said to be an ancient diagenetic effect, this may alternatively be related to weathering in the landslipped coastal area, and may not occur elsewhere. Above, the **Black Ven Marl Member**, 42 m thick, is somewhat similar being made up of rather dark to medium grey mudstone, some parts pyritic or mottled with burrows, and with a few limestone bands. The succeeding **Belemnite Marl Member**, about 24 m thick, comprises alternating paler and darker, more carbonaceous mudstones. Apart from sporadic belemnites, fossils are rare. The cyclical nature of the succession is believed to be due to climatic variations affecting plankton abundance and the input of detrital clays. The top is marked by the Belemnite Stone, a thin belemnite-bearing limestone. The top part of the Charmouth Mudstone comprises the **Green Ammonite Member**, about 35 m thick, comprising mid grey mudstone. The curious name derives from the coloration of the calcite infill found in some fossils preserved in limestone nodules at certain levels. The succession becomes more silty up-sequence heralding the transition to the succeeding Dyrham Formation.

2.2.2.3 Dyrham Formation

The Dyrham Formation comprises grey and greenish grey, silty and sandy mudstone, with interbeds of siltstone or fine-grained, often somewhat micaceous, calcareous sandstone. It is exposed on the Dorset coast between Seatown [SY 420 918] and Eype Mouth [SY 447 910] where it is about 122 m thick. It tends to thin northwards, in part through passage of the lowest part into less arenaceous beds (Figure 2.2). On the coast the succession has been divided into three members, but it is uncertain how readily these can be recognised further north. The lowest c. 65 m comprises the **Eype Clay Member**, made up predominantly of bluish grey, silty and micaceous shaly mudstone with common small sideritic ironstone nodules. The base is marked by the Three Tiers, a fine sandy unit about 6 m thick in which the base, middle and top parts are cemented into sandstone beds separated by weaker material. This unit is known only in the coastal area, dying out inland. Above the Eype Clay, the **Down Cliff Sand Member** comprises 30 m of greyish brown, thinly interbedded, argillaceous sandstone and sandy mudstone. The succeeding **Thorncombe Sand Member** comprises 26 m of yellow-weathering silty and fine-grained sandstone. Inland, in north Dorset and Somerset, the Dyrham Formation, formerly known as the Pennard Sands in this area, is essentially equivalent to the Thorncombe Sand Member only.

2.2.2.4 Beacon Limestone Formation

The Beacon Limestone is typically 0.6 to 1.5 m thick, equivalent to a much thicker succession farther north in England. The lower part, from zero to about 0.6 m thick, is the **Marlstone Rock Member**, made up of brown, or reddish, more or less ooidal limonitic ironstone, and is the equivalent of the Marlstone Rock Formation of the Worcester Basin and East Midlands Shelf. The upper part, the **Eype Mouth Limestone Member** is the so-called Junction Bed of most previous accounts. It comprises white, pinkish and yellowish nodular, conglomeratic and often highly fossiliferous limestone. It is a highly condensed unit incorporating many non-sequences, and is the equivalent of much of the Whitby Mudstone Formation as developed further north in England.

2.2.2.5 Bridport Sand Formation

The Bridport Sand Formation includes the former ‘Upper Lias sands’ incorporating, within the Wessex Basin, both the Bridport Sand of south Dorset and the Yeovil Sands of North Dorset and Somerset. These units form a single somewhat diachronous sand body that becomes younger to the south. The succession can be examined in spectacular cliffs between Broadwindsor [ST 437 026] and Burton Bradstock [SY 488 895] (Wilson et al., 1958) where it is c. 62 m thick (Figure 2.6). The lower c. 21 m constitutes the **Down Cliff Clay Member**, a uniform blue-grey fine sandy clay that weathers to a yellowish clay. The great bulk of the Bridport Sand Formation on the coast comprises grey, brownish yellow-weathering, micaceous silt and fine-grained sand, with calcite-cemented, more or less continuous into nodular sandstone beds occurring irregularly throughout the succession, typically every metre or so.

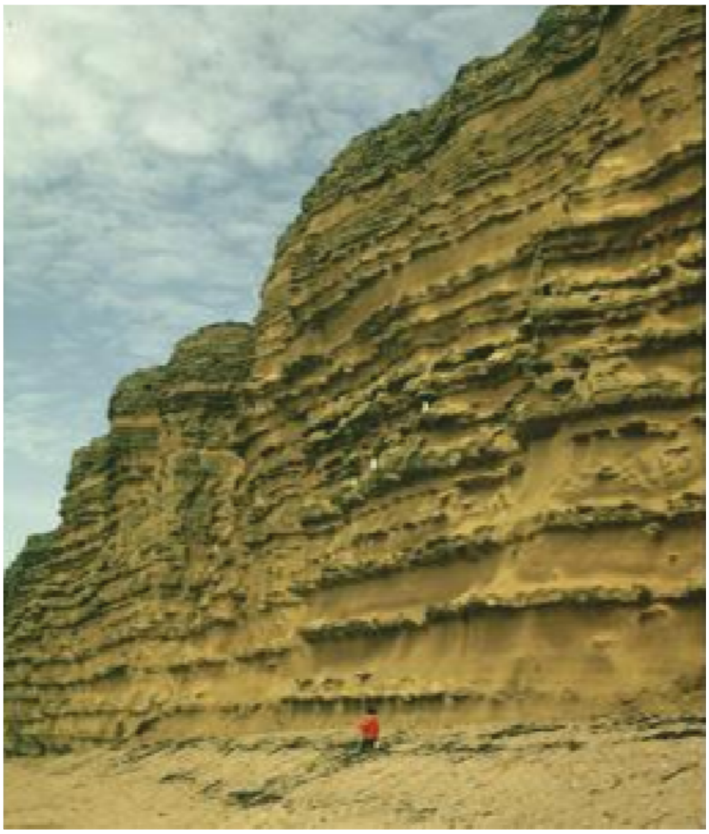


Figure 2.6 Cliffs in Bridport Sand Formation capped by Inferior Oolite limestone at Burton Bradstock, Dorset [NGR 348500,189200] (BGS photo: P005794)

The Bridport Sand Formation maintains its thickness into north Dorset and Somerset but may thicken locally to 90 m or more, and at depth in east Dorset, is more than double this thickness, with a much expanded Down Cliff Clay Member. In the Yeovil-Ilminster district, almost the whole of the succession is sands with nodular sandstones. A unit of brown-weathering shelly sandstone up to c. 27 m thick in the upper part is known as the Ham Hill Stone, and has been extensively quarried for building stone.

In north Somerset, the 60 m of Bridport Sand is generally present in the main outcrop, but this is cut out beneath Middle Jurassic beds as the Mendips are approached, near Shepton Mallet. Westwards, in the outlier of Glastonbury Tor, 11 m of silty mudstone occurs at the base in the lower part, and at Brent Knoll the mudstone succession thickens, and incorporates older zones than elsewhere in the Wessex Basin, in a succession somewhat like that in the Worcester Basin.

2.2.3 Mendip High and Bristol-Radstock Shelf

This area encompasses the immediate vicinity of the Mendip Hills, and parts just to the north, between Bristol and Bath. As in South Wales, the Carboniferous Limestone and associated rocks that now form the Mendip Hills and Bristol area formed an up-standing massif during deposition of the Lias so that the succession that laps on to it is thin and incomplete, and there is no Lias preserved on the Mendips proper; any that may once have been present was removed by erosion in the Middle Jurassic. The Blue Lias and Charmouth Mudstone are thin; at Dundry Hill just south of Bristol, for example, the Blue Lias is about 20 m thick and the Charmouth Mudstone about 125 m. As the Mendip massif is approached, the succession thins still more and both Blue Lias and the lower part of the Charmouth Mudstone become increasingly dominated by limestones which form a diachronous near-shore facies including gritty, shelly and ferruginous limestones, to which a variety of local names have been applied (Donovan and Kellaway, 1984). In the Radstock area south of Bath, these units and the succeeding Dyrham Formation are cut out by erosion beneath the Beacon Limestone Formation, which comprises up to 1.5 m of marly and ferruginous limestone. This is succeeded by up to about 30 m of Bridport Sand Formation, which was formerly known as the Midford Sands.

2.2.4 Worcester Basin and East Midlands Shelf

This extensive region stretches from the Bath area as far north as the Market Weighton High. The Worcester Basin, lying between the Malverns on the west, and the so-called Moreton Axis on the east, was an area of subsidence throughout the Triassic and Early Jurassic and the Lias succession is typically over 500 m thick, somewhat more than is usual in either the Wessex or Cleveland basins, and about twice the thickness typical on the adjoining East Midlands Shelf. Thinning at the eastern margin of the basin, i.e., the Vale of Moreton Axis, is gradual, but is concentrated in a zone a few kilometres wide, running approximately from Stratford-upon-Avon to Moreton-in-Marsh. The succession on the East Midlands Shelf thins to the southeast as the London Platform is approached, largely through progressive overlap of the basal beds. In the northern part of the East Midlands Shelf, the lower part of the succession changes in character such that different formational names are applied.

2.2.4.1 BLUE LIAS FORMATION

The Worcester Basin is the type area of the Blue Lias with the type locality at Saltford railway cutting [ST 685 671 to ST 681 676], southeast of Bristol (Donovan, 1956; Torrens and Getty, 1980; Donovan and Kellaway, 1984). In the basin, the formation is up to 90 m thick whilst on the East Midlands Shelf, 50 to 60 m is more typical. In lithological character it is much like the Blue Lias of the Wessex Basin, comprising mudstones with thin beds and nodule bands of pale grey, smooth-textured, more or less argillaceous limestones. These are seldom more than 0.2 to 0.3 m thick. Where fully developed it can be divided into three members. The **Wilmcote Limestone Member** at the base, present only in the Basin itself, comprises up to 8 m of mudstone with limestone interbeds, and is particularly limestone-rich at the base. It is succeeded by the mainly mudstone unit of the **Saltford Shale Member**, generally about 20 to 30 m thick, and of more widespread distribution than the Wilmcote Limestone, though possibly absent over the Vale of Moreton Axis. The uppermost part of the Blue Lias is known as the **Rugby Limestone Member**, which ranges from about 25 to 55 m in thickness. It is well exposed in quarries at Rugby (Figure 2.7) and elsewhere in Warwickshire, where it comprises about 36 m of alternating limestone and mudstone, the latter making up about 30 per cent of the succession. In the thicker, more expanded successions of the Basin, limestones form a somewhat lower proportion, of between 15 and 20 per cent.

Figure 2.7 Quarry in Charmouth Mudstone Formation overlying Blue Lias Formation, Parkfield Road (East) quarry, Rugby, Warks.

2.2.4.2 SCUNTHORPE MUDSTONE FORMATION

The outcrop of the Blue Lias can be traced northwards to Rugby, but there disappears beneath a thick cover of glacial drift. Where the Lias re-emerges in the Vale of Belvoir in north Leicestershire, the lower part of the Lias succession is substantially different and is termed the Scunthorpe Mudstone Formation. The precise details of the transition between the two stratigraphies are currently uncertain. Provisionally, the southern limit of the Scunthorpe Mudstone Formation is taken at the southern boundary of BGS sheet 142 or the nearby National Grid northing $^{3}15$; that is, just south of Melton Mowbray.

The Scunthorpe Mudstone Formation comprises grey, variably calcareous mudstone with thin beds of argillaceous limestone of various types, particularly near the base and in the upper part in which sandy and ferruginous beds occur. It is some 110 to 120 m thick in the south, but thins substantially northwards, being only about 60 to 80 m thick in the type area around Scunthorpe, in north Lincolnshire and only 40 m just north of the Humber. It thins still further towards the Market Weighton High. In the Cleveland Basin, it is approximately equivalent to the Calcareous Shale Member (of the Redcar Mudstone Formation), which is similar in facies.

The type section of the Scunthorpe Mudstone Formation is the BGS Blyborough Borehole (SK 99 SW/79; [SK 9206 9428]; Gaunt et al., 1992) near Scunthorpe, but it has been studied in greater detail in south Lincolnshire and north Leicestershire where it has been divided into five members (Brandon et al., 1990). It seems probable, from borehole geophysics, that these are, in principle, recognizable in the north too. The **Barnstone Member** at the base comprises 5 – 10 m of alternating grey mudstone and limestone. The limestone beds are 0.1 to 0.3 m thick, and those in the basal 2 –3 m are typically shelly. Argillaceous fine-grained limestones make up about 30 per cent of the succession, much like the Wilmcote Limestone Member of the Blue Lias in the Worcester Basin. Above, the **Barnby Member** comprises about 20 m of mudstone with sporadic limestone nodules and a few very thin limestone beds. It is essentially equivalent to the Saltford Shale. The succeeding **Granby Member**, 30 m thick, is, in terms of its age, approximately the equivalent the Rugby Limestone Member of the Blue Lias Formation. However, it contains considerably less limestone, making up only 10 to 15 per cent of the succession, and these limestones are generally coarser grained with much shell debris. They probably represent sediment winnowed by storms.

Above, the **Beckingham Member** comprises about 20 m of mudstone with rare thin limestones, and limestone nodules in the upper part. It is possible that this unit dies out northwards through development of additional limestones. The topmost unit of the Scunthorpe Mudstone Formation is the **Foston Member**. It comprises about 30 m of mudstones with shelly and somewhat sandy limestones. At the base in Leicestershire, the Stubton Limestone is a composite limestone about 1.5 m thick, characteristically containing ferruginous ooids in the upper part.

In a restricted area around Scunthorpe itself, the topmost unit of the Scunthorpe Mudstone Formation is the **Frodingham Ironstone Member**, up to about 10 m in thickness (Figure 2.2). It comprises more or less muddy or calcareous ooidal ironstone, and was formerly the basis of the Scunthorpe iron and steel industry. It dies out rapidly both north and south of that area and in Leicestershire the top of the Formation is drawn at a thin, composite conglomeratic bed (the Glebe Farm Limestone) which marks an important regional non-sequence which, however, is probably at a slightly higher horizon than the top of the Frodingham Ironstone of north Lincolnshire.

2.2.4.3 CHARMOUTH MUDSTONE FORMATION

The Charmouth Mudstone reaches almost 300 m in thickness in the Worcester Basin, though 250 m may be a more usual figure. On the East Midlands Shelf, thinner successions of about 100 to 150 m are typical. Northwards from the Leicester area, it is thinner still as a result of passage of the lower beds into the upper part of the Scunthorpe Mudstone Formation, and combined overall condensation towards the Market Weighton High. The Charmouth Mudstone is made up of grey mudstone with sporadic thin bands and nodules of limestone, some of which are markedly shelly. The upper part (say 50 to 70 m) is generally slightly more silty than the lower beds, and these higher beds may contain occasional sideritic ironstone nodules and beds, particularly in the north where the Dyrham Formation is absent. In this northern area, more or less coincident with the development of the Scunthorpe Mudstone Formation, the formation was formerly known as the Brant Mudstone (Brandon et al., 1990). It includes one or more fine sandstone beds near the base (Sandrock or Brandon Sandstone) and this part of the succession resembles equivalent beds in the upper part of the Siliceous Shale Member of the Cleveland Basin.

Whilst the Charmouth Mudstone of this region has not been subdivided into members, study of boreholes, particularly downhole geophysical logs, shows a remarkably uniform internal stratigraphy throughout the region. Various more calcareous units form geophysical marker bands which are useful for correlation; these include the so-called 70 and 85 Markers indicated on Figure 2.2 (see for example Horton and Poole, 1977; Horton et al., 1987). At outcrop, these are seen as units of mudstone, several metres thick, bearing abundant limestone nodules, and lenticular, often very shelly limestones.

2.2.4.4 DYRHAM FORMATION

The Worcester Basin is the type area of this unit, named after the village of Dyrham [ST 741 758], to the east of Bristol (Kellaway, 1960). It tends to form moderately steep slopes of an escarpment capped by the Marlstone Rock Formation. It is typically about 40 to 60 m thick in the Basin, though seldom more than 30 m thick on the Shelf. It can be traced as far north as the Grantham area, beyond which its characteristic sandy and silty lithologies do not appear to be developed and equivalent strata are included in the Charmouth Mudstone (Figure 2.2).

Overall, the succession is less sandy than in the Wessex Basin, being dominated by more or less silty, often finely micaceous mudstones which weather to a pale bluish grey, ochreous mottled clay. These beds were once favoured for brick making and there are several large, disused brickpits along the outcrop including the type section at Robin's Wood Hill, near Gloucester, Gloucestershire [SO 836 149] (Ager, 1956, 1969). Typically, the Dyrham Formation contains beds of fine-grained sand, which may be cemented into quite hard massive sandstones. These include the Subnodosus Sandstone, up to 1.5 m thick, which occurs near the top of the succession in the Gloucester to Moreton-in-Marsh area of the Cotswolds. The Capricornus Sandstone is a convenient marker for the base of the formation in this Cotswolds area, but where the sandstone is not well developed; the base of formation is gradational and hard to define.

2.2.4.5 MARLSTONE ROCK FORMATION

The Marlstone Rock Formation is restricted to this region, although a condensed representative is present as a member of the Beacon Limestone Formation in the Mendips and Wessex Basin areas. The Marlstone Rock is generally some 2 to 4 m in thickness and reaches a maximum of 7.5 m near Banbury. Up to 10 m are reported locally in Leicestershire, but this figure includes the so-called 'Sandrock' developed in much of the Midlands, which is a sandstone that strictly belongs to the Dyrham Formation (see above) but was not formerly mapped separately from the Marlstone Rock proper. The Marlstone Rock typically caps a prominent escarpment throughout the region, often forming an extensive shelf like dip-slope.

The Marlstone Rock is typically a more or less sandy, shell-fragmental, siderite and berthierine-bearing ooidal limestone, with calcareous sandstone and mudstone partings. It is commonly highly fossiliferous, particularly with belemnites and brachiopods (*Lobothyris* and *Tetrarhynchia*). In the Worcester Basin the formation is not generally especially ferruginous and may appear as a greenish-grey sandstone. However, on the Shelf, the iron concentration reaches 20 to 25 % and the rock weathers to a rust-brown limonitic ironstone. This was formerly worked for iron ore particularly in the Banbury area and in Leicestershire and can still be seen in abandoned quarries in these areas and also at the type section, Tilton railway cutting, east of Leicester [SK 762 055] (Hallam, 1955, 1968; Howarth, 1980c, 1992).

The base of the Marlstone proper is an erosive non-sequence, and the basal bed is commonly conglomeratic enabling its identification in sections where the 'Sandrock' facies is present (e.g. in the type section). The top is also generally erosive, with mudstones or limestones of the Whitby Mudstone resting sharply on it.

2.2.4.6 WHITBY MUDSTONE FORMATION

The Whitby Mudstone exceeds 100m in thickness in the northern part of the Worcester Basin, but thins to zero southwards due to replacement by the Bridport Sand Formation and Beacon Limestone Formation (see below). On the East Midlands Shelf thicknesses are very variable but 20 to 40 m are typical. The succession is incomplete compared with the type area in the Cleveland Basin, as the top beds are 'missing' beneath an erosive non-sequence at the base of the Middle Jurassic strata. The beds present are essentially equivalent to the Mulgrave Shale and Alum Shale members of the Cleveland Basin and are of similar lithology, being composed of generally rather dark to medium bluish grey, commonly shaly mudstone, with sporadic small dark grey limestone nodules. In the Worcester Basin and south-western part of the East Midlands shelf (Gloucestershire to Northamptonshire), brown to white thinly bedded or nodular limestones are developed in the basal few metres; these limestones are often highly fossiliferous with well preserved ammonites. Southwards, with increasing condensation of the succession these limestones become incorporated into the upper part (Eype Mouth Limestone) of the Beacon Limestone Formation.

Particularly in the Cotswold area and Leicestershire, the Whitby Mudstone typically forms a steep scarp slope capped by harder Middle Jurassic strata, and in this situation is very prone to landsliding (see Chapter 5).

2.2.4.7 Bridport Sand Formation

The Bridport Sand Formation, formerly known in this region as the Cotswold Sands, is restricted to the Worcester Basin. It is made up of yellowish brown, fine-grained micaceous sands, which rarely may be cemented into a weak calcareous sandstone. First appearing near Broadway in the north Cotswolds, followed southwards it replaces the Whitby Mudstone from the top downwards such that near Wotton-under-Edge, Gloucestershire, most of the succession, about 60 m thick, may be assigned to the Bridport Sand Formation. From there southwards, any mudstones at the base may be most conveniently treated as a part of the Bridport Sand Formation. In this southern area, condensed, ferruginous, often highly fossiliferous marls and limestones often occur in the topmost part. This ‘Cotswold Cephalopod Bed’ is seldom more than 1 m thick but reaches 4.6 m near Dursley.

3 MINERALOGY

The following account is taken from Kemp & McKervey (2001), Kemp & Hards (2000) and Kemp, et al., 2005.

3.1 GENERAL

There are key geohazards involved in the engineering geology of clays and mudstones. Due to their high surface area, residual charge and interaction with water, clay minerals (and smectite in particular) are most frequently cited as the reason for the distinctive shrink-swell behaviour noted in many fine-grained sedimentary rocks, and consequent structural damage resulting from seasonal and long-term volume changes. Oxidation of pyrite in the environment leads to the formation of sulphuric acid, which considerably reduces the pH of groundwater. Where such acidic groundwaters make contact with concrete foundations, the main cementitious binder, calcium silicate hydrate (C-S-H), or calcium silicate hydrogel, the main component of cement paste, may be converted to thaumasite (a non-binding calcium carbonate silicate sulphate hydrate) resulting in deterioration and failure (e.g. Hobbs & Taylor, 2000; Bensted, 1999; Burkart, *et al*. 1999). Greater awareness of the potential problems that thaumasite can cause has arisen with the increased use of limestone fillers in cements and limestone aggregates in concrete. Knowledge of the presence of sulphate-bearing species in Lias Group sediments is therefore crucial to foundation design and construction in such strata.

3.2 PREVIOUS MINERALOGICAL STUDIES OF THE LIAS GROUP

In view of its relatively good coastal and quarry exposure, it is perhaps surprising that studies of the mineralogy of the onshore Lias Group in England are relatively few. Several brief studies were carried out in the 1960's (e.g. Hallam, 1960; Cosgrove & Slater, 1966). These indicated that clay mineral assemblages for the Lias mudstones typically contain illite, interlayered illite/smectite and smectite with minor kaolinite and chlorite.

Pye & Krinsley (1986) produced a petrographic, geochemical and mineralogical study of the Whitby Mudstone Formation from the Cleveland Basin using the then recent development of backscattered scanning electron microscopy. Using a combination of techniques, they differentiated three facies; normal, restricted and bituminous. The normal facies (lower Grey Shale Member and upper Alum Shale Member) were rich in quartz, micas, chlorite and kaolinite, pyrite together with varying amounts of calcite and siderite (generally <10%) and traces of feldspar and carbonate-apatite. The restricted facies (upper Grey Shale Member) was mineralogically similar to the lower Grey Shale Member but with a lower siderite content. The same restricted facies (lower Alum Shale Member) contained more kaolinite but less quartz and chlorite than the restricted facies Grey Shales. The bituminous shale facies (Mulgrave Shale Member) was composed of quartz, kaolinite, mica, illite-smectite (I/S), chlorite, pyrite and calcite with subsidiary dolomite, feldspar and carbonate-apatite but no siderite. Textural evidence suggested that the authigenic mineralogy was predominantly early diagenetic and that the differences observed were due to changes in the prevailing sea bottom conditions.

As part of a site investigation for a low-level radioactive waste repository at Fulbeck, Lincolnshire, Bloodworth *et al*. (1987) carried out an extensive mineralogical and lithogeochemical study of the Lower Lias (now equivalent to those deposits corresponding broadly with the Redcar Mudstone Formation of the Cleveland Basin, and Scunthorpe Mudstone/Blue Lias Formation plus Charmouth Mudstone Formation elsewhere), and Middle Lias sequence of interbedded mudstones and limestones (now corresponding broadly to the Staithes Sandstone plus Cleveland Ironstone formations in the Cleveland Basin, and Dyrham plus Marlstone Rock formations elsewhere). Clay mineral assemblages were found to be dominated by illite with subordinate kaolinite, minor chlorite and interlayered illite/smectite (I/S). Surface areas for the mudstones varied from 112 to 172 m^2/g

with a mean of 140 m^2/g. Evolved gas and X-ray diffraction analyses revealed that pyrite was ubiquitous within the interval, typically forming 1-2% but occasionally reaching over 20% in some limestone samples. Trace amounts of gypsum were only sporadically detected.

Mitchell (1992) carried out an XRD study of the clay mineralogy of a 200 m thick borehole sequence of Lias mudstones from the Copperhill Quarry, near Ancaster, Lincolnshire, in order to identify any potential clay 'marker' horizons or distinctive variations in clay mineral assemblage. The Lias here was found to be composed of the non-clays: quartz, mica and pyrite with traces of feldspar and calcite. Clay mineral assemblages were dominated by kaolinite with illite, chlorite and I/S. However, clay mineral abundances were based on a direct comparison of uncorrected peak intensity data. A more recent study by Bessa & Hesselbo (1997) attempted to correlate the Lower Lias in southwest Britain using outcrop-based spectral gamma-ray spectroscopy. However, despite the fact that the gamma-ray signatures of such lithologies are predominantly determined by their clay mineralogy, no attempt was made to characterise the mineralogy of the mudstones. A similar study for the Cleveland Basin by Van Buchem *et al.* (1992) presented limited clay mineralogical and geochemical data.

As a part of the ongoing BGS programme, 'Engineering Geology of UK Rocks and Soils', Kemp & Hards (2000) investigated the mineralogy of Lias samples from two site investigation boreholes sited near the M5 motorway in Gloucestershire. They found non-clay mineral assemblages typically composed of carbonates (calcite and ankerite), quartz, feldspar (K-feldspar and albite), 'mica', gypsum and pyrite. Clay mineral assemblages were generally formed of illite (c.40%), kaolinite (c.35%), smectite (c.20%) and chlorite (c.5%). However, smectite contents were found to increase at certain levels to c.30%.

This mineralogical study of a suite of Lias Group sedimentary rocks has generally confirmed the findings of previous workers. However, the wide geographic and stratigraphic distribution of the analysed samples has provided important new information, which will aid not only interpretation of the engineering behaviour of these rocks but also their diagenetic and geological histories. The engineering properties of the UK Lias will be heavily influenced by its clay mineralogy and in particular the presence of discrete smectite or illite/smectite. This study has shown that rocks from the West Midlands and southern England (the Worcester and Wessex Basins) are likely to contain smectite and therefore have greater shrink-swell potential than those rocks from the East Midlands (East Midlands Shelf) and northern England (the Cleveland Basin). However, the degree of shrink-swell is moderated by the high carbonate content typically found in southern rocks compared to those in the north. As indicated by XRD modelling, the small crystallite size of the other clay minerals; illite, kaolinite and chlorite will also significantly contribute to any volume change. The type of swelling clay species present is also useful for determining the depth of burial for the Lias Group across England. The I/S (90% illite) present in the Cleveland Basin suggests a 4 km maximum depth of burial, which corroborates earlier vitrinite reflectance, fluid inclusion and sonic velocity-based estimates. The greater proportion of smectite present in the I/S (80% illite) detected in the single sample from the East Midlands Shelf, suggests shallower burial to perhaps 3 km. However, the discrete smectite present in the Worcester and Wessex Basins indicates even shallower burial to no more than 2 km. Studies of basin maturity can therefore be used to predict likely engineering properties for the Lias Group rocks. The very common presence of pyrite, together with gypsum and jarosite in the Lias Group means that concrete engineering sited in these rocks potentially risk acid and sulphate attack and thaumasite formation. The Whitby Mudstone Formation in the Cleveland Basin together with the Blue Lias and Charmouth Mudstone formations in the Worcester and Wessex Basins show the greatest occurrence of sulphur-bearing species.

3.3 RESULTS

Details of the samples taken for mineralogical analysis are given in Tables 3.1 and 3.2. The results of whole-rock XRD and surface area analyses are shown in Tables 3.3 and summarized in Figure 3.1. Analyses for <2 µm clay mineral XRD are given in Figure 3.2.

3.3.1 Whole-rock mineralogy and surface area

Up to thirteen different mineral phases were identified and quantified in the Lias Group samples. The non-clay mineralogy of the Lias Group rocks is composed of quartz, calcite, dolomite, feldspar (K-feldspar and albite), 'mica' (undifferentiated mica species), pyrite, gypsum and jarosite. The 'beef' sample from the Charmouth Mudstone Formation is almost totally composed of calcite with minor contaminants. In overall terms, the remaining samples are predominantly composed of quartz (6-52%, mean 30%), calcite (not detected, nd-81%, mean 18%), 'mica' (8-41%, mean 28%) and kaolinite (2-22%, mean 14%). The remaining minerals typically form <3% but may reach more elevated levels in selected samples. From whole-rock XRD analysis (Table 3.3 and Figure 3.1), it is apparent that the samples from Areas 3, 4 and 5 (East Midlands, Worcester and Wessex Basins, respectively) are highly calcareous (nd- 81%, mean 31%) when compared to Area 1 samples (Cleveland Basin) samples, which often contain no carbonate species or are only poorly calcareous (nd-24%, mean 3%). Dolomite is also more common in samples from the south (nd-14%, mean 3%) than in the north (nd-3%, mean 1%). Similarly the samples from Areas 5 and 4 (Wessex and Worcester Basins) contain discrete smectite while only interlayered illite/smectite was detected in Areas 3 and 1 (East Midlands Shelf and Cleveland Basin) samples (see below). The southern batch, excluding the 'beef' sample, has a mean surface area of 110 m^2/g but a relatively large range of values from 27 to 203 m^2/g. Surface areas for the northern batch are smaller in comparison with a mean of 85 m^2/g and a range of 24 to 134 m^2/g. Quartz contents are approximately similar for Areas 5 and 4 (6-52%, mean 27%) and Areas 3 and 1 (22-47%, mean 33%) samples while feldspar contents (predominantly albite) are typically low (mean 2%) but reach 9% in a few samples. Of the sulphur-bearing species, pyrite appears to be commonly developed (nd-6%, mean 2%) throughout the Lias Group while weathering products gypsum and jarosite are more sporadic but form up to 12% in a few samples.

3.3.2 Clay mineralogy

The Lias Group samples from Area 1 (Cleveland Basin) show relatively uniform clay mineral assemblages (Figure 3.2). A typical <2 μm fraction is composed of 48% illite/smectite (I/S), 27% illite, 19% kaolinite and 6% chlorite. However, modelling of the XRD traces is hindered by the almost complete overlap of peaks from different clay mineral species. In addition to peak overlap problems, the broad peak profiles of the I/S, produced by its relatively small crystallite size, leaves only the *d*001 (c.11 Å) adequately resolved for modelling. The I/S component was therefore necessarily modelled using the air-dry diffraction trace. Based on this limited data, modelling suggests that the I/S is 90% illite and 10% smectite R0 ordered interlayered clay, which has a mean defect-free distance of 3 layers (10Å units) and a size range of 1 to 15 layers. Illite has a mean defect-free distance of 7 layers and a size range of 1 to 28 layers. Chlorite was estimated to have similar mean defect-free distance of 7 layers (14Å units) and a size range of 1 to 32 layers. Kaolinite has a mean defect-free distance of 11 layers (7Å units) but a size range of 1 to 58 layers.

The clay mineralogy of the Harbury sample (LGD1) from the southwestern edge of Area 3 (East Midlands Shelf) is also composed of I/S, illite, kaolinite and chlorite, and appears to have similar characteristics to those already described for Area 1 (Cleveland Basin). However, the air-dry profile for the Area 3 (East Midlands Shelf) sample indicates a subtle shift in the I/S *d*001 to c.12Å, indicating an increased smectite component in the interlayered species to perhaps 20%.

The Lias samples from Areas 4 and 5 (Wessex and Worcester Basins) differ from their northern counterparts as they contain discrete smectite and no detectable illite/smectite (Figure 3.2). Although they are otherwise similarly composed of illite, kaolinite and chlorite, they display a greater range of clay mineral concentrations. However, modelling suggests that a typical <2 μm fraction is composed of 37% illite, 26% smectite, 25% kaolinite and 11% chlorite. Modelling of the 'southern' sample XRD traces is similarly hindered by the almost complete overlap of peaks from different clay mineral species. In addition to peak overlap problems, the broad peak profiles of smectite, produced by its relatively small crystallite size, leaves only the *d*001 (17.0Å) peak adequately resolved for modelling. Illite has a marginally greater mean defect-free distance of 9 layers (10Å units) and a size range of 1 to 35 layers. Kaolinite and chlorite have approximately similar mean defect-free distances and size ranges to those models produced for the 'northern' samples. In comparison, smectite has a much smaller mean defect-free distance of 1.5 layers (14.5Å units) and a size range of only 1 to 5 layers.

Table 3.1 List of mineralogical samples from the East Midlands Shelf, Worcester Basin and Wessex Basin

Sample No.	Location	NGR	Area	Basin	Stratigraphy		Detailed location	Description
					Formation	Member (zone)		
LGD1	Harbury, Warks. (quarry)	SP 3862 5880	3	East Mids. Shelf	Blue Lias	Rugby Limestone	upper waterfall near entrance	Dark grey mudstone with shell frags.
LGD2	Northcot, Blockley, Gloucs.(quarry)	SP 1795 3699	4	Worcester	Charmouth Mdst	N/A	Ibex zone	Dark grey mudstone with shell frags.
LGD3	Northcot, Blockley, Gloucs.(quarry)	SP 1803 3404	4	Worcester	Charmouth Mdst	N/A	Ibex zone	Dark grey mudstone with shell frags.
LGD4	Ware Cliff, Lyme Regis, Dorset (coast)	SY 3315 9138	5	Wessex	Blue Lias	(Angulata zone)	below Specketty Lst band	Dark grey, laminated mudstone
LGD5	, Lyme Regis, Dorset (coast)	SY 3337 9154	5	Wessex	Charmouth Mdst	Shales-with-Beef	upper semicostatum	Dark/pale grey, laminated mudstone
LGD5'	Ware Cliff, Lyme Regis, Dorset (coast)	SY 3337 9154	5	Wessex	Charmouth Mdst	Shales-with-Beef	upper semicostatum	Fibrous calcite
LGD6	Stonebarrow Hill, Dorset (coast)	SY 3816 9264	5	Wessex	Charmouth Mdst	Belemnite Marl	2m above base	Medium grey siltstone
LGD7	Cain's Folly, Stonebarrow Hill, Dorset (coast)	SY 3739 9288	5	Wessex	Charmouth Mdst	Black Ven Marl	below lowermost Pavior	Dark grey mudstone with shell frags.
LGD8	Cain's Folly, Stonebarrow Hill, Dorset (coast)	SY 3739 9288	5	Wessex	Charmouth Mdst	Black Ven Marl	1.5m above Pavior Limestone	Dark grey, laminated mudstone
LGD9	Seatown, Dorset (coast)	SY 4221 9162	5	Wessex	Dyrham	Eype Clay	4m below Eype nodule bed	Medium-dark grey mudstone
LGD10	Watton Cliff, Dorset (coast)	SY 4529 9094	5	Wessex	Bridport Sand	Down Cliff Clay	against Eypemouth fault	Green siltstone
LGD11 A	Robins Wood Hill, Gloucester (quarry)	SO 3835 2149	4	Worcester	Whitby Mdst	N/A	5m above Marlstone Rock Fm	Green mudstone with black 'root-like' material
LGD11 B	Robins Wood Hill, Gloucester (quarry)	SO 3835 2149	4	Worcester	Whitby Mdst	N/A	(3m depth)(weathered)	Pale green siltstone
LGD12	Robins Wood Hill, Gloucester (quarry)	SO 3835 2149	4	Worcester	Dyrham	N/A	15m below Marlstone	Dark grey, laminated mudstone with shell frags.

Table 3.2 List of mineralogical samples from the Cleveland Basin

Sample No.	Location	NGR	Area	Stratigraphy		Detailed location	Description
				Formation	Member (zone)		
LGD13	Ravenscar (golf course)	NZ 9799 0173	1	Whitby Mdst	Alum Shale	S. cliffs, Robin Hood's Bay	Dark grey, laminated mudstone
LGD14	Ravenscar (golf course)	NZ 9829 0211	1	Whitby Mdst	Mulgrave Shale	S. cliffs, Robin Hood's Bay	Dark grey, laminated mudstone, fossil frags.
LGD15	Ravenscar	NZ 9778 0223	1	Redcar Mdst	Pyritous Shale (lower)	S. cliffs, Robin Hood's Bay	Medium to dark grey, laminated mudstone
LGD16	Staithes	NZ 7880 1886	1	Cleveland Irst	3m below Avicula seam	S. harbour cliffs	Dark grey, laminated mudstone
LGD17	Staithes	NZ 7857 1888	1	Staithes Sst		S. harbour cliffs	Pale/medium grey, massive slst/sst, fossil frags
LGD18	Runswick Bay (cliff)		1	Whitby Mdst	Mulgrave Shale	'jet' workings 2m above beach	Dark grey, laminated mudstone, oxidised pyrite
LGD19	Kettleness (cliff)	NZ 8318 1603	1	Whitby Mdst	Grey Shales	1m above base of W.M.F.	Dark grey, laminated mudstone
LGD20	Kettleness (cliff)	NZ 8317 1599	1	Whitby Mdst	Grey Shales	4m above base of W.M.F.	Dark grey, laminated mudstone
LGD21	Kettleness (former alum quarry)	NZ 8346 1586	1	Whitby Mdst	Alum Shale	??	Dark grey, laminated mudstone, oxidised pyrite
LGD22	Kettleness (former alum quarry)	NZ 8321 1603	1	Whitby Mdst	Mulgrave Shale	5m below top of W.M.F.	Dark grey, laminated mudstone
LGD23	Robin Hood's Bay (harbour)		1	Redcar Mdst	Ironstone Shale	S. of current sea-wall works	Dark grey, laminated mudstone
LGD24	Boggle Hole	NZ 9644 0313	1	Redcar Mdst	Calcareous Shales (upper)	cliff near Stoupe Beck	Medium grey, laminated mudstone
LGD25	Boggle Hole	NZ 9631 0307	1	Redcar Mdst	Calcareous Shales (lower)	wave-cut plat., Stoupe Beck	Dark grey, laminated mudstone

Table 3.3 Summary of whole-rock XRD and surface area analyses (nd = not detected).

Sample	Location	Area	%mineral													S.A. m^2/g
			quartz	calcite	pyrite	dolomite	'mica'	K-feldspar	kaolin	chlorite	smectite	albite	gypsum	jarosite	illite/smectite	
LGD1	Harbury, Warks. (quarry)	3	22	47	2	1	20	nd	4	nd	nd	1	nd	nd	3	114
LGD2	Northcot, Blockley, Gloucs.(quarry)	4	52	1	1	nd	22	nd	20	nd	1	3	nd	nd	nd	86
LGD3	Northcot, Blockley, Gloucs.(quarry)	4	38	1	1	nd	39	nd	21	nd	nd	nd	nd	nd	nd	97
LGD4	Ware Cliff, Lyme Regis, Dorset (coast)	5	13	51	4	5	22	nd	2	nd	nd	nd	3	nd	nd	137
LGD5	Ware Cliff, Lyme Regis, Dorset (coast)	5	22	20	5	1	31	1	9	nd	2	nd	8	1	nd	203
LGD5'beef'	Ware Cliff, Lyme Regis, Dorset (coast)	5	2	86	nd	nd	6	nd	1	nd	1	nd	1	3	nd	23
LGD6	Stonebarrow Hill, Dorset (coast)	5	10	56	2	12	17	nd	2	nd	nd	1	nd	nd	nd	77
LGD7	Cain's Folly, Stonebarrow Hill, Dorset (coast)	5	22	27	4	4	33	nd	10	nd	nd	nd	nd	nd	nd	123
LGD8	Cain's Folly, Stonebarrow Hill, Dorset (coast)	5	17	23	6	14	33	nd	6	nd	nd	nd	1	nd	nd	179
LGD9	Seatown, Dorset (coast)	5	44	3	1	nd	28	nd	15	nd	2	7	nd	nd	nd	98
LGD10	Watton Cliff, Dorset (coast)	5	51	21	nd	nd	17	1	5	nd	2	3	nd	nd	nd	106
LGD11A	Robins Wood Hill, Gloucester (quarry)	4	12	69	nd	nd	15	nd	4	nd	nd	nd	nd	nd	nd	77
LGD11B	Robins Wood Hill, Gloucester (quarry)	4	6	81	nd	nd	8	nd	2	nd	nd	nd	1	2	nd	27
LGD12	Robins Wood Hill, Gloucester (quarry)	4	40	nd	1	nd	29	nd	22	nd	3	3	2	nd	nd	116
LGD13	Ravenscar (golf course)	1	30	nd	5	nd	42	nd	21	nd	nd	nd	nd	nd	2	96
LGD14	Ravenscar (golf course)	1	28	3	6	nd	38	nd	21	nd	nd	nd	nd	nd	4	85
LGD15	Ravenscar	1	29	8	3	nd	37	nd	21	nd	nd	nd	nd	nd	2	86
LGD16	Staithes	1	36	nd	2	nd	36	nd	17	nd	nd	7	nd	nd	2	66

LGD17	Staithes	1	40	24	1	3	13	nd	10	nd	nd	9	nd	nd	nd	24
LGD18	Runswick Bay (cliff)	1	25	nd	3	nd	28	nd	10	nd	nd	1	10	12	11	78
LGD19	Kettleness (cliff)	1	39	nd	3	nd	31	nd	21	nd	nd	4	nd	nd	2	66
LGD20	Kettleness (cliff)	1	31	nd	2	nd	40	nd	18	nd	nd	nd	nd	nd	9	96
LGD21	Kettleness (former alum quarry)	1	32	nd	nd	nd	38	nd	20	nd	nd	nd	nd	nd	10	134
LGD22	Kettleness (former alum quarry)	1	24	nd	1	nd	36	nd	17	nd	nd	nd	8	4	10	117
LGD23	Robin Hood's Bay (harbour)	1	24	6	2	nd	42	nd	21	1	nd	nd	1	nd	3	100
LGD24	Boggle Hole	1	38	1	1	3	37	nd	17	nd	nd	1	nd	nd	2	79
LGD25	Boggle Hole	1	47	nd	nd	1	32	nd	15	nd	nd	1	nd	nd	4	76

Figure 3.1 Summary of whole-rock mineralogical analysis and surface-area

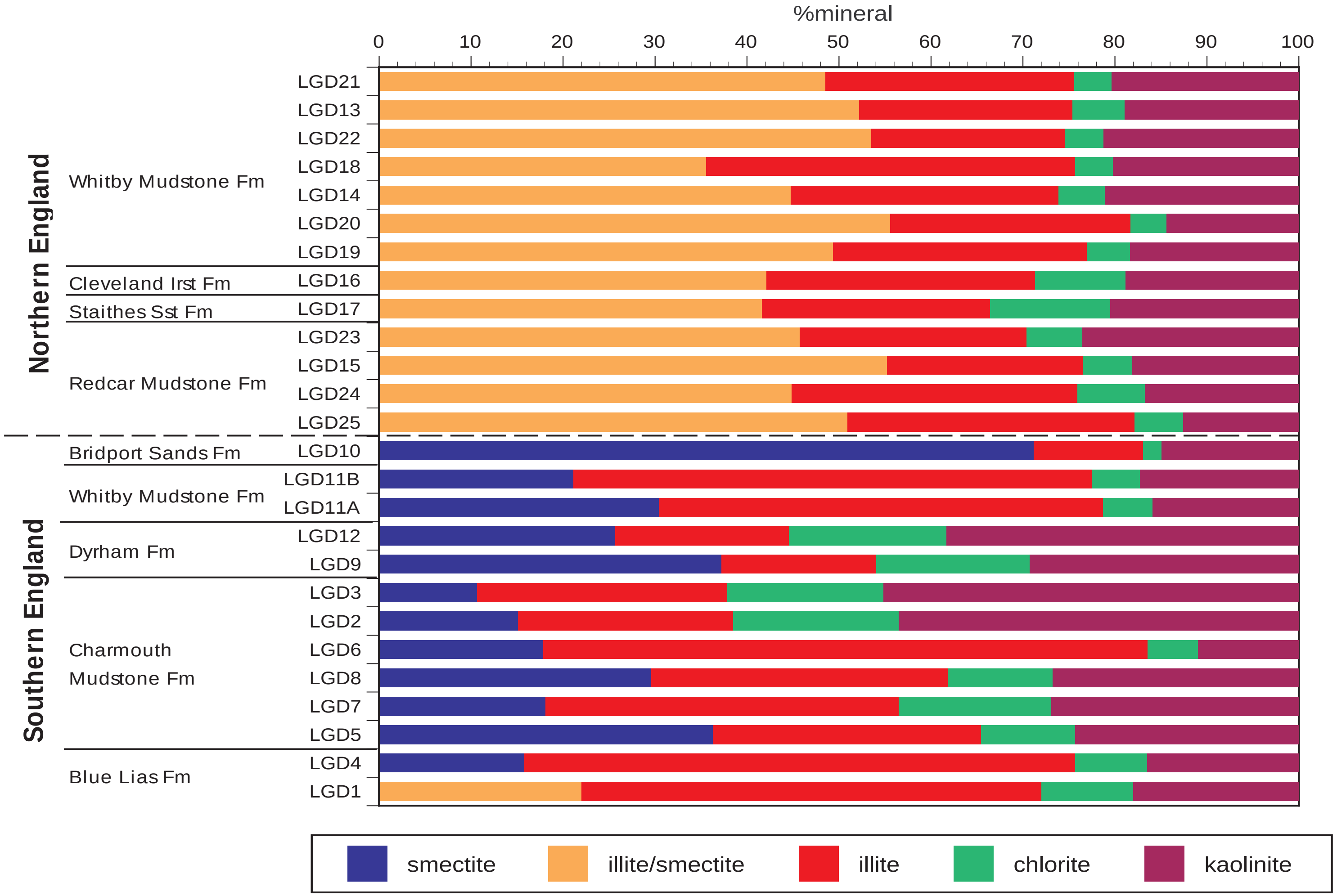


Figure 3.2 Summary of clay mineralogical analysis

3.4 DISCUSSION

Mineralogical analysis of Lias Group samples from various sites representing a relatively large geographic and stratigraphic range have generally similar mineralogies to those described in previous studies (e.g. Kemp & Hards, 2000; Mitchell, 1992; Bloodworth *et al.*, 1987; Pye & Krinsley, 1986; Cosgrove & Slater, 1966). Non-clay mineral assemblages are typically composed of carbonates (calcite and dolomite), quartz, feldspar (albite and occasional Kfeldspar), 'mica', pyrite, gypsum and jarosite. Clay mineral assemblages are generally formed of illite, smectite or illite/smectite, kaolinite and chlorite.

The relatively complex mineralogies of the Lias Group samples are difficult to quantify, even by employing state-of-the-art software modelling packages. For this reason the quoted mineral concentrations must be regarded with some caution. However, calculations using approximate values for %clay (from whole-rock XRD), the clay mineral concentrations from <2 µm XRD analysis and assuming theoretical surface area values for the individual clay minerals, reveal similar whole-rock surface area values to those determined empirically (Figure 3.3).

$$theo.\ surface\ area = \left[\frac{\%\,clay}{100}\right] * \left[\left[\frac{\%\,smectite}{100} * 800\right] + \left[\frac{\%\,illite}{100} * 100\right] + \left[\frac{\%\,chlorite}{100} * 50\right] + \left[\frac{\%\,kaolinite}{100} * 15\right]\right] m^2/g$$

e.g. sample LGD12, empirical surface area, 116 m^2/g

$$theo.\ surface\ area = \left[\frac{54}{100}\right] * \left[\left[\frac{26}{100} * 800\right] + \left[\frac{19}{100} * 100\right] + \left[\frac{17}{100} * 50\right] + \left[\frac{38}{100} * 15\right]\right] m^2/g$$

$$= 129\ m^2/g$$

$$where\ \%\,clay = \%'mica' + \%\,smectite + \%\,chlorite + \%\,kaolinite\ \ from\ whole-rock\ XRD\ analysis$$

Figure 3.3 Calculation of theoretical surface area

Nevertheless, this study has shown that Lias Group rocks of southern England (Wessex and Worcester Basins) and northern England (Cleveland Basin) have importantly different mineralogical characteristics. The mineralogy of the Harbury sample (Area 3 – Blue Lias F.) has an intermediate character, sharing similar characteristics to both northern and southern samples.

Southern rocks often contain large quantities of carbonate (principally as calcite with minor dolomite) while those from northern England contain little or no carbonate. [The only sample from northern England to contain appreciable calcite is the silt/sandstone from the Staithes Sandstone Formation.] The more calcareous nature of the southern rocks and sandier nature of those in the north has been noted previously, but not explained, by Anderton *et al*. (1979). Lithologically, both the analysed sample batches are dominated by mudstones with relatively few siltstones/sandstones and both were observed to contain fossil fragments. It would, therefore, appear that carbonate development is not lithologically controlled. Petrographic analysis is necessary to elucidate whether this apparent difference in mineralogy is due to different sediment source(s) or a different diagenetic overprint between the northern and southern rocks.

This study has also highlighted an important difference in the swelling clay species present in the Lias Group rocks. The samples from Areas 5 and 4 (Wessex and Worcester Basins) contain discrete smectite whereas illite/smectite, I/S (90% illite) is present in the Areas 3 and 1 (East Midlands Shelf and Cleveland Basin) samples. Modelling suggests that all the clay minerals present in the Lias Group have small mean defect-free distances, typically <10 layers thick. Such small crystallite sizes indicate that all species will provide an input to the surface area of the rock. However, the difference in swelling clay species does help to explain the larger surface area values for the southern batch (mean 110 m^2/g) compared with the northern batch (mean 85 m^2/g) despite the presence of more coarse-grained siltstone samples in the south. The smaller surface area of I/S compared to smectite might therefore be expected to produce a greater degree of swell-shrink in the southern strata. However, the high concentration of calcite in the southern samples 'dilutes' the effect of the smectite surface area. In trying to relate the mineralogy and the engineering properties of the Lias Group, it is therefore imperative not only to determine the quantity and type of clay minerals present but also the quantity of calcite present. It is also necessary to know whether the calcite is present as a cement, which will influence engineering behaviour, and/or as shell fragments, which would have a reduced effect. The only previous petrographic study of the Lias Group mudstones (Pye & Krinsley, 1986) suggests that calcite and siderite are present as randomly dispersed rhombs, irregularly shape grains and patches of intergranular cement in the more silty sediments. No primary biogenic carbonate was observed as foraminifera, coccoliths or shell debris. Interestingly these authors also note that although the mudstones have a well-developed lamination and high degree of parallelism shown by micas and clay minerals, they are not notably fissile. During weathering they split into flaggy slabs rather than sheets. Such behaviour was attributed to the high proportion of authigenic minerals (carbonate, pyrite and kaolinite), which act as cements and bind adjacent laminae together.

The difference between the type of swelling clay present in the northern and southern samples also suggests differences in their burial histories (Kemp, et al., 2005). During burial of sedimentary sequences, the clay minerals contained in mudstones and shales undergo diagenetic reactions in response to increasing depth and temperature. Quantitatively, the most important change is the progressive reaction of smectite to form illite via a series of intermediate illite/smectite (I/S) mixed-layer minerals. In general, progressive changes are irreversible so that where basinal sequences have been inverted clay mineral evidence of the maximum burial depth is retained and can be used to estimate the amount of uplift. According to the Basin Maturity Chart of Merriman & Kemp (1996), the presence of I/S (90% illite) in the rocks from the Cleveland Basin suggests burial depths of 4 km, assuming a 'normal' geothermal gradient of 25-30°C/km. The I/S (80% illite) in the sample from Area 3 (East Midlands Shelf), therefore, suggests shallower burial to perhaps 3 km while the presence of smectite and kaolinite suggest that the mudstones from southern England are more immature and have only been buried to depths of less than c.3 km if the same geothermal gradient is assumed. These estimates are compared with those obtained independently from geological evidence in Table 3.4. See also section 6.2.2.

Table 3.4 Estimated maximum burial depths by Area based on geological and mineralogical evidence. (Chapter 2, Geology; * Merriman & Kemp, 1996).

	Area 1	Area 2	Area 3	Area 4 (east)	Area 4 (west)	Area 5	Area 6
Burial depth (m) – based on geology #	2000	550	1000	1100	600	1500	600
Burial depth (m) – based on mineralogy *	4000		3000			< 3000	< 3000

Vitrinite reflectance data for Middle Jurassic coals from Area 1 (Cleveland Basin) show reflectivities of c.0.85% and a rank equivalent to high volatile bituminous coals (Hemingway & Riddler, 1982). Barnard & Cooper (1983) used a combination of vitrinite reflectance and spore colouration indices to conclude that the Middle Jurassic had reached a maximum palaeotemperature of 95°C in the central part of the Cleveland Basin. Furthermore, c.80°C palaeotemperatures for the Middle Jurassic were obtained from fluid inclusion microthermometry from sphalerite grains (Hemingway & Riddler, 1982). Together these palaeotemperatures were taken to indicate a palaeo-depth of c.2.5 km for the base of the Middle Jurassic (Hemingway & Riddler, 1982). The 440 m thickness of the Lias Group in the Cleveland Basin thus produces a maximum depth of burial of c.3km. More recent and detailed modeling (Holliday, 1999) indicate that if the time of maximum burial was end-Cretaceous, between c.2200 and 3000 m of Late Jurassic to Late Cretaceous strata have been removed from the main basin depositional centre, assuming a lack of over pressuring. Alternatively, if the time of maximum burial was during the mid-Cenozoic, the observed palaeotemperatures indicates that between 2300 and 3200 m of Late Jurassic, Cretaceous and Palaeogene strata have been removed. Again, if the thickness of the Lias Group is added, a maximum depth of burial of c.4 km is indicated and in agreement with the clay mineralogical data from this study. A combination of clay mineralogy, sonic log studies and palaeotemperature assessments suggest that the observed high palaeotemperatures for the Cleveland Basin can be accounted for by deep burial and there is no need to infer a local heating event.

Subsidence history plots and hydrocarbon potential studies reveal much shallower depth of burial for the Lias Group in the Worcester and Wessex Basins. Chadwick & Evans (1995) used mudstone densities to suggest that 1650 m of overburden had been removed from the Mercia Mudstone Group in the Kempsey borehole, south of Worcester whereas perhaps 1200 m had been removed from the eastern part of the basin. It would, therefore, appear that the Lias Group has only been buried to perhaps 1.5 km in the Worcester Basin. Calculated organic maturity values of <0.50% R_0 (Ebukanson & Kinghorn, 1986) and organic geochemical analyses (Colter & Havard, 1981) for the Base Lias of the Wytch Farm Oilfield, Dorset suggest organic immaturity. Although maturities are heavily influenced by the Purbeck-Isle of Wight Disturbance, burial thermal history projections based on such data suggest a maximum burial of c.2 km and peak palaeotemperatures of c.75°C for the locations sampled in the Wessex Basin for this study.

Mineralogical analysis also suggests that pyrite is very commonly developed throughout the Lias Group, typically forming 2% of the rock. Pye & Krinsley (1986) observed authigenic pyrite occurring as framboids and larger euhedral crystals, particularly in the Mulgrave Shale Member of the Whitby Mudstone Formation. The other sulphur-bearing minerals, gypsum and jarosite are more sporadically developed but can form up to 12% of the rock. Jarosite and gypsum typically form as weathering products of pyrite. Although it is difficult to comment with such a small sample batch, stratigraphically it would appear that the Whitby Mudstone Formation together with the Blue Lias and Charmouth Mudstone Formations show the greatest occurrence of sulphur-bearing species. Concrete engineering sited in rocks from these formations therefore potentially run the greatest risk of acid and sulphate attack and thaumasite formation.

3.5 CONCLUSIONS

This mineralogical study of a suite of Lias Group sedimentary rocks has generally confirmed the findings of previous workers. However, the wide geographic and stratigraphic distribution of the analysed samples has provided important new information, which will aid not only interpretation of the engineering behaviour of these rocks but also their diagenetic and geological histories. The engineering properties of the UK Lias are heavily influenced by its clay mineralogy and in particular whether discrete smectite or illite/smectite is present. This study has shown that rocks from the West Midlands and southern England (the Worcester and Wessex Basins) are likely to contain smectite and, therefore, have greater shrink-swell potential than those rocks from the East Midlands (East Midlands Shelf) and northern England (the Cleveland Basin). However, the degree of shrink-swell is moderated by the high carbonate content typically found in southern rocks compared to those in the north. As indicated by XRD modelling, the small crystallite size of the other clay minerals; illite, kaolinite and chlorite will also significantly contribute to any volume change and shrink/swell behaviour. The type of swelling clay mineral present is also useful for determining the depth of burial for the Lias Group across England. The illite/smectite, I/S (90% illite) present in the Cleveland Basin suggests a 4 km maximum depth of burial, which corroborates earlier vitrinite reflectance-, fluid inclusion- and sonic velocity-based estimates. The greater proportion of smectite present in the I/S (80% illite) detected in the single sample from the East Midlands Shelf, suggests shallower burial to perhaps 3 km. However, the discrete smectite present in the Worcester and Wessex Basins indicates even shallower burial to no more than 2 km. Studies of basin maturity can therefore be used to predict likely engineering properties for the Lias Group rocks. The common presence of pyrite, together with gypsum and jarosite in the Lias Group means that concrete engineering works sited in these rocks potentially risk acid and sulphate attack and thaumasite formation. The Whitby Mudstone Formation in the Cleveland Basin, together with the Blue Lias and Charmouth Mudstone Formations in the Worcester and Wessex Basins, show the greatest occurrence of sulphur-bearing species.

4 INDUSTRIAL APPLICATIONS

4.1 GENERAL

The Lias Group rocks have provided an important industrial resource, from well before the beginning of the industrial revolution in Britain. The juxtaposition of limestones and clays in the interbeds of the Lias Group formations, combined with other locally derived raw materials such as coal, first allowed local industries to flourish, without the need for imported goods. An example of this was the alum industry, which was one of the first chemical industries in Britain. Other examples include the brick and cement industries, both of which were vital in the development of other major industries, such as civil engineering. Less well-known 'cottage' industries, such as the production of 'jet' ornaments in North Yorkshire, flourished while fashionable in Victorian times. The abundance of fossils, occasionally of a spectacular nature, within the Lias Group, has benefited the study of palaeontology and also the tourist industry in Dorset and Yorkshire, in particular along the 'Jurassic Coast'.

4.2 ALUM

Alum is a potassium aluminium sulphate used as a fixing agent for dyes. The alum industry thrived from the late 17th to the mid 19th centuries and supplied alum for dyeing to the massive British woollen industry and also the tanning industry. However, it is believed that it was operating on a small scale from as early as the mid-15th century in Guisbrough when Sir T. Chaloner and associates were excommunicated by the Pope for ending Italy's monopoly of alum production (Fox-Strangways, 1892). As with many early industries, the alum industry in North Yorkshire developed at the same location as the quarrying of the raw materials. This was largely because transport was difficult, while labour was plentiful. Where necessary, ad hoc transport solutions were constructed, in many cases using the sea as a means of both importing some raw material and exporting the finished product. The industry was therefore centred on the cliff tops around Ravenscar, Sandsend, Kettleness, Saltwick, and Lofthouse, following earlier unsuccessful attempts on the Dorset coast (Jecock, 2003). Quarrying on the cliffs has resulted in major alterations to the natural cliff profiles, which are clearly seen today (Figure 4.1) (Osborne & Bowden, 2001). Frequently, multiple industries, sourced solely from the Lias Group formations, were located within the same small area, though not necessarily contemporaneously. A good example of this is found at Kettleness where the important alum industry, along with the smaller cement, iron, and jet industries, lasted from 1727 until 1871, and has been described in detail by Jecock (2003).

Figure 4.1 Eastern end of former cliff-top alum quarry, with shale baulk in foreground, Kettleness, North Yorkshire, Whitby Mudstone Formation (Alum Shales Member) overlain by sandstones, siltstones and mudstones of the Ravenscar Group [NZ 8346 1586]

The source material was shale from the Alum Shales Member of the Whitby Mudstone Formation. The middle part of the member, the ‘Main Alum Shales’, is particularly low in calcium carbonate and high in sulphate, and hence proved suitable for alum production. The on-site process called ‘calcining’ involved burning shale interlayered with wood in a large pile known as a ‘clamp’. In some cases these were cut into the bedrock in cells separated by ‘baulks’. The calcining process would take months to complete. Oxidised pyrite, and the resulting sulphate, reacted with the aluminium silicates from the shale. The aluminium sulphate produced then reacted with potash from the burning of brushwood or seaweed to produce potash alum. This last reaction was later replaced by producing ammonium alum from the reaction with urine, the bulk of which was shipped in from London (Jecock, 2003; Rayner & Hemingway, 1974). The alum was then concentrated and purified in liquid form by cycles of boiling and cooling in ‘steeping’ pits. These operations were again carried out on site. The pure alum was finally exported in crystalline form. Transport of raw materials and the alum was frequently by flat-bottomed boats beached at low tide. Access from the works to the beach was either by steep roadway using horse and cart, or by inclined tunnel. Evidence of rutways cut into the rock platform can still be found on the foreshore at Kettleness (Jecock, 2003). Over 20 tonnes of shale was required to produce 1 tonne of alum. The industry in North Yorkshire was replaced in the late 19th century by a process based on the treatment of Coal Measures carbonaceous shales by sulphuric acid. The hazards of setting up industries adjacent to sea-cliffs was demonstrated when the operations at Kettleness were disrupted by a major landslide within the sea-cliff in 1829 which destroyed the original alum house.

The preserved remains of the Peak Alum Works can be visited at Ravenscar. Other industrial archaeology remains are at Saltwick, Kettleness, and Boulby. English Heritage and the National Trust are responsible for investigating, archiving and preserving some of these sites.

4.3 BRICK

The Lias Group mudstones have been used for brick and earthenware manufacture since the Roman times (Woodward, 1893). Currently, there are a small number of brick-making operations within the Lias. One of these is operated by Northcot Bricks Ltd. at Wellacre, near Blockley, in Gloucestershire. Here, the Charmouth Mudstone Formation supplies the raw material for facing bricks (Figure 4.2).

Figure 4.2 Northcot brick clay quarry, Wellacre, nr. Blockley, Gloucestershire Charmouth Mudstone Formation (note: landslides) [SP 1796 3696]

Several former brick clay quarries are being converted to landfill. The liner materials are frequently sourced from the mudstone formations used for brick manufacture, and quarrying operations may be run in parallel with landfill development. An example of landfill embankment emplacement at Sidegate Lane landfill site, Finedon, Northamptonshire, is shown in Figure 4.3.

Figure 4.3 Whitby Mudstone, rolled landfill embankment construction, former Sidegate Lane quarry, Finedon, Northants. [SP 916 703]

In the East Midlands, the Charmouth Mudstone Formation (previously referred to as Middle Lias mudstones and siltstones) has provided brick clays (Berridge et al., 1999; Bloodworth et al., 2001).

4.4 CEMENT

During the 19th century hydraulic lime was produced from the Blue Lias in Dorset and Somerset, from the Alum Shale Member (formerly referred to as Cement Shales from the Alum Shale Series/Formation) of the Whitby Mudstone Formation in North Yorkshire (Rayner & Hemingway, 1974), and from the Barnstone Member of the Scunthorpe Mudstone Formation in the East Midlands (Carney et al., 2002). The process consisted of calcining in kilns and grinding to a fine powder. The heated calcium carbonate produced calcium oxide (quick-lime) with carbon dioxide given off. This unstable compound reacted with water to produce calcium hydroxide. This could then be mixed with sand to make mortar. Exposed to air, this slowly took on carbon dioxide and reverted to calcium carbonate (carbonation). The industry supplied several watertight Victorian structures at Scarborough (Fox-Strangways, 1892). The industry has recently been revived on a small-scale in the Blue Lias Formation at Tout quarry, Somerset, in order to provide authentic construction materials for restoration and conservation.

Cement has been produced in the Rugby area since 1820, the first operations having been sited at Newbold. Cement was produced under the ‘Portland’ name from 1870. Portland cement is composed principally of anhydrous calcium silicates, and is made by calcining a mixture of clay, silica and limestone to about 1,500°C. Currently, cement is produced from the Blue Lias at two locations in Rugby (Figure 4.4).

Some production of limestone for cement was closely associated with ironstone working, during the 20th c., in the Marlstone Rock Formation in Lincolnshire, Leicestershire, and Rutland.

Figure 4.4 Blue Circle quarry (south side) at Parkfield Road (eastern site), Rugby. Charmouth Mudstone Formation (top) and Blue Lias F. (bottom),

4.5 IRON

The once-thriving Teesside iron industry was based on the mining of the Kettleness Member of the Cleveland Ironstone Formation (Howard, 1985; Tuffs, 1999). It contains beds of siderite and berthierine, often somewhat nodular, ooidal ironstone, which occurs at the tops of sedimentary rhythms. There are six, named, ironstone bands which are best developed in the Guisborough-Loftus area near Middlesbrough, and were mined here and elsewhere in East Cleveland (Tuffs, 1999), and also in Rosedale and Eskdale. In these areas they form up to 20 per cent of the thickness of the formation. These were worked during the mid 19th to early 20th centuries. A few mines were situated near the cliff edge as at Huntcliff, Brotton (Chapman, 1997). The raw materials and products were transported by a network of railways, and via a specially constructed harbour, Port Mulgrave, between Staithes and Runswick Bay (Osborne & Bowden, 2001). The Cleveland Ironstone Formation at Kettleness was exploited for a short while during the 1830's at its outcrop on the foreshore and transferred directly to beached cargo vessels (Jecock, 2003).

A scattered iron industry was operated, beginning in the 1870's but principally during the 20th c., in the East Midlands, stretching from Corby to Scunthorpe. This used mainly shallow quarries, and in a few cases mines, connected by a complex network of railways and roadways. In the East Midlands, ironstone with a high carbonate content was quarried and mined on a small scale from the Marlstone Rock Formation, for example at Holwell and Wartnaby (Leicestershire) (Carney et al., 2002), and at Harlaxton, Caythorpe, and Fulbeck (Lincolnshire) (Berridge et al., 1999). However, the greater part of the industry, between Corby and Lincoln, and in the Wellingborough area of Northamptonshire, exploited low-carbonate ironstone in the nearby Northampton Sand Formation (Inferior Oolite Group) overlying the Whitby Mudstone Formation (Tonks, 1988). In many cases the two sources were combined to form a self-fluxing ore with optimum composition (Carney et al., 2002). The industry has now ceased, principally due to much greater volumes being readily obtainable from overseas, and the workings and infrastructure largely infilled and abandoned. Some quarries transferred to small-scale limestone extraction for cement, as this constituted the ironstone's overburden.

4.6 JET

Jet is a soft or hard, brown, lustrous, high-grade lithified lignite, representing fossilised driftwood of the monkey-puzzle (araucaria) tree, which is capable of being carved and polished to give a black colour. In North Yorkshire, the lowermost part of the Mulgrave Shale Member of the Whitby Mudstone Formation contains a 7 m bed called the Jet Rock. Near the top of the Jet Rock, sporadic bodies of jet were mined for making jewellery and ornaments, principally during the mid-19th century. At the foot of the cliffs at Sandsend, Runswick Bay, and Saltwick, the remains of so-called 'hob-holes' can be found which are shallow, adits dug into the cliff at beach level (a process known as 'dessing'). Some of these have collapsed. Whilst much primitive gathering was done by beachcombing, the in-situ jet was usually excavated as elongate slabs, known as 'plank jet', up to 2 m in length (Rayner & Hemingway, 1974; Fox-Strangways, 1892). In addition, jet was mined at Kettleness, on the cliff below the alum workings (Jecock, 2003), and also inland at Bilsdale, Bransdale, and Rosedale (Osborne & Bowden, 2001). The jet industry largely came to be associated with the town of Whitby where it was crafted and sold. The use of jet for ornamental purposes, such as brooches, has been traced back to the Romans and Celts (Fox-Strangways, 1892).

4.7 BUILDING STONE

The principal Lias Group rocks that have been used as a source of building stone are limestones and, to a much lesser extent, sandstones. Limestones within the Lias Group have been purposely quarried or mined for building stone, generally for local use (Woodward, 1893), but more often on an ad hoc basis where present as overburden in the pursuit of other minerals, and on the coast where quarrying and transport by sea was easy (Smith, 1974). Examples of limestone building stones exploited in the Lias Group are given in Table 4.1 (Smith, 1999).

Table 4.1 Examples of Lias Group limestone building stones [f=ferruginous, s=shelly]

Stone name	Formation	Location
Hornton (f)	Marlstone Rock	Edgehill, Banbury (Oxon.)
Wroxton (f)	Marlstone Rock	Hornton Grounds, Wroxton Heath (Oxon.)
Blue Lias Marble	Blue Lias.	Tout, Charlton Adam, Charlton Mackerell, Keinton Mandeville (Somerset)
Ham Hill (s)	Bridport Sand	Ham Hill, Stoke-sub-Hamdon, (Somerset)
Ham Hill (s)	Bridport Sand	Norton, Stoke-sub-Hamdon (Somerset)
	Marlstone Rock	Grantham (Lincs.)

The Lias Group limestones are not often used for 'dressing' stone, because of poor durability, poor frost-resistance, and thin bedding. They are more usually applied as thin 'coursed' stone. The Hornton, Wroxton, Blue Lias Marble, and Ham Hill varieties (Table 4.1) are either still quarried, or have been in the recent past (Hardy, 1999). Formerly, much more widespread use was made of Lias Group limestones for very localised construction. The Blue Lias Formation limestones were traditionally used in central Somerset in the form of large, flat wall, and floor/paving slabs.

The Marlstone Rock Formation, overlying the Dyrham Formation, or the Charmouth Mudstone Formation in the East Midlands Shelf, forms distinct escarpments and outliers, for example on the southeast edge of the Vale of Belvoir in the East Midlands (Carney et al, 2002). Here the formation has been used in the past to supply local building stone, in addition to its more recent use as a source of iron. However, the limestone/ironstone has proved to weather badly and is no longer in use.

In South Wales, limestones from Sutton, near Bridgend (Glamorgan) were of good quality and used for building and walling. Similar stone was quarried at Shepton Mallet and at Street, Somerset (Woodward, 1893).

Currently, building stone is extracted in Somerset (Yeovil, Somerton, Downslade, Tout), Avon (Stowey), Oxfordshire (Balscote), Gloucestershire (Marshfield), Warwickshire (Avon Dassett, Edgehill, Wellesbourne). Other smaller quarries in these counties supply aggregate and ornamental stone (Cameron et al., 2002).

5 GEOHAZARDS

Geohazards have particular significance in urban areas where, in addition to endangering human life, their consequences may affect large developments, individual homes, transport and services. The British Geological Survey has an ongoing programme to assess geohazard susceptibility and record geological hazard events in Britain. An integral part of this programme is the study and understanding of the processes and mechanisms involved. Those geohazards considered to be of particular relevance to the Lias Group are: landslides, shrink/swell potential, sulphate attack on buried concrete structures, and radon. These are discussed below.

5.1 LANDSLIDES

5.1.1 General

Britain does not suffer from landslide hazards on the physical or human scale experienced in some parts of the world. However, there are a large number of landslides (believed to be in excess of 10,000) existing largely as a result of Britain's glacial and periglacial history, and as a consequence of coastal erosion. Records of known landslides are maintained as part of the BGS's National Landslide Database; which incorporates data acquired from an earlier national study for the Department of the Environment by Geomorphological Services Ltd. (Jones & Lee, 1994). Contrary to popular belief, landslides *have* caused fatalities in Britain, albeit in most, but not all, cases as a result of consequential rail or traffic accidents. Many landslides on the coast are associated with coastal erosion, particularly in eastern and southern England, the great majority of which are unrecorded. The presence of these landslides raises economic and planning issues and, in some cases, safety issues. It is apparent that Lias Group rocks are markedly landslide-prone and include a particular form of mass movement known as 'cambering'.

Cambering is a mass movement process whereby a competent, relatively brittle caprock layer overlying a weak, 'extruding' clay layer, at the edge of a plateau or hilltop, is subject to 'hinging' or 'slumping' downward and outward, and subsequent gradual break-up. These masses then become involved in landslides on the slope. One effect of cambering is to exaggerate the apparent caprock thickness, and conversely reduce the apparent thickness of the sub-stratum. A good example of cambering is found on Bredon Hill, Worcestershire (between Tewkesbury and Evesham) where the base of the Inferior Oolite limestone caprock (overlying Whitby Mudstone) drops up to 53 m, from its original elevation. Associated with cambering are 'gulls'. These are open or infilled tension cracks within the caprock, usually formed along pre-existing joints and running mainly parallel with the valley or escarpment. In some cases, gulls may be 'bridged', that is they occur only in the lower beds of the caprock and are not visible at surface. Such gulls occur in the Great Oolite Formation of the Bath area where they form a network of orthogonal 'gull caves' deep within the hillside (Self, 1985).

5.1.2 Landslides in the Lias Group

There are many recorded landslides either within the Lias Group outcrop or involving materials derived from it. A small number of these are well documented. These are found particularly in the Cotswolds, the Bath area, the East Midlands, the North Yorkshire Moors, and the Dorset coast.

A total of 1,316 landslides involving Lias Group rocks were recorded as part of the DoE/GSL national database (Jones & Lee, 1994). The Lias Group landslides were shown to represent 15% of all those recorded in Britain with the most common landslide types found to be ‘rotational’, ‘flows’, ‘compound’, and also ‘cambers’. The ‘Upper Lias’ was found to be the most susceptible to landslides (distinction by Formations was not made in the DoE/GSL database; see Glossary for correlations), accounting for 50 % of the Lias Group landslides, and with a density of 42 landslides per 100 km^2 of outcrop. This compares with 28 and 10 landslides per 100 km^2 for the ‘Middle’ and ‘Lower Lias’ respectively. [*Note: These figures include major coastal landslides*]. Along with the London Clay, The Lias Group is probably the most widely studied with regard to landslides in Britain (Jones & Lee, 1994). It has been estimated (Butler, 1983) that as much as 51 % of the Upper Lias outcrop area in the Cotswolds is affected by either landsliding or cambering.

5.1.2.1 Inland landslides

The principal regions and types of inland landslides within the Lias Group are:

• Avon – Somerset -Wiltshire (multiple rotational, cambering, debris slides)

• Cotswold Hills (multiple rotational, cambering, debris slides, mudslides)

• East Midlands (cambering, rotational, mudslides, slab slides)

• North York Moors (multiple rotational, cambering, toppling, debris flows)

Note: For landslide types refer to: Varnes (1978) and Cruden & Varnes (1996).

Avon-Somerset-Wiltshire

The landslides surrounding the city of Bath, in Avon and West Wiltshire, are well documented (Chandler et al., 1976; Hawkins, 1977; Anson, 1996; Cook, 1973) and represent some of the best examples of their type. The Lias Group here forms the lowest part of a two-level landslide domain extending upward to the limestones of the Great Oolite Group forming the plateaux around the city. The Hengrove Wood landslide in the Limpley Stoke valley is a characteristic example (Figure 5.1).

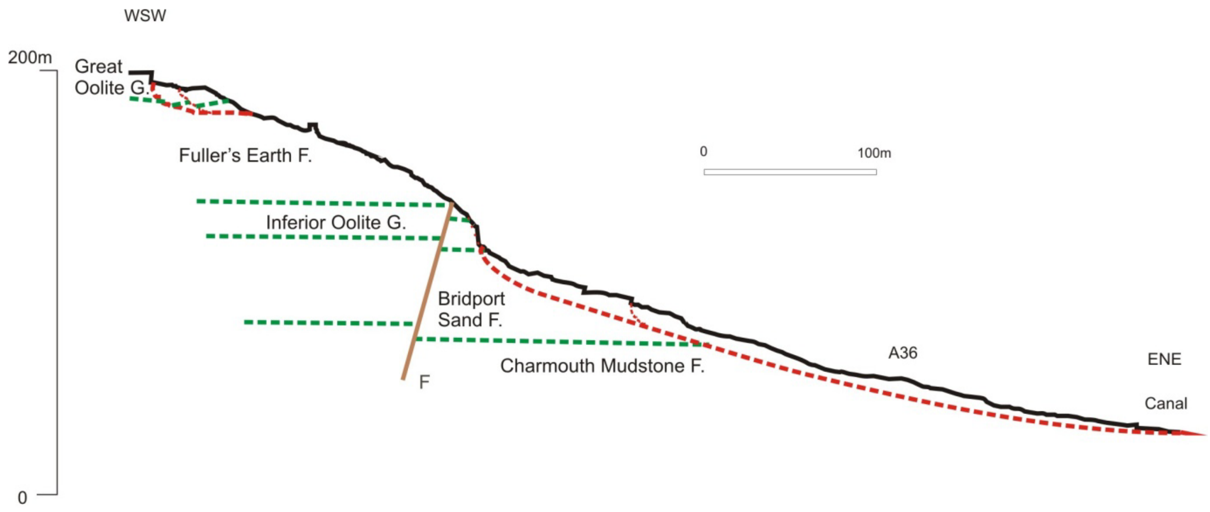


Figure 5.1 Slope cross-section: Hengrove Wood landslide, Limpley Stoke valley, Bath (Hobbs, 1980*) Note:* Likely slip surfaces shown in red

Here the Charmouth Mudstone Formation (Lias Group) is overlain by the Inferior Oolite Group limestones, which in this instance produce a prominent escarpment and appear un-cambered. The lower parts of this landslide have been active in recent times, and have involved the A36 road and the Kennet & Avon canal (Hobbs, 1980). However, evidence of cambering of the Inferior Oolite Group on the Lias in the Swainswick valley, Bath, was obtained by site investigations during the 1970's and 1980's for the A46 road re-alignment on the east side of the valley. A large number of continuously cored boreholes were drilled, several of which revealed no Inferior Oolite. These were interpreted as having been drilled through wide 'gulls' which had become infilled both from above by the Fuller's Earth Formation of the Great Oolite Group, and below by the Bridport Sands Formation (formerly Midford Sands) of the Lias. A landslide map of the Bath and Bristol area, showing the outcrop of the Lias Group in light brown is shown in Figure 5.2.

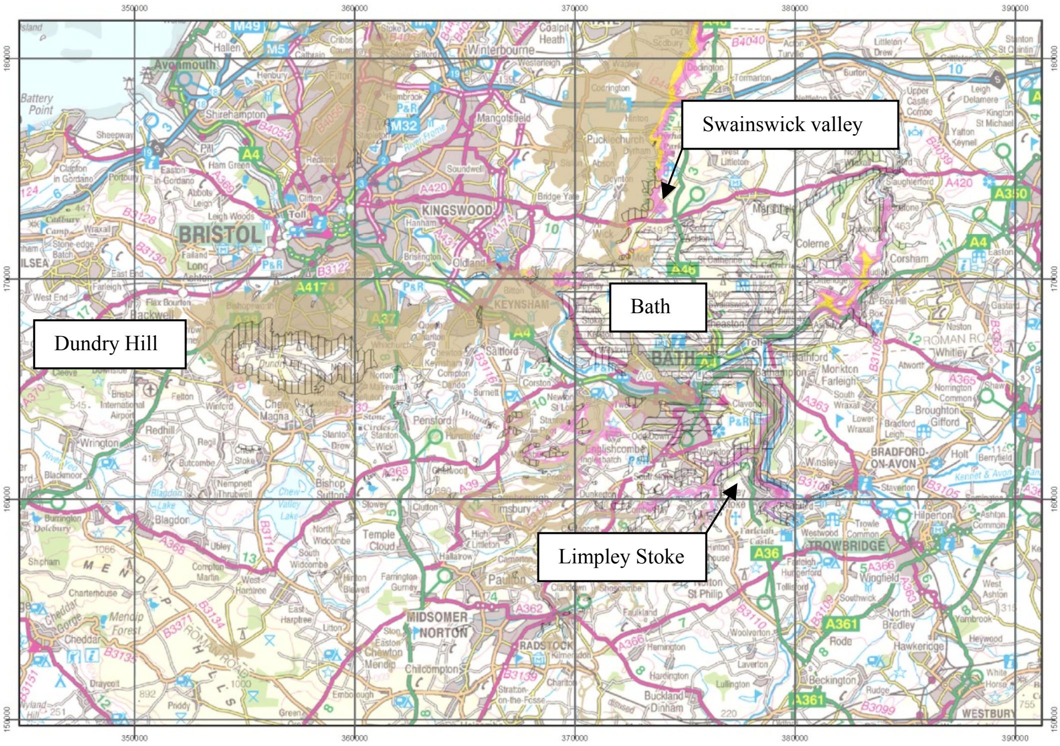


Figure 5.2 Landslides and Lias Group strata in the Bath/Bristol area
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide]

Cotswold Hills

The Cotswold Hills are well known for their escarpments, outlier hills, and the many examples of landslides and cambering associated with them (Goudie & Parker, 1996; Jones & Lee, 1994; Whitworth et al., 2003; Seedhouse, 1987). To the south, the Great Oolite is the main scarp-forming caprock and the Fuller’s Earth Formation (Great Oolite Group) provides a weak underlying mudstone. To the north, however, the Inferior Oolite becomes the main caprock and the Lias Group mudrocks the substrate. Landslide frequency is strongly influenced by this change in geology, which occurs in the area of Stroud; the frequency increasing from south to north (Figures 5.3, 5.4 and 5.5).

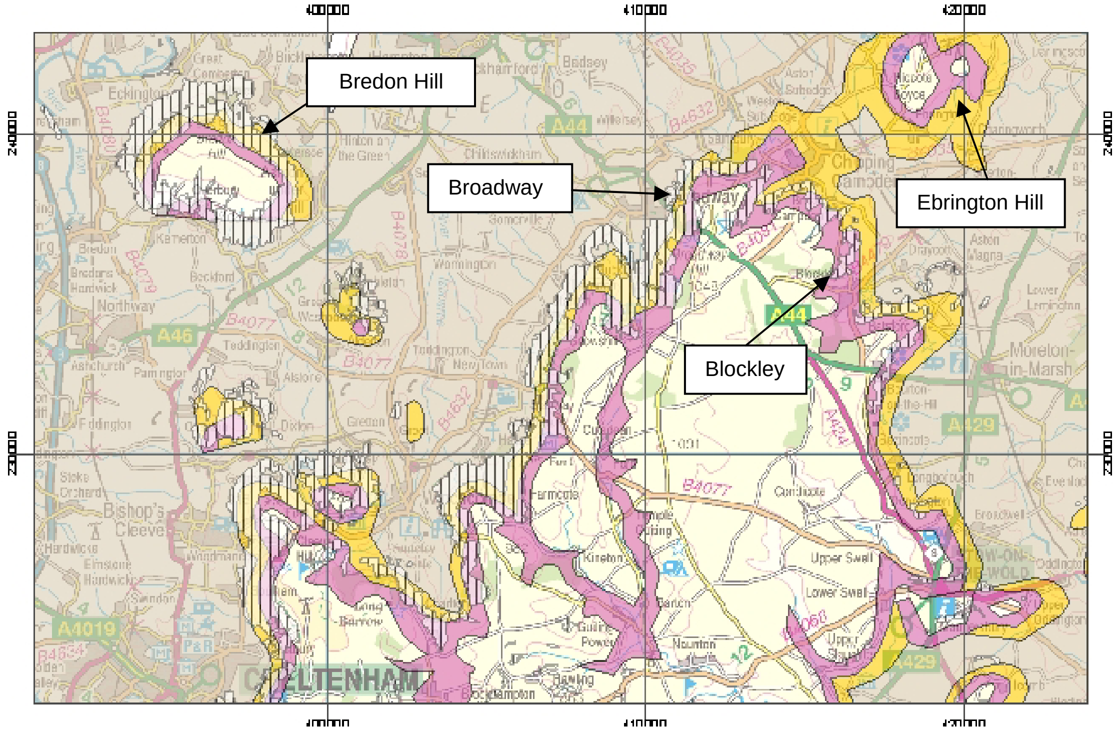


Figure 5.3 Landslides and Lias Group strata in the Cotswolds (northern section)
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide]

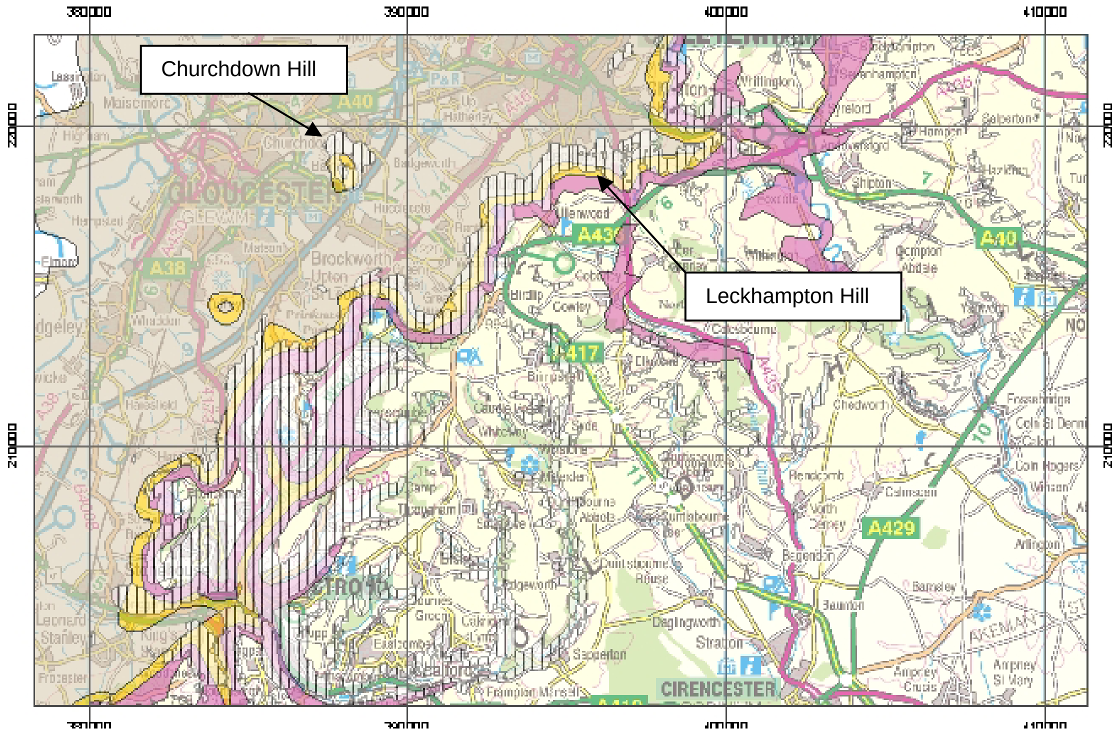


Figure 5.4 Landslides and Lias Group strata in the Cotswolds (central section)
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide]

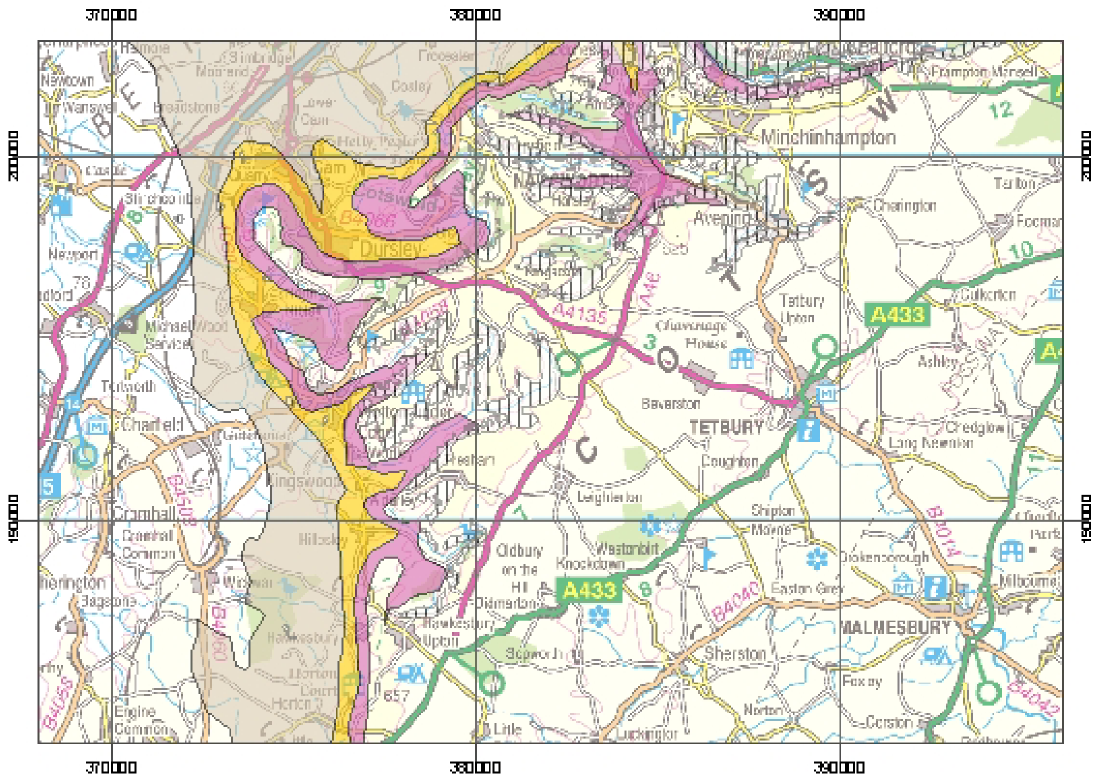


Figure 5.5 Landslides and Lias Group strata in the Cotswolds (southern section)
[Key: grey = Lower Lias, yellow = Middle Lias, purple = Upper Lias, hatching = landslide]

Whilst the landslides mainly date from times of periglacial conditions, some areas are currently active, and examples in the Lias occur at Broadway (Rowlands et al., 2003; Whitworth et al., 2003), Moreton-in-Marsh, and around Cheltenham. The principal (though not the only) mode of slope failure in the Lias Group is as shown in Figure 5.6 taken from Butler (1983):

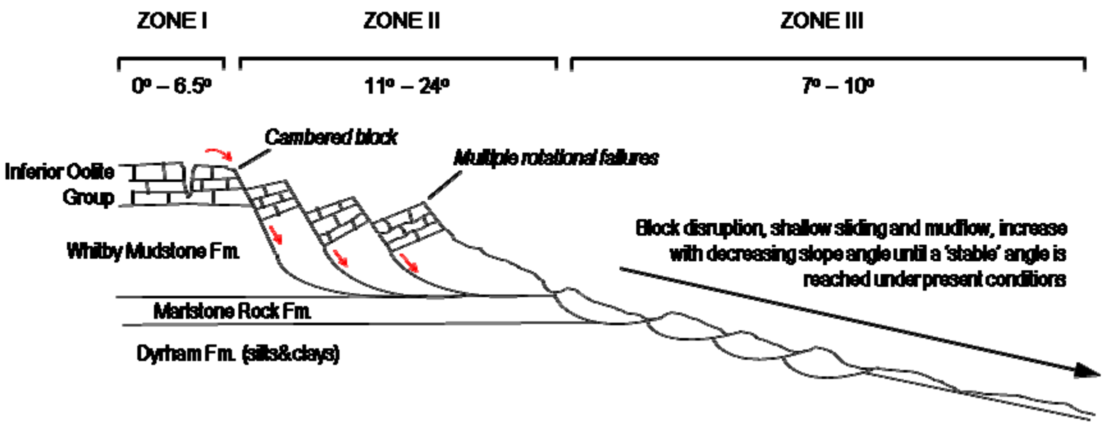


Figure 5.6 Mass movement processes in the Cotswolds (modified after Butler, 1983)

Figure 5.7 Photo showing active mass movement on slopes [Inferior Oolite Group overying Whitby Mudstone Formation] to the south-east of Blockley, Gloucs. (Cotswolds), Nov. 2001.

Landslide type is linked to slope angle and geology. Typical of Lias in the Cotswolds, the slopes around Blockley, Gloucestershire (Figure 5.7) feature both landsliding and cambering, elements of which remain active. Mudslides in Dyrham Formation have been recorded at Churchdown Hill, Leckhampton Hill, and Ebrington Hill, Gloucestershire (Butler, 1983; Hutchinson, 1988).

East Midlands

In the Midlands, Lias Group landslides were investigated at Uppingham in Whitby Mudstone Formation (Chandler, 1970) and on the A45 Daventry By-pass at Fox Hill and Newnham Hill, again within the Whitby Mudstone Formation overlain by the Northampton Sand Formation (Biczysko, 1981).

The influence of weathering on slope stability has been examined by Chandler (1972). Sites at Culworth, Stowehill, Gretton, and Rockingham (Northamptonshire), and at Wothorpe (near Stamford, Lincolnshire) were studied for relationships between degree of weathering and strength, in the light of landslides and cambers at the sites. The author noted that persistent instability of a road cut at Wothorpe appeared to be related to fabric disturbance of the Whitby Mudstone Formation, probably associated with cambering of the overlying ironstone (Northampton Sand Formation), and linked it with similar observations in the Bath and Wellingborough areas. The author also proposed a weathering scheme for the Whitby Mudstone Formation (Upper Lias Clay) (Chandler, 1972). Periglacial freeze/thaw effects on the Lias have been described (Kovacevic et al., 2007). These have resulted in a distinctive brecciated fabric and highly variable geotechnical properties (see also section 6.3.1).

Landslides feature on the Lincolnshire Limestone Formation and Marlstone Rock Formation escarpments of the East Midlands, for example in the Grantham area (Forster, 1992; Berridge et al., 1999), Melton Mowbray area (Carney et al., 2002), and on the Lincoln Scarp (Penn et al., 1983). Shallow slumps and mudflows characterise slope instability within the underlying Whitby Mudstone Formation between Grantham and Lincoln, and also to the southwest of Grantham bordering the Vale of Belvoir. These become readily re-activated and result in a hummocky surface. Cambering of the Marlstone Rock Formation has also been observed in the Grantham area (Berridge et al., 1999). In Rutland there are scattered landslides on the Whitby Mudstone Formation, between Uppingham and Oakham. Further south, landslides have been investigated at Rockingham, near Corby [at SP 874 918 and between SP 874 918 and 889 925] (Chandler, 1972). In the Market Harborough area, there are shallow landslides of shallow successive rotational slide type within the Whitby Mudstone Formation overlain by Northampton Sand Formation at Medbourne [SP 803 933] (Figure 5.8) and Slawston Hill [SP 782 941] (Poole et al., 1968).

Figure 5.8 Active shallow successive landslides in Whitby Mudstone Formation at Medbourne, Leics. (Feb 2003) [SP803 933]

The Lincoln Scarp has been modified by periglacial activity, including landsliding and cambering (Penn et al., 1983). Here, the scarp is formed by weathered and cambered Northampton Sand and Lincolnshire Limestone Formations (Inferior Oolite Group). These have supplied water to the slopes below underlain by Whitby Mudstone Formation, Marlstone Rock

Formation and Charmouth Mudstone Formation strata, and Head deposits, resulting in phases of shallow slumping, mudslide, and solifluction lobe re-activation. The cambering, and associated gull formation, is small-scale and oriented sub-parallel with the scarp due to jointing.

5.1.2.2 CAMBERING AND VALLEY BULGING

Cambering was first identified in Britain at ironstone quarries and river sections in the Shipton valley of Northamptonshire during the 1940's (Hollingworth et al., 1944). Subsequently, significant investigations and reviews into cambering, and the associated phenomena of 'valley bulging' and 'gulls', have been carried out (Hutchinson, 1988; Parks, 1991; Humpage, 1996). Other investigations involving the Lias Group include:

- Empingham Dam, Leicestershire [cambering & valley bulging] (Figure 5.9) (Horswill & Horton, 1976; Vaughan, 1976; Kovacevic et al., 2007)
- Pinbury Park, Stroud, [valley bulging] (Ackermann & Cave, 1967)
- Upper Slaughter, Cotswolds (Briggs & Courtney, 1972)

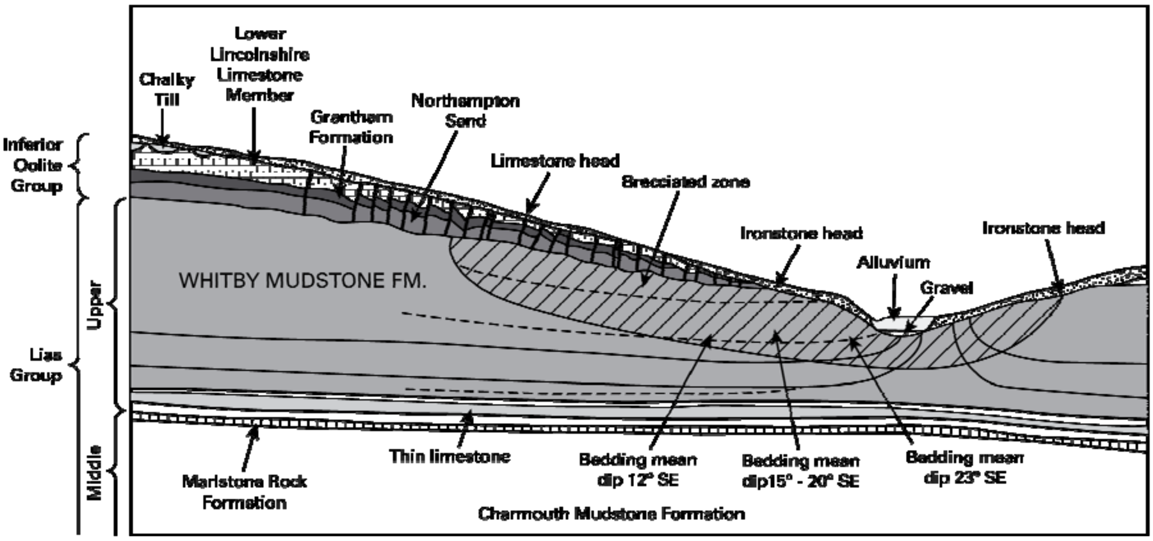


Figure 5.9 Cambering and valley bulging, Empingham, Rutland (after Horswill & Horton, 1976) [SK494308]

Elsewhere, cambering of the Lincolnshire Limestone and Northampton Sand Formations at Little Ponton, Wellingborough, Oundle, Eye Brook, Hollowell, Rothwell, Kettering, Thrapston, Kingsthorpe, Hunsbury Hill, and Little Addington have been described by Hollingworth et al. (1944), Hollingworth & Taylor (1951), and Poole et al. (1968). Most of these examples, but not all, are accompanied by valley bulging, usually involving Lias Group formations as the basal bed; the plastic extrusion or faulted displacement of which into the valley floor initiates the cambering process. Examples where valley bulging features are exposed at the present day are rare. Historically, evidence would have been perhaps more abundant due to the proliferation of mining, quarrying, dam building etc.

The pattern of cambering is usually the same throughout, though the severity varies, as does the presence of tensional features such as 'dip and fault' structures. Severe cambering is usually accompanied by basal shearing and landsliding. Hollingworth & Taylor (1951) noted that occasionally 'multi-formational' cambered layers were present in the same valley section. Cambering does not necessarily affect both sides of a valley equally. In some cases it may be absent on one side or replaced by conventional landsliding, as at Blockley [SP416235]. Vertical displacements due to valley bulging of as much as 30 m have been noted by Hollingworth & Taylor (1951). They also noted that the axis of the bulge may be off-line with the current river valley, as a result of stream migration. Severe upward extrusion, due to valley bulging, of Whitby Mudstone Formation clays at Irthlingborough [SP 935 703] in the Nene Valley has apparently coincided with a fault on the northern perimeter of a limestone quarry (Hollingworth & Taylor, 1951, pp. 34, 180, fig. 17).

Cambering at a site in Radstock, Avon, was described by Hawkins and Privett (1981). The site investigation for a housing development revealed hidden extension gulls associated with cambering of Blue Lias Formation limestones over Westbury Formation and Cotham Member (Penarth Group) clays and mudstones, and Mercia Mudstone Formation. The gulls were frequently bridged, and hence concealed, by Head deposits. Hawkins & Privett (1981) proposed a four-way classification of gulls based on the observations made during the investigation. Similar bridged gulls are found in the Limpley-Stoke valley near Bath, Avon (Hobbs, 1980), within the Great Oolite Series limestones. One of these is illustrated in Figure 5.10.

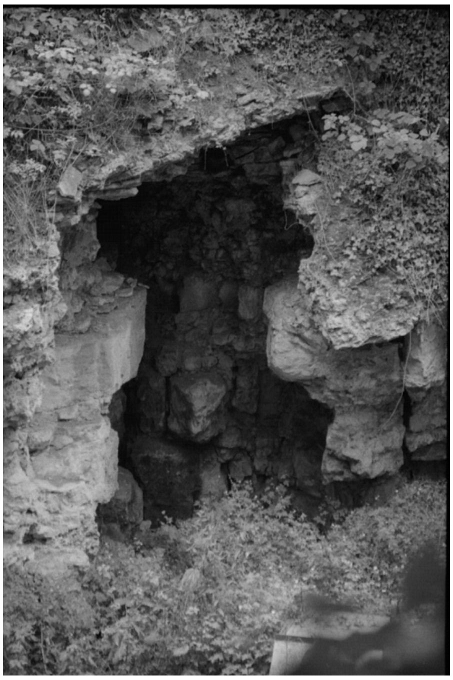


Figure 5.10 Bridged gull near Limpley Stoke, Avon [ST 780 610]

Geophysical investigation, using ground-probing radar and resistivity imaging, of superficial structures mappable at the surface in the Windrush and Eye valleys of the Cotswolds was described by Raines et al, (1999). This survey successfully imaged gulls in Mid-Jurassic limestones overlying the Whitby Mudstone Formation. However, the mechanism of cambering suggested by the geophysical data was not the classic one of ‘draped’ strata dipping valleywards as described in Parks (1991) and Hutchinson (1988), but rather a version, possibly modified by post-cambering landslides, where blocks are backtilted.

Valley bulging is a process of valley bottom uplift, extrusion or folding typically parallel to the valley axis, produced by erosive stress relief, probably during Pleistocene times. The process is linked to cambering and many occurrences are present within the Whitby Mudstone Formation. The process tends to fold and shear the relatively weak (possibly saturated) clay strata at the valley bottom, and may result in Lias outcropping above its normal position. The structures produced by valley bulging are often planed off by erosion or obscured by alluvium. Ackerman and Cave (1967) described examples from the Frome valley near Stroud. Examples of severe ‘contortion’, principally a ‘tight anticlinal fold’ aligned parallel with the Fishpool Brook valley, within the Barnstone Member (formerly the Hydraulic Limestone) of the Scunthorpe Mudstone Formation seen in former cement workings at Barrow-upon-Soar (Lamplugh et al., 1908), are probably attributable to valley bulging (Figure 5.11).

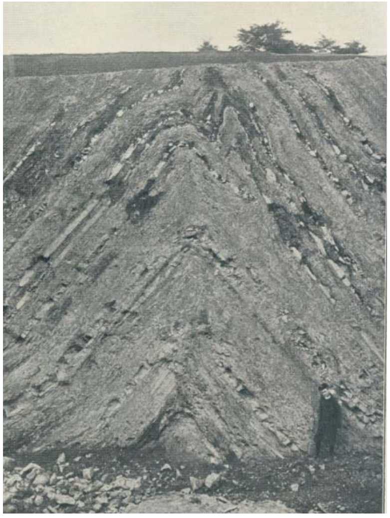


Figure 5.11 Possible valley bulging in Scunthorpe Mudstone Formation at Cream Lodge, Barrow-upon-Soar, Leicestershire (Lamplugh et al., 1909) [5915 1863]

Cambering/valley bulging and landsliding in the Lias Group rocks typically result from a process known as progressive failure. This is due to over-consolidation by overburden (including ice) followed by overburden erosion (or post-glacial ice melting) and stress relief, resulting in weakening of the rock mass. These factors are often associated with a delay in failure following slope alteration. This type of failure mechanism is believed to be common in cut slopes in overconsolidated clays. Coastal landslides in over-consolidated clays often differ significantly, due to the wide range of time scales of coastal erosion and the effects of this on pore pressure equilibration, and hence effective stress and stability. Whilst negative pore pressures have been demonstrated for cliffs in Tertiary clays (Dixon & Bromhead, 2002), it may also apply to some coastal Lias Group landslides where the erosion rate is particularly high and the landslide type is of low complexity.

5.1.2.3 Coastal landslides

The principal areas of coastal landslides within the Lias Group (with their typical modes of failure) are:

- Lyme Bay, Dorset (mudslides, mudflows, earthflows, multiple rotational, block slides)
- Watchet Bay, Somerset (debris slides, rockfalls)
- Glamorgan, South Wales (rockfalls, topples, translational)
- North Yorkshire coast (rock fall, debris slide)
- Inner Hebrides (multiple rotational, block slides, rock fall)

Lyme Bay

Dorset’s Lyme Bay coastline, from Axmouth to Burton Bradstock, has many famous examples of large and complex landslides in which the Blue Lias, Charmouth Mudstone, and Dyrham Formations feature. Many of these are active and have caused considerable damage in built-up areas. These include Bindon (Pitts & Brunsden, 1987), Lyme Regis (Sellwood et al., 2000; Lee

& Clark, 2002), Black Ven (Brunsden, 2002; Conway, 1974), Stonebarrow Hill (Ramli et al., 2000), Warbarrow, and Seatown (Atherton & Burbidge, 2000).

The well-known Black Ven landslide between Charmouth and Lyme Regis is large and complex. It is characterised by a series of benches (Figure 5.12) on which discrete landslides occur, and over which mudflows and mudslides move more or less continuously (Gibson, 2005). The upper platform and backscar consist largely of sands (‘Foxmould’ and ‘Chert’ of the Upper Greensand) on a thin layer of highly plastic Gault Formation clay. These strata are the principal source of groundwater to the landslide, and the origin of major rotational movements. The Stonebarrow Hill landslide (Figure 5.13) immediately to the east differs slightly in profile due to the eastward dip of the strata. Here the Belemnite Marl Formation provides a relatively stable bench caprock and, with the underlying Black Ven Marl Formation, the near-vertical sea cliff. The aftermath of a major re-activation in 2000 is shown in Figure 5.13. Landslides in the area are not confined to sea cliffs, and are also found on the slopes of the River Char valley (Jones & Lee, 1994).

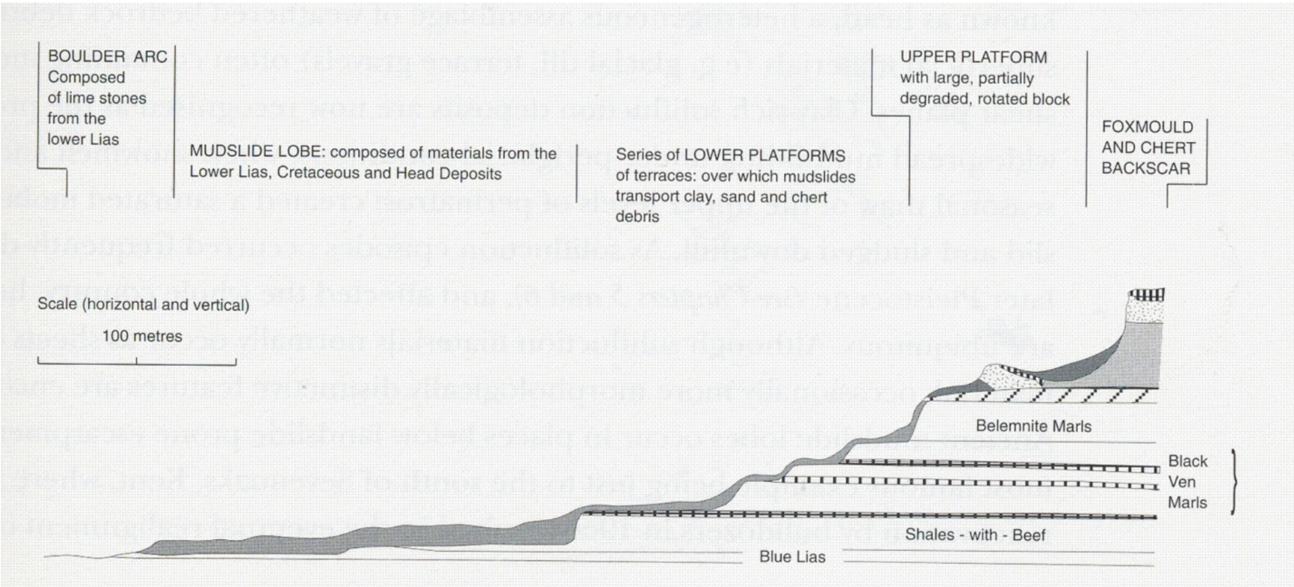


Figure 5.12 Cross-section through Black Ven landslide, Charmouth, Dorset (Conway, 1974) [SY 354 932]

Figure 5.13 Stonebarrow Hill landslide, Charmouth, Dorset

Photo: N. Gregory (Apex) 28/12/00 [SY 378 929]

As an interesting footnote with respect to Dorset coast landslides, there have been many instances reported of spontaneous combustion of shales within the Shales-with-Beef Member of the Charmouth Mudstone Formation, in particular in 1908 at the Spittles, Black Ven (Jukes-Brown, 1908). These appear to be similar to combustion events observed in the Kimmeridge Clay Formation at Kimmeridge, Dorset. The fires have been associated with recent landsliding (exposure of fresh rock), and wet conditions, and may therefore be initiated by the oxidation of pyrite, followed by ignition of bituminous material and vapour (West, 2003). The Lias Group rocks concerned typically have about a third the organic content of the bituminous Blackstone Member of the Kimmeridge Clay Formation.

Watchet Bay

The Somerset coastline of Bridgwater Bay, between Watchet and Burnham-on-Sea, features landslides on cliffs formed from an outlier of thick undifferentiated Langport Member (Rhaetian), Blue Lias Formation and Charmouth Mudstone Formation. These consist of limestones, shales, and bituminous shales. The Blue Lias east of Watchet is about 145 m thick.

Glamorgan

The 22 km Glamorgan Heritage Coastline, between Ogmore-by-Sea and Barry, features landslides on 15 to 80 m high cliffs in the Porthkerry and Lavernock Shale Members of the Blue Lias Formation (Williams et al., 1993; George, 1974). Examples of coastal exposures are shown in Figures 5.14 and 5.15.

Figure 5.14 View from Trwyn y Witch towards Nash Point, Glamorgan Heritage Coast

<u>Note:</u> Cliffs of Blue Lias Formation. Folds and faults on wave-cut platform. [SS 890 723]

Figure 5.15 Detail of Blue Lias Formation cliffs between Trwyn y Witch and Nash Point, Glamorgan Heritage Coast Note: joint-controlled stacks, block slide, and talus cone [SS 891 721]

North Yorkshire

Lias Group rocks are exposed on the 50 km section of the North Yorkshire coast from Robin Hood's Bay (Figure 5.16) to Redcar. A variety of landslides are found here. Whilst these principally occur within till, and other superficial deposits, overlying the Lias and other formations, the Lias Group formations may be involved. The Lias Group rocks of North Yorkshire are generally stronger and more durable than their equivalents on the Dorset or Bristol Channel coasts (refer to Chapter 7 and Kemp et al., 2005). Contemporary landslides are consequently less numerous, less spectacular, and less active. Considerable thicknesses of till and other superficial deposits are found frequently occupying the entire cliff section. These tend to concentrate ground water, and are particularly prone to rotational landslides and mudslides. Landslides within the Lias Group cliffs tend to be 'rock falls', 'debris slides', or 'topples', although in the geological past some deep-seated landslides have occurred.

Figure 5.16 Cliff and wave-cut platform and deep-seated landslides (distant, left) at Ravenscar, Robin Hood's Bay, N. Yorkshire, in Whitby Mudstone, Cleveland Ironstone, Staithes Sandstone, & Redcar Mudstone Formations)

Inner Hebrides

A few of the many large landslides on the Isles of Skye and Raasay involve Lias deposits. Notably, Dun Caan on the east coast of the Isle of Raasay (Figures 5.17 & 5.18) and Ben Tianavaig on the east coast of Skye, south-east of Portree and facing Raasay. These landslides are sliding on the relatively weak Portree Shale, Scalpay Sandstone, and Pabay Shale Formations of the Lias Group. Dun Caan is described as having been active in historical times (Anderson & Dunham, 1966). The extensive and structurally complex Trotternish landslide zone on the east coast of Skye extends from the famous Quiraing (Flodigarry) in the north [NG 449 716], via the Cleat and the Storr, to Ben Tianavaig (near Portree) in the south [NG 512 410] (Benn and Ballantyne, 2000), a distance of 23 km. However, only the southern part of this zone involves Lias Group rocks. Landsliding has been linked with de-glaciation around 17,500 years BP, but one landslide has been dated at only 6,500 years BP. It is thought that earthquakes may have been a factor (Benn and Ballantyne, 2000).

Figure 5.17 View of Dun Caan landslide, east coast of Raasay, Inverness-shire. [NG 586 392]

Note: Landslide in foreground. Loch a' Chada-charnaich (right) is a pond filling a depression formed at the rear of a back-tilted block. [Photo: BGS P002267]

Figure 5.18 North part of Dun Caan landslide, east coast of Raasay, Inverness-shire [NG 585 401]

Note: Cliff in Inferior Oolite overlying Lias Group Scalpay Sandstone and Pabay Shale Formations. Part of main slipped mass – left foreground. [Photo: BGS P002833]

5.2 SHRINK/SWELL

5.2.1 General

The mineralogy of the clay component of a rock or soil is the most significant factor determining its shrink/swell hazard. Swelling and shrinkage are the two sides of the volume-change 'coin', both result from changes in water content of the soil /rock fabric. A decrease in water content causes shrinkage (an overall volume decrease) and an increase in water content causes swelling (an overall volume increase). These conditions are neither permanent nor reversible. They are not intrinsic properties of the soil or rock, but respond to prevailing environmental conditions. The relationship between shrink/swell and water content is also not linear, but follows a so-called 'characteristic' curve such as that shown for a remoulded laboratory test specimen in Figure 5.19. Thus a moderately dry summer will not necessarily result in major shrinkage of a clay soil, whereas a drought will. This may result in structural damage for buildings with shallow foundations, and disruption to services such as gas and water mains. The amount of seasonal water content change is partly dependent on the type and location of vegetation, particularly trees, adjacent to a building or service (Building Research Establishment, 1993).

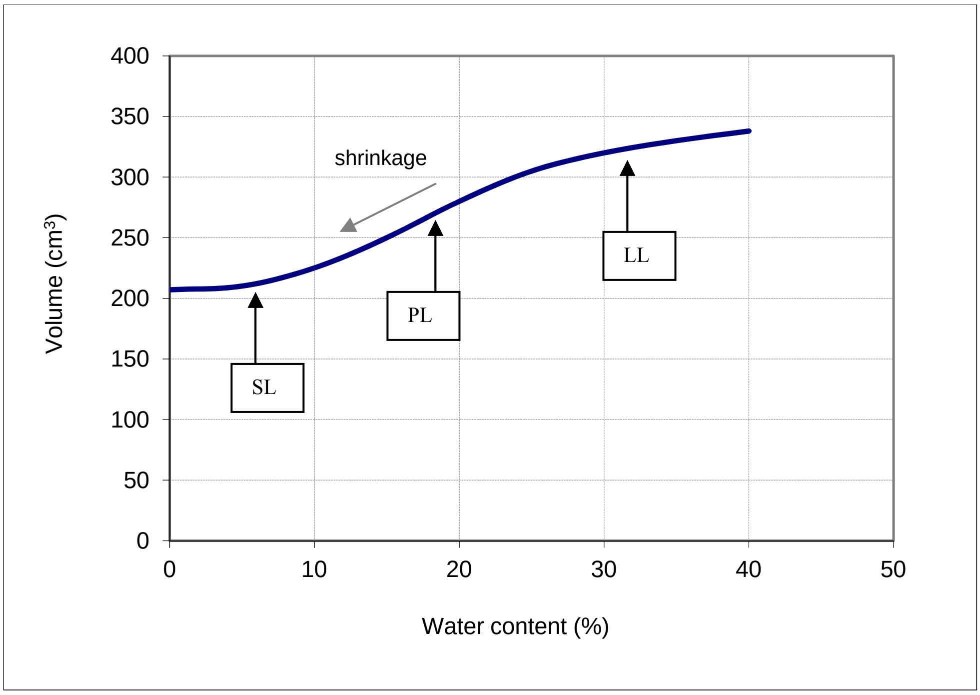


Figure 5.19 Shrinkage characteristic curve (idealised) showing Atterberg Limits (shrinkage limit, SL, plastic limit, PL, & liquid limit, LL) Refer to sections 7.2.4 and 7.2.11 for definitions

The capacity of a mudstone or clay to shrink or swell with water content change is largely a function of the following:

- Material composition
- Clay mineral type
- Over-consolidation / induration / weathering
- Current effective stress
- Time

The proportions and types of clay minerals present, and the way in which the distinctive surface properties of clay minerals react with 'free' water, is particularly significant in mudstones with a high clay content. The degree of over-consolidation, induration, and weathering principally affects the material stiffness, and thus the way in which the mudstone responds to stress changes including suction caused by desiccation. The effective stress is the relationship between total stress and pore water pressure. Changes in effective stress can be brought about by changes in either, or both, of these elements. A change in effective stress results in a change in strength, which in turn may cause a change in volume. The shrinkage shown in Figure 5.19 is in direct response to an effective stress increase caused by a water content decrease (suction increase). This relationship is non-linear.

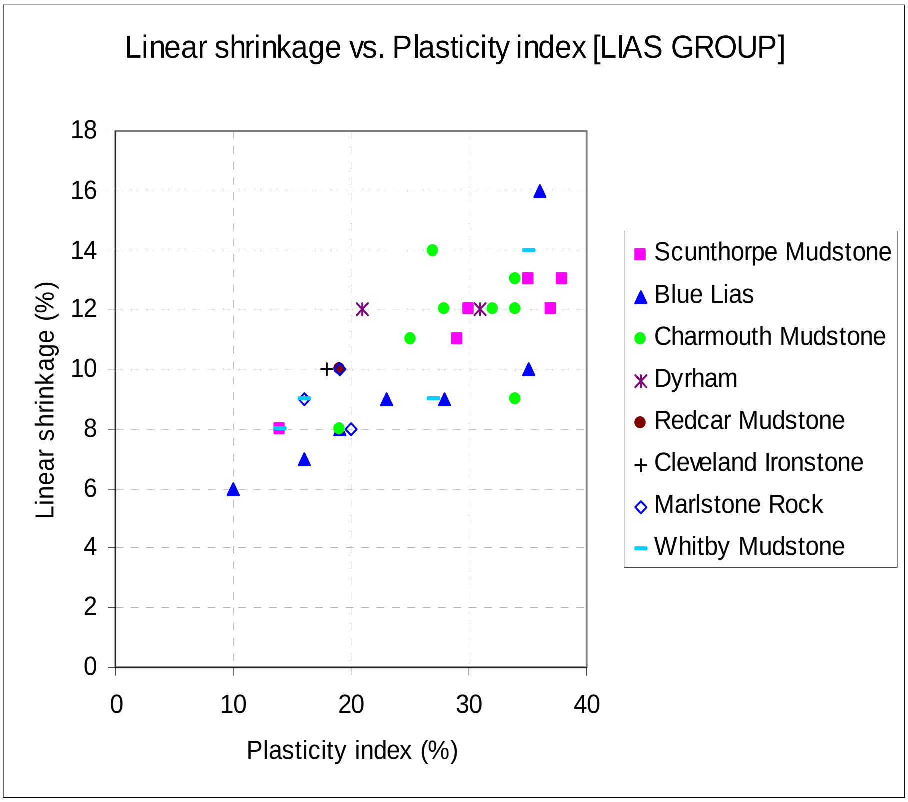


Figure 5.20 Linear shrinkage vs. Plasticity index by Formation (Hobbs et al., 2007)

There are tests available to directly measure the shrink/swell behaviour of soils, but these are seldom employed. More often, indirect properties such as plasticity index are used as a guide to shrink/swell behaviour (see Chapter 7). This is partly because direct tests, either in the field or in the laboratory, are more difficult and expensive to carry out. The two British Standard laboratory shrinkage tests are the 'shrinkage limit' (volumetric shrinkage) test and the 'linear shrinkage' test (BS1377:1990, Tests 6.3 & 6.5, respectively); the former representing a specific water content on the characteristic curve and the latter a percentage length reduction of a remoulded specimen. Two British Standard swelling tests are described in BS1377 1990: the swelling pressure test and the swelling (strain) test (BS1377:1990, Tests 4.3 & 4.4). These tests are described in detail in Head (1998) and Hobbs & Jones (1995).

The linear shrinkage test has a positive correlation with plasticity index (Figure 5.20) (Hobbs et al. 2007).

5.2.2 Lias Group shrink/swell behaviour

In the absence of direct shrink/swell data, the plasticity index (difference between liquid and plastic limits) is typically used as a guide to likely shrink/swell behaviour. A summary of Lias Group median values of plasticity index and derived shrink/swell rating is given in Table 5.1:

Table 5.1 Plasticity index median values and shrink/swell hazard rating

Formation	Plasticity index (%)	Shrink/swell rating
Bridport Sand	17	low
Whitby Mudstone	29	Medium
Dyrham	26	Medium
Charmouth Mudstone	30	Medium
Scunthorpe Mudstone	24	Medium
Blue Lias	29	Medium

The degree of over-consolidation or induration of the several Lias Group mudstones vary, and this variation imparts different shrink/swell behaviour and anisotropy, other factors being equal. Over-consolidation tends to result in greater lateral than vertical volume change. Increased induration tends to reduce the amount of overall volume change due to improved stiffness and the development of cementation. Weathering tends to have the reverse effect, whereby stiffness and stress-related anisotropy are reduced, thus tending to increase shrink/swell movement in the vertical plane.

A small number of swelling and shrinkage tests were carried out on Lias Group samples by BGS and reported in Hobbs et al. (2007). The results of one particular test, the 3-D swell strain test, are summarised in Table 5.2. These show that the more thinly bedded and shaly specimens within (e.g. All Blue Lias; Whitby Mudstone, Sidegate Lane 1) produced greater swell strain anisotropy (up to 8 x) in a 50 mm cube-shaped specimen at natural initial water content, than more uniform, non-shaly or thicker bedded, specimens (e.g. Charmouth Mudstone, Blockley Site 1; Whitby Mudstone, Brixworth 1).

Table 5.2 Results of 3-D swelling strain test; values represent maxima

Sample location	Formation	Strain ε_1 (%)	Strain ε_2 (%)	Strain ε_3 (%)	Volumetric Strain, Δ_v (%)	Strain anisotropy Ψ (%)
Bishop's Cleeve 1	Blue Lias F.	1.29	0.62	0.74	2.7	91
Southam 1	Blue Lias F.	2.24	0.25	0.25	2.8	804
Stowey 1	Blue Lias F.	0.39	0.26	0	0.7	208
Blockley Site 1	Charmouth Mudstone F.	0.35	0.85	0.58	1.8	*-52*
Dimmer 1	Charmouth Mudstone F.	0.98	0.62	0.6	2.2	61
Brixworth 1	Whitby Mudstone F.	1.82	2.13	2	6.1	*-10*
Sidegate Lane 1	Whitby Mudstone F.	7.13	2.9	2.02	12.5	194

NOTE: Strain vectors are orthogonal, ε_1 is perpendicular to bedding

5.3 SULPHATE

5.3.1 General

Sulphates and sulphides are very common in British stratigraphic formations, occurring naturally in a variety of forms in mudstones and other sediments, including Lias Group mudstones and clays. The distribution and classification of sulphate in British rocks and soils is described in BRE Digest 363 (Building Research Establishment, 1991; 1996) and Forster et al. (1995). Typically, sulphate content varies with depth and weathering state. The damaging effects of sulphate salts on concrete, particularly below the water table, are well documented. For example, during construction of the M40 motorway in Oxfordshire, England, heave of the carriageway was caused when lime stabilisation of pyrite-bearing Charmouth Mudstone Formation (formerly the 'Lower Lias Clay') was attempted. The layer concerned had to be removed (Anon, 1991b).

The best-known forms of sulphate in mudrocks are gypsum and anhydrite formed by the oxidation of sulphides. Sulphides, particularly pyrite (FeS_2), are formed in anaerobic conditions through the action of sulphate-reducing bacteria and are generally found as dispersed microscopic minerals. Pyrite oxidation is complex but may be summarised as follows:

a) Oxidation of pyrite to form ferric oxide (Fe_2O_3) and sulphuric acid (H_2SO_4),
b) Reaction of sulphuric acid with calcium carbonate to form gypsum ($CaSO_4.2H_2O$),
c) Reaction of sulphuric acid with clay minerals, if calcium carbonate is lacking, leaching them of exchangeable cations.

One of the end products of this process may be the formation of the sulphate mineral thaumasite. Oxidation of pyrite associated with weathering may be a slow process. However, buried concrete structures within Lias Group mudrocks are prone to thaumasite sulphate attack (TSA), particularly where the concrete is in contact with saturated un-weathered Lias-derived fill (Longworth, 2002). The result is a transformation of the concrete fabric into a weak paste, which has serious consequences for the integrity of the concrete, and may result ultimately in failure. TSA was notable on bridge foundations where concrete contacted pyritic Lias Group clays and clay-fill on the M5 motorway in Gloucestershire (Floyd et al., 2002). This topic is discussed in detail in section 5.3.3.

The effects of stockpiling conditions on the sulphur content of Lias (and other) clays has been discussed in Czerewko et al. (2003). Inappropriate storage conditions (viz. excessive duration, insufficiently low temperatures) were found to result in much reduced sulphide values, much increased sulphate values, and consequent changes in geotechnical properties.

5.3.2 Lias Group sulphates

There are three types of sulphate content test routinely used in geotechnical laboratories (BS1377:1990, Part 3, Test 5), results from which are contained in the Lias Group database of properties compiled for this study:

a) Total sulphate [solids]: “acid extraction test” (preparation 5.2)
b) Water soluble sulphate [solids]: “2:1 aqueous extract test” (preparation 5.3)
c) Dissolved sulphates in ground water [water]: (preparation 5.4)

BRE Digest 363 (Building Research Establishment, 1991; 1996) suggested that if total sulphate is greater than 0.24 % then aqueous sulphate tests should be carried out. The ‘total sulphate’ test does not test for sulphides, as these are destroyed in preparation, and is not now considered a good guide to sulphate attack (Longworth, 2004). Different sulphates have different rates of dissolution, and hence degrees of hazard with respect to concrete foundations. A rigorous analysis, going beyond the simple ‘geotechnical’ tests listed above, would require geochemical tests to identify the full potential of this geohazard. A new sulphate classification has been developed and described in BRE Special Digest 1 – *Concrete in Aggessive ground* (Building Research Establishment, 2005). This is summarised in Table 5.3 with the addition of a verbal descriptor.

The overall total sulphate content median value (for the Lias Group formations for which data were available) is 0.16 %. The equivalent ‘water-soluble’ and ‘ground water’ values are 1.01 and 0.14 g/l, respectively. This places the Lias Group median within the new sulphate class DS-2 (low) (Building Research Establishment, 2005). However, individual results lie in the range DS-1 to DS-4, i.e. ‘very low’ to ‘high’ (Table 5.4). The Lias Group dataset is dominated by mudstones, in particular the Charmouth Mudstone and Whitby Mudstone Formations. The Charmouth Mudstone Formation demonstrated the highest overall aqueous extract sulphate values and hence the greatest sulphate geohazard potential, whilst the Scunthorpe Mudstone Formation recorded the highest median total sulphate content (Table 5.4).

NOTE 1: The Lias Group database revealed poor correlation between different sulphate test results.

NOTE 2: Sulphates present in ground water may have originated in other formations outside the area of interest.

5.3.3 Sulphate attack of concrete

Thaumasite (derived from the Greek word “thaumasion” meaning surprising) may be formed by sulphate attack on concrete and has been found on twenty to thirty year old concrete structures on the M5 and other major trunk roads in Gloucestershire, Somerset and Wiltshire, in the Charmouth Mudstone Formation. Of the concrete structures investigated 75% had been damaged, with abutments and columns being the most severely affected members. In each case Charmouth Mudstone Formation backfill had been used. There has been some confusion in the past regarding the classification schemes, based on the different sulphate tests described in BS1377:1990, their precision, and their relationship to TSA (Longworth, 2004). In the majority of cases, the sulphate class limits based on soil extract tests were both lower than sulphate class based on sulphate in groundwater and were also low when compared to the actual occurrence of TSA. The new limits given in BRE Special Digest 1 bring sulphate classification based on 2:1 water / soil extract tests into parity with the groundwater based tests.

Table 5.3 Table of old and new sulphate classes based on 2:1 soil extraction test (Building Research Establishment, 2005)

Sulphate class	Old limits g/l SO_4	New limits mg/l SO_4	Description
DS-1	<1.2	<500	Very low
DS-2	1.2 – 2.3	500 - 1500	Low
DS-3	2.4 – 3.7	1600 - 3000	Medium
DS-4	3.8 - 6.7	3100 - 6000	High
DS-5	>6.7	>6000	Very high

Table 5.4 Table of Lias Group sulphate medians with new classification based on SO_4 (aqueous extract) test data: medians and maxima

Formation	SO_4 (total) (%)	SO_4 (aqueous extract) (mg/l)	SO_4 (water) (%)	New (median) sulphate classification (BRE, 2005)	New (maximum) sulphate classification (BRE, 2005)
Blue Lias	0.06	340	0.17	DS-1	DS-3
Charmouth Mudstone	0.19	1060	0.20	DS-2	DS-4
Dyrham	0.07	220	0.05	DS-1	DS-1
Scunthorpe Mudstone	0.38	1230	0.10	DS-2	DS-3
Whitby Mudstone	0.18	710	0.14	DS-2	DS-3

The following is a summary of the findings of a Building Research Establishment study (Longworth, 2002) and also those of Bensted (1999), Floyd et al (2002), and Hobbs & Taylor (2000):

Thaumasite sulphate attack (TSA) is characterised by softening and expansion of the concrete surface as discrete blisters or across the full width of the face. The surface has a white pulpy appearance, or occasionally a 'crust' of apparently 'fresh' concrete, beneath which the coarse aggregate is surrounded by white rings or halos of reaction products.

Thaumasite can be identified by a combination of petrographic examination and scanning electron microscope (SEM) microprobe analysis. The process of thaumasite formation, leading to TSA, was found to create four zones within structural quality concrete with a sharp reaction front. Rust staining and chloride contamination, associated with reinforcement corrosion, were present in TSA affected structures several metres below ground level. The degree of TSA at each site could be classified using depth of attack and area of softening. The typical pattern of attack to buried vertical members was found to be: no attack within 1m of ground level, local patches of softening or blistering at mid-height and increasingly severe attack towards the base. The position of these areas of attack appears to be associated with groundwater level. At Tredington Ashchurch Road Bridge, one of the worst affected structures investigated, the maximum depth of softening and amount of expansion were approximately 45mm and 33mm, respectively. Concrete cast directly against undisturbed Charmouth Mudstone Formation clay was often found to have sulphate contents in excess of 5% by mass of cement but there was no evidence of TSA. The degree of thaumasite attack appeared to be related to the availability of water. Bituminous coatings appeared to have provided partial protection to some structures. Visual assessment of the depth of TSA had limitations for estimating the concrete to be removed prior to repair work as sulphate contents in excess of 5% by mass of cement occur within apparently sound concrete.

The formation of thaumasite follows the hydration of cement:

$$6CaO.SiO_2 + 6H_2O = (Ca_3.Si_2O_7.3H_2O) + 3Ca(OH)_2 \quad (1)$$

Following the reaction with sulphate, bicarbonate and hydrogen ions (acid), all present in oxidising Charmouth Mudstone Formation, thaumasite is formed.

$$(Ca_3.Si_2O_7.3H_2O) + 3Ca(OH)_2 + 2SO_4^{2-} + 2HCO_3^- + 20H_2O + 6H^+ = 2[Ca_3Si(OH)_6 \times 12H_2O](SO_4)(CO_3) \quad (2)$$

Thaumasite was found to form where the backfill consisted of heterogeneous, predominantly reworked and gravel size lithorelicts of unweathered and weathered Charmouth Mudstone Formation. This was found to contain calcite, pyrite and clay minerals (see Chapter 3).

- There was a decrease in pyrite content and an increase in acid-soluble sulphate as the Charmouth Mudstone Formation was weathered, because of the reaction of pyrite oxidation to form sulphuric acid, which was buffered by calcium carbonate to precipitate gypsum (selenite) crystals (see reactions (1) and (2)). The process was confirmed by laboratory storage tests.
- In the study area the gypsum concentration was greatest approximately 3 to 4 m below ground level in the Charmouth Mudstone Formation .

No significant relationships were found between chemical, mineralogical or physical soil parameters and distance from concrete or degree of thaumasite attack. However, several trends in the data with proximity to concrete were identified (Longworth, 2002).

The pH value and calcium carbonate concentration were found to increase towards concrete (both vertical members and footings) at less than 1.5m offset, possibly due to leaching of calcium hydroxide from the concrete. Total sulphur and moisture content also increased. Water-soluble magnesium decreased with proximity to concrete; there was an inverse relationship between water-soluble magnesium and pH.

There was less pyrite and sulphide in thaumasite damage zone 3 (full attack) than in zones 1 and 2 (none and partial attack). This suggested that most thaumasite attack occurred where there was the most pyrite oxidation, generally in the deepest and wettest section of fill at each structure. Water-soluble sulphate, acid-soluble sulphate and total sulphur increased with increasing thaumasite attack (associated with individual structures and bridge piers). In general, thaumasite was not found where there were lower values of the water-soluble sulphate and acid-soluble sulphate and, to a lesser degree, total sulphur. The highest values occurred where there was partial attack (with the values decreasing away from the face) and consistently high values occurred where there was a major attack. Again, this may have been partly related to groundwater level.

Gypsum results were limited but values were higher where there was partial attack but lower where there was full attack. The pH value increased with increasing thaumasite. Water-soluble magnesium decreased with increasing thaumasite attack.

The extent of thaumasite attack was strongly related to groundwater level. Thaumasite damage zones correlated with the maximum and minimum groundwater levels measured at the structures over the 12 to 18-month monitoring period. Generally the concrete was not attacked above the maximum water level (i.e. permanently dry, except for percolating water); greatest attack usually occurred below the minimum water level (i.e. permanently wet), and partial attack where the groundwater level was between a maximum and minimum value. **Also, sufficient groundwater sulphate and carbonate were *both* found to be required in order to form thaumasite.**

Over twenty structures were investigated including over-bridges, under-bridges and culverts. Soil and groundwater sampling and testing was undertaken in conjunction with exposure, inspection and testing of the buried concrete.

All of the structures investigated were founded on undisturbed Charmouth Mudstone Formation, with backfill predominantly of reworked Charmouth Mudstone Formation, occasionally mixed with some alluvium. All of the backfill contained lithorelicts of Charmouth Mudstone Formation (generally fine to medium gravel size) in a clay matrix.

The majority of the structures investigated were constructed during 1968-1971, using Grade C35-C40 *in situ* concrete containing limestone coarse aggregate and meeting BRE 363 sulphate resistance Classes 1 to 2.

5.4 RADON

5.4.1 General

Radon (Rn-222) is a naturally occurring radioactive gas, resulting from the radioactive decay of uranium, which is released from bedrock and ground water. If radon is allowed to collect, for example beneath buildings, it may constitute a health hazard. This is assessed, in areas of known risk, according to a Government Action Level, above which remedial measures have to be carried out. The areas of risk broadly correspond with geology and exposure of the bedrock at any particular location. Since 1987 the National Radiological Protection Board (NRPB) has carried out tests and produced maps of Britain based on a 5km square grid. The Lias Group rocks have a high radon hazard (either a ‘full’ or ‘basic’ radon hazard rating); the ironstones and ferruginous limestones of the Marlstone Rock Formation and Northampton Sand Formation being particularly highly rated (Berridge et al., 1999; Sutherland & Sharman, 1996), with the Charmouth and Scunthorpe Mudstone formations ranking slightly lower in this respect. These conclusions are borne out by airborne High-Resolution radiometric surveys recently carried out by the BGS in the East Midlands.

Radon tends to migrate from the source rocks by association with other gases, in particular methane and carbon dioxide. It may also be transported in groundwater, returning to a gas phase in areas of water turbulence or pressure decrease (e.g. waterfalls and springs). Radon may therefore occur in high permeability rocks present *above* a source rock. Major faults can act as conduits for radon migration while impermeable surface deposits, such as till, may form a surface capping, reducing levels of radon reaching the ground surface. Although concentrations of radon in open air normally do not present a hazard, in poorly vented confined spaces the gas can accumulate and may cause a health hazard, including lung cancer, to individuals exposed to it for long periods of time.

Advice on potential radon hazard and measures for the alleviation of radon build-up in properties can be obtained on application to the Enquiries Desk at the British Geological Survey, Keyworth.

6 WEATHERING

6.1 INTRODUCTION

The weathering of rocks and soils alters the moisture content, density, spacing and type of discontinuities, material and mass strength, stiffness and, in many cases, the mineralogy. Some weathering products such as calcium sulphate (gypsum or selenite) are deleterious to man-made materials such as cement and concrete. The oxidation of iron pyrites, one of the chemical alteration stages that can produce calcium sulphate, may result in highly acidic conditions potentially attacking construction materials. It is important, also, to identify the depth to which the increased jointing and fissuring of weathered mudstones and clays increase the likelihood of slope or cut failure.

Different degrees of weathering have an important bearing on the engineering behaviour and precautions required for construction. This section describes the changes that occur during weathering and considers:

- The length of time that weathering has taken place by considering weathering domains (Ballantyne and Harris, 1993).
- The influence of chemical and physical weathering.
- The effect of different degrees of lithification relating to the maturation of the minerals within the sediment.

Much of the information available is confined to the mudstones, as these are the thickest and most widespread of the lithologies of the Lias Group. The weathering of this lithology is more likely to produce engineering problems and for this reason the description and classification of weathering for these materials are better understood.

6.2 WEATHERING DOMAINS

6.2.1 Time domains

In general terms, the deposits that have been exposed to subaerial weathering for longest will have better developed and (probably) thicker weathering profiles under similar weathering conditions. In the UK, time-related domains are generally described with reference to the extent of glaciations. Physical weathering will have progressed most rapidly during periods of periglacial climate that have dominated in the last 400,000 years. In comparison, it is likely that weathering in the relatively short interglacial periods has been slow, and there are no periods of time in the past 2 million years when the climate was sufficiently warm to give rise to “tropical or sub-tropical” weathering as occurred before the Quaternary.

Using information on the extent and timing of the three main ice sheet advances in Great Britain Ballantyne and Harris (1993) differentiated five distinct periglacial regions each distinguished by the length of time over which the land surface has been exposed to interglacial and periglacial weathering (Figure 6.1 and Table 6.1). This is necessarily a highly simplified approach, neglecting variables such as altitude, local climate, erosion and the influence of periglacial and interglacial deposition.

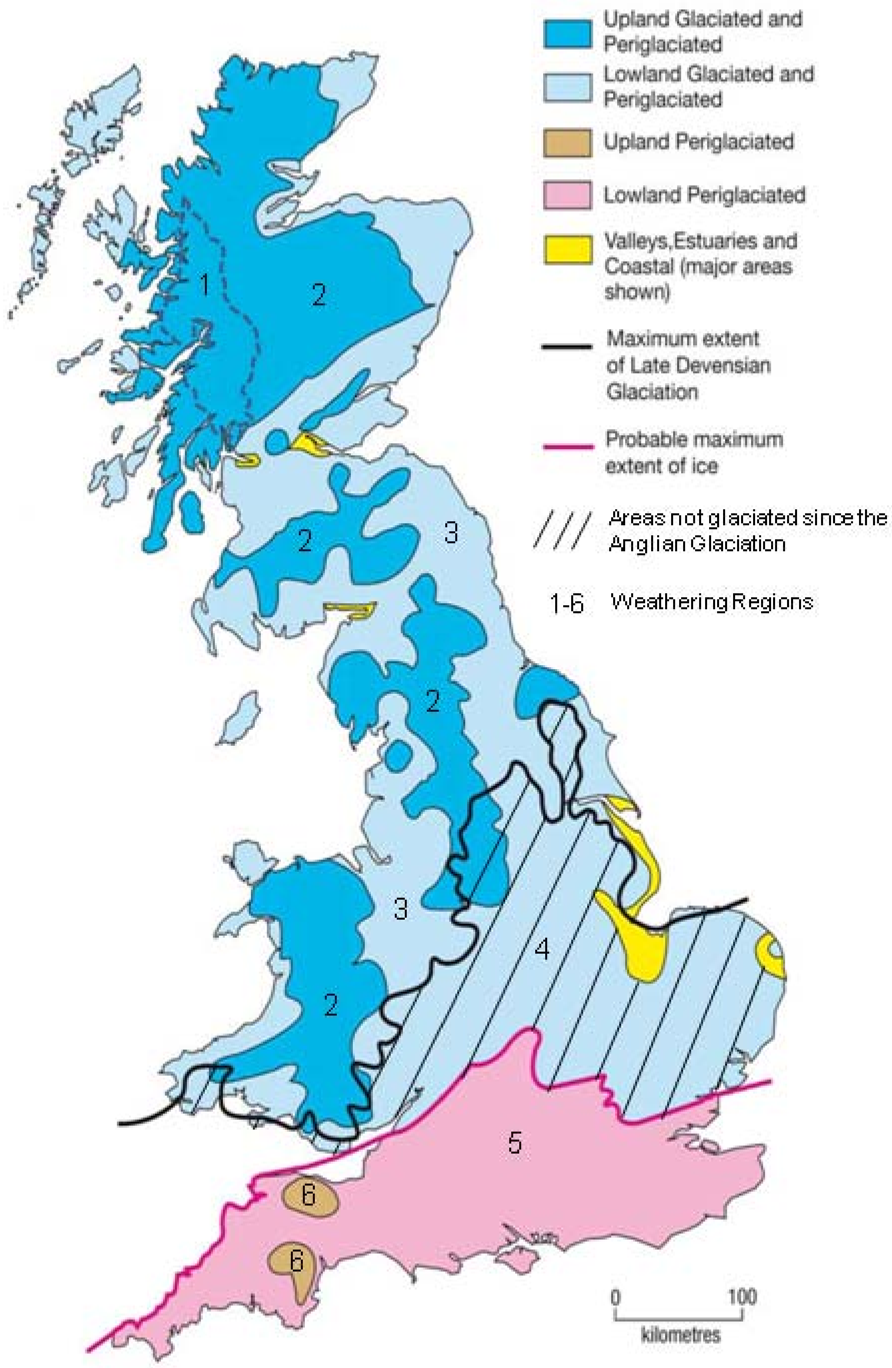


Figure 6.1 Quaternary provinces of Britain (after Foster, et al., 1999). Details of weathering regions 1-6 are described in Table 6.1.

Table 6.1 Weathering under periglacial and interglacial condition in the UK

Glacial Provinces	Beginning of Glaciation	Weathering characteristics	Region
Upland Glaciated and Periglaciated (Western Scotland)	10,000 BP (Loch Lomond Readvance)	Weathering and dissolution features likely to have been removed.	1
Upland Glaciated and Periglaciated	c.18,000 BP	High water flow during deglaciation promoted dissolution	2
Lowland Glaciated and Peiglaciated (Northern and Western Britain)	c. 18,000 BP	High water flow during deglaciation promoted dissolution	3
Lowland Glaciated and Peiglaciated (Central and Eastern England)	C 400,000 BP (Not glaciated since Anglian Glaciation)	Generally thin weathering profiles likely; Head deposits largely in valleys	4
Lowland Periglaciated	at least 800,000 BP (Not glaciated during the Quaternary)	Thick head deposits; often deep weathered bedrock profiles, including those due to Neogene (warmer climate) weathering	5
Upland Periglaciated	at least 800,000 BP (Not glaciated during the Quaternary)	Veneers of weathered deposits on variably weathered bedrock	6

Table 6.2 Weathering regions for each Lias Group Area (refer to Figure 1.1)

Lias Area	Weathering region
1	2, 3 or 4
2	3 or 4
3	4
z4	4 and 5
5	5
6	4

Table 6.2 shows the weathering domains in each of the Lias areas (defined in Figure 1.1). It is likely that the deepest and most intensively weathered Lias Group deposits will be in area 5. This area has not been glaciated and has potentially undergone deep sub-tropical chemical weathering followed by permafrost and freeze/thaw processes during ice advance and retreat. However, in this area the Lias may be covered by, or mixed with, Head deposits typical of areas south of the (most extensive) Anglian Glaciation. Parts of Area 1 and 2 were glaciated during the most recent Devensian glaciation, and most of the earlier weathering products would have been removed. Much of the weathering of these materials would have occurred during the last 18,000 years. The depth of weathering will also be affected by erosion, largely controlled by local conditions.

6.2.2 Lithology-based domains

Weathering characteristics not only depend on the weathering conditions and time but also on lithology and the degree of induration. Rock and sediments compress and alter when buried and the amount of compression and alteration depends on the depth of burial, temperature and the length of time buried. In general the weathering depth will tend to be less in more indurated rocks. From the geological record, the estimated depths of burial for the Lias depositional basins are shown in Table 6.3. The Cleveland Basin and Wessex Basins have the greatest burial depths and the ‘highs’ at Market Weighton, Mendip, and the Bristol and Radstock shelf, along with the

Bristol Channel Basin, have the shallowest depths of burial. The East Midlands Shelf and Worcester Basin are of intermediate depth. This suggests that the Lias of the Cleveland and Wessex Basins will be the most indurated and the 'highs' of Market Weighton, Mendip, Radstock and Bristol the least indurated.

Table 6.3 Estimated maximum depth of burial of the Lias for major depositional basins

	Cleveland Basin	Market Weighton High	East Midlands Shelf	Worcester Basin	Mendip High - Bristol Radstock Shelf	Bristol Channel Basin	Wessex Basin (Dorset)
Quaternary Ice	(1,500)	(1,000)	(500)	(100)	(0)	(200)	(0)
Quaternary	(50)	(100)	(100)	(50)	(0)	(100)	(0)
Tertiary	(<50)	(<50)	(<50)	(<50)	(<50)	(<50)	(200)
U Cretaceous	700	500	400	300	200	200	300
L Cretaceous	400	0	100	50	50	50	50
U Jurassic	400	0	300	300	200	100	600
M Jurassic	300	0	50	200	100	100	250
L Jurassic	(450)	(100)	(300)	(550)	(100)	(350)	(500)
Typical max burial depth	**2,000 m**	**550 m**	**1,000 m**	**1,100 m**	**600 m**	**600 m**	**1,500 m**

However, estimates of burial depth assessed from the mineralogy, most notably the presence of smectite and the ratio of illite to smectite in mixed layer clays (see Chapter 3), indicate somewhat different maximum burial depths (Table 6.4). These estimations suggest greater burial depths across the main depositional basins and the East Midlands Shelf, with the rocks of the Cleveland Basin and East Midlands Shelf having undergone deeper burial than those of the Worcester and Wessex Basins. On this basis it is likely that similar unweathered Lias rocks in the Cleveland Basin and East Midland Shelf areas will be stronger than the less indurated rocks of the Worcester and Wessex Basins.

Table 6.4 Estimated maximum depth of burial for four depositional basins based on mineralogical data.

	Cleveland Basin	East Midlands Shelf	Worcester Basin	Wessex Basin (Dorset)
Typical max burial depth (m)	4,000	3,000	2,000	2,000

6.2.3 Overall Lias Group weathering domain

If the 'time' and 'lithological' domains are considered together, then the Lias of the Cleveland Basin could generally be expected to have the thinnest weathering profile (having potentially stronger rocks due to greater burial depths and undergoing glaciation during the Anglian, but effectively not the Devensian, period). The Lias of the Wessex Basin could be expected to have the thickest weathering profile (having been subjected to shallower burial depths and being unglaciated during the Quaternary). However, there will be other local factors that affect the degree and depth of weathering at specific sites.

6.3 WEATHERING PROCESSES

The weathering process involves the alteration and/or breakdown of rock and soil materials near the earth's surface by physical disintegration and chemical decomposition. The type of weathering and the nature of the weathering products are greatly influenced by climate. Chemical decomposition is most active in hot, wet climates and least active in dry, cold climates. Intermediate rates occur in humid temperate climates. Even within Britain there are differences in weathering rates related to climate, chemical weathering being more active in the warmer south than in the mountains of Scotland.

Physical and chemical weathering processes often act together. For example, chemical weathering frequently occurs along joints that may be formed, or are opened up, during stress relief as a result of erosion of the surface rock or freeze-thaw mechanisms. Fractures may also open up because of chemical and mineralogical changes resulting in volume change within the soil or rock, for example as a result of gypsum formation.

6.3.1 Physical Weathering

Physical weathering involves the breakdown of rock into fragments with little change (chemical alteration) in the minerals of the rock, and is by far the most important weathering process in very cold and dry, or very hot and dry, climates.

The first stage of disintegration is generally the development of jointing, due to stress relief where the rock is closer to the surface. The joints have considerably greater hydraulic conductivity than the rock material, which may result in chemical weathering along joint/discontinuity surfaces. In cool climates, further physical breakdown may take place because of volume change due to freeze-thaw action. Near surface, physical breakdown may also occur because of seasonal moisture content changes resulting in shrinking and swelling, most notably in clays and mudstones. A summary description of the types of physical weathering processes and their effects in clays and mudstones, such as those in the Lias Group, is shown in Figure 6.2, after Spink and Norbury (1993).

These processes can be classified into a few main types:

- Stress relief due to surface erosion.
- Periglacial conditions.
- Disruption due to subordinate chemical weathering.
- Moisture content change resulting in desiccation cracks.

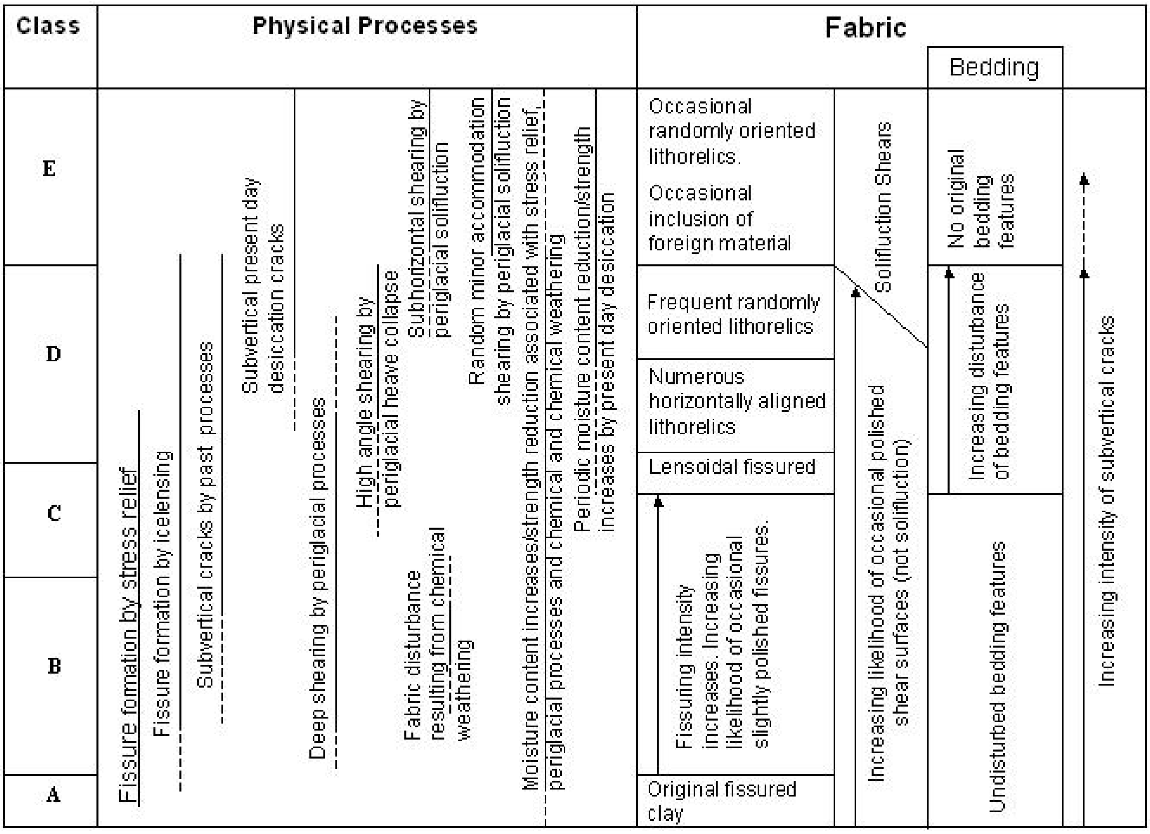


Figure 6.2 The physical weathering, description and classification of grey clays and mudstones (After Spink and Norbury, 1993).

These processes occur at different depths. Fissuring and shearing formed in periglacial conditions due to permafrost may occur at depths greater than 10 m; for instance borehole logs from some sites in Northamptonshire show fissuring to more than 17 m. Brecciation of the Whitby Mudstone Formation, attributed to periglacial freeze/thaw deformation and pore-pressure rise, has also been described at the Empingham Dam, Leicestershire, constructed in the early 1970's to form Rutland Water reservoir (Horswill & Horton, 1976). The dam was founded on, and formed largely from, Whitby Mudstone Formation material excavated locally. Brecciation is in the form of lithorelics of relatively stiff clay within a matrix of softer, highly disturbed clay. Individual lithorelics tend to retain the fabric and properties of the un-brecciated Lias, but the brecciated rock mass as a whole is highly heterogeneous with variable strength and deformation properties (Kovacevic et al., 2007). The disturbance which caused the brecciation has been attributed to plane shear deformations extending considerable distances (> 100 m) and at depths of 10 to 50 m, associated with cambering and valley bulging of the Gwash valley. The processes described above tend to reduce the value of the coefficient of earth pressure at rest (K_0) from a value >1, related to geological over-consolidation, to a value close to unity (Kovacevic et al., 2007).

6.3.2 Chemical weathering

Chemical weathering occurs when the rock-forming minerals are altered. The rate of chemical weathering depends primarily on water and temperature, with the highest rates occurring in hot humid climates. Chemical weathering processes include oxidation, hydrolysis, dissolution and re-deposition.

The overall effect of chemical weathering is determined by the accessibility of meteoric water, moisture content change and the types of minerals present. The effects of present-day chemical weathering of British Jurassic rocks seldom exceed the top 3 to 5 m.

6.3.2.1 OXIDATION AND ACIDIFICATION

In many deposits chemical weathering is, to a large extent, caused by oxidation. The most notable effects are colour changes in grey deposits, which on oxidation of iron sulphide (iron pyrites) become yellow, brown, orange and red iron oxide and hydroxides. The colour will also depend on the hydration (amount of water) in the mineral. The overall oxidation may be represented by equation 1:

$$4FeS_2 + 15O_2 + 14\ H_2O \rightarrow 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-} \qquad (1)$$

The oxygen is initially supplied by oxygenated water that flows along discontinuities or regions of preferential groundwater flow. This may act progressively, increasing the penetration of the oxidised region. Nearer the surface, there is an increased chance of the deposit drying and becoming unsaturated allowing for much greater ingress of oxygenated waters. This leads to more rapid and extensive oxidation. Here, the rock mass is likely to become oxidised and brown. This takes longer in low permeability rocks such as clays and mudstones than higher permeability sands and sandstones.

Chemical weathering by oxidation and acidification is greatly reduced where the ground in permanently saturated and there is little oxidising water flow. This greatly restricts or stops oxidation and, therefore, the colour changes and chemical alterations associated with weathering. This may occur beneath river deposits. However, such rocks may have fissures and joints caused by physical weathering.

6.3.2.2 GYPSUM

A consequence of pyrite oxidation is the liberation of hydrogen and sulphate ions. The hydrogen ions lower the pH of the porewater/groundwater. The reaction between acid sulphate groundwater and calcium carbonate (calcite), which is commonly found in Lias Group deposits either as fine particles or as shells, produces hydrated calcium sulphate or gypsum (equation 2).

$$CaCO_3 + 4H^+ + SO_4^{2-} \rightarrow Ca\ SO_4.2H_2O + CO_2 \qquad (2)$$

The simple replacement of calcite by gypsum causes an increase in volume by 103%. The expansion causes disruption to the rock fabric but also produces heave, which may damage buildings and other man-made structures (Hawkins and Pinches, 1987). The net effect of the removal of calcium carbonate and formation of gypsum increases porosity and permeability, reducing the strength of the deposit and allowing greater movement of water or air thereby increasing the rate of weathering. Gypsum is commonly found in lenses and along fissures and joints generally where iron oxide staining is found, ahead of the main oxidation front.

The visible effects, processes and weathering Class are summarised in Figure 6.3, after Spink and Norbury (1993).

Class	Visible chemical changes	Chemical Processes
E	Brown and light grey mottled clay. Gypsum crystals rare or absent.	Increasing reduction (gleying); Increasing leaching or deposition of minerals by surface waters
D	Brown and light grey mottled clay, centre of lithorelics and lensoidal fissure blocks brown. Common gypsum crystals	
	Brown clay with light grey gleying on fissures. Common gypsum crystals	
C	Brown clay. Common gypsum crystal	Oxidation substantially complete
B	Brown clay around fissures. Centre of blocks grey. Occasional gypsum crystals	Increased oxidation
	Grey clay with brown staining and rare gypsum crystals on fissures	
A	Grey clay	Original unweathered clay

Figure 6.3 Chemical weathering and classification for clays and mudstones. (After Spink and Norbury, 1993).

Gypsum is relatively soluble and may be removed in solution, causing further increases in fabric disruption (including formation of voids), increased porosity and permeability. Gypsum is associated with sulphate attack on buried concrete, a hazard that is discussed more fully in section 5.3.3.

6.3.2.3 GLEYING

Near-surface chemical weathering also takes place when brown or orange iron oxides and hydroxides are reduced to grey iron II oxide. This generally takes place in the presence of organic matter such as roots and initially produces pale grey streaks or mottles in oxidised, generally brown material that often follow root traces. The rotting of the roots and other organic materials requires oxygen and this may come from iron oxides, leading to reduction and the change from brown to pale grey. This process, known as ‘gleying’, increases with increasing biological activity towards the surface. Gleying may also occur where initially oxidised ground is waterlogged.

6.3.2.4 CALCIUM CARBONATE

Calcium carbonate may be deposited near the surface as fine localised powder or as hard nodules (often described by geologists as ‘race’). The formation of the calcium carbonate is likely to be partly due to the respiration of roots, which produce carbon dioxide that reacts with calcium in the pore water. In general, these deposits are localised and are sometimes seen associated with root systems.

6.4 DESCRIPTION & CLASSIFICATION OF WEATHERED MATERIALS

Grey mudstones and siltstones dominate the Lias Group and most available information concerns these lithologies. Descriptions from ground investigation entered into the BGS National Geotechnical Properties Database occasionally contain weathering zones or grades based on early work on the weathering of the Lias Group from the East Midlands by Chandler (1972) or BS5930 (1981). Chandler's (1972) weathering classification is shown in Table 6.5 and the classification according to BS5930:1981 in Table 6.6.

Table 6.5 Weathering of Whitby Mudstone Formation (Upper Lias Clay) at Rockingham and Gratton, Northamptonshire (after Chandler, 1972).

Zone	Description	Fabric	Discontinuities	1) % $CaCO_3$ 2) Gypsum
Landslip/ solifluction	Mottled light brown and light grey CLAY becoming grey with depth. Considerable oxidation near surface (frequent small haematite pellets), minimal oxidation at depth (i.e. >3 m). Extensive gleying at shallow depths.	*0 – 2 m depth*: Heterogeneous with small (<1 mm) rotated lithorelics *Greater depths*: rotated lithorelics (up to 30 mm); otherwise as Zone II.	*Fissure spacing*: Apparently intact (except for desiccation cracks) at shallow depths; 10–30 mm spacing at greater depths. *Shears*: minor shearing in gleyed fissures is common	1) 0.4 % 2) None observed
IV	Not observed – probably absent on slopes (mixed with landslip/solifluction material)			
III	Fissured CLAY with light grey (gleyed) fissure surfaces. Centre of lithorelics generally oxidised to pale brown	Lithorelics (up to 30 mm) have horizontal bedding; matrix occupies less than 50% of section, is often gleyed, and where limited in extent is usually sheared; larger areas of matrix show oriented bands	*Fissures spacing:* 10–30 mm *Shears*: minor shearing in gleyed fissures is common	1) 5 - 6% 2) Common
IIb	Grey or blue grey CLAY with brown (oxidised) areas typically along fissures.	Bedding horizontal; fabric as from depositional changes with brown staining usually in areas parallel to fissures	*Fissures spacing:* 20–100 mm *Shears*: minor, 1–2 mm displacement, sometimes associated with oxidation	1) 0 – 5% 2) Infrequent
IIa	Blue grey weak MUDSTONE and very stiff CLAY.	Bedding horizontal; fabric as from depositional changes; brown staining along fissures and joint surfaces only	Fissures spacing: 20–100 mm Shears: none	1) 1 – 6% 2) rare
I	Weak, blue-grey MUDSTONE.	Bedding horizontal; fabric variations resulting from depositional changes. No oxidation.	*Fissures spacing*: >100 mm *Shears*: none	1) 1 – 7% 2) None observed

In 1995 the Geological Society Engineering Group Working Party Report on the description and classification of weathered rocks for engineering purposes (Anon, 1995) found that it was not feasible to use one all-encompassing scheme of weathering description and/or classification. The report proposed a number of "Approaches" depending on different situations and scales. The most important recommendation was for a mandatory full description ("Approach 1") which might provide sufficient information for a classification be made for a particular purpose. Where appropriate, the formal classification must be unambiguous and used only where it is advantageous to do so.

Table 6.6 Scale of weathering classes of rock mass (after BS5930, 1981)

Term	Description	Weathering Grade
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large volume change, but the soil has not been significantly transported.	VI
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	V
Highly weathered	More than half the rock material is decomposed or disintegrated. Fresh or discoloured rock is present either as a discontinuous framework or as corestones.	IV
Moderately weathered	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.	III
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. Weathering may discolour all the rock material.	II
Fresh	No visible sign of rock material weathering: perhaps slight discoloration on major discontinuities	I

The mandatory description is factual and should be carried out at material and mass scales as appropriate. It is often the only possible way of dealing with weathering where the full profile is not seen and aids interpretation of how the rock has reached its observed condition. Descriptions should use BS5930 (1999) methods (adopted from Anon 1995) and take particular note of colour including colour changes, discontinuities, strength and strength changes, and the nature and extent of weathering products.

The classification requires knowledge of the unweathered material as well as the various stages of weathering. In addition to the mandatory description (Approach 1), four additional "Approaches" are proposed for the classification of varying material types and weathering states (see Appendix D1). These comprise:

Approach 1: Factual description of weathering (mandatory).

Approach 2: Classification for uniform materials that tend to weather gradationally (may not be applicable to the Lias Group).

Approach 3: Classification for heterogeneous masses that tend to weather gradationally and develop profiles which comprise a mixture of relatively strong and weak material in the mass.

Approach 4: Classification incorporating material and mass features (for describing rocks that weather in a gradational manner, but where the material and mass characteristics cannot be readily or usefully separated, including 'stiff' to 'hard' clays and 'weak' mudstones and siltstones, such as the Charmouth Mudstone and Whitby Mudstone Formations).

Approach 5: For rocks whose weathering state does not follow the above patterns, such as karst (which can only be described by reference to other characteristics such as landforms) and the particular effects of arid climates (not applicable to the Lias Group).

Note that BS EN ISO 14689-1 (BSI, 2003) does not currently support Approaches 2 and 3.

6.5 THE EFFECT OF WEATHERING ON THE LIAS GROUP

Previous studies of the Whitby Mudstone Formation in the East Midlands by Chandler (1972) and of the Charmouth Mudstone Formation in Gloucestershire by Coultard and Bell (1993), both found an increase in moisture content with increased weathering and, in the latter case, a general increase in liquid limit with increased weathering.

Most of the information on the Lias Group in the BGS National Geotechnical Properties Database is for those Formations that have the greatest surface exposure, that is, the Blue Lias, Charmouth Mudstone, Scunthorpe Mudstone and Whitby Mudstone Formations. The assessment of the changes due to weathering of moisture content, plasticity, strength, sulphate and pH required a weathering classification method based on Anon (1995) and BS5930 (1999). The weathering 'class' adopted for classification in the present study was based on colour as this was generally well described. This is a simplification of the current code but provides a useful guide to the weathering condition of the argillaceous rocks. Change from grey to brown is commonly used to distinguish between unweathered and weathered horizons. The 'classes' used are listed below:

'Disturbed' – Predominantly light grey, soliflucted or landslipped material (where there is sufficient data, landslip, reworked and soliflucted materials are shown separately in depth profile plots).

Class D – Brown with light grey streaks

Class C - Brown

Class B - Grey with brown on fissure surfaces or mottled brown and grey.

Class A - Grey or dark grey (unweathered)

6.5.1 Depth of weathering

Differing burial depths and weathering domains indicate that the likely depth of weathering for Lias Group formations should also differ. Table 6.7 shows the general maximum depths of the weathering 'classes' for data taken from the geotechnical properties database. Some Class A material may be found near the surface where deposits are permanently saturated (thus inhibiting oxidation) or because surface material has been removed by erosion, mass movement or as part of earlier engineering activities and there has not been sufficient time for colour changes to develop.

The data (Table 6.7) indicate that there is a general increase in the depth of weathering, for all classes, in the more southerly Lias depositional areas (see Figure 1.1). This is the case for each formation. The deepest weathering profiles are found in the Dyrham and the Charmouth Mudstone Formations and shallowest in the Blue Lias and Scunthorpe Mudstone Formations. This indicates that the general maximum depth of colour changes tends to follow the weathering domains and degree of lithification due to depth of burial as proposed above.

Table 6.7 General maximum depths below ground level of weathering 'classes' (except Class A).

Formation	Area	Depth of 'weathering class' (mbgl)			
		Class B	Class C	Class D	Disturbed
Blue Lias	3		4	3	6
Blue Lias	4	12	6	5	9
Charmouth M.	3	11	6	4	7
Charmouth M.	4	14	9	8	8
Charmouth M.	5	17	10	4	8
Dyrham	3	15	6	3	3
Dyrham	5	20	13	10	10
Scunthorpe M.	2	11	6		5
Whitby M.	3	16	6	6	5

6.6 WEATHERING OF FORMATIONS

6.6.1 Blue Lias Formation

The unweathered Blue Lias is generally a weak, thinly laminated to thinly bedded, grey to dark grey mudstone with bands of strong pale grey argillaceous limestone. The weathering of the mudstones is similar in character to that of the Whitby Mudstone and Charmouth Mudstone Formation as described by Spink and Norbury (1993).

The limestone may remain strong and pale grey even when the mudstone is highly weathered resulting in an increased contrast in strength between the two rock types. Near surface, the limestone may be moderately weak to moderately strong, highly jointed pale grey and orange, or may be broken down into angular gravel or cobbles particularly where the limestone is the more important component.

The depth of weathering of the Blue Lias varies due to local conditions but completely weathered rocks are generally found within the top 5 m. At depths greater than10 m below ground level most rocks are generally unweathered.

Summaries of the effects of weathering on selected Blue Lias geotechnical index and effective strength parameters are given in Table 6.8 and Table 6.9.

Table 6.8 The effect of weathering on the Blue Lias Formation.

Parameter	Box and whisker plots (Appendix D2)	Profile Plots (Appendix D3)
Moisture Content	i) Wide range of values in each weathering class. ii) Moisture content of class A generally lower than other classes	i) General trend of decreasing moisture content with depth in top 10-12 m. ii) Highest moisture contents generally found in weathered material in top 5 m.
Liquid limit	i) Wide range of values in each weathering class. ii) Liquid limit generally increases with increasing weathering, most notable between class A and B.	i) Most of the higher values are in the weathered material in the top 5 m.
Plasticity Index	i) Wide range of values in each weathering class. ii) Plasticity Index generally increases with increasing weathering class, apart from 'reworked'	i) Most of the higher values are in the weathered material in the top 5 m.
Liquidity index	i) Wide range of values in each weathering class. ii) Most of the lower values are class A, which tends to be slightly lower than the other classes.	i) A slight trend of higher liquidity index in the more weathered upper 5 m.
Bulk Density	i) Wide range of values in each weathering class. ii) Most of the higher values are class A	i) Most of the lower values are in the upper 5 m, which tend to be weathered.
Cohesion	i) Wide range of values in each weathering class. ii) Class A generally has higher values than class B. iii) Little data for the more highly weathered materials	i) A trend of increasing strength with depth. ii) Most of the lower values are in the upper 5 m, which tend to be weathered.
Total sulphate and pH	i) Little difference in total sulphate between class A and class B. ii) pH of class A slightly higher than Class B	i) General decrease in total sulphate with depth in upper 10 m. Highest values generally in top 5 m. ii) No observable trends of pH with depth.

Table 6.9 Blue Lias Group median effective stress parameters for each weathering class

Weathering class	Number of tests	Median effective stress parameters	
		c′ (kPa)	ϕ′ °
A	4	85	35
B	5	11	27.5
C	5	26	26
D	1	5	28
E/reworked	0		

- Moisture content, liquid limit and plasticity index tend to be lower in unweathered class A materials than other weathering classes.
- Cohesion is generally greater in class A materials.
- Sulphate content is not controlled by weathering class.
- pH tends to be slightly higher in class A rocks. There is little data for the Class C, D and 'reworked'materials.
- Changes in behaviour due to weathering tend to occur mainly in the top 5 m.

- The limited data set of effective test data indicates that Class A has higher effective cohesion, c', and friction angle, ϕ'°, than the other weathering classes; however, there are too few data to make firm conclusions.

6.6.2 Charmouth Mudstone Formation

The weathering profile of typical Charmouth Mudstone Formation is described in Coultard and Bell (1993) and can be classified using Anon. (1995) weathering 'Approach' 4 (See section 6.4).

Geotechnical property plots showing variations of water content, plasticity index and total cohesion with depth for the Charmouth Mudstone Formation, with the data distinguished according to weathering state ('class'), are given in Figures 6.4, 6.5 and 6.6.

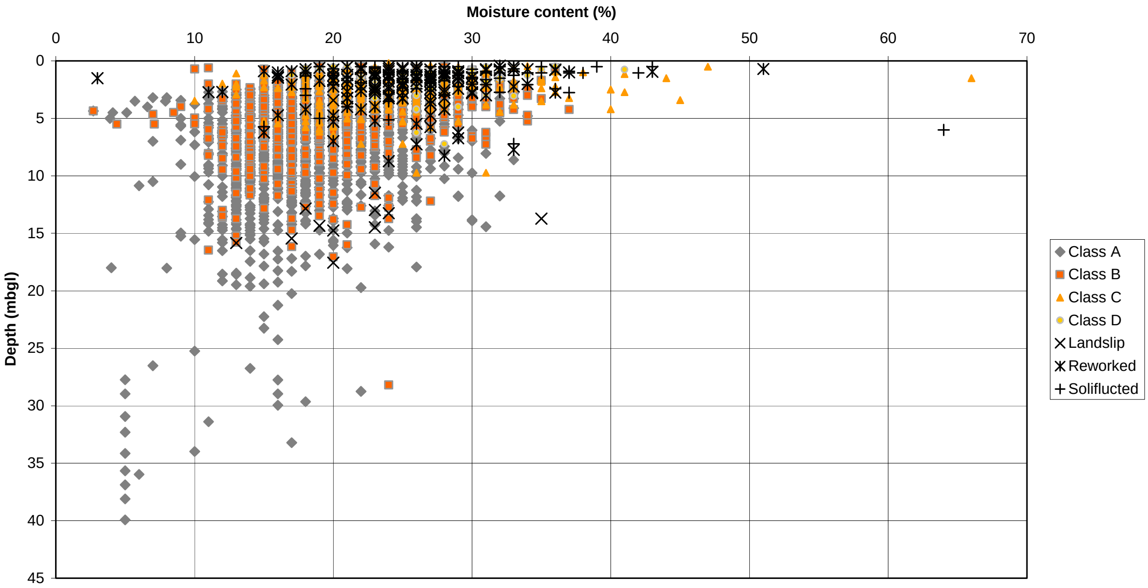


Figure 6.4 Plot of Water content vs. Depth for Charmouth Mudstone Formation classified by weathering class.

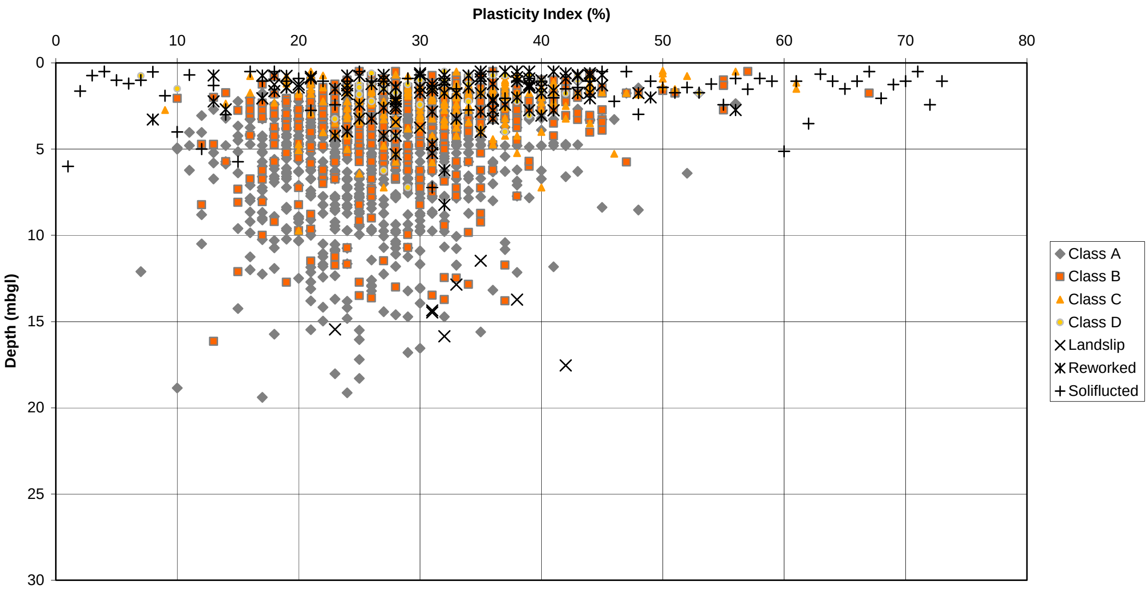


Figure 6.5 Plot of Plasticity index vs. Depth for Charmouth Mudstone Formation classified by weathering class.

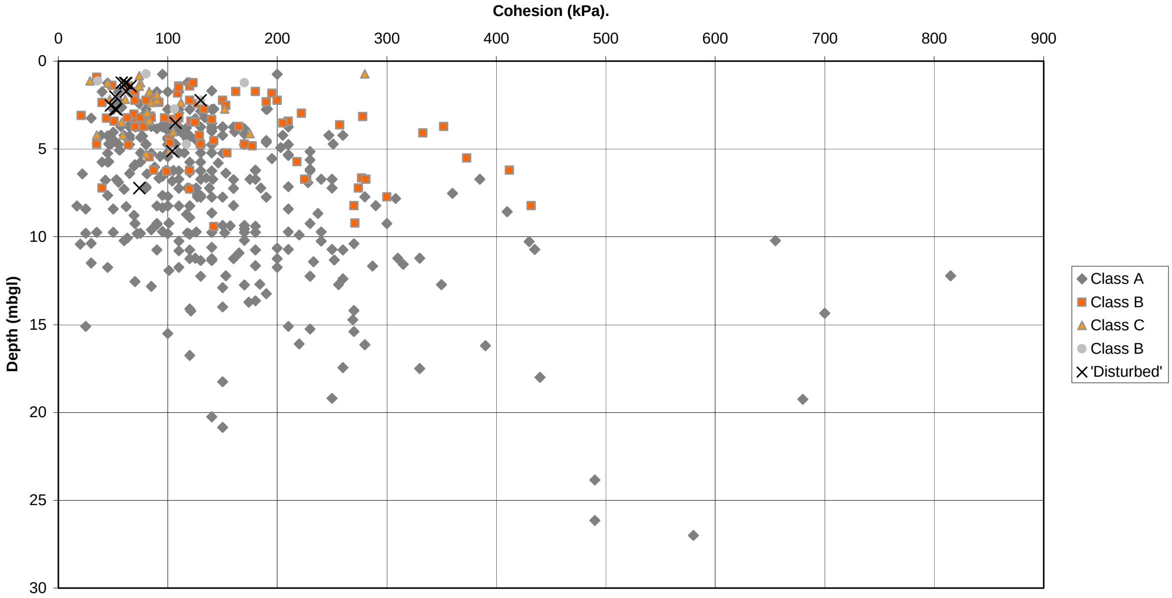


Figure 6.6 Plot of Total Cohesion (triaxial) vs. Depth for Charmouth Mudstone Formation classified by weathering class.

A brief description of the effect of weathering on selected parameters is given in Table 6.10 and effective strength parameters in Table 6.11.

Table 6.10 The effect of weathering on the Charmouth Mudstone Formation.

Parameter	Box and whisker plots (Appendix D2)	Profile Plots (Appendix D3)
Moisture Content	i) Wide range of values in each weathering class. ii) Moisture content generally increases with weathering class.	i) Most weathered material generally occurs in the top 10 m, with highest water contents within top 5 m. ii) General trend of increasing moisture content between 15 m depth to ground surface.
Liquid limit	i) A wide scatter of data for all weathering classes ii) A slight trend of a increasing liquid limit with increasing weathering class from A to D.	i) The highest liquid limit values are generally in the top 10 m, with most weathered material associated with highest moisture contents in the topmost 5 m.
Plasticity Index	i) Wide range of values in each weathering class. ii) A slight trend of increasing plasticity index with weathering classes from A to C. iii) Classes D and E are similar to C.	i) Greatest range of plasticity indices occur in the top 5-10 m within the most weathered materials. ii) Within the top 5 m, soliflucted materials tend to record the majority of higher PI values.
Liquidity index	i) Wide range of values in each weathering class. ii) Trend of higher values with increasing weathering.	i) Highest values generally in the upper 10 m, in most weathered materials. ii) In the top 7 m some class A samples record very high liquidity indices.
Bulk Density	i) Wide range of values in all weathering classes. ii) Bulk density tends to decrease slightly with increasing weathering.	i) Slight trend of bulk density increase with increasing depth. ii) Most of the lower values are in the upper 10 m, in most weathered materials.
Cohesion	i) Wide range of values, particularly in weathering class A. ii) Nearly all the higher values (>200 kPa) are class A samples. iii) 'Reworked' samples tend to be weaker than samples from other classes.	i) A general trend of increasing strength with depth. ii) Majority of the lower values occur in the upper 5-10 m generally, but not entirely, in most weathered materials. iii) In the top 10 m the strength of weathered and unweathered (class A) samples are often similar.
Sulphate and pH	Total Sulphate i) Wide range of values in each weathering class. ii) Values tend to generally increase with weathering class. iii) Weathering class A and reworked samples tend to have the lowest values. Water soluble sulphate i) Weathering classes A, B and C have generally similar values. pH i) Similar values for the different weathering classes. ii) Most samples tend to fall within the range pH 7.5 to 8.5. iii) Lowest values tend to be class A.	Total Sulphate i) Higher values generally occur in the topmost 5 m. ii) Higher values, in the top 5 m, are generally associated with weathering classes B, C and D. iii) Between 5-10 m a few class A (unweathered) samples record high total sulphate contents. Water soluble sulphate i) There appears to be no clear trend with depth although the highest values occur in the top 5 m. pH i) There is a very slight trend of increasing pH with increasing depth and less weathered samples.

Table 6.11 Charmouth Mudstone F. median effective stress parameters for each weathering class

Weathering class	Number of tests	Median effective stress parameters	
		c′ (kPa)	ϕ′ °
A	48	25	24.5
B	27	10	30
C	8	18.5	24.5
D	1	0	39
E/reworked	8	10.5	22

- Moisture content, liquid limit, plasticity index and liquidity index tend to increase with increasing weathering; the highest values being found in the top 5-10 m.
- Bulk density and cohesion both appear to be controlled more by depth than by weathering, but there is a trend of lower values with increasing weathering near surface (within the topmost 5 m).
- Weathering appears to control total sulphate. Most class A values have values below that required for aqueous extraction sulphate testing, whereas about half of class B samples and most class C samples would require further testing. The reworked samples generally had low total sulphate content, presumably because the sulphate had already been removed by groundwater. Aqueous soluble sulphate does not appear to be controlled by weathering; however there are few data for the more highly weathered materials. pH values do not appear to be controlled by depth or degree of weathering.
  The variation in sulphate and pH may be partly explained by oxidation of samples during storage.
- There is a trend of decreasing effective cohesion, c′, with increased weathering; however, there is no clear trend for ϕ′° apart from that shown by 'reworked' material.

6.6.3 Dyrham Formation

Typical descriptions of Dyrham Formation deposits for each weathering class are given below.

Class A

Generally weak to moderately weak, very thinly bedded to thinly laminated, grey or dark grey, micaceous MUDSTONE or SILTSTONE.

Class B

Weak to moderately weak locally strong widely fissured very thinly bedded grey micaceous clayey SILTSTONE. Occasional red-brown staining on discontinuity surfaces. Fissures are sub-vertical. Slightly weathered.

Firm to stiff horizontally laminated grey mottled orange-brown micaceous SILT with a little clay and fine sand. Contains occasional thin (<4mm) laminae of very stiff dark grey silty clay.

Class C

Stiff fissured grey brown and light brown shaly CLAY with iron staining on larger fissures. Occasional ironstone fragments.

Firm to stiff, extremely closely to closely fissured, thinly bedded multi-coloured grey-brown, brown-grey, orange-brown, red-brown, very micaceous clayey SILT with a trace of fine sand. Fissures are sub-vertical.

Firm to stiff, extremely closely to closely fissured, very thinly irregularly bedded, multi-coloured yellow-brown, light grey orange-brown, and red-brown, micaceous sandy SILT with a trace of clay. Locally calcareous. Fissures are sub-vertical.

Class D

Stiff, extremely closely fissured orange-brown and light grey mottled calcareous silty CLAY with a trace of sand. Gleyed. Occasional small red-brown weathered siltstone nodules (<5mm). Fissures randomly orientated.

Firm very closely fissured thinly interbedded (100mm) dark brown mottled brown-grey clayey SILT and silty CLAY. Weakly gleyed. Fissures are sub-vertical.

Class E and reworked

Firm to stiff brown-orange mottled clayey SILT with a trace of sand.

The effects of weathering on the Dyrham Formation are shown in Table 6.12 (index properties) and in Table 6.13 (effective strength parameters).

Table 6.12 The effect of weathering on the Dyrham Formation.

Parameter	Box and whisker plots (Appendix D2)	Profile Plots (Appendix D3)
Moisture Content	i) Wide range of values in each class. ii) Moisture content generally increases with weathering class.	i) Majority of the highest moisture content values are in the top 5-10 m. ii) Below 10 m weathered material tends to have higher moisture contents than class A material.
Liquid limit	i) Class A, B and C have similar ranges of liquid limits. ii) Class D and 'reworked' materials tend to have higher liquid limits.	i) Virtually all the highest liquid limit values (above 60%) are in the top 5 m and are generally class D or 'reworked' material.
Plasticity Index	i) Wide range of values in each class. ii) Similar to liquid limit, class A, B and C all having generally similar ranges of plasticity index. iii) Class D and 'reworked' materials tend to have higher plasticity indices.	i) Most high plasticity index values (>30%) are in the top 7 m and are predominantly, but not exclusively, in class D or 'reworked' material.
Liquidity index	i) Wider range of values for weathering classes A to C. ii) Trend of higher values with increasing weathering most notably for class D. ii) Classes A, B and C contain majority of the lowest values (-0.25).	i) Values below 10 m are less variable (-0.4 to 0.3) than those in overlying more weathered material (mainly –1 to 0.6).
Bulk Density	i) General trend of bulk density decreasing with increasing weathering, with classes D and 'reworked' giving lowest values.	i) Bulk density tends to increase with increasing depth (and decreasing weathering class). ii) All the low values (<1.95 $Mg/m^{3)}$ occur in the top 10 m.
Cohesion	i) Wide range of values in each class. ii) There is a general trend of decreasing strength with increasing weathering class. iii) The median values of classes A and B are markedly higher than those of more weathered materials.	i) A general trend of increasing strength with depth. ii) The majority of the lower values are in the upper 10 m, in weathered material.
Sulphate and pH	Insufficient data.	Insufficient data.

Table 6.13 Dyrham Formation, median effective stress parameters for each weathering class

Weathering class	Number of tests	Median effective stress parameters	
		c′ (kPa)	ϕ′ °
A	1	114	21.5
B	12	20.5	32.5
C	12	17.5	33
D	3	24	27
E/reworked	2	5.5	33

- Moisture content tends to increase and bulk density decrease with increased weathering.
- Liquid limit, plasticity index and liquidity index tend to increase in the most weathered classes, that is class D and 'reworked'.
- Cohesion tends to decrease with weathering class; most of the low values (<100 kPa) are in the top 10 m.
- The limited set of effective strength data indicates a general reduction in cohesion with increased weathering but little change in ϕ′°; however, there are too few data to make firm conclusions.

6.6.4 Scunthorpe Mudstone Formation

Typical descriptions of Scunthorpe Mudstone Formation for different weathering classes are given below:

Class A

Very weak, locally thinly to thickly laminated, dark grey, calcareous silty MUDSTONE.

Very stiff, fissured, dark bluish grey, slightly sandy, very silty CLAY with occasional fossils, limestone bands and silt partings.

Weak, fissured, thinly laminated, dark grey silty MUDSTONE.

Class B

Very weak, closely to medium fissured, laminated, grey and grey brown, silty MUDSTONE.

Firm to stiff, fissured, grey with a little brown mottling, CLAY.

Very stiff, fissured, dark bluish grey with a little brown mottling, slightly sandy CLAY with occasional fossils.

Stiff, fissured, yellowish brown and dark grey mottled slightly sandy CLAY with occasional calcareous nodules and shell fragments.

Class C

Stiff, thinly laminated, green grey mottled grey and orange brown, calcareous CLAY.

Firm, very closely fissured, grey brown CLAY with trace of shells and fine to coarse gravel.

Class D

Firm becoming stiff, fissured, light brown and light grey mottled, slightly sandy CLAY with occasional calcareous nodules and rootlets.

‘Reworked’

Firm, becoming stiff, yellowish grey and grey mottled sandy becoming slightly sandy very silty CLAY with some weak calcareous nodules and decayed roots.

The effects of weathering on the Scunthorpe Mudstone Formation are in Table 6.14 (index properties) and in Table 6.15 (median effective stress parameters).

Table 6.14 The effects of weathering on the Scunthorpe Mudstone Formation.

Parameter	Box and whisker plots (Appendix D2)	Profile Plots (Appendix D3)
Moisture Content	i) Wide range of values in each class. ii) There is a marked increase in moisture content between unweathered materials (class A) and the other classes.	i) Majority of highest moisture content values occur in the top 10 m, with weathered material predominating in the top 5 m.
Liquid limit	i) There is a marked increase in liquid limit between unweathered materials (class A) and the other classes. ii) 75% of class A samples have liquid limit values <50%, whereas the other classes have liquid limits generally >50%.	i) Most of the higher liquid limit values (above 60%) are in the top 10-15 m with weathered material dominating the top 5 m. ii) Most samples below 15 m have liquid limits < 50%.
Plasticity Index	i) Wide range of values in each class. ii) As for the liquid limit, class A samples generally have lower values than other weathering classes.	i) Wide range of plasticity indices in the top 10-15 m (10 ->50%), dominated by weathered samples. ii) Below 10 m the great majority of samples are unweathered with plasticity indices of less than 30%.
Liquidity index	i) Class A samples tend to have generally lower values than other weathering classes. ii) Class A materials comprise the majority of samples with liquidity indices <– 0.25.	i) General trend of decreasing liquidity index with increasing depth. ii) Nearly all samples below 5 m are unweathered (class A) with liquidity indices predominantly < 0.0. iii) About 25% of values above 5 m are > 0.0, mainly comprising class B, C, D and 'reworked' samples.
Bulk Density	i) Class A samples tend to have greater bulk density values than weathered samples.	i) General trend of increasing bulk density with increasing depth. ii) Virtually all values of bulk density below 5 m are > 2.0 Mg/m^3. iii) Wide range of bulk density values in top 3-5 m in predominantly weathered material, with c. 50% of values less than 2.0 Mg/m^3.
Cohesion	i) Over 50% of class A samples have cohesion values > 200 kPa. ii) Over 75% of the weathered samples have cohesion values less than 200 kPa.	i) Great majority of cohesion values less than 100 kPa occur within the top 5 m. ii) Majority of the lower values are in the upper 10 m, in predominantly weathered material.
Sulphate and pH	Total Sulphate i) Based on a limited dataset, Class B samples may tend to have higher values than class A samples. pH i) Class A samples tended to have generally higher pH values than weathering classes B and C.	Total Sulphate i) All values greater than 1% are found in the top 6 m. pH Insufficient data

Table 6.15 Scunthorpe Mudstone Formation median effective stress parameters for each weathering class

Weathering class	Number of tests	Median effective stress parameters	
		c′ (kPa)	ϕ′ °
A	3	8	23
B	3	23	27.5
C	2	18	16
D	0		
E/reworked	0		

- Class A (unweathered) samples tend to have a narrower range and generally lower moisture contents, liquid limit, plasticity index and liquidity index values than weathered classes.
- Most of the higher values of moisture contents, liquid limit, plasticity index and liquidity index are within 5-10 m of the ground surface.
- There is a marked reduction in undrained strength in weathered materials compared to unweathered classes A samples, with a clear trend of increasing cohesion with depth and decreased weathering.
- There appears to be no weathering class trend of total sulphate or pH values.
- There are insufficient effective stress results to draw meaningful relationships with weathering class.

6.6.5 Whitby Mudstone Formation

Typical descriptions of Whitby Mudstone Formation for different weathering classes are given below:

Class A

Stiff, extremely closely fissured, thinly laminated, dark grey, slightly calcareous CLAY with weak mudstone regions.

Very stiff, very closely fissured, thickly laminated, dark grey CLAY.

Very stiff, very closely to closely vertically fissured, thinly (<2mm) laminated to very thinly bedded dark grey calcareous micaceous silty CLAY with abundant shell fragments. Rare selenite.

Stiff, extremely closely fissured, thinly laminated, dark grey silty CLAY.

Firm to stiff fissured dark grey silty shaly CLAY.

Class B

Very stiff, very closely fissured, dark grey CLAY, with occasional silt lenses and rare calcareous siltstone nodules (<80mm). Fissures <60mm. Slightly fossiliferous. Faintly oxidized.

Stiff to very stiff, dark grey, very closely fissured, silty CLAY. Occasional shell fragments. Rare calcareous siltstone nodule (<40mm). A trace of oxidation along fissure surfaces. Minor shears.

Firm, multicoloured grey, orange and yellow CLAY.

Stiff extremely closely fissured thinly to thickly laminated bluish dark grey occasionally mottled yellow brown silty CLAY with a trace of fine gravel sized pockets of gypsum and rare partings of light grey silt.

Class C

Stiff to very stiff, very closely fissured mottled olive and grey, silty CLAY. Fissure lumps <60mm. Abundant Selenite.

Stiff, fissured light brown micaceous silty CLAY. Occasionally brown on fissure surfaces with occasional selenite crystals becoming locally abundant on fissures. Lithorelicts 40%.

Class D

Soft to firm, closely fissured, light grey mottled orange, CLAY, highly gleyed and oxidized.

Stiff, extremely closely fissured, thinly laminated, light grey mottled orange brown, CLAY.

Soft, extremely closely fissured, light grey mottled brown CLAY with occasional rootlets. Fissures are columnar. Minor shear surface <2mm thick, showed undulating striated surface of soft grey clay.

Firm, extremely closely vertically fissured light grey mottled orange CLAY. Approximately 70% pale grey (gleyed) matrix encloses small (<10mm) orange-brown relic fissure blocks. Abundant rootlets.

'Reworked'

Stiff, extremely closely fissured, mottled orange-brown and grey CLAY. Occasional ironstone nodules (<10mm). Extensively gleyed and oxidized.

Firm to stiff, mottled dark grey and orange-brown, silty CLAY with occasional rootlets and occasional calcareous mudstone concretions (<3mm). Abundant shear surfaces. Highly oxidized.

Soft to firm, light grey and orange-brown, silty CLAY with occasional rootlets and rare ironstone fragments towards top. Gleyed and highly oxidized. Minor shear surfaces at 0.70m. Major shear surface at 0.90m. Occasional lenses of orange-brown silty sand.

The effects of weathering on the Scunthorpe Mudstone Formation are in Table 6.16 (index properties) and in Table 6.17 (effective strength parameters).

Table 6.16 Effects of weathering on the Whitby Mudstone Formation

Parameter	Box and whisker plots (Appendix D2)	Profile Plots (Appendix D3)
Moisture Content	i) Wide range of values in each weathering class. ii) Moisture content generally increases with increasing weathering.	i) There is a clear trend of decreasing moisture content with depth in the upper 5-10 m. This is particularly marked in the upper 5 m where highest moisture contents occur for all weathering classes.. ii) Below 10 mbgl there are a few high moisture content values (>20%) for class A samples, but no general trend with depth is observed.
Liquid limit	i) Wide range of values most notably for classes A, B and 'Reworked'. ii) There is a general increase in liquid limit with increased weathering.	i) Liquid limit values are very variable in the upper 10-15 m. ii) No clear trend with depth is observed other than less variability in liquid limit values (Class A) below c. 15m depth.
Plasticity Index	i) Wide range of values in each class particularly for class A and 'Reworked'. ii) There is a general increase in plasticity with weathering class apart from class B, which tends to have lower plasticity values than the other classes.	i) Plasticity indices are very variable in the upper 10-15 m. ii). No clear trend with depth is observed other than less variability in plasticity indices (Class A) below c. 15m depth
Liquidity index	i) There is a general trend of increasing liquidity with increasing weathering. ii) Class A is very variable, with higher values similar to more weathered material.	i) A large majority of values below 5 m are <0.0 mostly represented in class A and B samples. ii) Higher values >0.0 increase from 10 m depth to the surface. iii) Highest values markedly occur in the top 5 m, predominantly in weathered materials.
Bulk Density	i) General trend of decreasing bulk density with increasing weathering class. ii) .Great majority (c. 90%) of class A samples have bulk densities greater than 2.0 Mg/m^3.	i) Marked trend of increasing bulk density with depth in the upper 15 m. ii) Below 10 m majority of bulk density values are above 2.0 Mg/m^3 and tend to be class A (unweathered) samples. iii) Approximately half the bulk density values above 5 m are less than 2.0 Mg/m^3.
Cohesion	i) General trend of decreasing cohesion with increasing weathering. ii) Over 75% of class A samples have cohesion values > 100 kPa.	i) General increase of cohesion values with increasing depth. ii)Generally wide spread of values below 15 m depth in unweathered Class A samples.
Sulphate and pH	Total Sulphate i) Based on limited data, Class B samples tend to show slightly higher values than class A samples. pH i) Class A samples tend to show higher pH values than class B. ii) Classes A and B have a few very low values.	Total Sulphate i) Limited data indicate that higher values are generally found between 2 and 8 mbgl. pH i) pH becomes more variable near surface. i) Lower values (<6.5) are observed in the top 10 m, with most acidic values (<6) in the upper 4 m.

Table 6.17 Whitby Mudstone Formation median effective stress parameters for each weathering class

Weathering class	Number of tests	Median effective stress parameters	
		c´ (kPa)	ɸ´°
A	5	20	30
B	3	25	26
C	0		
D	3	5	21
E/reworked	0		

- Depth of sample appears to be a major control on moisture content in the top 5-7 m.
- Class A samples are generally denser than weathered samples and the lower bound of densities appears to be depth controlled.
- The liquid limit and plasticity index of near surface ‘disturbed’ samples are very variable probably due the variation of mixing of coarse and fine material; no clear trend with depth other than less variability (dominantly Class A samples) below c. 15m depth.
- Class A samples are generally stronger than more weathered material. Cohesion generally increases with depth.
- Total sulphate values tend to be higher between 2 and 8 mbgl.
- The limited data indicates that there is a reduction in effective cohesion, c’ and friction angle, ɸ´ with increased weathering.

6.7 SUMMARY

The effects of weathering on the argillaceous deposits of the Lias Group are generally well understood. The depth and degree of weathering are generally controlled by the duration of exposure, i.e. the time since the last ice age, and the degree of lithification which is controlled by temperature and the depth of burial. These factors indicate that the thickest weathered deposits occur in the south of England, an area that has not been glaciated and with the shallowest burial depth. The thinnest weathering profiles occur in the Cleveland Basin, which was partly glaciated in the last ice age and has the greatest depth of burial. In general, the data collected for this project indicates that this is the case. However, local conditions will also have an effect at specific sites.

The two main weathering processes, physical and chemical weathering, are dominant under different climatic conditions. Physical weathering is most important in cold dry and hot dry climates, whereas chemical weathering is most active in hot and wet conditions. Jointing and fissuring due to physical weathering would have been most active to the south of the glaciations in Southern England during the most extensive Anglian glaciation, and in much of the Midlands and Southern England again during the most recent Devensian glaciation. Here permafrost including ice lensing at depth and freeze-thaw may result in the formation of joints and fissures at significant depths, potentially to 10’s of metres.

The greatest depth of chemical weathering occurs to the south of the Anglian glaciation particularly where there are remnant materials that were subjected to subtropical weathering. Chemical weathering occurs generally where there is ingress of oxygen, which reacts with iron pyrites changing the colour from grey to red, brown and orange. Gypsum forms in grey mudstone and siltstone where iron sulphide (iron pyrites) is oxidised and one of the products of this reaction, sulphuric acid, reacts with calcium carbonate. The formation of gypsum disrupts the mudstone/clay fabric. However, gypsum is soluble and may be removed near surface where there is water flow, further disrupting the fabric and increasing porosity.

The weathering changes for the Blue Lias, Charmouth Mudstone, Dyrham, Scunthorpe and Whitby Formations are described. The effect of weathering and depth on moisture content, plasticity, liquidity index, bulk density, strength, sulphate and pH were investigated using box and whisker plots and depth profiles annotated for weathering class (‘class’ with a lower case ‘c’ is used to distinguish it from the weathering classification scheme ‘approach D’ in BS5930 (British Standards,1999), which requires a full description). The current classification system of weathering is given in the Appendix D1.

The weathering class can be used as a proxy for chemical weathering, and changes with depth as an indicator of physical weathering where the trends are different from the weathering class. In general, there is an increase in moisture content, liquid limit and plasticity index and a decrease in density and strength with increasing weathering although there are variations between the different formations. Aqueous sulphate content does not appear to be controlled by weathering class, but the total sulphate content increases with weathering class for Charmouth Mudstone Formation. However, this may be due to oxidation of samples during storage. There is no observable trend of pH with weathering class which may be due to buffering of sulphuric acid and calcium carbonate, or alteration during storage.

Increases in moisture content, liquid limit, plasticity index and reductions in cohesion are generally greatest between Class A and Class B material for Blue Lias and Scunthorpe Mudstone Formations. The same parameters for the Charmouth Mudstone Formation change more gradually with weathering class.

In general, the highest values of moisture content, liquid limit, plasticity index and lowest values of cohesion occur within 10 m of the ground surface, apart from Blue Lias Formation where this occur within 5 m of the surface.

7 GEOTECHNICAL PROPERTIES

7.1 DATA SUB-DIVISION AND PRESENTATION

The geotechnical properties of the Lias Group, are described in this section. Geotechnical data were primarily obtained from external commercial site investigation reports, and supplemented by a small number of tests carried out at the BGS laboratories. The acquired data was entered into the BGS National Geotechnical Properties Database, where it continues to be maintained and managed to QA standards. The data represent the results of tests carried out in accordance with contemporary British Standard procedures (e.g. British Standards BS 5930: 1981,1999; and BS 1377: 1990).

It is stressed that the geotechnical values quoted in this report should be used as a general guide only and not as a substitute for adequate site investigation, or in detailed design calculations.

The data acquired relate mainly to the clay-rich lithologies of the Lias Group. This is due to the fact that these lithologies are the subject of the majority of ground investigations, as they cover the greatest area and have the potential for causing the greatest engineering problems (see Chapter 5). Relatively few data exist for the limestone and sandstone lithologies and have been reported where appropriate. Data have been included only where they have been considered reliable and capable of lithostratigraphic attribution. Where less than 5 data points exist in the database for a particular formation/parameter combination, these data have not been included in the statistical analysis. Robust statistics have been used throughout. That is, they are portrayed in terms of ‘medians’ and ‘percentiles’, rather than ‘means’ and ‘standard deviations’ (Hallam, 1990). This is explained in greater detail in the text boxes below.

A basic statistical analysis of the data is presented in the form of tables. A variety of plots are also used to display the data. These include ‘extended box & whisker’, ‘scatter’, ‘line’, and ‘ternary’ plots and are used to show distribution and trends of various key geotechnical parameters.

The ***extended box and whisker plot*** (Hallam, 1990) is a method of summarising a frequency distribution based on the robust *median* and *quartiles*. Unlike mean and standard deviation, it portrays all the data. It shows the percentiles as a central box icon (refer to Appendix B) the ends of which are the 25th and 75th percentiles (or quartiles), and the centre-line of which is the 50th percentile (or median*)*, and the latter as values with the median shown in bold. Values lying above or below the box are shown as subsidiary boxes, representing percentiles above the 75th and below the 25th. The height of the box is proportional to the square root of the number of data. The median is the value which has 50 % of data above it and 50 % below, and in a normal distribution has the same value as the mean. Several extended box plots may be compared by placing them on the same scale.

Scatter plots show the direct relationship between two parameters, measured on the same sample, one scale on each axis. Each parameter pair is represented by a point (or locus) on the plot. The bubble plot is a form of scatter plot where the size of the point is proportional to the number of data having common values. For example, if there are 5 samples with identical loci, the point on the graph will be proportionately larger than one representing a single sample. This gives a clearer indication of data concentration than a simple scatter plot in which coincident points are simply overwritten.

The extended box & whisker plots and summary statistical tables are presented in Appendices B, C and D1. Parameter vs depth plots (depth profiles) in relation to weathering class and Formation are presented in Appendix D3. Other plots to show data trends are given in the text as appropriate.

Selected geotechnical parameters are plotted against depth or against one another (Figures 7.1 to 7.23), in order to determine variations caused by depth, and other related factors, and to characterise likely engineering behaviour at different depths. Weathering may be related in a general sense to depth below ground level, but this is not necessarily a simple relationship of decreasing weathering with increasing depth in the case of the Lias Group. Mechanical properties, such as water content, density, permeability, and strength may also relate to depth. A large proportion of the database was assembled from transport project site investigations (e.g. road and rail), supplied to the BGS by consulting and contracting engineers, and by government and local authorities. Many of these have been carried out on embankments or in cuttings, for example where existing routes are to be widened. This means that ground levels reported in the site investigation are not necessarily the original ground levels. *Plots of parameters with depth should therefore be treated with some caution as they only give a general trend.*

Data in the statistical tables and plots are subdivided according to a location code (Database Areas 1 to 6), nominally based on depositional basins and lithostratigraphy (Formations and Members). In the case of some Areas and Formations few data are available, and may not be shown. The Areas do not have any significance outside the database, and are *not* represented by uniformly distributed data. *The samples from any general location identified should not necessarily be considered as representative of that area as a whole.* The Area codes (Figure 1.1) represent the following general locations:

Area	*Location*
1	Cleveland Basin
2	East Midlands Shelf (North)
3	East Midlands Shelf (South).
4	Worcester Basin & adjoining shelf areas
5	Wessex Basin
6	South Wales

The great majority of data is taken from site investigation reports supplied to BGS by commercial consulting and contracting engineering companies. These data have been vetted to some extent, using the criteria of reliability, clarity, test methodology, traceability, and stratigraphical provenance. A significant proportion of site investigation reports have been supplied in the Association of Geotechnical Specialists (AGS) digital format, which is reflected in the structure and nomenclature of the National Geotechnical Properties Database.

7.2 GEOTECHNICAL DATA

7.2.1 General

Geotechnical data reported in this section of the report are derived in the main from routine laboratory testing using either British Standards, e.g. British Standards: BS1377, (1990); BS5930 (1999); Head, (1992, 1998), or recommended British or American procedures, e.g. International Society for Rock Mechanics, ISRM (1981). In general, research data are not included unless stated otherwise. Geotechnical tests on soils and rocks may be broadly sub-divided into 'index' and 'mechanical' property tests. The term 'index' implies a simple, rapid test, the equipment and procedure for which are recognised worldwide (e.g. liquid limit) and which can be repeated in any competent geotechnical laboratory; or a test which measures a fundamental physical property of the material (e.g. particle density). A mechanical property test may measure the behaviour of the material under certain imposed conditions (e.g. a triaxial strength test), and be more complex and time consuming. If conditions are changed the result of the test will be different. Mechanical property tests tend to require carefully prepared ‘undisturbed’ specimens. Index tests, often carried out on ‘disturbed’ or ‘bulk’ samples, tend to be used to generally characterise a deposit and to plan further testing, whereas mechanical property tests may be used for design calculations. For mechanical properties where little or no data are available (e.g. shrink/swell, permeability, durability), index tests are often used as a guide if relationships have been established elsewhere.

7.2.2 Density and water content

The density of a soil is the amount of material within a given volume. It may be expressed in units of (mass) density, ρ (g/cc = Mg/m^3) or unit weight, γ (kN/m^3); the ratio of the two being the acceleration due to gravity (g ≈ 9.807 m/s^2). Density determines the self-weight and hence the load applied by the soil to underlying strata. The density of a soil in its natural state, or any other non-specific state, is called the bulk density, ρ, and is defined as follows:

$$\rho = \frac{W}{V}$$

where: W = total weight of specimen

V = overall volume of specimen

The voids within this soil may contain air or water, or both in various proportions. This fact leads to the definition of the quantities: dry density, ρ_d (density after oven drying at 105 °C), and saturated density, ρ_{sat} (density with all voids filled with water) which may be considered as a specific value of bulk density. It should be noted that the density of a soil is usually measured by preparing a test specimen of known volume (in a ring or cylinder) and weighing it. This means that the specimen is relatively small and *intact,* and does not necessarily represent the bulk of the soil mass, which will have a lower density due to the presence of discontinuities.

The water content, w of a soil or rock is defined as follows:

$$w = \frac{W_w}{W_s}.100\%$$

where: W_w = weight of water (driven off by oven drying at 105°C)

W_S = weight of solids (after oven drying at 105°C)

The water content is usually expressed as a percentage. From the above it will be seen that water content can exceed 100 %. *Note: in some scientific and technological fields (other than geotechnical) water content may be defined as the weight of water divided by the total weight (i.e. solids and water) rather than the weight of solids; in which case water content cannot exceed 100 %.* The water content (or moisture content) of a soil in-situ is normally referred to as its ‘natural water content’. If this is not the case the condition of the soil should be specified (e.g. remoulded, compacted etc.). The water content determined in the laboratory may be slightly lower than the true natural water content as some water may be lost during transport and storage. The natural water content itself may fluctuate seasonally, so that it is rarely a fixed quantity, except at considerable depth.

The database contains 3644 values of bulk densities. The density and natural water contents of the Lias Group are affected principally by lithology, but also by cementation, and other structural features. Considerable lateral and vertical variations on a scale of metres and centimetres are seen. These changes also affect strength. Bulk density (ρ or BD) for undisturbed samples is recorded in units of Mg/m^3. Values of bulk density range from 1.14 to 2.72 Mg/m^3. The median values for the Formations are similar, lying in the range 1.99 to 2.05 Mg/m^3. Analysis of all the data shows a relatively small but perceptible overall decrease in bulk density southward. Some higher values within the Blue Lias Formation may be due to the presence of ironstones.

The dry density, ρ_d (or dry unit weight, γ_d) is the density of the oven-dried soil, i.e. with no 'free' water contained in the voids. Dry densities are fewer in number than bulk density; there being only 1505 data for which the overall median dry density is 1.66 Mg/m^3. The Scunthorpe and Whitby Mudstone Formations have median dry densities greater than 1.70 Mg/m^3, whereas the Bridport Sand, Blue Lias, Dyrham, and Charmouth Mudstone Formations all have median dry densities less than 1.65 Mg/m^3. As with bulk density, the data show a relatively small but perceptible overall decrease in dry density southward. Particle density (specific gravity) medians range from 2.62 to 2.72 Mg/m^3; the overall median being 2.66 Mg/m^3 (number of data results, n=263).

There are 12,464 natural water content results in the database, for which the overall median value is 21 %. The Redcar and Scunthorpe Mudstones are the only formations with median water contents below 20 % (18 and 17 %, respectively). The remainder lie between 21 and 23 %, with the exception of 'undifferentiated' Lower Lias (Blue Lias and Charmouth Mudstone) which has a median water content of 31 %. The reason for this is unclear. There is a general trend of increasing water content from north to south, although the overall difference, based on analysis of all data, is relatively small. Variation in water content is largely a consequence of the differences in lithology between the clay rich basin areas and the more granular platform deposits. Cripps and Taylor (1987) point out that due to variation in the lithologies the ranges are wide and reduced overburden and weathering action typically accounts for a 60 to 100% increase in moisture content in depth profiles.

Plots of water content with depth (Figures 7.1) and water content vs. bulk density (Figure 7.2) show considerable scatter with no clear overall trend. However, it is possible to see that the upper bound on water content values decreases with depth, reaching a constant value of around 12% below a depth of about 50 m. The greatest variation is to be found near-surface where weathering and seasonal effects operate. There are no clear distinctions in the relationships between water content and bulk density for *formations* or *areas*, so these have not been shown.

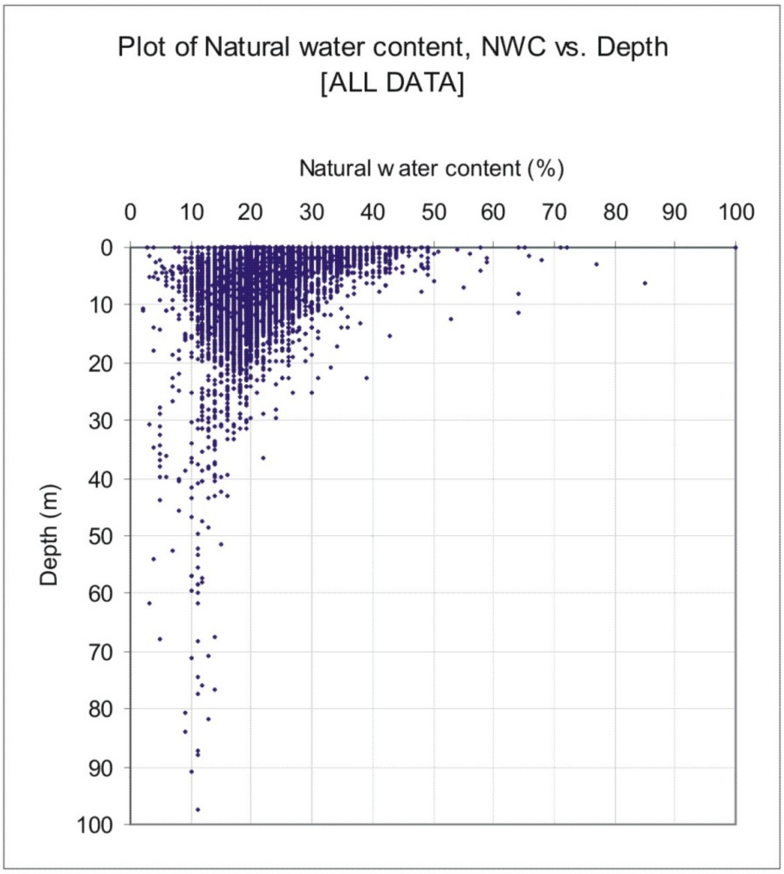


Figure 7.1 Plot of water content vs. depth

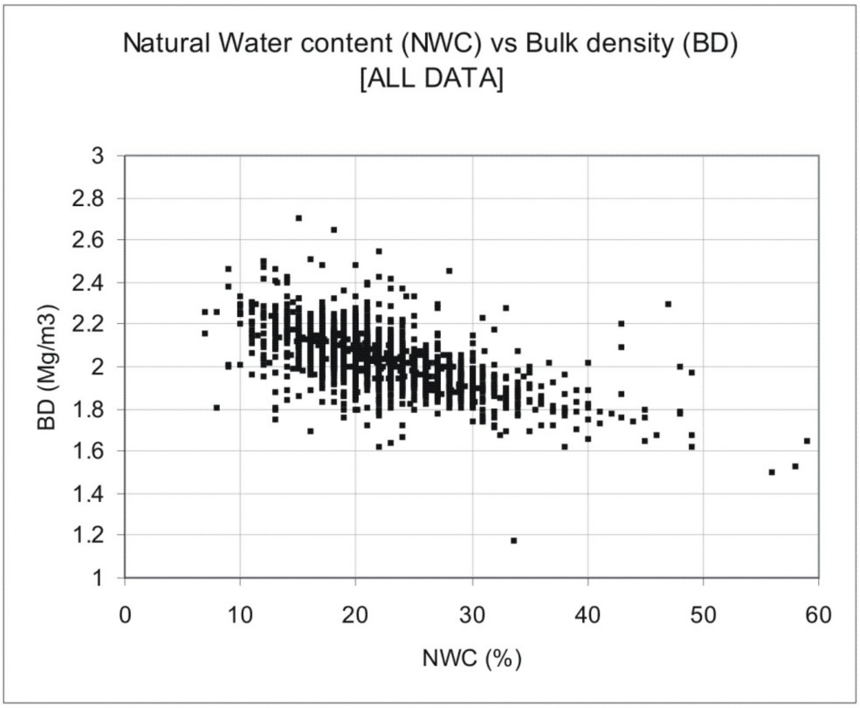


Figure 7.2 Plot of water content vs. bulk density

7.2.3 Particle size

Particle size data for soils are usually carried out by combining the results of sieving and sedimentation analyses (British Standards: BS1377: Part 2: 1990; Head, 1992). The *coarse* fraction (> 0.060 mm) is determined by dry or wet sieving, and the *fine* fraction (< 0.060 mm) by sedimentation using the hydrometer or pipette methods (automated indirect methods may also be used such as the Sedigraph™ or the Coulter Counter™). The results are usually shown as triangular (or ternary) plots with clay/silt/sand+gravel fractions or clay+silt/sand/gravel as the three axes, and also as grading curves, which have 'percentage passing' (0 to 100 %) on the Y-axis and particle size as a log scale (0.002 to 60mm) on the X-axis (see Table 7.1 for size ranges and definitions).

Table 7.1 Particle-size ranges (BS5930: 1999)

clay size	< 0.002 mm		
silt size	0.002 to 0.06 mm		
		fine silt size	0.002 to 0.006 mm
		medium silt size	0.006 to 0.02 mm
		coarse silt size	0.02 to 0.06 mm
sand size	0.06 to 2.0 mm	fine sand size	0.06 to 0.20 mm
		medium sand size	0.2 to 0.6 mm
		coarse sand size	0.6 to 2.0 mm
gravel size	2 to 60 mm	fine gravel size	2.0 to 6.0 mm
		medium gravel size	6 to 20 mm
		coarse gravel size	20 to 60 mm

A total of 671 particle-size tests were selected for the database, of which 383 have full particle-size distributions shown as grading curves. Ternary (triangular) plots of selected test results (Figures 7.3 and 7.4) show the distributions for the main formations. Three of the main mudstone formations (Charmouth, Scunthorpe, and Whitby) show similar trends of high 'silt' and 'clay' particle concentrations, the silt content predominating slightly, and low 'sand+gravel' contents (particularly so for the Whitby Mudstone Formation). The Dyrham Formation has a distribution similar in pattern to those of the main mudstone formations, but with more silt and less clay. The Bridport Sand Formation shows a reasonable scatter between the 'silt' and 'sand+gravel' apices, with a clay content consistently less than 30 %.

The Blue Lias, Scunthorpe, Whitby, and Charmouth Formations have similar median clay contents of 42, 41, 40, and 37 %, respectively. Median silt contents for the same formations are 35, 48, 52, and 48 %, respectively. The Bridport Sand and Dyrham Formations have median clay and silt contents of 15 & 51% and 22 & 64%, respectively. The Bridport Sand Formation, whilst having the highest sand content (28 %), does have much higher silt content (51 %) and therefore the lowest clay content. Selected median gradings are shown in Table 7.2.

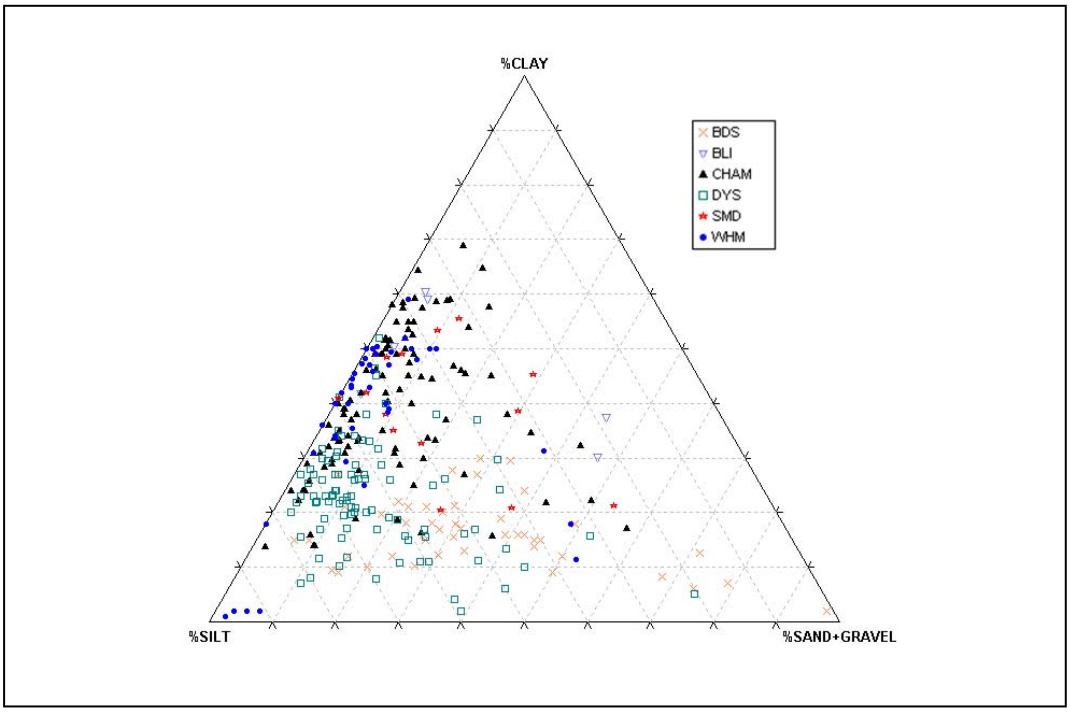


Figure 7.3 Ternary plot of particle size distributions for selected formations [BDS = Bridport Sand Formation, BLI = Blue Lias Formation, CHAM = Charmouth Mudstone Formation, DYS = Dyrham Formation, SMD = Scunthorpe Mudstone Formation, WHM = Whitby Mudstone Formation].

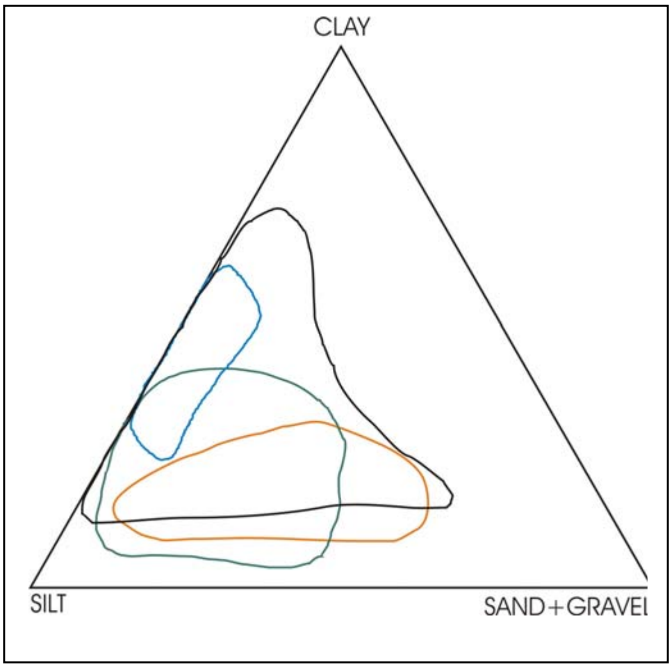


Figure 7.4 Ternary plot of particle size distribution envelopes for selected formations [Bridport Sand Formation (orange), Charmouth Mudstone Formation (black), Dyrham Formation (green), Whitby Mudstone Formation (blue)].

Table 7.2 Summary of particle-size grading medians for the Lias Group by Formation [*n* = *number of data (clays)*]

Formation	*n*	Clay %	Silt %	Sand %	Gravel %
Bridport Sand F	*53*	15	51	28	0
Blue Lias F	*9*	42	35	10	2
Charmouth Mudstone F	*159*	37	48	5	0
Dyrham F	*121*	22	64	10	0
Scunthorpe Mudstone F	*263*	41	48	19	0
Whitby Mudstone F	*46*	40	52	3	0

The grading medians for the different depositional areas (defined in Figure 1.1) are presented in Table 7.3 and show an overall decrease in clay content from 42 % (Area 2) to 23 % (Area 5). Areas 3 and 5 show the highest silt contents, 58 % and 59 %, respectively. Lowest silt contents occur in Areas 2 and 4, 48% and 45 %, respectively. It should be noted, however, that Areas 1 and 6 are not represented in the database and the results are affected by the relative proportions of data from each formation within each area. For example, a major proportion of Area 5 consists of Bridport Sand Formation and Dyrham Formation data.

Table 7.3 Summary of particle-size grading medians for the Lias Group by Area [*n* = *number of data (clays)*]

Area	*n*	Clay %	Silt %	Sand %	Gravel %
2	*311*	42.0	48.0	13.5	1.0
3	*100*	31.0	58.0	4.0	0.0
4	*97*	33.0	44.9	9.1	1.0
5	*162*	23.0	59.0	9.0	0.0

7.2.4 Plasticity

Plasticity is a property of clay soils which is largely dependent on clay mineralogy and particle size. If a clay contains enough water to form a slurry it behaves as a viscous fluid (liquid state). If the clay begins to dry out it reaches a point where it is capable of withstanding a shear stress (plastic state). On further water loss the clay becomes stronger and brittle (semi-solid state). The water content above which the clay changes from a plastic to liquid state is defined by the liquid limit, w_L (or LL); the water content below which the clay changes from a plastic to semi-solid state is defined by the plastic limit, w_p (or PL). The range of water content over which the clay soil behaviour is plastic (and often 'sticky') is usually expressed in terms of the plasticity index, I_p (or PI), defined as follows:

$$I_p = w_L - w_p$$

The liquid and plastic limits (Atterberg, or consistency limits) are universally recognised empirical values on the water content scale, as is shrinkage limit (Section 5.2.11). In addition, the liquidity index, I_L is defined as follows:

$$I_L = \frac{(w - w_P)}{I_p}$$

where: w = natural water content

I_p = plasticity index

The results of liquid and plastic limit tests, for individual formations, are shown in Figure 7.5 as Casagrande, or A-line, plasticity plots (liquid limit, w_L vs. plasticity index, I_P).

A total of 5930 combined (i.e. for all formations) liquid and plastic limit results are held in BGS National Geotechnical Properties Database. The overall medians for liquid and plastic limit are 52 % and 24 %, respectively, giving a median plasticity index of 28 %. Values for liquid limit range from 20 to 134 %. Medians for the individual formations range from 41 % to 61 % (liquid limit) and 22 % to 24 % (plastic limit).

As shown in Table 7.4 the range of plastic limit medians is very small (two percentage points). The variation in plasticity index, I_P, is thus due principally to variations in liquid limit.

Table 7.4 Summary of plasticity medians for the Lias Group *n = number of data*

Formation	n	w_L %	w_P %	I_P %	Plasticity Class
Bridport Sand Fm	*55*	41	23	18	Intermediate
Blue Lias Fm	*380*	51	23	28	High
Charmouth Mudstone Fm	*3182*	52	24	28	High
Dyrham Fm	*586*	46	23	23	Intermediate
Redcar Mudstone Fm	*36*	*51*	*23*	*28*	High
Scunthorpe Mudstone Fm	*439*	46	22	24	Intermediate
Whitby Mudstone Fm	*1013*	53	24	29	High

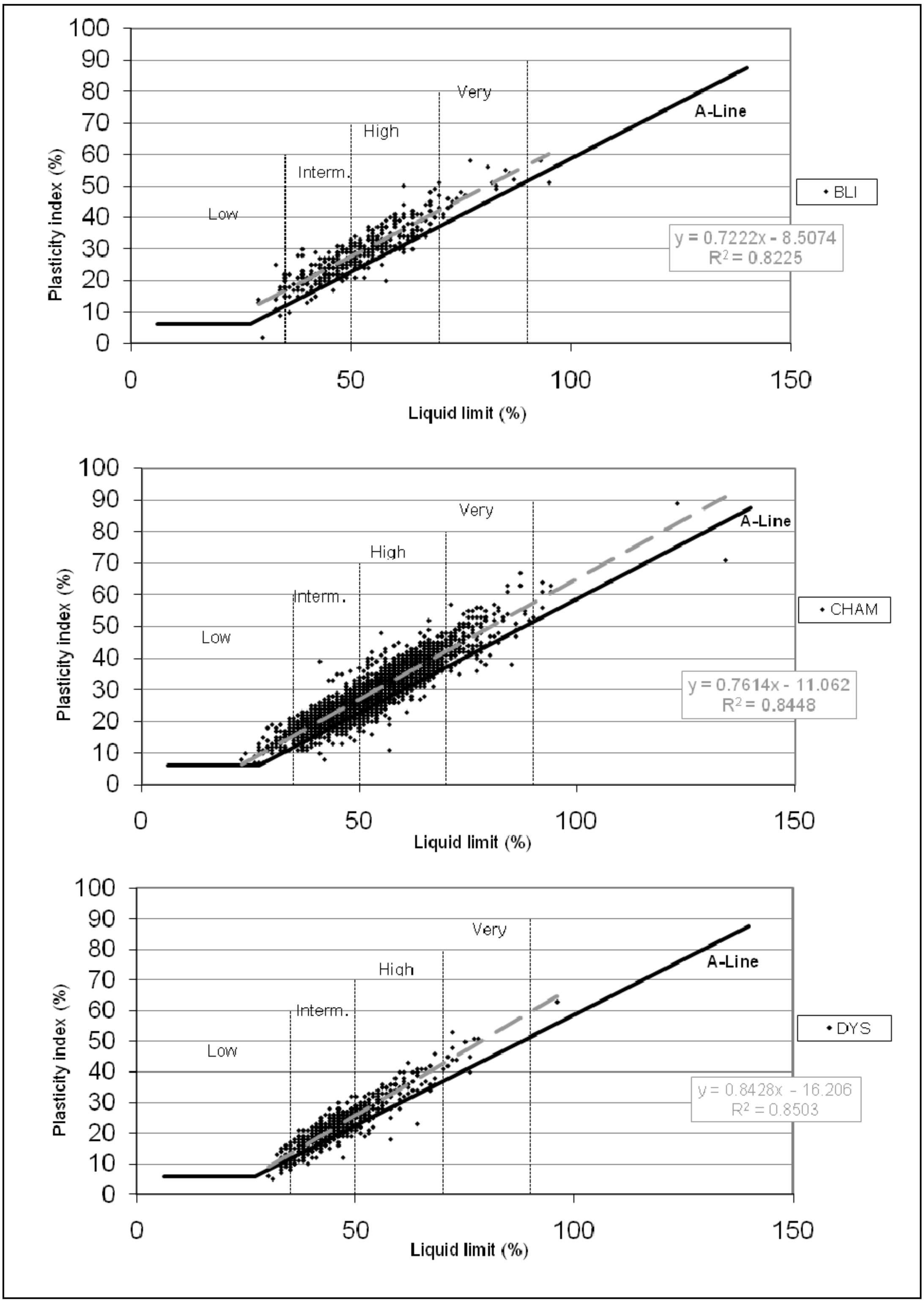


Figure 7.5 Casagrande plasticity plots by formation [BLI = Blue Lias Formation, CHAM = Charmouth Mudstone Formation, DYS = Dyrham Formation].

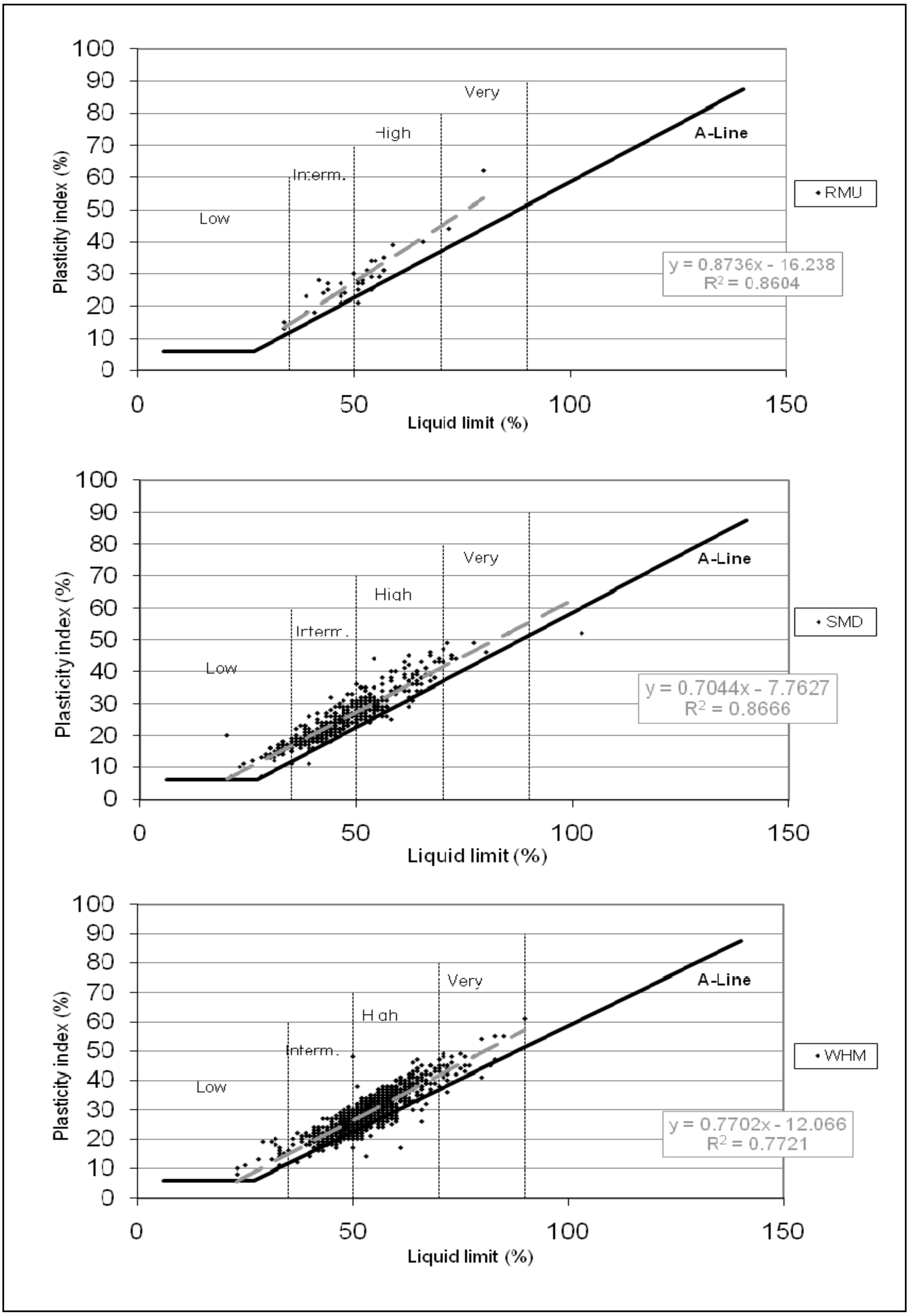


Figure 7.5 (cont'd) Casagrande plasticity plots by formation [RMU = Redcar Mudstone Formation SMD = Scunthorpe Mudstone Formation, WHM = Whitby Mudstone Formation].

The 'best-fit' linear formulae derived from the formations' Casagrande plasticity plots are shown in Table 7.5.

Table 7.5 Summary of best-fit lines (Casagrande plot) for the Lias Group formations (*n = number of data*)

Formation	n	Best-fit linear	r^2
Blue Lias F	*380*	$I_P = 0.72w_L - 8.51$	0.82
Charmouth Mudstone F	*3182*	$I_P = 0.76w_L - 11.06$	0.84
Dyrham F	*586*	$I_P = 0.84w_L - 6.21$	0.85
Redcar Mudstone F	*36*	$I_P = 0.87w_L - 16.24$	0.86
Scunthorpe Mudstone F	*439*	$I_P = 0.70w_L - 7.76$	0.87
Whitby Mudstone F	*1013*	$I_P = 0.77w_L - 12.07$	0.77

For comparison, the equation of the Casagrande A-line is:

$$I_P = 0.72w_L - 13.47$$

Thus, all the formations have a best-fit line with a steeper gradient than the A-line, with the exception of the Scunthorpe Mudstone Formation.

The range of plasticity values within the Lias Group, and within its Formations, is high (Figure 7.5). Data are distributed from the 'low' to the 'extremely high' categories, although the great majority are contained within the ‘intermediate’ and ‘high’ categories. The Bridport Sand and Scunthorpe Mudstone Formations, and to a lesser extent the Redcar Mudstone and Dyrham Formations, tend to have lower plasticities than the remaining formations. However, the differences are not great. Statistically, the Scunthorpe Mudstone Formation has the lowest plasticity of the ‘mudstone’ formations. Wide variations in numbers of samples per formation make direct comparison difficult in some cases. Of the well-represented areas (Areas 2 to 5) (Figure 1.1), Area 2 stands out as having a trend of lower plasticity than the remainder, though the differences are small. Areas 1 and 6 have very few data points. The ‘best-fit’ lines for the Casagrande plots are generally similar. The gradients of the best-fit lines (Table 7.6) increase from Area 2 to Area 5, the former being almost parallel with the A-line (0.72).

Table 7.6 Summary of best-fit lines (Casagrande plot) for the Lias Group areas

Area	Best-fit linear	r^2
2	$I_P = 0.74w_L - 9.87$	0.85
3	$I_P = 0.75w_L - 11.35$	0.84
4	$I_P = 0.755w_L - 10.42$	0.81
5	$I_P = 0.81w_L - 13.33$	0.90

Liquidity index, I_L is a ratio (defined above) which allows the locus of the in-situ condition of a soil to be placed in its consistency range (that is in relation to the Atterberg limits. A value of zero indicates that the natural water content equals the plastic limit, while a value of +1.00 indicates that the natural water content equals the liquid limit. Values of liquidity index may be used as a guide to desiccation or, where equilibrium water content is established, the remoulded strength of a soil. There are 5523 liquidity indices in the Lias Group database, for which the overall median is –0.06. The median liquidity index values for the various formations range from zero to –0.22, the lowest being for the Scunthorpe and Redcar Mudstone Formations (Table 7.7). This reflects the overall north to south trend (from Areas 2 to 5) of increasing plasticity, decreasing density, decreasing lithification and decreasing over-consolidation (Table 7.8) (see also Chapter 3).

Table 7.7 Summary of liquidity indices and Activity for the Lias Group formations

Formation	LI (median)	A_c (median)
Bridport Sand F	0.00	0.88
Blue Lias F	0.00	-
Charmouth Mudstone F	-0.06	0.73
Dyrham F	0.00	1.00
Redcar Mudstone F	-0.19	-
Scunthorpe Mudstone F	-0.22	0.55
Whitby Mudstone F	-0.09	0.70

Table 7.8 Summary of liquidity indices and Activity for the Lias Group areas

Area	LI (median)	A_c (median)
2	-0.16	0.55
3	-0.12	0.76
4	-0.03	0.70
5	0.00	0.89

Activity is a parameter intended to describe the contribution of clay minerals, within the clay fraction of the soil, to shrink/swell and other engineering behaviour. Activity, A_c, was defined (Skempton, 1953) as follows:

$$A_c = \frac{I_p}{\%clay\ fraction}$$

where: I_p = plasticity index; % clay fraction = % by weight passing 0.002 mm sieve

A soil with a relatively low clay-size fraction, but where that fraction consists mainly of the very 'active' clay mineral sodium smectite will, in theory at least, produce a high Activity whereas a soil with a high clay-size fraction consisting mainly of illite will not. The Lias Group formations and areas are not uniformly represented in terms of amount of Activity data. The Activity data summarised in Tables 7.7 and 7.8, and shown in Figure 7.6, are widely scattered. Median values range from 0.55 to 1.00. The highest values are likely to be unreliable as a result of incorrect particle-size preparation. For example, a few values over 5.00 were obtained for the Dyrham and Scunthorpe Mudstone Formations. The Dyrham and Bridport Sand Formations give high Activity values, possibly due to their smectite content. It is probably the case that these sand- and silt-rich formations are not comparable directly with the clay-rich formations in terms of Activity, and it is doubtful whether Activity should be applied to clays with low clay-size content (see Chapter 3), in common with parts of the Charmouth Mudstone Formation in the south. The presence of the clay mineral smectite would tend to increase activity significantly. The data contained in other BGS databases (Hobbs et al., 1998) suggest that silt-sized particles (i.e. >0.002 mm) can result in measurable liquid and plastic limits, and hence plasticity indices (for such materials it is theoretically possible for an Activity value of infinity to be obtained).

Table 7.9 Classification for Activity (Skempton, 1953)

Activity (A_c)	Description
> 1.75	Very active
1.25 - 1.75	Active
0.75 - 1.25	Normal
< 0.75	Inactive

Using the Activity classification shown in Table 7.9 the Lias Group data are scattered across all categories (Figure 7.6). However, the median values are confined to the categories ‘inactive’ and ‘normal’. From a total of about 500 test results less than 5 % fall in the ‘very active’ class and almost 70% within the ‘inactive’ class. It is interesting to compare the results for the Dyrham and Scunthorpe Mudstone Formations. The Dyrham Formation has double the Activity of the Scunthorpe Mudstone Formation, apparently solely as a result of the former’s clay content being half that of the latter (plasticity indices are identical). There appears to be an overall increase in Activity from north to south (Areas 2 to 5), possibly due to the increased presence of more active clay minerals, i.e. smectite, in the Lias of southern England, though comparison of individual areas is not useful due to non-uniformity of data. It has been noted (refer to Chapter 3; Kemp & McKervey, 2001; Kemp et al., 2005) that significant proportions of the clay mineral smectite, normally associated with high plasticity and high activity, are also accompanied in Southern England and the West Midlands by significant proportions of carbonate. This carbonate (in the form of calcite and dolomite, and probably in part authigenic and fine-grained) tends to ‘dilute’ the effect of the higher smectite in the southern England and West Midlands deposits. This may also explain the relatively low values for Activity and the poor distinction in terms of plasticity and activity between the Lias of southern and Northern England.

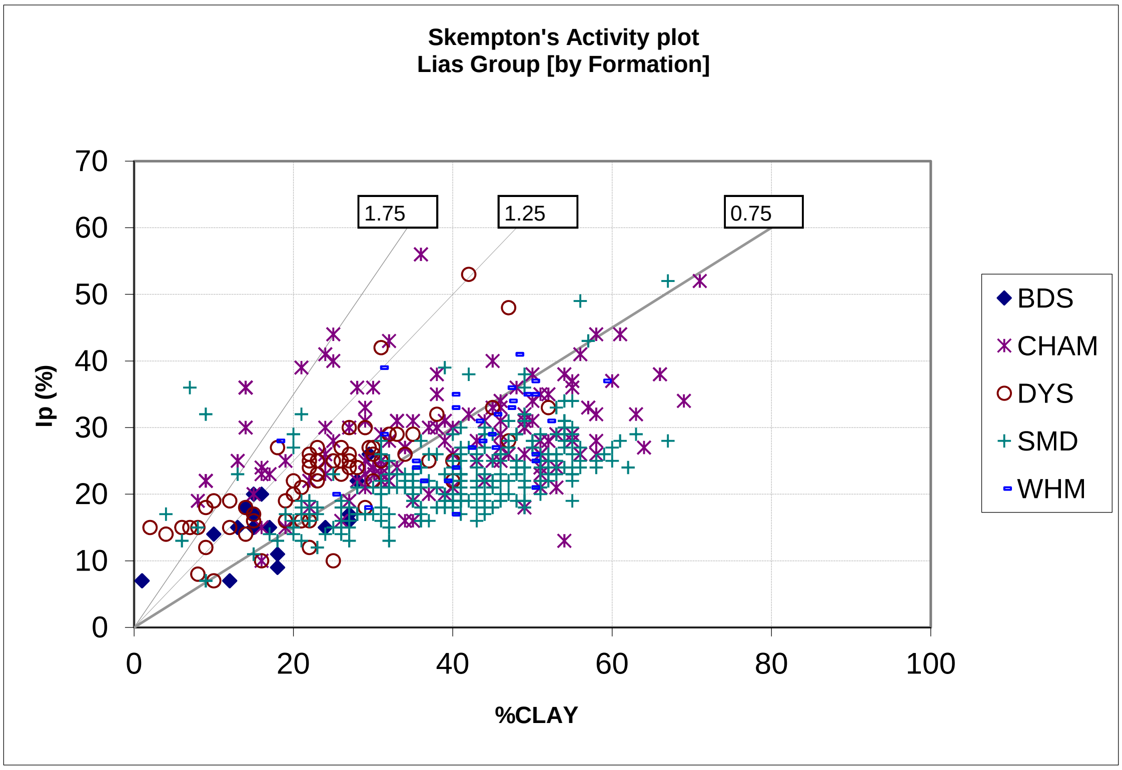


Figure 7.6 Skempton’s Activity plot by formation (individual test results)

BDS=Bridport Sand F., CHAM=Charmouth Mudstone F., DYS=Dyrham F., SMD=Scunthorpe Mudstone F., WHM=Whitby Mudstone F.

7.2.5 Sulphate, pH, and other chemical tests

A small group of relatively simple chemical tests for soils is usually included in geotechnical testing. These are: total sulphate content, aqueous extract sulphate content, pH, carbonate content, and organic content (BS1377:1990; Head, 1992). In addition, there is a test for the sulphate content of ground water used in modern chemistry laboratories.

As noted in some detail in section 5.3, groundwater and pore-water containing sulphate can attack concrete and other materials containing cement. A reaction takes place between the sulphate and aluminium compounds in the cement, causing crystallisation of complex compounds. This process causes expansion and internal damage. A former classification for sulphate in soils is given by the Building Research Establishment, BRE, (Building Research Establishment, 1981; 1991) as shown in Table 7.10. This would have informed many of the test regimes carried out prior to 1996 and hence a significant proportion of the Lias Group sulphate database. The more recent BRE classification (Building Research Establishment, 1996) is slightly more complex and requires assessment of total sulphate followed, if above the threshold for class A, the aqueous sulphate test to decide on the appropriate cement type.

Table 7.10 Classification of total sulphate content of soils (Building Research Establishment, 1991)

Total Sulphate content (%)	Class	
> 2.0	5	↑
1.0 - 2.0	4	
0.5 - 1.0	3	
0.2 - 0.5	2	
< 0.2	1	increasing potential for attack

Excessive acidity or alkalinity of the ground can also have detrimental effects on concrete below ground level and even moderate acidity can corrode metals. Some soil stabilisation agents may be unsuited to alkaline conditions; pH also affects the solubility of some ions.

Results from five 'chemical' laboratory test parameters are contained in the database: total (soil) sulphate, aqueous extract (soil) sulphate, sulphate in ground water, pH, and organic content.

Total sulphate (T.Sul.) is the acid-soluble sulphate content, whilst aqueous 2:1 water/soil extract sulphate (A.Sul.) is the water-soluble sulphate content. Both are obtained from liquid extracts but give the content of the soil itself rather than of the ground water, and are expressed as a percentage by weight (T.Sul.) and as grams per litre (A.Sul.). Unfortunately, it is often the case that sulphate content data are quoted as below detection level. This makes statistical assessment of the raw data difficult if these data are included. If they are not included, then the dataset is unrepresentative and may be biased. However, the use of classes for cement type does not have this problem as the 'below detection level' data will all be class 1.

A summary of the sulphate results for the main Lias Group Formations is shown in Table 7.11. The highest total sulphate content median was obtained for the Scunthorpe Mudstone Formation and the lowest for the Blue Lias and Dyrham Formations. Fewer data are available for the aqueous extract sulphate content and the sulphate content of groundwater. A plot of Total vs. Aqueous sulphate is shown in Figure 7.7. Using the 1996 BRE scheme (Building Research Establishment, 1996), sixty-five percent of the Total sulphate data lie below 0.24 %, placing them in BRE's Class 1. Of the remainder, the majority are Class 2. Correlation of sulphate content parameters with depth is generally poor. However, no results for Total sulphate in excess of 1.0 % (BRE Sulphate Class 4) are recorded below 10 m.

Table 7.11 Sumary of sulphate contents of Lias Group formations

Formation	T.Sul. (%) median	A.Sul. (g/l) median	W.Sul. (%) median
Bridport Sand F	-		
Blue Lias F	0.06	0.34	0.17
Charmouth Mudstone F	0.19	1.06	0.20
Dyrham F	0.07	-	0.05
Redcar Mudstone F	0.22*	-	-
Scunthorpe Mudstone F	0.38	1.23	0.10
Whitby Mudstone F	0.18	0.71*	0.14

* less than 10 data points

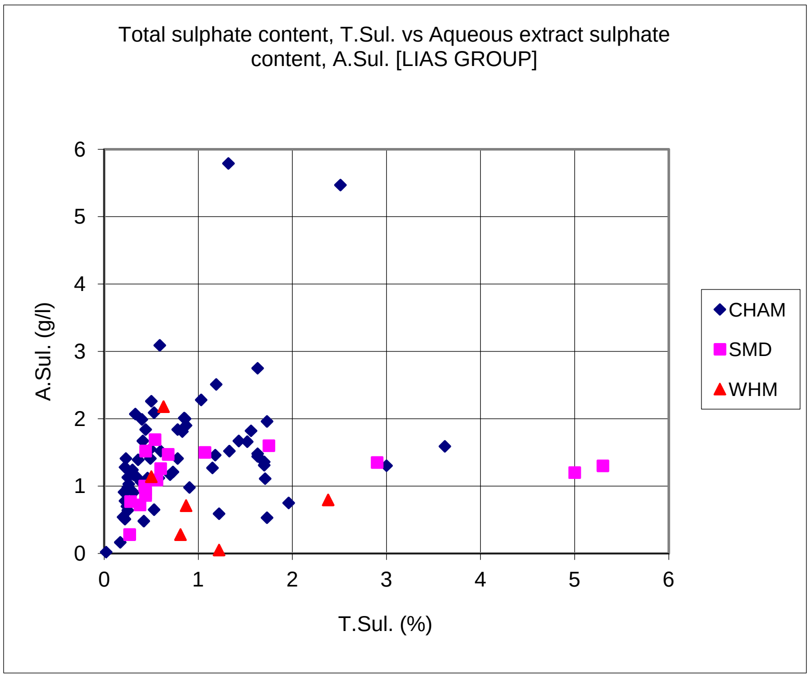


Figure 7.7 Plot of total sulphate vs. aqueous extract sulphate

CHAM=Charmouth Mudstone F., SMD=Scunthorpe Mudstone F., WHM=Whitby Mudstone F.

As noted above, excessive acidity or alkalinity of the groundwater in soils can have a highly detrimental effect on buried metals and reinforced concrete. Acidity and alkalinity is quantified in terms of the pH value. This is a measure of the 'active' acidity rather than the acid content and is a logarithmic scale. The test is usually carried out in tandem with the sulphate content test (British Standards: BS1377:1990; Head, 1992). Results of pH tests in the database show that all medians for Formations lie between 7.3 and 7.9, i.e. slightly alkaline. The Scunthorpe Mudstone and the Blue Lias Formations have the highest pH medians, while the Dyrham and Whitby Mudstone have the lowest. Of the Areas, 3 and 4 have the highest and 5 the lowest pH medians, though the variability is slight.

There are two BS tests dealing with organic matter in the soil. The first is the 'Walkley and Black' method, which determines the percentage by dry mass of organic matter within a soil by dichromate oxidation and titration (British Standards: BS1377: Part 3:1990, Test 3). The second determines the mass loss on ignition, LOI, as a percentage of the dry mass of the soil (British Standards: BS1377: Part 3:1990, Test 4). The LOI is related to organic content, but not for all soil types. Organic content data are poorly represented in the database. A total of 28 samples, most from Area 2, gave a range of 0.01 to 3.5 % with an overall median of 2.0 %. The highest values for organic content were obtained for the Charmouth Mudstone Formation.

7.2.6 Strength

The strength of a soil or rock is a measure of its capability to withstand a stress (or stresses) in a particular direction or configuration. Strength is not a fundamental property of a soil or rock, but is dependent on the soil/rock condition and the type of stresses applied to it. The strength of soils is particularly sensitive to the drainage conditions and duration of the test. If drainage is allowed the test is capable of measuring *effective* strength parameters. If the conditions are undrained the test is assumed to measure *total* strength parameters, unless pore-water pressures are measured, in which case the effective stress parameters may be calculated. Strength may be analysed as a compressive, shear, or tensile strength parameter. Strength is usually determined on intact laboratory specimens but may be determined by tests on the soil/rock mass in the field (either at surface outcrops, in trial pits, or in boreholes) or, in the case of soils, on remoulded specimens.

There are a variety of tests that measure strength. In both laboratory and field the methods differ from soils to rocks although the principles are the same. The most common tests for rock, usually acquired during normal site investigations, are the uniaxial (unconfined) compression test (UCS), and the point load index test (PTL), whilst for soils it is the triaxial test of which there are several versions, and which, for a cohesive soil, produce the parameters of cohesion, c, and internal friction angle, ϕ. Total shear strength is usually defined by the Mohr-Coulomb failure criteria, the equation of which is as follows:

$$\tau = c + \sigma \tan\phi$$

where: σ = normal stress (perpendicular to shearing)

For a fully saturated, intact specimen, prevented from draining at all stages of the test, the value of the internal friction angle, ϕ, is zero. The undrained shear strength, s_u, thus equals the undrained cohesion, c_u. This failure criterion is known as the Tresca criterion. However, if triaxial test specimens are consolidated at each stress level by allowing drainage, as in the consolidated-undrained (CU) or consolidated-drained (CD) tests, effective shear strength may be measured if pore-water pressure (u) is measured and subtracted from the total stresses. This is reported in terms of the ‘effective’ cohesive and frictional strength parameters c' and ϕ'. The effective shear strength, s', is then calculated from the Mohr-Coulomb equation as follows:

$$s' = c' + (\sigma - u)\tan\phi'$$

It is difficult to give typical or average values of strength for the Lias Group, or individual Formations and Members within it, because of the variability of lithology, fabric, structure, and cementation and the post-depositional processes of weathering and consolidation it has undergone. This results in variable depth profiles for intact strength on a scale of metres or centimetres, whether these are determined in-situ or in the laboratory. It should be borne in mind that the great majority of data within the Lias Group database are from 'routine' engineering investigations where samples are taken at relatively shallow depths, either from trial pits or from shallow drilling; over 75 % of the triaxial strength data are derived from sample depths less than 10 m. At depths greater than 20 m the absence of weathering and other stress-relief factors means that the strength of the rock mass tends to be much greater than is represented here in the database. In some cases one or even two orders of magnitude difference may be anticipated, depending on the precise nature of the strength test (Haydon & Hobbs, 1977).

Undrained (total) triaxial strength data are reported in site investigations either with the assumption that the friction angle, ϕ, is zero, or that it has a positive value, despite this being contrary to the principles of the test (Head, 1992; 1998). Undrained strength data containing a positive friction angle have been omitted from the database. A total of 2,965 results were obtained for c_u, and 204 for c' and ϕ'. A summary of triaxial test median values for these strength parameters is given in Table 7.12.

Table 7.12 Summary of triaxial test results – total and effective strength median values

Formation	c_u (kPa)#	c' (kPa)	ϕ'(degrees)
Blue Lias F	139	34	26
Charmouth Mudstone F	125	12	28
Dyrham F	113	19	33
Scunthorpe Mudstone F	127	26*	23*
Whitby Mudstone F	123	15	26

* less than 10 results

friction angle, $\phi_u = 0$

The range of undrained cohesion values, c_u, for the Lias Group was from 7 to 1650 kPa, for drained cohesion, c', from 0 to 400 kPa, and for drained friction angle, ϕ', from 0 to 47 degrees. The Scunthorpe Mudstone, Whitby Mudstone, and Charmouth Mudstone Formations show a remarkable similarity in terms of undrained cohesion; their medians being separated by only 4 kPa. The Blue Lias and Dyrham Formations medians for c_u are higher and lower, respectively. Undrained cohesions are lowest for Area 5 and highest for Area 4.

The profile with depth of c_u is highly scattered (Figure 7.8) although an overall trend of increasing strength with depth is seen.

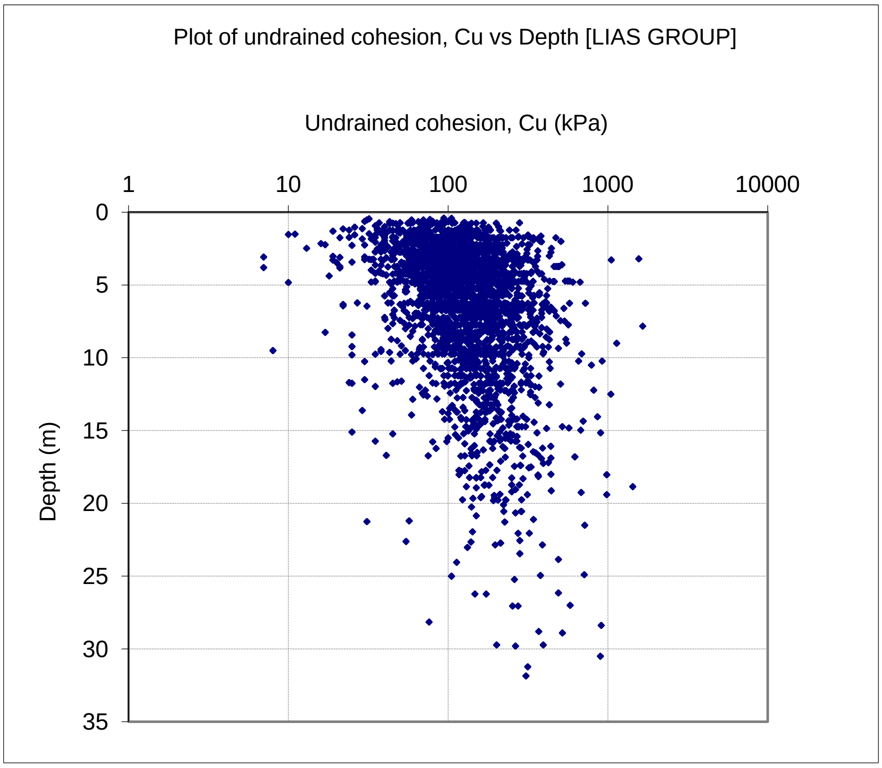


Figure 7.8 Plot of undrained cohesion (triaxial) vs. depth

Effective cohesion, c′, for the Blue Lias Formation was higher than the other formations tested, possibly as a result of calcareous cementation. Effective angles of friction did not vary greatly between formations, medians lying between 23 and 33 degrees.

Residual shear strength is the minimum strength of a soil achieved after continuous shearing along a pre-determined shear plane, usually within a remoulded sample, in a laboratory shear box test . The results are expressed in terms of the residual angle of internal friction, ϕ'_r, and residual cohesion, c'_r, obtained from a plot of effective normal stress vs. shear stress. A summary table of both peak (c_p', ϕ_p') and residual shear-box strength results for those formations tested is shown in Table 7.9. The table also shows the ratio of peak to residual friction angle (ϕ_p'/ϕ_r') for those formations with greater than 5 results; the average ratio based on data from 38 Lias Group samples being 1.75.

Table 7.13 Summary of shear-box test results – medians

Formation	c'_p (kPa)	ϕ'_p (degrees)	c'_r (kPa)	ϕ'_r (degrees)	ϕ'_p / ϕ'_r
Bridport Sand F	11*	38*	8*	36*	1.04
Charmouth Mudstone F	15	24.5	9	14	1.89
Scunthorpe Mudstone F	-	-	13*	13*	-
Whitby Mudstone F	-	-	2	8	-

* less than 10 results

Residual shear strength (angle of internal friction) has been plotted against plasticity index in Figure 7.9. This shows a good inverse correlation between residual shear strength and plasticity index as demonstrated for various formations by Cripps & Taylor (1981), Lupini et al. (1981), and Voight (1973). The plot suggests an approximate division of residual behaviour at a plasticity index, I_p, between 20 and 35 %. Burland et al. (2001) stated that for 'low' plasticity clays (I_p < 25 %) undrained shear strength, c_u was mainly a function of water content, and the ratio ϕ_p' / ϕ_r' equalled 1.0. However, for more plastic clays (I_p > 25 %) c_u was mainly a function of maximum previous overburden stress, p_c' and initial stress, p_i', and ratio ϕ_p' / ϕ_r' was greater than 1.0. This change in behaviour was attributed to the occurrence of *turbulent* shear in low plasticity clays and *sliding* shear in high plasticity clays, at large strains (Burland et al., 2001). There also appears to be a similar pattern with the Lias Group samples (though with the I_p division closer to 20 %), where the ratio ϕ_p' / ϕ_r' increases from 1.0 for samples with I_p < 20 % (e.g. Bridport Sand Formation) up to 3.0 for the samples with I_p > 20 % (e.g. most of the Charmouth Mudstone Formation).

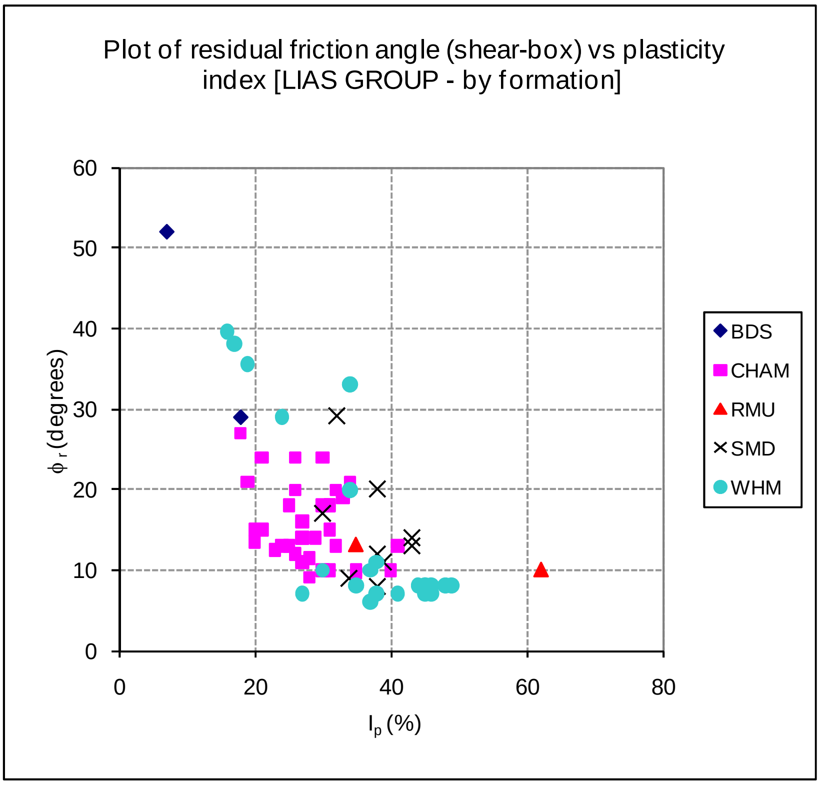


Figure 7.9 Plot of residual friction angle (shear-box) vs. plasticity index

BDS=Bridport Sand F., CHAM=Charmouth Mudstone F., RMU=Redcar Mudstone F., SMD=Scunthorpe Mudstone F., WHM=Whitby Mudstone F.

A relationship suggested by Wesley (2003), related to residual shear strength of a sample and its plotted position on the Casagrande plasticity chart, was also investigated. Specifically, this correlated the residual strength with the distance of the sample point from the A-line on the plasticity chart (+*ve* above the A-line and –*ve* below it). Improved correlations of the type described above were reported for a wide variety of soil types with liquid limit in excess of 50%. However, in the case of the Lias Group test data a poor relationship was obtained. This was probably due to the fact that the Lias Group data are relatively uniform in terms of their position on the Casagrande chart.

Because of the strength variability within the Lias, both 'soil' and 'rock' testing methods may be undertaken to determine strength parameters. An important difference between 'rock' and 'soil' tests is the method of specimen preparation. Rock specimens for Uniaxial Compressive Strength (UCS) testing require machining of undisturbed samples. Soil specimens may be undisturbed, remoulded, or compacted. Reference should be made to Head (1998). Data from 'rock' strength tests are few, and consist mainly of uniaxial compression test (UCS) results. The results are summarised in Table 7.14. These tests were carried out mainly on calcareous mudstones, mudstones, argillaceous limestones, and shales.

Table 7.14 Summary of Uniaxial strength, UCS, and Point-load index, $I_{S(50)}$, test medians

(n = number of samples tested (UCS). Mst = Mudstone, Lst. = Limestone)

Formation	*n*	UCS (MPa)	$I_{S(50)}$	$I_{S(50)}$ *Mst.*	$I_{S(50)}$ *Lst.*
Blue Lias	*82*	1.82	2.11	1.94	2.48
Charmouth Mudstone	*37*	1.69	0.21	-	-
Whitby Mudstone	*27*	6.00	2.19	2.52	2.18
Scunthorpe Mudstone		-	0.20	0.19	0.16

The results of UCS tests are plotted (on a log scale) against depth for Blue Lias and Charmouth Mudstone Formations in Figure 7.10. The plot shows a breakdown by broad lithological type. It can be seen that carbonate content has an influence on uniaxial compressive strength and that samples without limestone do not exceed 5 MPa (with the exception of two samples from the Blue Lias Formation).

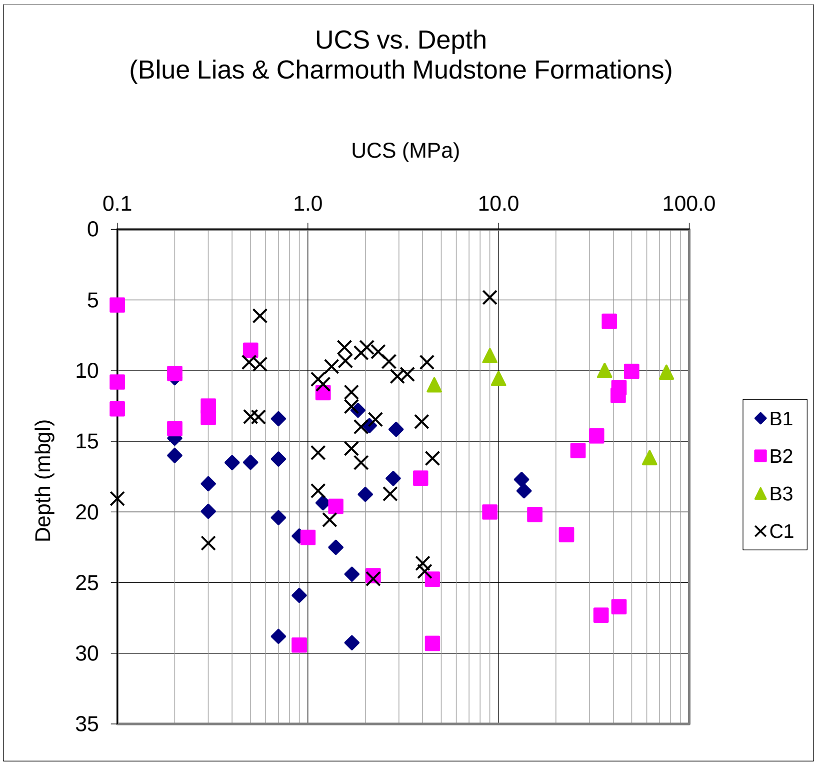


Figure 7.10 Plot of Uniaxial compressive strength (rock) vs. Depth for different lithologies

B = Blue Lias F., C = Charmouth Mudstone F.

1 = mudstone/shale, 2 = mudstone+ limestone, 3 = argillaceous limestone

Results from the Point load index test ($I_{S(50)}$) are also summarised in Table 7.14 with an additional breakdown according to lithology. These tests were carried out on mudstones and limestones on a variety of sample types, but all with diameter corrections to 50 mm. There is an order of magnitude covering the four formations represented; the Blue Lias and Whitby Mudstone formations providing the highest and the Charmouth and Scunthorpe Mudstone Formations the lowest. The lithology breakdown shows a 28% greater point load median for the Blue Lias limestone compared with mudstone, but the opposite, though lesser, trend for the Whitby and Scunthorpe Mudstone Formations.

7.2.7 Consolidation

Consolidation is the process whereby pore water is expelled from a soil as the result of applied, static, external stresses, resulting in structural densification of the soil. For most purposes, the external stress is considered to be unidirectional, and usually vertical. Swelling strain data may also be obtained from the oedometer test. The oedometer is a simple laboratory apparatus, which applies a vertical load to a small disc-shaped soil specimen, laterally confined in a ring. The consolidation test is normally carried out on undisturbed specimens by doubling the load at 24-hour intervals, and measuring the resulting consolidation deformation (BS1377: 1990; Head, 1998).

The *rate* at which the consolidation process takes place is characterised by the coefficient of consolidation, c_v (m^2/yr), and the *amount* of consolidation by the coefficient of volume compressibility, m_v (m^2/MN). Consolidation data derived from the oedometer test on undisturbed specimens are used in the calculation of likely foundation settlement, and may also provide information on the stress history, geological history, state of disturbance, permeability, and elastic moduli of clay soils.

The consolidation data selected for inclusion in the database are confined to oedometer tests where loading increments are doubled, as recommended in British Standards: BS1377 (1990). The stress range is 25 to 3,200 kPa, but with only a small proportion of tests reaching 3,200 kPa, this range is inadequate to characterise the Lias Group materials fully, but adequate for most engineering purposes. There are a total of 284 consolidation data points in the database. Statistical analyses of the coefficients of volume compressibility, m_v, and coefficient of consolidation, c_v, at specific stresses are shown in Appendix B. A summary of the data for specific applied stresses is shown in Table 7.15. The overall median values for c_v range from 1.24 to 14.79 m^2/yr. A plot of medians by Formation is shown in Figure 7.11. This reveals almost uninterrupted decreases in c_v with stress increase for all Formations except the Dyrham Formation. The Dyrham Formation curve stands apart from the others with significantly higher overall values of c_v, and a pattern of decreasing c_v from 50 to 200 kPa but increasing c_v from 200 to 3,200 kPa. Above 100 kPa, the Blue Lias, Charmouth Mudstone, Scunthorpe Mudstone, and Whitby Mudstone Formations are very closely grouped. The results place the Lias Group in the 'medium' c_v class, typical of medium plasticity soils, with the exception of the Dyrham which is placed in the 'high' category, typical of low plasticity, more permeable soils (e.g. silts) (Lambe & Whitman, 1979).

Table 7.15 Coefficient of consolidation results at 100 and 400kPa applied stress

(n = number of data @ 400 kPa)

Formation	*n*	c_v (m^2/yr) @100kPa	c_v (m^2/yr) @400kPa
Blue Lias	*12*	2.08	1.67
Charmouth Mudstone	*181*	3.40	1.50
Dyrham	*22*	15.79	15.98
Scunthorpe Mudstone	*12*	3.70	1.27
Whitby Mudstone	*55*	5.01	0.91

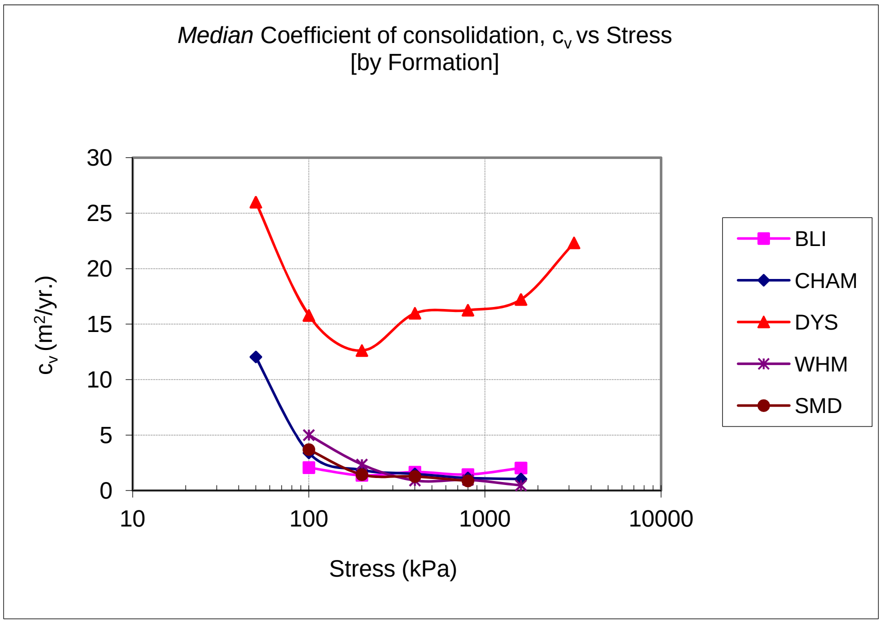


Figure 7.11 Plot of coefficient of consolidation medians with stress

The overall median values for m_v range from 0.013 to 0.160 m^2/MN. A summary of data for specific applied stresses is shown in Table 7.16. A plot of medians by Formation is shown in Figure 7.12. This reveals uninterrupted decreases in m_v with increasing stress (above 200 kPa) for all Formations. As with the c_v data, the mudstone formations are grouped closely together, while the Dyrham Formation (silt) lies below. The mudstone data tend to merge between 200 and 400 kPa. These results place the Lias Group coefficient of volume compressibility results in the 'very low' to 'medium' category.

Table 7.16 Coefficient of volume compressibility results at 100 and 400kPa applied stress

(n = number of data @ 400 kPa)

Formation	*n*	m_v (m^2/MN) @100kPa	m_v (m^2/MN) @400kPa
Blue Lias	*11*	0.12	0.11
Charmouth Mudstone	*111*	0.16	0.10
Dyrham	*23*	0.11	0.06
Scunthorpe Mudstone	*12*	0.16	0.11
Whitby Mudstone	55	0.10	0.10

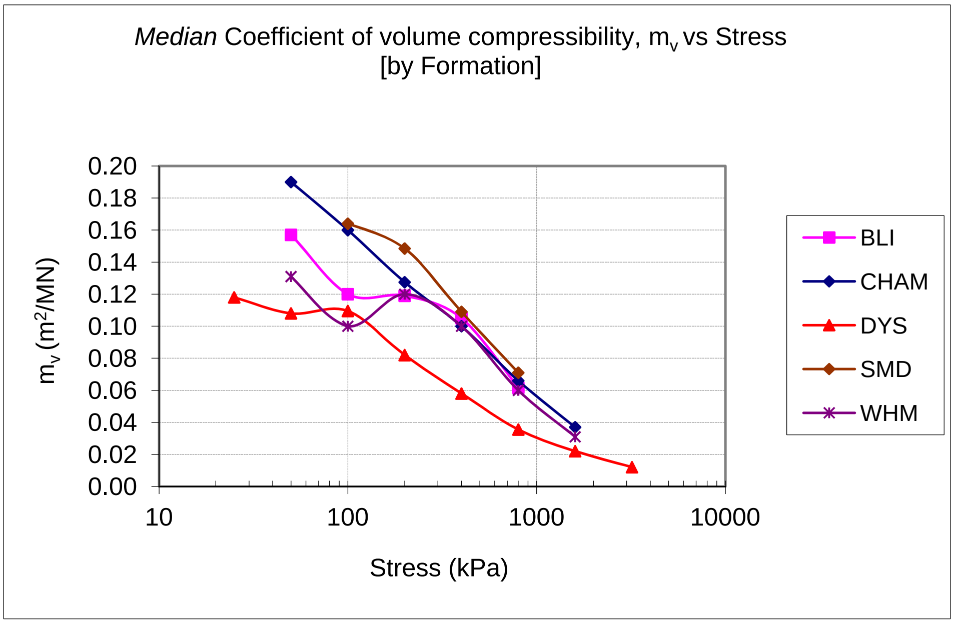


Figure 7.12 Plot of coefficient of volume compressibility medians with stress

(*note:* Figures 7.11 and 7.12 do not represent individual test curves, but are simply a visual representation of the statistics at each stress increment). Initial void ratio medians for Formations, from the oedometer consolidation test, range from 0.52 to 0.63.

A total of 11 oedometer consolidation tests were carried out at BGS on samples of Lias Group clays undertaken as part of an assessment of shrink/swell geohazards (Nelder & Jones, 2004). The oedometer results, along with matching plasticity results, are summarised in Table 7.17. Plots of voids ratio vs. stress and coefficient of volume compressibility vs. stress are given in Figures 7.13 and 7.14, respectively. These data show a wide variety of behaviour, apparently unrelated to formation, with some samples having very high voids ratios and coefficients of volume compressibility at low applied stresses compared with the medians shown in Figure 7.12. This may be due to fissuring and softening caused by stress-relief, despite the use of carefully hand-prepared 'undisturbed' tube samples. It may be considered, however, that the use of such preparation methods has captured the true behaviour of weathered Lias Group mudstones. The oedometer results do not appear to relate to plasticity in any straightforward manner. A plot of compression index (the change in voids ratio for one log cycle of pressure change), C_c, vs. liquid limit, w_L, for some Lias Group formations is shown in Figure 7.15 (BGS data). Also shown are Skempton's C_c vs. w_L relationships for undisturbed and remoulded soils, where $C_c = 0.009 (w_L-10)$ is representative of undisturbed and $C_c' = 0.007 (w_L-10)$ of remoulded soils. The data do not conform to the Skempton relationship, though this has been found elsewhere with indurated mudrocks (Hobbs et al, 1998). There are too few data with which to establish such a relationship, should it exist, for the Lias Group.

Table 7.17 Summary of BGS oedometer test data (Nelder & Jones, 2004)

Sample Site	Formation	Diam (mm)	Voids ratio e_o	m_v range (m^2/MN)	c_v range (m^2/year)	w_L (%)	w_P (%)	c_c	c_e
Southam	BLI	50	0.444	0.012-0.033	0.75-1.02	57	35	0.17	0.02
Stowey	BLI	75	1.049	0.024-3.439	0.55-157.13	65	36	0.27	0.12
Bishops Cleeve	CHAM	50	0.613	0.003-0.937	1.63-10.55	45.8	23	0.17	0.05
Blockley Site 1	CHAM	50	0.731	0.005-0.501	1.83-33.87	54.7	32	0.21	0.07
Blockley Site 2	CHAM	75	0.595	0.012-2.614	0.98-160.52	56	34	0.16	0.07
Dimmer	CHAM	50	0.520	0.005-0.626	0.01-3.06	56.5	34		
Brixworth	WHM	50	0.710	0.004-0.191	0.84-2.86	55	27	0.23	0.08
Conesby Site 2	WHM	75	0.299	0.006-0.121	1.13-58.92	61	38	0.06	0.03
Flixborough	WHM	75	0.338	0.007-0.183	1.93-5.5	60	37		
Ravenscar	WHM	50	1.285	0.005-1.765	10.17-499.6	41	16	0.32	0.06
Sidegate Lane	WHM	50	0.629	0.004-0.139	1.93-4.24	61	35	0.15	0.07

BLI = Blue Lias, CHAM = Charmouth Mudstone, WHM = Whitby Mudstone

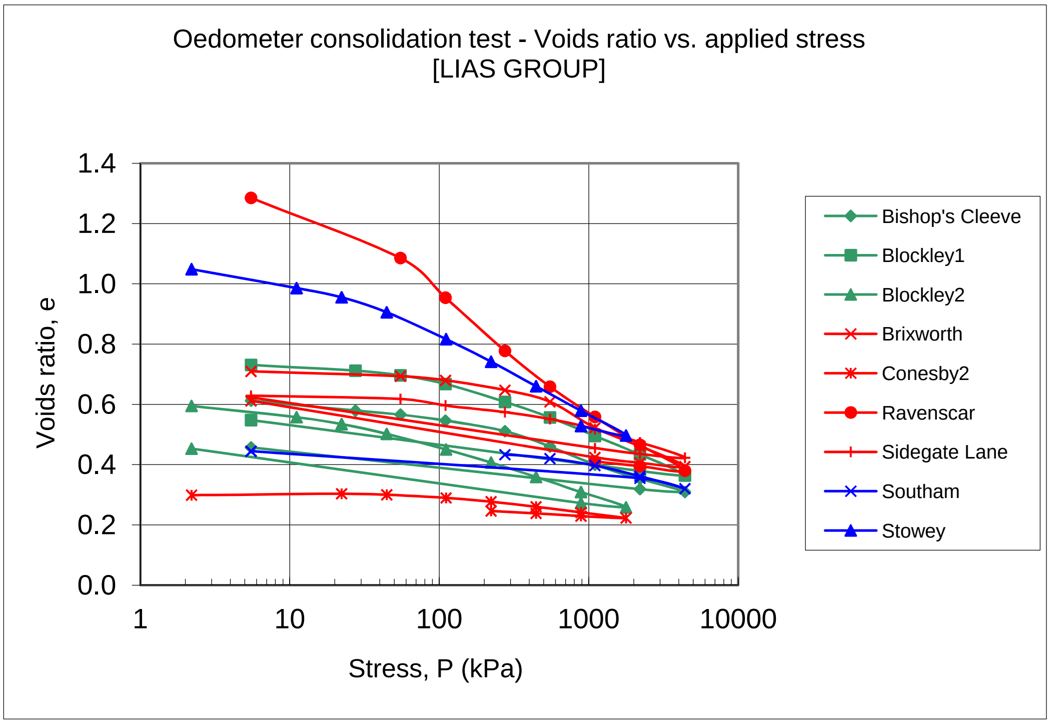


Figure 7.13 Plot of BGS oedometer test results - voids ratio vs. applied stress

(Charmouth Mudstone F. = green, Whitby Mudstone F. = red, Blue Lias F. = blue) (Nelder & Jones, 2004)

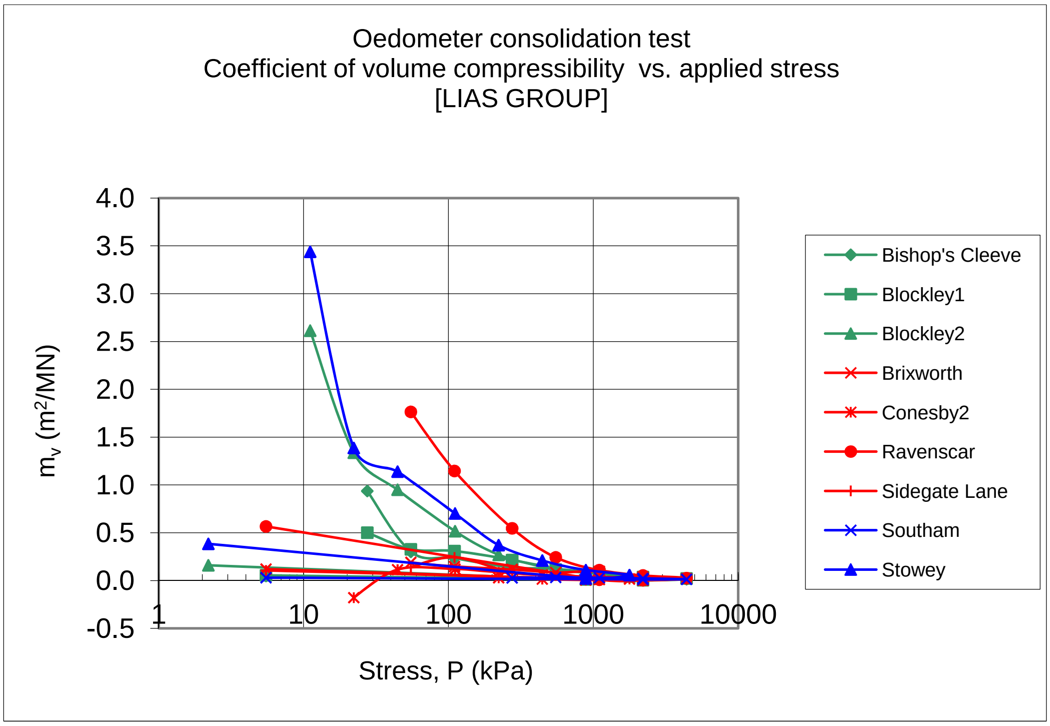


Figure 7.14 Plot of BGS oedometer test results – Coefficient of volume compressibility vs. applied stress (Charmouth Mudstone F. = green, Whitby Mudstone F. = red, Blue Lias F. = blue). (Nelder & Jones, 2004).

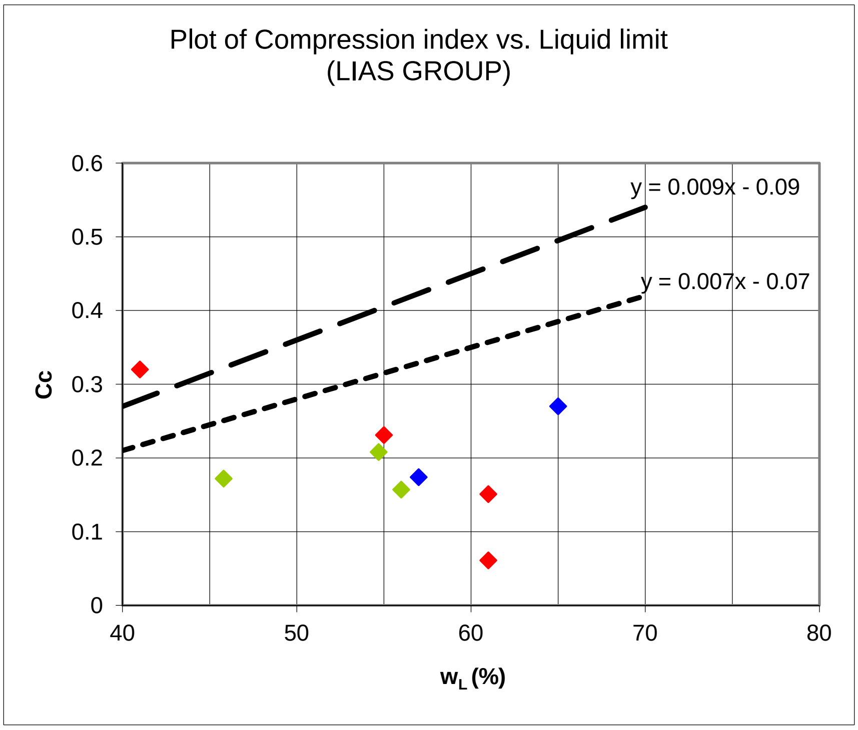


Figure 7.15 Plot of Compression index, C_C vs. Liquid limit, w_L (BGS oedometer tests)

Note: Skempton's relationship for undisturbed (dashed) and remoulded (dotted) clays

Note: (Charmouth Mudstone F. = green, Whitby Mudstone F. = red, Blue Lias F. = blue)

The state of consolidation (i.e. normally, over-, or under- consolidated) of a soil in its current natural condition, and hence its maximum previous overburden stress, can be estimated from oedometer consolidation tests, where a yield point can be identified from the voids ratio vs. stress curve.

An over-consolidated clay is one in which the maximum previous overburden exceeds the present overburden, resulting in a denser, stronger, and less deformable soil.

Clays are often classified or discussed in terms of their degree of consolidation in their natural state, i.e. the natural, geological stress history. The over-consolidation of a clay is an important engineering descriptor, particularly where the degree of over-consolidation is high. Over-consolidation affects undrained shear strength, lateral stress, pore-water response, and allowable bearing pressure and settlement (Borowczyk & Szymanski, 1995). It is not always possible to obtain stress-history information from standard oedometer tests, due to the fact that near-surface disturbance tends to remove the effects of over-consolidation. Disturbance may be caused by natural factors such as weathering and glaciation, whilst man-made factors might include drainage, loading, and excavation.

7.2.8 Deformability

Deformability (the terms compressibility and stiffness may also be used) is a measure of the strain undergone by a soil or rock subjected to a particular stress amount and direction. This strain may be unidirectional or volumetric. Deformability may be measured in both laboratory (intact) and field (rock or soil mass). Usually, test data are interpreted from stress-strain plots, with several parametric variants of deformability available. The elastic properties of a material are defined by the fundamental properties: bulk modulus, *K*, and shear modulus, *G*. Bulk modulus represents the change in all-round stress per unit change in volume, whereas shear modulus represents the change in shear stress per unit change in shear strain. The simplest form of deformability measurement is that of Young's modulus, *E*, which is derived from a uniaxial compression test and is defined as follows:

$$E = \frac{\sigma_1}{\varepsilon_1}$$

where: σ_1 = major principal stress

ε_1 = strain in direction of major principal stress

The relationship between strain in the direction of stress and strain at right angles to it is defined by the Poisson's ratio, ν, as follows:

$$\nu = \frac{\varepsilon_{2,3}}{\varepsilon_1} \qquad = \frac{E\,\varepsilon_{2,3}}{\sigma_1}$$

where: σ_1 = major principal stress

ε_1 = strain in direction of major principal stress

$\varepsilon_{2,3}$ = strain at right angles to major principal stress

E = Young's modulus

Shear modulus, G, is defined as:

$$G = \frac{E}{2(1+\nu)}$$

where: E = Young's modulus

ν = Poisson's ratio

$$\text{Also:} \quad E' = 2G(1+\nu')$$

where: G= shear modulus

E' = drained Young's modulus

ν' = drained Poisson's ratio

Shear modulus may be measured in a variety of ways from the stress vs. strain plots. The most commonly quoted are the initial shear modulus, G_i, (determined from the initial slope of the stress vs strain curve) and the unload/reload modulus, G_{ur}.

Only one deformability result is contained in the database. This is for a highly weathered mottled greenish-grey/brown, highly fissured, mudstone (Scunthorpe Mudstone F.) from 8m depth at Cotgrave, Nottinghamshire, the Young's Modulus and Poisson's Ratio for which were 2.55 MPa and 0.25. This sample had compressional and shear velocities of 0.0012 m/s and 0.0007 m/s, respectively. Dynamic Poisson's ratios, ν_{DYN}, ranging from 0.30 to 0.34 and dynamic Young's moduli, E_{DYN}, are shown in Table 7.18 for geophysical laboratory tests on fine-grained argillaceous limestones from the Dorset coast (Area 5). This also shows a positive correlation between Young's Modulus (dynamic) and both dry unit weight, γ_d, and compression wave velocity, V.

NOTE: the dynamic versions of these deformation properties are determined by interpretation of velocities of ultrasonic compressional and shear-waves passed through the rock.

Table 7.18 Dynamic deformation moduli and compression wave velocities, Area 5 (Hobbs, 1974)

Formation	γ_d (Mg/m^3)	E_{DYN} (GPa)	ν_{DYN}	V (km/s)
Blue Lias	2.50	29.02	0.34	4.24
Blue Lias	2.46	25.62	0.34	3.93
Blue Lias	2.53	43.23	0.32	4.84
Blue Lias	2.54	48.07	0.32	5.12
Charmouth Mudstone (Black Ven Marl M.)	2.38	24.28	0.30	3.61

7.2.9 Permeability

Permeability, or hydraulic conductivity, in the geotechnical context, is a measure of the ability of soil or rock to allow the passage of fluid subject to a pressure gradient. The permeability measured on intact specimens in the laboratory (k_{LAB}) is usually distinct from that measured in the field (k_{FIELD}), as a result of the huge scale difference, and hence the involvement in the field tests of discontinuities and gross lithological variations. The database contains 56 field permeability determinations, representing the major litho-stratigraphic units. These are of the 'falling head', 'rising head', 'variable head', and 'packer' type tests applied to boreholes. Packer tests enable a particular horizon to be isolated for testing whereas the other test types allow water transmission throughout its unlined length of the borehole.

The field permeability results range over seven orders of magnitude, from 1.8 x 10^{-11} to 1.7 x 10^{-4} m/s. The median value is 1.7 x 10^{-7} m/s. A plot of permeability vs. depth is shown for the formations in Figure 7.16. The Whitby Mudstone Formation appears to cluster at lower permeabilities than the other formations. It is notable that for the data examined, the Dyrham and Bridport Formations do not register higher permeabilities than the more mudstone-dominant formations.

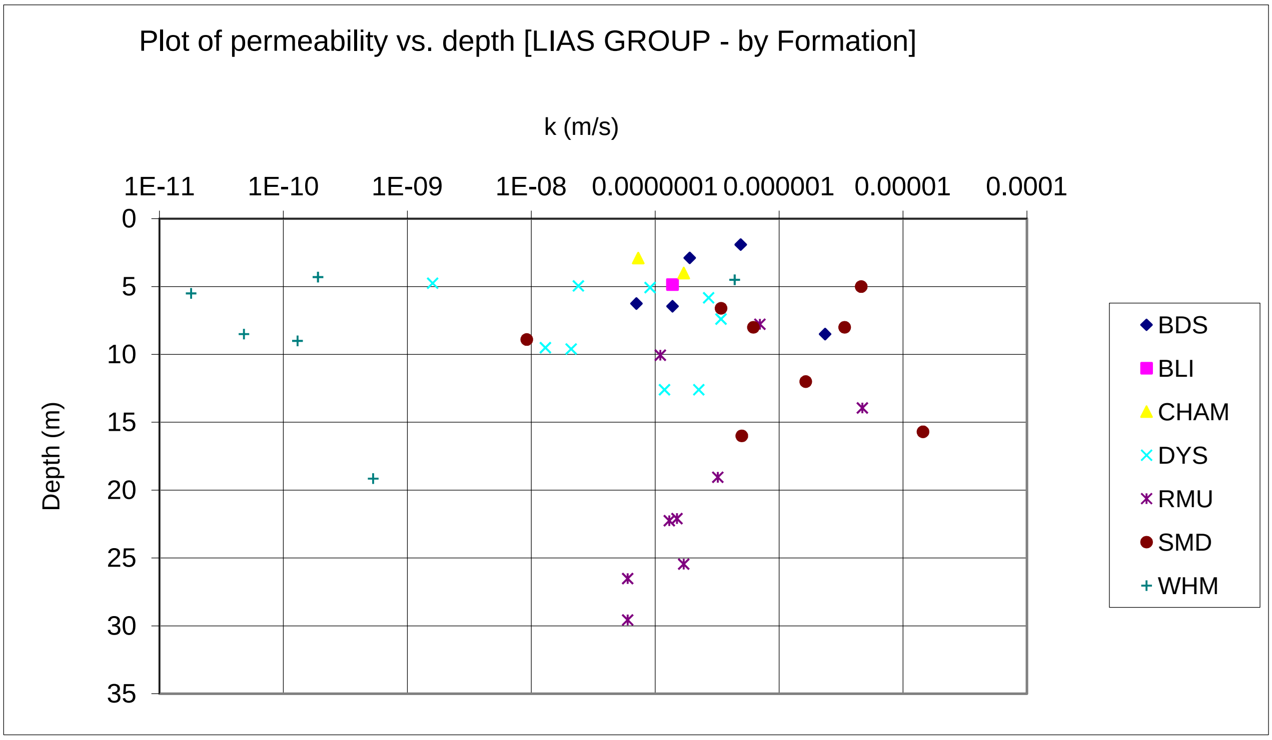


Figure 7.16 Plot of coefficient of permeability vs. depth by formation

Key: **BDS=Bridport Sand F, BLI=Blue Lias F., CHAM=Charmouth Mudstone F., DYS=Dyrham F., RMU=Redcar Mudstone F., SMD=Scunthorpe Mudstone F., WHM=Whitby Mudstone F.**

A plot of field permeability with depth for broad lithological types is shown in Figure 7.17. This shows that whilst all samples below 10^{-8} m/s are clay or mudstone, the higher permeabilities include all lithology types. This may be due to weathering and water movement through fissures. The general ranges shown in Table 7.19 may be used for comparison.

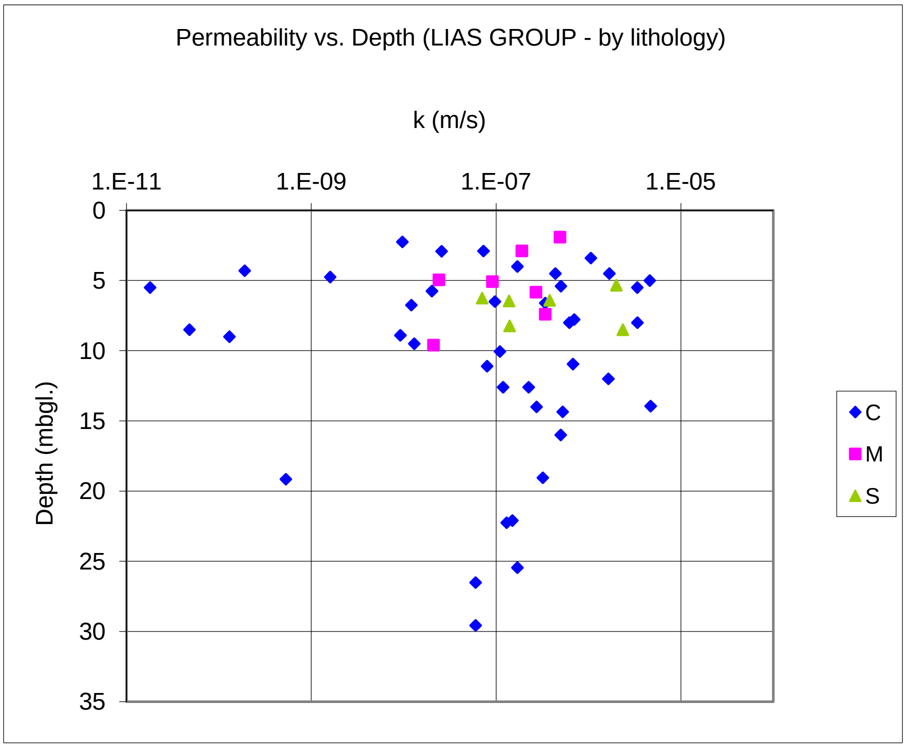


Figure 7.17 Plot of coefficient of permeability vs. depth by lithology (C = Clay/mudstone, M = Silt/siltstone, S = Sand/sandstone)

Table 7.19 Typical permeabilities of main soil types

Soil	Permeability (m/s)
Gravels	1 - 10^{-2}
Clean sands	10^{-2} - 10^{-5}
Very fine or silty sands	10^{-5} - 10^{-8}
Silt, loess	10^{-5} -10^{-9}
Fissured & weathered clays	10^{-4} - 10^{-8}
Intact clays	10^{-8} - 10^{-13}
Glacial till	10^{-6} - 10^{-12}

Permeability is an important parameter in the selection of materials for engineered (reworked and compacted) structures such as clay liners (see section 8.3), where an upper limit of 1×10^{-9} m/s is common (Murray, 1998).

The anisotropy of permeability has not been examined here, due either to the fact that data in the database refer to a 'global' value, or that the orientation of the test has not been reported. However, it should be noted that horizontal permeabilities may be expected to exceed vertical permeabilities by a factor of about 2, though locally in the presence of limestone and sandstone layers this will tend to increase.

7.2.10 Compaction

Compaction is the process whereby soil, usually reworked, is densified, usually in layers, in order to produce an engineering fill of known properties. This is achieved by applying dynamic forces, using special plant, such as rollers, vibratory rollers, rammers, or by special ground improvement processes. The densification is achieved by the solid soil particles packing closer together and producing a stronger soil mass. The water content of the placed fill and the amount of energy input are critical to the density that can be produced. The process is not the same as consolidation (section 7.2.7).

Compaction properties may be measured in the field and in the laboratory. Field methods include the nuclear probe and the cone penetrometer. The laboratory method is standardised and usually employs the 1 litre compaction mould where layers of a disturbed soil sample are compacted into the mould and sub-samples taken for water content determination (British Standards: BS1377, 1990). There are two forms of the laboratory test, the 'light' (2.5 kg rammer) and the 'heavy' (4.5 kg rammer) Proctor Test. The results are shown in the form of a dry density vs. water content relationship, from which the maximum dry density (MDD) and corresponding optimum water content (OMC) are calculated.

A total of 238 compaction test results are contained in the dataset. For the Lias Group overall, the test data give median values for maximum dry density (MDD) of 1.76 Mg/m^3 and optimum water content (OMC) of 16 %. Formation medians are in the ranges 1.70 to 1.78 Mg/m^3 and 15.4 to 18 %, respectively. A summary table showing formation medians is given in Table 7.20. A plot of MDD vs. OMC is given in Figure 7.18.

Table 7.20 Compaction medians by formation

Formation	MDD (Mg/m^3)	OMC (%)
Bridport Sand F	1.70	18.0
Blue Lias F	1.75	18.0
Charmouth Mudstone F	1.78	16.0
Dyrham F	1.77	16.0
Scunthorpe Mudstone F	1.77	15.6
Whitby Mudstone F	1.71	15.4

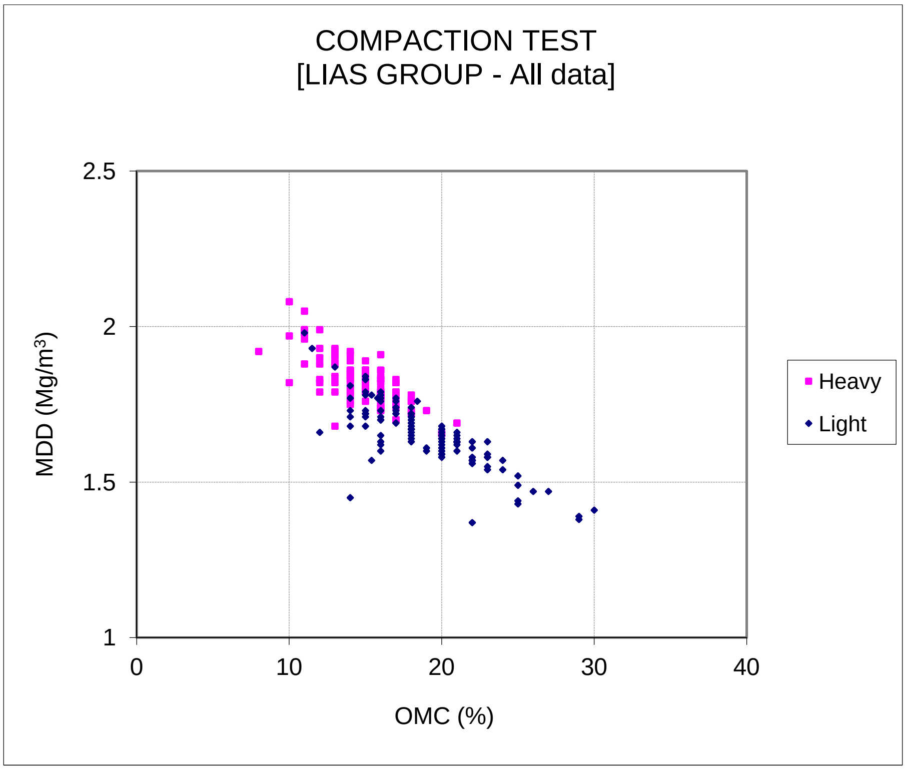


Figure 7.18 Plot of optimum moisture content vs. maximum dry density

The permeability (hydraulic conductivity) for a soil increases dramatically below the OMC (Murray, 1998). This is particularly true of field compacted permeability where 'clod' size influences the development of fissures at water contents below OMC.

The Moisture Condition Value (MCV) is a test capable of being used in the laboratory or field, and is becoming an increasingly popular means of selection, classification, and specification of fill material (British Standards: BS1377, 1990; Highways Agency, et al., 1991; Caprez & Honold, 1995). The test aims to determine the minimum compactive effort required to produce near-full compaction of a single 1.5 kg sample passing a 20mm mesh sieve. The test differs from the traditional Proctor compaction test in that the compaction energy is applied across the entire sample surface, and compaction energy can be assessed as an independent variable. The degree of compaction involved in the MCV test probably lies between those of the standard and heavy compaction tests (Murray, 1998).

A total of 684 MCV data values for the Lias Group are contained in the database, ranging from 0 to 19.8 %, with an overall median of 11.7 %. The medians for each formation tested are shown in Table 7.21. The formation medians range from 9.7 to 13.2%. MCV values less than 7 tend to indicate very poor trafficability.

Table 7.21 Summary of Moisture Condition Value, MCV, median values by formation

Formation	*n*	MCV (%)
Bridport Sand F	*42*	9.7
Blue Lias F	*23*	13.2
Charmouth Mudstone F	*212*	12.6
Dyrham F	*220*	10.3
Scunthorpe Mudstone F	*5*	12.0
Whitby Mudstone F	*155*	12.5

n = number of samples

7.2.11 Swelling & shrinkage

Swelling and shrinkage are two mechanical properties of a soil which, though driven by related physico-chemical mechanisms, are usually treated separately in the laboratory. Swelling sensu-strictu is mainly a function of the clay minerals present in the soil or rock. The engineering phenomenon of *heave* may be caused by factors other than swelling of clay; for example, by stress relief. The geological processes affecting swelling and shrinkage were described by Gostelow (1995). Assessment of swelling and shrinkage usually does not involve direct measurement, but rather indirect estimation of volume change *potential* from index tests on reworked samples. Direct shrink/swell tests are not well catered for in British Standards.

The wide variety of test methods applicable to shrink/swell was described in Hobbs & Jones (1995). Laboratory tests may be carried out on *undisturbed* or *disturbed* samples. Undisturbed samples are as near to their in-situ condition as possible, whereas disturbed samples may be reworked, reconstituted, or compacted depending on the engineering application. Swelling tests usually either measure the *strain* due to swelling, resulting from access of a partially saturated sample to water, or the *pressure* produced when the sample is restrained from swelling. Swelling strain samples may be disc-shaped oedometer-type samples for 1-D testing of soils and slaking rocks, or cubes for 3-D testing of non-slaking rocks. The 1-D samples are laterally restrained. Swelling pressure samples are usually oedometer discs and may be mounted in a normal oedometer or a special swelling pressure apparatus. There are two shrinkage tests specified by British Standards: BS1377:1990. These are the Shrinkage Limit Test, carried out on undisturbed or disturbed samples, and the Linear Shrinkage Test, carried out on reworked soil ‘paste’ (prepared as for Atterberg limits). *It should be noted that the shrinkage limit is a specific water content below which little or no volumetric shrinkage occurs, whereas the linear shrinkage is a percentage reduction in length (strain) on oven drying.*

The clay-dominant formations of the Lias Group are generally considered to be of ‘low’ to ‘medium’ shrink/swell potential depending on lithology and mineralogy, while the dominantly sandy formations are ‘low’. This is borne out by the database (see below).

The Building Research Establishment (BRE) Digest 240 (1993) gives a scale of susceptibility to volume change (i.e. swelling or shrinkage), or volume change ‘potential’, for over-consolidated clays in terms of a modified plasticity index, I_p' (Table 7.22),

where: I_p’ (modified plasticity index):

$$I_p' = I_p\left(\frac{\% < 0.425mm}{100\%}\right)$$

Table 7.22 Volume change potential related to modified plasticity index

I_p‘	Volume change potential
> 60	Very high
40 - 60	High
20 - 40	Medium
< 20	Low

The purpose of the modified plasticity index is to take account of the proportion of fines in relation to the total sample and to reduce the measured plasticity index in proportion. Many Atterberg limit data in the database do not include < 0.425mm results. A total of 3,671 (out of 5,930) contain < 0.425mm results. This may be because the sample did not require sieving, or that a small number of coarse particles were removed by hand, without sieving. The modified plasticity index and volume change potential data are shown in Table 7.23:

Table 7.23 Volume change potential for Lias Group formations, from modified plasticity index

(Refer to Table 7.22)

Formation	Median Ip‘ (%)	Volume change potential
Bridport Sand	16.0	Low
Blue Lias	27.0	Medium
Charmouth Mudstone	27.0	Medium
Dyrham	22.0	Medium
Redcar Mudstone	25.1	Medium
Scunthorpe Mudstone	29.9	Medium
Whitby Mudstone	28.0	Medium

Overall, the percentage of data falling in the ‘high’ category was 2.5 %, these being distributed across the clay-dominant formations. Only four samples gave a ‘very high’ classification. These were from the Charmouth Mudstone and Redcar Mudstone Formations. The Building Research Establishment (BRE) Digest 240 (1993) classification does not indicate the actual volumetric shrinkage to be expected for each of the volume change potential categories. Net volume changes depend on the initial saturation condition of the test sample. In the case of the shrinkage limit test this is usually natural moisture content, whereas in the case of the linear shrinkage test it is close to the liquid limit.

Linear Shrinkage results for the Lias Group were obtained from samples collected as part of an assessment of the shrink/swell hazard (Hobbs et al., 2007). Sample details are given in Appendix D4. A plot of linear shrinkage versus plasticity index is given in Figure 7.19. The dashed line shows a relationship ($L_s = 0.47I_p$) suggested in British Standards: BS1377:1990. This compares with a best-fit line (solid line) for all the Lias samples tested of ($L_s = 0.22I_p + 5$). The plot shown in Figure 7.19 suggests that at low plasticity indices, the linear shrinkages are less scattered.

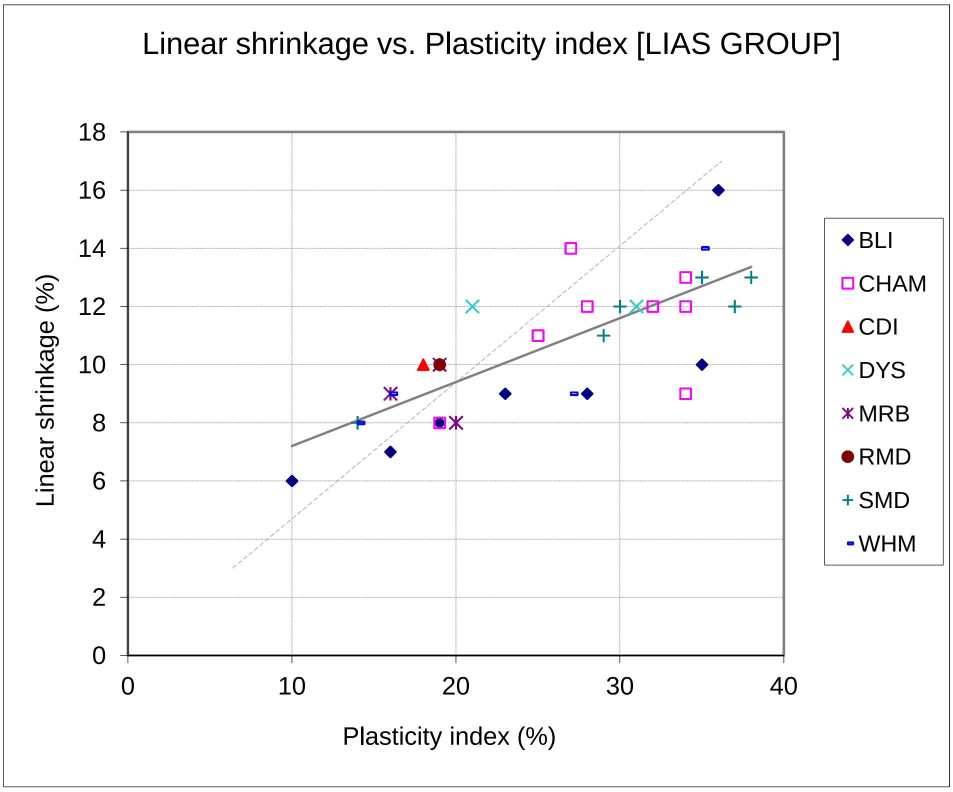


Figure 7.19 Plot of linear shrinkage vs. plasticity index (BGS samples). (Hobbs et al., 2007)

Key: **BDS=Bridport Sand F, BLI=Blue Lias F., CHAM=Charmouth Mudstone F., DYS=Dyrham F., RMU=Redcar Mudstone F., SMD=Scunthorpe Mudstone F., WHM=Whitby Mudstone F.**

7.2.12 Standard Penetration Test (SPT) results

The Standard Penetrometer Test (SPT) is a long-established method of in-situ geotechnical testing. This dynamic method employs a falling weight to drive a split-sampler and cutting shoe (or solid 60^o cone in the case of coarse soils or soft rock) 300 mm into the ground from a position 150 mm below the base of a borehole; the initial 150 mm being the 'seating' drive. The use of the test is described in British Standard 5930 (1999) and the methodology in British Standard 1377: Part 9: Clause 3.3 (1990). There has been much discussion concerning the test method, test apparatus, and test interpretation (Stroud & Butler, 1975; Stroud, 1989). International variations in practice have been a feature of its use.

It was recommended (Clayton, 1995; British Standard 5930, 1990; International Society for Rock Mechanics, 1988) that test results be reported in the form of six 75 mm penetration increments; the first two representing the 'seating' drive and the final four the 'test' drive, the sum of the latter providing the SPT 'N' value. This is often not the case in site investigation reports, though it does form part of the Association of Geotechnical Specialists (AGS) format.

The Standard Penetration Test (SPT) may be regarded as crude, but it is inexpensive and effective. In most cases site investigation reports included a record of the incremental blows and penetrations. These have been entered into the geotechnical database for analysis. The summaries presented for the SPT are derived from over 2,000 tests. The data from these tests were processed in the following stages:

1	*Seating blows and penetration.* The current test standard (British Standard BS1377, 1990) has specified that the seating drive is complete after an initial penetration of 150 mm or 25 blows, whichever is first achieved. This recognises that, in harder soils and weak rocks, the test equipment is adequately seated with a penetration of <150 mm. Thus it is no longer permissible to report tests as "seating blows only". Few of the site investigations used to acquire data for this study had complied with this requirement. Some drillers had apparently carried out the test correctly, and yet the formal report records these tests as incomplete. Where the blow count to 150 mm was greater than 25, the data within this interval were examined. The seating penetration was taken at the increment for which the total blow count was proportionately closest to 25. In the cases where this occurred at the first increment, all the subsequent data were shifted to the right and the next four increments taken as the main test drive. Tests in which data have only been recorded for a single increment were discarded, as they left no scope to distinguish 'seating' from 'test drive''.

2	*Variability of the incremental blows.* The purpose in recording the SPT test in 75 mm increments is not clear, either in the British Standard or in the otherwise comprehensive report by Clayton (1995). In this study, the incremental data were analysed on the premise that in each test an attempt is made to derive a measure of resistance for a single and, at least locally, consistent material. Thus, when the test interval crosses between two materials of differing resistance, the result will reflect the properties of neither, nor the overall properties of the two materials when considered together. Data from the final increment of each test were examined. Where the penetration for this increment had been recorded as zero, the test was discarded. It was taken that the test interval had reached a second material of very much higher resistance, for which the available data indicated an infinite N value. For the remaining tests, the penetration rate (blows/mm) for the final increment was compared to the rate for the first increment of the main test drive. Where this ratio was higher than about 4:1, the tests were again discarded.

For a small proportion of tests neither digital nor incremental data were available. In these cases, tests giving a full N value were accepted, together with those in which a partial main test drive could be distinguished from a seating drive. For the remainder, extrapolated N values were calculated from the main test drive penetration (where less than 300 mm) and the corresponding blow count. Much of the discarded data represents high but unquantifiable N values.

A total of 3,812 SPT N values are contained in the database. The majority of these represent the Charmouth Mudstone, Whitby Mudstone, and Dyrham Formations. The overall median value is 42, with a range from 2 to 277. The summary statistics are shown in Table 7.24. Plots of SPT vs. depth for the principal formations are shown in Figures 7.21 to 7.23. These show trends of increasing N value with depth to 25 m (there are few data below this depth). The scatter of data is considerable and linear correlations between N and depth are poor. However, some trends can be discerned, for example the rate of increase in N with depth is less for the Whitby Mudstone Formation than for the other mudstone formations. In fact, the Whitby Mudstone Formation has about half the rate of increase of the Charmouth Mudstone Formation, and about two-thirds that of the Dyrham Formation. The results analysed by *Area* show that the rate of increase of N with depth appears greater for Areas 2 and 4 compared with the remainder.

Table 7.24 Summary statistics for Standard Penetration Test (SPT)

Formation	N (blows / 300mm)			
	median	range	25th percentile	75th percentile
Bridport Sand	42	8 - 144	23	73
Blue Lias	41	6 - 137	29	58
Charmouth Mudstone	46	2 - 277	27	76
Dyrham	36	2 - 165	24	57
Redcar Mudstone	39	12 - 111	30	76
Scunthorpe Mudstone	57	10 - 126	30	77
Whitby Mudstone	38	4 - 164	25	51

For information, Stroud (1989) and Clayton (1995) give log-log correlations between N value (derived from SPT, pressuremeter, and pile tests) and unconfined compressive strength data for various clay and mudrock formations, obtained from a variety of sources. From this Clayton (1995) quoted the following relationship for 'clays':

$$c_u = 5.N_{60} \qquad \text{kPa}$$

where: N_{60} = equivalent SPT resistance corrected to 60% of energy

Assessment of this correlation for the Lias'clays' SPT data acquired for this report has not yet been undertaken.

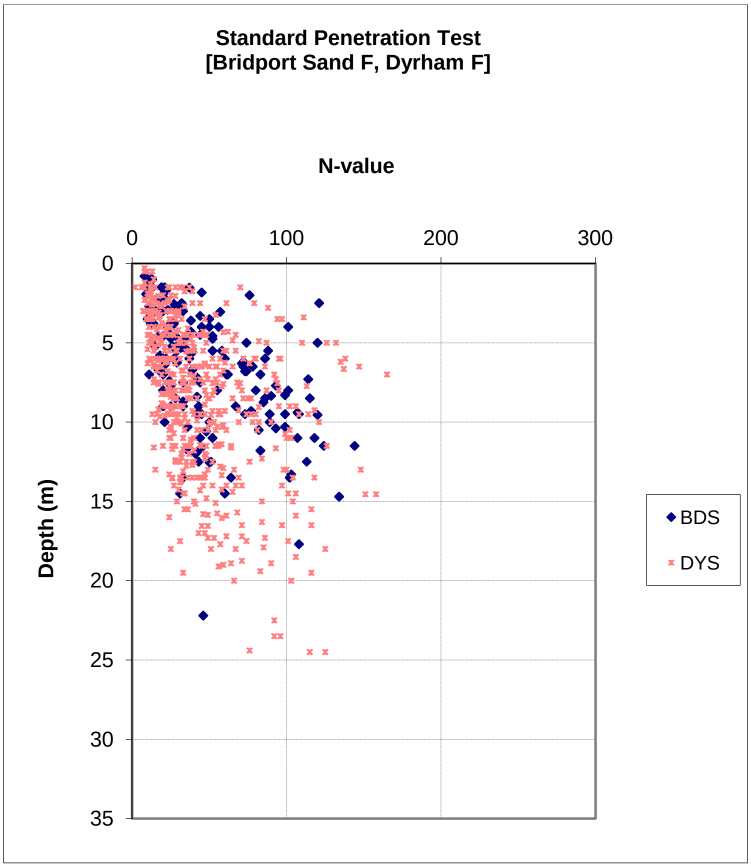


Figure 7.20 Plot of SPT 'N' value vs. Depth for sand/silt-rich formations.

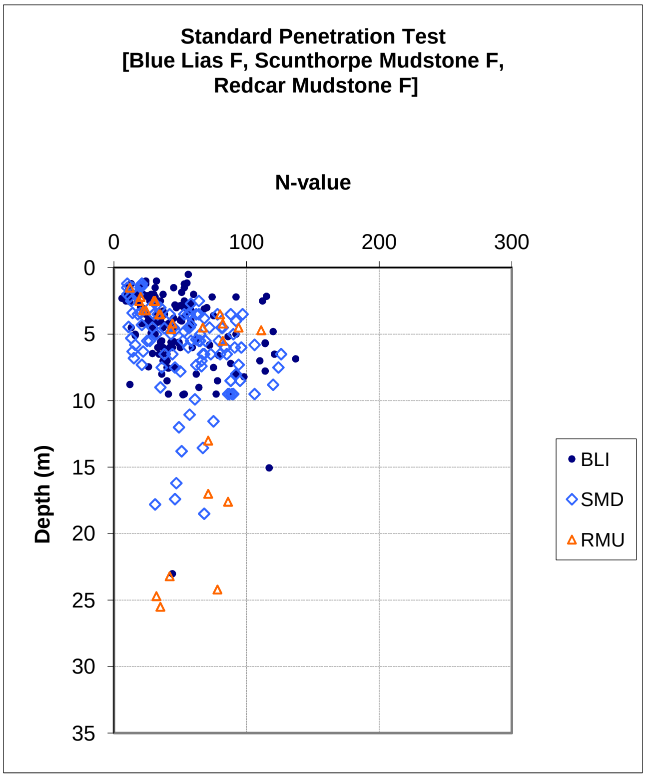


Figure 7.21 Plot of SPT 'N' value vs. Depth for mudstone formations

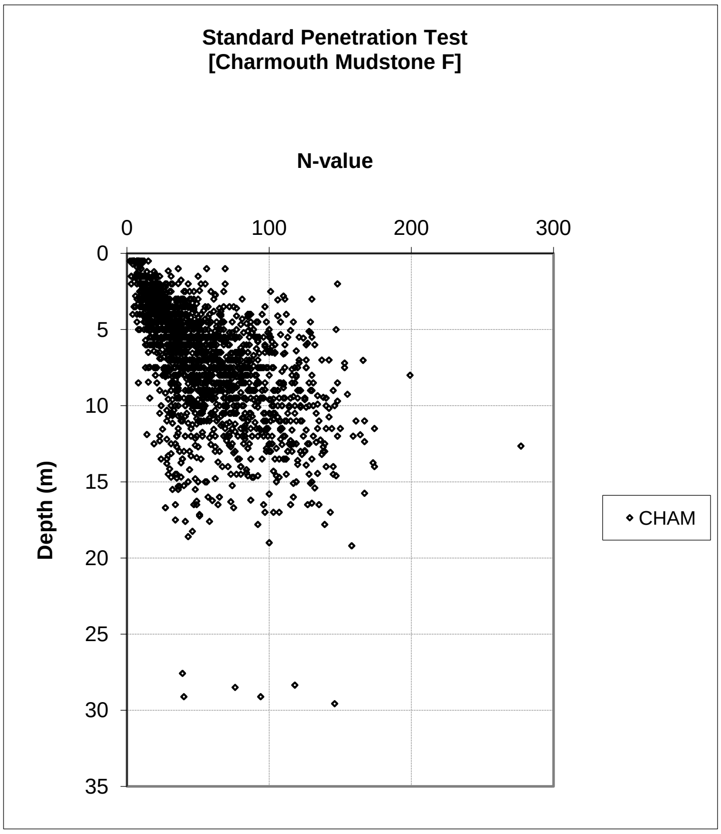


Figure 7.22 Plot of SPT ‘N’ value vs. Depth for mudstone formations (contd.)

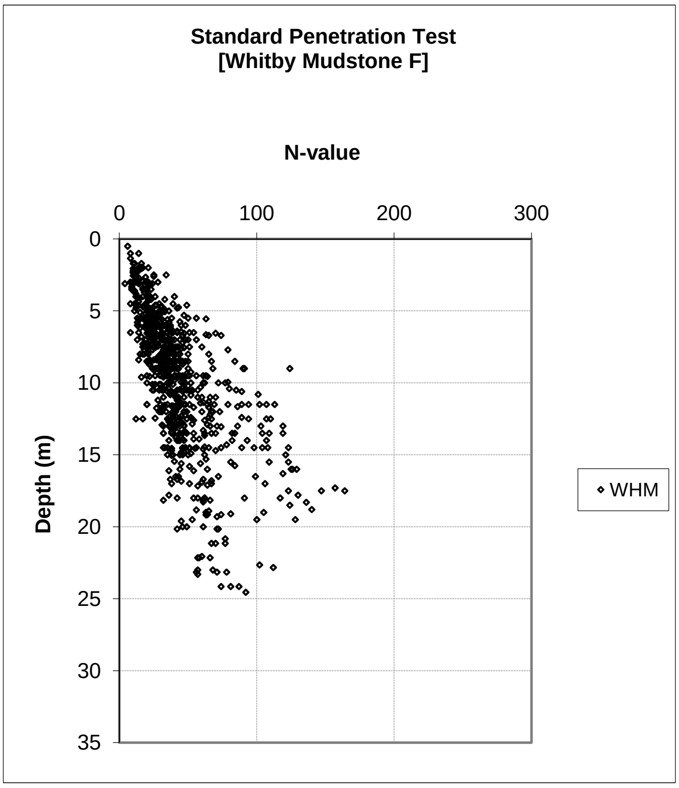


Figure 7.23 Plot of SPT ‘N’ value vs. Depth for mudstone formations (contd.)

7.3 DISCUSSION

Analysis of the Lias Group geotechnical data, described in Section 7.2, has revealed some trends in the properties and engineering behaviour of the principal formations. Data have been analysed by Formation and Member (where available), combined with correlation according to defined geographical Areas.

In terms of particle size, the Bridport Sand and Dyrham Formations are distinct from the other mudstone-dominant formations, having lower clay contents and higher silt and sand contents. In terms of Areas, the clay fraction data for Area 5 are notably lower (and notably skewed) compared with the other Areas represented. Area 2 has the highest clay content, with Areas 3 and 5 having displaying the highest silt contents. Compared to the formation clay contents, the sand and gravel data in all areas are also highly skewed (see Appendix C).

Variations in geotechnical properties analysed by *Area* usually result in north-south trends. For example, from north to south there are trends of decreasing density, increasing water content, increasing plasticity, and decreasing sulphate content. Whilst these variations are consistent, they are, overall, relatively minor in the case of density and water content.

Plasticity classifications range from ‘low’ to ‘extremely high’, although the great majority of data lie within the ‘intermediate’ and ‘high’ classes. As is the case with many clay-rich rocks and soils, the best-fit lines for the Casagrande plasticity chart are steeper than the A-Line, with the exception of the Scunthorpe Mudstone Formation, and their equations are reported. Plastic limits fall within a very narrow range. This means that plasticity index variations are largely caused by variations in liquid limit. The Scunthorpe Mudstone Formation has the lowest plasticity of the mudstones, while the remainder are very similar. Whilst Area 5 shares the lowest liquid limit median with Area 2, it has a skewed upper range of liquid limit compared with the other Areas. This is not repeated in the case of plastic limit. There is little variation in liquidity index across Areas.

The calculation of Skempton’s Activity (Ac), designed to highlight the relative influence of the clay mineral content on plasticity, revealed that the formations with the lowest clay-size fraction returned the highest activity. This may in part be due to the presence of smectite, but is probably also due to the inapplicability of the concept to clay-poor materials.

The majority of sulphate data fall within BRE classes 1 and 2. Plots of total sulphate content against depth show that there is a reduction below a depth of about 10m. This may be associated with the transition from the weathered to the unweathered state with increasing depth. The highest median total sulphate content was recorded for the Scunthorpe Mudstone Formation and for Area 3, although the Area differences are, overall, relatively small.

8 ENGINEERING GEOLOGY

8.1 GENERAL

The Lias Group consists of thick sequences of shallow marine deposits which have been subject to varying amounts of over-consolidation, cementation, and changes in clay mineralogy. This variability stems from the fact that the Lias Group was deposited in a series of geographically persistent subsiding basins. The Lias Group is dominated by mudstones and shaly mudstones, but with significant limestones and sandstones formed during shallowing of the sea and deltaic inputs, respectively. The dispositions and proportions of these lithologies vary between formations and across the country, and reflect changes between deep marine and deltaic environments throughout the Liassic period. However, the characteristically alternating sequences of mudstone and limestone usually result from cyclical patterns of deposition. The mudstones are variable in mineralogy, stress-history, and strength, but all weather at the near-surface to a clay-rich material, which is investigated by *soil* mechanics, rather than *rock* mechanics, methods. The result is that within the depth range of normal engineering operations, that is to about 20m below ground level, the engineering behaviour of the Lias Group is frequently found to be close to the borderline between soil and rock. This same depth zone is applicable to the majority of entries in the geotechnical database forming the basis of this report.

Typical proportions of limestone lithologies and overall thickness are shown in Table 8.1. These figures are very approximate.

Table 8.1 Typical percentages of limestone lithologies and overall thicknesses

Formation	Typical % limestone	Typical thickness (m)
Whitby Mudstone	<30	40 - 120
Marlstone Rock	>70	2 - 10
Dyrham	<10	40 - 125
Bridport Sand	<10	30 - 180
Charmouth Mudstone	<20	100 - 290
Scunthorpe Mudstone	<30	40 - 120
Blue Lias	20 - 50	40 - 150

Detailed lithological descriptions of the formations, their component members, and variation across the country, are contained in Chapter 2.

Whilst increasing age and burial depth tend to be accompanied by a decrease in water content, weathering tends to result in an increase in water content. Weathering also produces progressive breakdown in cementation, reduction in strength in addition to an increase in water content, and a general homogenisation of the material, except very near to the ground surface where variability is re-established. Weathering also tends to produce an increase in plasticity. Unfortunately, adequate description of weathering state is patchy within the database and could not be used as a variable in a comprehensive geotechnical analysis. Further detail relating to weathering is contained in Chapter 6.

8.2 FOUNDATIONS

8.2.1 Thaumasite attack

The high sulphate content of much of the Lias Group mudstones is responsible for high levels of thaumasite concrete attack reported within the last few years in the West Midlands. Typically, sulphate content varies with depth and weathering state. During construction of the M40 motorway in Oxfordshire, England, heave of the carriageway was caused when lime stabilisation of pyrite-bearing Charmouth Mudstone Formation (Lower Lias Clay) was attempted (Building Research Establishment, 1991). One end product of pyrite oxidation, resulting for example from weathering, is the mineral thaumasite. Buried concrete structures within Lias Group mudrocks are subject to thaumasite attack (TSA), particularly where saturated Lias-derived fill is in contact (Longworth, 2002), transforming the concrete into a weak paste. Clearly, this has serious consequences for the integrity of the concrete, and may result ultimately in failure. TSA was notable on bridge foundations where concrete contacted pyritic Lias Group clays and clay-fill on the M5 motorway in Gloucestershire (Floyd et al., 2002).

8.2.2 Shrink/swell

The uppermost few metres of outcropping geological formations are subject to seasonal water content variations. These are often exacerbated by the presence of trees and shrubs, and soakaways and fractured water pipes. In the case of clays, a decrease in water content causes shrinkage (an overall volume decrease) and an increase in water content causes swelling (an overall volume increase). These conditions are neither permanent nor exactly reversible, and may take years to develop due to the extremely low permeability of clays. Neither are they intrinsic properties of the soil or rock, but rather a response to prevailing environmental conditions. It is significant that the relationship between shrink/swell and water content is also non-linear. The shrink/swell phenomenon becomes particularly significant where shallow, light foundations are concerned. This applies to houses and especially old properties where foundation depths were generally shallower than modern structures and foundation design did not make allowance for the effects of shrink/swell processes.

Clays containing the clay mineral smectite are particularly prone to swelling and shrinkage. The smectite content of the Lias Group is variable (see Chapter 3), and whilst the Lias Group overall has a 'medium' volume change potential rating, and the component Formations also have a 'medium' rating, certain data samples within them contain smectite-rich layers which have a 'high' rating. Such samples are found within the Whitby Mudstone, Charmouth Mudstone and Blue Lias Formations, and within the Dyrham and Bridport Sands Formations.

8.3 ENGINEERED FILL AND LINERS

Engineered fill is suitable material that has been placed to an appropriate specification under controlled conditions (Charles, 1993). Key factors when assessing the Lias Group in terms of its use as engineered fill for construction purposes are strength, durability, excavatability, and compaction (Charles, 1993). A further consideration is the possibility of sulphate attack on concrete, as outlined in section 5.3.3.

Durability depends on mineralogy, porosity, cementation, and structure. Whilst older mudstones tend to be more durable, changes on exhumation and exposure to air can result in rapid breakdown and loss of durability (Cripps & Taylor, 1981).

The engineering properties of clay liners have been addressed by Murray (1998). In this case, the key parameter is the hydraulic conductivity of the material forming the barrier to advection or diffusion of contained liquids. Material selection and the method of placement both affect final hydraulic conductivity. Whilst low permeability is the aim, other properties such as shrink/swell and compaction behaviour must be considered. Thus a clay with 'extremely high' plasticity (e.g.

some Gault, London Clay, and Fuller's Earth Formation clays) may be deemed 'unsuitable' or 'marginal' based on factors other than its hydraulic conductivity. However, a plasticity index minimum is usually specified for a suitable clay, in addition to the requirement for a position above the Casagrande A-line (i.e. non-silt). Perhaps surprisingly, gravel contents of up to 30 % are permissible from the hydraulic conductivity standpoint. A hydraulic conductivity of 1×10^{-9} m/s is usually specified as the maximum acceptable following tests on the engineered liner material (Murray, 1998). Other tests for construction control include Compaction (Light and Heavy), Moisture Condition Value (MCV), and undrained shear strength.

As mentioned earlier, the post-placement volume change characteristics of a fill need to be considered (Charles, 1993). This is particularly true in the case of the Lias Group mudstones which contain varying amounts of pyrite, which oxidise on exposure and the products react with limestone (widely available within the Lias) to produce gypsum (section 5.3). Additionally, gypsum already exists in the form of selenite, particularly within discontinuities in the mudstone lithologies. Added to this the clay minerals within the mudstones themselves have the ability to change volume with water content change (section 5.2).

8.4 SLOPE STABILITY

The Lias Group rocks are on record as having the highest incidence of landsliding in the UK (Jones & Lee, 1994); the Upper Lias (Whitby Mudstone Formation) having as many as 42 landslides per 100 km^2 of outcrop. Whilst this database is almost certainly incomplete, and the size of the landslides is not taken into account in this statistic, it is nevertheless an indication of the importance of slope instability when considering the engineering of natural slopes in the Lias Group.

The principal regions and types of inland landslides within the Lias Group are:

- Avon – Somerset -Wiltshire (multiple rotational, cambering, debris slides)
- Cotswolds (multiple rotational, cambering, debris slides, mudslides)
- East Midlands plateau (cambering, rotational, mudslides, slab slides)
- North York Moors (multiple rotational, cambering, toppling, debris flows).

Engineering within, or adjacent to, a landslide or landslide complex requires certain precautions and procedures to be carried out. These cover methods of site investigation, slope stability assessment, remediation (in the event of landslide activity), and monitoring. Landslide complexes within the Lias Group may be extensive, and though ancient in origin, may become partially re-activated by engineering and building activity or by changes in climate and water regime. Identification of landslide prone areas at an early stage of an investigation is made possible using stereo air photos and, more recently, by analysis of digital terrain models (DEMs). Remediation of potentially active landslides almost always involves enhanced drainage, often in combination with other engineering measures such as retaining structures, slope re-profiling, and re-vegetation.

Analysis of slope stability requires the input of geotechnical parameters, in particular *strength* and *density,* or alternatively, where appropriate, a *rock mass rating* value. These are used to calculate and compare the 'driving' and 'resisting' forces within a 2-D or 3-D model of the landslide. Key parts of the model are the positions of the slip plane and the water table (or piezometric surfaces). Such information is usually obtained from a ground investigation involving boreholes, trial pits, and in some cases instrumentation or monitoring to indicate water pressures, ground movement, etc. However, frequently such information is unavailable and the model remains purely conceptual.

A detailed account of the occurrence of landslides in the Lias Group is given in section 5.1.

8.5 SITE INVESTIGATION

Routine site investigations carried out within the uppermost 5-10 m of the Lias Group are likely to utilise soil mechanics principles, that is, *soils-type* drilling, sampling, and laboratory testing, in order to characterise the materials in terms of engineering behaviour in accordance with British Standards BS5930 (1999) and BS1377 (1990). This is certainly reflected in the prevalence of this type of information in the geotechnical database on which this report is based. Within this zone, the Lias Group materials are usually in a weathered state. This tends to alter the geotechnical properties, compared with the unweathered state, for example by increasing plasticity, reducing strength, and increasing fissuring. Care should therefore be taken in extrapolating data obtained for less weathered material to highly weathered material (see Chapter 6).

An important part of the preliminary stage of a site investigation is the walk-over survey. This enables the local geology to be checked and for potential geohazards to be identified for further desk study, survey, or ground investigation. Seasonal ground conditions can also be assessed. Self-boring pressuremeters and self-boring permeameters are becoming increasingly popular in site investigations for large engineering projects such as dams, cofferdams and tunnels. Instruments combining deformation/stress with pore-pressure monitoring are now available. In some cases these may be used to monitor ground conditions after construction, in addition to before and during construction. Other parameters increasingly becoming the focus for field testing and monitoring are suction and thermal properties.

An important parameter with respect to the Lias Group is that of permeability anisotropy.

As is the case with many sedimentary clay-rich formations, horizontal permeability may be expected to be greater than vertical by a factor of about 2.

8.6 TUNNELLING

Information about tunnelling within the Lias Group is limited. Whilst there have been many tunnels excavated within the Lias Group, these have mainly been as part of the Victorian canal and railway networks, and little or no geotechnical information was obtained or retained. For example, the 2.85 km Blisworth Tunnel on the Grand Union Canal took 12 years to build (1793 – 1805) through Whitby Mudstone Formation and has been the subject of a re-alignment and much remedial work during its lifetime. Braunston Tunnel (1.85 km), north of Daventry, also on the Grand Union, was bored through Charmouth Mudstone Formation.

Modern projects involving tunnelling within the Lias Group include the proposed A417 re-alignment between Birdlip Hill and Crickley Hill, Gloucestershire (www.highways.gov.uk/roads) where a 2.8 km twin-bore tunnel has been proposed beneath a cambered and landslipped escarpment. The water-bearing properties of the Dyrham Formation and also the Bridport Sand Formation are important considerations for tunnelling. Artesian conditions may apply locally, particularly in landslipped terrain. In addition, the likelihood of mixed-ground working faces exposing clays, limestones, and sands, presents difficulties in the choice of tunnelling method. Such mixed ground conditions may be particularly variable and (in some cases) highly unpredictable in areas of cambering and deep-seated landslides.

The proportions of limestone to mudstone are an important consideration in the case of tunnelling in the Lias Group. This proportion varies from one formation to another and within formations. The Blue Lias Formation for example has a characteristic 50/50 to 60/40 ratio of mudstone to limestone for most of its thickness, a product of cyclic deposition processes. Each bed is typically 0.1 to 0.5 m in thickness, and is reasonably persistent laterally, except where faults have displaced them. Strong nodules of argillaceous limestone and ironstone are common within the Whitby Mudstone Formation. Strong cementstone nodules are found within the Dyrham Formation.

8.7 WEATHERING

The Lias Group mudrocks typically feature a high clay content, much of which consists of swelling clay minerals, and a laminated or shaly structure. These tend to produce high rates of breakdown on exposure, variation in water content, and stress relief fissures. In addition, chemical breakdown may occur very rapidly on exposure to air, and result in further mechanical breakdown. Where cementing agents strengthen the rock, breakdown may be gradual, but cycles of wetting and drying eventually produce failure. The development of tensile stresses due to desiccation and pore water suction also has a disruptive effect on mudrocks (Taylor, 1988). In the East Midlands, examples of periglacial freeze/thaw action have been described that have resulted in deformation structures and brecciation (Kovacevic et al., 2007). This has produced a weaker, more heterogeneous material compared with the un-brecciated source rock.

For the Lias rocks, a weathering classification scheme was developed, and the effects of weathering on strength assessed, by Chandler (1972). The current appropriate procedures for describing, and where possible classifying, weathering effects in variable mudrock sequences such as the Lias are described in British Standards BS5930 (1999). Further detail is contained in Chapter 6.

8.8 SUMMARY

A summary engineering geological assessment is shown in Table 8.2. This describes in general terms some key engineering geological factors affecting engineering behaviour. The bearing capacity column was derived from guidelines given in BS 8004, Foundations (British Standard: BS 8004, 1986). The diggability column was formulated using SPT, UCS and Point Load data, in addition to lithological description and case histories and the application of methods described in Pettifer & Fookes (1994) and Reeves et al., Chapter 11 (2006).

Table 8.2 Summary engineering geological assessment of the Lias Group

Formation	Main lithologies	Bearing capacity#	Plasticity	Shrink/swell potential	Slope stability (natural)	Diggability*	Trafficability	Concrete attack potential
Bridport Sand	Sand, sandstone, siltstone	Moderate	Intermed.	Low	Moderate-Poor	Medium	Good	Low
Blue Lias	Mudstone, limestone (+sandstone)	Moderate	High	Medium	Moderate	Medium to Hard, hard ripping	Good	Low
Charmouth Mudstone	Mudstone, limestone	Good	High	Medium	Poor	Medium to Hard, easy ripping	Moderate - Poor	High
Dyrham	Mudstone, ironstone, sandstone, siltstone	Moderate	Intermed.	Medium	Moderate	Medium	Moderate - Good	Medium
Redcar Mudstone	Mudstone, siltstone, limestone, sandstone	Moderate	High	Medium	Moderate	Medium to Hard, hard ripping	Moderate - Good	High?
Scunthorpe Mudstone	Mudstone, limestone	Very good	Intermed.	Medium	Good	Medium to Hard, hard ripping	Good	Medium
Whitby Mudstone	Mudstone, siltstone, limestone	Moderate	High	Medium	Moderate	Medium to Hard, easy ripping	Moderate	High

* refer to Pettifer & Fookes (1994), Reeves et al., Chapter 11 (2006); # refer to British Standards BS 8004 (1986).

References

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

Ackermann, K J and **Cave, R. 1967.** Superficial deposits and structures, including landslip, in the Stroud district, Gloucestershire. *Proceedings of the Geologists' Association*, Vol. 78, 567-586.

Ager, D V. 1956. Field meeting in the central Cotswolds. *Proceedings of the Geologists' Association*, Vol. 66, 356-365.

Ager, D V. 1969. Cotswolds and Vale of Gloucester. B27-B43 *in* TORRENS, H S (editor) *International Field Symposium on the British Jurassic*. Excursion No. 2 Guide for north Somerset and Gloucestershire. (Keele: Geology Department, Keele University).

Allison, R. and **Long, A. 1999.** Coast erosion project, Boulby Mine. Durham University *for: Cleveland Potash Ltd*.

Ambrose, K. 2001). The lithostratigraphy of the Blue Lias Formation (Late Rhaetian-Early Sinemurian) in the southern part of the English Midlands. *Proceedings of the Geologists' Association*. 112, pp97-110.

Anderson, F W and **Dunham, K C. 1966.** Geology of the Northern Skye. *Memoir of the British Geological Survey*, Scotland, explanation of sheets 80 and parts of 81, 90, 91. HMSO, Edinburgh.

Anderton, R., Bridges, P.H., Leeder, M. and Selwood, B.W. 1979. A Dynamic Stratigraphy of the British Isles: A Study in Crustal Evolution. *George Allen & Unwin Ltd*., London.

Anon 1995. The description and classification of weathered rocks for engineering purposes. *Geological Society, Engineering Group Working Party Report*.

Anon 1991b. Soil lime reaction causes M40 heave. *Ground Engineering*, Jan/Feb 1991, 8.

Anson, R. 1996. The study of an active landslide in the Swainswick Valley, North of Bath. P*hD Thesis, Bristol University, 46-14573*

Atherton, D. and **Burbidge, K. 2000.** Coastal protection in a proposed world heritage site. *In:* Landslides in Research, Theory, & Practice. *Thomas Telford*, London, Vol. 1, pp85-90.

Ballantyne, C.K. and **Harris, C. 1993).** The periglaciation of Great Britain. *Cambridge University Press*.

Barnard, C.E. and **Cooper, B.S. 1983.** A review of geochemical data related to the northwest European Gas Province. 19-33 in *Petroleum geochemistry and exploration of Europe*. BROOKS, J. (editor). Geological Society (London) and Blackwell Scientific Publishers, Oxford.

Benn, D. and **Ballantyne, C. 2000.** Classic landforms of Skye. *Geographical Association / British Geomorphological Research Group.*

Bensted, J. 1999. Thaumasite - background and nature in deterioration of cements, mortars and concretes. *Cement and Concrete Composites* 21 (2), 117-121.

Berridge N.G., Pattison J., Samuel, M.D.A., Brandon, A., Howard, A.S., Pharaoh, T.C. and **Riley, N. J. 1999.** Geology of the country around Grantham. *Memoir British Geological*

Survey. Sheet 127 (England and Wales).

Bessa, J.L. and Hesselbo, S.P. 1997. Gamma-ray character and correlation of the Lower Lias, SW Britain. *Proceedings of the Geologists' Association*, 108, 113-129.

Biczysko, S J. 1981. Relic landslip in west Northamptonshire. *Quarterly Journal Engineering Geology,* 14, pp.169-174

Bloodworth, A J, Kemp, S J, Inglethorpe, S D J and **Morgan, D J. 1987.** Mineralogy and lithochemistry of strata beneath proposed low-level radioactive waste site at Fulbeck, Lincolnshire; Report to Sir Alexander Gibb and Partners, Site Investigation Consultants. *British Geological Survey*, *Mineralogy and Petrology Technical* Report No 87/15/C.

Bloodworth, A.J., Cowley, J.F., Highley, D.E. and **Bowler, G.K. 2001.** Brick clay: Issues for planning. *British Geological Survey, Technical Report* No. WF/00/1R.

Borowczyk, M. and Szymanski, A. 1995. The use of in situ tests for determination of stress history. *Proceedings of the XI European Conference on Soil Mechanics and Foundation Engineering – The Interplay between Geotechnical Engineering and Engineering Geology*, Copenhagen. Vol. 1, pp17–22.

Brandon, A, Sumbler, M G and **Ivimey-Cook, H C. 1990.** A revised lithostratigraphy for the Lower and middle Lias (Lower Jurassic) east of Nottingham, England. *Proceedings of the Yorkshire Geological Society*, 48, 121-141.

Briggs, D/J. and **Courtney, F.M. 1972.** Ridge and trough topography in the North Cotswolds. *Proc. of the Cotteswold Naturalist Field Club*. Vol. 36, pp94-103.

Bristow, C R and **Westhead, R K. 1993.** Geology of the Evercreech - Batcombe district (Somerset). *British Geological Survey* Technical Report, WA/93/89.

British Standards: BS 5930. 1981; 1999. Code of practice for site investigations. *British Standards Institution*, BS 5930.

British Standards: BS 8004. 1986. Code of practice for foundations. *British Standards Institution*, BS 8004.

British Standards: BS 1377. 1990. Methods of test for soils for civil engineering purposes. British Standards Institution, BS 1377.

Brunsden, D. 1969. Moving cliffs of Black Ven. *Geographical Magazine*. Vol. 41, pp372-374.

Brunsden, D. and **Jones, D.K.C. 1976.** The evolution of landslide slopes in Dorset. *Phil. Trans. Roy. Soc*., London. Vol. A283, pp605-631.

Brunsden, D. and **Goudie, A.S. 1981.** Coastal landforms of Dorset. Classic Landform Guides. *British Geomorphological Research Group and Geographical Association.*

Brunsden, D. 2002. Geomorphological roulette for engineers and planners: some insights into an old game. The 5th Glossop Lecture. *Quarterly Journal Engineering Geology*, Vol. 35, Part 2, pp101-142

Building Research Establishment. 1991. Sulphate and acid resistance of concrete in the ground. Building Research Establishment, BRE Digest 363.

Building Research Establishment. 1993. Low-rise buildings on shrinkable clay soils. *Building Research Establishment*, BRE Digest 240.

Building Research Establishment. 1996. Sulphate and acid resistance of concrete in the ground. Building Research Establishment, BRE Digest 363.

Building Research Establishment. 2005. Concrete in aggressive ground. *Building Research Establishment*, BRE Special Digest 1.

Burkart, B., Goss, G.C. and **Kern, J.P. 1999.** The role of gypsum in production of sulfate-induced deformation of lime-stabilized soils. *Environmental and Engineering Geoscience,* 5 (2), 173-187.

Burland, J.B., Standing, J.R. and **Jardine, F.M. 2001.** Building response to tunnelling - case studies from construction of the Jubilee Line Extension, London. Volume 1: The project. Volume 2: Case studies *Construction Industry Research and Information Association (CIRIA) Report,* No. SP200.

Butler, P.B. 1983. Landsliding and other large scale mass movements on the escarpment of the Cotswold Hills. *BA Thesis (unpublished) Hertford College, Oxford.*

Callomon, J H and **Cope, J C W. 1995.** The Jurassic geology of Dorset. 51-103 in *Field Geology of the British Jurassic*. Taylor, P D (editor). (Bath: The Geological Society.)

Cameron, D.G., Bartlett, E.L., Coats, J.S., Highley, D.E., Lott, G.K., Flight, D., Hillier, J., and **Harrison, J. 2002.** Directory of Mines and Quarries, 6th ed., 2002 *British Geological Survey*. NERC

Caprez, M. and **Honold, P. 1995).** Moisture condition as a basis for compaction standard (MCV-Verdichtung). *Proceedings XI European Conference on Soil Mechanics & Foundation Engineering., ECSMFE* Copenhagen, 1995.

Carney, J.N., Ambrose, K., and **Brandon, A. 2002.** Geology of the Melton Mowbray district: a brief explanation of the geological map Sheet 142, Melton Mowbray. *British Geological Survey*. NERC.

Chadwick, R.A. and **Evans, C.J. 1995.** The timing and direction of Permo-Triassic extension in southern Britain. 161-192 in *Permian and Triassic rifting in Northwest Europe*. BOLDY, S A R. (editor). Geological Society Special Publication No. 91.

Chandler, R J. 1970. Solifluction on low-angled slopes in Northamptonshire. *Quarterly Journal Engineering Geology* 3 pp. 65-69.

Chandler, R J. 1972. Lias clay: weathering processes and their effect on shear strength.

Geotechnique, 22, 403-431.

Chandler, R. J., Kellaway, G. A., Skempton, A. W. and Wyatt, R. J. 1976. Valley slope sections in Jurassic strata near Bath, Somerset. *Philosophical Transactions of the Royal Society, London* A283, 527-556

Chandler, R.J. 2000. Clay sediments in depositional basins: the geotechnical cycle. The 3rd Glossop Lecture. *Quarterly Journal of Engineering Geology,* Vol. 33, Part 1, pp7-38.

Chapman, S. 1997. Wheels turning and smoke rising. Cleveland Ironstone Series. Vol. 1. Publ. *Peter Tuffs.*

Charles 1993. Building on fill: geotechnical aspects. *Building Research Establishment* Report BR230.

Clayton, C.R.I. 1995. The Standard Penetration Test (SPT): Methods and use. *Construction Industry Research and Information Association (CIRIA) Report,* No. 143.

Colter, V.S. and **Havard, D.J. 1981.** The Wytch Farm oilfield, Dorset. 494-503 in *Petroleum Geology of the Continental Shelf of NW Europe*. ILLING, L V and HOBSON, D G. (editors). Hayden & Sons, London.

Conway, B. W. 1974. The Black Ven landslip, Charmouth, Dorset. An example of the effect of a secondary reservoir of groundwater in an unstable area. *British Geological Survey* Report No. 7413.

Conway, B. W. 1976. Coastal terrain evaluation and slope stability of the Charmouth-Lyme Regis area of Dorset. *British Geological Survey*, Geophysical Division, Engineering Geology Unit Report No. EG76/10.

Cook, D. A. 1973. Investigation of a landslip in the fullers earth clay, Lansdown, Bath. *Quaternary Journal of Engineering Geology*. 6, 233:240.

Cosgrove, M.E. and Slater, D.L. 1966. The stratigraphical distribution of kaolinite in the post-Armorican formations of South-West England. *Proceedings of the Ussher Society*, 1, 5, 249-252.

Coulthard, J M and **Bell, F G. 1993.** The influence of weathering on the engineering behaviour of Lower Lias clay. *In:* "The engineering geology of weak rocks". Editors, J C Cripps, J M Coulthard, M G Culshaw, A Forster, S R Hencher and C F Moon. *Proceedings of the 26th annual conference of the Engineering Group of the Geological Society*, Leeds, 9-13 September 1990.

Cox, B.M., Sumbler, M.G., & Ivimey-Cook, H.C. 1999. A formational framework for the Lower Jurassic of England and Wales. (Onshore Area). *British Geological Survey*, Research Report No. RR/99/01.

Cripps, J.C. and **Taylor, R.K. 1981.** The engineering properties of mudrocks. *Quart. Journ. of Eng. Geol*., London, Vol. 14, pp325-346.

Cripps, J.C. and **Taylor, R.K. 1987.** Engineering characteristics of British over-consolidated clays and mudrocks, II. Mesozoic deposits. *Engineering Geology*, Vol. 23, pp213-253.

Cruden, D.M. and **Varnes, D. J. 1996.** Landslide types and processes. *In:* Turner A.K.; Shuster R.L. (eds) Landslides: Investigation and Mitigation. *Transp Res Board, Spec Rep* 247, pp 36-75.

Czerewko, M.A., Cripps, J.C., Reid, J.M., and **Duffell, C.G. 2003.** The effects of storage conditions on the sulphur speciation in geological material. *Quarterly Journal of Engineering Geology*, London. Vol. 36, Part 4, pp331-342.

Dixon, N. and **Bromhead, E.N. 2002.** Landsliding in London Clay coastal cliffs. *Quarterly Journal of Engineering Geology & Hydrology*, Vol. 35, pp327-343.

Donovan, D T. 1956. The zonal stratigraphy of the Blue Lias around Keynsham, Somerset. *Proceedings of the Geologists' Association*, Vol.66, 182-212.

Donovan, D T, Horton, A and **Ivimey-Cook, H C. 1979.** The transgression of the Lower Lias over the northern flank of the London Platform. *Journal of the Geological Society of London*, Vol. 136, 165-173.

Donovan, D T and **Kellaway, G A. 1984.** Geology of the Bristol district: the Lower Jurassic rocks. Memoir for the 1:63 360 Bristol geological special sheet. *British Geological Survey, HMSO, London.*

Duff, P. McL. D. and **Smith, A.J. (eds). 1992.** Geology of England and Wales. *Geological Society, London.*

Ebukanson, E.J. and **Kinghorn, R.R.F. 1986.** Maturity of organic matter in the Jurassic of southern England and its relation to the burial history of the sediments. *Journal of Petroleum Geology*, 9, 259-280

Floyd, M., Czerewko, M.A., Cripps, J.C., and **Spears, D.A. 2002.** Pyrite oxidation in Lower Lias Clay at Concrete highway structures affected by thaumasite, Gloucestershire, UK. *Proc. 1st Int. Conf. on Thaumasite in Cementitious Materials*. BRE, Garston, UK. June 2002.

Forster, A. 1992. The slope stability of the Lincolnshire limestone escarpment between Welbourne and Grantham. 1:50 000 Geological Map sheet 127*British Geological Survey* Technical Report WN/92/5

Forster, A., Culshaw, M.G., and **Bell, F.G. 1995.** Regional distribution of sulphate in rocks and soils of Britain. *In:* Eddleston, M., Walthall, S., Cripps, J.C., & Culshaw, M.G. (eds.) Engineering Geology of Construction. *Geol. Soc. Spec. Publ*. No. 10, pp95-104.

Foster, S.S.D., Morigi, A.N. and Browne, M.A.E. 1999. *Quaternary Geology – towards meeting user requirements*. British Geological Survey (Keyworth, Nottingham).

Fox-Strangways, C. 1892. The Jurassic rocks of Britain. Vols 1 and 2 Yorkshire. *Memoir of the Geological Survey of Great Britain.*

Gaunt, G D, Fletcher T P and **Wood, C J. 1992.** Geology of the country around Kingston upon Hull and Brigg. Memoir for the 1:50 000 geological sheets 80 and 89 (England and Wales). *British Geological Survey, HMSO, London*.

Geological Society. 1995. **Geological Society Engineering Group Working Party Report "The description and classification of weathered rocks for engineering purposes.**

George, T.N. 1974. The Cenozoic evolution of Wales. *In:* Owen, T.R. (ed.) The Upper Palaeozoic and post-Palaeozoic rocks of Wales. *Univ of Wales Press, Cardiff*, pp 323-340.

Gibson, A, D. 2005. Spectral Properties and Characterization of Debris from the Black Ven Landslide Complex, Dorset, England. *Unpublished PhD Thesis, University of Portsmouth*.

Gostelow, T.P. 1995. Some geological aspects of clay swelling and shrinkage. *British Geological Survey,* Technical Report No. WN/95/16.

Goudie, A. S. and **Parker, A. G. 1996.** The geomorphology of the Cotswolds. Cotteswolds Naturalists' Field Club

Gourvenec, S. M., Lacy, M., Powrie, W. and **Stevenson, M. 1996.** Observation of diaphragm wall movements in Lias Clay during construction of the A4/A46 Batheaston bypass. *Proc. ISSMGE, IS-TC 28 London, Balkema, pp 143-148.*

Hallam, A. 1955. The palaeontology and stratigraphy of the Marlstone Rock-bed in Leicestershire. *Transactions of the Leicester Literary and Philosophical Society. Vol. 49, 17-35.*

Hallam, A. 1960. A sedimentary and faunal study of the Blue Lias of Dorset and Glamorgan. *Philosophical Transactions of the Royal Society, London, Vol.B243, 698, 1-44.*

Hallam, A. 1968. The Lias. 188-210 in *The geology of the East Midlands*. Sylvester -Bradley, P C and Ford, T D (editors). (Leicester: Leicester University Press.)

Hallam, J. H. 1990. The statistical analysis and summarization of geotechnical databases. *British Geological Survey*, Technical Report No. WN/90/16.

Hardy, P. 1999. The geology of Somerset. *Ex Libris Press.*

Hawkins, A. B. 1977. The Hedgemead Landslip, Bath, Avon. Conference on Large Ground Movements and Structures. (ed. Geddes, D.) *Conference papers session V. University of Wales. Department of Civil Engineering and Building Technology*.

Hawkins, A B. and **Pinches, G M. 1987.** Cause and significance of heave at Llandough Hospital, Cardiff-a case history of ground floor heave due to gypsum growth. *Quarterly Journal of Engineering Geology* 20, pp. 41-57.

Hawkins, A B. and **Privett, K D. 1981.** A building site on cambered ground at Radstock, Avon. *Quarterly Journal of Engineering Geology* 14 pp.151-167.

Haydon, R.E.V. and **Hobbs, N.B. 1977.** The effect of uplift pressures on the performance of a heavy foundation on layered rock. *Proc. Conf. Rock Engineering*, Newcastle, pp457-472.

Head, K. H. 1992; 1998. Manual of Soil Laboratory Testing. (3 vols.) *Wiley*, 2nd Ed.

Hemingway, J.E. and Riddler, G.P. 1982. Basin inversion in North Yorkshire. *Transactions of the Institution of Mining & Metallurgy*, B91, 175-186.

Hesselbo, S P and **Jenkyns, H C. 1995.** A comparison of the Hettangian to Bajocian successions of Dorset and Yorkshire. 105-150 *In:* Field geology of the British Jurassic. Taylor, P D (editor). (*Bath: The Geological Society of London.*)

Highways Agency, Scottish Executive Development Department, The National Assembly for Wales and

The Department for Regional Development, Northern Ireland. 2001. Manual of contract documents for highway works: Volume 1. Specification for highway works 15 Volume 2. Notes for guidance on the specification for highway works. *The Stationery Office, London*.

Hobbs, P.R.N. 1974. Dynamic and static laboratory testing of Jurassic limestones from the Dorset coast. *B.Sc. Thesis, Middlesex Polytechnic*.

Hobbs, P.R.N. 1980. Slope stability studies in the Avon valley (Bath to Limpley Stoke). *BGS Report No. EG80/10.*

Hobbs, P.R.N. and **Jones, L.D. 1995.** The shrinkage and swelling behaviour of UK soils: Methods of testing for swelling and shrinkage of soils. *British Geological Survey*. Technical Report No. 95/15

Hobbs, P.R.N., Hallam, J.R., Forster, A., Entwisle, D.C., Jones, L.D., Cripps, A.C., Northmore, K.J., Self, S.J., and **Meakin, J.L. 1998.** Engineering geology of British rocks and soils: Mercia Mudstone (1998) by *BGS Technical Report* No.WN/98/4.

Hobbs, P.R.N., Jones, L.D., and **Freeborough, K. 2007.** Swell / shrink behaviour of UK rocks and soils: Lias Group. *British Geological Survey*, Technical Report No. IR/07/032.

Hobbs, D. W. and Taylor, M. G. 2000. Nature of the thaumasite sulfate attack mechanism in field concrete. *Cement and Concrete Research,* 30 (4), 529-533.

Holliday, D.W. 1999. Palaeotemperatures, thermal modelling and depth of burial studies in northern and eastern England. *Proceedings of the Yorkshire Geological Society*, 52 (4), 337-352.

Hollingworth, S.E., Taylor, J.H., and **Kellaway, G.A. 1944.** Large scale superficial structures in the Northampton Ironstone field. *Quarterly Journal of the Geological Society*. 99-100, pp1-44.

Hollingworth, S.E. and **Taylor, J.H. 1951.** The Northampton Sand ironstone, stratigraphy, structure, and reserves. *Memoirs of the Geological Survey of Britain. HMSO, London*.

Horswill, P. and **Horton, A. 1976.** Cambering and valley bulging in the Gwash Valley at Empingham, Rutland. *Phil. Trans. Roy. Soc*., London. Vol. A283, pp427-462.

Horton, A. and **Poole, E G. 1977.** The lithostratigraphy of three geophysical marker horizons in the Lower Lias of Oxfordshire. *Bulletin of the Geological Survey of Great Britain*, No. 62, 13-24.

Horton, A, Poole, E G Williams, B J, Illing, V C and **Hobson, G D. 1987.** Geology of the country around Chipping Norton. Memoir for the 1:50 000 geological sheet 218 (England and Wales). *British Geological Survey*. HMSO, London

Howard, A S. 1985. Lithostratigraphy of the Staithes Sandstone and Cleveland Ironstone formations (Lower Jurassic) of north-east Yorkshire. *Proceedings of the Yorkshire Geological*

Society, Vol.45, 261-275.

Howarth, M K. 1955. Domerian of the Yorkshire coast. *Proceedings of the Yorkshire Geological Society*, Vol.30, 147-175.

Howarth, M K. 1962. The Jet Rock Series and the Alum Shales Series of the Yorkshire coast. *Proceedings of the Yorkshire Geological Society*, Vol.33, 381-422.

Howarth, M K. 1973. The stratigraphy and ammonite fauna of the Upper Liassic Grey Shales of the Yorkshire coast. *Bulletin of the British Museum (Natural History), Geology Series*, Vol.29, 235-288.

Howarth, M K. 1980. Pliensbachian correlation chart. 48-53 *In:* A correlation of Jurassic rocks in the British Isles. Part One: Introduction and Lower Jurassic. *Special Report of the Geological Society London*, No. 14.

Howarth, M K. 1980b. Toarcian correlation chart. 53-59. *In:* A correlation of Jurassic rocks in the British Isles. Part One: Introduction and Lower Jurassic. Cope, J C W (editor). *Special report of the Geological Society London*, No. 14.

Howarth, M K. 1980c. The Toarcian age of the upper part of the Marlstone Rock Bed of England. *Palaeontology*, Vol. 23, 637-656.

Howarth, M K. 1992. The ammonite family Hildoceratidae in the Lower Jurassic of Britain. Part 1.

Monograph of the Palaeontographical Society London: 1 -106, pls 1-16. (Publ. No. 586, part of vol. 145 for 1991).

Humpage, A. J. 1996. Cambering and valley bulging in Great Britain – a review of distribution, mechanisms of formation, and implications for ground movement. *British Geological Survey*, Technical Report WA/96/104.

Hutchinson, J.N. 1988. General Report: Morphological & geotechnical parameters of landslides in relation to geology and hydrogeology. 3-35 in Landslides, Vol. 1, *Proc. 5th Symp. On Landslides, Lausanne*, July 1988. Bonnard, C. (ed.). Balkema, Rotterdam.

International Society for Rock Mechanics, ISRM. 1981. Rock Characterization Testing and Monitoring: ISRM Suggested Methods. E.T. Brown (ed.), *Published for the Commission on Testing Methods, International Society for Rock Mechanics*,. Pergamon Press.

International Society for Soil Mechanics and Foundation Engineering. 1988. International Reference Test Procedure. Proc. ISOPT-1 Standard Penetration Test (SPT*). International Society for Soil Mechanics and Foundation Engineering,* Vol. 1, pp3–26.

Jecock, M. 2003. The Alum Works and other industries at Kettleness, North Yorkshire: an archaeological and historical survey. *English Heritage, Archaeological Investigation Report Series* AI/24/2003 (ISSN 1478-7008).

Jones, D.C.K. and **Lee, E.M. 1994.** Landsliding in Great Britain. London *HMSO*, 361p.

Judd, J W. 1875. The geology of Rutland and parts of Lincoln, Leicester, Northampton, Huntingdon, and Cambridge. *Memoir of the Geological Survey. England and Wales.*

Jukes-Browne, A.J. 1908. The burning cliff and the landslip at Lyme Regis. *Proceedings of Dorset Natural History and Antiquarian Field Club* 29, 153-160. [by A.J. Jukes-Browne, F.G.S., read July 22nd, 1908. With 4 plates, including two photographs of the Lyme Volcano and one illustration of the Burning Cliff at Ringstead. With a map showing the exact location of the cliff fire, the burning mound.]

Kellaway, G A. 1960. 1: 10 560 Geological Sheet ST 67 SE. Geological Survey of Great Britain (England and Wales).

Kemp, S J. and **Hards. V L. 2000.** The mineralogy of Lower Jurassic (Lias) mudstones from the M5, Gloucestershire. *British Geological Survey* Technical Report WG/00/11

Kemp, S.J. and **McKervey, J.A. 2001.** The mineralogy of mudrocks from the Lias Group of England. *British Geological Survey* Internal Report, IR/01/124.

Kemp, S.J., Merriman, R.J., and **Bouch, J.E. 2005.** Clay mineral reaction progress – the maturity and burial history of the Lias Group of England and Wales. *Clay Minerals*, 40, pp43-61.

Knox, R W O'B. 1984. Lithostratigraphy and depositional history of the late Toarcian sequence at Ravenscar, Yorkshire. *Proceedings of the Yorkshire Geological Society*, 45, 90-108.

Kovacevic, N., Higgins, K.G., Potts, D.M., and **Vaughan, P.R. 2007.** Undrained behaviour of brecciated Upper Lias Clay at Empingham Dam. *Geotechnique*, 57, No. 2, pp181-195.

Lambe, T.W. and **Whitman, R.V. 1979.** Soil mechanics, SI version. *John Wiley & Sons*

Lamplaugh, G W, Gibson, W, Sherlock, R L and **Wright, W B. 1908.** Geology of the country between Newark and Nottingham. *Memoir for the British Geological Survey*, explanation of sheet 126 (England and Wales). HMSO, London.

Lang, W D. 1924. The Blue Lias of the Devon and Dorset coasts. *Proceedings of the Geologists' Association*, Vol.35, 169-185.

Lee, E.M. and **Clark, A.R. 2002.** Investigation and management of soft rock cliffs. *Department for Environment, Food, and Rural Affairs. Thomas Telford.*

Longworth, T.I. 2002. Contribution of construction activity to aggressive ground conditions causing the thaumasite form of sulphate attack to concrete in pyritic ground. *Proc. 1st Int. Conf. on Thaumasite in Cementitious Materials*. BRE, Garston, UK. June 2002.

Longworth T. I. 2004. Development of guidance on classification of sulphate-bearing ground for concrete. *Concrete*. Vol 38, No 2, February 2004, pp 25 –26.

Lupini, J.F., Skinner, A.E. and **Vaughan, P.R. 1981.** The drained residual strength of cohesive soils. *Geotechnique,* 31, 2, 181.

Merriman, R.J. and **Kemp, S.J. 1996.** Clay minerals and sedimentary basin maturity. *Mineralogical Society Bulletin*, **111**, 7-8.

Mitchell, C. J. 1992. Clay mineralogy of the Lias, Copperhill Quarry, Grantham. *British Geological Survey* Technical Report, WG/92/9.

Murray, E.J. 1998). Discussion on: 'Observations on soil permeability, moulding moisture content and dry density relationships' by Wright, S.P., Walden, P.J., Sangha, C.M., and Langdon, N.J. *Quaternary Journal of Engineering Geology*, 31, Part 1, pp73-74.

Nelder, L.M. and **Jones, L.D. 2004.** Determination of the swelling and shrinkage properties of the Lias Clay: Oedometer consolidation testing. *British Geological Survey*, Internal Report No. IR/04/137

Norwest Holst 1992). Ground investigation, Robin Hood's Bay access road for Yorkshire Water. (Consulting engineers: *Babtie Geotechnical*) Report No. RJR/TW/F9481, May 1992 [NGDC Acc. No; 35553]

Osborne, R. and Bowden, A. 2001. The Dinosaur Coast; Yorkshire rocks, reptiles, and landscape. *North York Moors National Park. Falcon Press.*

Parks, C.D. 1991. A review of the mechanisms of cambering and valley bulging. *In:* Forster, A., Culshaw, M.G., Cripps, J.C., Little, J.A., & Moon, C.F. (Eds.) *Quaternary Journal of Engineering Geology. Geological Society, Engineering Group Special Publication* No. 7, pp373-380.

Penn, S., Royce, C. J., and **Evans, C. J. 1983.** The Periglacial modification of the Lincoln Scarp *Quarterly Journal of Engineering Geology* 16 pp. 309-318

Pettifer, G.S. and **Fookes, P.G. 1994.** Memoirs of William Smith LLD, author of the Map of the Strata of England and Wales by his nephew & pupil John Phillips FRS, FGS. First published 1844. *Bath Royal Literary and Scientific Institute.*

Pitts, J. and **Brunsden, D. 1987.** A reconsideration of the Bindon Landslide of 1839. *Proceedings of the Geologists Association,* **98**, (1), 1-18.

Poole, E G, Williams, B J and **Hains, B A. 1968.** Geology of the country around Market Harborough. *Memoir of the Geological Survey of Great Britain*, explanation of sheet 170 (England and Wales). HMSO, London.

Pye, K and **Krinsley, D H. 1986.** Microfabric, mineralogy and early diagenetic history of the Whitby Mudstone Formation (Toarcian), Cleveland Basin, U.K.*Geological Magazine*, 123, 191-203.

Raines, M.R., Greenwood, P.G. and **Morgan, D.J. 1999.** Geophysical survey to investigate the internal structure of gulls in cambered strata in the North Cotswolds. *British Geological Survey*, Technical Report No. WK/99/13.

Ramli, M.F., Petley, D.N., Murphy, W., and **Inkpen, R.J. 2000.** The detection of relict landslides using airborne thematic mapper imagery. *In:* Landslides in Research, Theory, & Practice. *Thomas Telford*, London, Vol. 3, pp1269-1274.

Rayner, D.H. and **Hemingway, J.E. 1974.** The geology and mineral resources of Yorkshire. ix+405 pp. 79 figs, 24 tables. *Yorkshire Geological Society*. Leeds.

Reeves, G.M, Sims, I. and Cripps, J.C. (eds). 2006. Clay Materials Used in Construction. Geological Society, London, Engineering Geology Special Publication, 21.

Rowlands, K.A., Jones, L.D., and **Whitworth, M. 2003.** Landslide laser scanning: a new look at an old problem. *Quarterly Journal of Engineering Geology & Hydrogeology.* Vol. 36, Part 2, pp155-157.

Seedhouse, R.L. 1987. Lias clay slopes in the Evesham area: a general assessment of slope stability. M.Sc Thesis, Dept. of Geology, *Imperial College*, London.

Self, C.A. 1985. Two gull caves from the Wiltshire/Avon border *Proc. Univ. Bristol Spelaeol. Soc.*, 1985, 17(2), pp153-174.

Sellwood, M., Davis, G., Brunsden, D., and **Moore, R. 2000.** Ground models for the coastal landslides at Lyme Regis, Dorset, UK. *In:* Landslides in Research, Theory, & Practice. *Thomas Telford*, London, Vol. 3, pp1361-1366.

Skempton, A.W. 1953. The colloidal activity of clays. *Proc. 3rd. Int. Conf. on Soil Mechanics*. Vol. 1. pp57-61.

Smith, E.G. 1974. Constructional materials and miscellaneous mineral products, 361-371. *In:* The geology and mineral resources of Yorkshire. Rayner, D H and Hemingway, J E (editors). (*Leeds: Yorkshire Geological Society.*)

Smith, M.R (ed). 1999. Stone: building stone, rock fill and armourstone in construction. *Geological Society, London. Engineering Geology Special Publications*, 16.

Spink, T.W. and Norbury, D.R. 1993. The engineering geological description of weak rocks and overconsolidated soils. In: The engineering geology of weak rock, Engineering Geology Special Publication, 8, *Balkema*, Rotterdam.

Stroud, M.A. and Butler, F.J. 1975. The standard penetration test and the engineering properties of glacial materials. *Proc. Symp. on the Behaviour of Glacial Materials.* Univ. of Birmingham, pp124-135.

Stroud, M.A. 1989. The standard penetration test – its application and interpretation. pp 29–49 *In: Proceedings of the Symposium on Penetration Testing in the UK*. University of Birmingham. (London: Thomas Telford.)

Sumbler, M G, Barron, A J M, and Morigi, A N. 2000. Geology of the Cirencester district. *Memoir of the British Geological Survey*, Sheet 235 (England and Wales).

Sutherland, D. and Sharman, G. 1996. Radon – in Northamptonshire? *Geology Today, 12 (2), pp63-67.*

Taylor, R.K. 1988. Coal Measures mudrocks: composition, classification and weathering processes. *Quarterly Journal of Engineering Geology,* 21, 85-99.

Tonks, E.S. 1988. The ironstone quarries of the Midlands: history, operation and railways. Part 1: Introduction. *Runpast Publishing*, Cheltenham

Torrens, H S and **Getty, T A. 1980.** The base of the Jurassic System. Special Report of the Geological Society of London, No.14, 17-22.

Tuffs, P. 1999. Catalogue of Cleveland ironstone mines. Cleveland Ironstone Series. Industrial Archaeology of Cleveland. *Publ: P. Tuffs.*

Van Buchem, F S P, Melnyk, D H and **McCave, I N. 1992.** Chemical cyclicity and correlation of Lower Lias mudstones using gamma ray logs, Yorkshire, UK. *Journal of the Geological Society*, London, 149, 991-1002

Varnes, D. J. 1978. Slope movement types and processes. In: Schuster R. L. & Krizek R. J. Ed., Landslides, analysis and control. Transportation Research Board Special. Report. No. 176, National. Academy. of Sciences, pp. 11-33, 1978.

Vaughan, P.R. 1976. The deformations of the Empingham Valley slope. Appendix to: Horswill & Horton, 1976.

Voight, B. 1973. Correlation between Atterberg plasticity limits and residual strength of natural soils: *Geotechnique*, v. 23, p. 265-267.

Warrington, G and **Ivimey-Cook, H C. 1995.** The Late Triassic and Early Jurassic of coastal sections in West Somerset and South and Mid-Glamorgan. pp9-30 *In:* Field Geology of the British Jurassic. Taylor, P D (editor). (Bath: *The Geological Society.)*

Waters, R A and **Lawrence, D J D. 1987.** Geology of the South Wales Coalfield, Part III, the country around Cardiff. Memoir for the 1:50 000 geological sheet 263 (England and Wales). *British Geological Survey, HMSO, London*.

Wesley, L.D. 2003. Residual strength of clays and correlations using Atterberg limits. *Geotechnique*, 53, No. 7, pp669-672.

West, I.M. 2003. Burning Beach, Burning Cliffs and the Lyme Volcano: Oil-Shale Fires; Geology of the Dorset Coast. Internet site: www.soton.ac.uk/~imw/kimfire.htm. *School of Ocean and Earth Sciences, Southampton University, UK*. Version: H21.09.03.

Whittaker, A and **Green, G W. 1983.** Geology of the country around Weston-super-Mare. Memoir for the 1:50 000 geological sheet 279, New Series, with parts of sheets 262 and 295 (England and Wales). *British Geological Survey*, HMSO, London.

Whittaker, A, Holliday, D W and **Penn, I E. 1985.** Geophysical logs in British stratigraphy. *Special Report of the Geological Society of London*, No.18.

Whitworth, M., Giles, D., and **Murphy, W. 2003.** Landslides of the Cotswold Escarpment, Broadway, Worcestershire UK. *Proc. Cotteswold Naturalists Field Club*. XLII (II).pp118-127.

Williams, A.A.B. and **Donaldson, G.W. 1980.** Building on expansive soils in South Africa, 1973-1980. *Proc. 4th Int. Conf. on Expansive Soils*, ASCE, Denver, Vol. 2, pp834-844.

Williams, A.T., Davies, P. and **Bomboe, P. 1993.** Geometrical simulation studies of coastal cliff failures in Liassic strata, South Wales, UK. *Earth Surface Processes & Landforms*, 18(8) 1993, pp703-720.

Wilson, D, Davies, J R, Fletcher, C J N and **Smith, M. 1990.** Geology of the South Wales Coalfield, Part VI, the country around Bridgend. Memoir for the 1:50 000 geological sheets 261 and 262 (England and Wales). *British Geological Survey*, HMSO, London.

Wilson, V, Welch F B A, Robbie, J A and **Green, G W. 1958.** Geology of the country around Bridport and Yeovil. *Memoir of the Geological Survey of Great Britain*, explanation of sheets 327and 312 (England and Wales). *HMSO, London*.

Woodland, A W (Ed.) 1971. The Llanbedr (Mochras Farm) Borehole. *Report of the Institute of Geological Sciences*, No. 71/18.

Woodward, H B. 1893. The Jurassic rocks of Britain. Vol.3. The Lias of England and Wales (Yorkshire excepted). *Memoir of the Geological Survey of the United Kingdom.*

Woodward, H.B. and **Ussher, W.A.E. 1911.** Geology of the country near Sidmouth and Lyme Regis. (Explanation of sheets 326 and 340). *British Geological Survey Memoir*, 2nd ed.

Appendix

A1 Abbreviations

A2 Glossary

B Extended box & whisker plots by Formation

C Extended box & whisker plots by Area

D1 Weathering classes

D2 Extended box & whisker plots by weathering class

D3 Depth profiles by weathering class

D4 Summary shrink-swell data by Formation

APPENDIX A1

Abbreviations

Formation abbreviations for geotechnical data

BDS	Bridport Sand Formation
BLI	Blue Lias Formation
BNLS	Beacon Limestone Formation
CDI	Cleveland Ironstone Formation
CHAM	Charmouth Mudstone Formation
DYS	Dyrham Formation
MRB	Marlstone Rock Formation
RMU	Redcar Mudstone Formation
SMD	Scunthorpe Mudstone Formation
WHM	Whitby Mudstone Formation

Glossary of geotechnical abbreviations & units

Parameter	*Main*	*Alternative(s)*	*Units*
Liquid limit	w_L	LL	%
Plastic limit	w_P	PL	%
Plasticity index	I_P	PI	%
Modified Plasticity index	I_P'		%
Liquidity index	I_L	LI	-
Bulk density	g_b	BD	Mg/m^3
Dry density	g_d	DD	Mg/m^3
Particle density	g_p	PD	Mg/m^3
Natural water content	w	NWC, NMC	%
Voids ratio	e		-
Clay-size fraction	%CLAY	CLAY	%
Silt-size fraction	%SILT	SILT	%
Sand-size fraction	%SAND	SAND	%
Gravel-size fraction	%GRAVEL	GRAVEL	%
Activity	A_C		-
Linear shrinkage	LS		%
Total sulphate	SO_4 (tot)	T.Sul.	%
Aqueous sulphate	SO_4 (aq)	A.Sul.	g/l
Sulphate in groundwater	SO_4 (w)	W.Sul.	%
Acidity	pH	PH	-
Organic content	ORG		%
Carbonate content	CARB		%
Acid soluble Chloride	CHL (as)		%
Water soluble chloride	CHL (ws)		%
Moisture Condition Value	MCV		%
Maximum Dry density	MDD		Mg/m^3
Optimum Water Content	OWC	OMC	%
California Bearing Ratio	CBR		%
Permeability	k		m/s
Coefficient of volume compressibility	m_V		m^2/MN
Coefficient of consolidation	c_V		m^2/yr
Compression index	C_C		-
Swelling index	Ce		-

Glossary of geotechnical abbreviations & units (contd.)

Parameter	*Main*	*Alternative*	*Units*
Triaxial	TX	TRIAX	
Shear-box	SH-BX	SHB	
Triaxial - Total cohesion	c_u	TX-Cu	kPa
Triaxial - Effective cohesion	c'	TX-C	kPa
Triaxial - Effective friction angle	ϕ'	TX-PHI	degrees
Shear box - Peak cohesion	c_p	SHB-Cpeak	kPa
Shear box - Residual cohesion	c_r	SHB-Cresid	kPa
Shear box - Peak friction angle	ϕ'_p	SHB-PHIpeak	degrees
Shear box - Residual friction angle	ϕ'_r	SHB - PHIresid	degrees
Standard Penetration Test	SPT		N, blows/300mm pen.
Uniaxial compressive strength	UCS		MPa
Young's modulus	E		MPa
Poisson's ratio	ν		-
Sonic velocity (P-wave)	v_p	Vel (p)	m/s
Sonic velocity (S-wave)	v_s	Vel (s)	m/s
Point load index	I_{S50}	PT-LOAD	-

APPENDIX A2

Glossary

APPENDIX A2

Glossary of terms

(Refer to Appendix A1 for abbreviations and units)

ALUM A potassium aluminium sulphate.

ARGILLACEOUS Containing clay. Typically applied to fine-grained sedimentary rocks composed of clay and silt-sized particles.

ATTERBERG LIMITS Consistency criteria for defining key water contents of a clay soil. They are: liquid limit, plastic limit and shrinkage limit.

BASIN A geological depression containing significant thicknesses of sediment, or in which sediment is able to accumulate. Frequently circular or elliptical in plan.

BEARING CAPACITY The ability of a material to support an applied load. Ultimate bearing capacity is the pressure at which shear failure of the supporting soil immediately below and adjacent to a foundation. A foundation is usually designed with a working load that is some proportion of the bearing capacity.

BED. The smallest stratigraphic unit.

BEDDING The arrangement of sedimentary rocks in beds or layers of varying thickness or character.

BEDROCK. Unweathered rock beneath a cover of soil or superficial deposits.

BERTHIERINE A green iron ore.

CALCAREOUS Carbonate-rich.

CALCITE. The crystalline form of calcium carbonate, $CaCO_3$.

CAMBERING The process whereby a brittle caprock is undermined by the lateral stress relief displacement of a weaker substrate, resulting in cantilever stresses, development of gulls, and ultimately downslope movement. Often associated with periglacial conditions.

CLAY A naturally occurring material which is a plastic material at natural water content and hardens when dried to form a brittle material. It is the only type of soil/rock susceptible to significant shrinkage and swelling. It is made up mainly, but not exclusively, of clay minerals. It is defined by its particle-size range (< 0.002 mm). Clay does not have to be the dominant component of a soil in order to impart clay-like properties to it.

CLAY MINERALS A group of minerals with a layer lattice structure which occur as minute platy or fibrous crystals. These tend to have a very large surface area compared with other minerals, thus giving clays their plastic nature and the ability to support large suction forces. They have the ability to take up and retain water and to undergo base exchange.

CLAYSTONE A fine-grained sedimentary rock composed of predominately clay sized particles.

COEFFICIENT OF CONSOLIDATION A measure of the rate at which consolidation takes place.

COEFFICIENT OF VOLUME COMPRESSIBILITY A measure of the amount of compression that takes place during consolidation, measured as a change in dimension per log interval of applied stress.

COHESION Attractive force between soil particles (clay) involving a complex association of solid and water. Specifically, the shear strength of a soil at zero normal stress.

COHESIVE SOIL. A soil in which particles adhere after wetting and subsequent drying and significant force is required to crumble the soil.

COMPACTION The reduction of voids (densification) of a soil mass by engineering action to produce a more stable, stronger material.

COMPRESSION INDEX The slope of the normal consolidation line with respect to the change in voids ratio over a log cycle of applied stress.

CONSOLIDATION. The process in which pore water drains from a material under an applied load with a consequent reduction in volume of the material (see subsidence).

DENSITY The mass of a unit volume of a material. Often used (incorrectly) as synonym for Unit weight. Usually qualified by condition of sample (e.g. saturated, dry).

DIACHRONOUS A lithostratigraphic unit that varies in age.

DIAMICT / DIAMICTON Sediment (usually glacial) containing wide range of particle types and sizes.

DIGGABILITY Measure of the ability for an excavation to be made in a material by a mechanical digger.

DIP The inclination of a planar surface from horizontal. Usually applied to bedding planes.

DISCONTINUITY Any break in the continuum of a rock mass (e.g. faults, joints).

DOGGER Flattened calcareous or ferruginous concretion in a clay or sand deposit. Often stronger than the remainder of the deposit.

DRAINED Condition applied to strength tests where pore fluid is allowed to escape under an applied load. This enables an effective stress condition to develop.

DRIFT Archaic synonym for 'superficial' geological deposits; i.e. those overlying bedrock.

EFFECTIVE STRESS The total stress minus pore pressure. The stress transferred across the solid matter within a rock or soil.

ELASTICITY Deformation where strain is proportional to stress, and is recoverable.

EXCAVATABILITY A measure of the ability for an excavation to be made in a material by earth-moving equipment such as backacters, face shovels, scrapers, bulldozers etc. using digging, ripping and blasting as the difficulty of removing material increases.

EXPOSURE A visible part of an outcrop that is unobscured by soil or other materials.

FAULTING The displacement of blocks of strata relative to each other along planar fractures. Movement may take place in several ways, depending on the direction of the compressive or extensional forces acting on the rock mass forming normal, reverse or strike slip faults.

FAULTS Planes in the rock mass on which adjacent blocks of rock have moved relative to each other. The relative vertical displacement is termed 'throw'. The faults may be discrete single planes but commonly consist of zones, perhaps up to several tens of metres wide, containing several fractures which have each accommodated some of the total movement. The portrayal of such faults as a single line on the geological map is therefore a generalization.

FERRUGINOUS. Iron-rich. Applied to rocks or soils having a detectable iron content.

FILL. Material used to make engineered earthworks such as embankments and capable of acquiring the necessary engineering properties during placement and compaction.

FISSILITY The ability of a rock (e.g. Mudstone) to be broken along closely spaced parallel planes (e.g. Shale).

FLUVIAL/FLUVIATILE Of, or pertaining to, rivers.

FORMATION The basic unit of subdivision of geological strata, and comprises strata with common, distinctive, mappable geological characteristics.

GLACIAL Of, or relating to, the presence of ice or glaciers; formed as a result of glaciation.

GRADING A synonym (engineering) for particle-size analysis (see also Sorting).

GROUNDWATER Water contained in saturated soil or rock below the water-table.

GROUP A stratigraphical unit usually comprising one or more formations with similar or linking characteristics.

GULLS Tension fissures produced in a brittle caprock by cambering. Gulls may not be visible at the surface. This may be due to bridging, that is, they may not extend to the ground surface or to infilling with superficial material.

GYPSUM Mineral consisting of hydrous calcium sulphate ($CaSO_4.2H_20$), common in weathered mudstone where it is formed by the breakdown of sulphide minerals in the presence of lime-rich groundwater.

HEAD A deposit comprising material derived, transported and deposited by solifluction in periglacial regions. May include material derived also by hillwash, creep and other non-glacial slope processes. Composition is very variable and dependent on source material. Thickness is also very variable.

HOLOCENE The most recent subdivision of geologic time (RECENT) which represents the last 10,000 years.

HYDRAULIC CONTINUITY Juxtaposition of two or more permeable deposits or rock units such that fluids may pass easily from one to another.

ILLITE A 2:1 clay mineral, common in sedimentary rocks, not noted for susceptibility to shrink/swell behaviour.

INDEX TESTS Simple geotechnical laboratory tests which characterise the properties of soil (usually) in a remoulded, homogeneous form, as distinct from ‘mechanical properties’ which are specific to the conditions applied.

IRONPAN Hard layer formed by re-precipitation of iron compounds leached from overlying deposits.

JOINT A surface of fracture or parting in a rock, without displacement; commonly planar and part of a set.

JURASSIC The middle period of the Mesozoic (208.0 to 145.6 Ma.).

KAOLIN A group of 2 layer, 1:1 structure clay minerals usually of low plasticity (e.g. kaolinite). The most common clay mineral.

LANDSLIDE A down slope displacement of bedrock or superficial deposits subject to gravity, over one or more shear failure surfaces. Landslides have many types and scales. Landslides may be considered both as ‘events’ and as geological deposits. Synonym of ‘landslip’.

LIGNITE Soft, brown-black earthy type of coal.

LINEAR SHRINKAGE The percentage length reduction of a prism of remoulded clay subjected to oven drying at 105^{o} C.

LITHOLOGY The characteristics of a rock such as colour, grain size and mineralogy. The material constituting a rock.

LITHOSTRATIGRAPHIC UNIT A rock unit defined in terms of lithology and not fossil content (Biostratigraphic unit).

LIQUID LIMIT The moisture content at the point between the liquid and the plastic state of a clay. An Atterberg limit.

LOWER LIAS Equivalent to those deposits corresponding broadly with the Redcar Mudstone Formation of the Cleveland Basin, and Scunthorpe Mudstone/Blue Lias Formation plus Charmouth Mudstone Formation elsewhere.

MARL A calcareous mudstone, sensu-strictu having > 30 % carbonate content.

MASSIVE Applied to a rock mass containing no visible internal structure.

MEDIAN The 50th percentile of a distribution; that is, the value above and below which 50 % of the distribution lies.

MEMBER A distinctive, defined unit of strata within a formation characterised by relatively few and distinctive rock types and associations (for example, sandstones, marls, coal seams).

MICACEOUS Containing mica, a sheet silica mineral.

MIDDLE LIAS Corresponds broadly to the Staithes Sandstone plus Cleveland Ironstone formations in the Cleveland Bsin, and Dyrham plus Marlstone Rock formations elsewhere.

MINERAL A naturally occurring chemical compound (or element) with a crystalline structure and a composition which may be defined as a single ratio of elements or a ratio which varies within defined end members.

MOISTURE CONDITION VALUE (MCV) Test to determine suitability of soil as compacted fill. The test measures the minimum compactive effort required to produce a state of near-full compaction.

MOISTURE CONTENT See Water content.

MUDROCK A term used by engineers, synonymous with mudstone.

MUDSTONE A fine-grained, non-fissile, sedimentary rock composed of predominately clay and silt-sized particles.

NATURAL WATER CONTENT The water content of a geological or engineering material in its natural or ‘as found’ state.

NORMALLY CONSOLIDATED (NC) A deposit, such as clay, that is compacted by exactly the amount to be expected from the pressure exerted by the overburden. This deposit has never been subject to an overburden greater than its present overburden.

OCHREOUS Containing hydrated iron oxides, usually reddish or orange in colour.

OEDOMETER Laboratory apparatus for measuring consolidation properties of a soil.

OOLITE Rock (limestone) consisting of, or containing, carbonate or iron-coated grains (ooids)

OUTCROP The area over which a particular rock unit occurs at the surface.

OUTLIER. A deposit or an outcrop of rock surrounded by the outcrops of older deposits or rocks and separated from the main body by erosion.

OVERBURDEN Material, or stress applied by material, overlying a particular stratum. Unwanted material requiring removal (quarrying).

OVER-CONSOLIDATED (OC) Deposit, such as clay, that in previous geological times was loaded more heavily than now and consequently has a tendency to expand if it has access to water and is subject to progressive shear failure. The moisture content is less than that for an equivalent material which has been normally consolidated.

PARTICLE-SIZE ANALYSIS (PSA) The measurement of the range of sizes of particles in a dis-aggregated soil sample. The tests follow standard procedures with sieves being used for coarser sizes and various sedimentation, laser or X-ray methods for the finer sizes usually contained within a suspension.

PARTICLE-SIZE DISTRIBUTION (PSD) The result of a particle-size analysis. It is shown as a ‘grading’ curve, usually in terms of % by weight passing particular sizes. The terms ‘clay’, ‘silt’, ‘sand’ and ‘gravel’ are defined by their particle sizes.

PERCHED GROUND WATER Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

PERIGLACIAL An environment beyond the periphery of an ice sheet influenced by severe cold, where permafrost and freeze-thaw conditions are widespread. Fossil periglacial features may persist to the present day or may have been removed by subsequent glaciation or erosion.

PERMEABILITY The property or capacity of a rock, sediment or soil for transmitting a fluid; frequently used as a synonym for ‘hydraulic conductivity’ (engineering). The property may be measured in the field or in the laboratory using various direct or indirect methods.

PERMAFROST Permanently frozen ground, may be continuous (never thaws), discontinuous (with unfrozen patches, especially in summer) or sporadic (unfrozen areas exceed frozen areas). The surface layer subject to seasonal thaw is the ‘active layer’.

pH Measure of acidity/alkalinity on a scale of 1 to 14 (< 7 is acid, > 7 is alkaline).

PLASTICITY INDEX The difference between the liquid and plastic limits. It shows the range of water contents for which the clay can be said to behave plastically. It is often used as a guide to shrink/swell behaviour, compressibility, strength and other geotechnical properties.

PLASTIC LIMIT The water content at the lower limit of the plastic state of a clay. It is the minimum water content at which a soil can be rolled into a thread 3mm in diameter without crumbling. The plastic limit is an Atterberg limit.

PLEISTOCENE The first epoch of the Quaternary Period prior to the Holocene from about 2 million years to 10.000 years ago.

POINT LOAD A simple test to determine the strength of a strong rock, the result of which is a Point Load Index (Is). It may be used on drill core or random lumps.

POISSON’S RATIO The ratio of the strain parallel to an applied stress to that perpendicular to it [rock mechanics]

PORES The microscopic voids within a soil or rock.. The non-solid component of a soil or rock.. May be filled with liquid or gas.

PORE PRESSURE The pressure of the water (or air) in the pore spaces of a soil or rock. It equals total stress minus effective stress. The pore pressure may be negative.

PYRITE The most widespread sulphide mineral, FeS_2 (iron pyrites).

QUARTZ The most common silica mineral (SiO_2).

QUARTZITE. A sandstone composed (almost) entirely of cemented quartz (silica) grains.

QUATERNARY A sub-era that covers the time from the end of the Tertiary to the present, approximately the last 2.0 Ma, and includes the Pleistocene and Holocene.

RESIDUAL SHEAR STRENGTH The strength along a shear surface (clay) which has previously failed or has undergone significant displacement. Generally the minimum shear strength. Tends to be constant for a given soil.

ROCKHEAD The upper surface of bedrock at surface (or its position) or below a cover of superficial deposits.

RUNNING SAND Fluidisation of sand and flow into an excavation below the water table or into a perched water table, under the influence of water flow into an excavation.

SAND A soil with a particle-size range 0.06 to 2.0 mm. Typically consists of quartz particles in a loose state.

SANDSTONE Sandstones are clastic rocks of mainly sand-sized particles (0.06 - 2.0mm diameter), generally with quartz being the dominant component. Sandstones exhibit some form of cementation.

SATURATION The extent to which the pores within a soil or rock are filled with water (or other liquid).

SEDIMENTARY ROCKS Rocks which formed from sediments deposited under the action of gravity through a fluid medium and were subsequently lithified. Commonly: mudstone, siltstone, sandstone and conglomerate.

SETTLEMENT The lowering of the ground surface due to an applied load (see consolidation).

SHALE A fissile mudstone.

SHEAR PLANES/SURFACES A series of closely spaced, parallel surfaces along which differential movement has taken place. Usually associated with landslides or stress-relief. May be polished (slickensides).

SHEAR STRENGTH The maximum stress that a soil or rock can withstand before failing catastrophically or being subject to large unrecoverable deformations.

SHRINKAGE The volume reduction of a clay (or clay-rich soil or rock) resulting from reduction of water content. Shrinkage may cause subsidence of shallow foundations.

SHRINKAGE LIMIT The water content below which little or no further volume decrease occurs during drying of a clay (or clay-rich soil or rock). The laboratory tests which measure shrinkage limit have largely fallen into disuse in the UK. An Atterberg limit.

SIDERITE Carbonate mineral of iron ($FeCO_3$).

SILT A soil with a particle-size range 0.002 to 0.06 mm (between clay and sand).

SILTSTONE A sedimentary rock intermediate in grain size between sandstone and mudstone.

SLAKE DURABILITY A measure of the ability of a rock to resist degradation by the combined action of wetting/drying cycles and mechanical abrasion.

SLICKENSIDES See shear planes.

SMECTITE A group of 2:1 clay minerals noted for their high plasticity and susceptibility to shrink/swell behaviour (e.g. montmorillonite).

SOLID A term used in geology to indicate mappable bedrock (see also Superficial).

SOLIFLUCTION The slow, viscous, down slope flow of waterlogged surface material, especially over frozen ground.

SORTING A descriptive term to express the range and distribution of particle sizes in a sediment or sedimentary rock, which has implications regarding the environment of deposition. Well-sorted (=poorly graded of engineering geology terminology) indicates a small range of particle sizes, poorly sorted (=well-graded) indicates a larger range.

STANDARD PENETRATION TEST (SPT) A long-established in-situ test for soil where the number of blows (N) with a standard weight falling through a standard distance to drive a standard cone or sample tube a set distance is counted. Used as an indication of lithology and bearing capacity of a soil.

STIFFNESS The ability of a material to resist deformation.

STRAIN A measure of deformation resulting from application of stress.

STRATIGRAPHY The study of the sequence of deposition of rock units through time and space.

STRESS The force per unit area to which it is applied. Frequently used as synonym for pressure.

SUBCROP The area over which a particular rock unit or deposit occurs immediately beneath another deposit, e.g. the Solid unit lying below Superficial Deposits (i.e. at rockhead).

SUBSIDENCE The settling of the ground or a building in response to physical changes in the subsurface such as under ground mining, clay shrinkage or drained response to overburden (consolidation).

SUCTION The force exerted when fluid within pores in a soil or rock is subjected to reduced atmospheric (or other environmental) pressure.

SUPERFICIAL DEPOSITS A general term for usually unlithified deposits of Quaternary age overlying bedrock; formerly called ‘drift’.

SWELLING The volume increase of a clay (or clay-rich soil or rock) resulting from an increase in water content. Swelling behaviour may cause heave of shallow foundations.

SWELLING INDEX The rebound (unloading) equivalent of the Compression index.

THAUMASITE Sulphate mineral produced by pyrite oxidation. It is extremely aggressive to concrete foundations (‘thaumasite attack’, TSA).

TILL An unsorted mixture which may contain any combination of clay, sand, silt, gravel, cobbles and boulders (diamict) deposited by glacial action without subsequent reworking by meltwater.

TRAFFICABILITY The capacity of a soil to support vehicle movement. This is influenced by soil shear strength, water content, and surface friction, ground pressure and vehicle wheel or track configuration.

TRIAXIAL TEST A laboratory test designed to measure the stress required to deform a sample until it fails, or until a constant rate of deformation is obtained.

UNCONFORMITY A break in the sedimentary record indicating cessation of deposition.

UNCONSOLIDATED See Consolidation.

UNDRAINED Condition applied to strength tests where pore fluid is prevented from escaping under an applied load. This does not enable an effective stress condition to develop.

UNIAXIAL COMPRESSIVE STRENGTH The strength of a rock sample (usually a cylinder) subjected to an axial stress causing failure (usually in an undrained condition) in the laboratory.

UNIT WEIGHT The weight of a unit volume of a material. Often used (incorrectly) as synonym for Density. Usually qualified by condition of sample (e.g. saturated, dry)

UPPER LIAS Corresponds broadly to the Whitby Mudstone Formation plus Blea Wyke Sandstone Formation in Cleveland Basin, and to Whitby Mudstone Formation plus Bridport Sand Formation elsewhere.

VALLEY BULGING The folding and displacement of incompetent beds in a valley floor due to stress relief (lateral forces exceeding vertical forces). Usually associated with periglacial conditions.

WATER CONTENT In a geotechnical context: the mass of water in a soil/rock as a % of the dry mass (usually dried at 105^{o} C). Synonymous with moisture content.

WATER TABLE The level in the rocks at which the pore water pressure is at atmospheric, and below which all voids are water filled; it generally follows the surface topography, but with less relief, and meets the ground surface at lakes and most rivers. Water can occur above a water table.

WEATHERING The physical and chemical processes leading to the breakdown of rock materials (e.g. due to water, wind, temperature).

YOUNG’S MODULUS A measure of linear stiffness. The slope of the stress-strain graph for elastic deformation [rock mechanics].

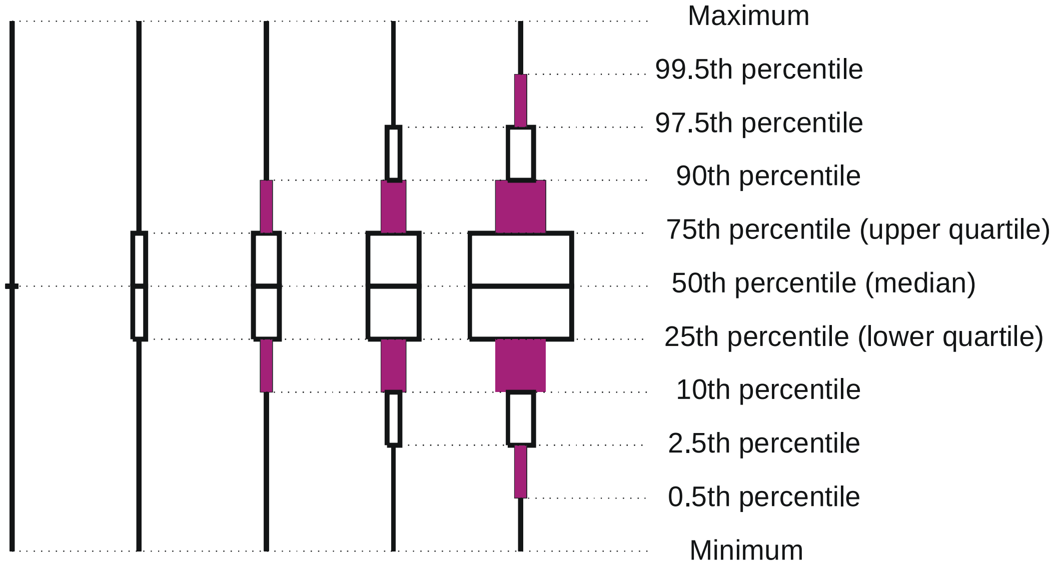
APPENDIX B

Extended box & whisker plots
[by Formation]

Key to 'Extended Box and Whisker' plots

No. of samples, n

Increasing n

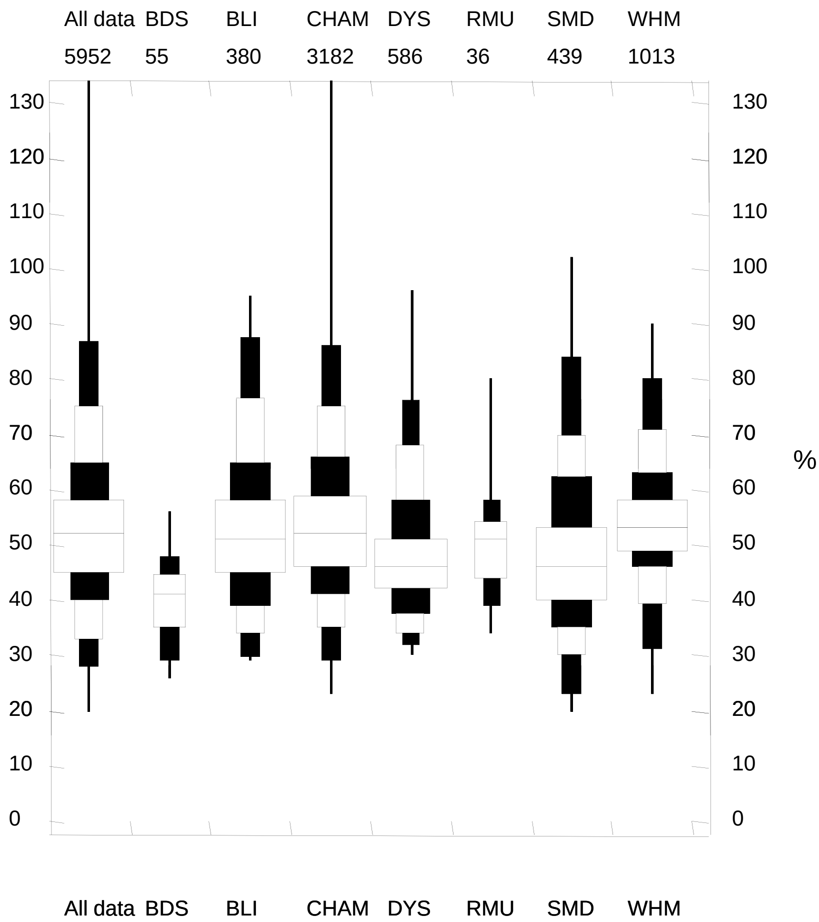


Extended box & whisker plots

[by Formation]

LIQUID LIMIT, LL,%

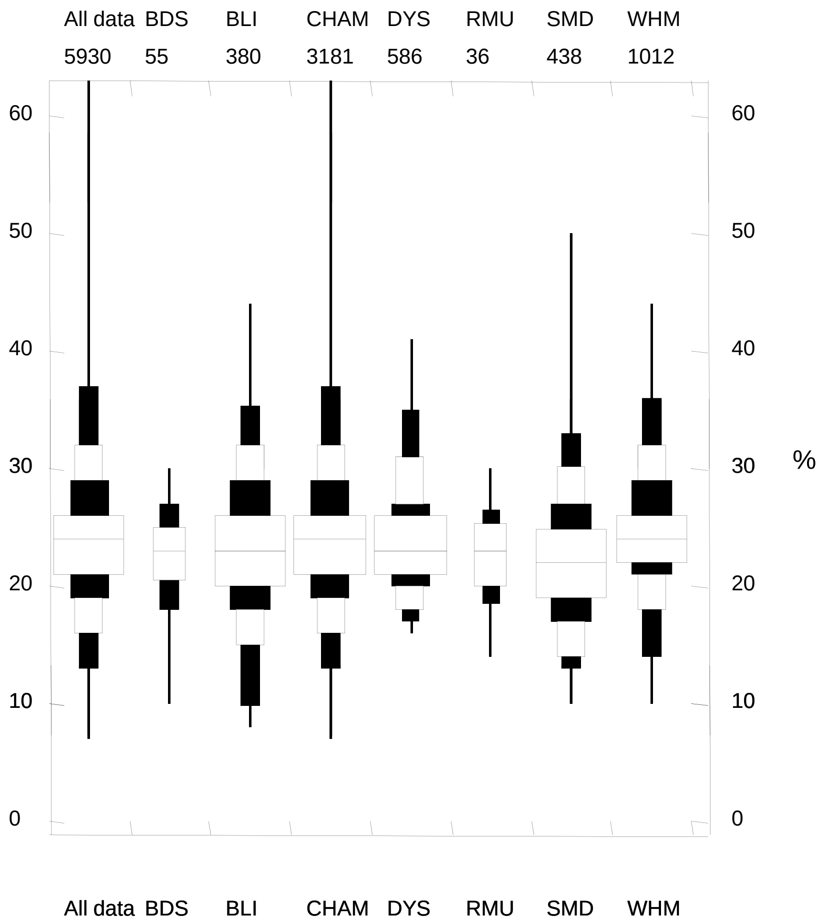
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	5952	55	380	3182	586	36	439	1013
min	20.0	26.0	29.0	23.0	30.0	34.0	20.0	23.0
0.005	28.0	26.0	29.9	29.0	31.9	34.0	23.2	31.0
0.025	33.0	26.4	34.0	35.0	34.0	34.0	30.0	39.3
0.1	40.0	29.0	39.0	41.0	37.5	39.0	35.0	46.0
0.25	45.0	35.0	45.0	46.0	42.0	44.0	40.0	49.0
0.5	**52.0**	**41.0**	**51.0**	**52.0**	**46.0**	**51.0**	**46.0**	**53.0**
0.75	58.0	44.5	58.3	59.0	51.0	54.3	53.0	58.0
0.9	65.0	48.0	65.0	66.0	58.0	58.0	62.2	63.0
0.975	75.0	50.7	76.5	75.0	68.0	73.0	70.0	71.0
0.995	87.0	54.7	87.6	86.0	76.1	78.6	84.1	80.0
max	134.0	56.0	95.0	134.0	96.0	80.0	102.0	90.0



Extended Box & Whisker plot for Liquid Limit

PLASTIC LIMIT, PL, %

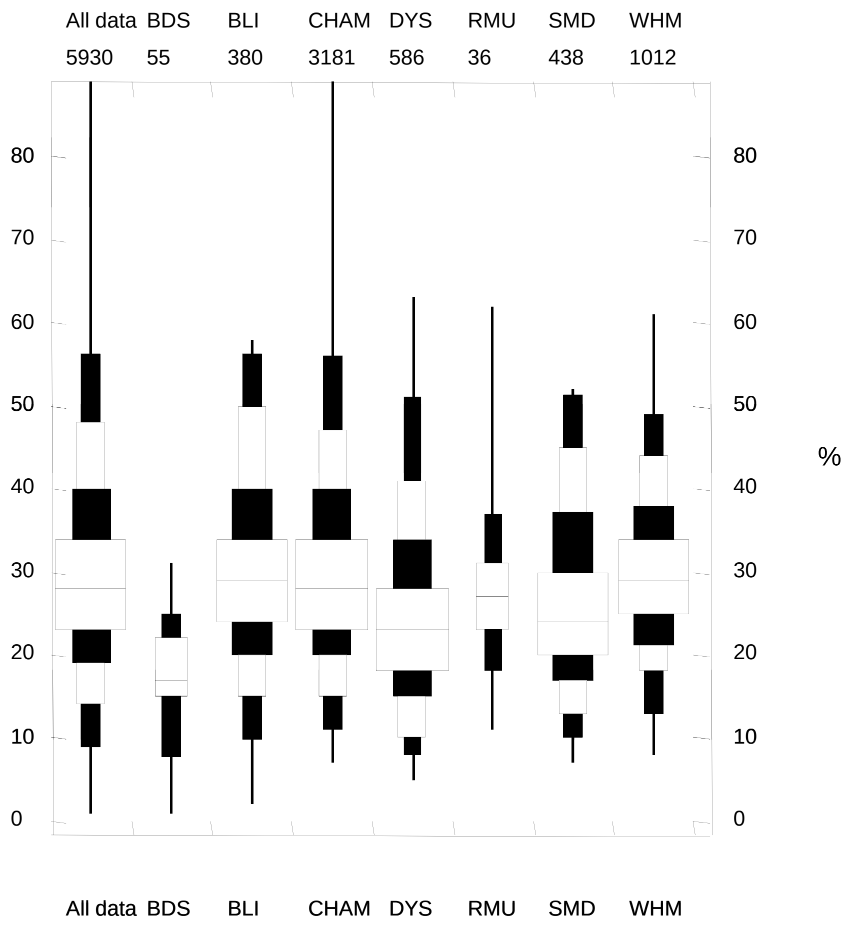
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	5930	55	380	3181	586	36	438	1012
min	7.0	10.0	8.0	7.0	16.0	14.0	10.0	10.0
0.005	13.0	10.5	9.9	13.0	16.9	14.4	13.0	14.0
0.025	16.0	13.4	15.0	16.0	18.0	15.8	14.0	18.0
0.1	19.0	18.0	18.0	19.0	20.0	18.5	17.0	21.0
0.25	21.0	20.5	20.0	21.0	21.0	20.0	19.0	22.0
0.5	**24.0**	**23.0**	**23.0**	**24.0**	**23.0**	**23.0**	**22.0**	**24.0**
0.75	26.0	25.0	26.0	26.0	26.0	25.3	24.8	26.0
0.9	29.0	27.0	29.0	29.0	27.0	26.5	27.0	29.0
0.975	32.0	28.0	32.0	32.0	31.0	29.1	30.1	32.0
0.995	37.0	29.5	35.3	37.0	35.1	29.8	33.0	36.0
max	63.0	30.0	44.0	63.0	41.0	30.0	50.0	44.0



Extended Box & Whisker plot for Plastic Limit

PLASTICITY INDEX, PI, %

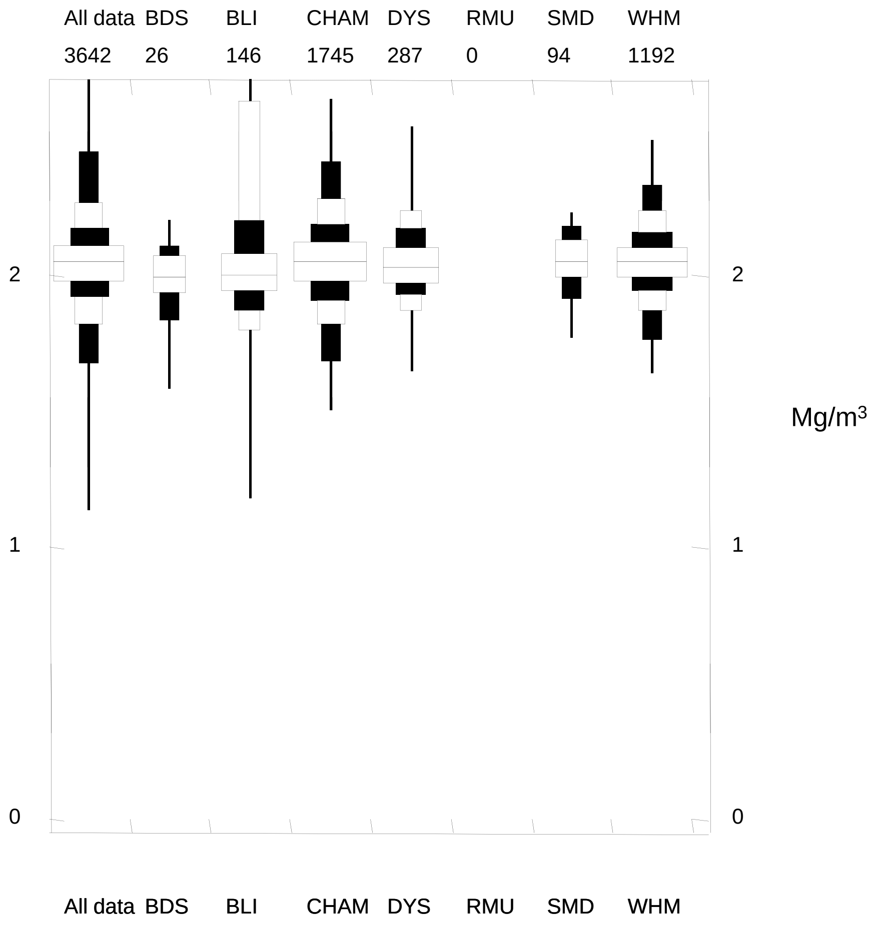
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	5930	55	380	3181	586	36	438	1012
min	1.0	1.0	2.0	7.0	5.0	11.0	7.0	8.0
0.005	9.0	1.3	9.9	11.0	7.9	11.4	10.2	13.0
0.025	14.0	3.1	15.0	15.0	10.0	12.8	13.0	18.0
0.1	19.0	7.8	19.9	20.0	15.0	18.0	17.0	21.1
0.25	23.0	15.0	24.0	23.0	18.0	23.0	20.0	25.0
0.5	**28.0**	**17.0**	**29.0**	**28.0**	**23.0**	**27.0**	**24.0**	**29.0**
0.75	34.0	22.0	34.0	34.0	28.0	31.0	30.0	34.0
0.9	40.0	25.0	40.0	40.0	34.0	37.0	37.3	38.0
0.975	48.0	29.7	50.0	47.0	41.0	46.3	45.0	44.0
0.995	56.4	30.7	56.2	56.0	51.0	58.9	51.4	48.9
max	89.0	31.0	58.0	89.0	63.0	62.0	52.0	61.0



Extended Box & Whisker plot for Plasticity Index

BULK DENSITY, BD, Mg/m^3

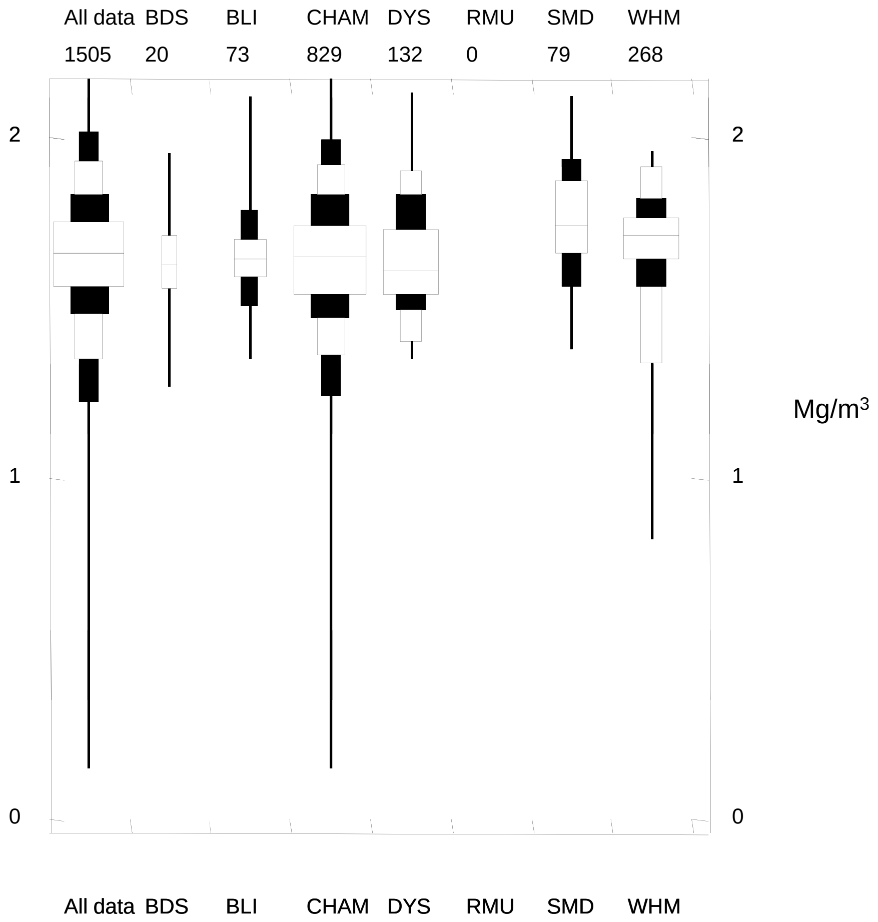
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	3642	26	146	1745	287		94	1192
min	1.14	1.58	1.18	1.50	1.65		1.77	1.64
0.005	1.68	1.59	1.54	1.69	1.78		1.80	1.76
0.025	1.82	1.65	1.80	1.82	1.87		1.84	1.87
0.1	1.92	1.84	1.87	1.91	1.93		1.91	1.94
0.25	1.98	1.93	1.94	1.98	1.97		1.99	1.99
0.5	2.05	1.99	2.00	2.05	2.03		2.05	2.05
0.75	2.11	2.08	2.08	2.12	2.10		2.13	2.10
0.9	2.17	2.11	2.20	2.19	2.17		2.18	2.16
0.975	2.27	2.15	2.64	2.28	2.24		2.22	2.24
0.995	2.45	2.19	2.71	2.42	2.31		2.23	2.33
max	2.72	2.20	2.72	2.65	2.55		2.23	2.50



Extended Box & Whisker plot for Bulk Density

DRY DENSITY, DD, Mg/m³

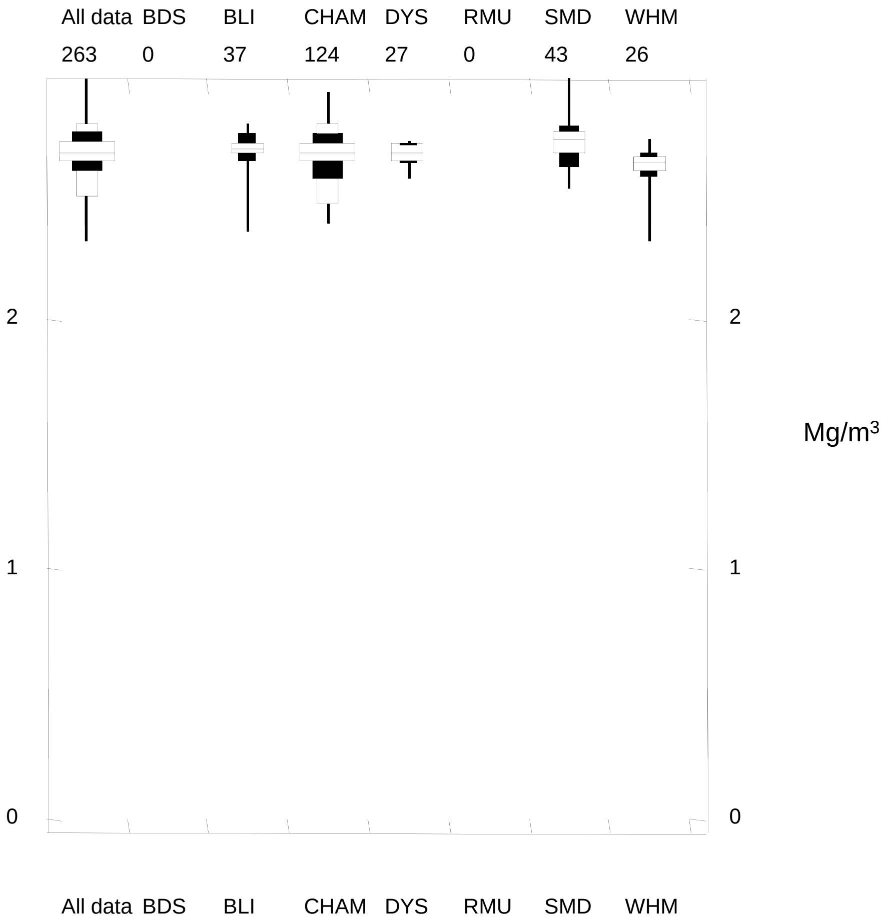
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	1505	20	73	829	132		79	268
min	0.15	1.27	1.35	0.15	1.35		1.38	0.82
0.005	1.22	1.29	1.35	1.24	1.35		1.39	1.19
0.025	1.35	1.37	1.39	1.36	1.40		1.40	1.34
0.1	1.48	1.53	1.50	1.47	1.49		1.56	1.56
0.25	1.56	1.56	1.59	1.54	1.54		1.66	1.64
0.5	1.66	1.63	1.64	1.65	1.61		1.74	1.71
0.75	1.75	1.71	1.70	1.74	1.73		1.87	1.76
0.9	1.83	1.78	1.79	1.83	1.83		1.93	1.82
0.975	1.93	1.90	1.89	1.92	1.90		2.03	1.91
0.995	2.01	1.94	2.04	1.99	2.03		2.12	1.96
max	2.17	1.95	2.12	2.17	2.13		2.12	1.96



Extended Box & Whisker plot for Dry Density

PARTICLE DENSITY, PD, Mg/m^3

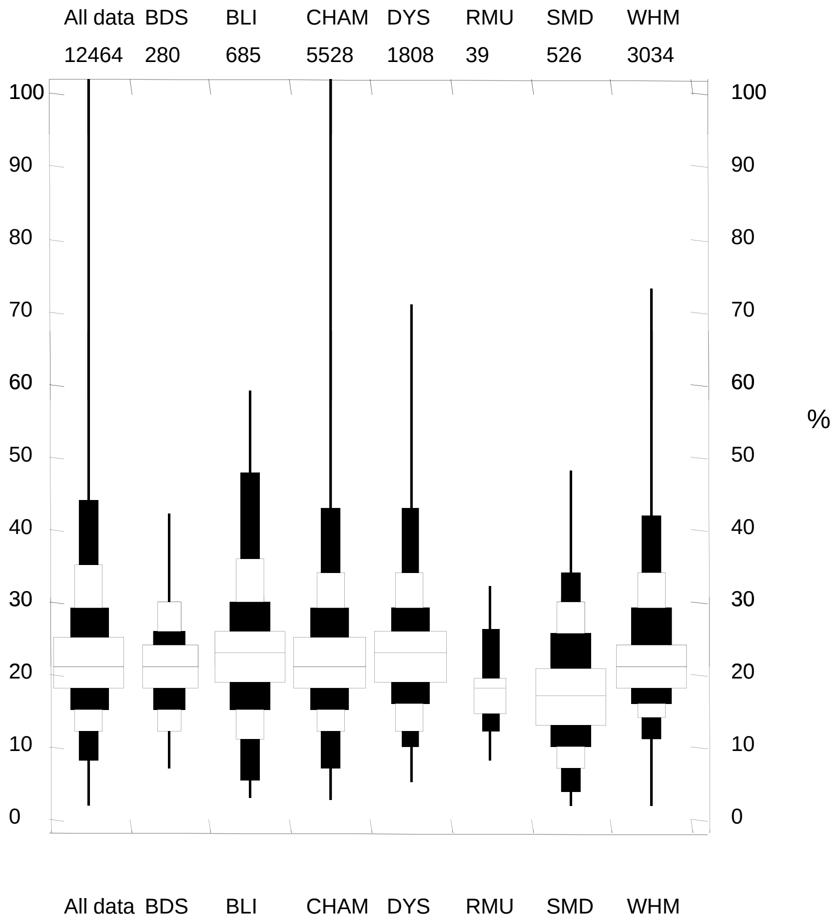
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	263		37	124	27		43	26
min	2.31		2.35	2.38	2.56		2.52	2.31
0.005	2.36		2.38	2.42	2.57		2.53	2.34
0.025	2.49		2.49	2.46	2.59		2.56	2.44
0.1	2.59		2.63	2.56	2.62		2.60	2.57
0.25	2.63		2.66	2.63	2.63		2.66	2.59
0.5	2.66		2.68	2.66	2.66		2.72	2.62
0.75	2.71		2.70	2.70	2.70		2.75	2.65
0.9	2.75		2.74	2.74	2.70		2.77	2.66
0.975	2.78		2.76	2.78	2.71		2.88	2.69
0.995	2.90		2.78	2.87	2.71		2.94	2.71
max	2.96		2.78	2.91	2.71		2.96	2.72



Extended Box & Whisker plot for Particle Density

NATURAL WATER CONTENT, NWC,%

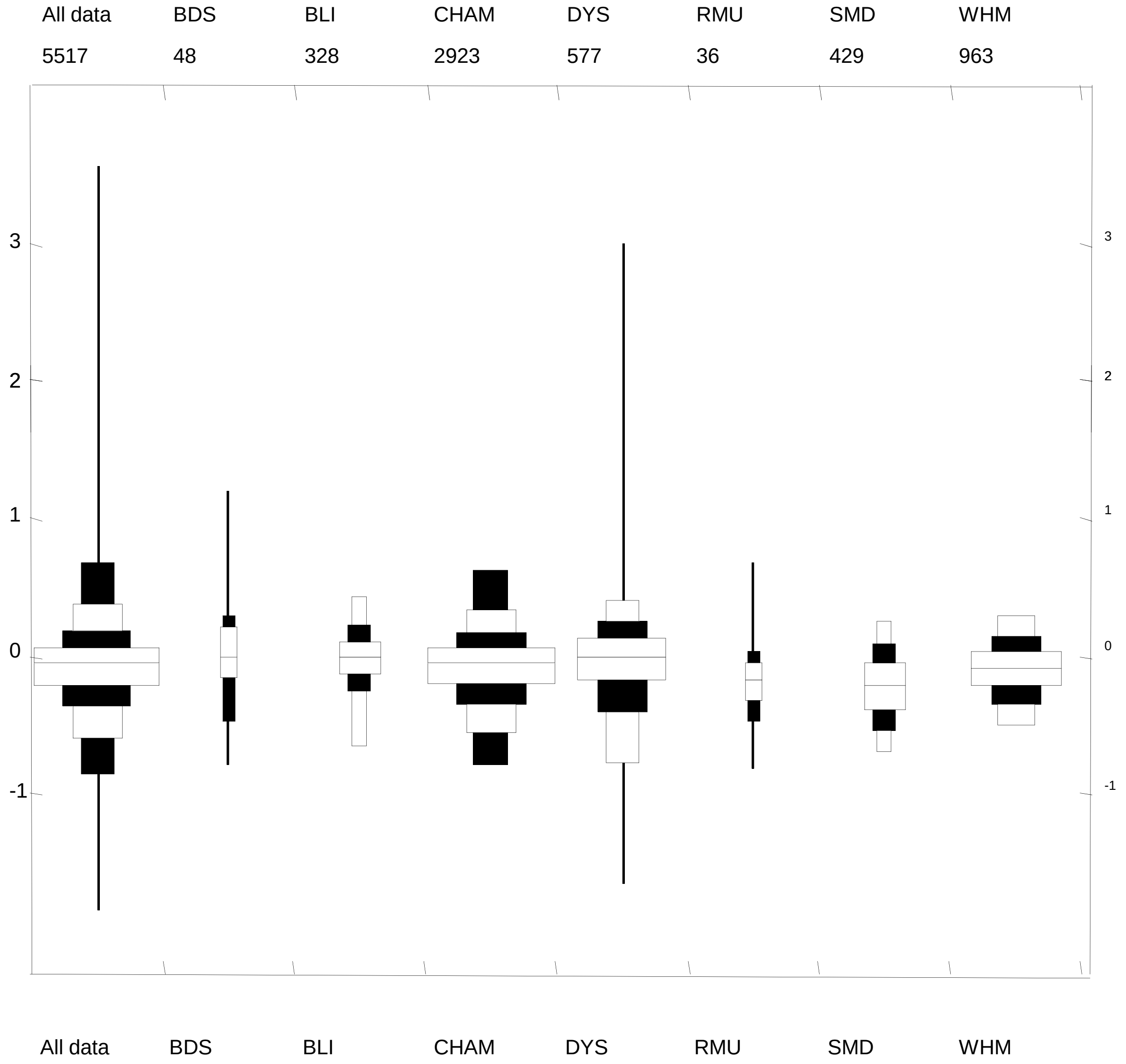
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	12464	280	685	5528	1808	39	526	3034
min	2.00	7.00	3.00	2.70	5.00	8.00	2.00	2.00
0.005	8.00	9.79	5.42	7.00	10.00	8.57	3.63	11.00
0.025	12.00	12.00	11.00	12.00	12.00	10.85	7.00	14.00
0.1	15.00	15.00	15.16	15.00	16.00	12.00	10.00	16.00
0.25	18.00	18.00	19.00	18.00	19.00	14.50	13.00	18.00
0.5	**21.00**	**21.00**	**23.00**	**21.00**	**23.00**	**18.00**	**17.00**	**21.00**
0.75	25.00	24.00	26.00	25.00	26.00	19.50	20.88	24.00
0.9	29.00	26.00	30.00	29.00	29.00	26.20	25.70	29.00
0.975	35.00	30.03	36.00	34.00	34.00	29.15	30.00	34.00
0.995	44.00	35.18	47.74	43.00	43.00	31.43	34.06	41.84
max	102.00	42.00	59.00	102.00	71.00	32.00	48.00	73.00



Extended Box & Whisker plot for Natural Water Content

LIQUIDITY INDEX, LI

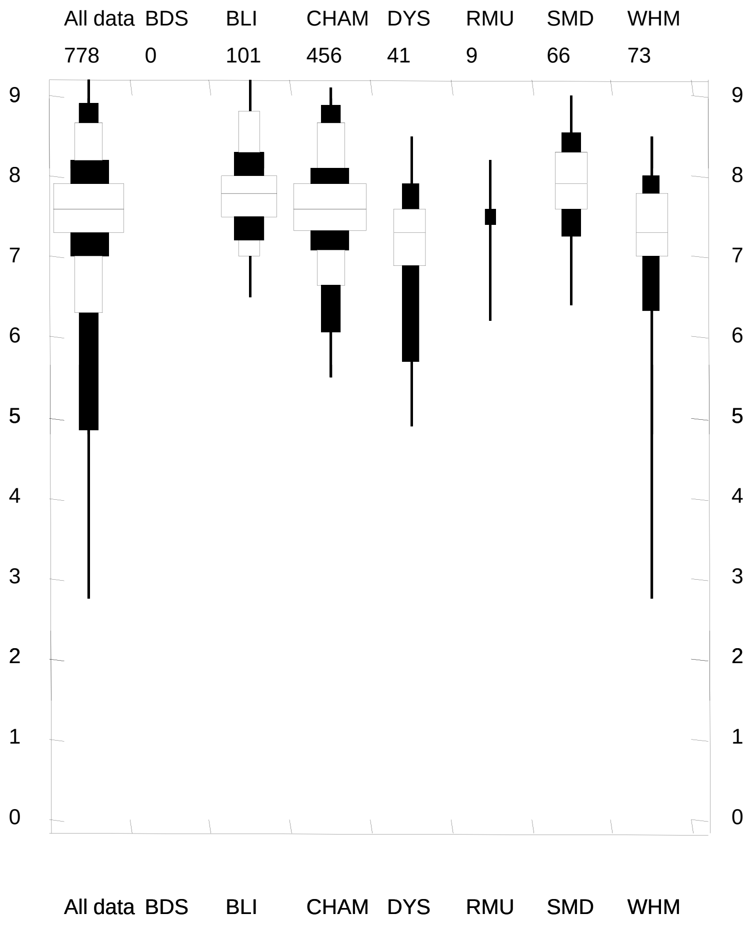
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	5517	48	328	2923	577	36	429	963
min	-1.86	-0.80	-1.61	-1.86	-1.67	-0.82	-1.43	-0.83
0.005	-0.86	-0.77	-1.06	-0.80	-1.39	-0.80	-0.78	-0.66
0.025	-0.60	-0.66	-0.66	-0.56	-0.77	-0.71	-0.69	-0.50
0.1	-0.38	-0.49	-0.27	-0.34	-0.41	-0.49	-0.55	-0.35
0.25	-0.21	-0.16	-0.13	-0.20	-0.19	-0.32	-0.40	-0.21
0.5	**-0.06**	**0.00**	**0.00**	**-0.06**	**0.00**	**-0.19**	**-0.22**	**-0.09**
0.75	0.06	0.20	0.10	0.05	0.13	-0.04	-0.04	0.03
0.9	0.18	0.29	0.22	0.15	0.25	0.03	0.08	0.15
0.975	0.37	0.80	0.42	0.32	0.39	0.16	0.25	0.29
0.995	0.67	1.11	0.51	0.62	0.91	0.57	0.52	0.56
max	3.55	1.18	0.90	3.55	3.00	0.67	1.50	0.80



Extended Whisker plot for SHEET1

pH

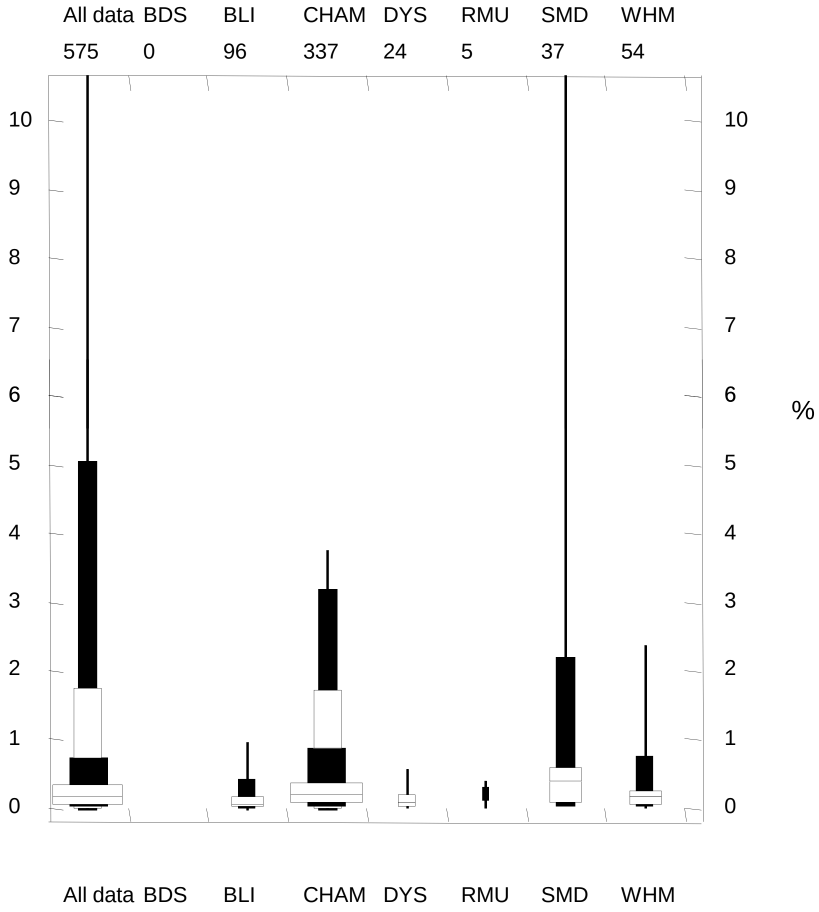
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	778		101	456	41	9	66	73
min	2.75		6.50	5.50	4.90	6.20	6.40	2.75
0.005	4.84		6.55	6.06	4.90	6.24	6.47	3.13
0.025	6.30		7.00	6.64	4.90	6.38	6.79	4.12
0.1	7.00		7.20	7.09	5.70	6.92	7.25	6.32
0.25	7.30		7.50	7.34	6.90	7.40	7.60	7.00
0.5	**7.60**		**7.80**	**7.60**	**7.30**	**7.50**	**7.90**	**7.30**
0.75	7.90		8.00	7.90	7.60	7.80	8.30	7.80
0.9	8.20		8.30	8.10	7.90	8.04	8.55	8.00
0.975	8.66		8.80	8.66	8.20	8.16	8.78	8.34
0.995	8.91		9.05	8.87	8.44	8.19	8.97	8.50
max	9.20		9.20	9.10	8.50	8.20	9.00	8.50



Extended Whisker plot for PH

TOTAL SULPHATE, $SO_{4(TOT)}$ %

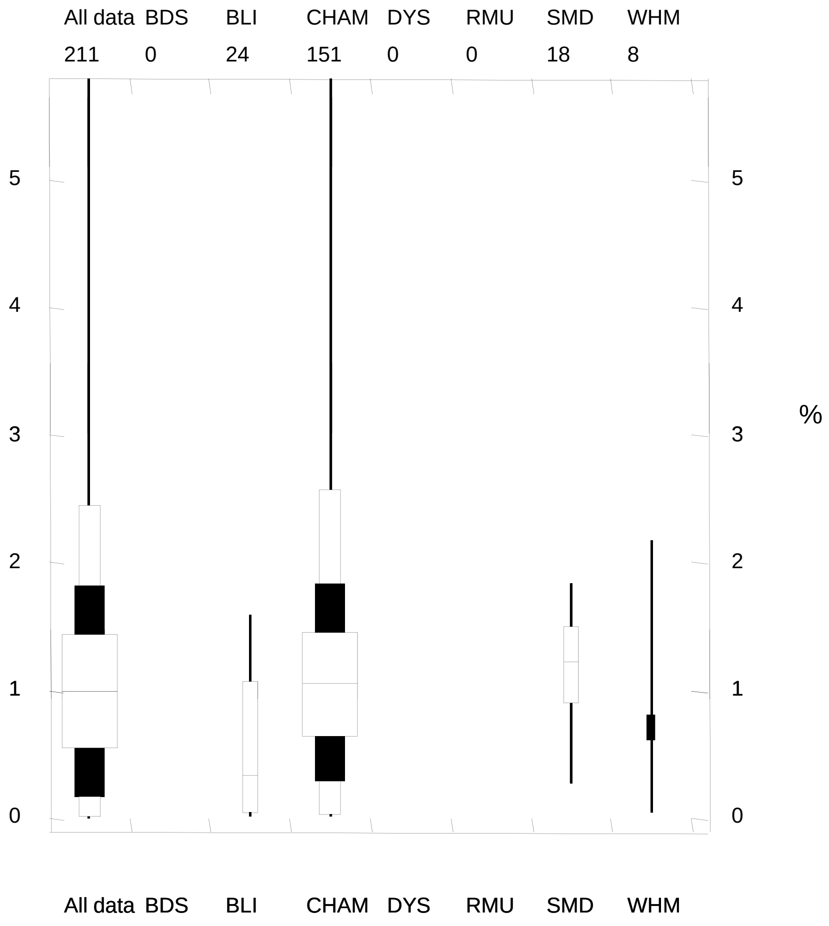
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	575		96	337	24	5	37	54
min	0.00		0.01	0.00	0.01	0.01	0.02	0.01
0.005	0.01		0.01	0.01	0.01	0.01	0.02	0.01
0.025	0.01		0.01	0.01	0.01	0.01	0.02	0.01
0.1	0.02		0.01	0.03	0.01	0.03	0.02	0.01
0.25	0.05		0.02	0.08	0.02	0.05	0.09	0.06
0.5	**0.16**		**0.06**	**0.19**	**0.07**	**0.22**	**0.38**	**0.18**
0.75	0.35		0.18	0.37	0.20	0.33	0.58	0.25
0.9	0.72		0.42	0.86	0.40	0.36	2.21	0.76
0.975	1.74		0.67	1.71	0.50	0.38	5.84	1.48
0.995	5.04		0.83	3.20	0.54	0.38	9.70	2.18
max	10.66		0.96	3.74	0.55	0.38	10.66	2.38



Extended Whisker plot for Total Sulphate

AQUEOUS SULPHATE, $SO_{4(AQ)}$ %

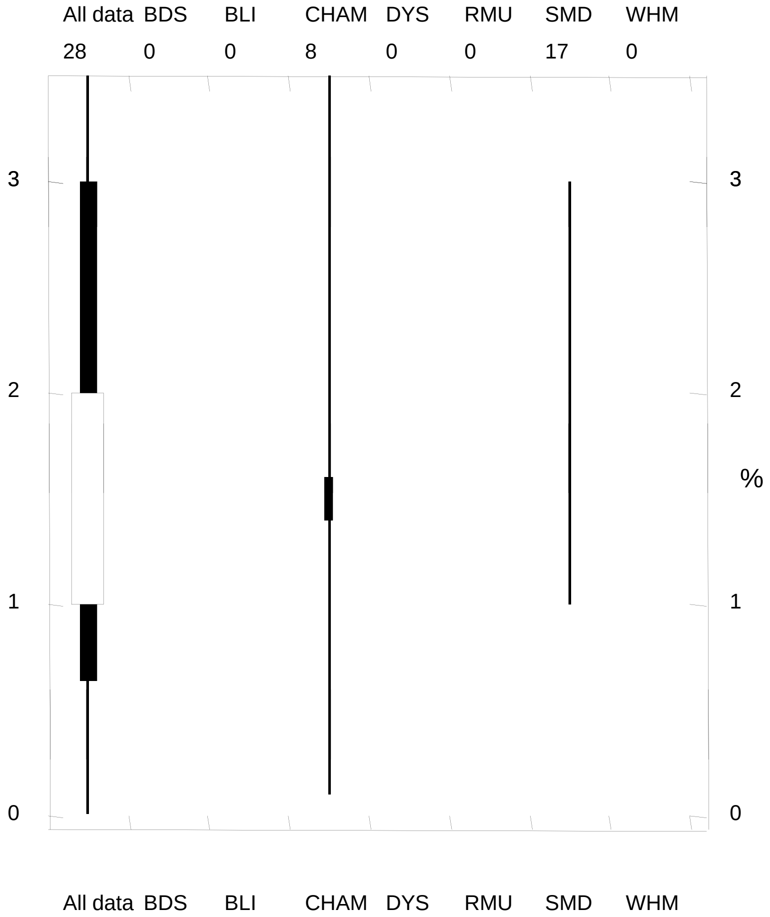
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	211		24	151			18	8
min	0.01		0.01	0.01			0.28	0.05
0.005	0.01		0.01	0.02			0.32	0.06
0.025	0.01		0.01	0.03			0.47	0.09
0.1	0.17		0.01	0.29			0.76	0.21
0.25	0.56		0.04	0.65			0.91	0.37
0.5	**1.00**		**0.34**	**1.06**			**1.23**	**0.71**
0.75	1.45		1.07	1.46			1.49	0.88
0.9	1.82		1.54	1.84			1.63	1.45
0.975	2.45		1.58	2.57			1.77	2.00
0.995	5.35		1.59	5.55			1.82	2.14
max	5.79		1.59	5.79			1.83	2.18



Extended Whisker plot for Aqueous Sulphate

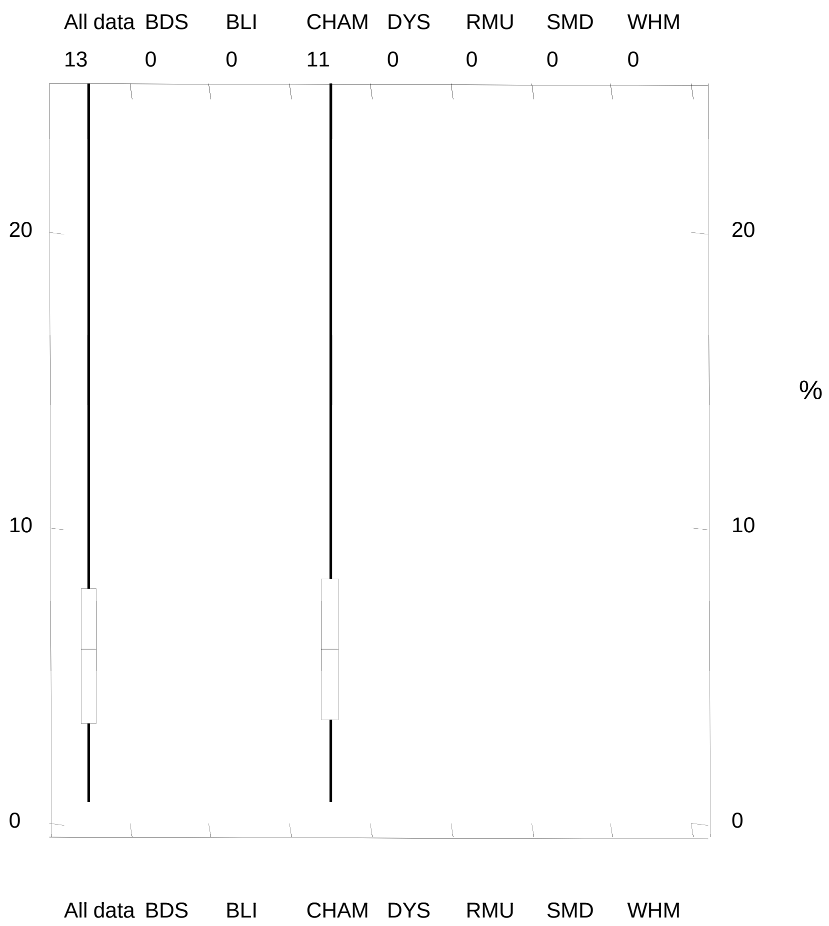
ORGANIC CONTENT %

stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	28			8			17	
min	0.01			0.10			1.00	
0.005	0.02			0.12			1.00	
0.025	0.07			0.22			1.00	
0.1	0.64			0.59			1.00	
0.25	1.00			0.88			2.00	
0.5	**2.00**			**1.50**			**2.00**	
0.75	2.00			2.00			2.00	
0.9	3.00			2.45			3.00	
0.975	3.16			3.24			3.00	
0.995	3.43			3.45			3.00	
max	3.50			3.50			3.00	



Extended Whisker plot for Organic Content

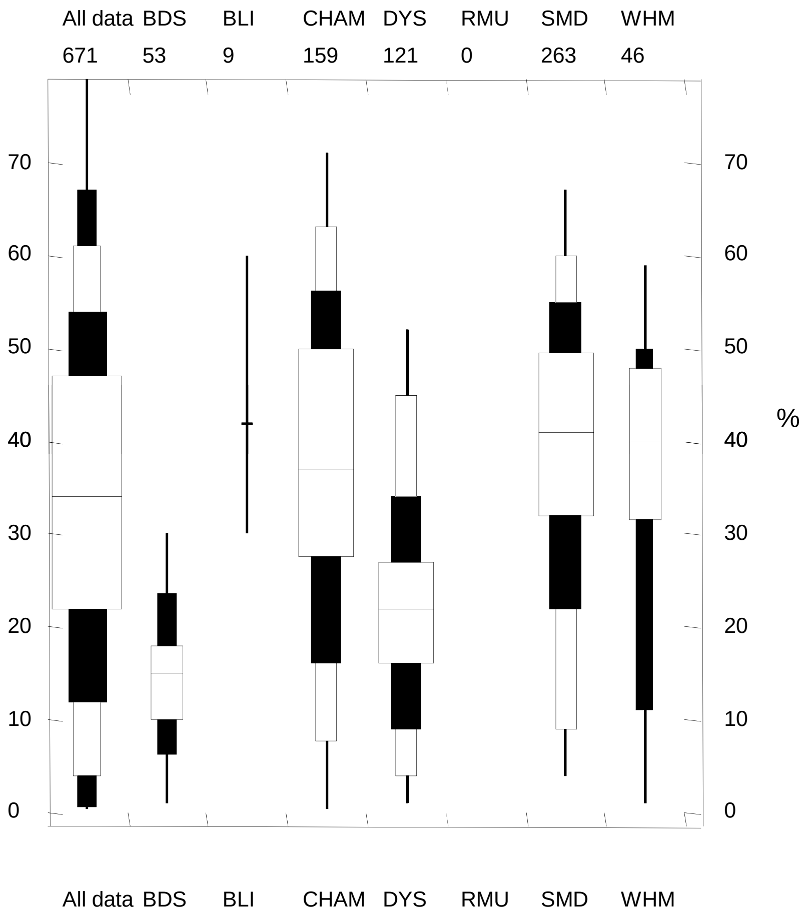
CARBONATE CONTENT %								
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	13			11				
min	0.70			0.70				
0.005	0.71			0.83				
0.025	0.74			1.36				
0.1	1.33			3.34				
0.25	3.40			3.51				
0.5	**5.90**			**5.90**				
0.75	7.90			8.25				
0.9	16.10			17.90				
0.975	22.87			23.23				
0.995	24.57			24.65				
max	25.00			25.00				



Extended Whisker plot for CARB

CLAY-SIZE FRACTION %

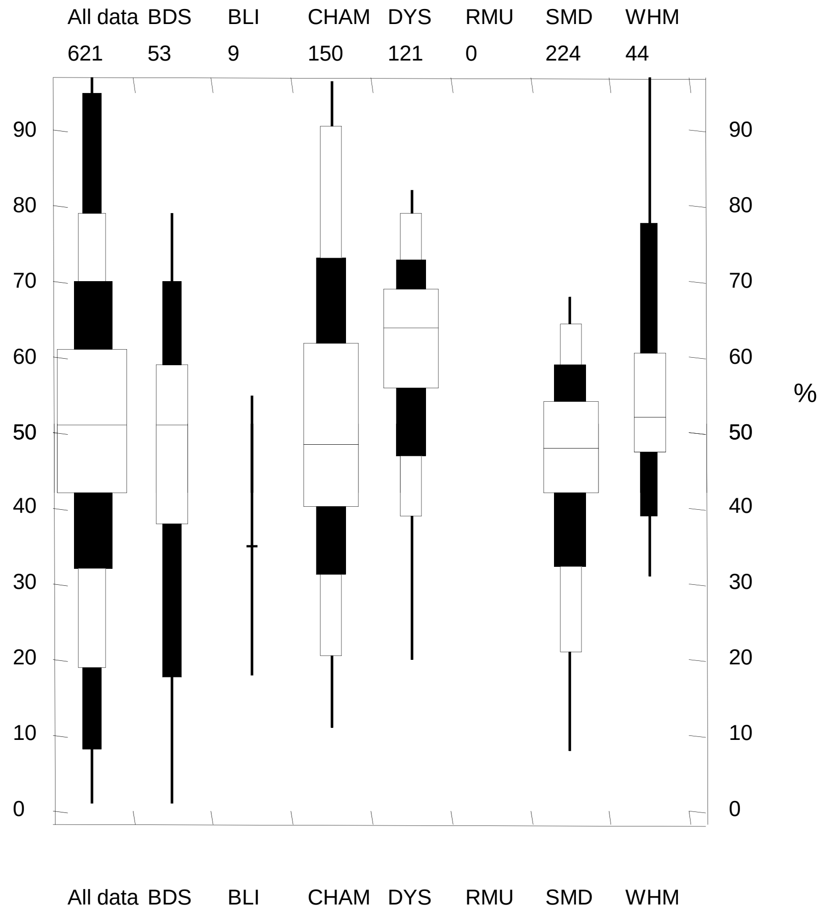
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	671	53	9	159	121		263	46
min	0.5	1.0	30.0	0.5	1.0		4.0	1.0
0.005	0.7	1.3	30.0	0.5	1.6		5.3	1.2
0.025	4.0	2.0	30.0	7.6	4.0		9.0	2.0
0.1	12.0	6.2	30.0	16.0	9.0		22.0	11.0
0.25	22.0	10.0	37.0	27.5	16.0		32.0	31.5
0.5	**34.0**	**15.0**	**42.0**	**37.0**	**22.0**		**41.0**	**40.0**
0.75	47.0	18.0	50.0	50.0	27.0		49.5	47.8
0.9	54.0	23.6	58.4	56.2	34.0		55.0	50.0
0.975	61.0	29.1	59.6	63.1	45.0		60.0	51.8
0.995	67.0	29.9	59.9	69.4	49.0		65.8	57.4
max	79.0	30.0	60.0	71.0	52.0		67.0	59.0



Extended Box & Whisker plot for Clay-size fraction

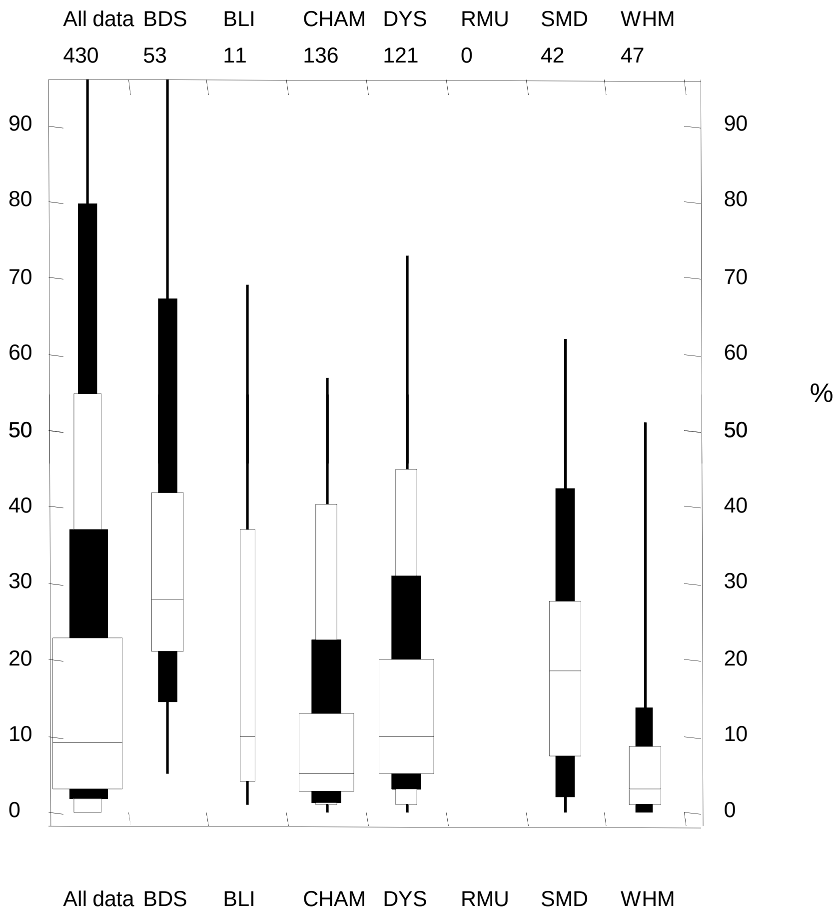
SILT-SIZE FRACTION %

stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	621	53	9	150	121		224	44
min	1.0	1.0	18.0	11.1	20.0		8.0	31.0
0.005	8.3	1.0	18.2	14.2	27.2		15.0	31.2
0.025	19.0	2.8	18.8	20.6	39.0		21.2	32.2
0.1	32.0	17.6	21.2	31.2	47.0		32.3	39.0
0.25	42.0	38.0	23.0	40.3	56.0		42.0	47.5
0.5	**51.0**	**51.0**	**35.0**	**48.5**	**64.0**		**48.0**	**52.1**
0.75	61.0	59.0	45.0	62.0	69.0		54.3	60.5
0.9	70.0	70.0	48.6	73.1	73.0		59.0	77.8
0.975	79.0	76.4	53.4	90.7	79.0		64.4	94.9
0.995	94.9	78.5	54.7	95.8	80.8		65.9	96.6
max	97.0	79.0	55.0	96.5	82.0		68.0	97.0



Extended Box & Whisker plot for Silt-size fraction

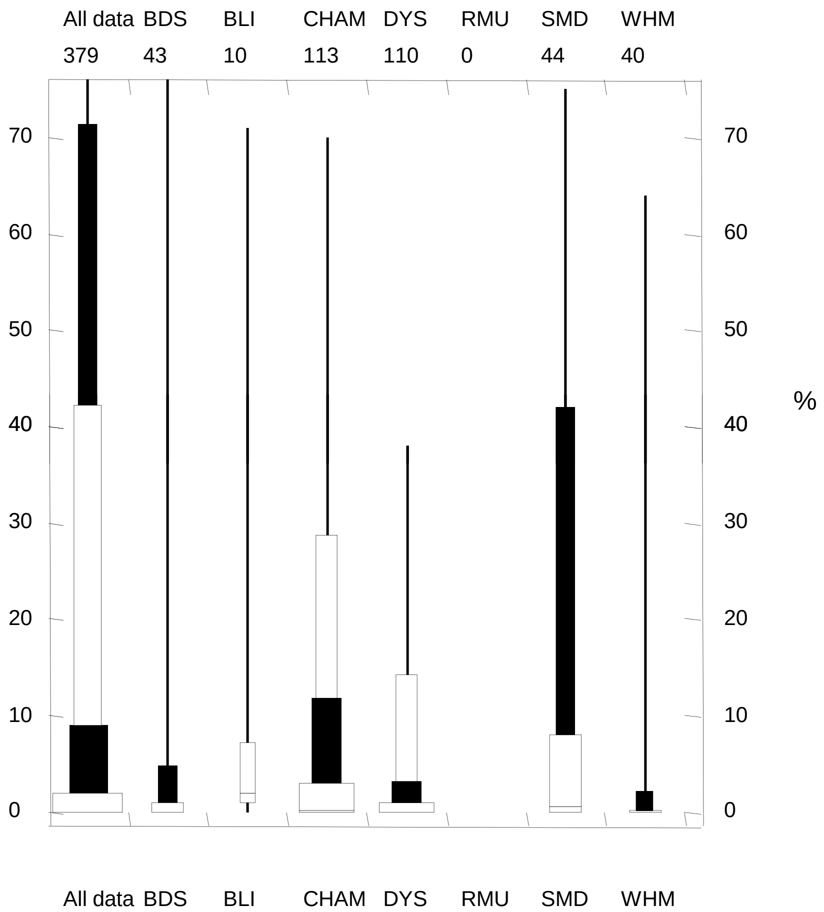
SAND-SIZE FRACTION %								
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	430	53	11	136	121		42	47
min	0.0	5.0	1.0	0.0	0.0		0.0	0.0
0.005	0.0	5.3	1.1	0.3	0.6		0.0	0.0
0.025	0.0	6.3	1.5	1.0	1.0		0.0	0.0
0.1	1.7	14.4	3.0	1.2	3.0		2.0	0.0
0.25	3.0	21.0	4.0	2.9	5.0		7.3	1.0
0.5	**9.0**	**28.0**	**10.0**	**5.0**	**10.0**		**18.5**	**3.0**
0.75	22.8	42.0	37.0	13.0	20.0		27.8	8.5
0.9	37.0	67.4	46.0	22.6	31.0		42.4	13.8
0.975	54.8	91.2	63.4	40.3	45.0		54.0	46.0
0.995	79.7	96.0	68.0	51.6	60.4		60.4	49.9
max	96.0	96.0	69.2	57.0	73.0		62.0	51.0



Extended Box & Whisker plot for Sand-size fraction

GRAVEL-SIZE FRACTION %

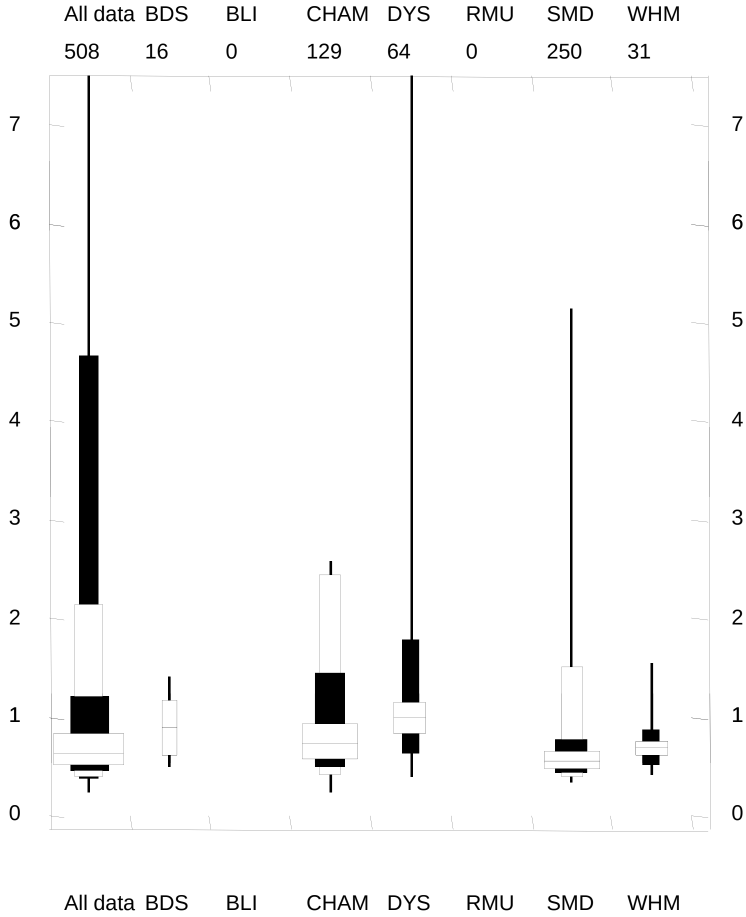
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	379	43	10	113	110		44	40
min	0.0	0.0	0.0	0.0	0.0		0.0	0.0
0.005	0.0	0.0	0.0	0.0	0.0		0.0	0.0
0.025	0.0	0.0	0.2	0.0	0.0		0.0	0.0
0.1	0.0	0.0	0.9	0.0	0.0		0.0	0.0
0.25	0.0	0.0	1.0	0.0	0.0		0.0	0.0
0.5	**0.0**	**0.0**	**2.0**	**0.2**	**0.0**		**0.5**	**0.0**
0.75	2.0	1.0	7.2	3.0	1.0		8.0	0.3
0.9	9.0	4.8	23.3	11.7	3.1		42.1	2.1
0.975	42.2	39.6	59.1	28.7	14.3		56.7	10.4
0.995	71.4	68.4	68.6	49.8	27.1		71.1	53.3
max	76.0	76.0	71.0	70.0	38.0		75.0	64.0



Extended Box & Whisker plot for Gravel-size fraction

ACTIVITY, A_c

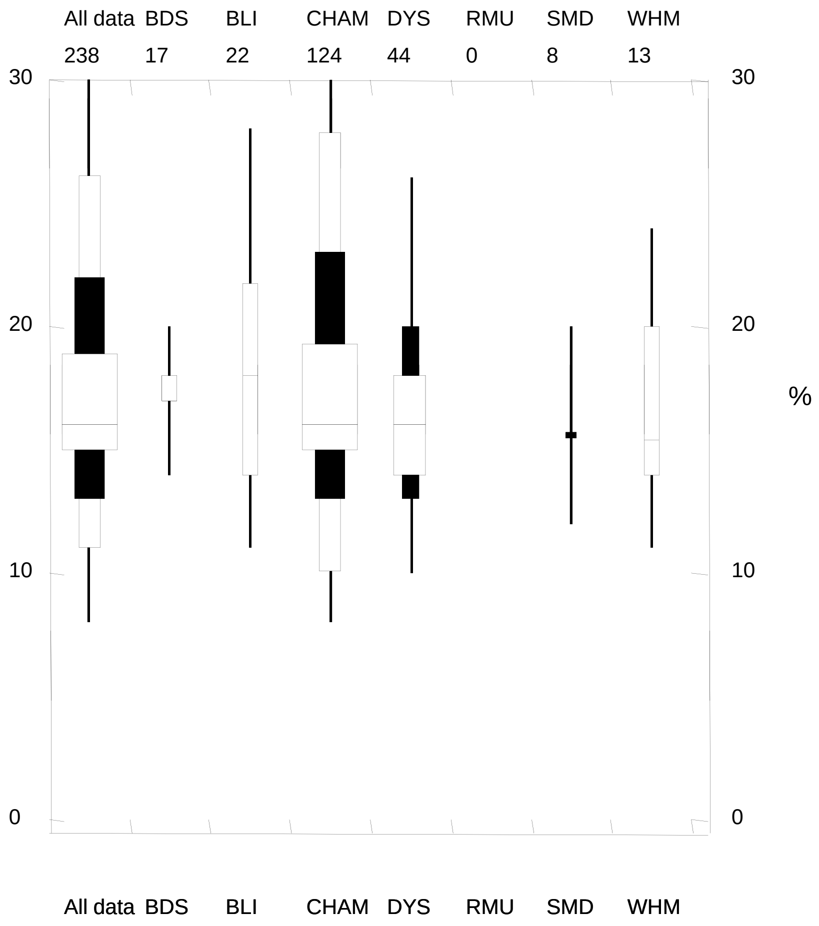
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	508	16		129	64		250	31
min	0.24	0.50		0.24	0.40		0.35	0.42
0.005	0.37	0.51		0.32	0.45		0.37	0.42
0.025	0.40	0.53		0.41	0.55		0.39	0.42
0.1	0.45	0.59		0.49	0.63		0.43	0.52
0.25	0.51	0.62		0.58	0.82		0.47	0.61
0.5	**0.63**	**0.88**		**0.73**	**1.00**		**0.55**	**0.70**
0.75	0.82	1.18		0.94	1.15		0.66	0.75
0.9	1.22	1.31		1.45	1.79		0.78	0.88
0.975	2.15	1.38		2.43	2.93		1.51	1.33
0.995	4.67	1.40		2.57	6.24		4.08	1.51
max	7.50	1.40		2.57	7.50		5.14	1.56



Extended Box & Whisker plot for Activity, A_c

OPTIMUM WATER CONTENT, OWC % (Compaction)

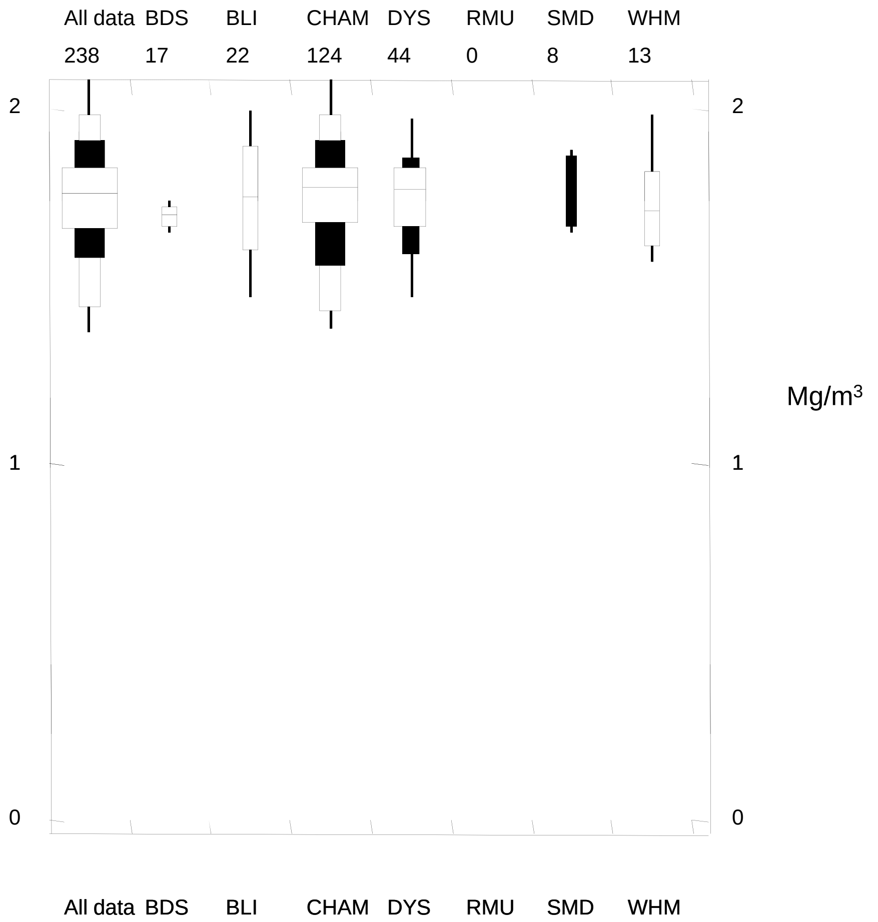
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	238	17	22	124	44		8	13
min	8.0	14.0	11.0	8.0	10.0		12.0	11.0
0.005	10.0	14.1	11.0	9.2	10.4		12.0	11.0
0.025	11.0	14.4	11.0	10.1	12.0		12.2	11.2
0.1	13.0	15.6	12.1	13.0	13.0		12.7	12.0
0.25	15.0	17.0	14.0	15.0	14.0		13.8	14.0
0.5	**16.0**	**18.0**	**18.0**	**16.0**	**16.0**		**15.6**	**15.4**
0.75	18.9	18.0	21.8	19.3	18.0		16.6	20.0
0.9	22.0	18.0	23.8	23.0	20.0		18.9	20.0
0.975	26.1	19.2	27.5	27.9	22.9		19.7	22.8
0.995	29.0	19.8	27.9	29.4	25.4		19.9	23.8
max	30.0	20.0	28.0	30.0	26.0		20.0	24.0



Extended Whisker plot for Optimum Water Content

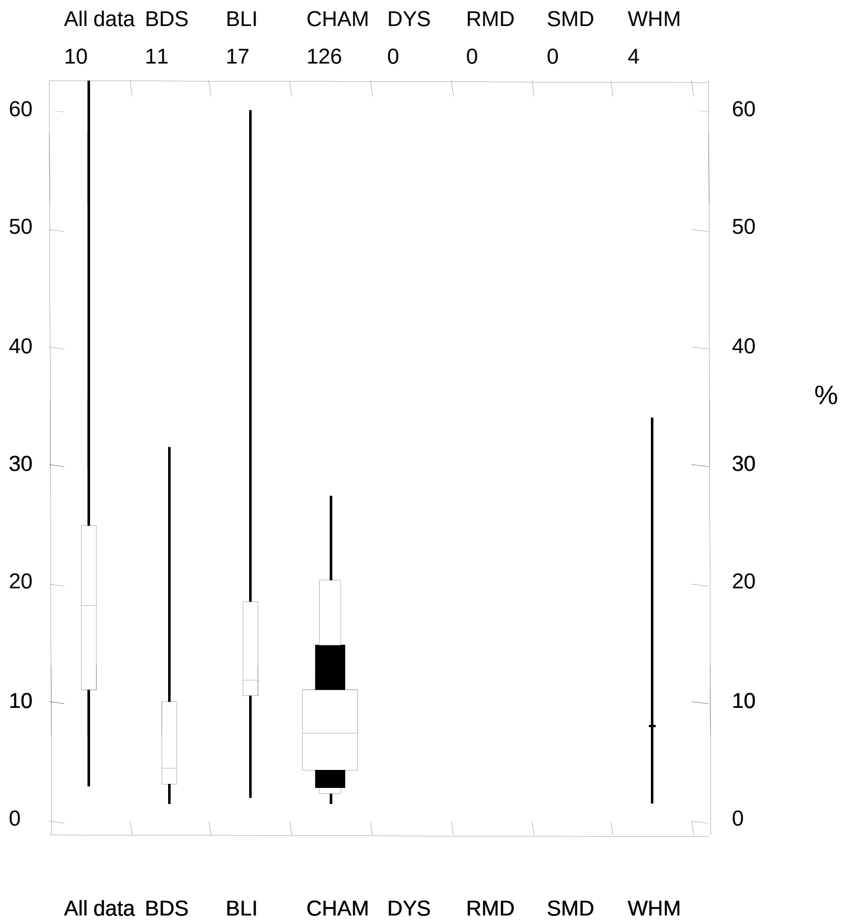
MAXIMUM DRY DENSITY, MDD Mg/m^3 (Compaction)

stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	238	17	22	124	44		8	13
min	1.37	1.65	1.47	1.38	1.47		1.65	1.57
0.005	1.38	1.65	1.48	1.39	1.49		1.65	1.57
0.025	1.44	1.65	1.50	1.43	1.58		1.65	1.57
0.1	1.58	1.67	1.56	1.56	1.59		1.66	1.58
0.25	1.66	1.67	1.60	1.68	1.67		1.68	1.61
0.5	**1.76**	**1.70**	**1.75**	**1.78**	**1.77**		**1.77**	**1.71**
0.75	1.83	1.72	1.89	1.83	1.83		1.79	1.82
0.9	1.91	1.73	1.98	1.91	1.86		1.83	1.92
0.975	1.98	1.74	1.99	1.98	1.90		1.87	1.97
0.995	2.04	1.74	1.99	2.06	1.95		1.88	1.98
max	2.08	1.74	1.99	2.08	1.97		1.88	1.98



Extended Whisker plot for Maximum Dry Density

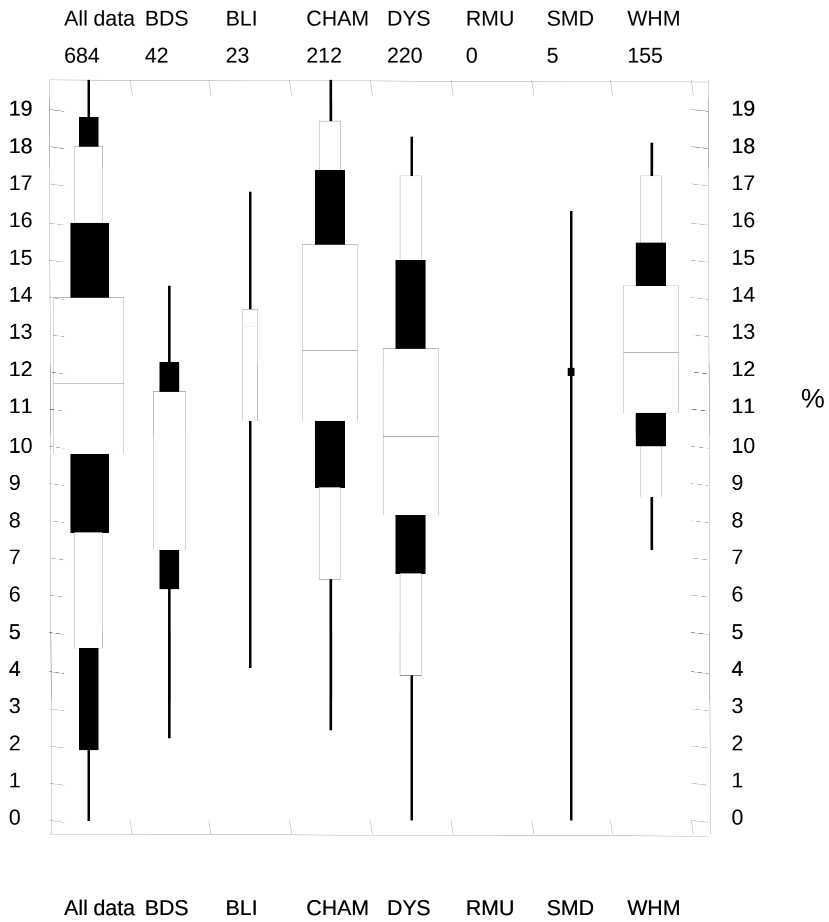
CALIFORNIA BEARING RATIO, CBR %	at Natural Water Content							
stats	*All data*	BDS	BLI	CHAM	DYS	RMD	SMD	WHM
count	10	11	17	126				4
min	3.0	1.4	2.0	1.6				1.6
0.005	3.2	1.4	2.0	1.7				1.7
0.025	4.0	1.6	2.2	2.3				2.1
0.1	7.1	2.0	7.0	2.8				3.0
0.25	11.1	3.1	10.5	4.3				4.4
0.5	**18.3**	**4.5**	**11.9**	**7.5**				**8.0**
0.75	24.9	10.2	18.5	11.0				11.5
0.9	39.1	19.0	33.2	14.8				16.1
0.975	56.7	28.4	56.0	20.4				24.1
0.995	61.3	30.9	59.2	25.9				33.0
max	62.5	31.5	60.0	27.5				34.0



Extended Whisker plot for CBR@NWC

MOISTURE CONDITION VALUE, MCV %

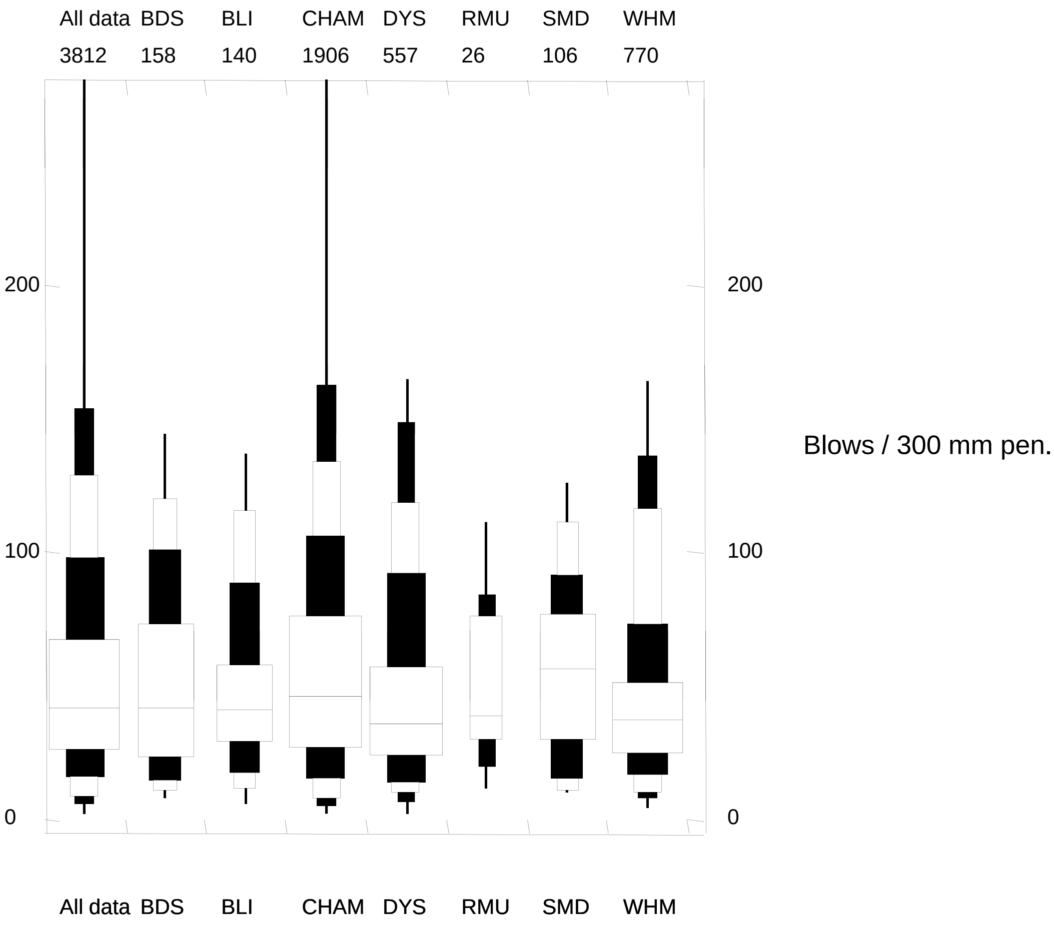
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	684	42	23	212	220		5	155
min	0.0	2.2	4.1	2.4	0.0		0.0	7.2
0.005	1.9	2.4	4.3	2.8	0.2		0.2	7.6
0.025	4.6	3.0	5.0	6.4	3.9		1.2	8.7
0.1	7.7	6.2	8.8	8.9	6.6		4.7	10.0
0.25	9.8	7.2	10.7	10.7	8.2		11.7	10.9
0.5	**11.7**	**9.7**	**13.2**	**12.6**	**10.3**		**12.0**	**12.5**
0.75	14.0	11.5	13.7	15.4	12.6		12.1	14.3
0.9	16.0	12.3	14.0	17.4	15.0		14.6	15.5
0.975	18.0	13.0	15.3	18.7	17.3		15.9	17.2
0.995	18.8	14.0	16.5	19.0	18.1		16.2	18.0
max	19.8	14.3	16.8	19.8	18.3		16.3	18.1



Extended Box & Whisker plot for Moisture Condition Value

STANDARD PENETRATION TEST, SPT Blows/300mm pen.

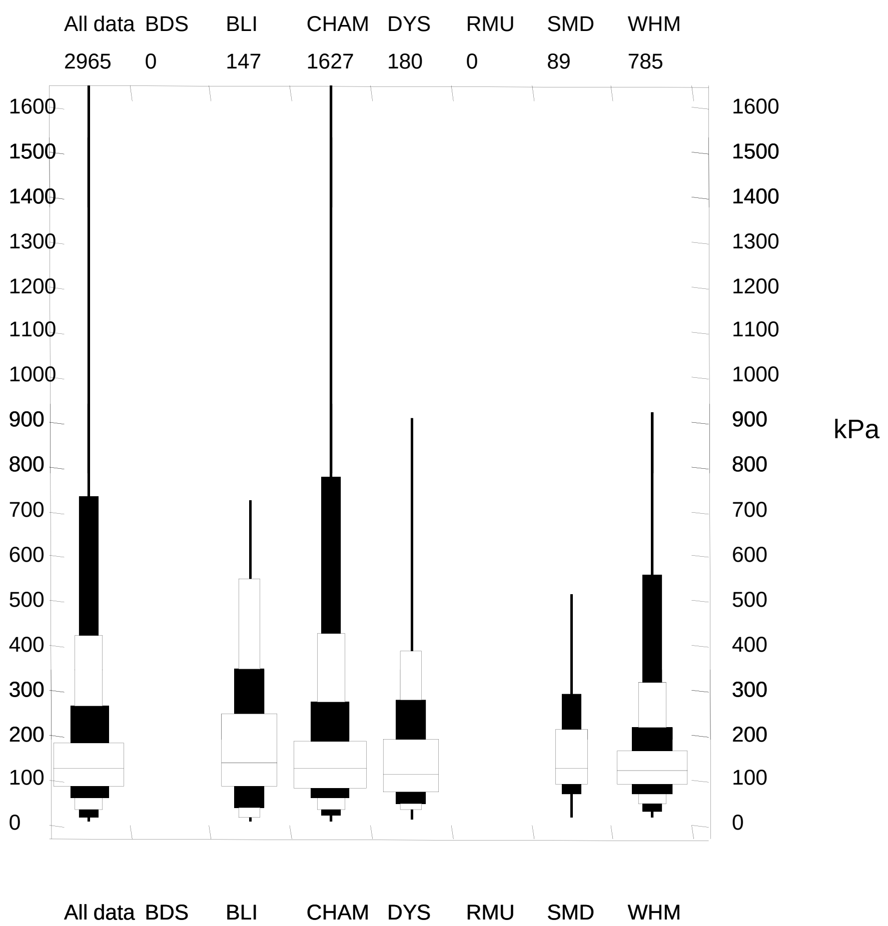
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	3812	158	140	1906	557	26	106	770
min	2.0	8.0	6.0	2.0	2.0	12.0	10.0	4.0
0.005	6.0	8.8	8.1	5.0	6.8	12.9	10.0	8.0
0.025	9.0	10.9	11.5	8.0	10.0	16.4	10.6	10.0
0.1	16.0	14.7	17.8	15.5	14.0	20.0	15.5	17.0
0.25	26.0	23.3	29.0	27.0	24.0	30.0	30.3	25.0
0.5	**42.0**	**42.0**	**41.0**	**46.0**	**36.0**	**38.5**	**56.5**	**37.5**
0.75	67.0	73.0	58.0	76.0	57.0	76.3	77.3	51.0
0.9	98.0	101.3	88.4	106.0	92.0	84.0	91.5	73.1
0.975	128.7	120.1	116.1	134.4	118.3	100.4	111.3	116.1
0.995	153.9	136.2	125.9	162.4	148.7	108.9	125.0	136.6
max	277.0	144.0	137.0	277.0	165.0	111.0	126.0	164.0



Extended Box & Whisker plot for Standard Penetration Test

TRIAX - Total Cohesion, Cu, kPa

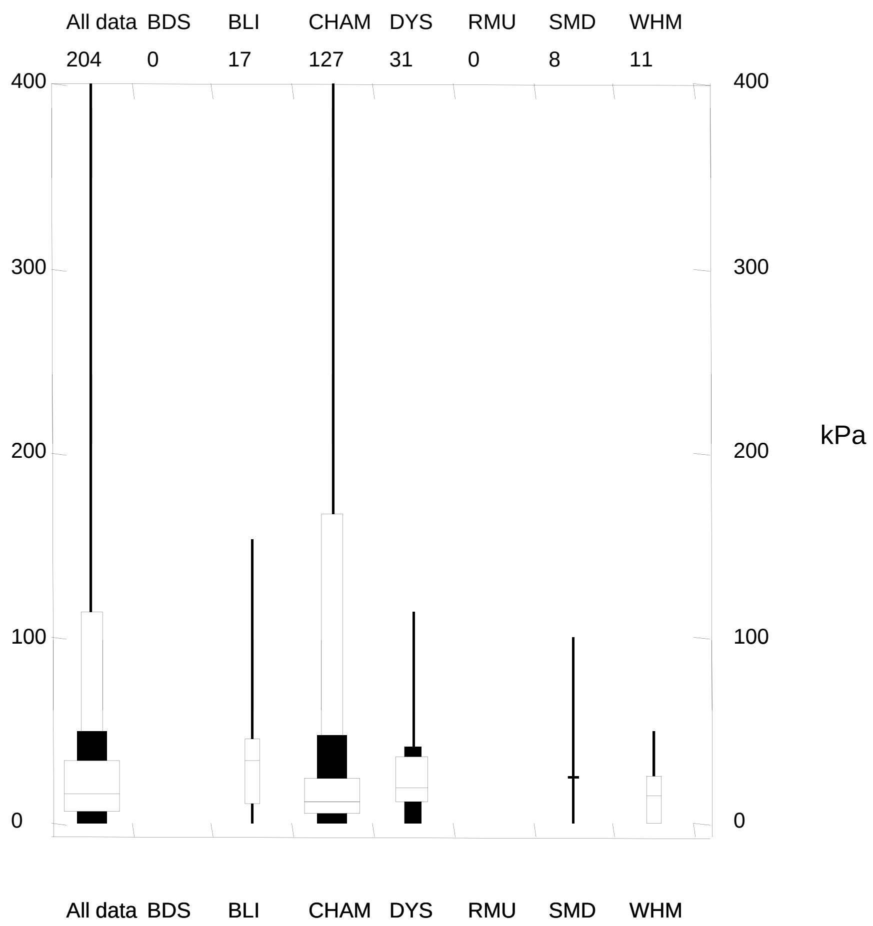
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	2965		147	1627	180		89	785
min	7.0		7.0	8.0	13.0		17.0	19.0
0.005	19.0		7.0	21.1	23.7		23.6	31.8
0.025	35.0		18.7	35.0	35.0		40.2	45.6
0.1	60.0		38.6	59.0	46.0		69.2	69.4
0.25	86.0		87.5	84.0	71.8		91.0	93.0
0.5	**125.0**		**139.0**	**125.0**	**113.0**		**127.0**	**123.0**
0.75	182.0		249.5	187.0	190.8		215.0	164.0
0.9	268.0		348.8	274.0	279.2		292.0	216.2
0.975	421.8		549.4	426.1	390.3		372.0	317.0
0.995	734.9		615.0	777.4	547.3		457.8	558.3
max	1650.0		723.0	1650.0	908.0		515.0	920.0



Extended Box & Whisker plot for Triaxial Total Cohesion, TX-Cu

TRIAX - Effective Cohesion, c', kPa

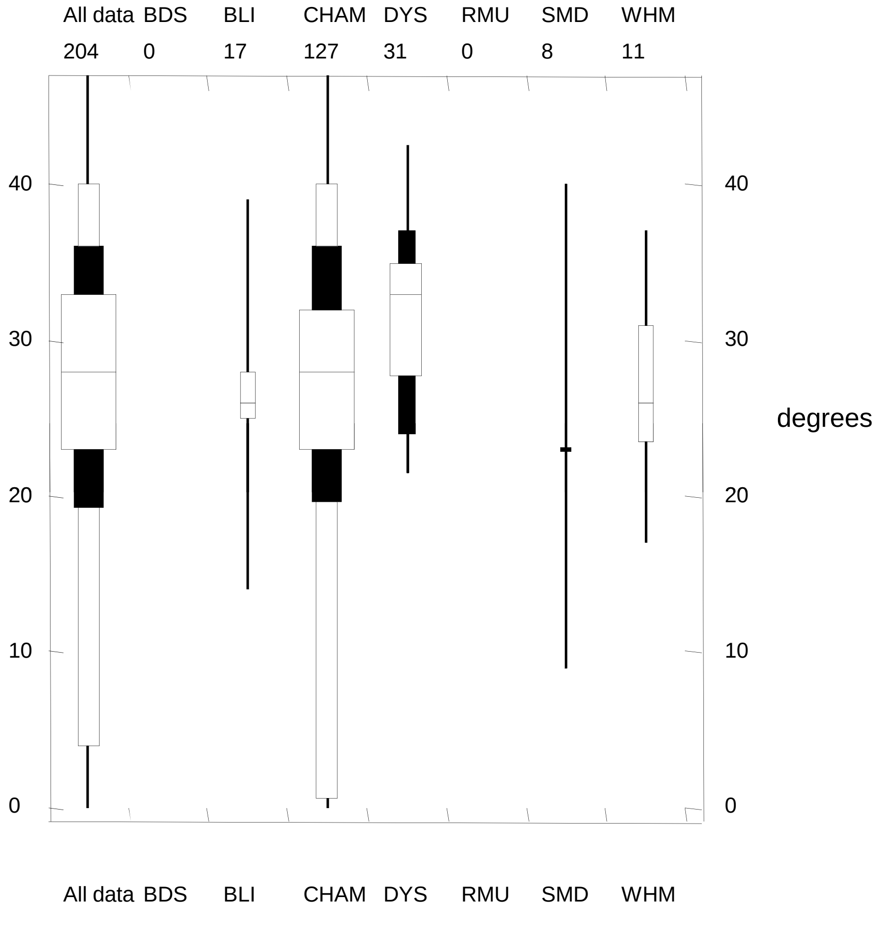
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	204		17	127	31		8	11
min	0.0		0.0	0.0	0.0		0.0	0.0
0.005	0.0		0.4	0.0	0.0		0.3	0.0
0.025	0.0		2.0	0.0	0.0		1.6	0.0
0.1	0.0		6.2	0.0	0.0		6.3	0.0
0.25	6.0		11.0	5.0	11.5		17.3	0.0
0.5	**16.0**		**34.0**	**12.0**	**19.0**		**25.5**	**15.0**
0.75	33.3		45.0	24.5	36.0		50.0	25.0
0.9	50.0		80.0	47.6	41.0		86.0	40.0
0.975	113.7		135.8	167.3	73.5		96.5	47.5
0.995	239.1		149.6	299.2	105.9		99.3	49.5
max	400.0		153.0	400.0	114.0		100.0	50.0



Extended Box & Whisker plot for Triaxial Effective Cohesion, TX-C

TRIAX - Effective Friction angle, ϕ', degrees

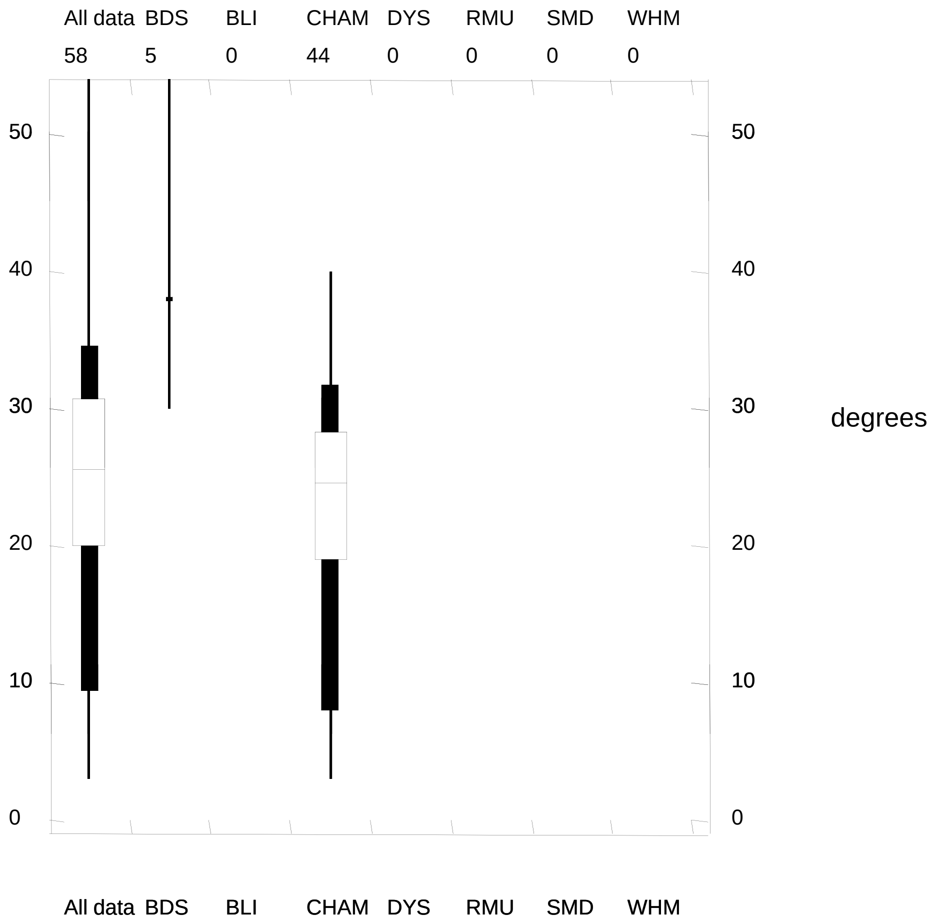
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	204		17	127	31		8	11
min	0.0		14.0	0.0	21.5		9.0	17.0
0.005	0.0		14.1	0.0	21.7		9.2	17.2
0.025	4.0		14.4	0.6	22.3		10.1	17.8
0.1	19.3		18.0	19.6	24.0		13.2	20.0
0.25	23.0		25.0	23.0	27.8		19.5	23.5
0.5	**28.0**		**26.0**	**28.0**	**33.0**		**23.0**	**26.0**
0.75	33.0		28.0	32.0	35.0		27.6	31.0
0.9	36.0		34.0	36.0	37.0		31.6	36.0
0.975	40.0		38.2	40.0	39.9		37.9	36.8
0.995	45.9		38.8	46.4	42.0		39.6	37.0
max	47.0		39.0	47.0	42.5		40.0	37.0



Extended Box & Whisker plot for Triaxial Effective Friction Angle, TX-PHI

SHEAR BOX - Peak Friction Angle, $\phi_{PEAK,}$ degrees

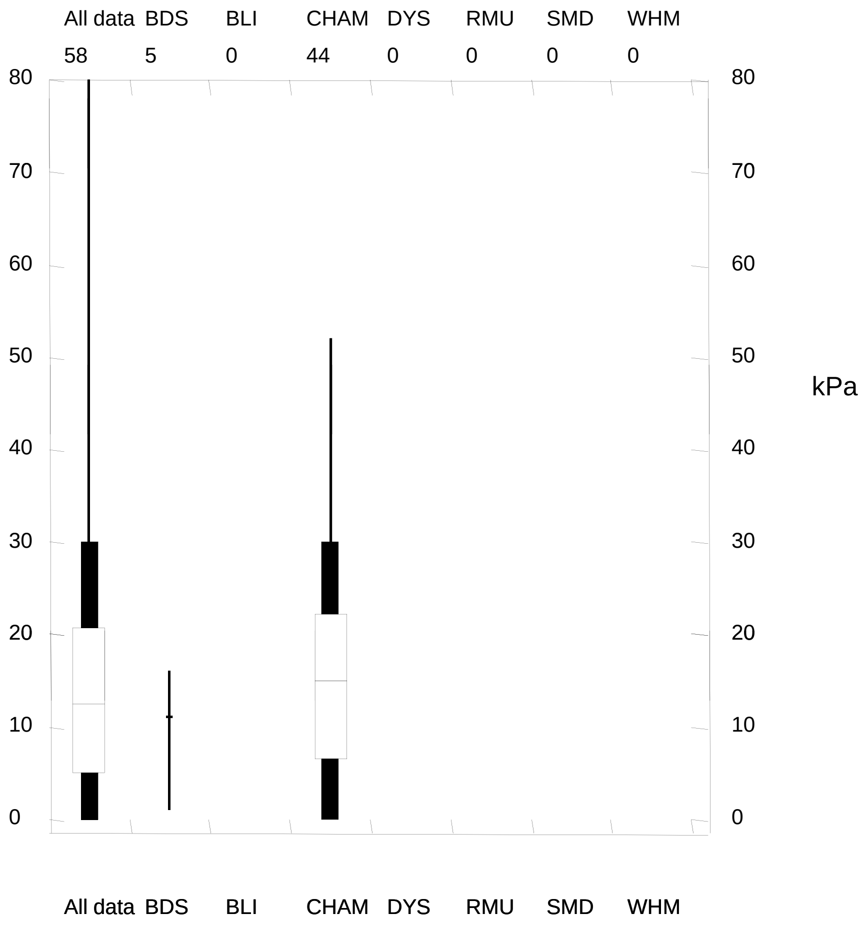
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	58	5		44				
min	3.0	30.0		3.0				
0.005	3.6	30.1		3.4				
0.025	5.0	30.6		5.0				
0.1	9.4	32.4		8.0				
0.25	20.0	36.0		19.0				
0.5	**25.5**	**38.0**		**24.5**				
0.75	30.8	40.0		28.3				
0.9	34.6	48.4		31.7				
0.975	40.0	52.6		36.7				
0.995	50.0	53.7		39.4				
max	54.0	54.0		40.0				



Extended Box & Whisker plot for Shear Box Peak Friction Angle, SHB-PHIPEAK

SHEAR BOX - Peak Cohesion, Cpeak, kPa

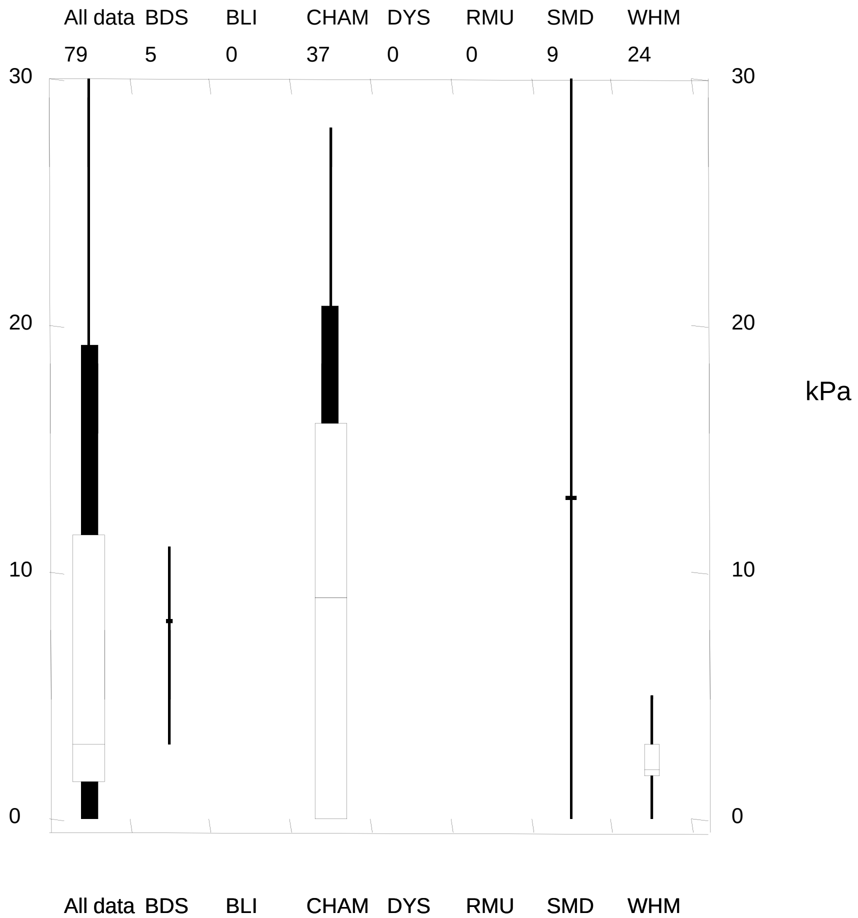
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	58	5		44				
min	0.0	1.0		0.0				
0.005	0.0	1.2		0.0				
0.025	0.0	1.8		0.0				
0.1	0.0	4.2		0.0				
0.25	5.0	9.0		6.5				
0.5	**12.5**	**11.0**		**15.0**				
0.75	20.8	11.0		22.3				
0.9	30.0	14.0		30.0				
0.975	50.3	15.5		47.8				
0.995	72.0	15.9		51.1				
max	80.0	16.0		52.0				



Extended Box & Whisker plot for Shear-Box Peak Cohesion, SHB-CPEAK

SHEAR BOX - Residual Cohesion, C_{RESID}, kPa

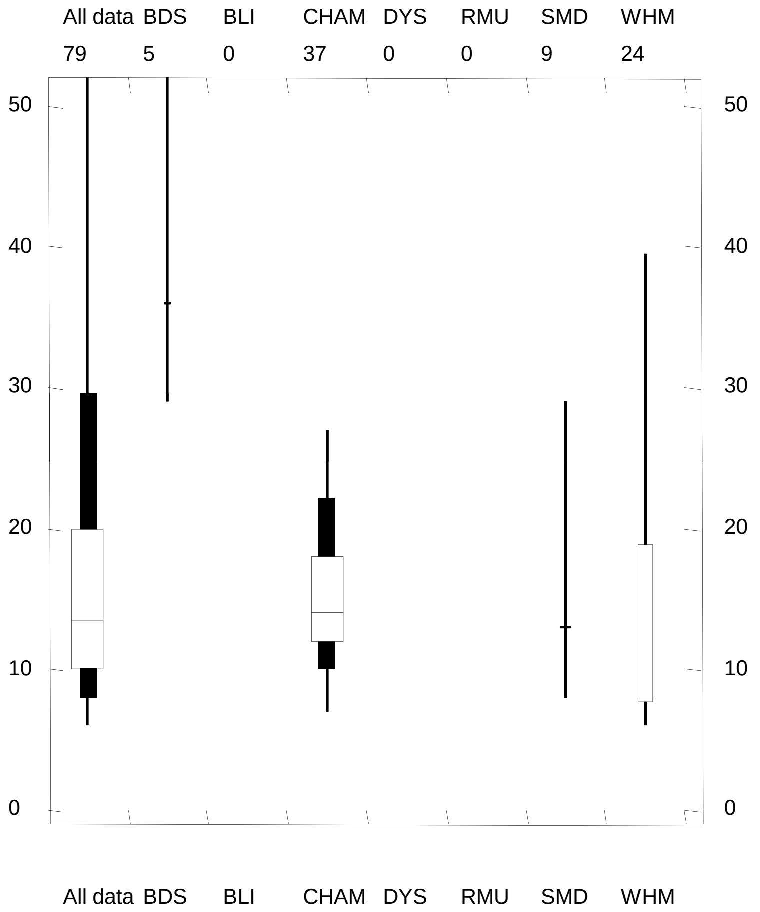
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	79	5		37			9	24
min	0.0	3.0		0.0			0.0	0.0
0.005	0.0	3.0		0.0			0.3	0.0
0.025	0.0	3.0		0.0			1.6	0.0
0.1	0.0	3.0		0.0			6.4	0.0
0.25	1.5	3.0		0.0			9.0	1.8
0.5	**3.0**	**8.0**		**9.0**			**13.0**	**2.0**
0.75	11.5	9.0		16.0			17.0	3.0
0.9	19.2	10.2		20.8			28.4	3.7
0.975	28.0	10.8		26.2			29.6	4.4
0.995	29.2	11.0		27.6			29.9	4.9
max	30.0	11.0		28.0			30.0	5.0



Extended Box & Whisker plot for Shear Box Residual Cohesion, SHB-CRESID

SHEAR BOX - Residual Friction Angle, $\phi_{RESID,}$ degrees

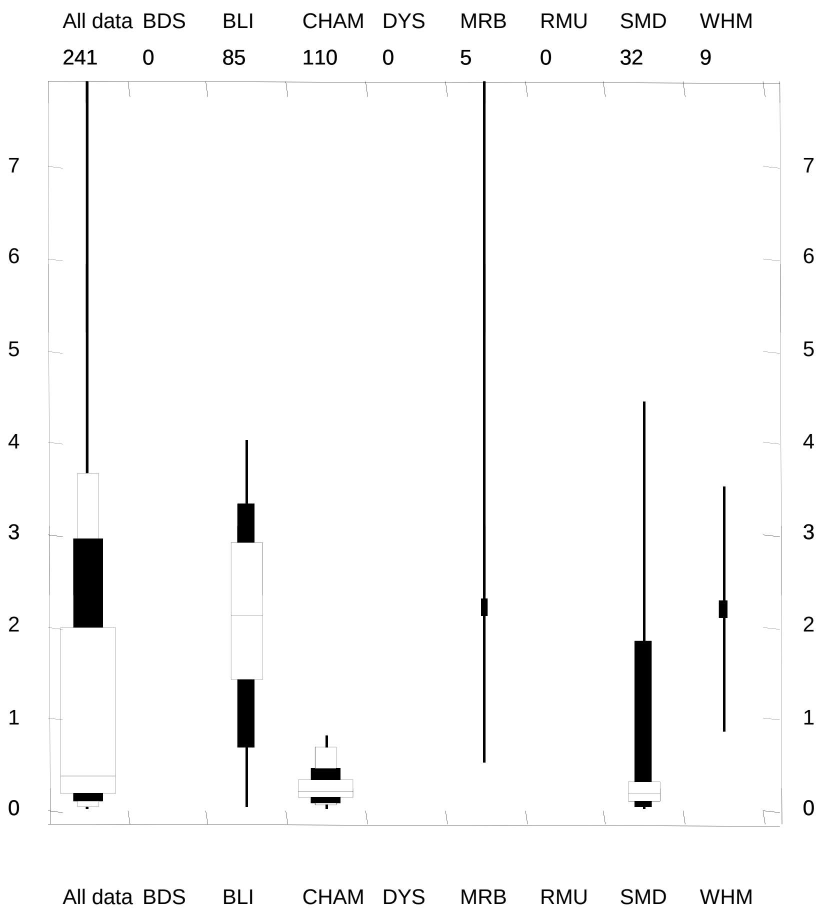
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	79	5		37			9	24
min	6.0	29.0		7.0			8.0	6.0
0.005	6.4	29.1		7.4			8.0	6.1
0.025	7.0	29.3		8.8			8.2	6.6
0.1	8.0	30.2		10.0			8.8	7.0
0.25	10.0	32.0		12.0			11.0	7.8
0.5	**13.5**	**36.0**		**14.0**			**13.0**	**8.0**
0.75	20.0	37.0		18.0			17.0	18.9
0.9	29.6	46.0		22.2			21.8	34.8
0.975	38.1	50.5		24.3			27.2	38.6
0.995	47.1	51.7		26.5			28.6	39.3
max	52.0	52.0		27.0			29.0	39.5



Extended Box & Whisker plot for Shear Box Residual Friction Angle, SHB-PHIRESID

POINT LOAD INDEX, I_{S50}, PTLOAD

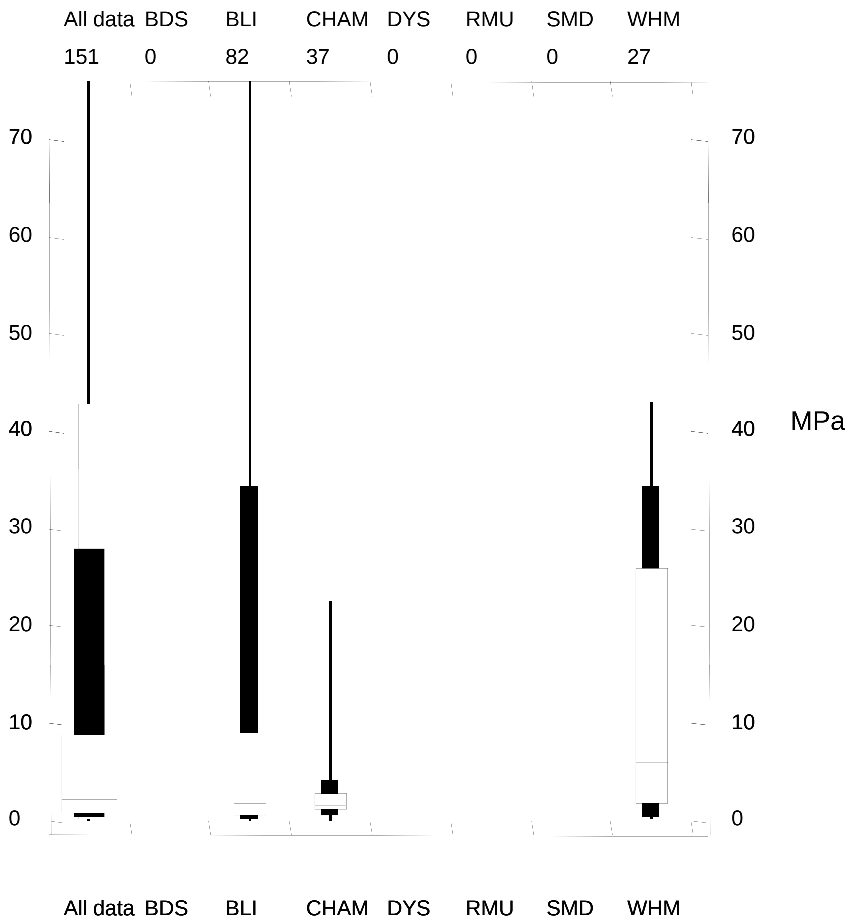
stats	*All data*	BDS	BLI	CHAM	DYS	MRB	RMU	SMD	WHM
count	241		85	110		5.0		32	9
min	0.0		0.0	0.0		0.5		0.0	0.9
0.005	0.0		0.0	0.0		0.5		0.0	0.9
0.025	0.1		0.1	0.1		0.7		0.0	0.9
0.1	0.1		0.7	0.1		1.1		0.1	1.0
0.25	0.2		1.4	0.1		2.0		0.1	2.1
0.5	0.4		2.1	0.2		2.2		0.2	2.2
0.75	2.0		2.9	0.3		3.1		0.3	2.5
0.9	3.0		3.3	0.5		6.0		1.8	3.1
0.975	3.7		3.8	0.7		7.4		3.7	3.4
0.995	4.4		4.0	0.8		7.8		4.3	3.5
max	7.9		4.0	0.8		7.9		4.4	3.5



Extended Box & Whisker plot for Point Load Index, PTLOAD

UNIAXIAL COMPRESSIVE STRENGTH, UCS, MPa

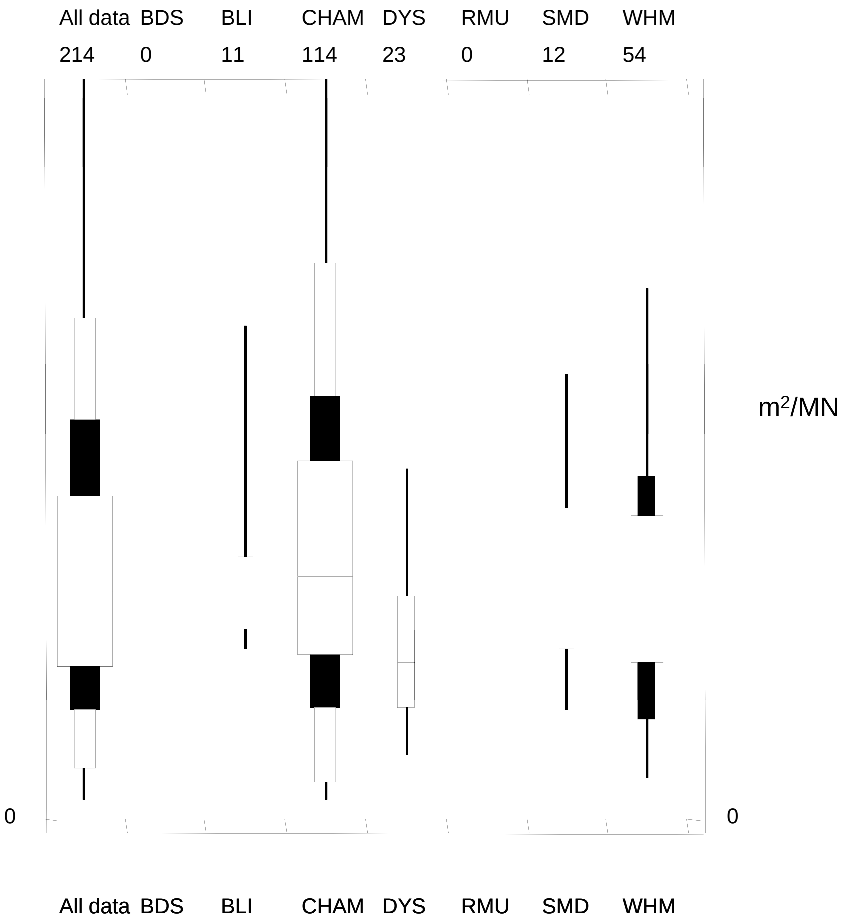
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	151		82	37				27
min	0.0		0.0	0.0				0.1
0.005	0.0		0.0	0.0				0.1
0.025	0.1		0.1	0.1				0.2
0.1	0.3		0.2	0.5				0.5
0.25	0.7		0.6	1.1				1.9
0.5	**2.2**		**1.8**	**1.7**				**6.0**
0.75	8.8		9.0	2.7				26.0
0.9	28.0		34.3	4.1				34.4
0.975	42.9		49.7	10.4				39.1
0.995	65.5		70.3	20.1				42.2
max	76.0		76.0	22.6				43.0



Extended Box & Whisker plot for Uniaxial Compressive Strength, UCS

COEFFICIENT OF VOLUME COMPRESSIBILITY, m_v m2/MN at 200KPa

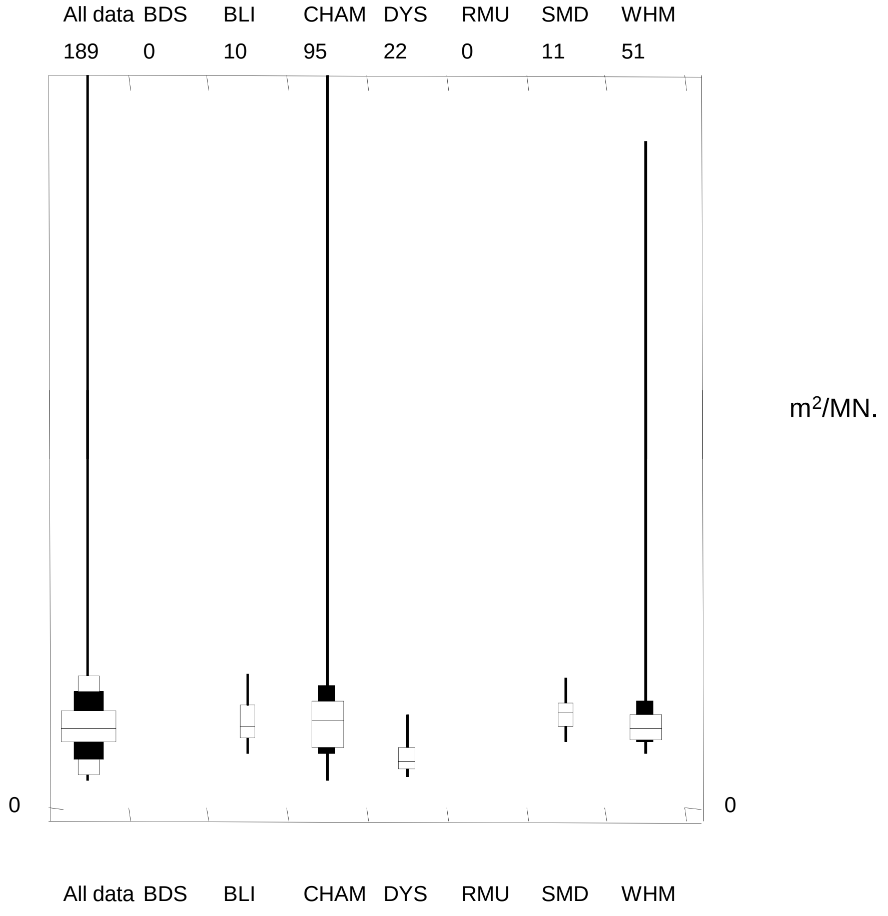
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	214		11	114	23		12	54
min	0.010		0.090	0.010	0.034		0.058	0.022
0.005	0.020		0.090	0.016	0.035		0.059	0.023
0.025	0.027		0.090	0.020	0.038		0.064	0.029
0.1	0.057		0.090	0.058	0.043		0.080	0.053
0.25	0.081		0.100	0.086	0.059		0.090	0.083
0.5	**0.120**		**0.119**	**0.128**	**0.082**		**0.149**	**0.120**
0.75	0.170		0.138	0.189	0.118		0.164	0.160
0.9	0.210		0.189	0.223	0.158		0.226	0.180
0.975	0.264		0.242	0.293	0.179		0.233	0.234
0.995	0.305		0.256	0.343	0.184		0.234	0.269
max	0.390		0.260	0.390	0.185		0.234	0.280



Extended Box & Whisker plot for Coefficient of Volume Compressibility at 200 kPa

COEFFICIENT OF VOLUME COMPRESSIBILITY, m_v m^2/MN at 800KPa

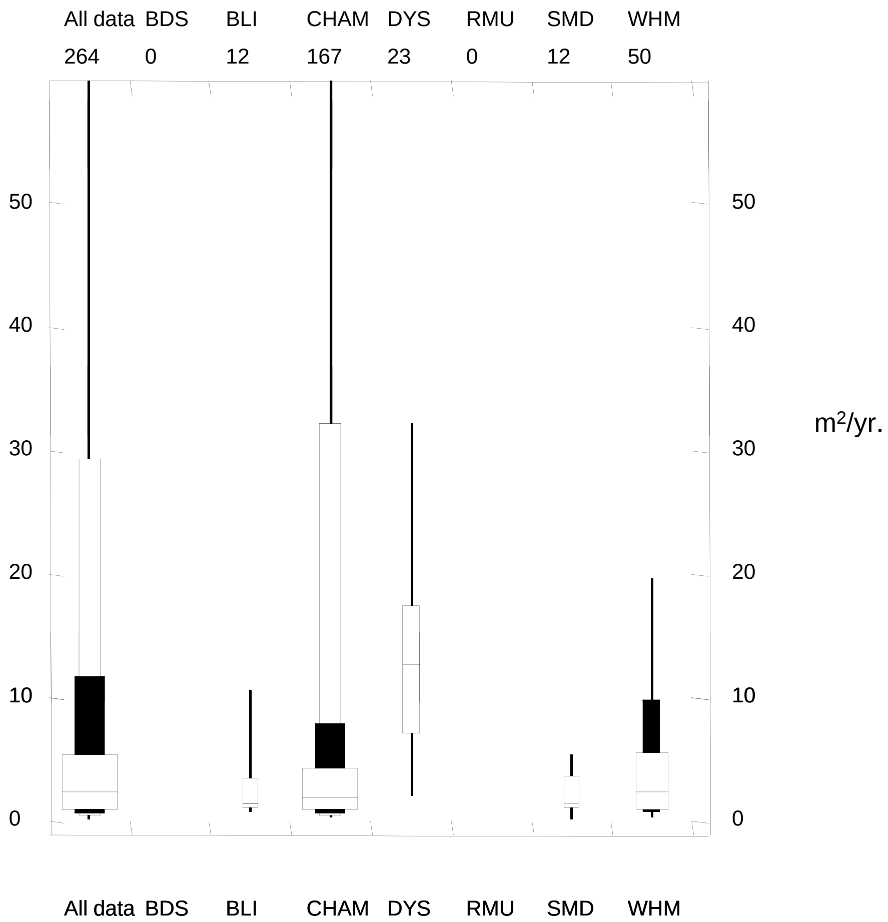
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	189		10	95	22		11	51
min	0.020		0.040	0.020	0.023		0.050	0.040
0.005	0.022		0.040	0.021	0.023		0.050	0.041
0.025	0.025		0.042	0.030	0.023		0.052	0.042
0.1	0.037		0.049	0.040	0.025		0.059	0.050
0.25	0.049		0.052	0.046	0.029		0.061	0.051
0.5	**0.060**		**0.062**	**0.066**	**0.036**		**0.071**	**0.060**
0.75	0.073		0.078	0.080	0.045		0.079	0.070
0.9	0.087		0.089	0.092	0.063		0.091	0.080
0.975	0.099		0.097	0.104	0.070		0.096	0.090
0.995	0.503		0.099	0.353	0.070		0.097	0.398
max	0.550		0.100	0.550	0.070		0.097	0.500



Extended Box & Whisker plot for Coefficient of Volume Compressibility at 800 kPa

COEFFICIENT OF CONSOLIDATION, c_v m^2/yr at 200KPa

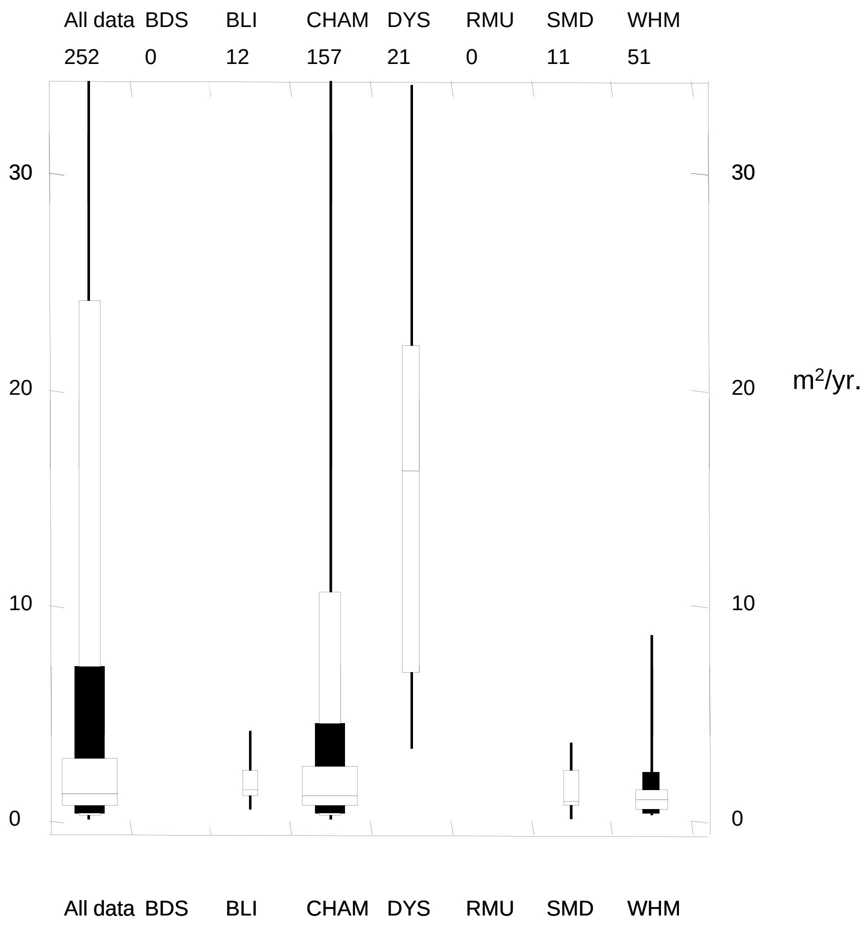
stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	264		12	167	23		12	50
min	0.16		0.80	0.24	2.05		0.16	0.30
0.005	0.26		0.80	0.31	2.08		0.20	0.31
0.025	0.41		0.82	0.41	2.19		0.35	0.41
0.1	0.67		0.89	0.65	5.79		0.86	0.72
0.25	1.00		1.03	0.92	7.12		1.05	0.97
0.5	**2.30**		**1.37**	**1.86**	**12.62**		**1.44**	**2.35**
0.75	5.42		3.43	4.20	17.48		3.63	5.50
0.9	11.75		9.28	7.92	24.51		4.61	9.85
0.975	29.26		10.41	32.22	30.00		5.19	19.16
0.995	42.16		10.62	45.62	31.74		5.36	19.65
max	59.90		10.67	59.90	32.18		5.40	19.71



Extended Whisker plot for Coefficient of Consolidation at 200 kPa

COEFFICIENT OF CONSOLIDATION, c_v $m^2/yr.$ at 800KPa

stats	*All data*	BDS	BLI	CHAM	DYS	RMU	SMD	WHM
count	252		12	157	21		11	51
min	0.05		0.50	0.10	3.39		0.05	0.28
0.005	0.12		0.52	0.16	3.39		0.07	0.29
0.025	0.26		0.61	0.25	3.40		0.15	0.31
0.1	0.39		0.92	0.40	3.49		0.44	0.38
0.25	0.73		1.16	0.71	6.87		0.76	0.58
0.5	**1.24**		**1.45**	**1.14**	**16.26**		**0.87**	**0.96**
0.75	2.86		2.36	2.50	22.06		2.36	1.46
0.9	7.18		4.00	4.51	29.81		3.05	2.26
0.975	24.10		4.17	10.57	33.91		3.46	6.25
0.995	33.99		4.20	26.95	34.05		3.57	8.25
max	34.30		4.21	34.30	34.08		3.60	8.62



Extended Whisker plot for Coefficient of Consolidation at 800 kPa

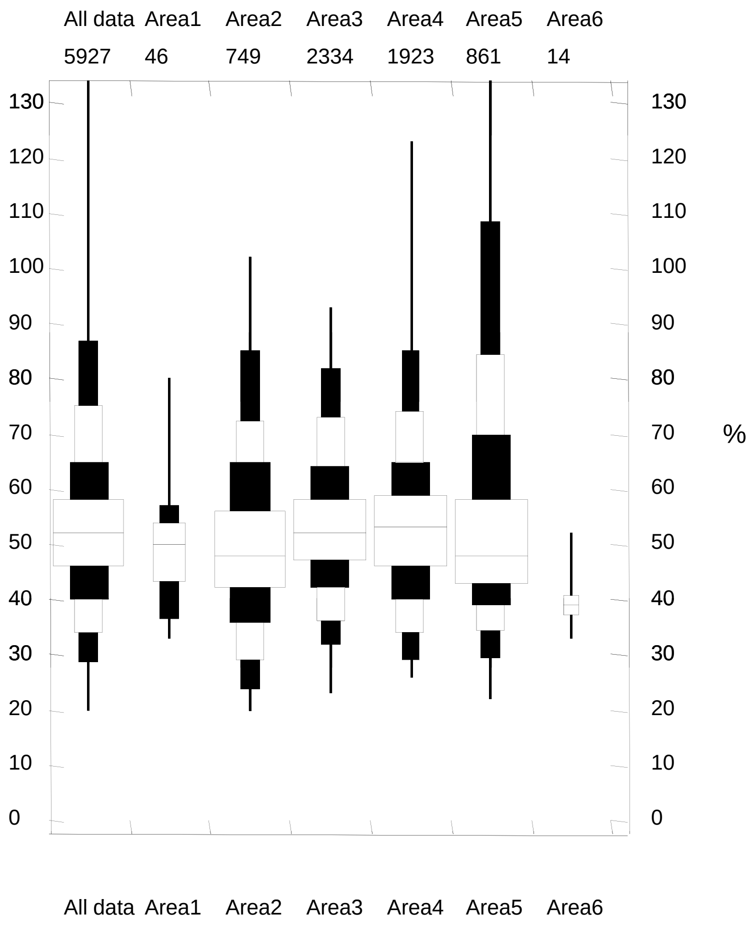
APPENDIX C

Extended box & whisker plots
[by Area]

LIQUID LIMIT, LL, %

stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	5927	46	749	2334	1923	861	14
min	20.0	33.0	20.0	23.0	26.0	22.0	33.0
0.005	28.6	33.2	23.7	32.0	29.0	29.3	33.0
0.025	34.0	34.0	29.0	36.0	34.0	34.5	33.0
0.1	40.0	36.5	35.8	42.0	40.2	39.0	33.0
0.25	46.0	43.3	42.0	47.0	46.0	43.0	37.3
0.5	**52.0**	**50.0**	**48.0**	**52.0**	**53.0**	**48.0**	**39.0**
0.75	58.0	53.8	56.0	58.0	59.0	58.0	40.8
0.9	65.0	57.0	65.0	64.0	65.0	70.0	43.7
0.975	75.0	71.3	72.3	73.0	74.0	84.5	49.4
0.995	87.0	78.2	85.0	82.0	85.0	108.4	51.5
max	134.0	80.0	102.0	93.0	123.0	134.0	52.0

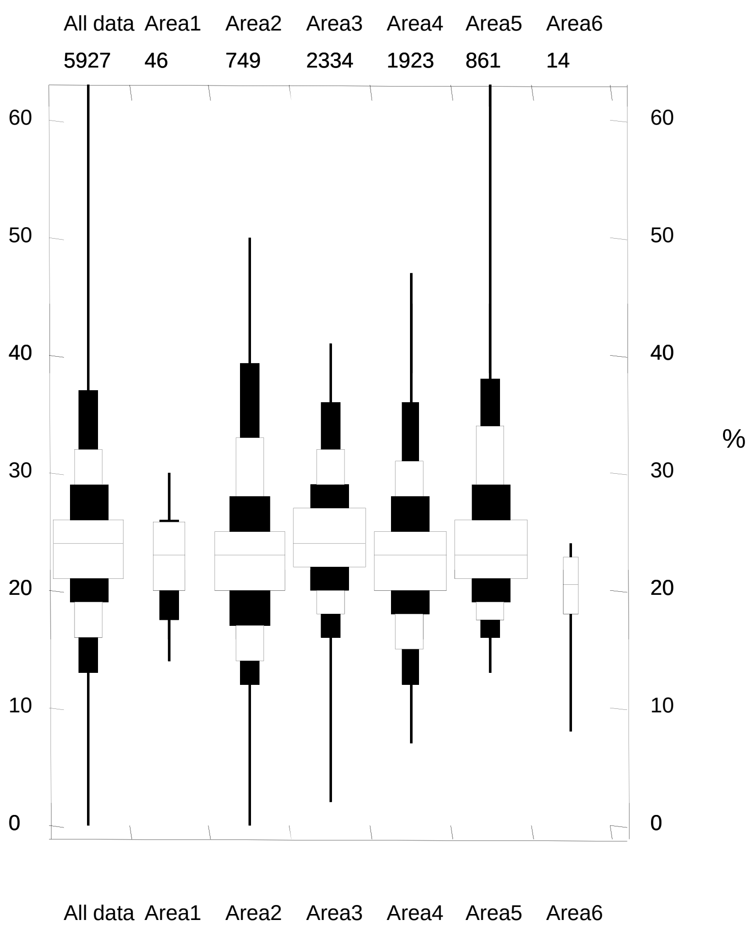
(Area spans Area1–Area6.)



Extended Box & Whisker plot for Liquid Limit, LL

PLASTIC LIMIT, PL, %

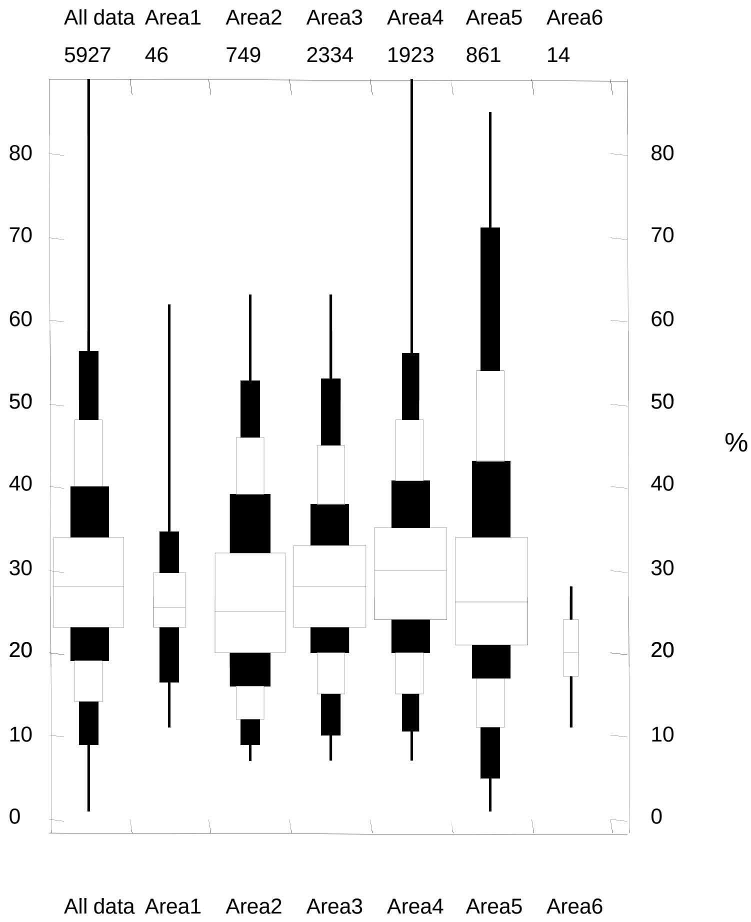
		Area					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	5927	46	749	2334	1923	861	14
min	0.0	14.0	0.0	2.0	7.0	13.0	8.0
0.005	13.0	14.2	12.0	16.0	12.0	16.0	8.1
0.025	16.0	15.1	14.0	18.0	15.0	17.5	8.7
0.1	19.0	17.5	17.0	20.0	18.0	19.0	10.3
0.25	21.0	20.0	20.0	22.0	20.0	21.0	18.0
0.5	**24.0**	**23.0**	**23.0**	**24.0**	**23.0**	**23.0**	**20.5**
0.75	26.0	25.8	25.0	27.0	25.0	26.0	22.8
0.9	29.0	26.0	28.0	29.0	28.0	29.0	23.7
0.975	32.0	28.9	33.0	32.0	31.0	34.0	24.0
0.995	37.0	29.8	39.3	36.0	36.0	38.0	24.0
max	63.0	30.0	50.0	41.0	47.0	63.0	24.0



Extended Box & Whisker plot for Plastic Limit, PL

PLASTICITY INDEX, PI, %

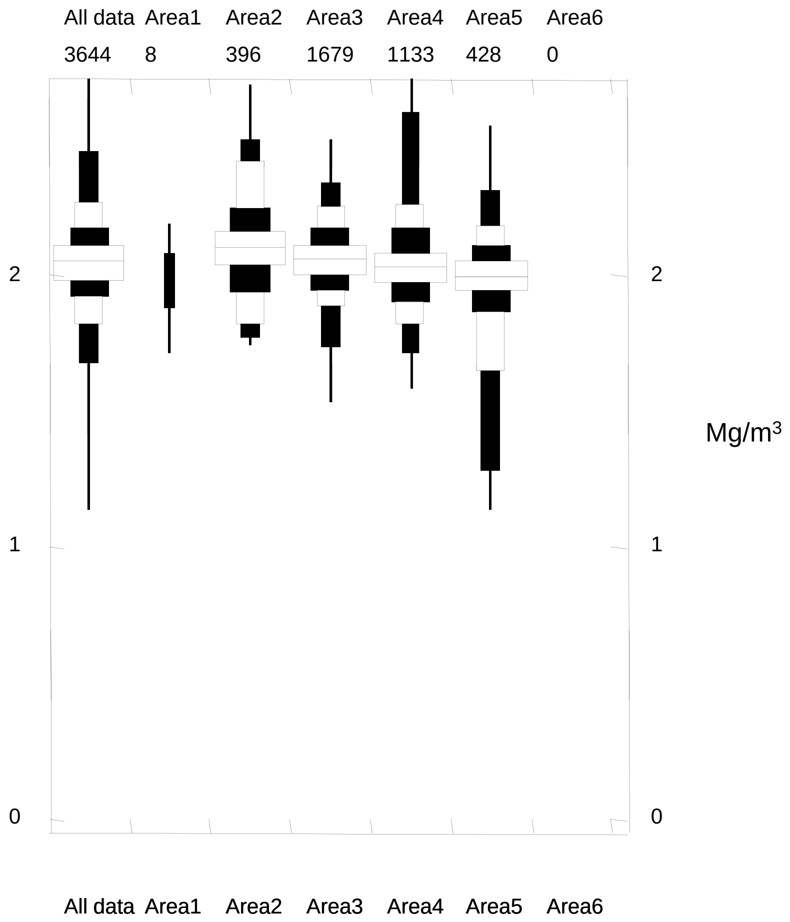
stats	*All data*	**Area** Area1	Area2	Area3	Area4	Area5	Area6
count	5927	46	749	2334	1923	861	14
min	1.0	11.0	7.0	7.0	7.0	1.0	11.0
0.005	9.0	11.0	9.0	10.0	10.6	5.0	11.3
0.025	14.0	11.0	12.0	15.0	15.0	11.0	12.3
0.1	19.0	16.5	16.0	20.0	20.0	17.0	15.0
0.25	23.0	23.0	20.0	23.0	24.0	21.0	17.3
0.5	**28.0**	**25.5**	**25.0**	**28.0**	**30.0**	**26.0**	**20.0**
0.75	34.0	29.8	32.0	33.0	35.0	34.0	24.0
0.9	40.0	34.5	39.0	38.0	40.8	43.0	28.0
0.975	48.0	43.5	46.0	45.0	48.0	54.0	28.0
0.995	56.4	58.0	52.8	53.0	56.0	71.0	28.0
max	89.0	62.0	63.0	63.0	89.0	85.0	28.0



Extended Box & Whisker plot for Plasticity Index, PI

BULK DENSITY, BD, Mg/m³

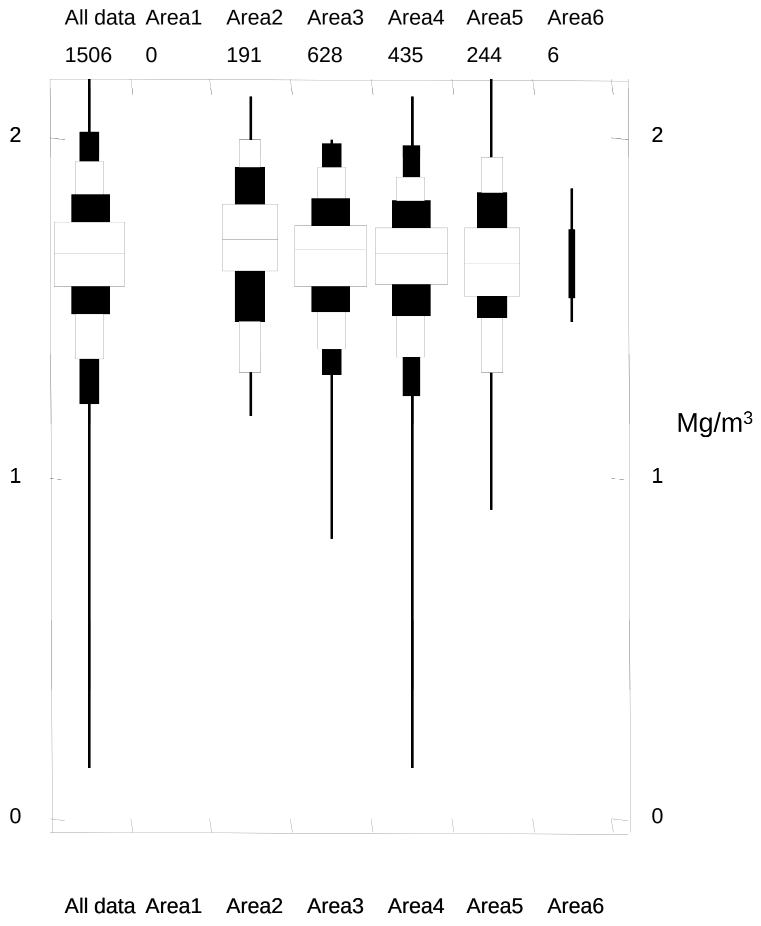
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	3644	8	396	1679	1133	428	
min	1.14	1.71	1.74	1.53	1.58	1.14	
0.005	1.68	1.71	1.77	1.73	1.71	1.28	
0.025	1.82	1.72	1.82	1.88	1.82	1.65	
0.1	1.92	1.74	1.94	1.94	1.90	1.87	
0.25	1.98	1.88	2.04	2.00	1.97	1.94	
0.5	2.05	1.98	2.10	2.06	2.03	1.99	
0.75	2.11	2.09	2.16	2.11	2.08	2.05	
0.9	2.17	2.18	2.25	2.17	2.17	2.11	
0.975	2.27	2.19	2.42	2.25	2.26	2.18	
0.995	2.45	2.19	2.50	2.34	2.60	2.31	
max	2.72	2.19	2.70	2.50	2.72	2.55	



Extended Box & Whisker plot for Bulk Density, BD

DRY DENSITY Mg/m³

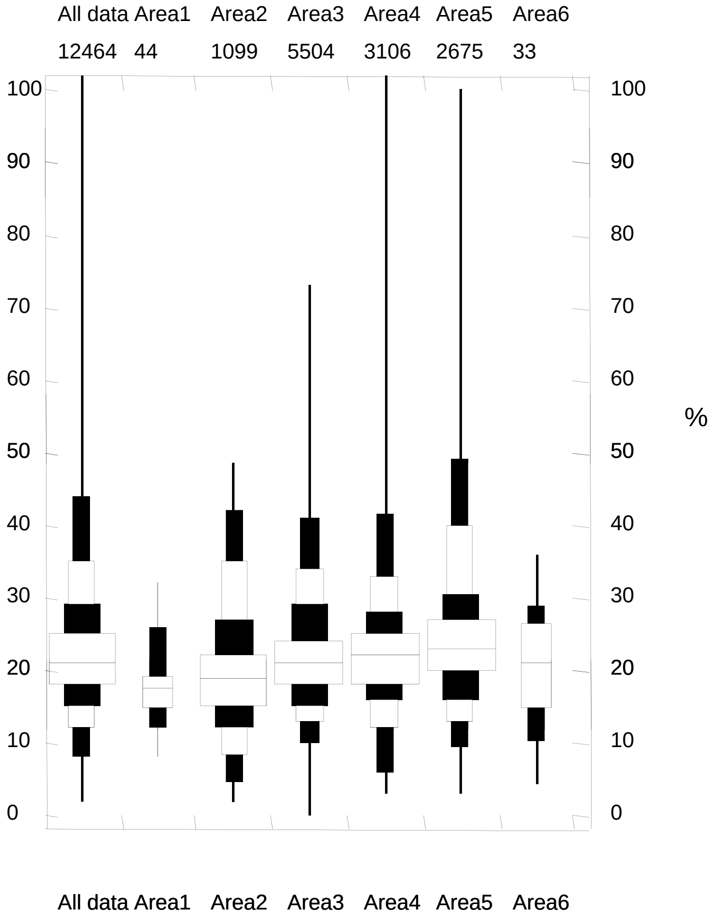
		Area					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	1506		191	628	435	244	6
min	0.15		1.18	0.82	0.15	0.90	1.46
0.005	1.22		1.21	1.30	1.24	1.08	1.46
0.025	1.35		1.31	1.38	1.35	1.31	1.46
0.1	1.48		1.46	1.49	1.48	1.47	1.46
0.25	1.56		1.61	1.56	1.57	1.53	1.50
0.5	1.66		1.70	1.67	1.66	1.63	1.63
0.75	1.75		1.80	1.74	1.74	1.74	1.67
0.9	1.83		1.91	1.82	1.81	1.84	1.76
0.975	1.93		2.00	1.91	1.88	1.94	1.83
0.995	2.01		2.12	1.98	1.98	2.10	1.84
max	2.17		2.12	1.99	2.12	2.17	1.85



Extended Whisker plot for DD

NATURAL WATER CONTENT, NWC, %

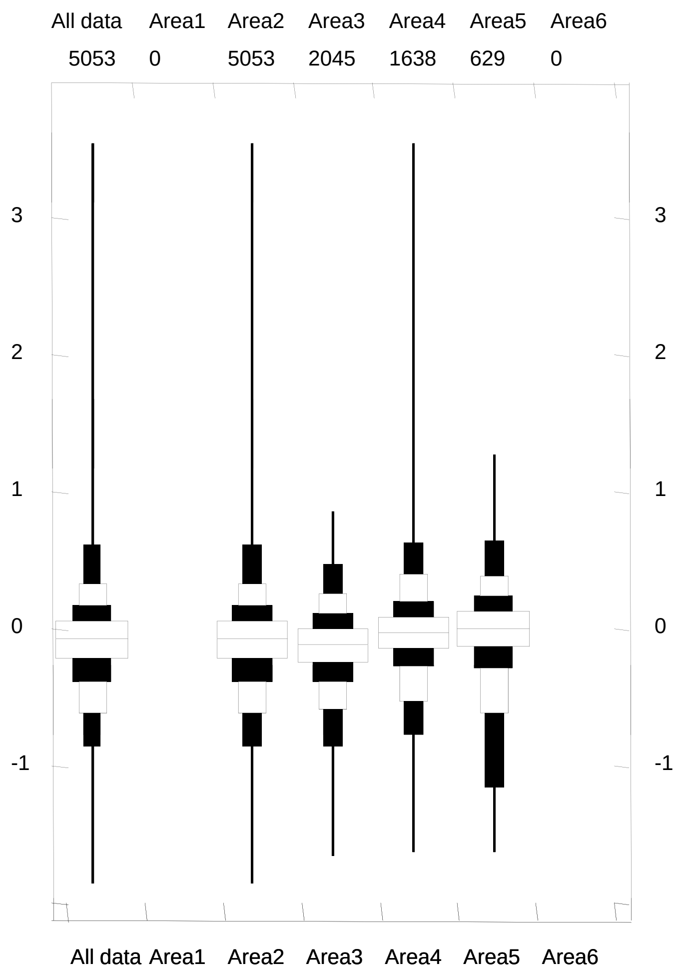
		Area					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	12464	44	1099	5504	3106	2675	33
min	2.00	8.00	2.00	0.00	3.00	3.00	4.30
0.005	8.00	8.65	4.49	10.00	5.86	9.37	4.96
0.025	12.00	11.08	8.45	13.00	12.00	13.00	7.58
0.1	15.00	12.00	12.00	15.00	16.00	16.00	10.32
0.25	18.00	14.75	15.05	18.00	18.00	20.00	14.80
0.5	**21.00**	**17.50**	**19.00**	**21.00**	**22.00**	**23.00**	**21.00**
0.75	25.00	19.25	22.00	24.00	25.00	27.00	26.40
0.9	29.00	26.00	27.00	29.00	28.00	30.60	28.92
0.975	35.00	28.93	35.00	34.00	33.00	40.00	35.52
0.995	44.00	31.36	42.00	41.00	41.47	49.00	35.90
max	102.00	32.00	48.60	73.00	102.00	100.00	36.00



Extended Box & Whisker plot for Natural Water Content, NWC

LIQUIDITY INDEX, LI, %

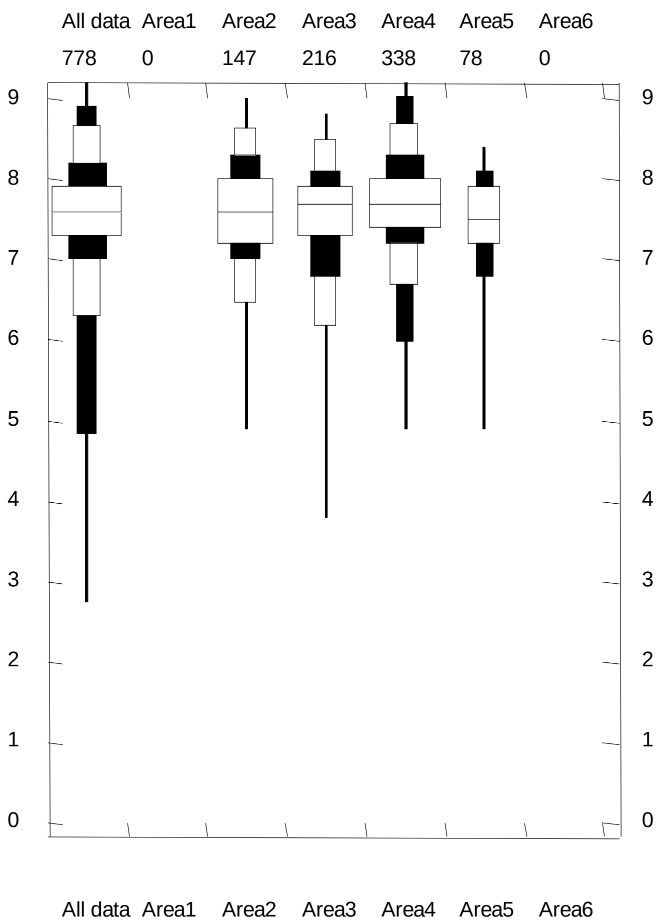
		Area					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	5053		5053	2045	1638	629	
min	-1.86		-1.86	-1.67	-1.64	-1.63	
0.005	-0.86		-0.86	-0.85	-0.77	-1.16	
0.025	-0.61		-0.61	-0.59	-0.53	-0.62	
0.1	-0.38		-0.38	-0.39	-0.28	-0.29	
0.25	-0.22		-0.22	-0.25	-0.15	-0.13	
0.5	**-0.07**		**-0.07**	**-0.12**	**-0.03**	**0.00**	
0.75	0.05		0.05	0.00	0.08	0.12	
0.9	0.17		0.17	0.11	0.20	0.24	
0.975	0.33		0.33	0.26	0.40	0.38	
0.995	0.61		0.61	0.47	0.62	0.65	
max	3.55		3.55	0.86	3.55	1.27	



Extended Box & Whisker plot for Liquidity Index, LI

pH

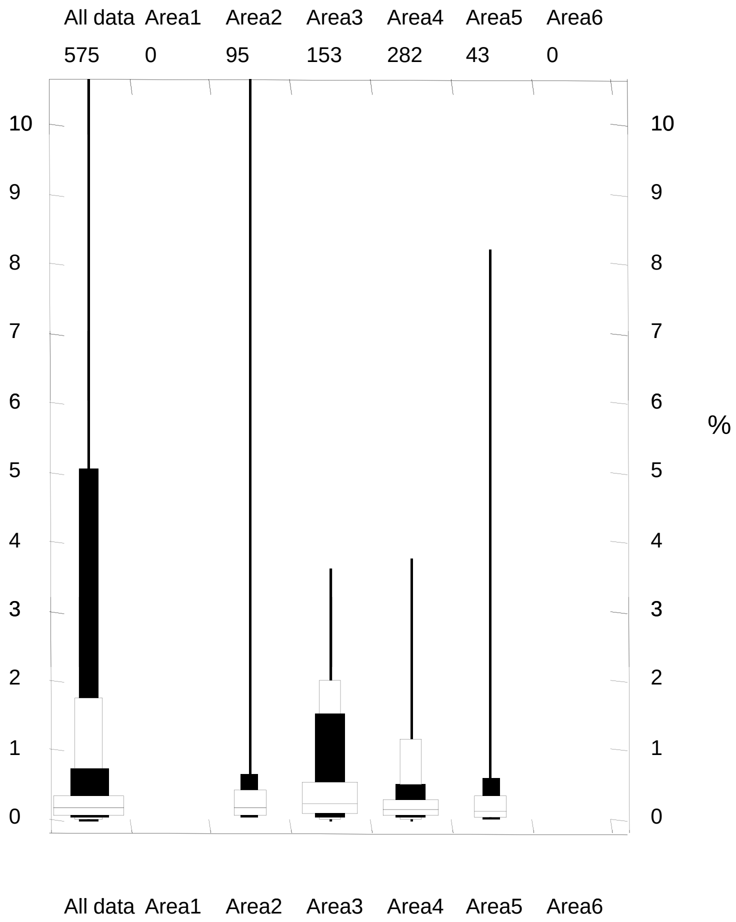
stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	778		147	216	338	78	
min	2.75		4.90	3.80	4.90	4.90	
0.005	4.84		5.12	4.22	5.98	4.90	
0.025	6.30		6.47	6.18	6.70	5.27	
0.1	7.00		7.00	6.80	7.20	6.78	
0.25	7.30		7.20	7.30	7.40	7.20	
0.5	**7.60**		**7.60**	**7.70**	**7.70**	7.50	
0.75	7.90		8.00	7.90	8.00	7.90	
0.9	8.20		8.30	8.10	8.30	8.10	
0.975	8.66		8.64	8.50	8.70	8.21	
0.995	8.91		8.93	8.79	9.03	8.36	
max	9.20		9.00	8.80	9.20	8.40	



Extended Box & Whisker plot for PH

TOTAL SULPHATE %

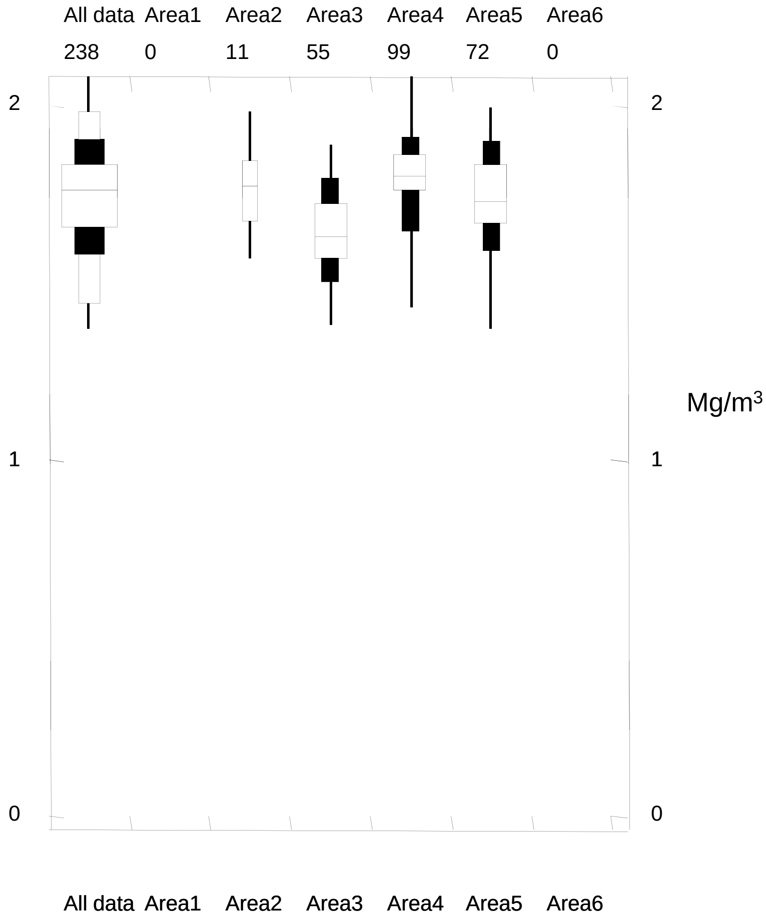
stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	575		95	153	282	43	
min	0.00		0.02	0.01	0.00	0.01	
0.005	0.01		0.02	0.01	0.00	0.01	
0.025	0.01		0.02	0.01	0.01	0.01	
0.1	0.02		0.04	0.03	0.01	0.02	
0.25	0.05		0.06	0.09	0.04	0.03	
0.5	**0.16**		**0.17**	**0.22**	**0.15**	0.11	
0.75	0.35		0.42	0.53	0.27	0.33	
0.9	0.72		0.66	1.52	0.50	0.58	
0.975	1.74		4.26	2.01	1.15	3.31	
0.995	5.04		8.14	2.78	2.38	7.18	
max	10.66		10.66	3.62	3.74	8.20	



Extended Box & Whisker plot for Total Sulphate, SO4TOT

COMPACTION - MAXIMUM DRY DENSITY, Mg/m^3

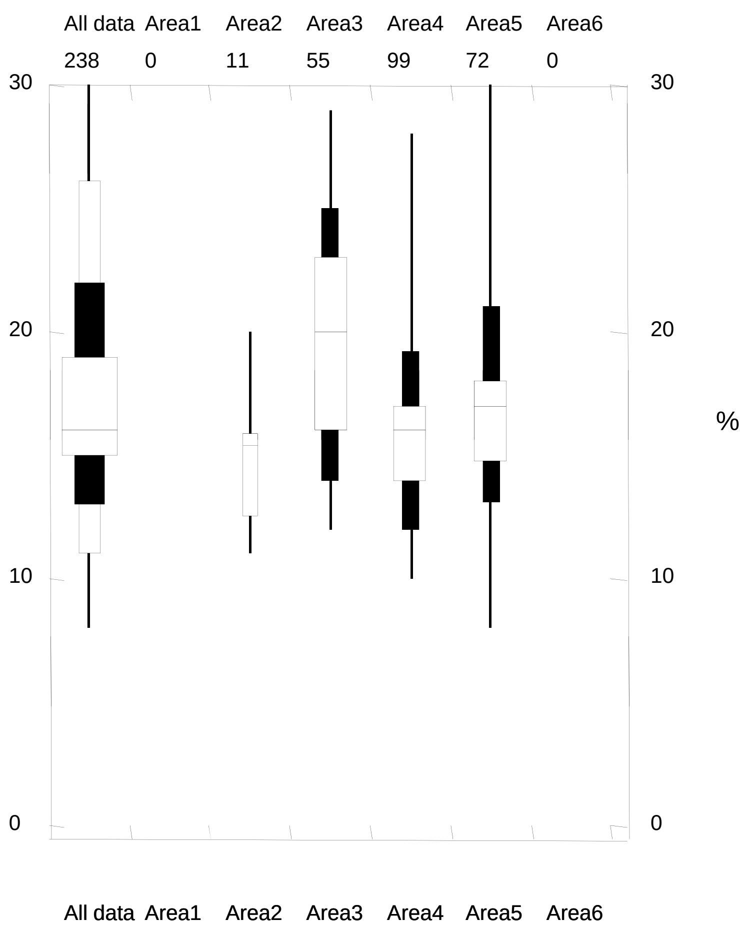
		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	238		11	55	99	72	
min	1.4		1.6	1.4	1.4	1.4	
0.005	1.4		1.6	1.4	1.4	1.4	
0.025	1.4		1.6	1.4	1.6	1.4	
0.1	1.6		1.7	1.5	1.6	1.6	
0.25	1.7		1.7	1.6	1.8	1.7	
0.5	**1.8**		**1.8**	**1.6**	**1.8**	1.7	
0.75	1.8		1.8	1.7	1.9	1.8	
0.9	1.9		1.9	1.8	1.9	1.9	
0.975	2.0		2.0	1.9	2.0	2.0	
0.995	2.0		2.0	1.9	2.1	2.0	
max	2.1		2.0	1.9	2.1	2.0	



Extended Box & Whisker plot for Compaction - Maximum Dry Density, MDD

COMPACTION - OPTIMUM WATER CONTENT %

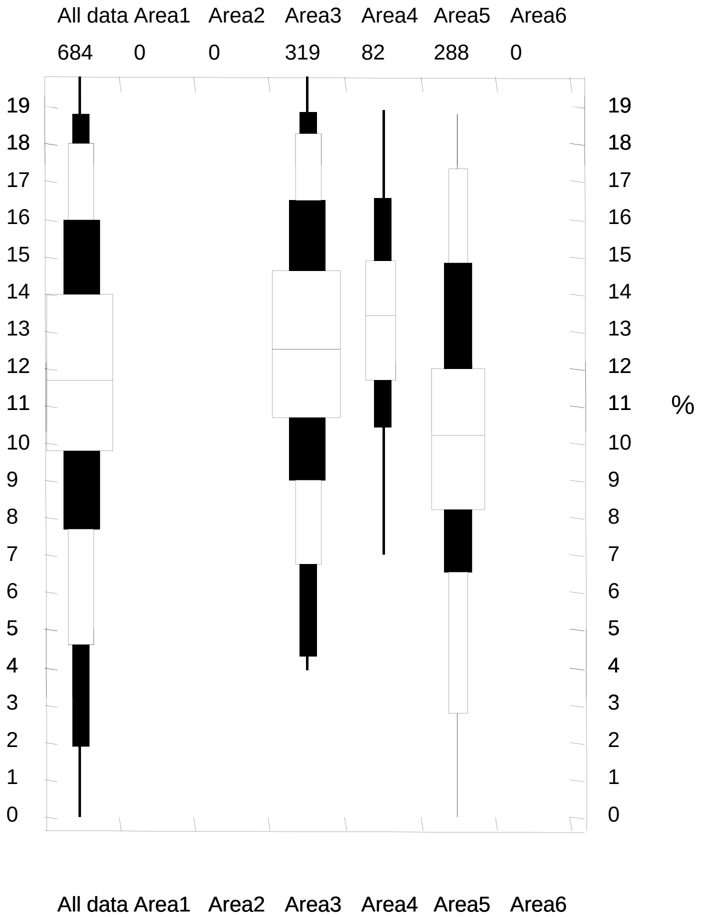
		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	238		11	55	99	72	
min	8.0		11.0	12.0	10.0	8.0	
0.005	10.0		11.0	12.3	10.0	8.7	
0.025	11.0		11.1	13.4	10.5	10.8	
0.1	13.0		11.5	14.0	12.0	13.1	
0.25	15.0		12.5	16.0	14.0	14.8	
0.5	**16.0**		**15.4**	**20.0**	**16.0**	17.0	
0.75	19.0		15.9	23.0	17.0	18.0	
0.9	22.0		18.4	25.0	19.2	21.0	
0.975	26.1		19.6	28.7	22.0	23.7	
0.995	29.0		19.9	29.0	27.0	28.6	
max	30.0		20.0	29.0	28.0	30.0	



Extended Whisker plot for Compaction - Optimum Water Content, OMC

MOISTURE CONDITION VALUE, MCV, %

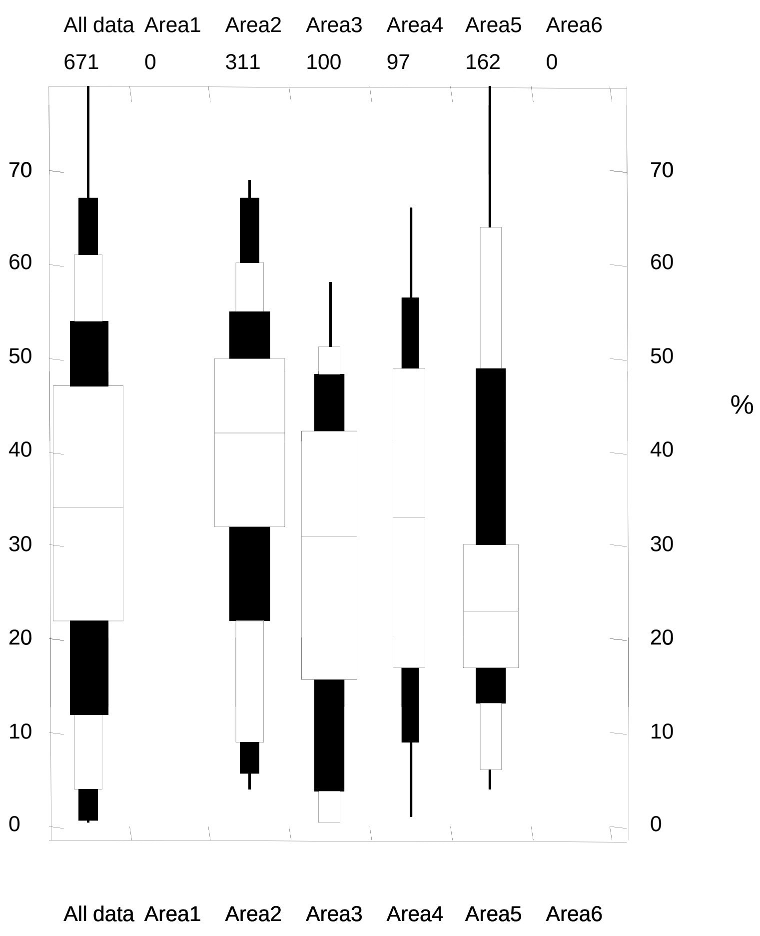
stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	684			319	82	288	
min	0.0			3.9	7.0	0.0	
0.005	1.9			4.3	7.3	0.8	
0.025	4.6			6.8	8.9	2.8	
0.1	7.7			9.0	10.4	6.5	
0.25	9.8			10.7	11.7	8.2	
0.5	**11.7**			**12.5**	**13.4**	10.2	
0.75	14.0			14.6	14.9	12.0	
0.9	16.0			16.5	16.6	14.8	
0.975	18.0			18.3	18.4	17.4	
0.995	18.8			18.9	18.7	18.1	
max	19.8			19.8	18.9	18.8	



Extended Box & Whisker plot for Moisture Condition Value, MCV

CLAY FRACTION, CLAY, %

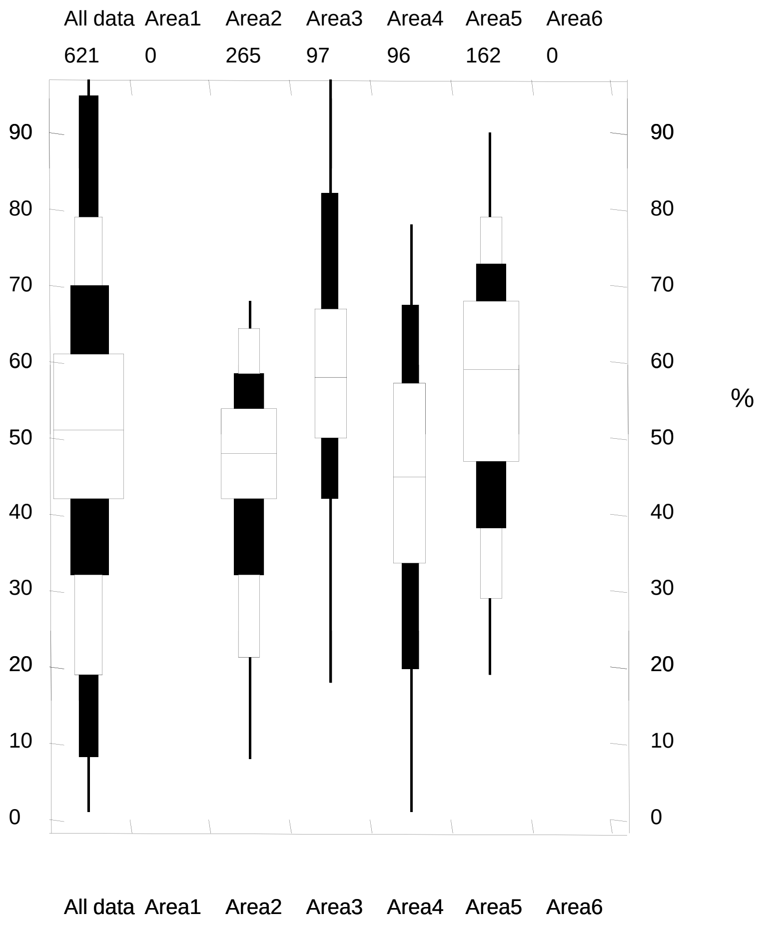
stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	671		311	100	97	162	
min	0.5		4.0	0.5	1.0	4.0	
0.005	0.7		5.6	0.5	1.5	4.8	
0.025	4.0		9.0	0.5	2.0	6.1	
0.1	12.0		22.0	3.8	9.0	13.1	
0.25	22.0		32.0	15.8	17.0	17.0	
0.5	**34.0**		**42.0**	**31.0**	**33.0**	23.0	
0.75	47.0		50.0	42.3	49.0	30.0	
0.9	54.0		55.0	48.4	56.4	49.0	
0.975	61.0		60.3	51.2	60.6	64.0	
0.995	67.0		67.0	56.0	65.0	72.6	
max	79.0		69.0	58.0	66.0	79.0	



Extended Box & Whisker plot for Clay Fraction, CLAY

SILT FRACTION, SILT, %

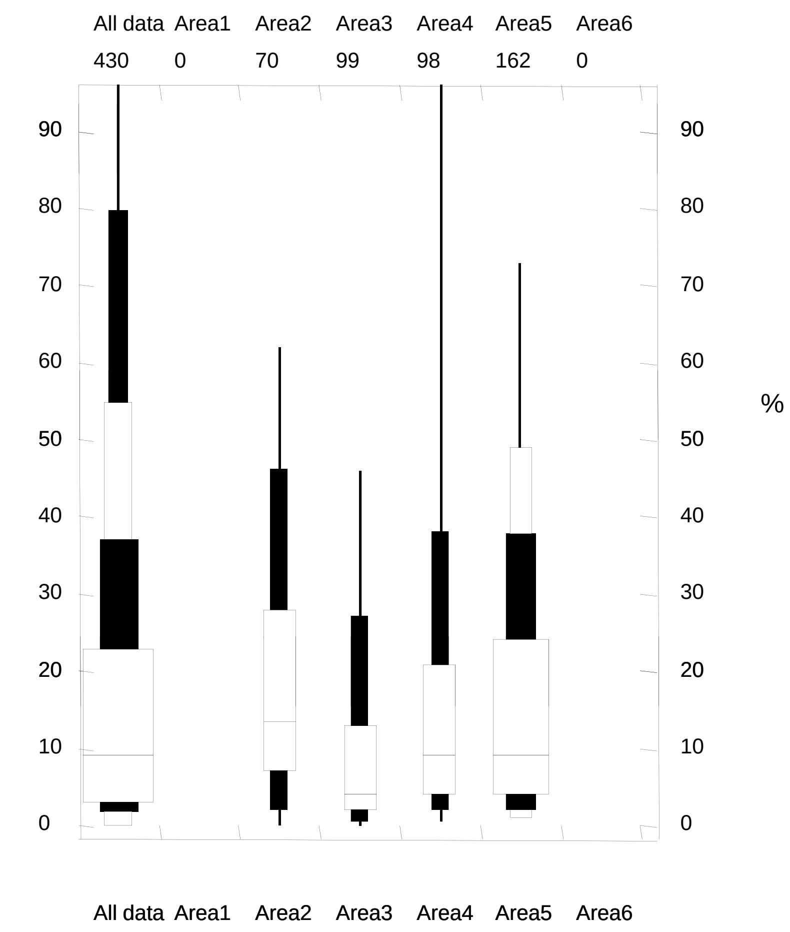
stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	621		265	97	96	162	
min	1.0		8.0	18.0	1.0	19.0	
0.005	8.3		15.0	19.9	1.0	19.8	
0.025	19.0		21.2	23.4	8.5	29.1	
0.1	32.0		32.0	42.0	19.7	38.1	
0.25	42.0		42.0	50.0	33.7	47.0	
0.5	**51.0**		**48.0**	**58.0**	**44.9**	59.0	
0.75	61.0		54.0	67.0	57.2	68.0	
0.9	70.0		58.6	82.0	67.5	73.0	
0.975	79.0		64.4	95.3	75.8	79.0	
0.995	94.9		67.4	96.8	77.2	86.0	
max	97.0		68.0	97.0	78.0	90.0	



Extended Box & Whisker plot for Silt Fraction, SILT

SAND FRACTION, SAND, %

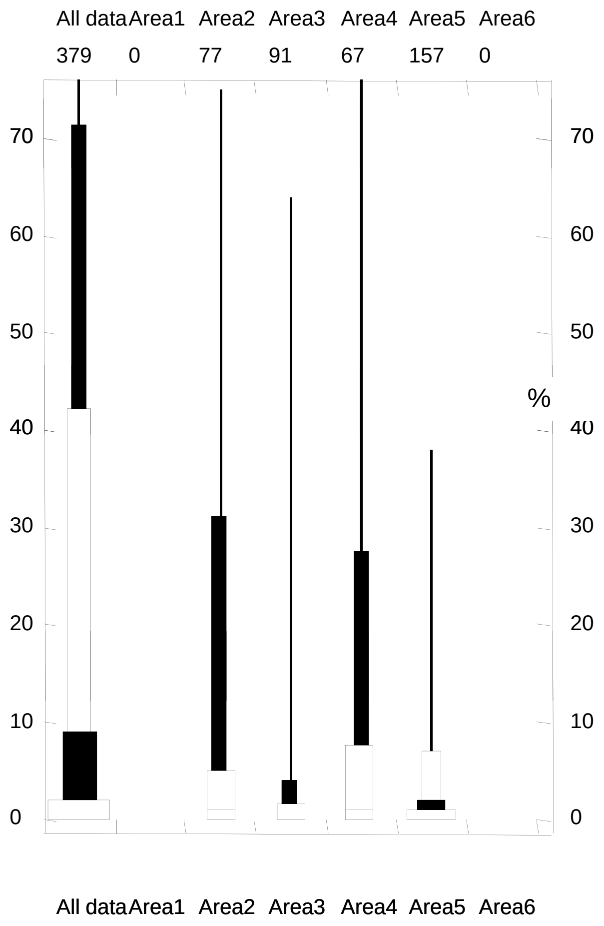
		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	430		70	99	98	162	
min	0.0		0.0	0.0	0.4	1.0	
0.005	0.0		0.0	0.0	0.5	1.0	
0.025	0.0		0.0	0.0	1.0	1.0	
0.1	1.7		2.0	0.6	2.0	2.0	
0.25	3.0		7.0	2.0	4.1	4.0	
0.5	**9.0**		**13.5**	**4.0**	**9.1**	**9.0**	
0.75	22.8		28.0	13.0	20.8	24.0	
0.9	37.0		46.2	27.2	38.1	37.9	
0.975	54.8		54.0	42.1	79.2	48.9	
0.995	79.7		59.2	46.0	96.0	60.1	
max	96.0		62.0	46.0	96.0	73.0	



Extended Box & Whisker plot for Sand Fraction, SAND

GRAVELFRACTION, GRAVEL, %

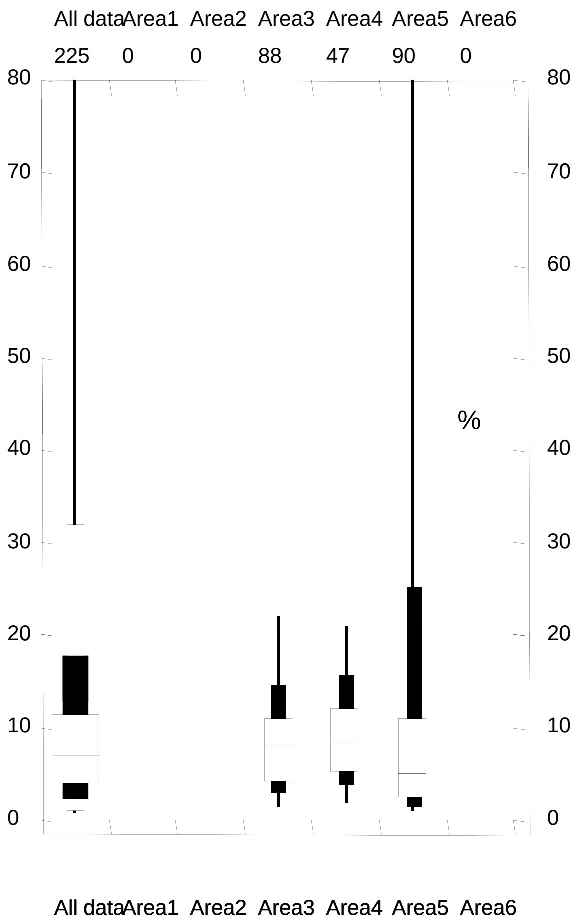
stats	All data	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	379		77	91	67	157	
min	0.0		0.0	0.0	0.0	0.0	
0.005	0.0		0.0	0.0	0.0	0.0	
0.025	0.0		0.0	0.0	0.0	0.0	
0.1	0.0		0.0	0.0	0.0	0.0	
0.25	0.0		0.0	0.0	0.0	0.0	
0.5	**0.0**		**1.0**	**0.0**	**1.0**	**0.0**	
0.75	2.0		5.0	1.5	7.7	1.0	
0.9	9.0		31.2	4.0	27.6	2.0	
0.975	42.2		58.3	15.5	50.8	7.1	
0.995	71.4		73.1	43.3	74.4	22.4	
max	76.0		75.0	64.0	76.0	38.0	



Extended Box & Whisker plot for Gravel Fraction, GRAVEL

CALIFORNIA BEARING RATIO (at NWC), %

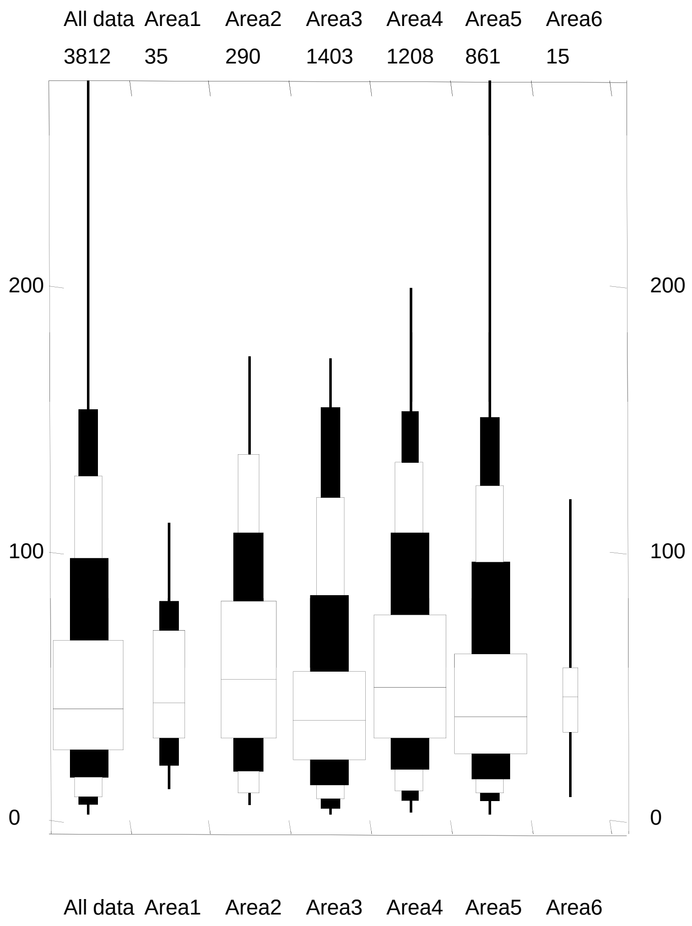
		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	225			88	47	90	
min	0.95			1.55	1.85	0.95	
0.005	1.00			1.72	2.02	0.97	
0.025	1.00			2.27	2.62	1.00	
0.1	2.29			2.93	3.80	1.49	
0.25	4.00			4.25	5.35	2.53	
0.5	**7.00**			**8.00**	**8.50**	5.00	
0.75	11.50			11.00	11.98	10.99	
0.9	17.80			14.50	15.70	25.25	
0.975	31.90			18.74	19.48	46.62	
0.995	58.80			21.06	20.69	71.10	
max	80.00			22.00	21.00	80.00	



Extended Box & Whisker plot for California Bearing Ratio, CBR (at NWC)

STANDARD PENETRATION TEST, SPT, N value, blows/300mm

		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	3812	35	290	1403	1208	861	15
min	2.0	12.0	6.0	2.0	3.0	2.0	9.0
0.005	6.0	13.2	7.0	4.0	7.0	7.0	9.3
0.025	9.0	18.0	10.0	8.0	11.0	10.0	10.4
0.1	16.0	20.8	18.0	13.0	19.0	15.0	17.4
0.25	26.0	31.0	31.0	22.5	31.0	25.0	33.0
0.5	**42.0**	**44.0**	**53.0**	**37.0**	**50.0**	39.0	**46.0**
0.75	67.0	71.0	82.0	56.0	77.0	62.0	57.0
0.9	98.0	82.0	108.0	84.0	108.0	97.0	99.6
0.975	128.7	96.6	136.9	121.0	134.0	125.5	117.9
0.995	153.9	108.1	161.8	154.9	152.9	151.0	119.6
max	277.0	111.0	174.0	173.0	199.0	277.0	120.0

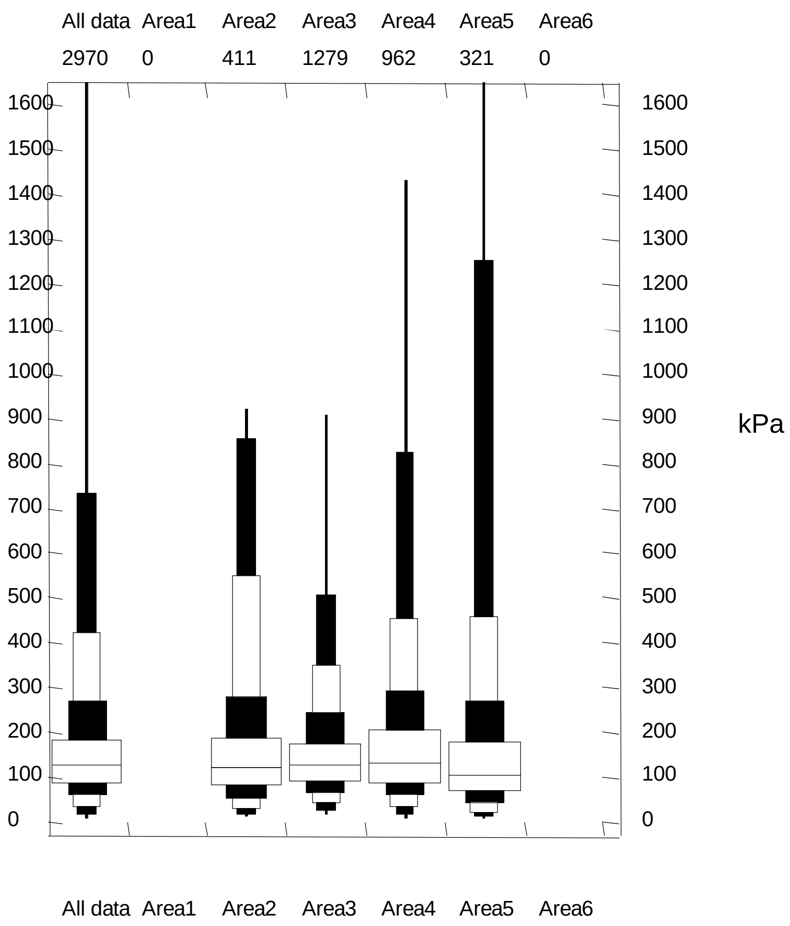


N value, blows/300 mm

Extended Box & Whisker plot for Standard Penetration test, SPT

TRIAXIAL - Total Cohesion, Cu, kPa

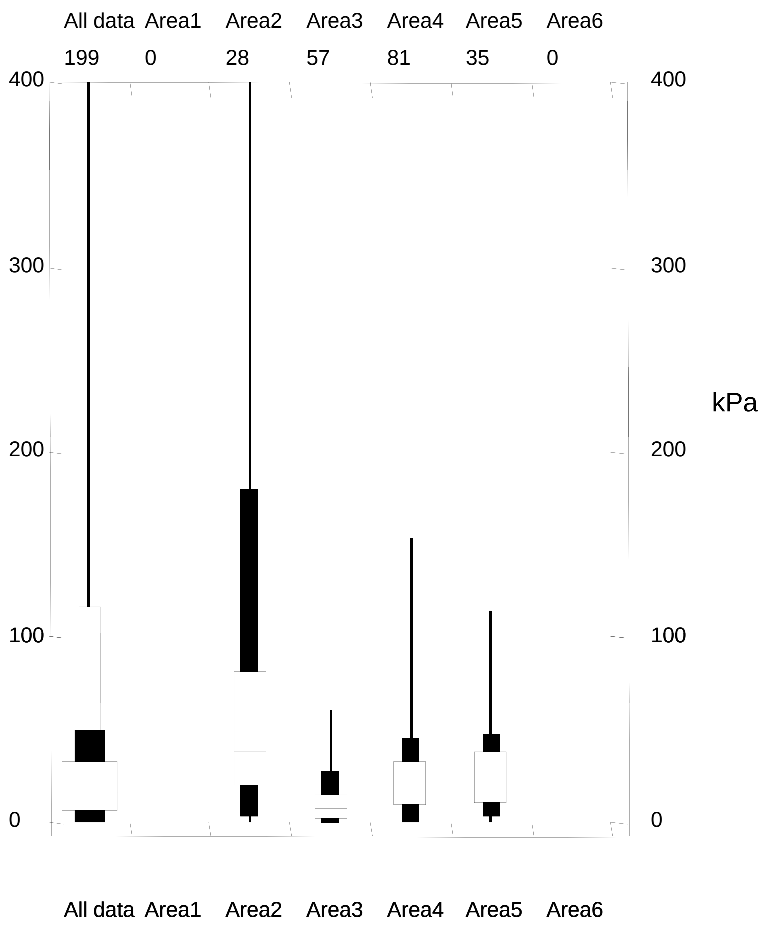
		AREA					
stats	*All data*	Area1	Area2	Area3	Area4	Area5	Area6
count	2970		411	1279	962	321	
min	7.0		17.0	18.0	7.0	10	
0.005	19.0		19.1	25.0	18.4	12.2	
0.025	35.0		30.0	43.0	36.0	22	
0.1	60.0		53.0	67.0	61.0	42	
0.25	86.0		84.0	91.0	89.0	68	
0.5	**125.0**		**120.0**	**125.0**	**131.0**	105	
0.75	183.0		187.5	175.0	204.0	180	
0.9	269.0		280.0	245.0	293.9	270	
0.975	424.0		550.0	350.0	454.7	460	
0.995	733.2		857.8	507.1	826.8	1254	
max	1650.0		920.0	908.0	1431.0	1650	



Extended Box & Whisker plot for Triaxial Total Cohesion, TX-CU

TRIAXIAL - Effective Cohesion, c', kPa

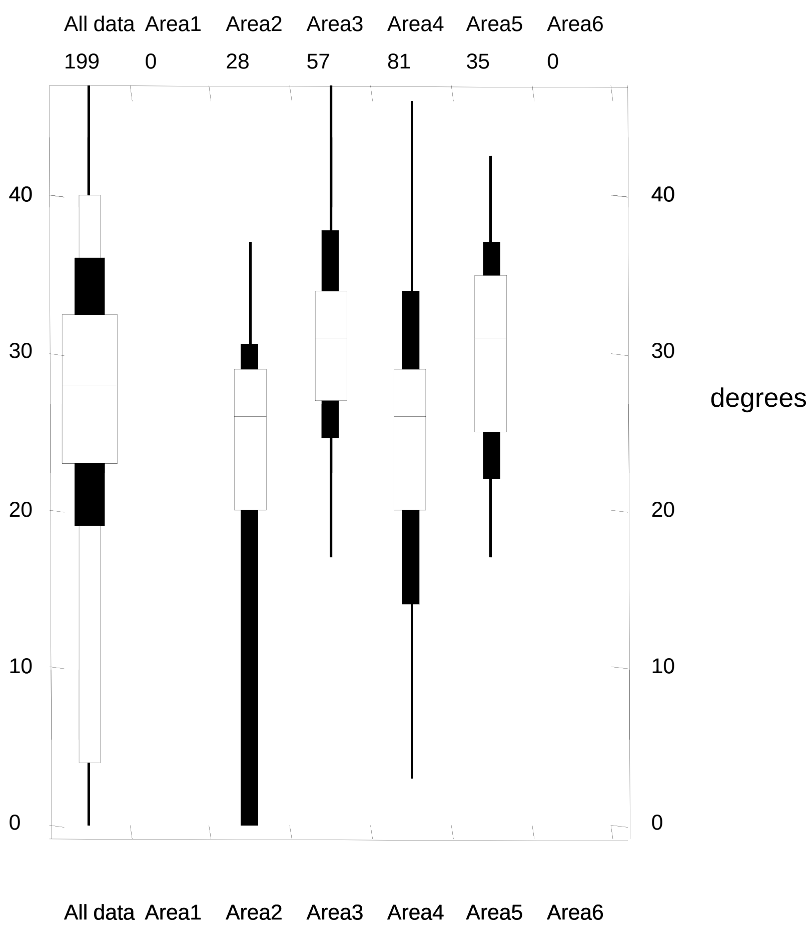
stats	All data	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	199		28	57	81	35	
min	0.0		0.0	0.0	0.0	0	
0.005	0.0		0.0	0.0	0.0	0	
0.025	0.0		0.0	0.0	0.0	0	
0.1	0.0		3.5	0.0	0.0	2.8	
0.25	6.0		19.5	2.0	9.0	11	
0.5	**16.0**		**37.5**	**7.0**	**19.0**	16	
0.75	33.0		81.5	15.0	33.0	38.5	
0.9	50.0		180.0	27.0	45.0	47.2	
0.975	115.9		292.0	53.0	77.0	110.6	
0.995	241.6		378.4	58.6	125.0	113.32	
max	400.0		400.0	60.0	153.0	114	



Extended Box & Whisker plot for Triaxial Effective Cohesion, TX-C

TRIAXIAL - Effective Friction angle, ϕ', degrees

stats	*All data*	AREA Area1	Area2	Area3	Area4	Area5	Area6
count	199		28	57	81	35	
min	0.0		0.0	17.0	3.0	17.0	
0.005	0.0		0.0	17.8	3.4	17.8	
0.025	4.0		0.0	20.8	4.0	20.8	
0.1	19.0		0.0	24.6	14.0	22.0	
0.25	23.0		20.0	27.0	20.0	25.0	
0.5	**28.0**		**26.0**	**31.0**	**26.0**	**31.0**	
0.75	32.5		29.0	34.0	29.0	35.0	
0.9	36.0		30.6	37.8	34.0	37.0	
0.975	40.0		36.3	40.6	39.0	39.5	
0.995	46.0		36.9	45.3	43.2	41.9	
max	47.0		37.0	47.0	46.0	42.5	



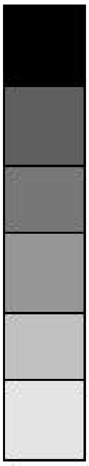
Extended Box & Whisker plot for Triaxial Effective Friction Angle, TX-PHI

APPENDIX D1

Weathering classes

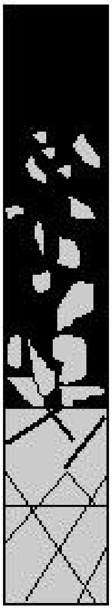
Classification of weathering (BS5930, 1999)

Weathering Classification for uniformly weathering rocks.



Grade	Description	Typical characteristics
VI	Residual soil	Soil derived from *in situ* weathering and lost original texture and fabric.
V	Completely weathered	Considerably weakened, slakes. Original textured apparent.
IV	Highly weathered	Large pieces broken by hand. Does not readily slake.
III	Moderately weathered	Considerably weakened, penetrative discolouration. Large pieces cannot be broken by hand.
II	Slightly weathered	Slight discolouration, slight weakening.
I	Fresh	Unchanged

Weathering Classification for heterogeneous masses



6	100% Material Grades IV-VI not necessarily all residual soil	May behave as soil although relict fabric may still be significant
5	<30% Material Grades I-III 70-100% Material Grades IV-VI	Weak grades will control behaviour. Corestones significant for investigation and construction.
4	30-50% Material Grades I-III 50-70% Material Grades IV-VI	Rock framework contributes to strength; Matrix or weathered discontinuities controls E, k.
3	50 to 90% Material Grades I-III 10 to 50% Material Grades IV-VI	Rock fragments still locked, controls strength and E, matrix controls k.
2	>90% Material Grades I-III <10% Material Grades IV-VI	Weak materials along discontinuities. Shear strength, E, k affected
1	100% Material Grades I-III (not necessarily all fresh rock)	Behaves as rock; apply rock mechanics principles to mass assessment.

Key

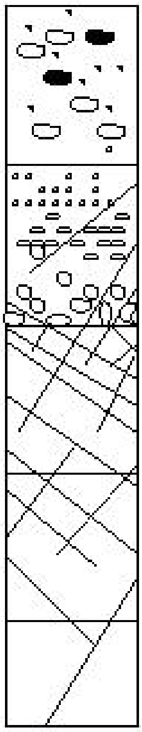
Material too strong to be broken by hand.

Material can be broken by hand.

E Stiffness

k permeability

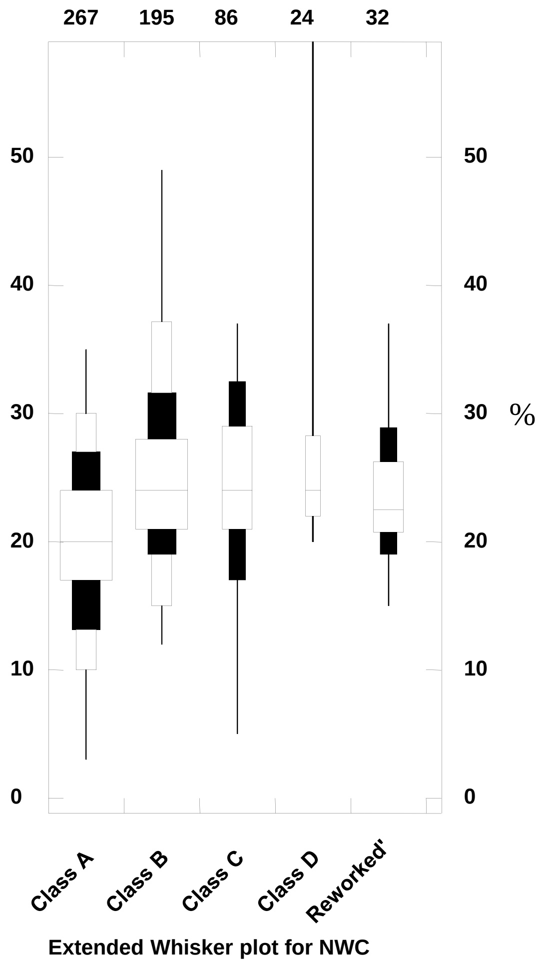
Weathering classification for material and mass features



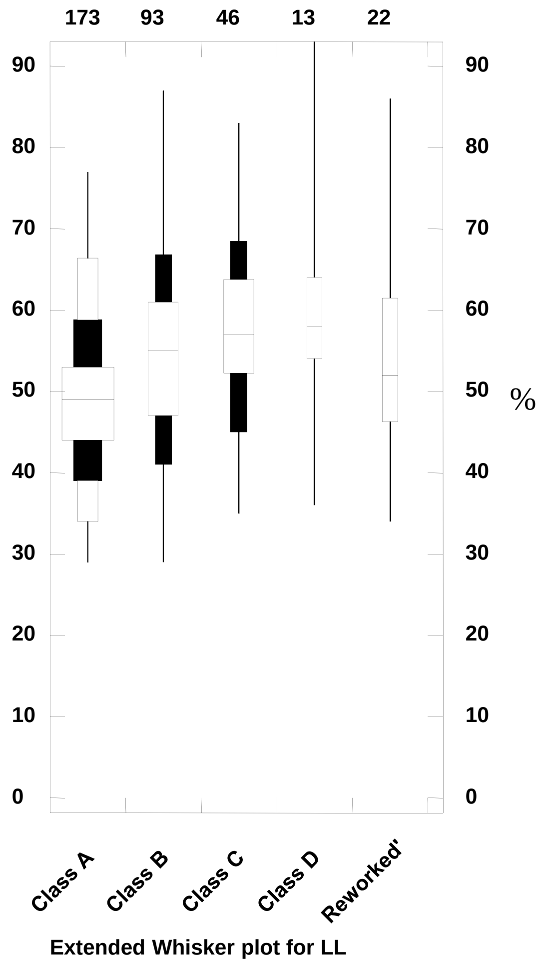
Class	Descriptor	Typical characteristics
E	Residual or reworked	Matrix with occasional altered random lithorelicts, bedding destroyed. Reworked - contains foreign inclusions.
D	Destructed	Greatly weakened, mottled, lithorelicts in matrix becoming weakened and disordered, bedding disrupted.
C	Distinctly weathered	Further weakened, much closer fracture spacing, grey reduction.
B	Partially weathered	Slight strength reduction, closer fracture spacing, weathering penetrating from fractures, oxidation.
A	Unweathered	Original strength, colour, fracture spacing.

APPENDIX D2

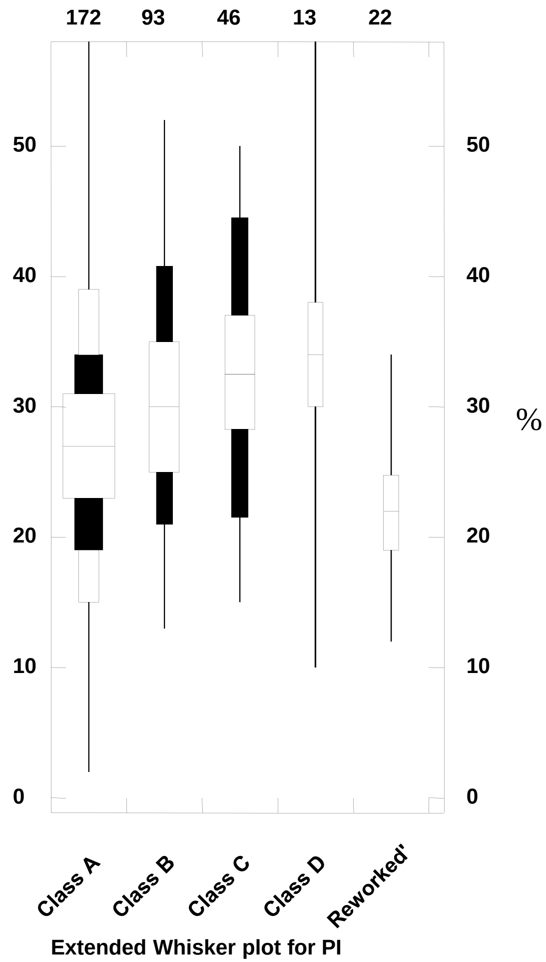
Extended box & whisker plots
[by weathering class and Formation]



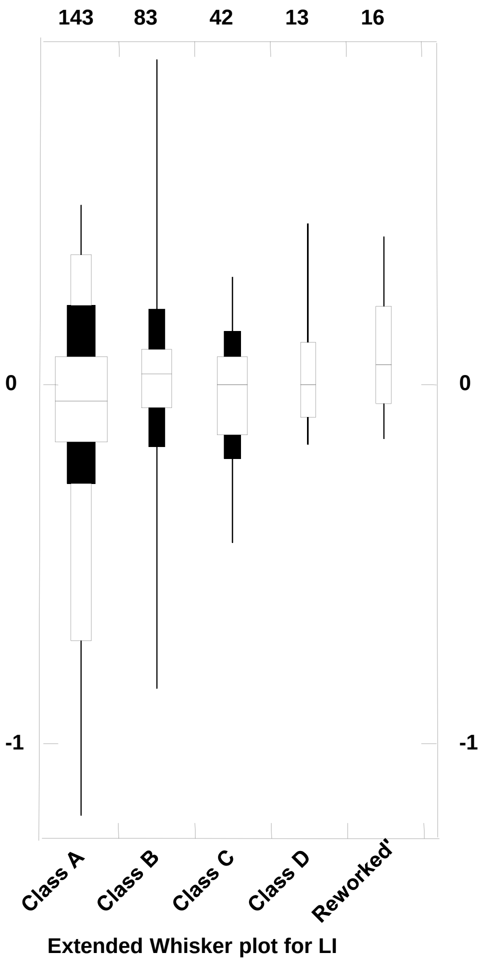
Box and whisker plot of Natural Water Content Blue Lias Formation



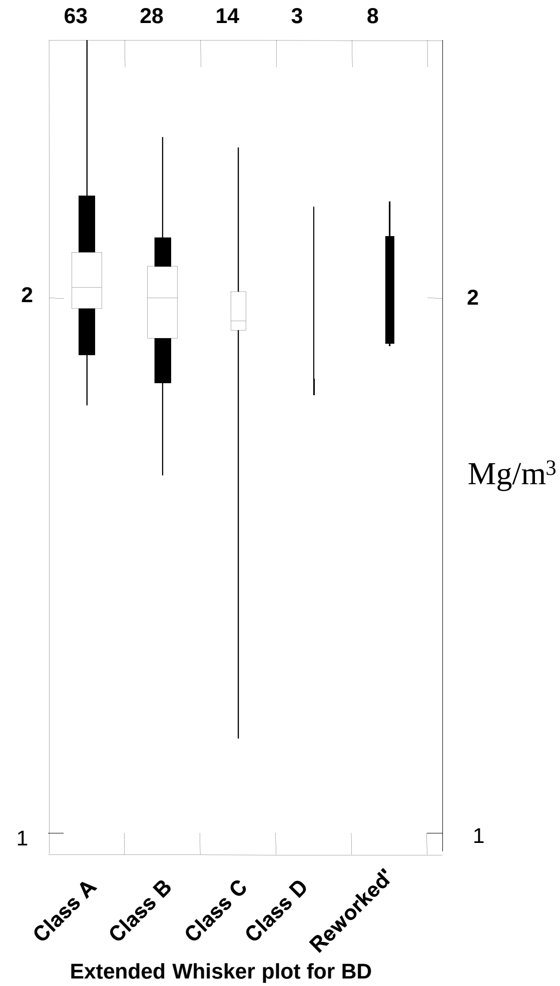
Box and whisker plot of Liquid Limit Blue Lias Formation



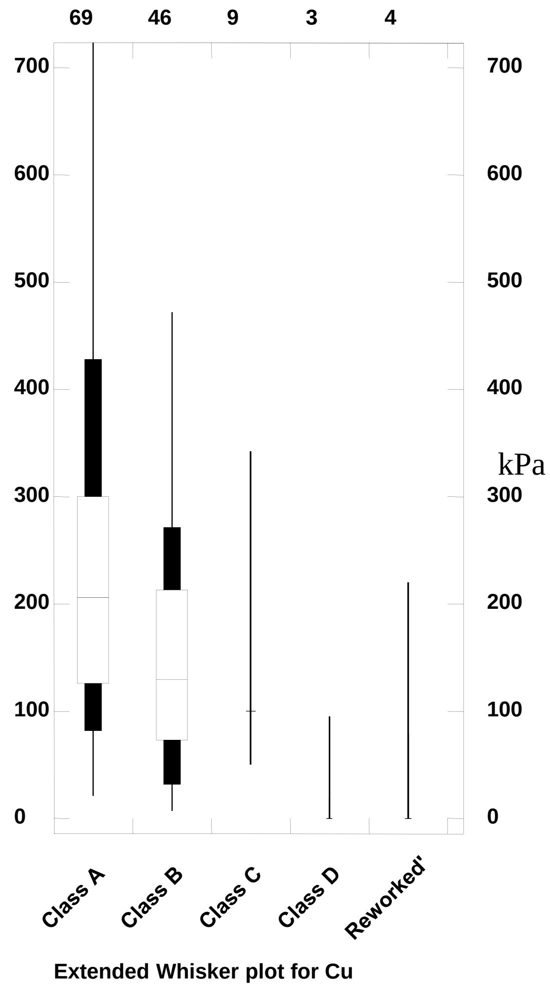
Box and whisker plot of Plasticity Index of Blue Lias Formation



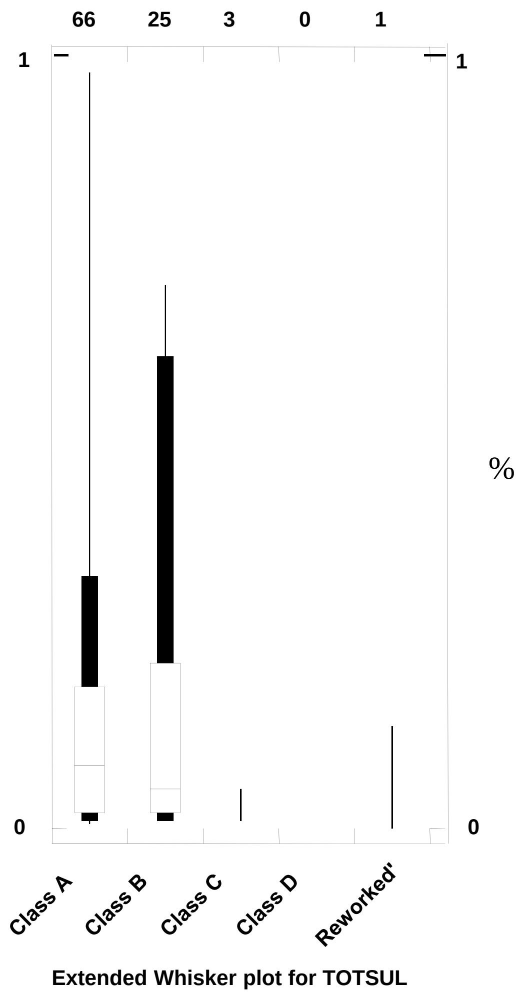
Box and whisker plot of Liquidity Index of Blue Lias Formation



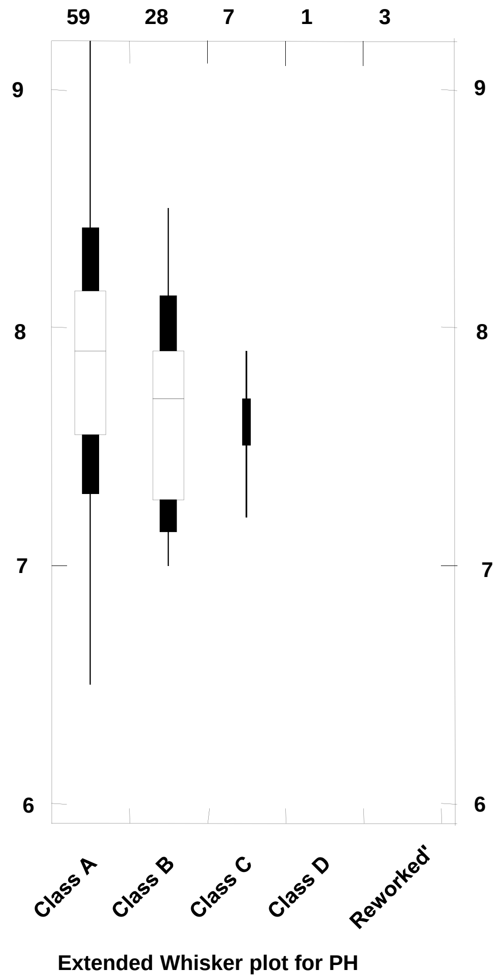
Box and whisker plot of Bulk Density of Blue Lias Formation



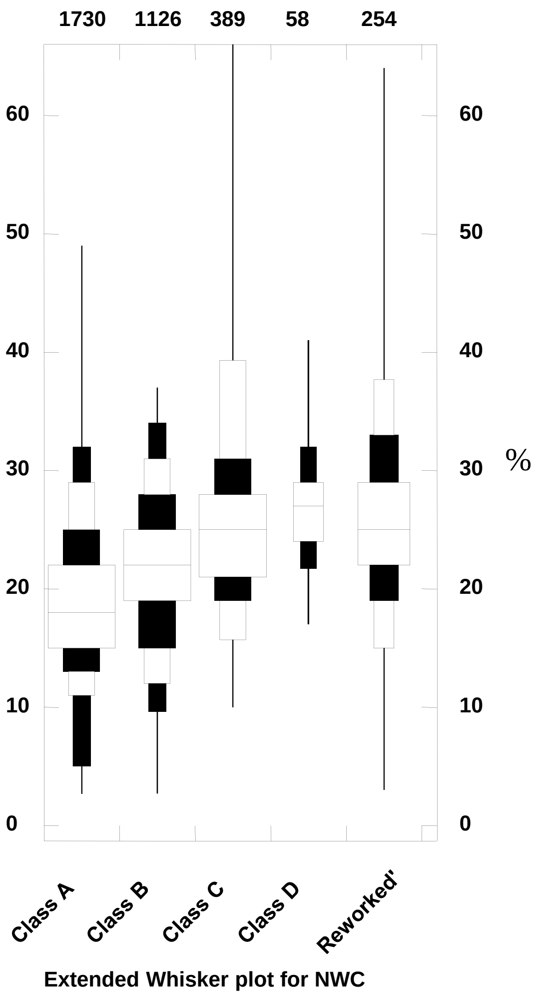
Box and whisker plot of Cohesion of Blue Lias Formation



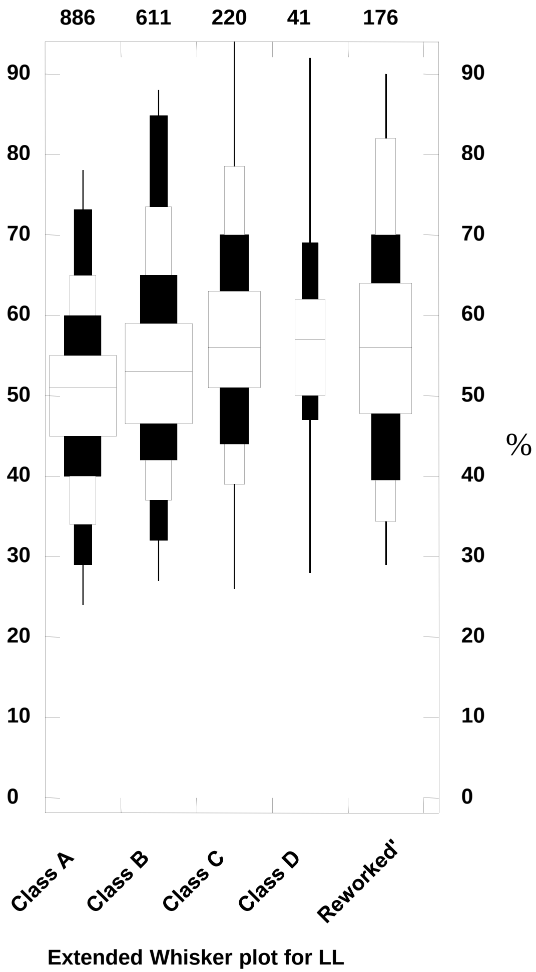
Box and whisker plot of Total sulphate of Blue Lias Formation



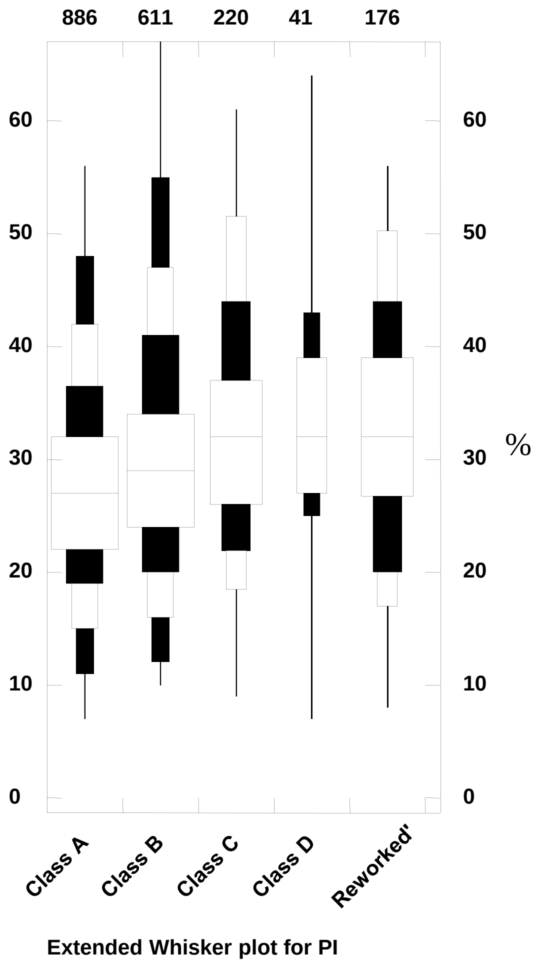
Box and whisker plot of pH of Blue Lias Formation



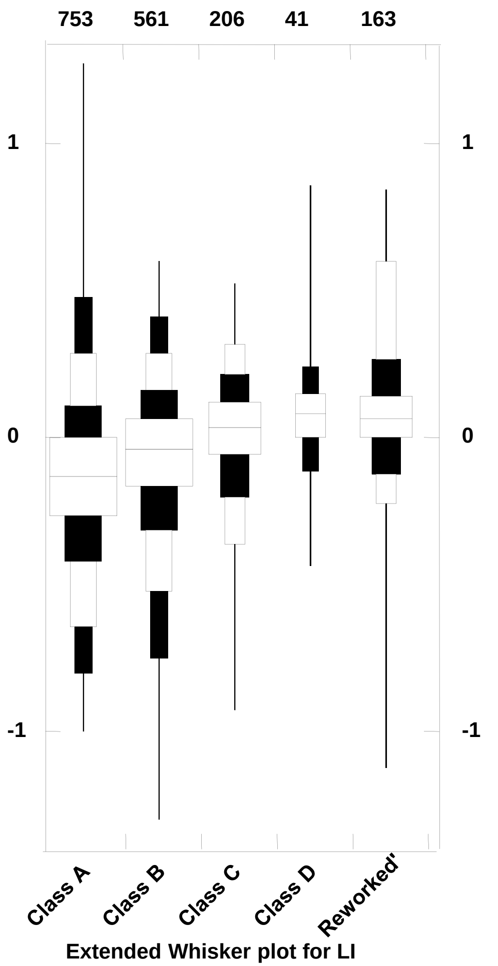
Box and whisker plot of Natural Water Content Charmouth Mudstone Formation



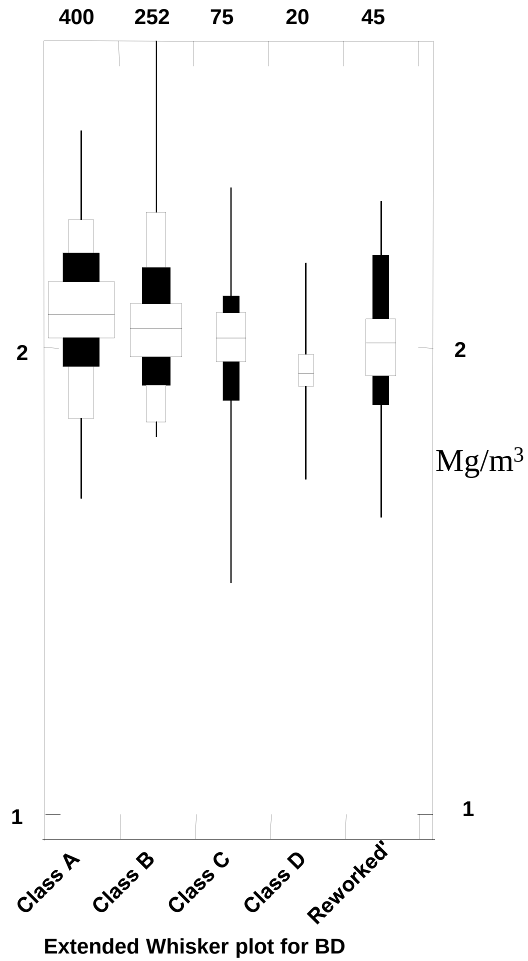
Box and whisker plot of Liquid Limit of Charmouth Mudstone Formation



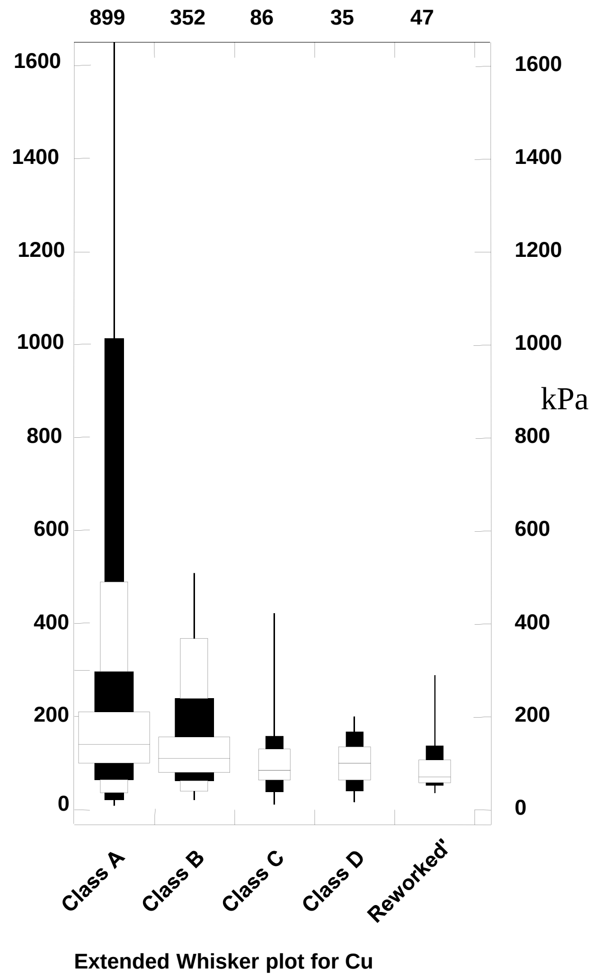
Box and whisker plot of Plasticity Index of Charmouth Mudstone Formation



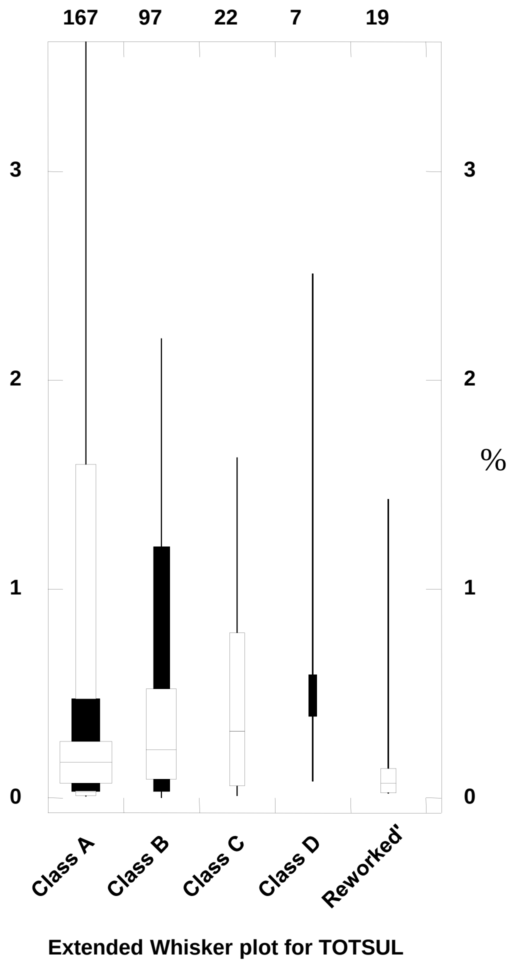
Box and whisker plot of Liquidity Index of Charmouth Mudstone Formation



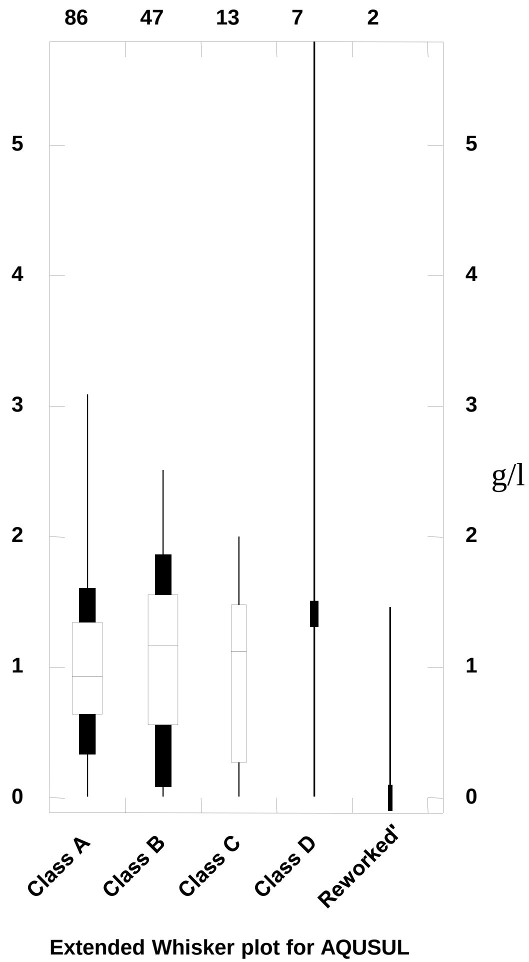
Box and whisker plot of Bulk Density of Charmouth Mudstone Formation



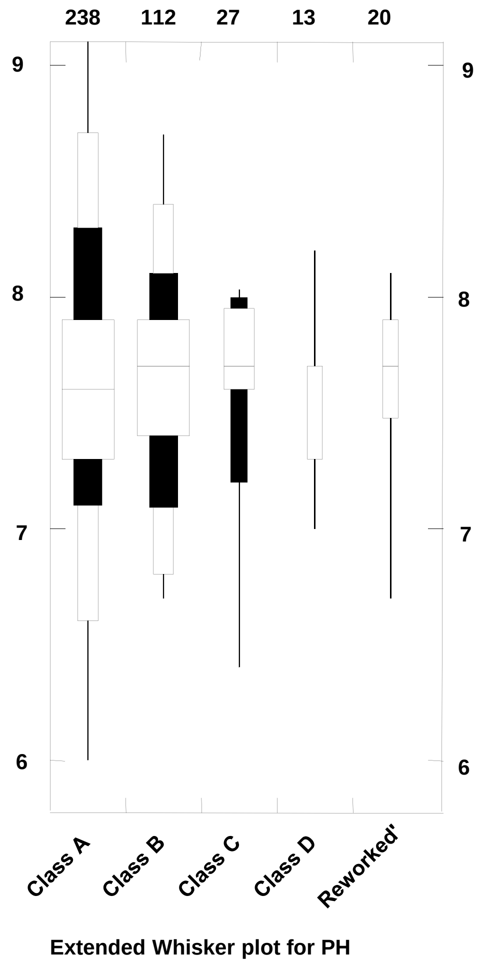
Box and whisker plot of Cohesion of Charmouth Mudstone Formation



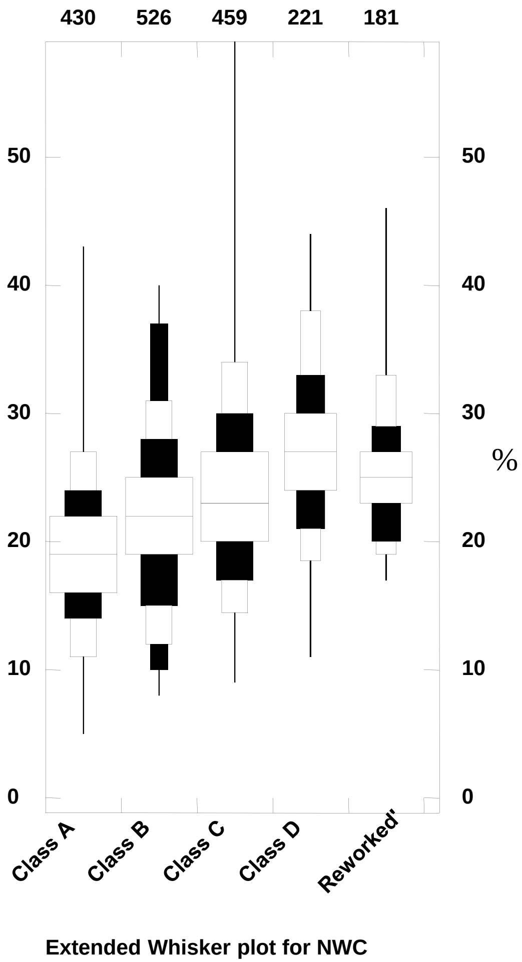
Box and whisker plot of Total sulphate Charmouth Mudstone Formation



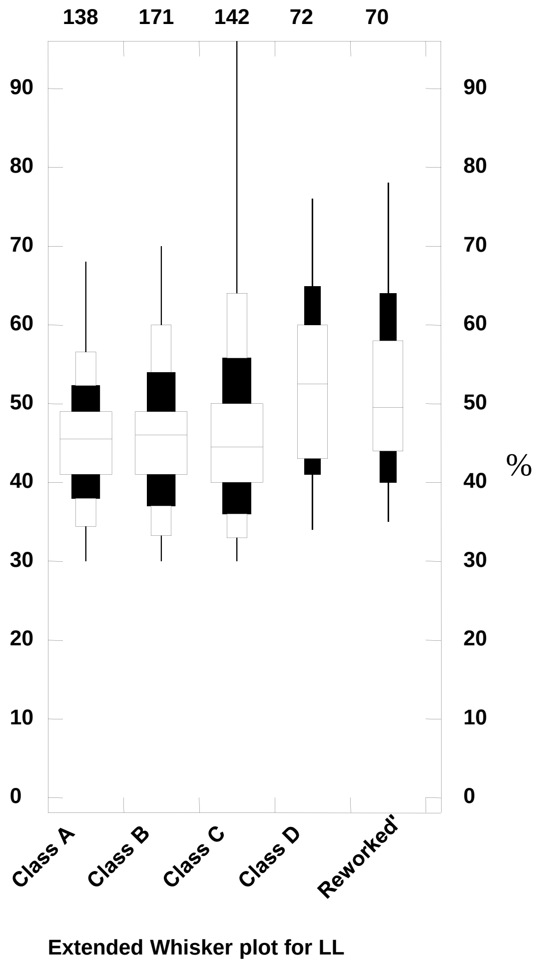
Box and whisker plot of water soluble sulphate Charmouth Mudstone Formation



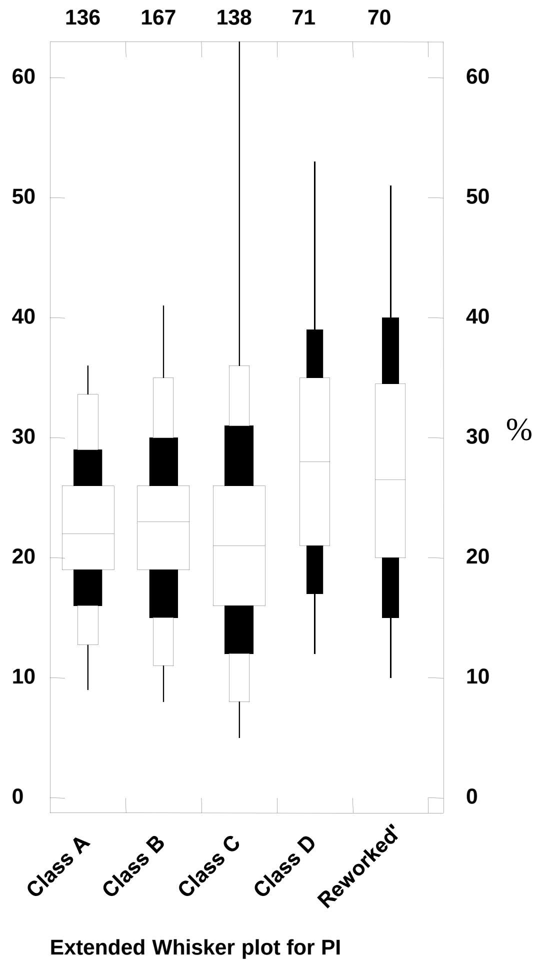
Box and whisker plot of pH Charmouth Mudstone Formation



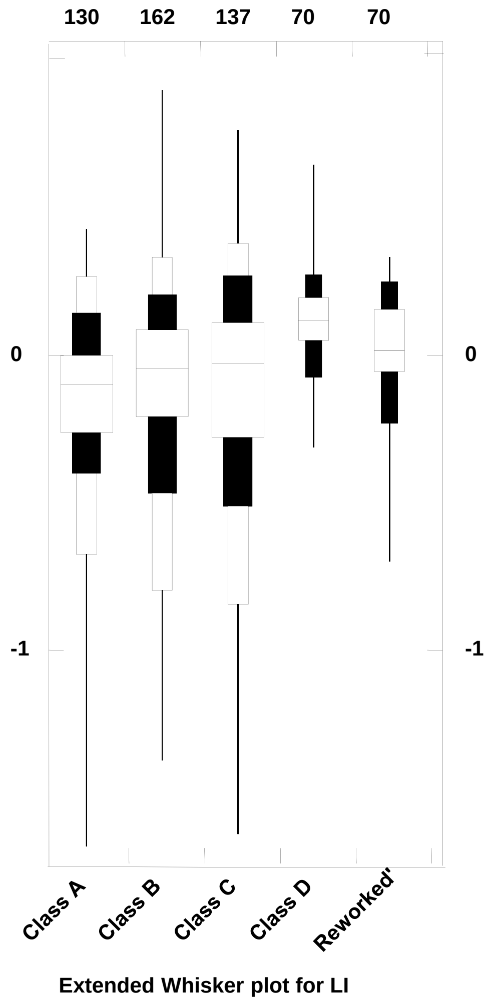
Box and whisker plot of Natural Water Content of Dyrham Formation



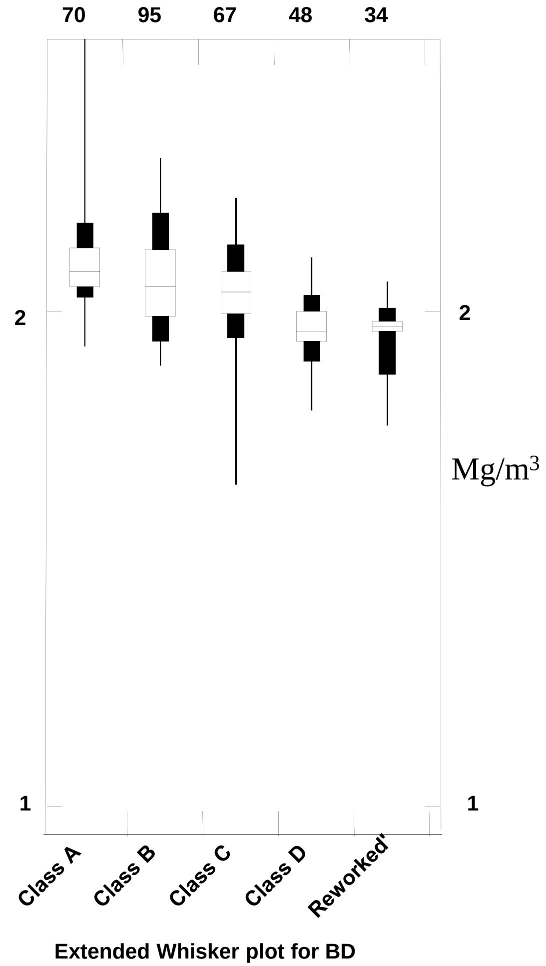
Box and whisker plot of Liquid Limit of Dyrham Formation



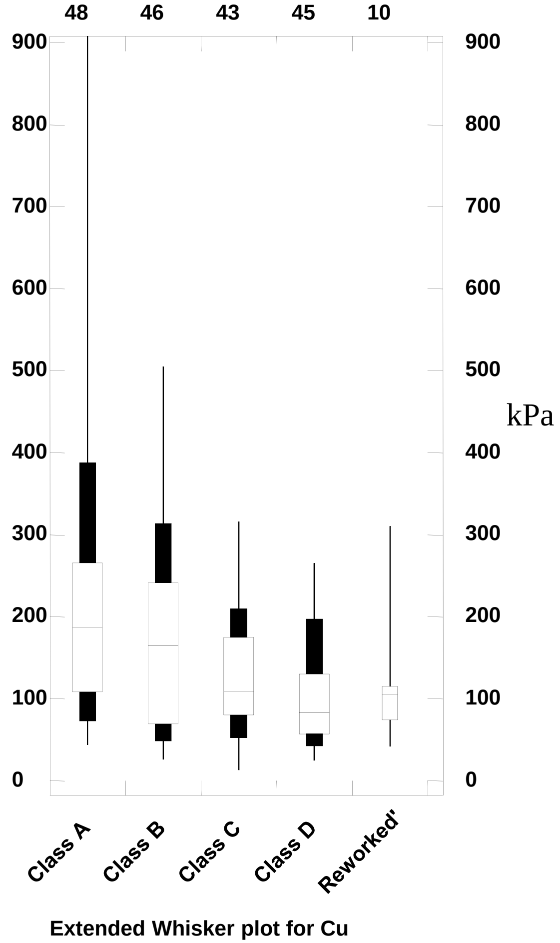
Box and whisker plot of Plasticity Index of Dyrham Formation



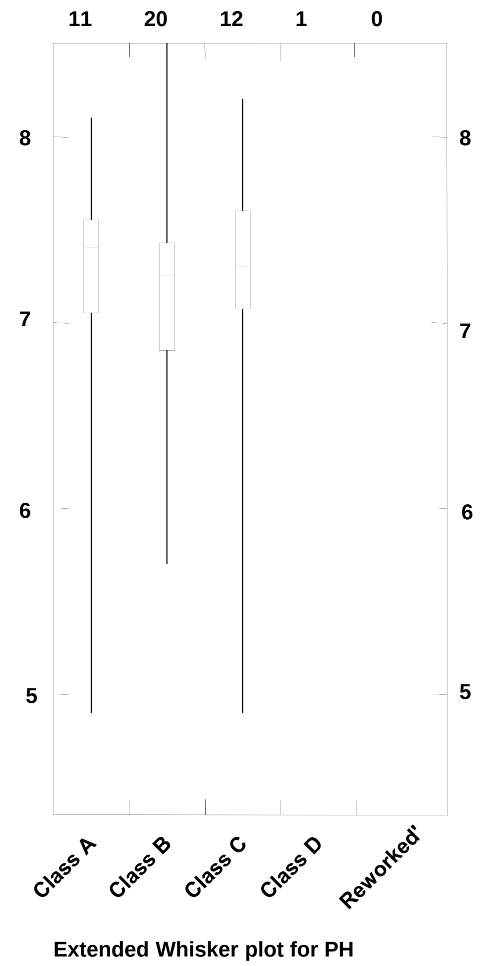
Box and whisker plot of Liquidity Index of Dyrham Formation



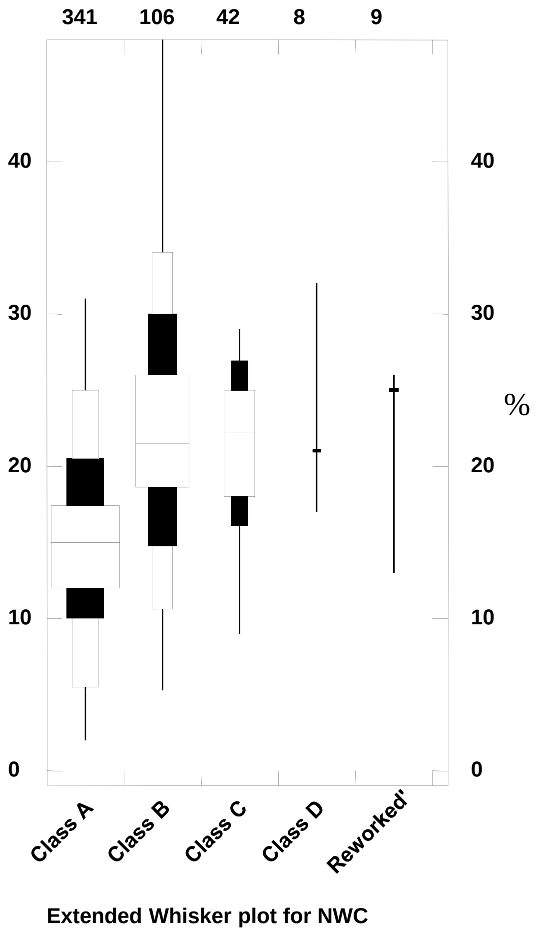
Box and whisker plot of Bulk Density of Dyrham Formation



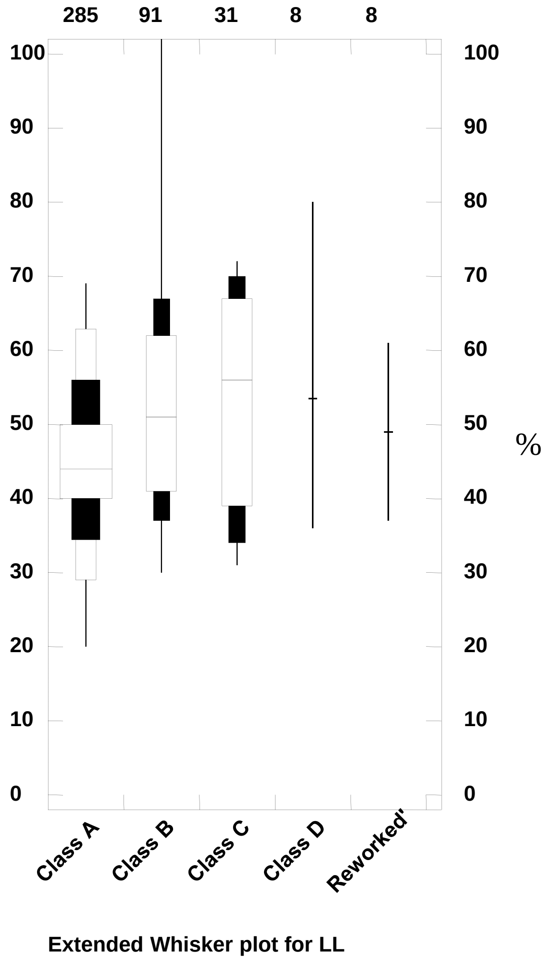
Box and whisker plot of Cohesion of Dyrham Formation



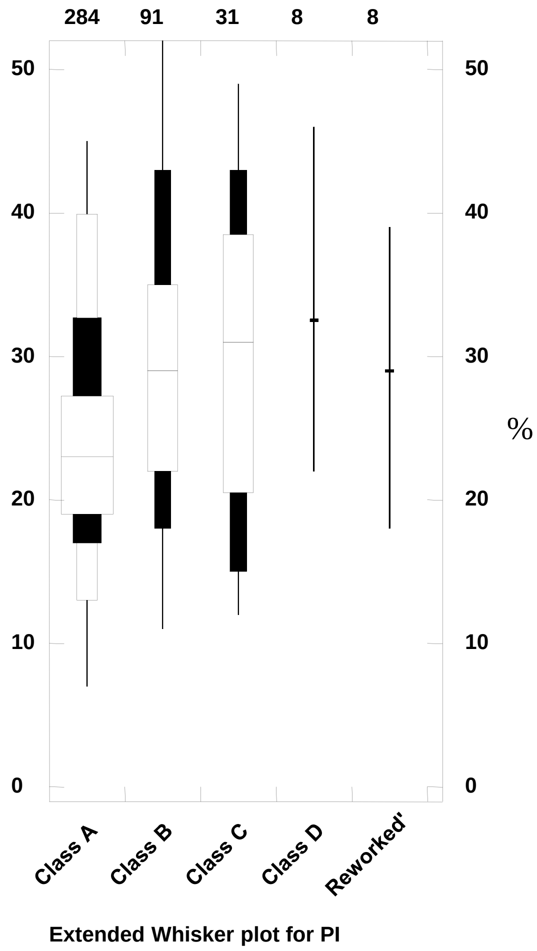
Box and whisker plot of pH of
Dyrham Formation



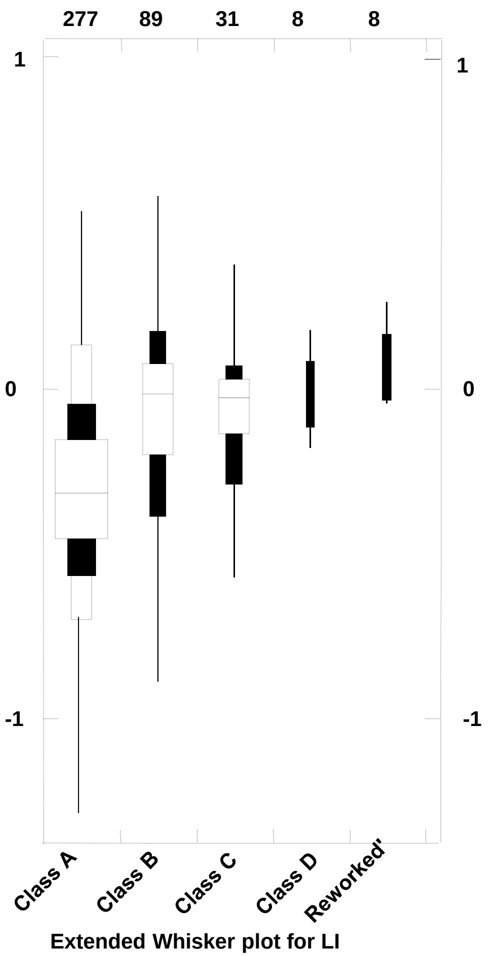
Box and whisker plot of Natural Water Content Scunthorpe Mudstone Formation



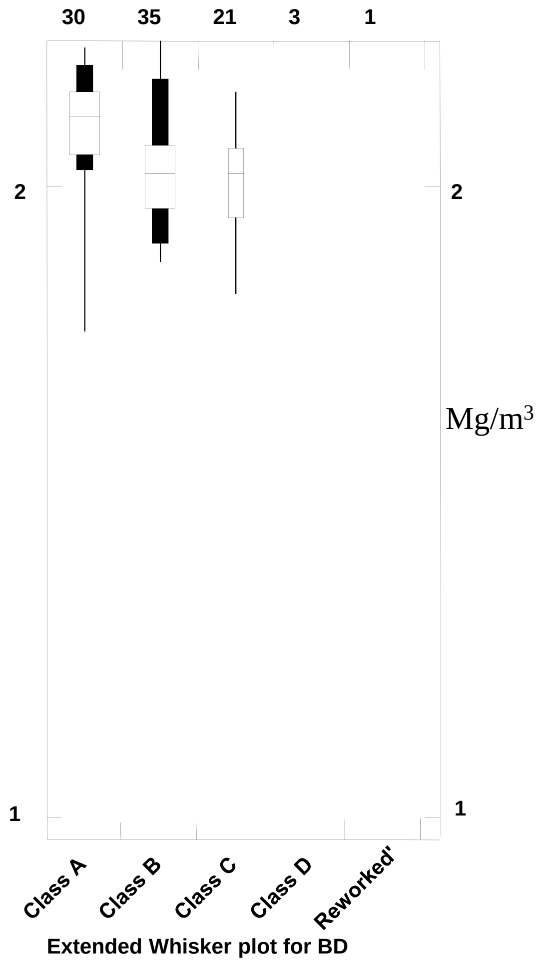
Box and whisker plot of Liquid Limit Scunthorpe Mudstone Formation



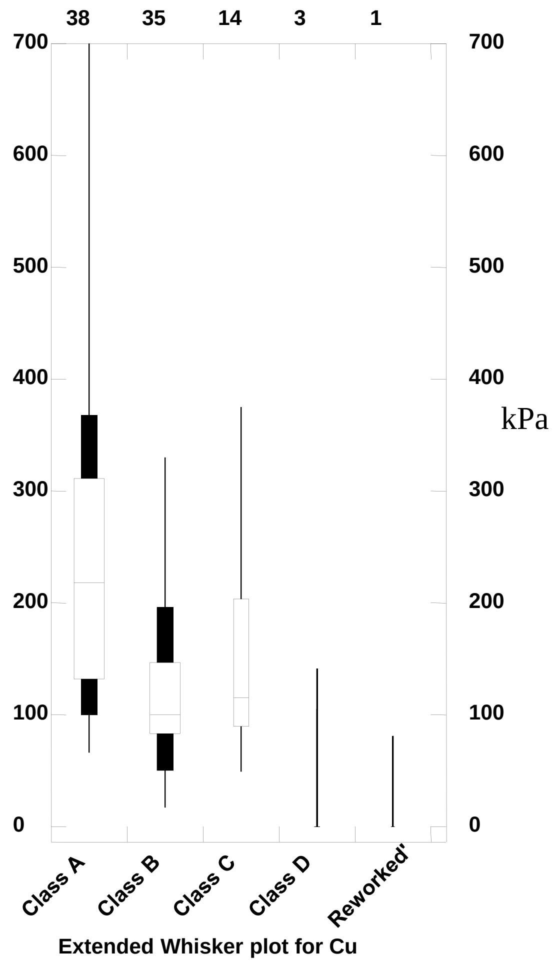
Box and whisker plot of Plasticity Index of Scunthorpe Mudstone Formation



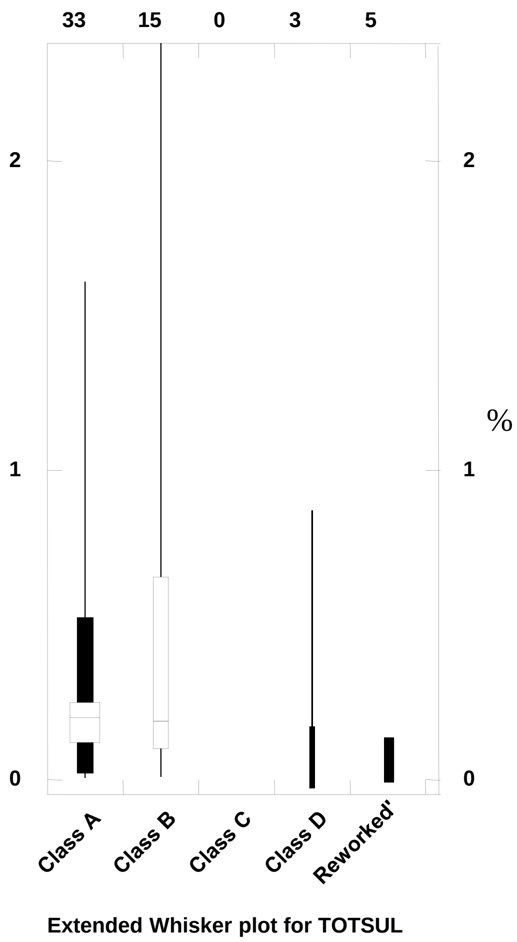
Box and whisker plot of Liquidity Index of Scunthorpe Mudstone Formation



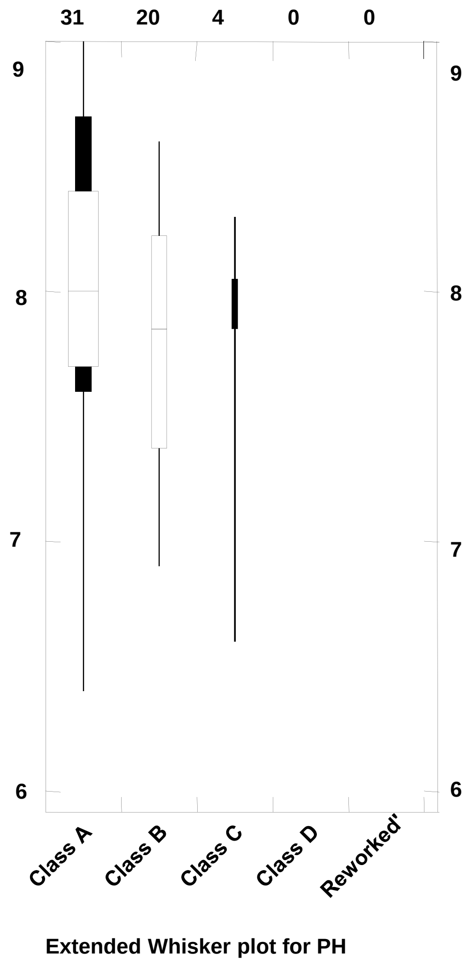
Box and whisker plot of Bulk Density of Scunthorpe Mudstone Formation



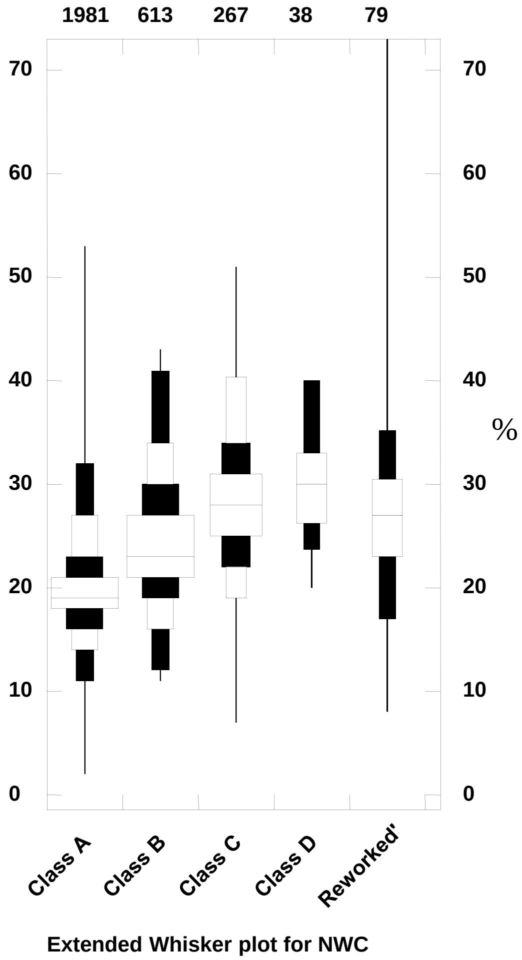
Box and whisker plot of Cohesion of Scunthorpe Mudstone Formation



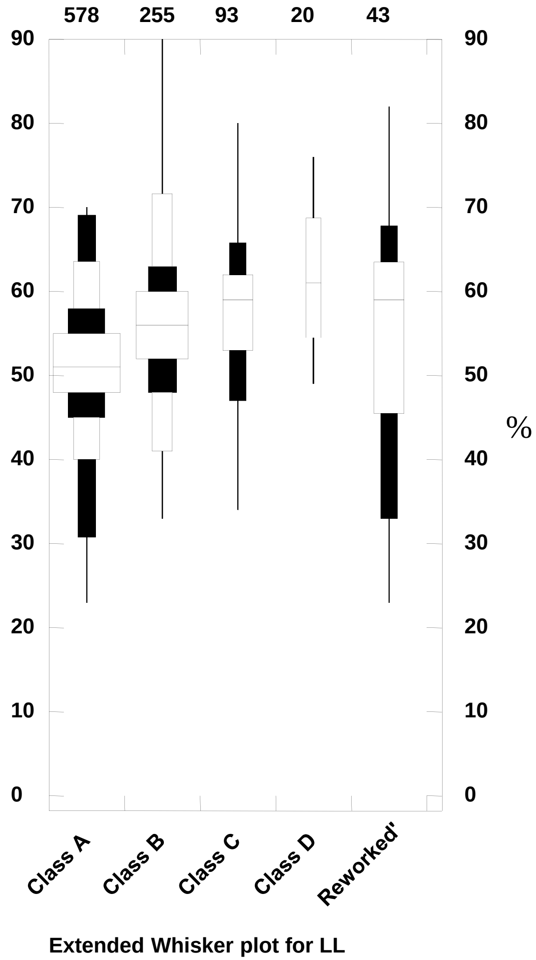
Box and whisker plot of Total sulphate of Scunthorpe Mudstone Formation



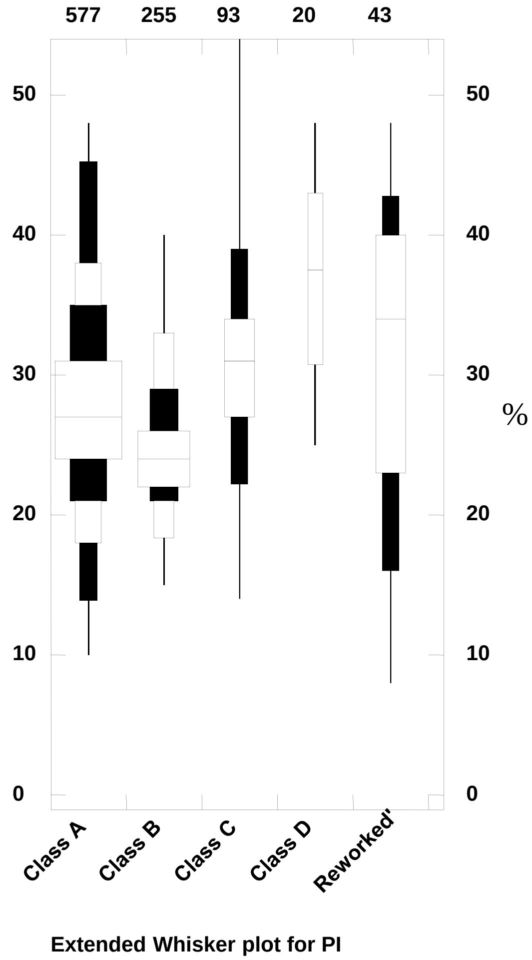
Box and whisker plot of pH of Scunthorpe Mudstone Formation



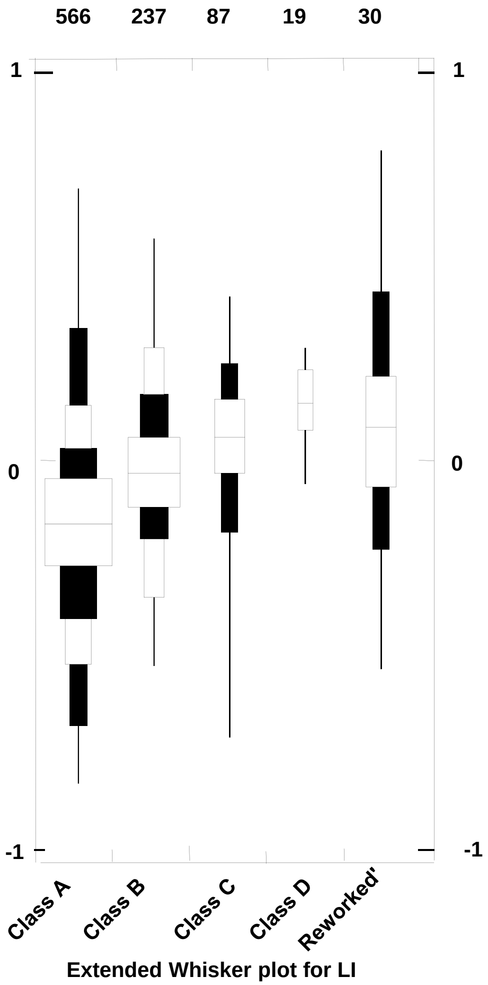
Box and whisker plot of Natural Water Content Whitby Mudstone Formation



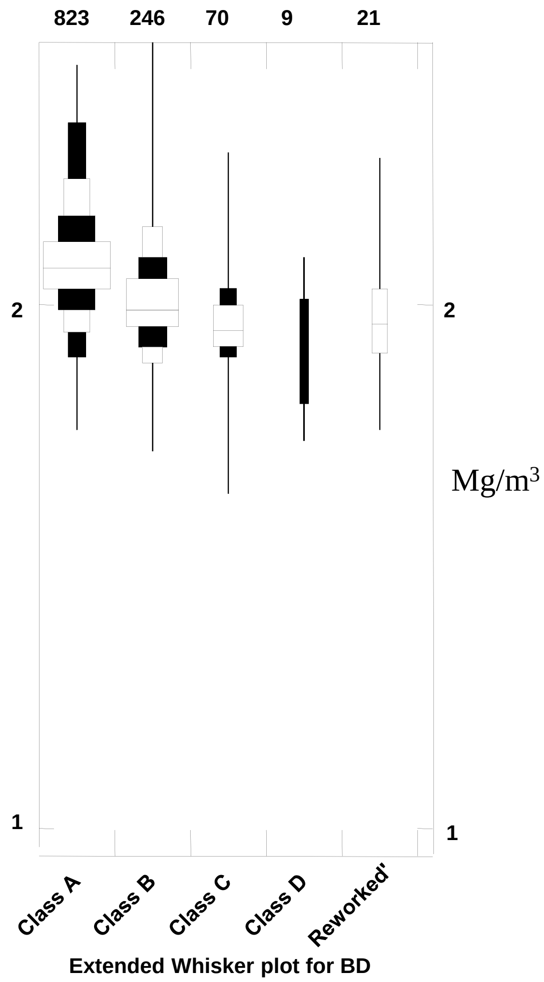
Box and whisker plot of Liquid Limit Whitby Mudstone Formation



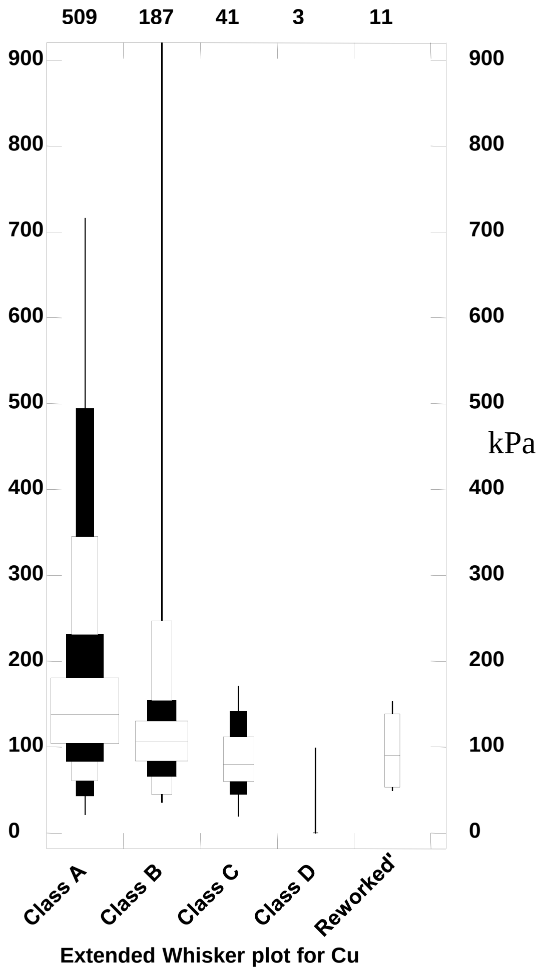
Box and whisker plot of Plasticity Index of Whitby Mudstone Formation



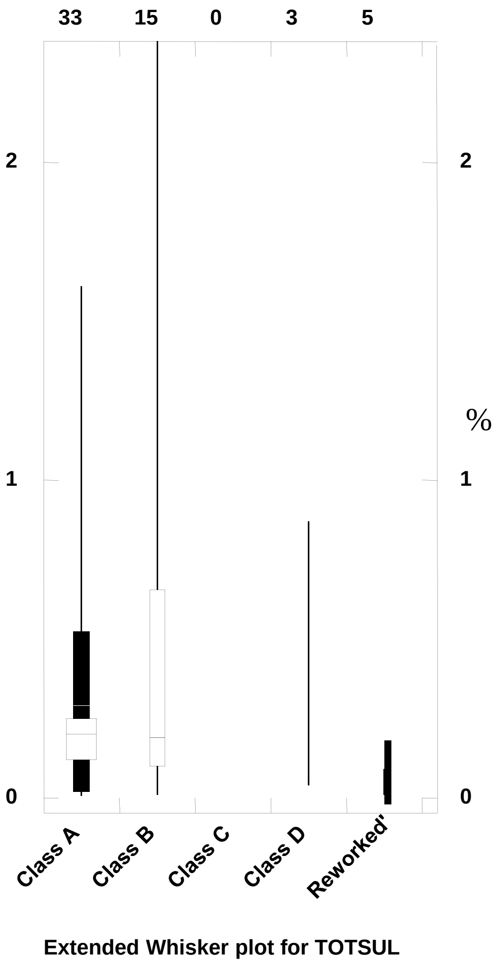
Box and whisker plot of Liquidity index of Whitby Mudstone Formation



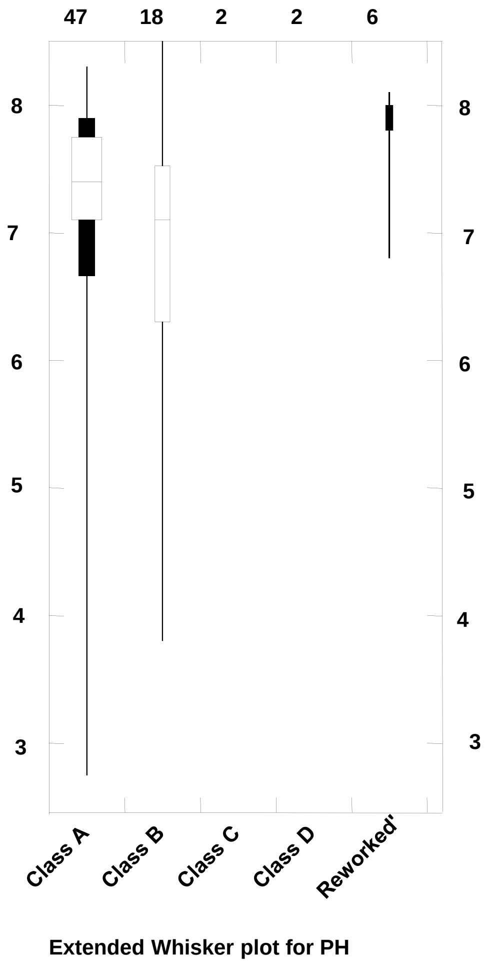
Box and whisker plot of Bulk Density of Whitby Mudstone Formation



Box and whisker plot of Cohesion of Whitby Mudstone Formation



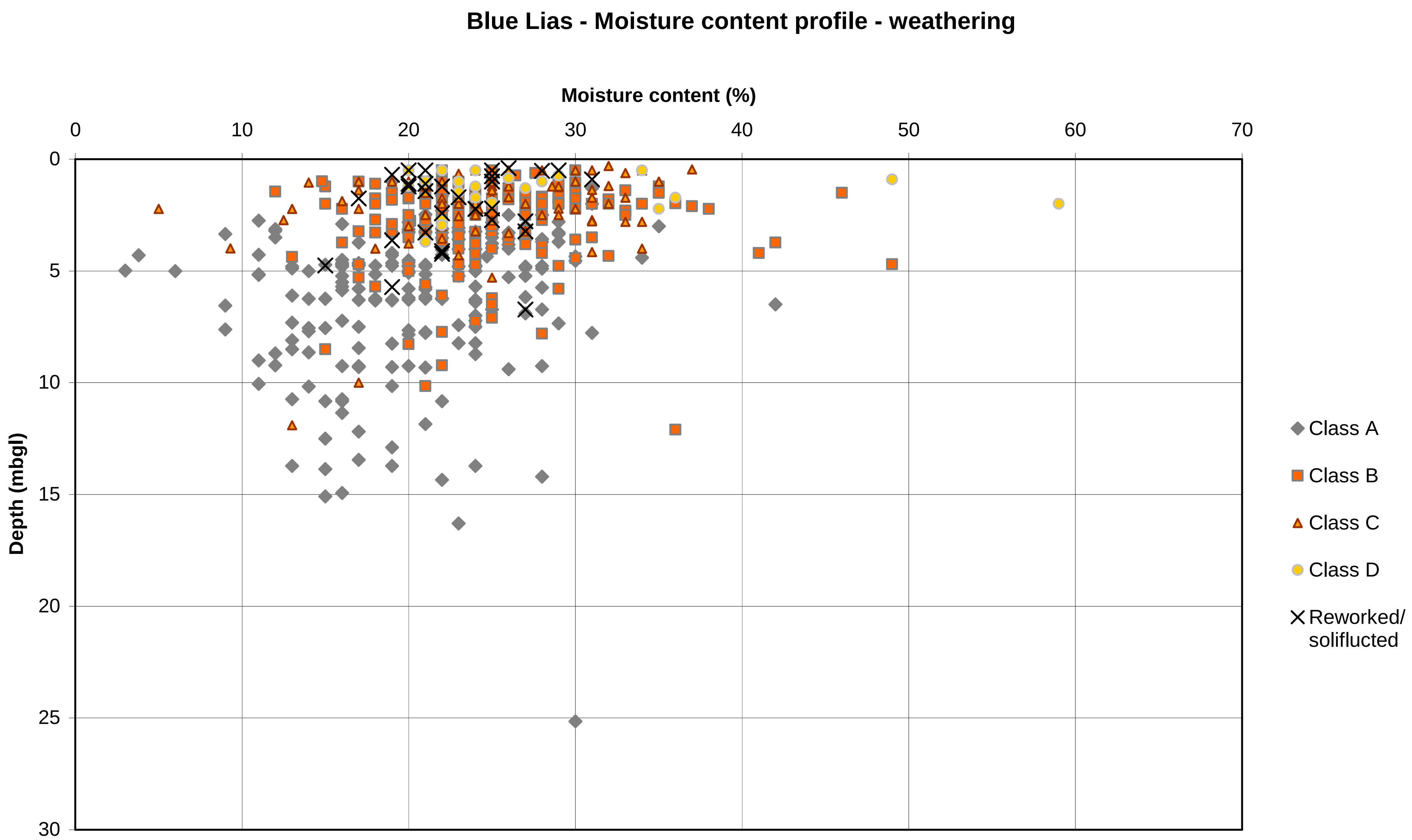
Box and whisker plot of Total Sulphate of Whitby Mudstone Formation



Box and whisker plot of pH of Whitby Mudstone Formation

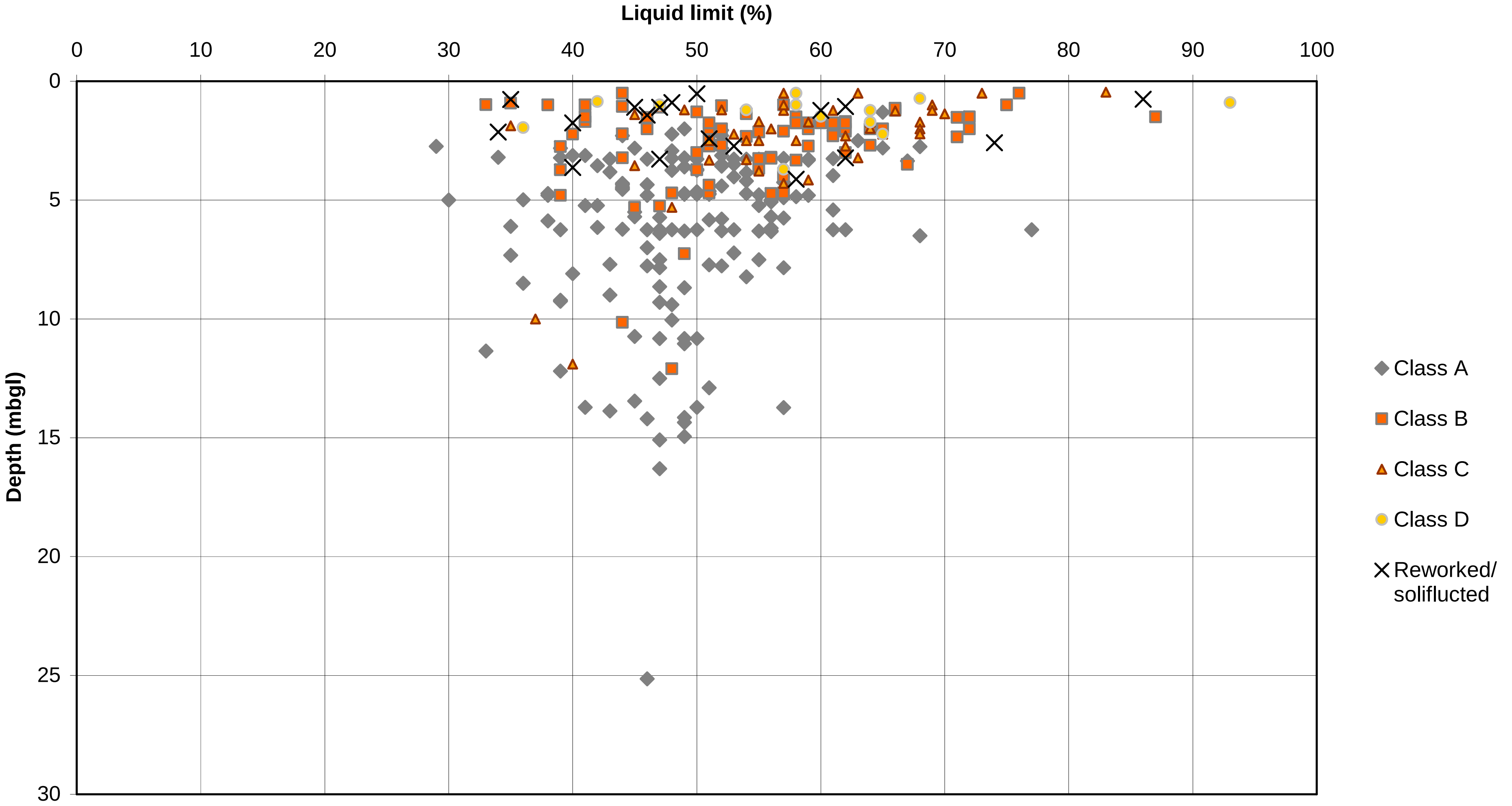
APPENDIX D3

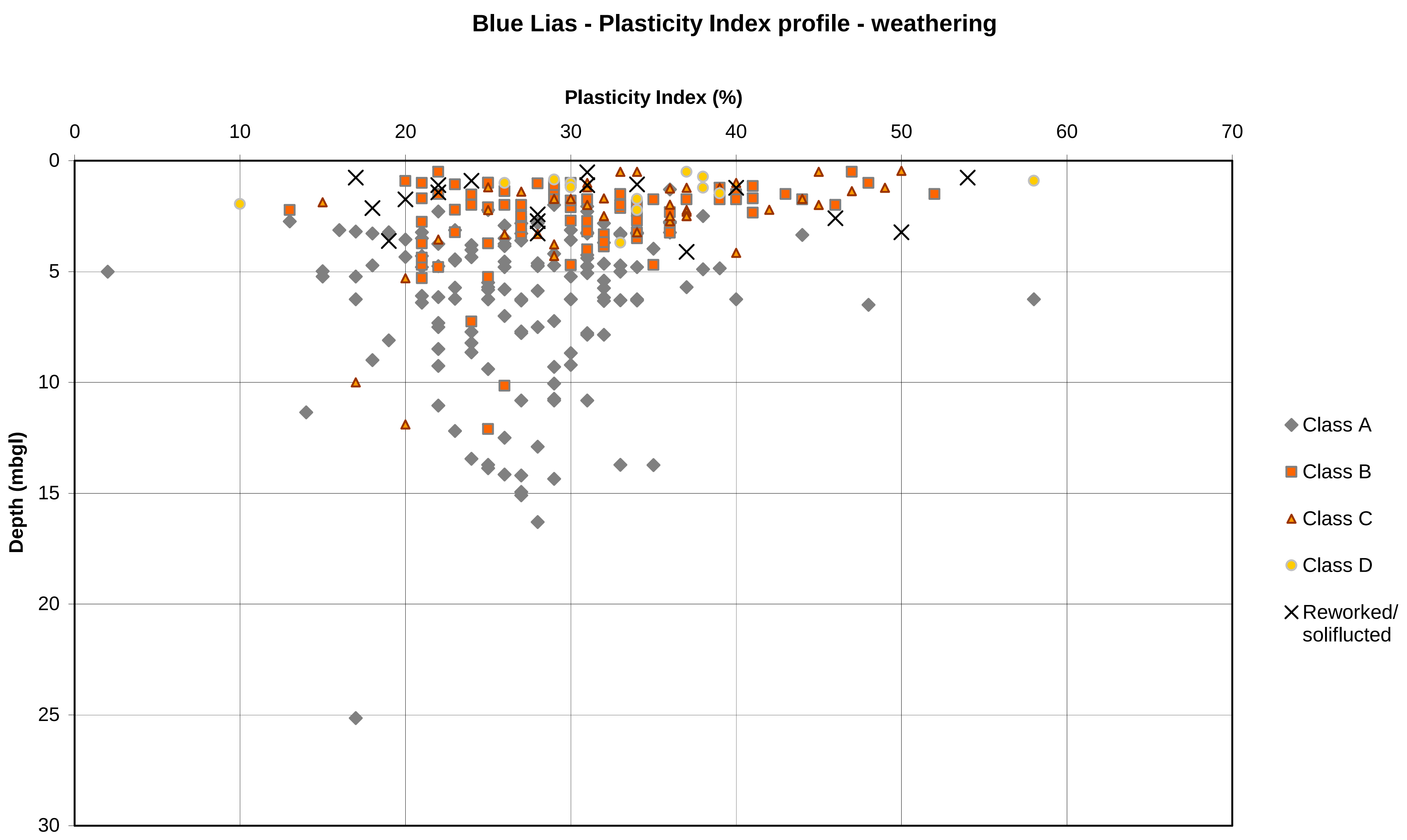
Depth profiles
[by weathering class and Formation]



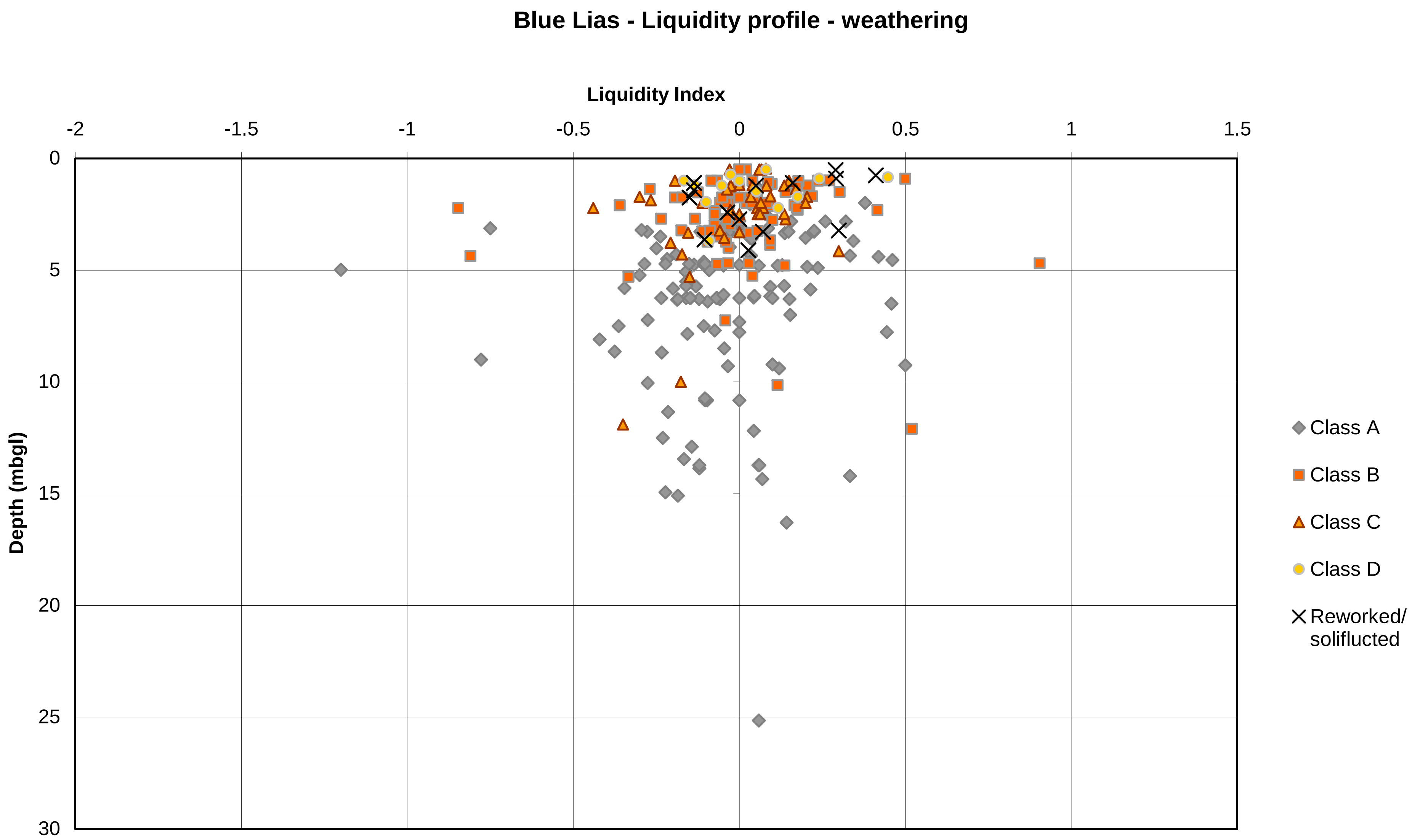
Blue Lias - Moisture content profile - weathering
Moisture content (%)
0
10
20
30
40
50
60
70
Depth (mbgl)
0
5
10
15
20
25
30
Class A
Class B
Class C
Class D
Reworked/
soliflucted

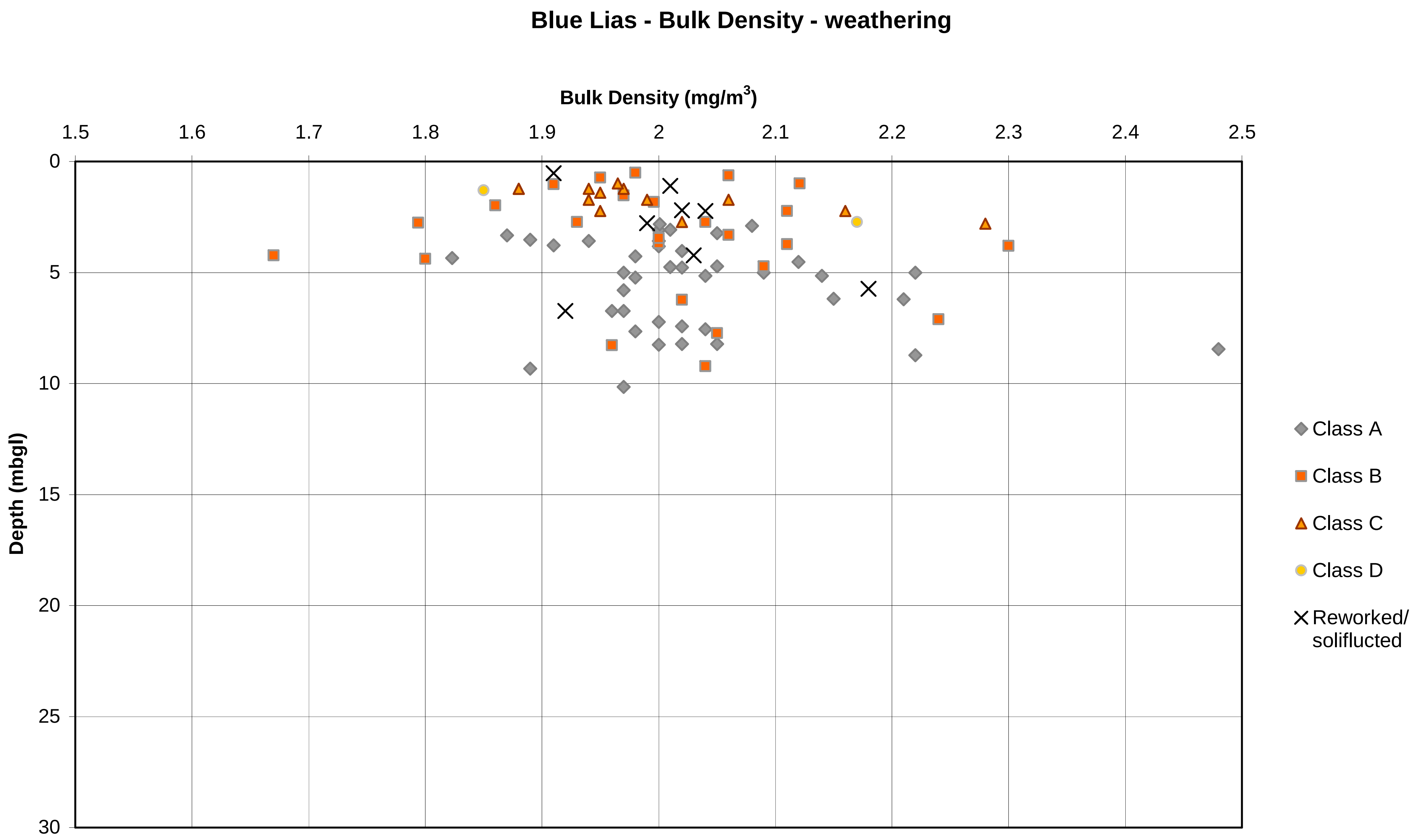
Blue Lias - Liquid limit profile - weathering



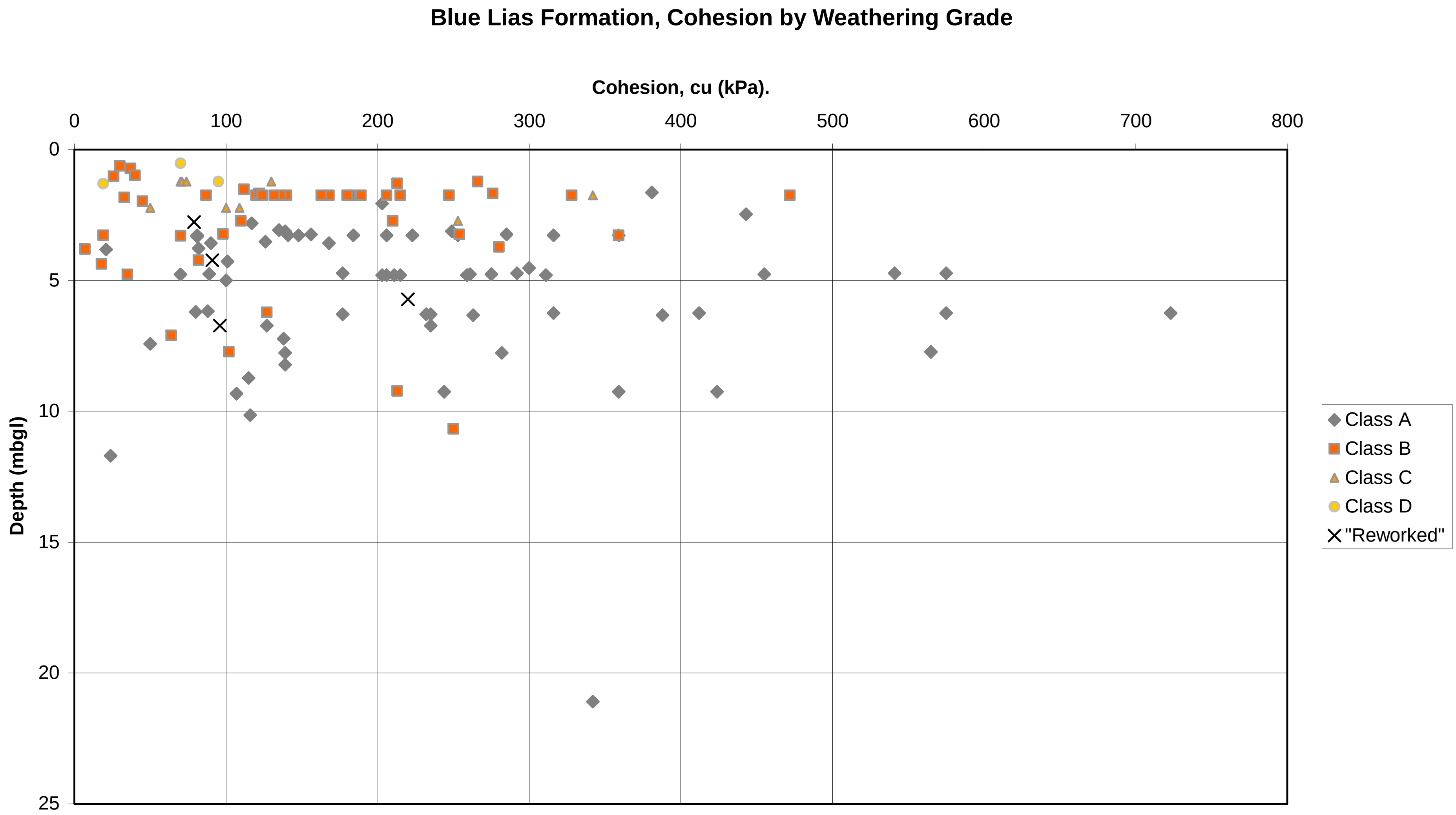


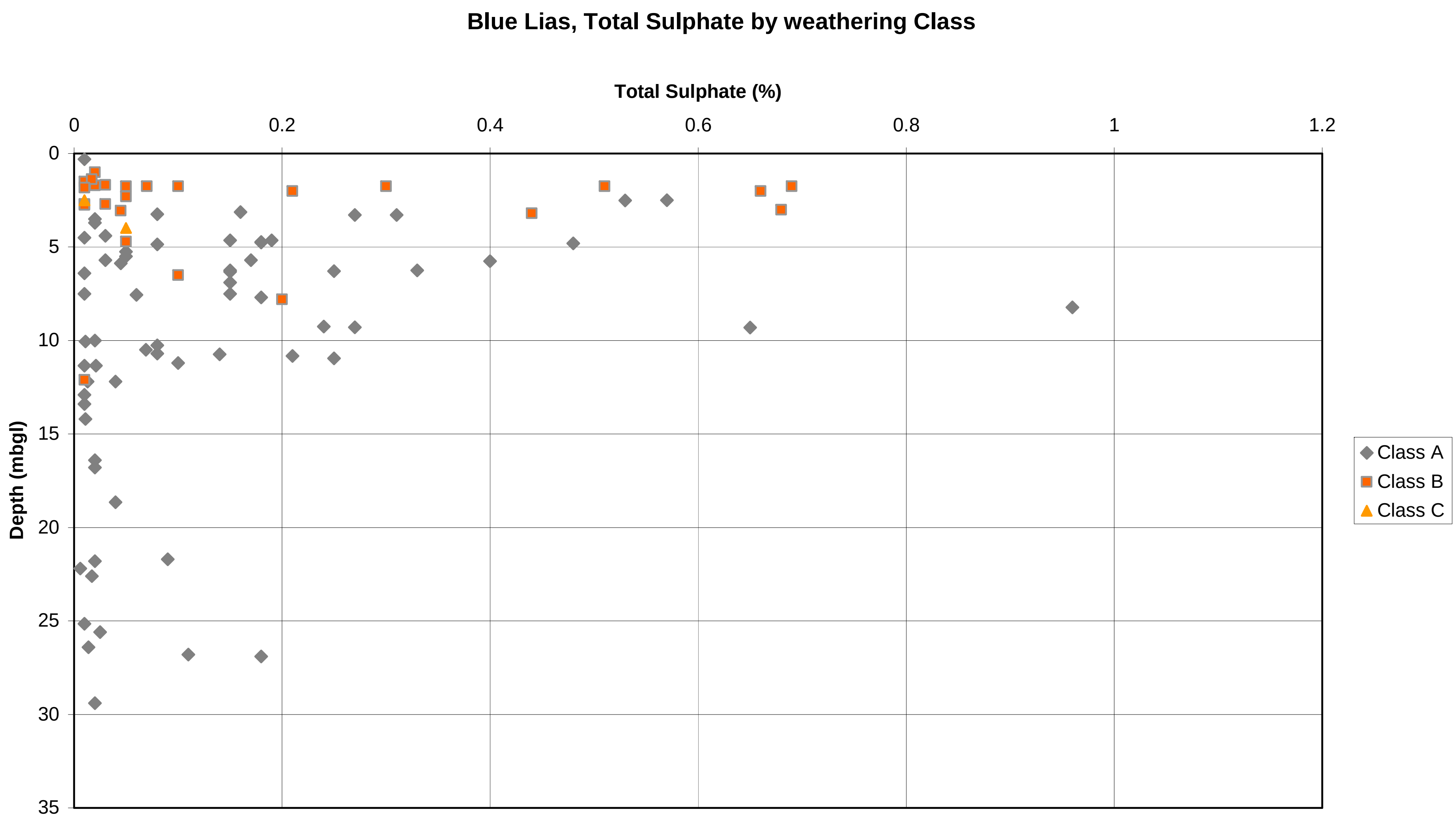
Blue Lias - Plasticity Index profile - weathering
Plasticity Index (%)
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
Depth (mbgl)
Class A
Class B
Class C
Class D
Reworked/
solifluctuted

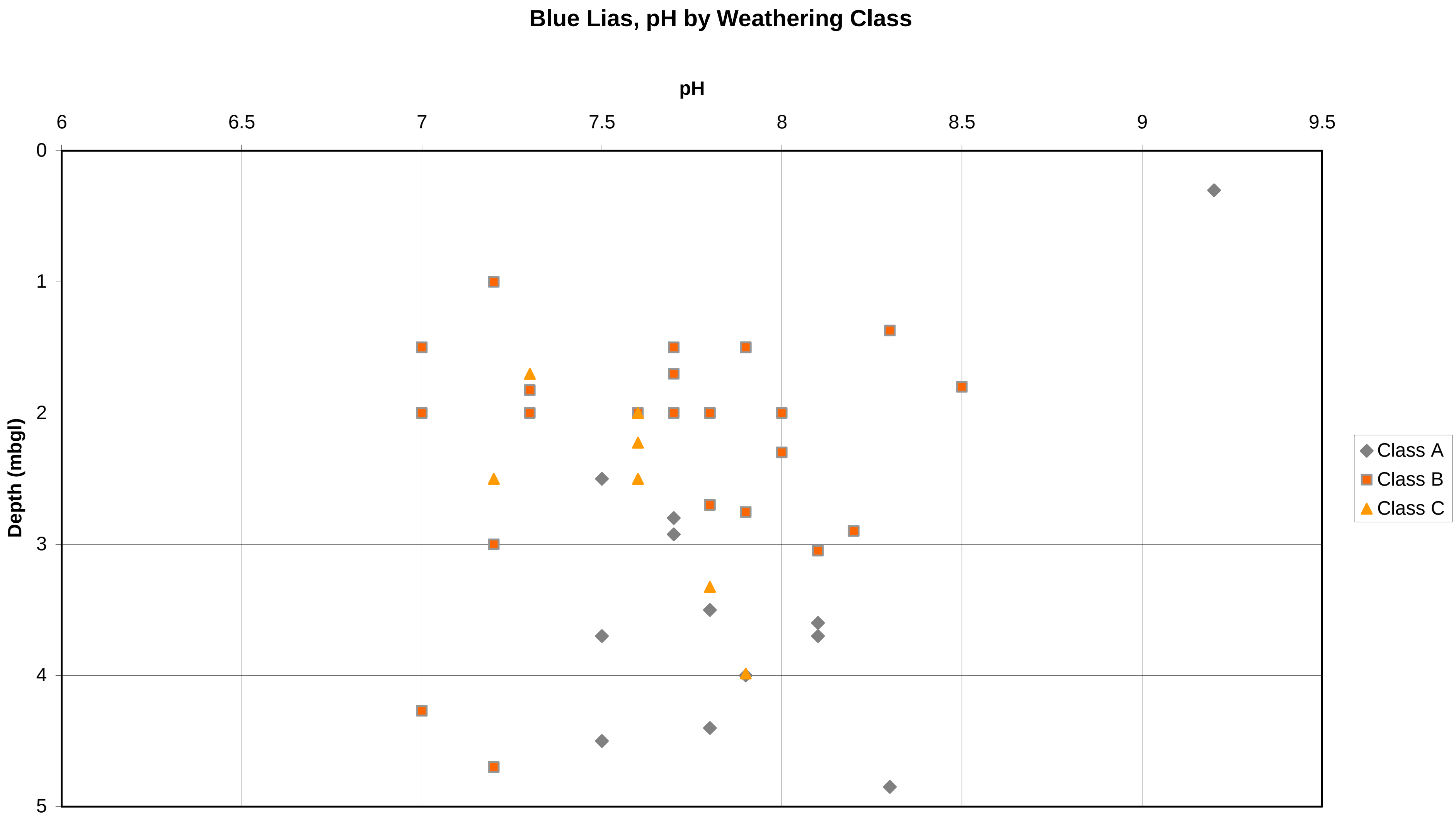

Blue Lias - Liquidity profile - weathering
Liquidity Index
-2
-1.5
-1
-0.5
0
0.5
1
1.5
0
5
10
15
20
25
30
Depth (mbgl)
Class A
Class B
Class C
Class D
Reworked/
soliflucted



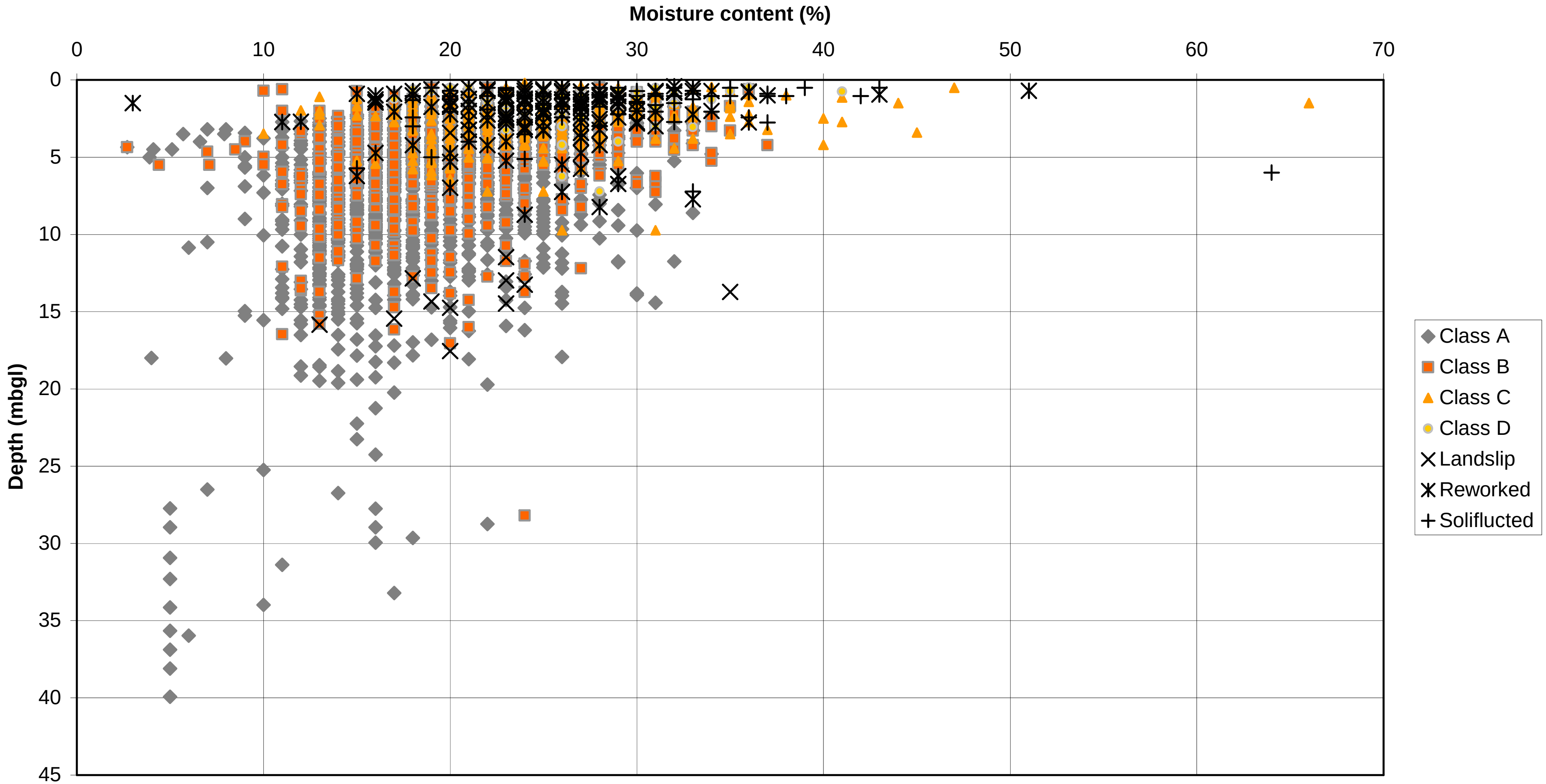
Blue Lias - Bulk Density - weathering
Bulk Density (mg/m^3)
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
0
5
10
15
20
25
30
Depth (mbgl)
Class A
Class B
Class C
Class D
Reworked/ solifluncted


Blue Lias Formation, Cohesion by Weathering Grade
Cohesion, cu (kPa).
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
Depth (mbgl)
Class A
Class B
Class C
Class D
"Reworked"

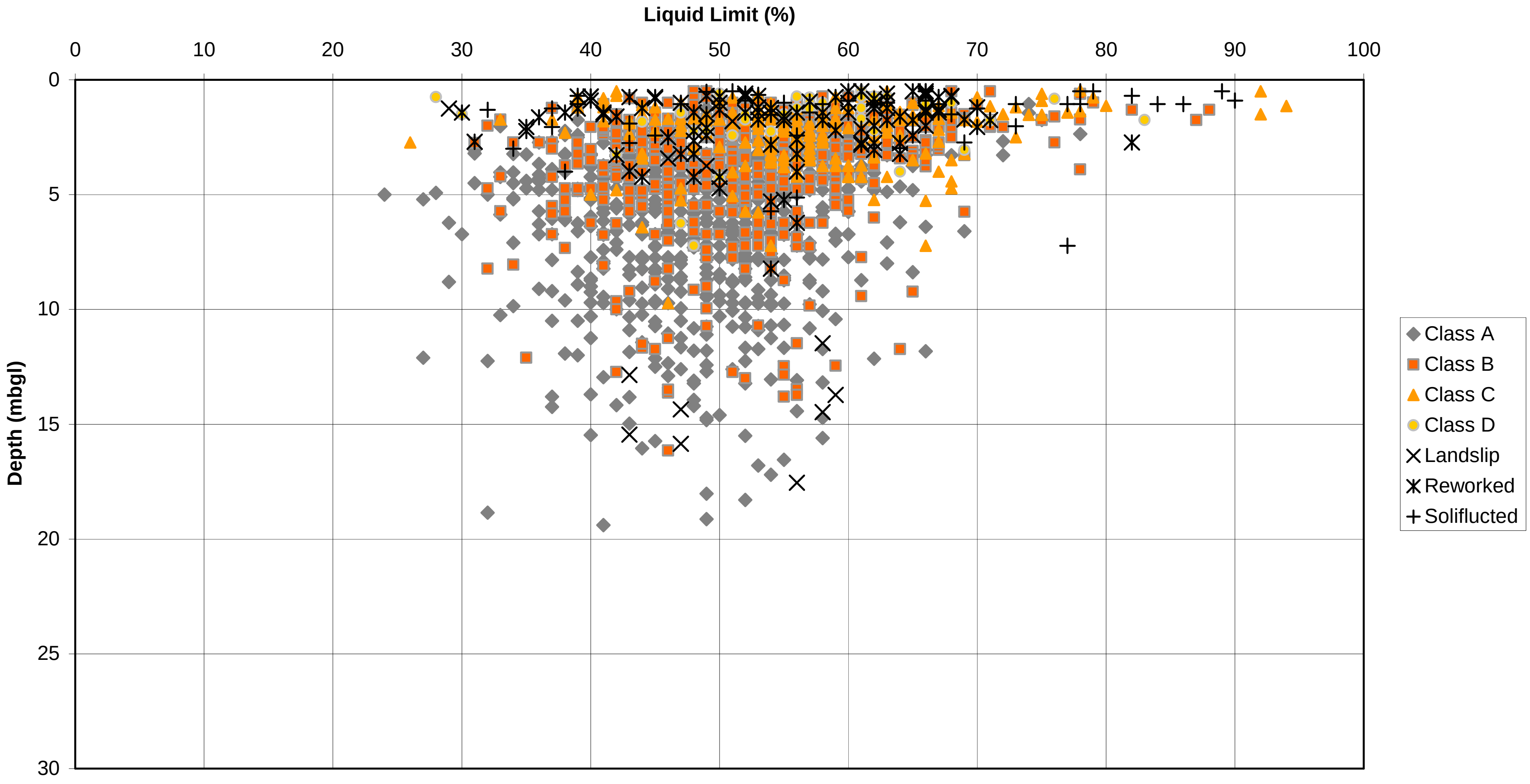

Blue Lias, Total Sulphate by weathering Class
Total Sulphate (%)
0
0.2
0.4
0.6
0.8
1
1.2
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C

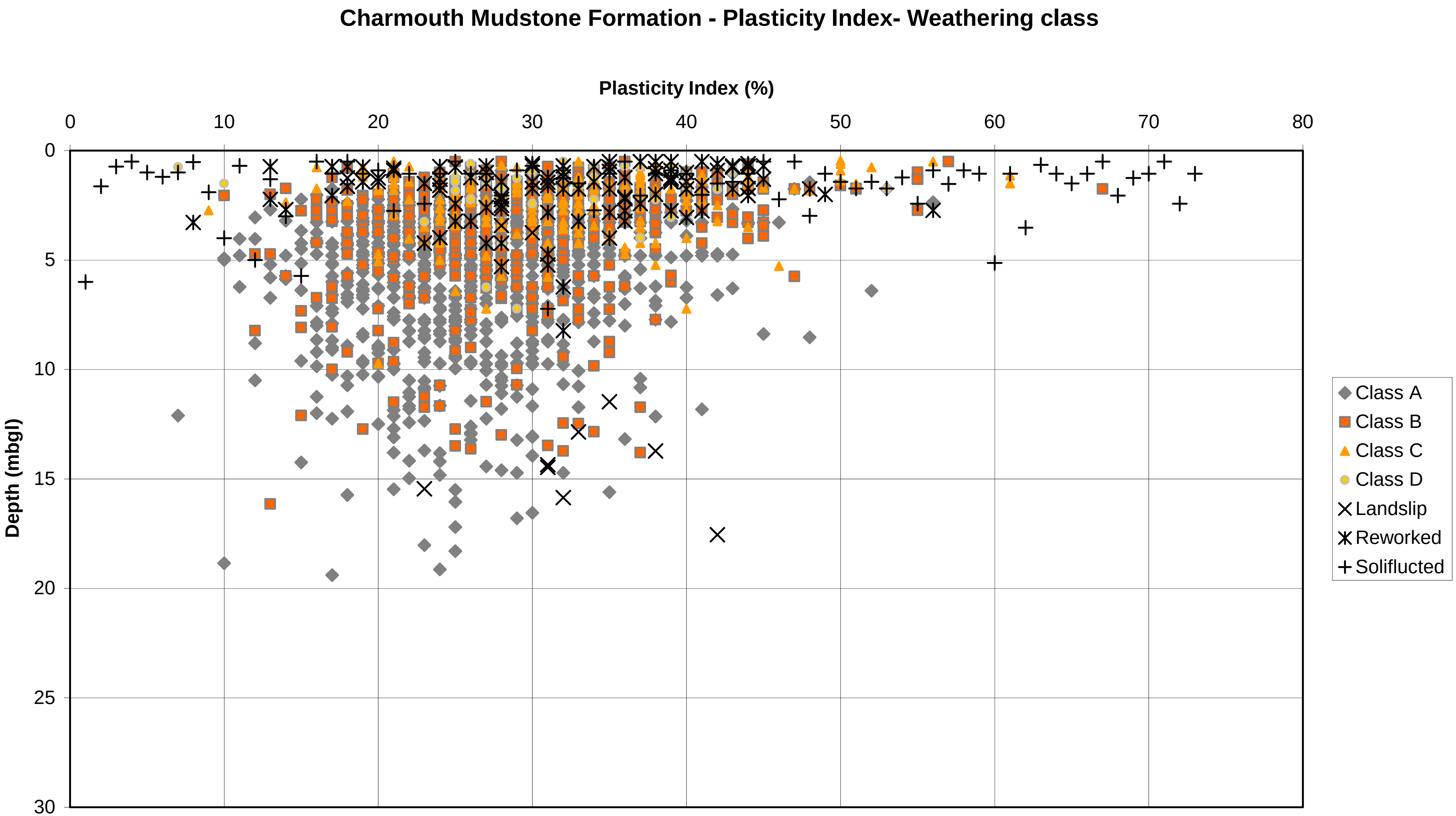

Blue Lias, pH by Weathering Class
pH
6
6.5
7
7.5
8
8.5
9
9.5
0
1
2
3
4
5
Depth (mbgl)
Class A
Class B
Class C

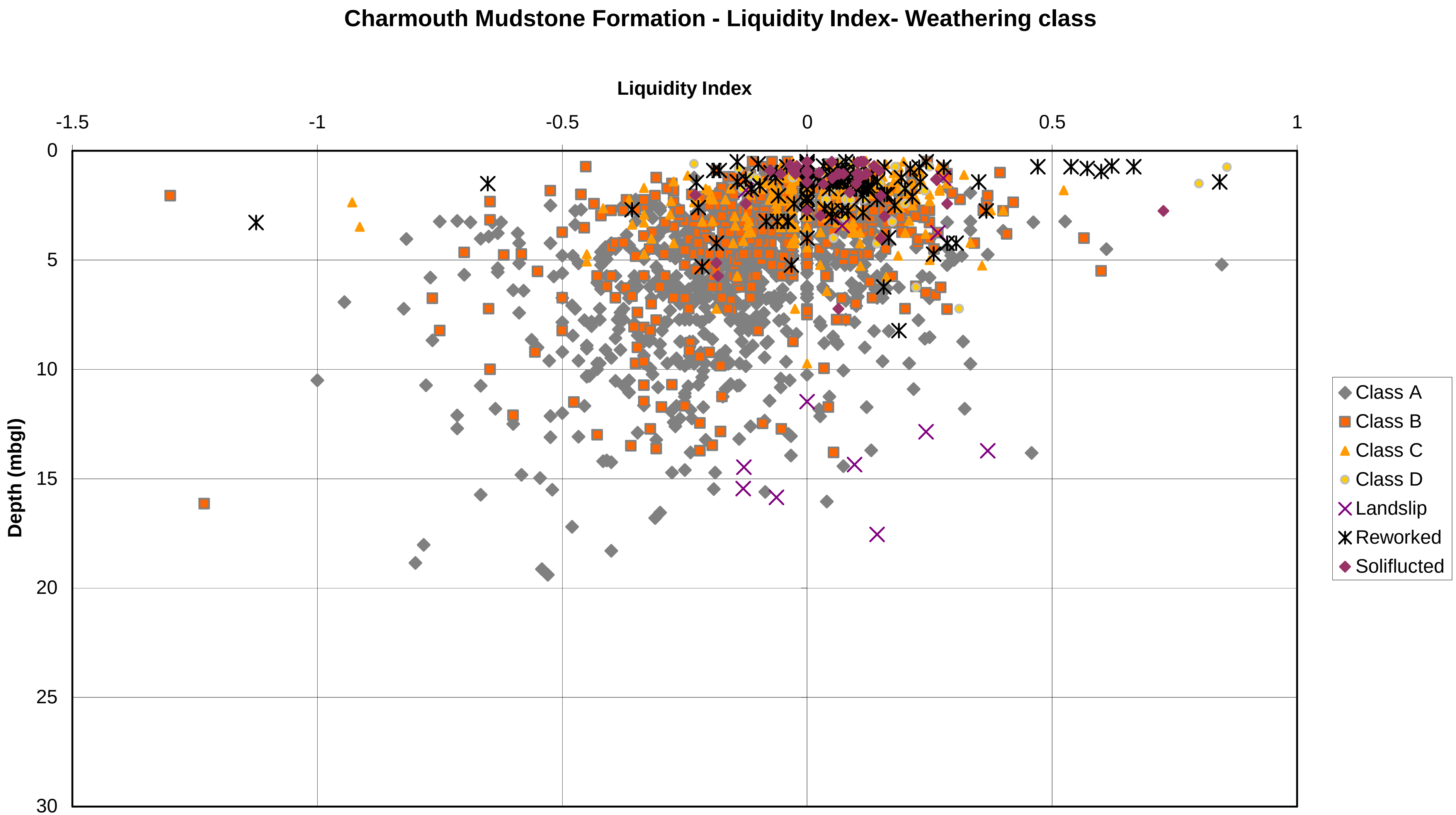
Charmouth Mudstone Formation - Moisture Content - Weathering class



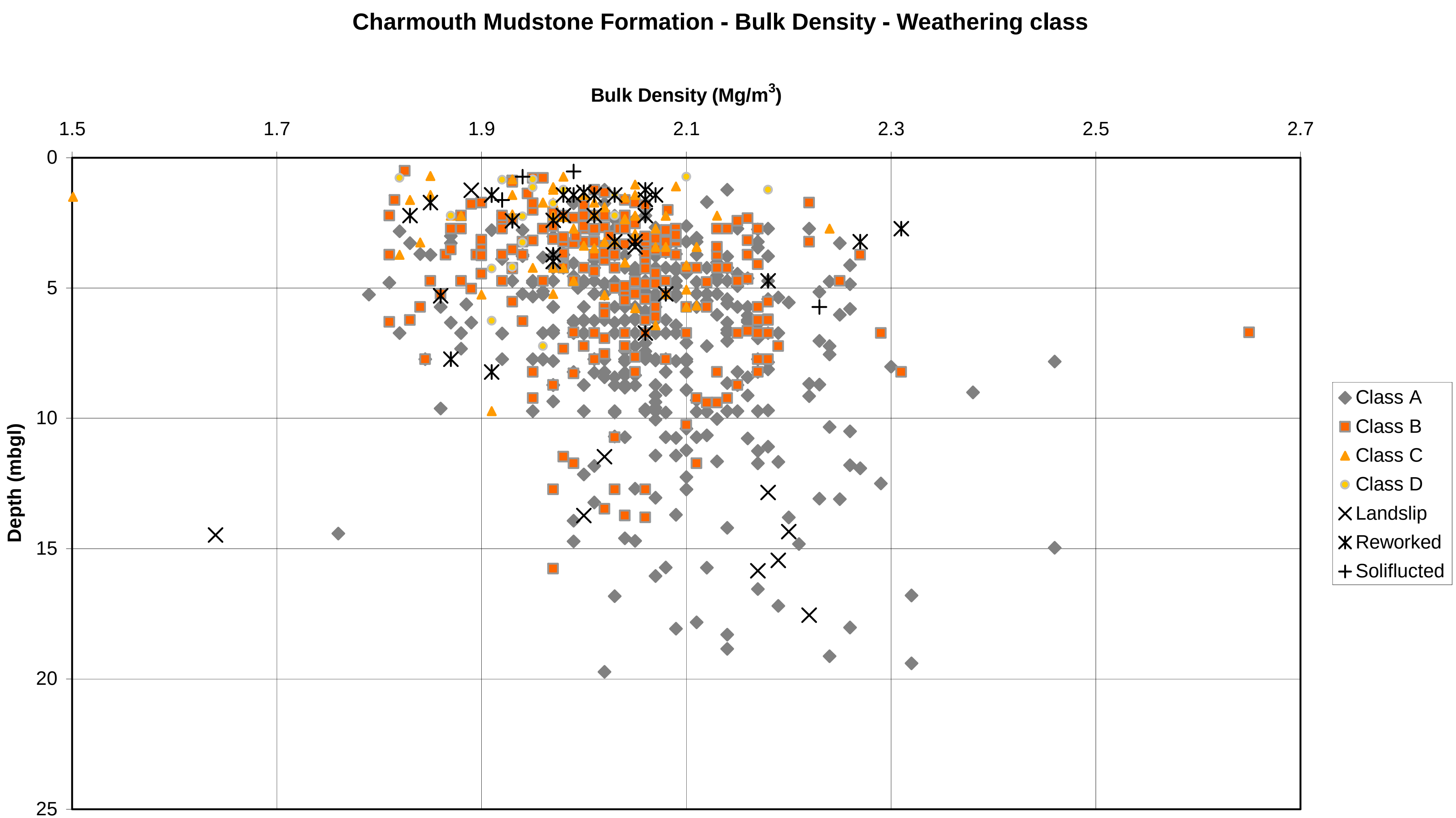
Charmouth Mudstone Formation - Liquid limit- Weathering class




Charmouth Mudstone Formation - Plasticity Index- Weathering class
Plasticity Index (%)
0
10
20
30
40
50
60
70
80
Depth (mbgl)
0
5
10
15
20
25
30
Class A
Class B
Class C
Class D
Landslip
Reworked
Solifluncted

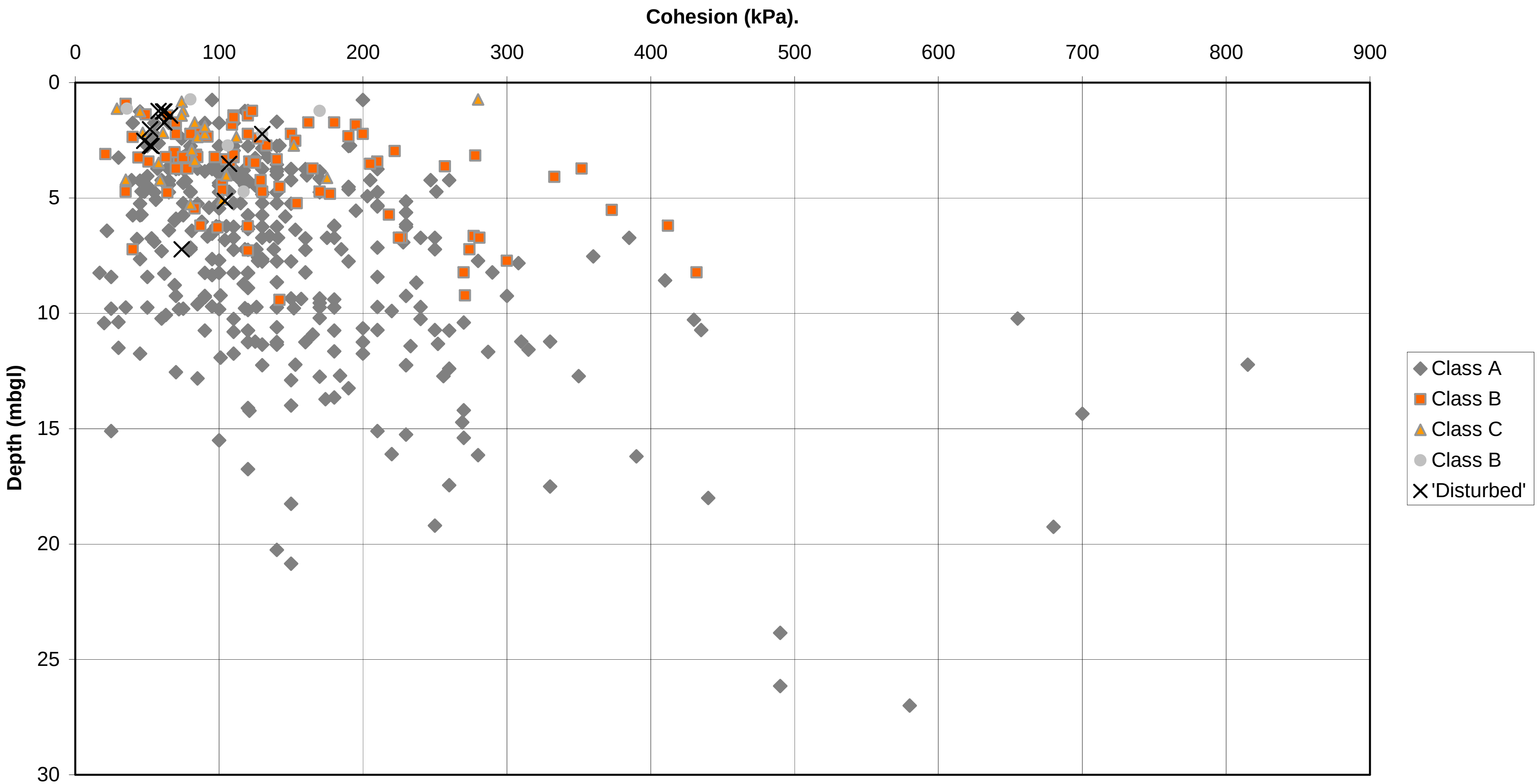


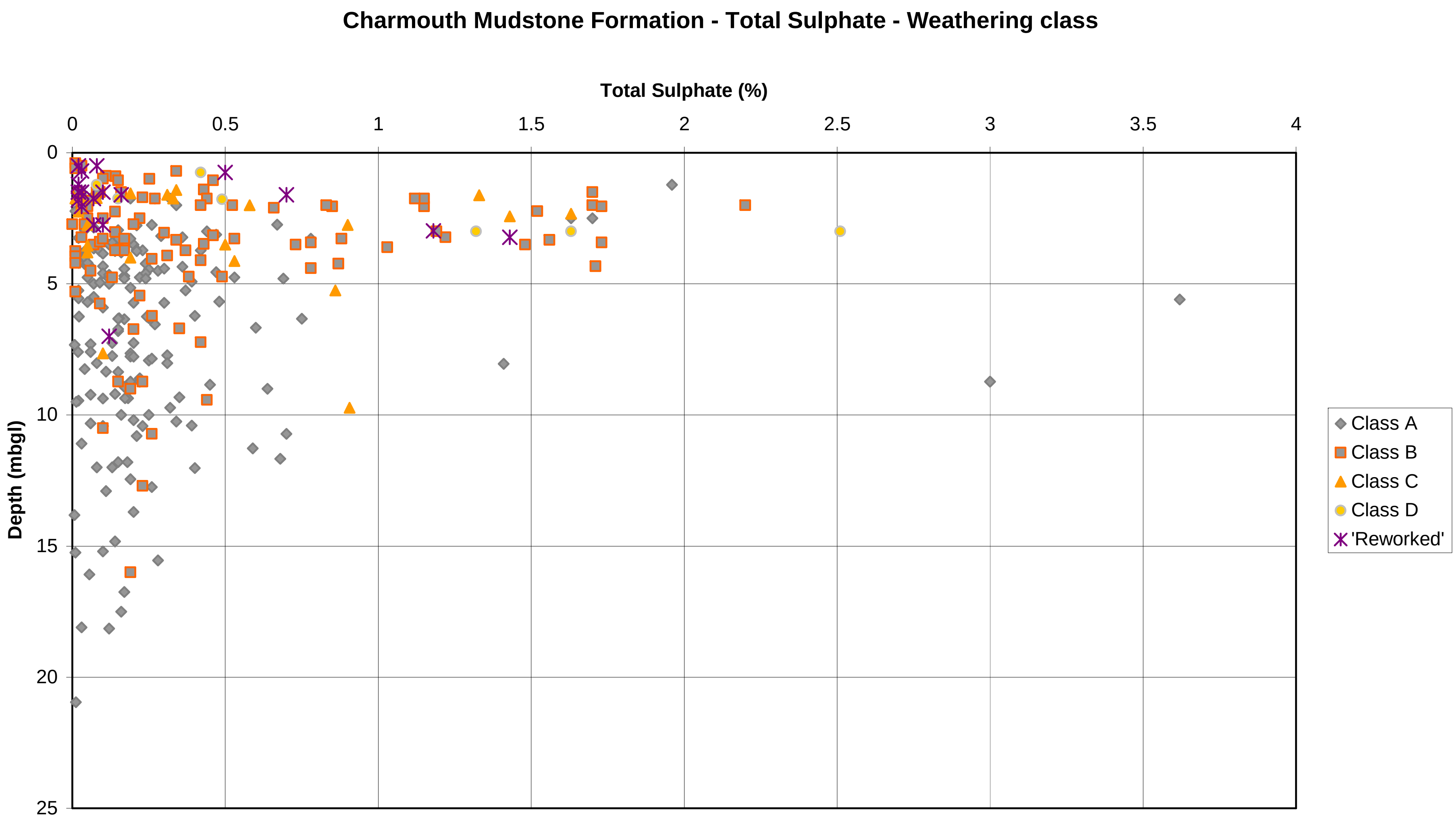
Charmouth Mudstone Formation - Liquidity Index- Weathering class
Liquidity Index
-1.5
-1
-0.5
0
0.5
1
Depth (mbgl)
0
5
10
15
20
25
30
Class A
Class B
Class C
Class D
Landslip
Reworked
Solifluected



Charmouth Mudstone Formation - Bulk Density - Weathering class
Bulk Density (Mg/m3)
1.5
1.7
1.9
2.1
2.3
2.5
2.7
Depth (mbgl)
0
5
10
15
20
25
Class A
Class B
Class C
Class D
Landslip
Reworked
Solifluction

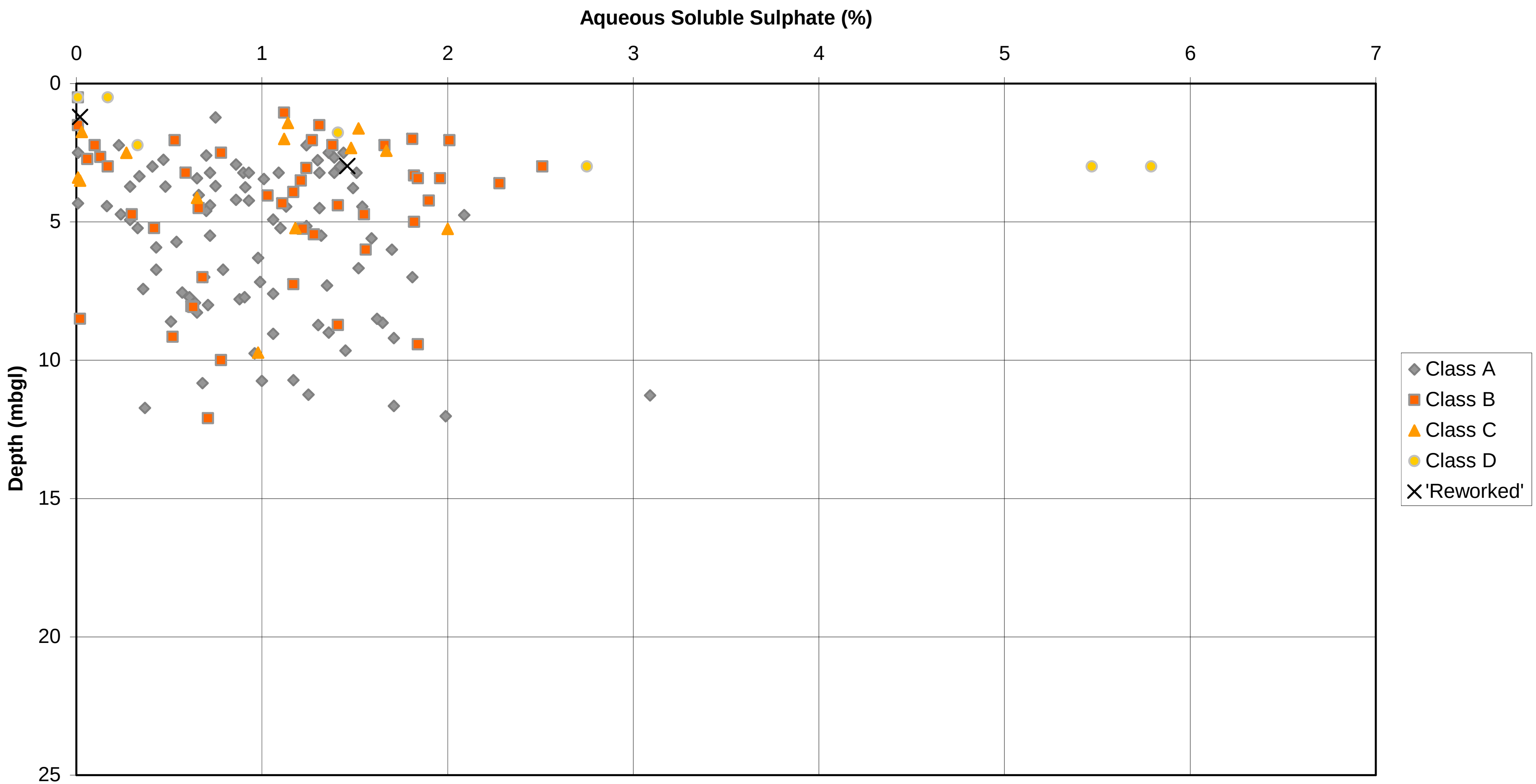
Charmouth Mudstone Formation, Cohesion profile - weathering class

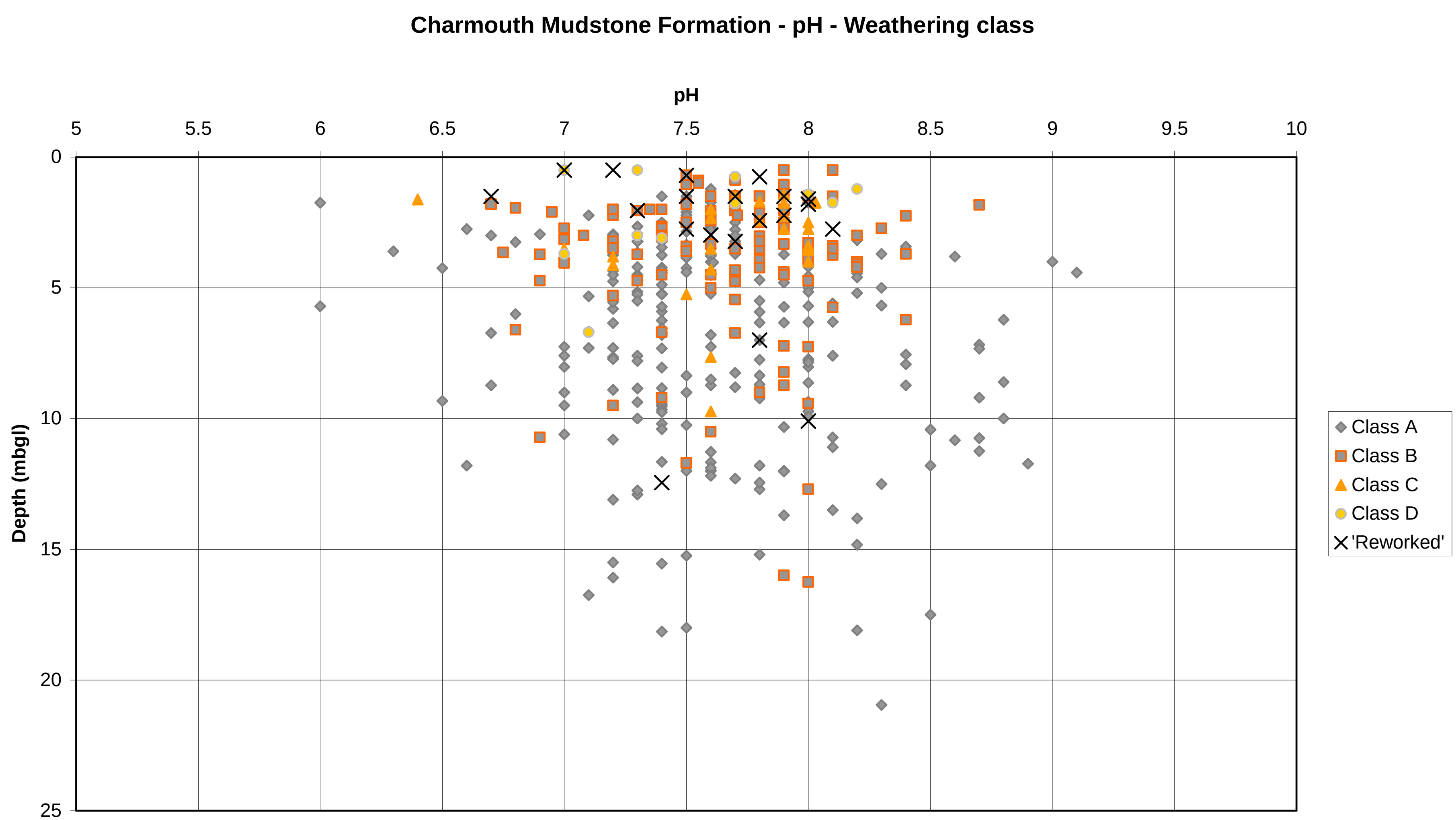




Charmouth Mudstone Formation - Total Sulphate - Weathering class
Total Sulphate (%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Depth (mbgl)
0
5
10
15
20
25
Class A
Class B
Class C
Class D
'Reworked'

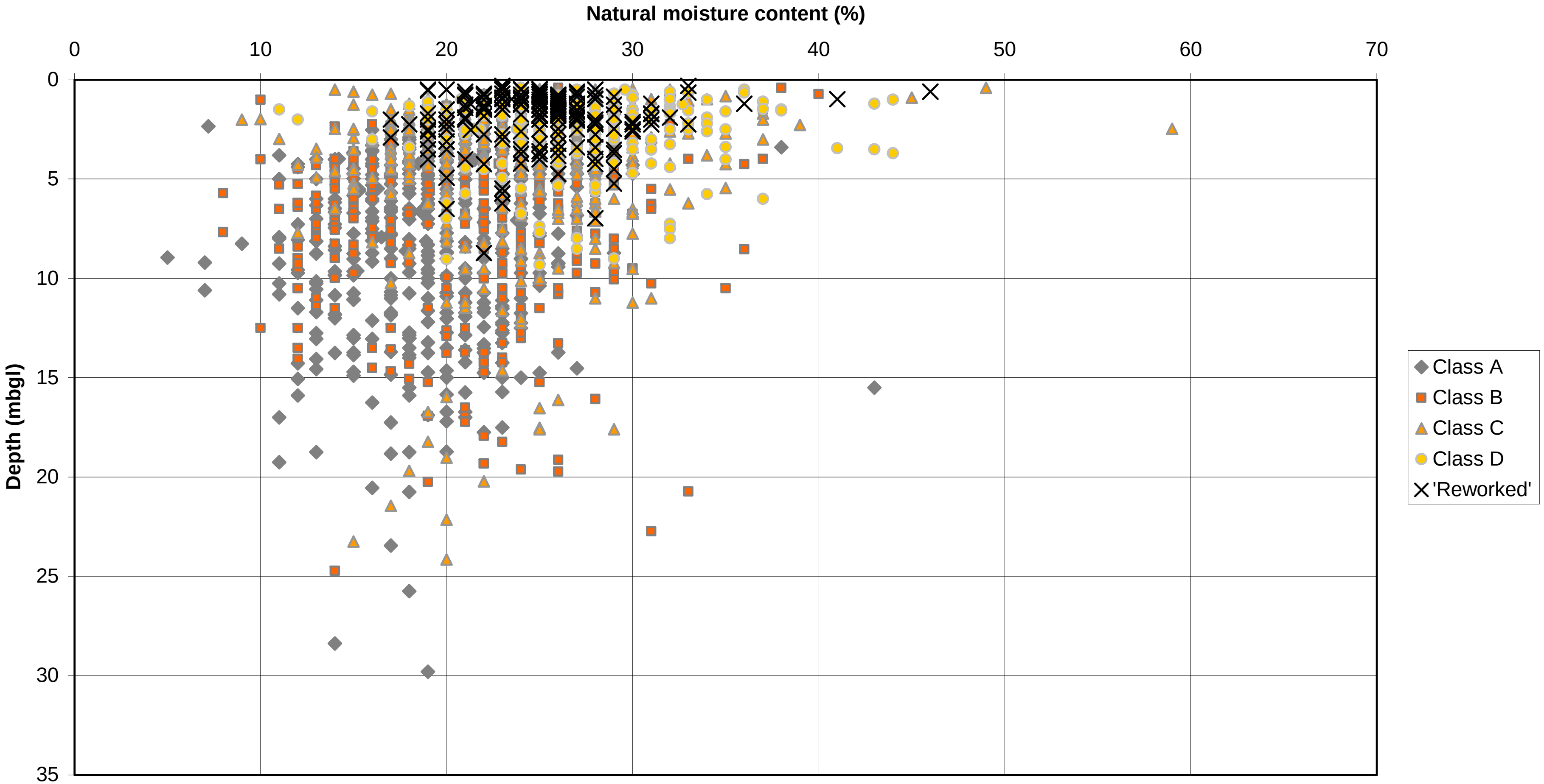
Charmouth Mudstone Formation - Aqueous Soluble Sulphate - Weathering Zone

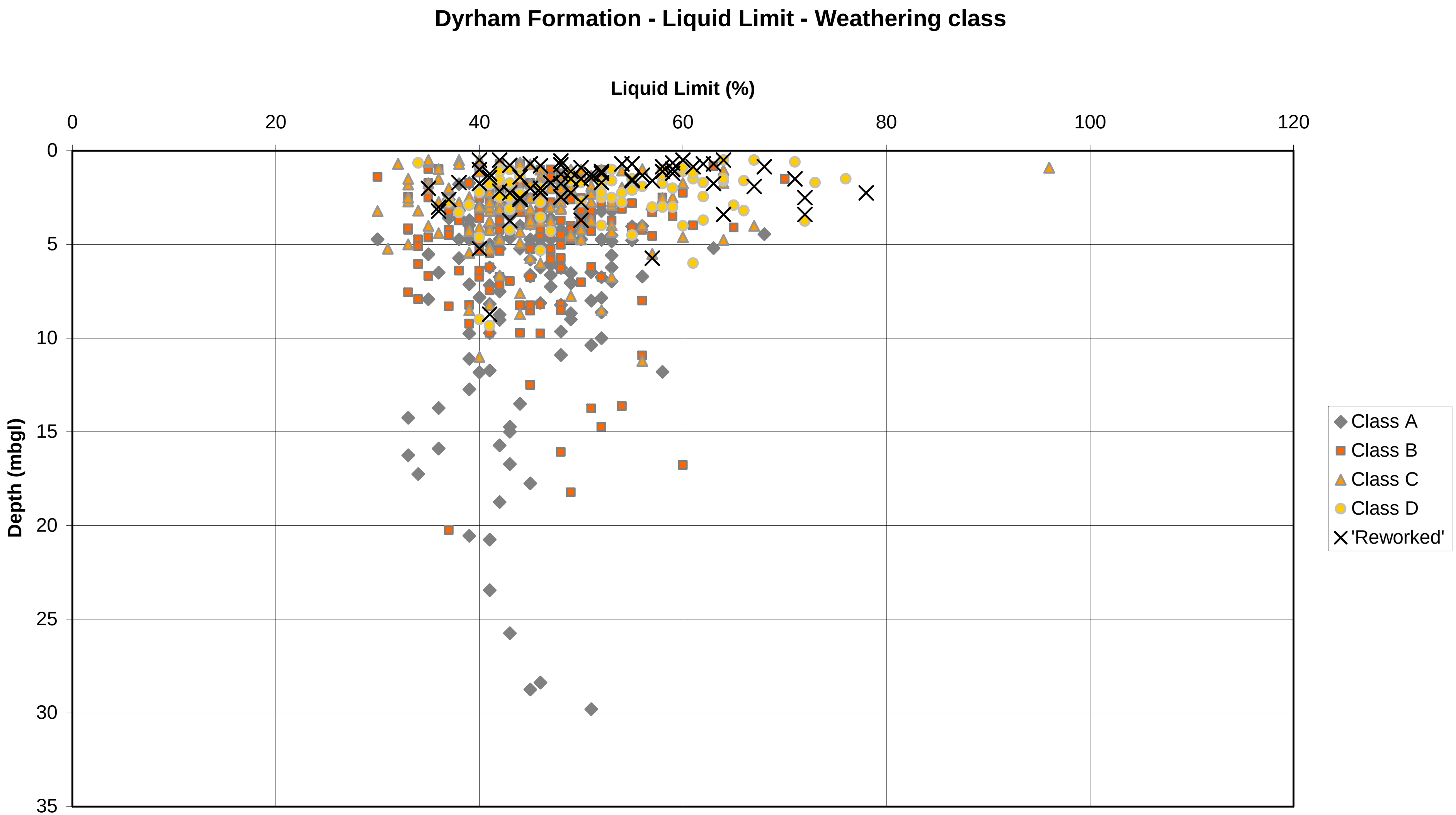




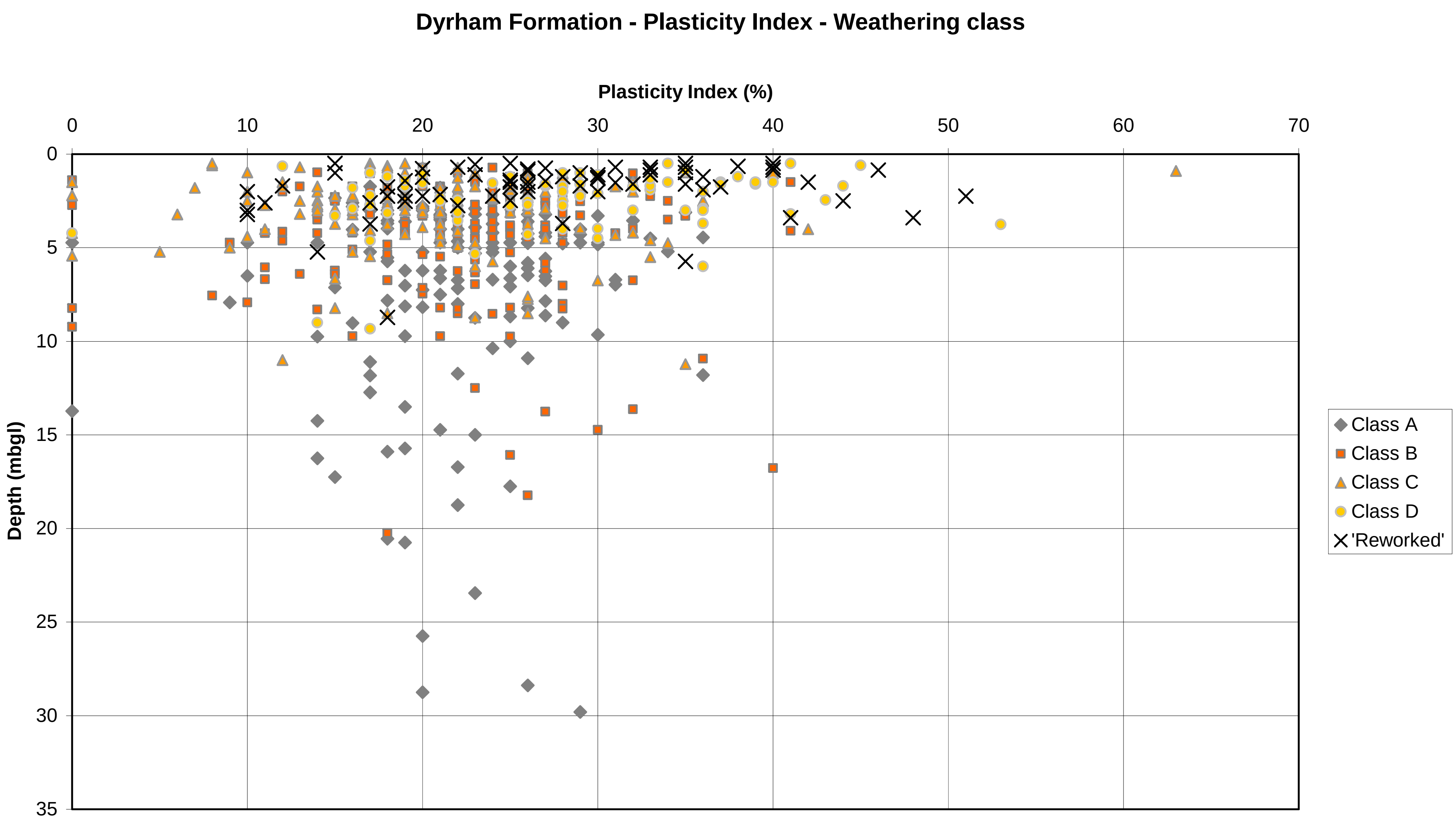
Charmouth Mudstone Formation - pH - Weathering class
pH
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
0
5
10
15
20
25
Depth (mbgl)
Class A
Class B
Class C
Class D
'Reworked'

Dyrham Formation - Natural moisture content - Weathering class

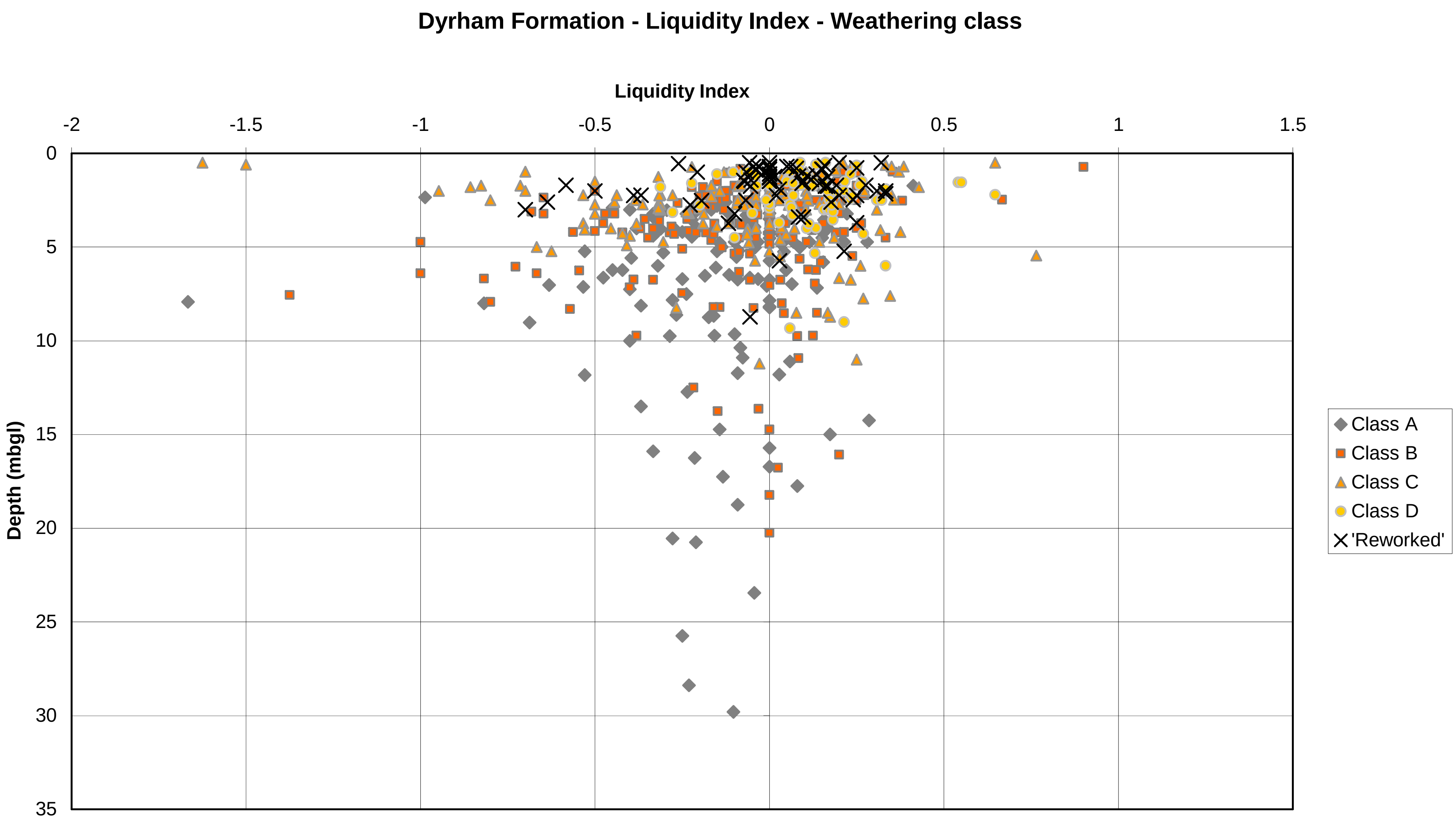


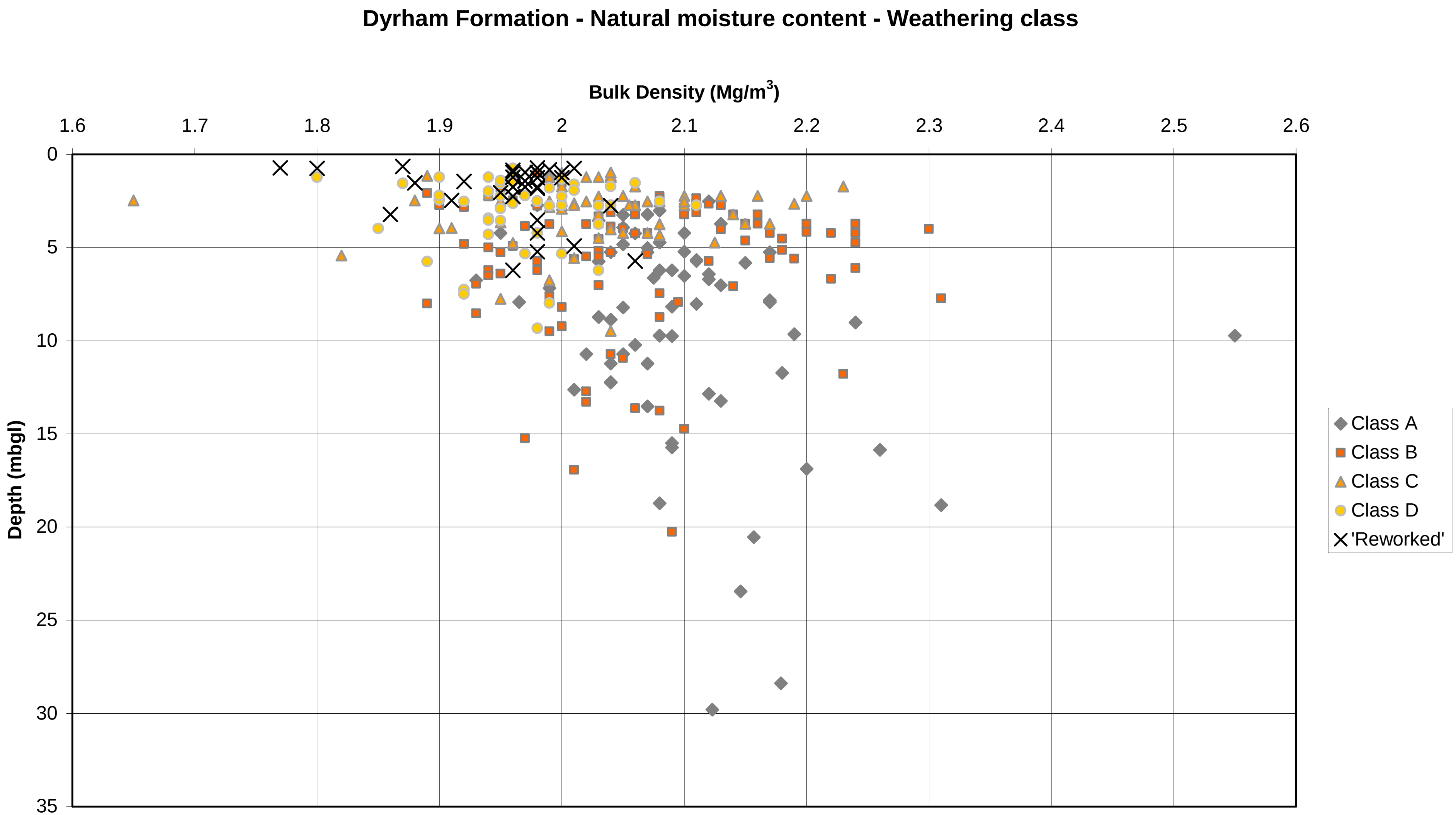


Dyrham Formation - Liquid Limit - Weathering class
Liquid Limit (%)
0
20
40
60
80
100
120
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
'Reworked'

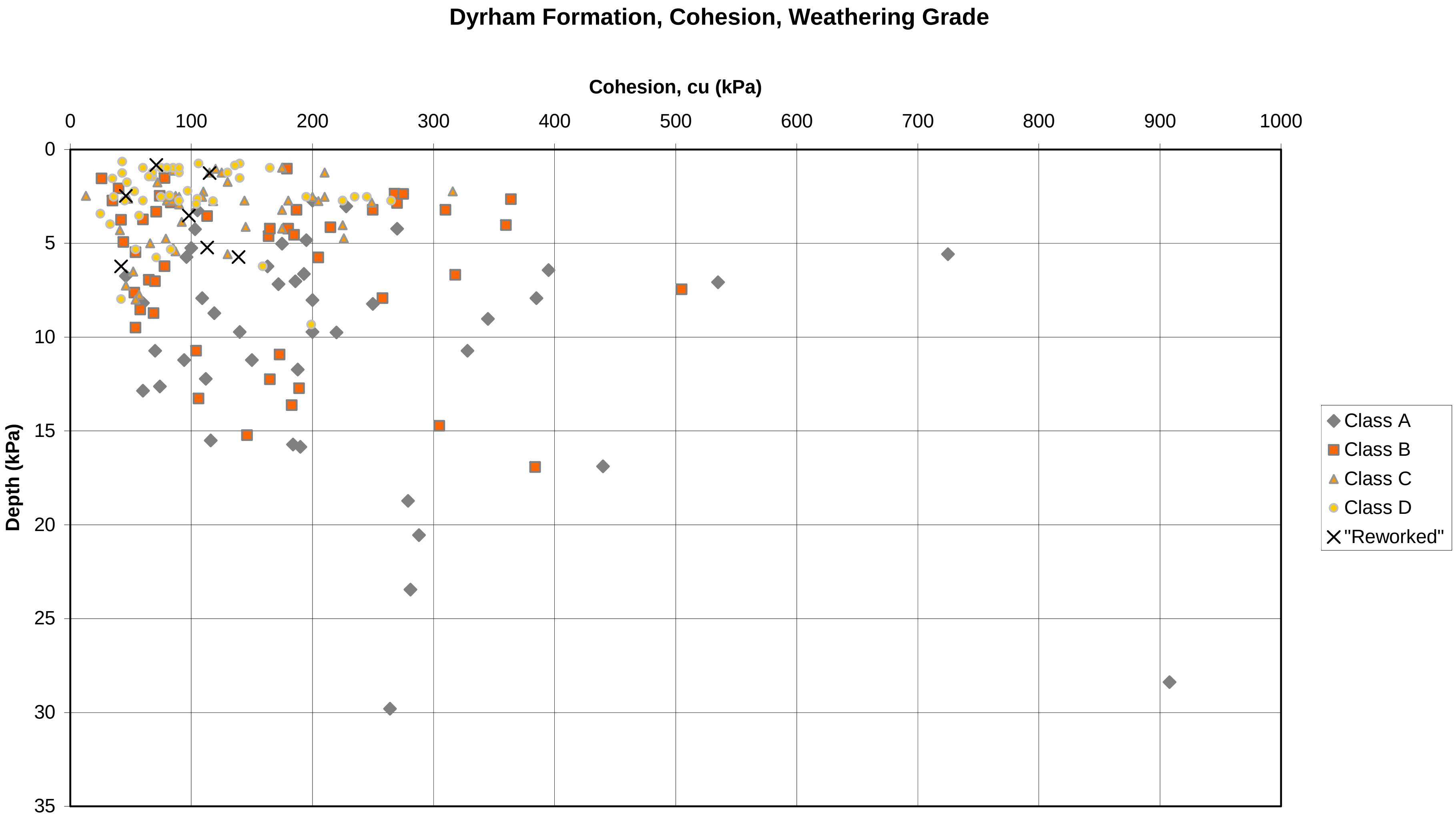


Dyrham Formation - Plasticity Index - Weathering class
Plasticity Index (%)
0
10
20
30
40
50
60
70
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
'Reworked'

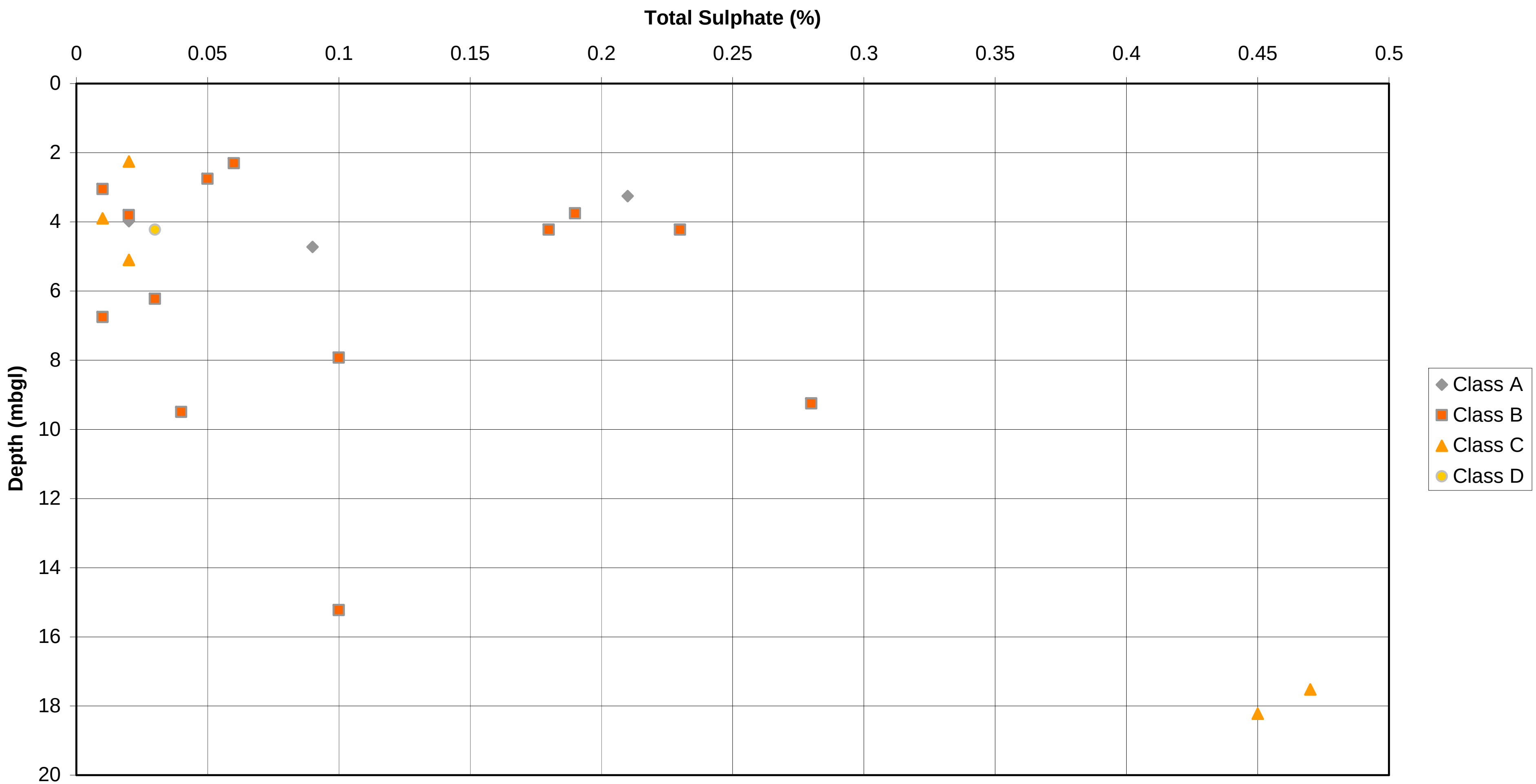

Dyrham Formation - Liquidity Index - Weathering class
Liquidity Index
-2
-1.5
-1
-0.5
0
0.5
1
1.5
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
'Reworked'



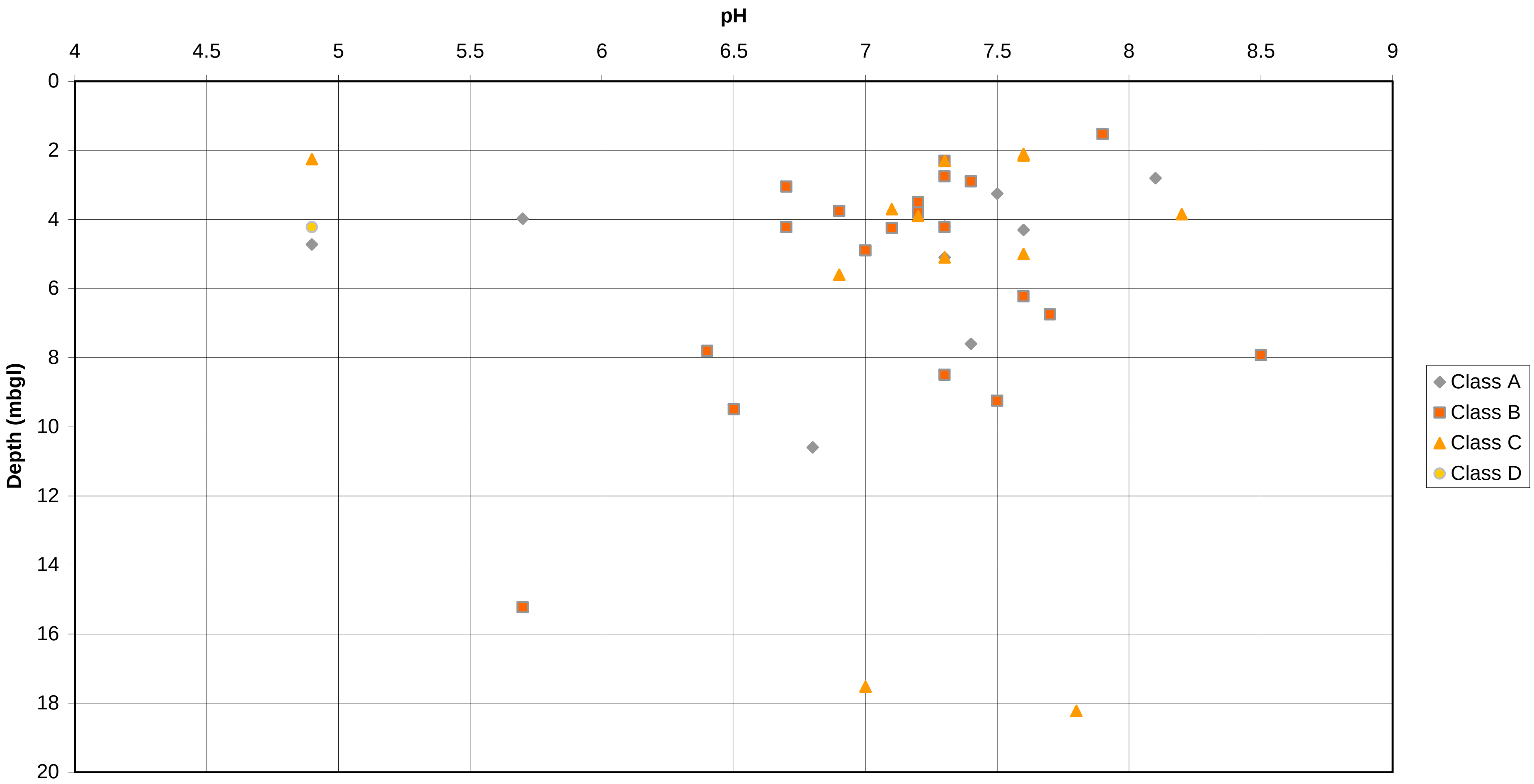
Dyrham Formation - Natural moisture content - Weathering class
Bulk Density (Mg/m3)
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
'Reworked'

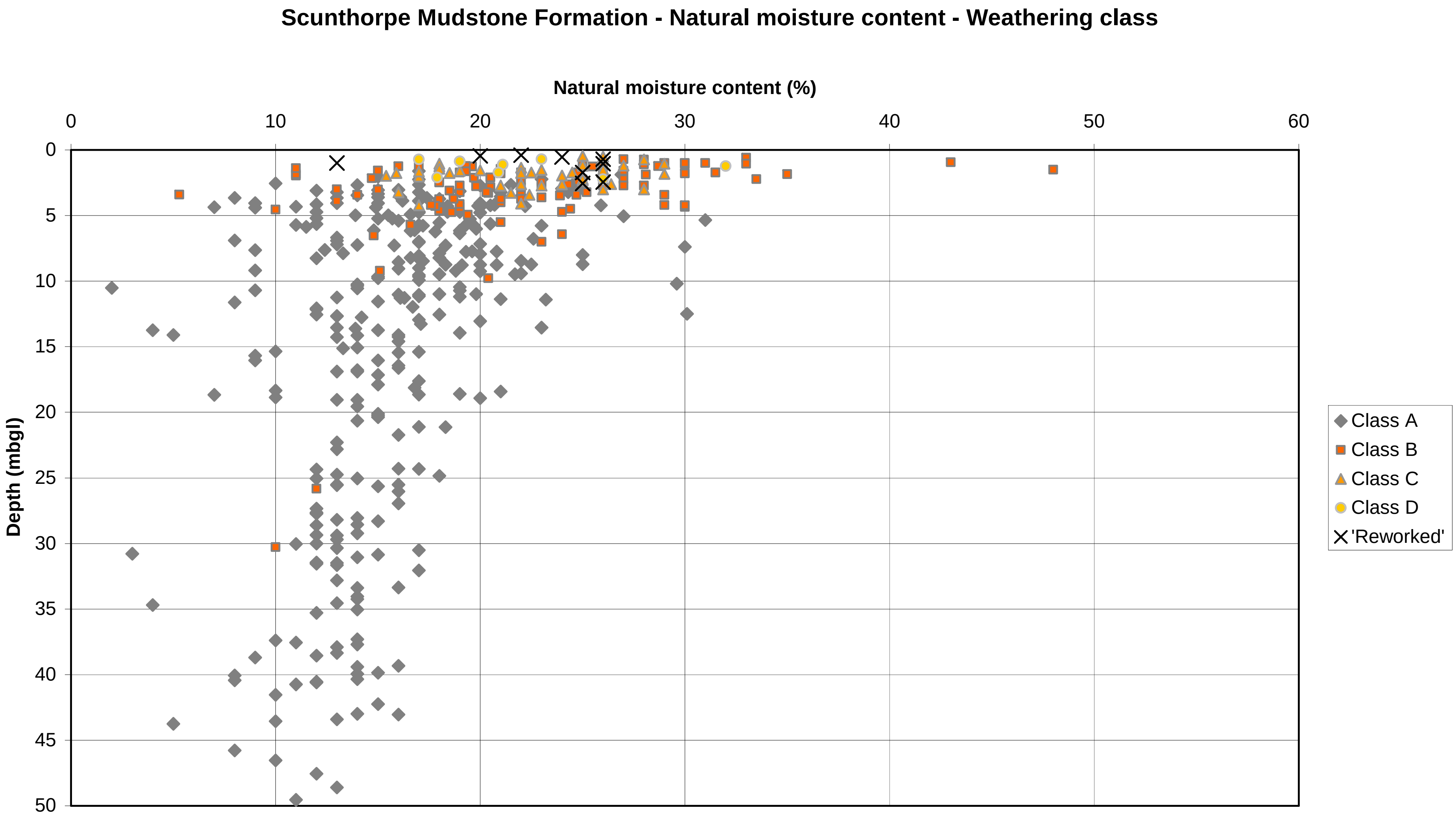

Dyrham Formation, Cohesion, Weathering Grade
Cohesion, cu (kPa)
0
100
200
300
400
500
600
700
800
900
1000
Depth (kPa)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
"Reworked"

Dyrham Formation - Total Sulphate - Weathering Class



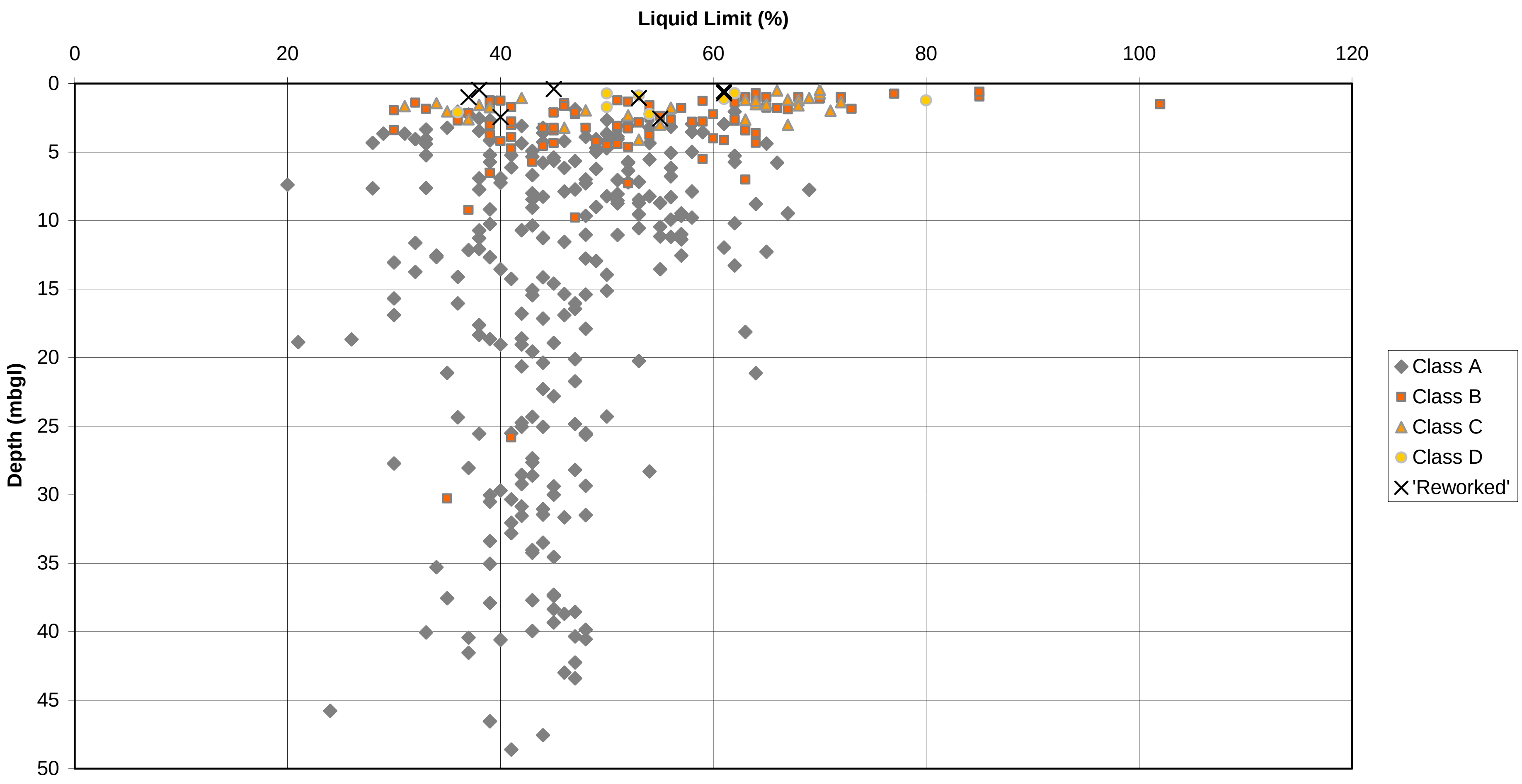
Dyrham Formation - pH - Weathering Class

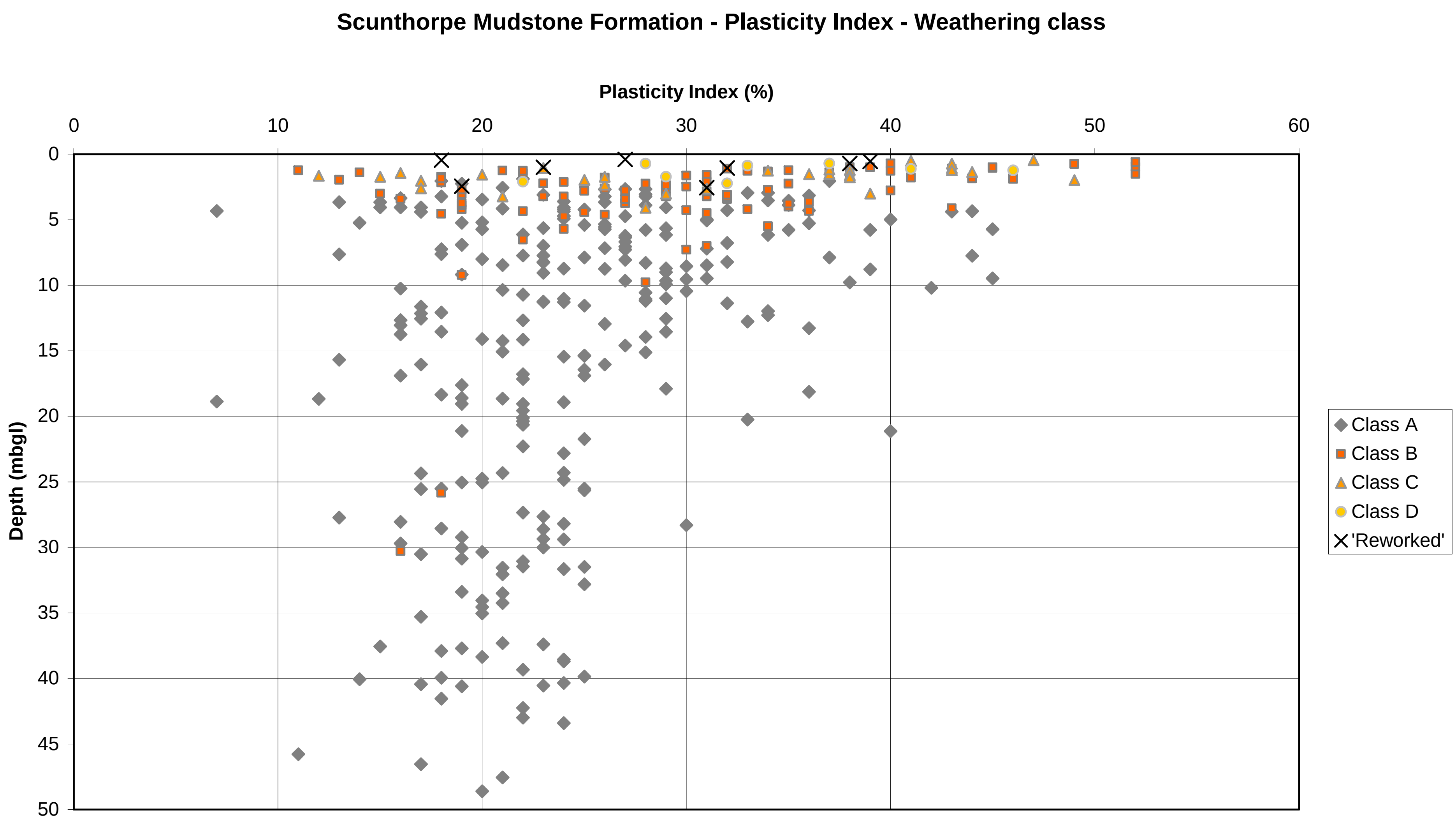




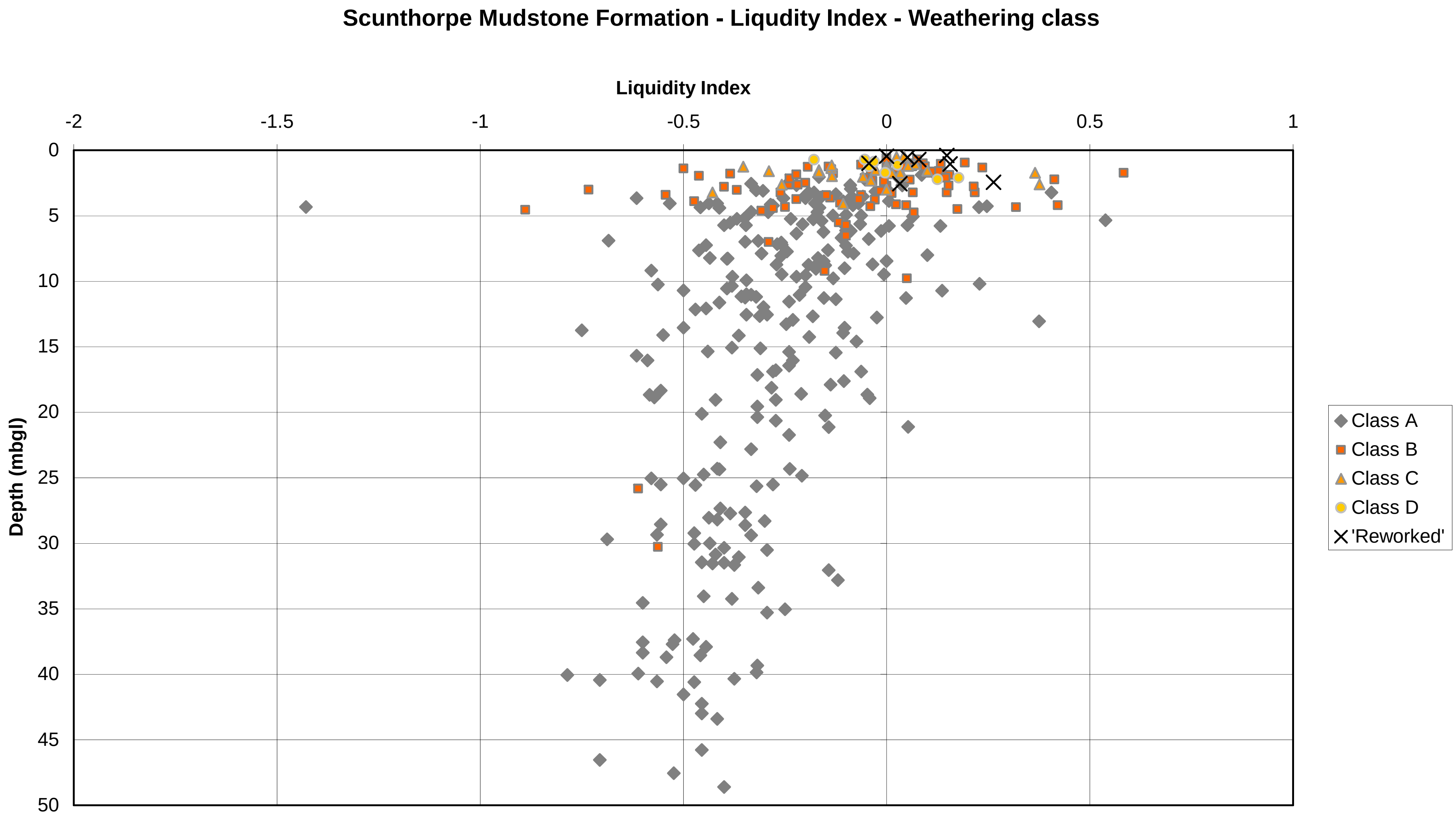
Scunthorpe Mudstone Formation - Natural moisture content - Weathering class
Natural moisture content (%)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50
Depth (mbgl)
Class A
Class B
Class C
Class D
'Reworked'

Scunthorpe Mudstone Formation - Liquid limit - Weathering class



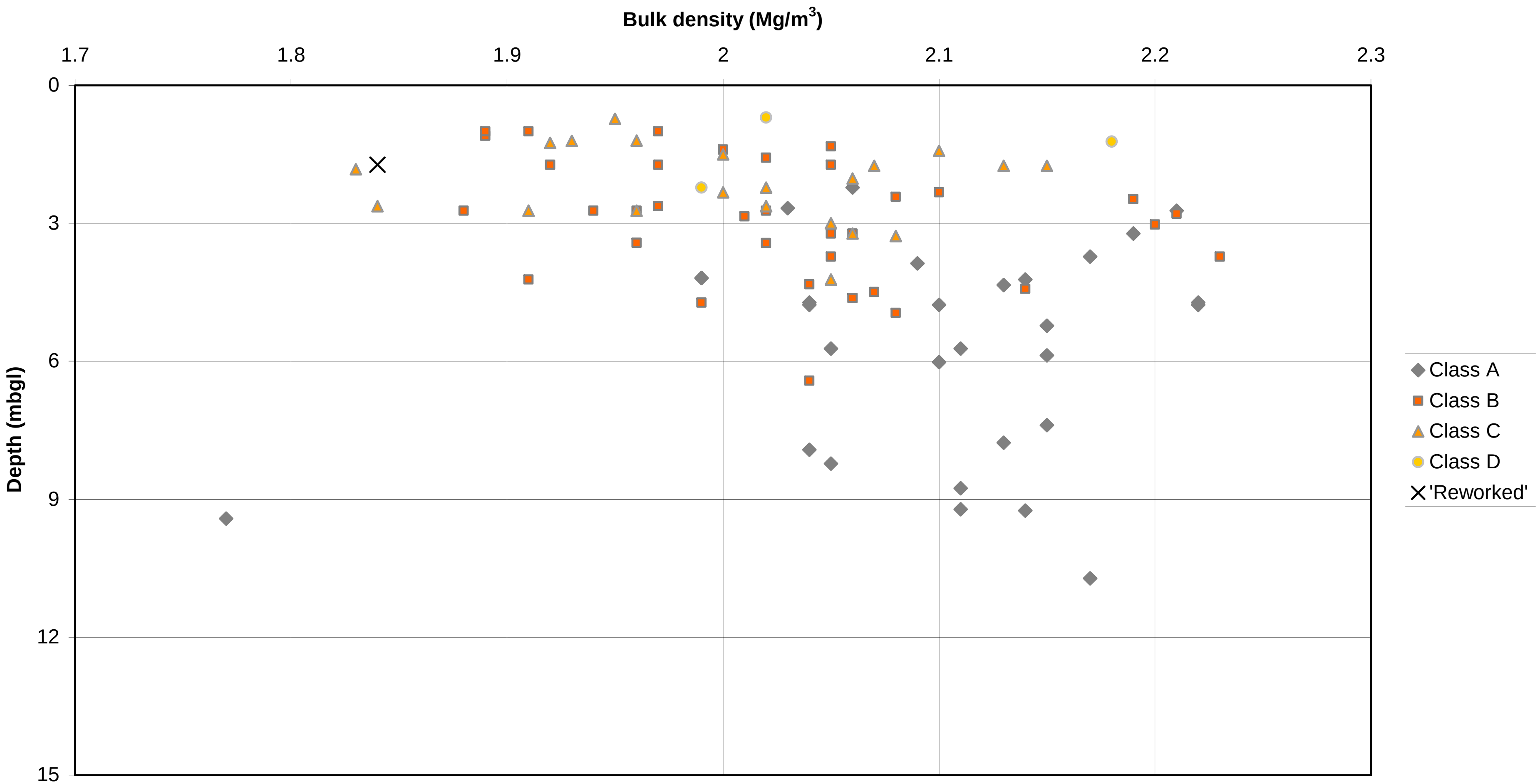


Scunthorpe Mudstone Formation - Plasticity Index - Weathering class
Plasticity Index (%)
0
10
20
30
40
50
60
Depth (mbgl)
0
5
10
15
20
25
30
35
40
45
50
Class A
Class B
Class C
Class D
'Reworked'

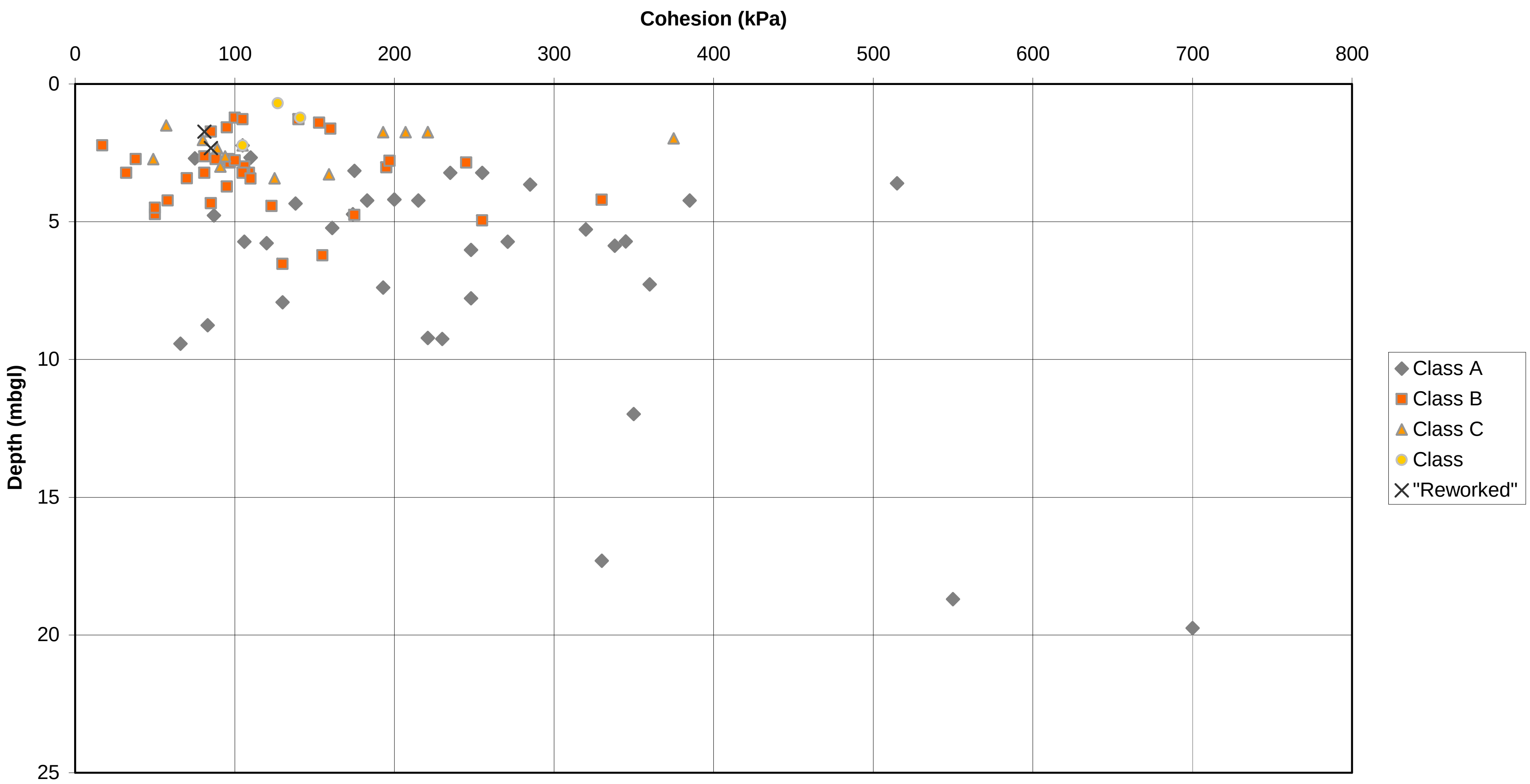


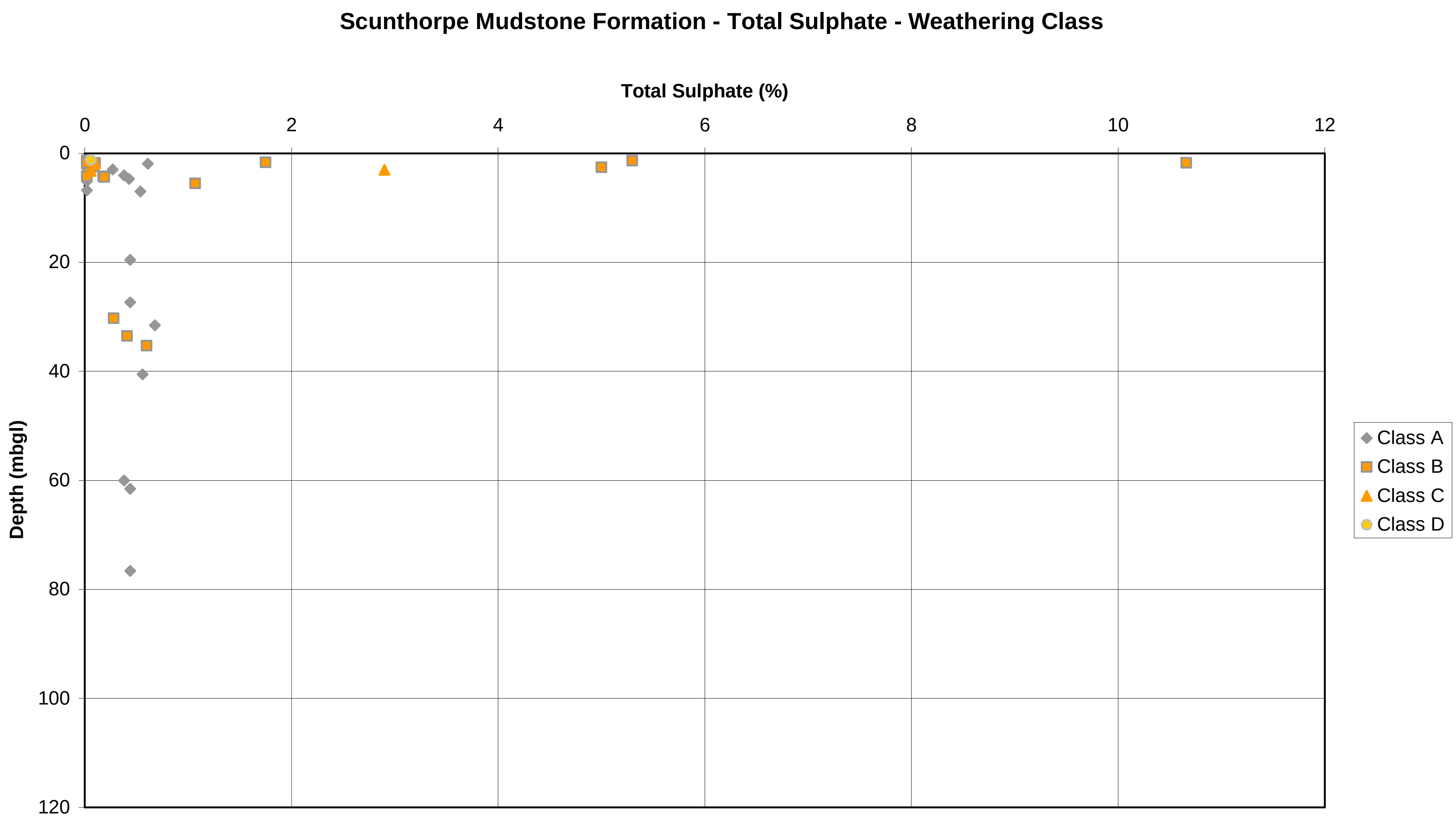
Scunthorpe Mudstone Formation - Liqudity Index - Weathering class
Liquidity Index
-2
-1.5
-1
-0.5
0
0.5
1
Depth (mbgl)
0
5
10
15
20
25
30
35
40
45
50
Class A
Class B
Class C
Class D
'Reworked'

Scunthorpe Mudstone Formation - Bulk Density - Weathering class



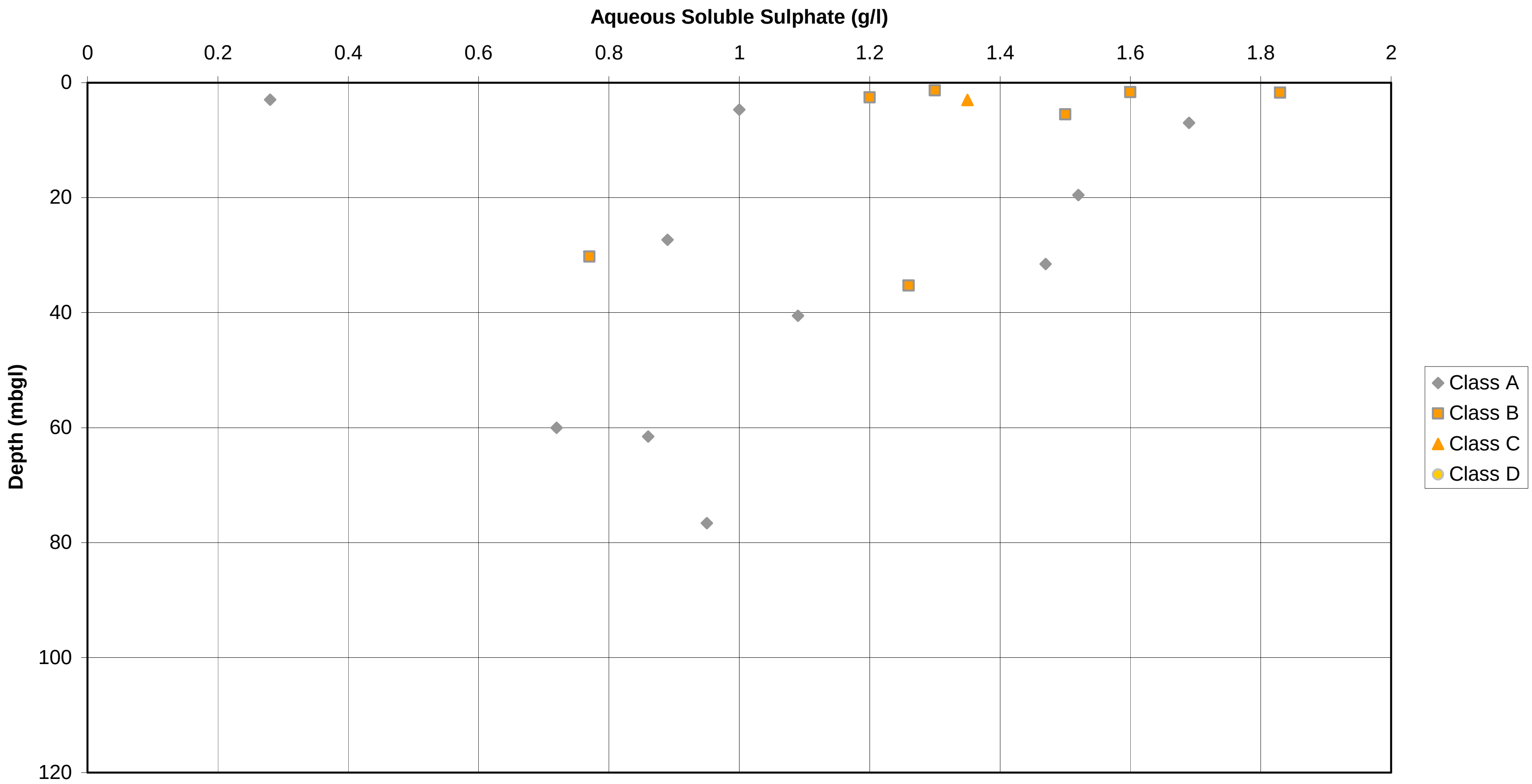
Scunthorpe Mudstone Formation - Cohesion profile by weathering





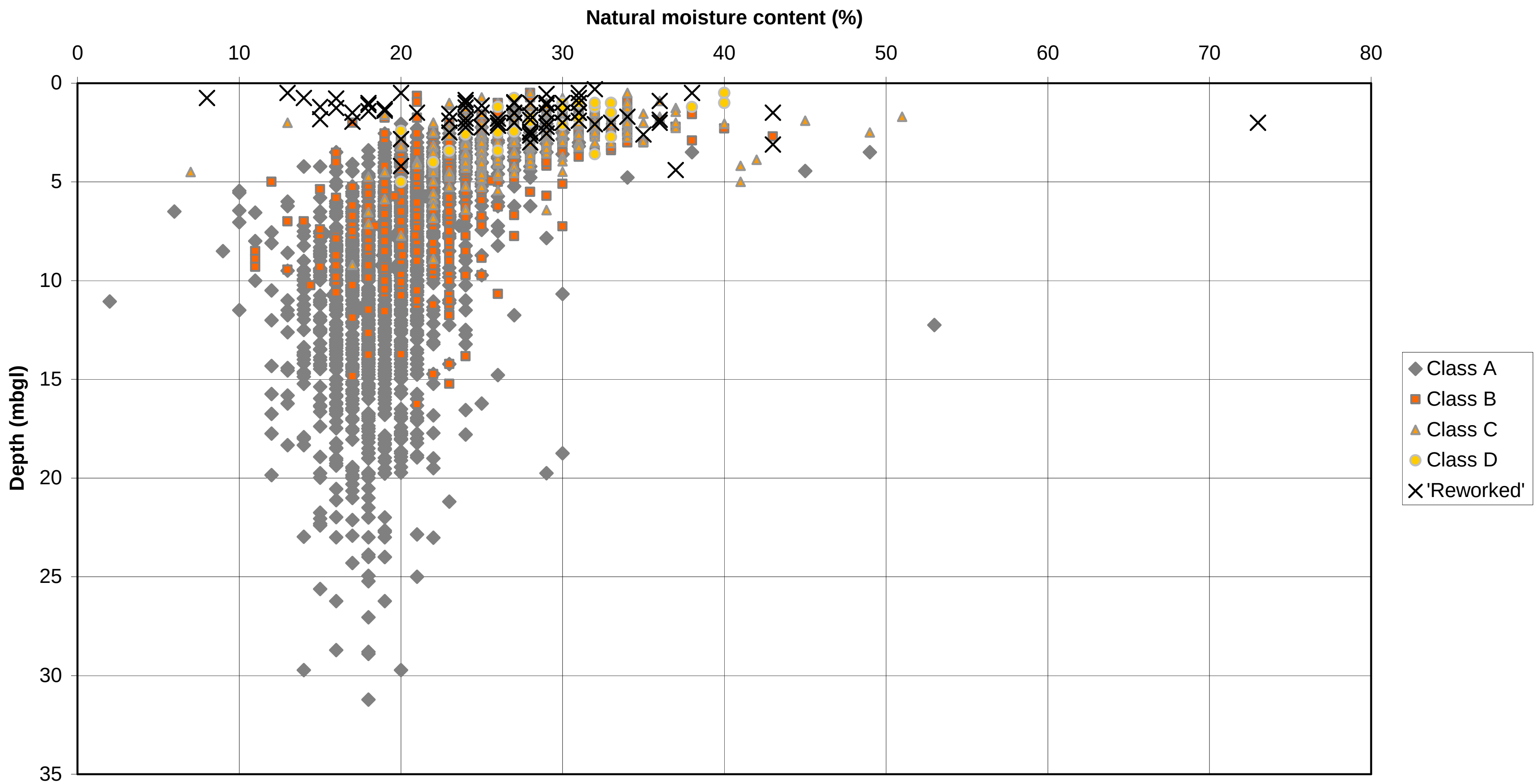
Scunthorpe Mudstone Formation - Total Sulphate - Weathering Class
Total Sulphate (%)
0
2
4
6
8
10
12
Depth (mbgl)
0
20
40
60
80
100
120
Class A
Class B
Class C
Class D

Scunthorpe Mudstone Formation - Aqueous Soluble Sulphate - Weathering Class

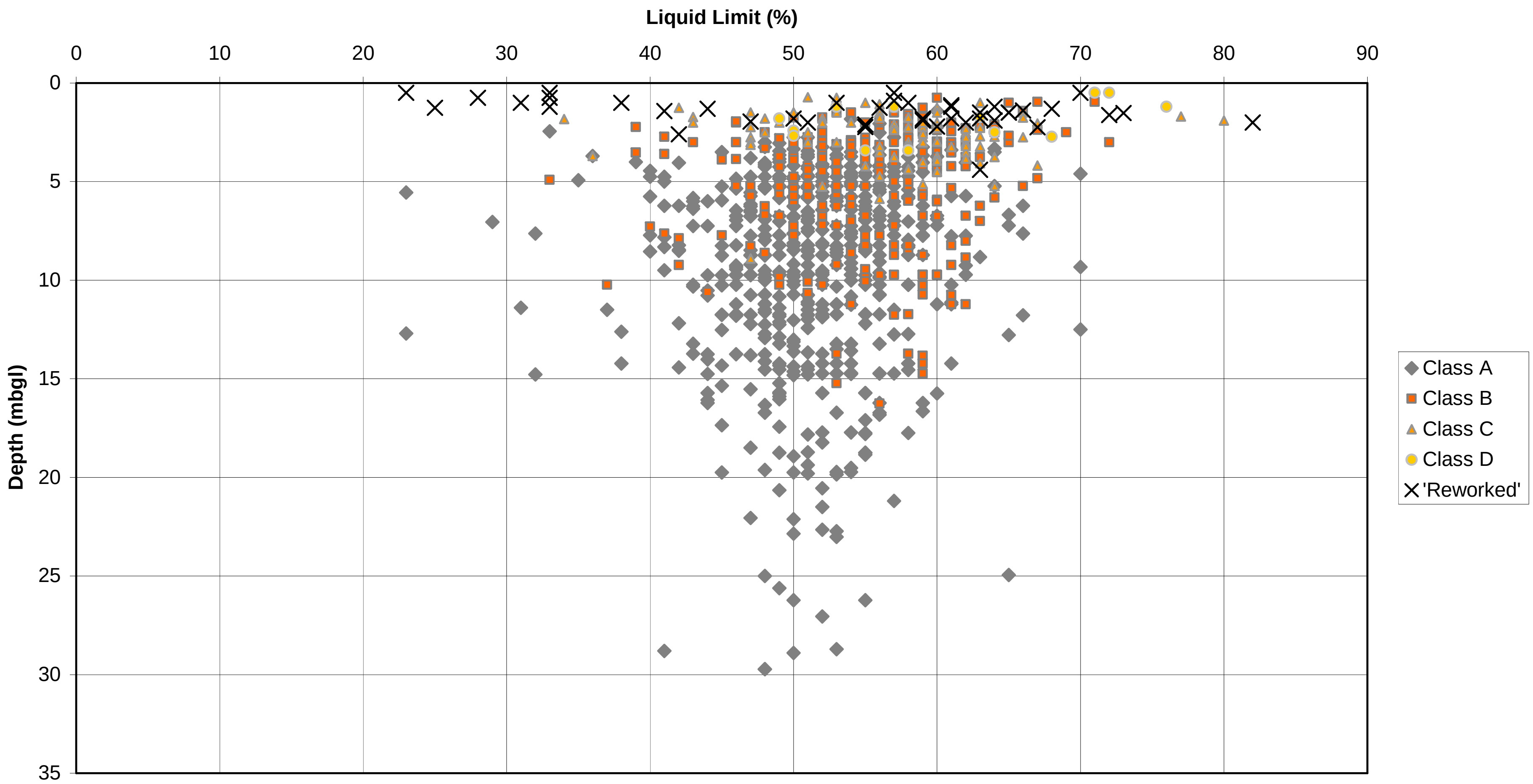



Scunthorpe Mudstone Formation - pH - Weathering Class
pH
6
6.5
7
7.5
8
8.5
9
Depth (mbgl)
0
2
4
6
8
10
12
14
16
18
20
Class A
Class B
Class C
Class D

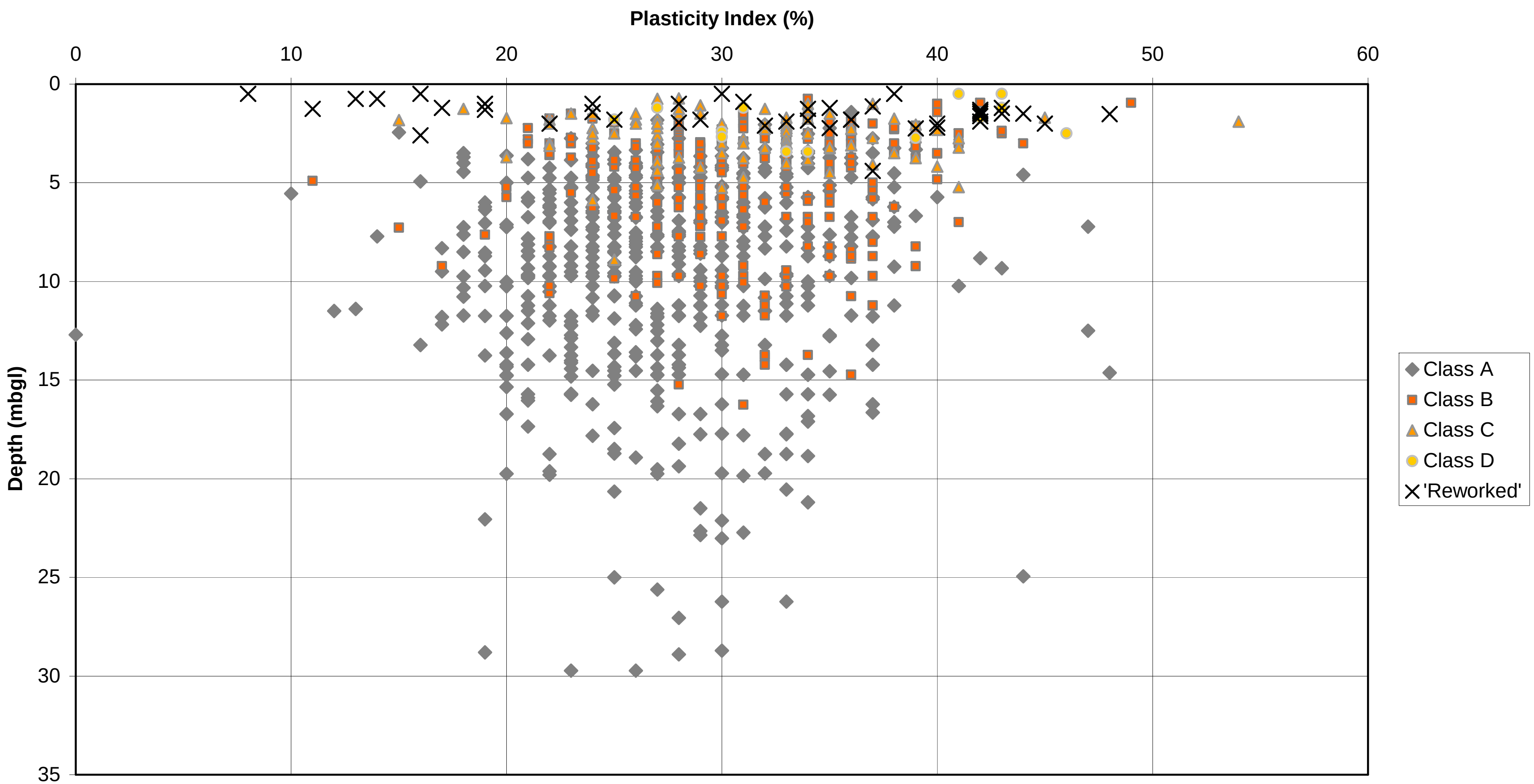
Whitby Mudstone Formation - Natural moisture content - Weathering class

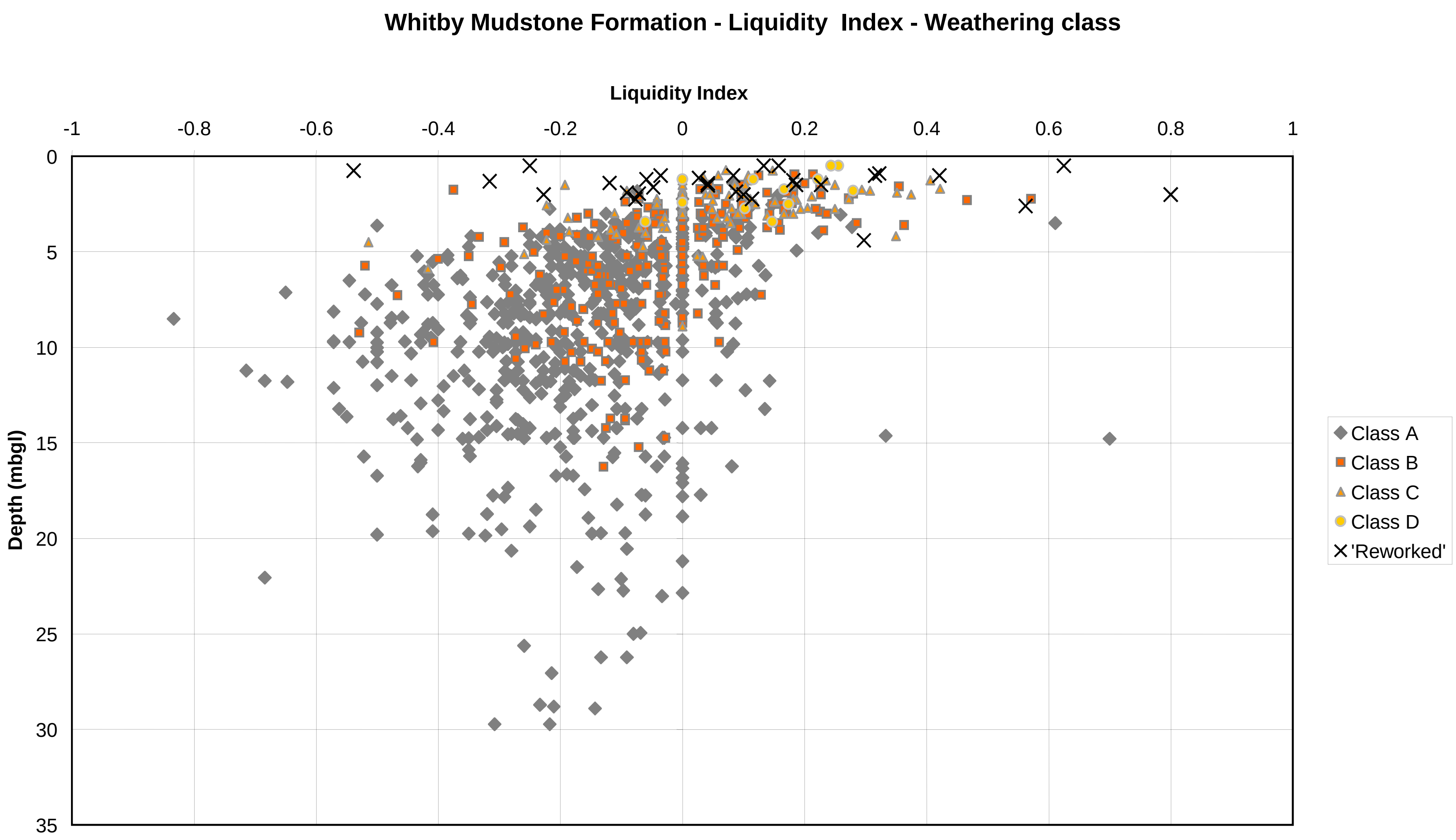


Whitby Mudstone Formation - Liquid limit - Weathering class

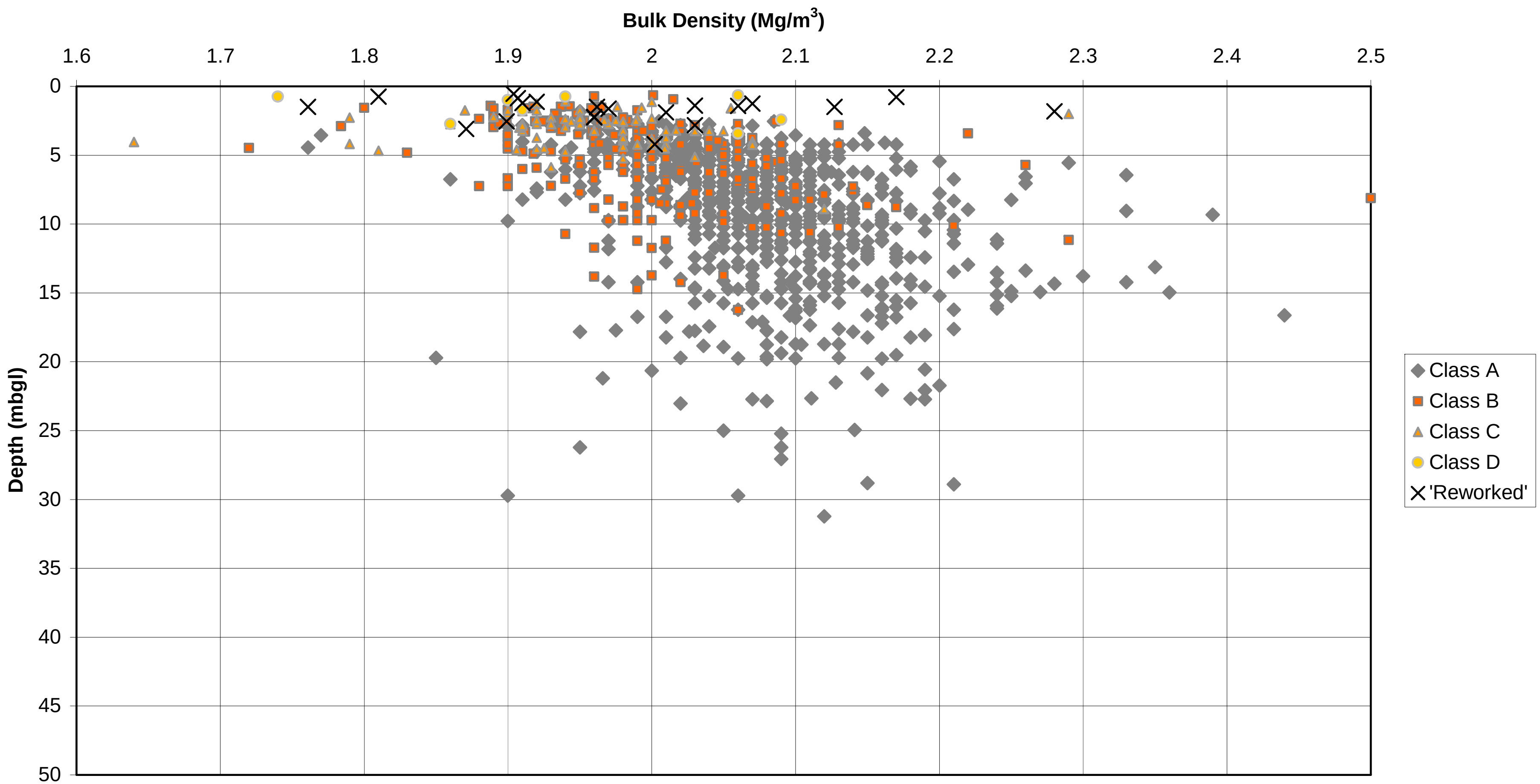


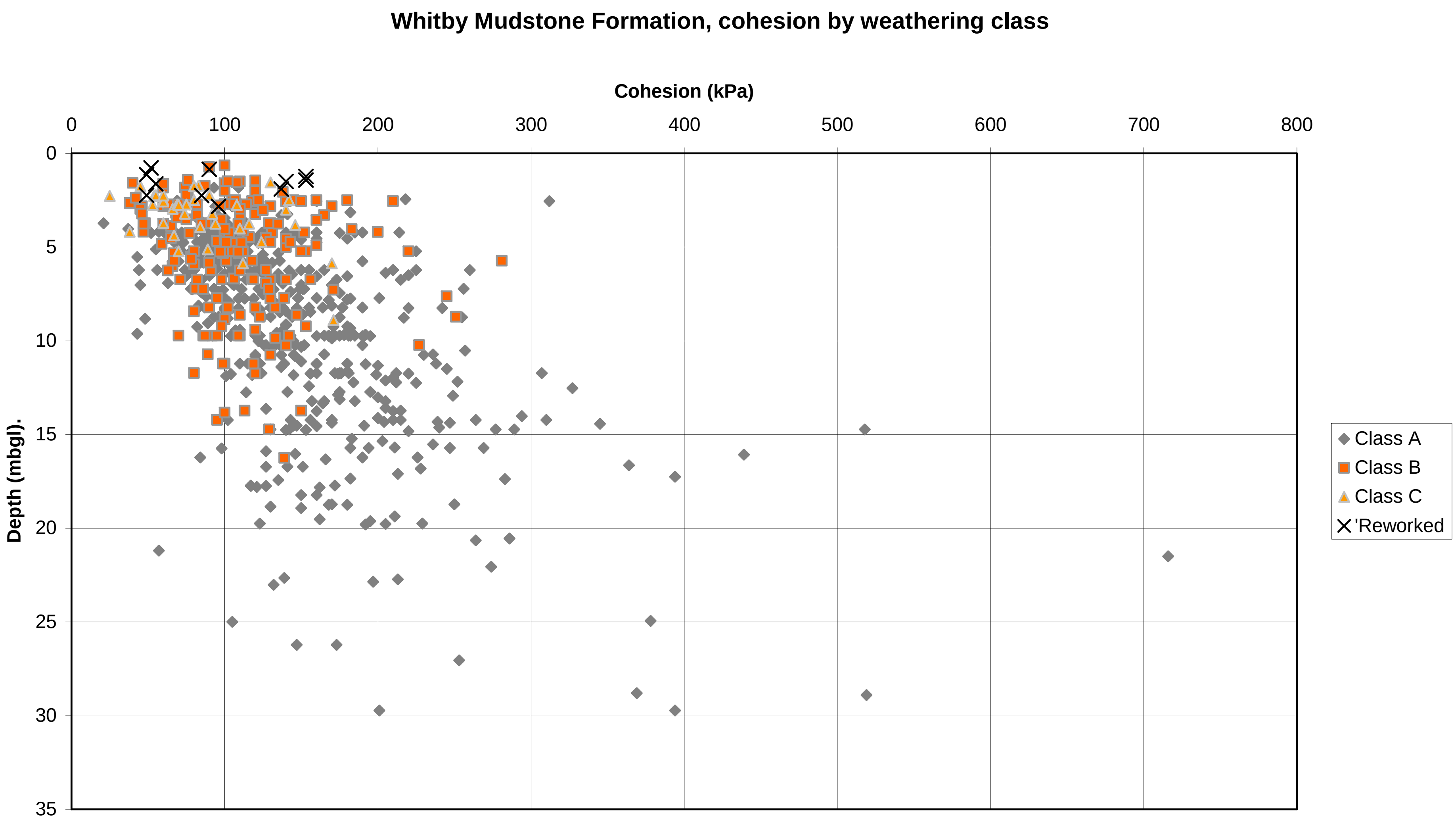
Charmouth Mudstone Formation - Plasticity Index - Weathering class



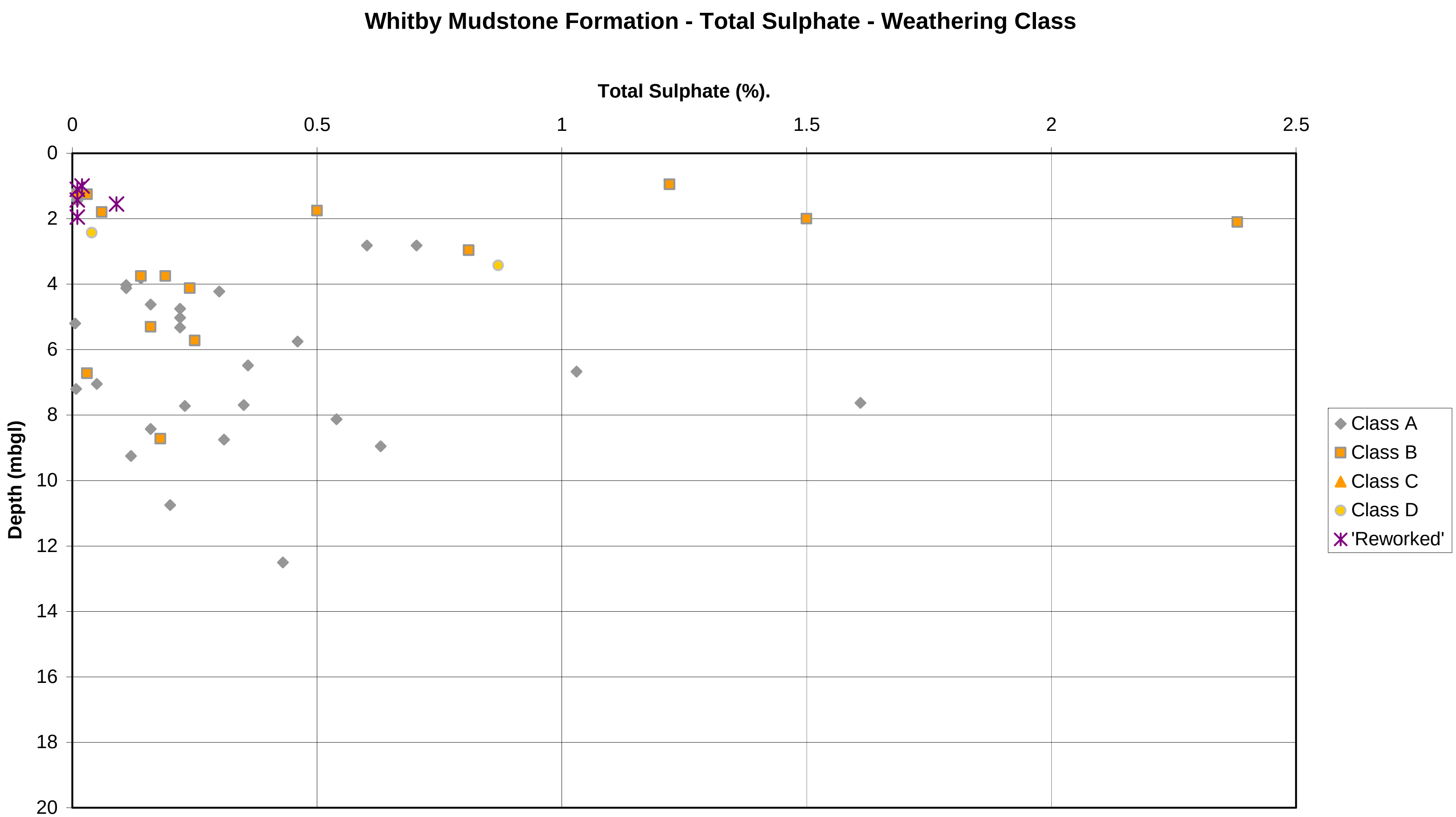

Whitby Mudstone Formation - Liquidity Index - Weathering class
Liquidity Index
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Depth (mbgl)
0
5
10
15
20
25
30
35
Class A
Class B
Class C
Class D
'Reworked'

Whitby Mudstone Formation - Bulk Density - Weathering class



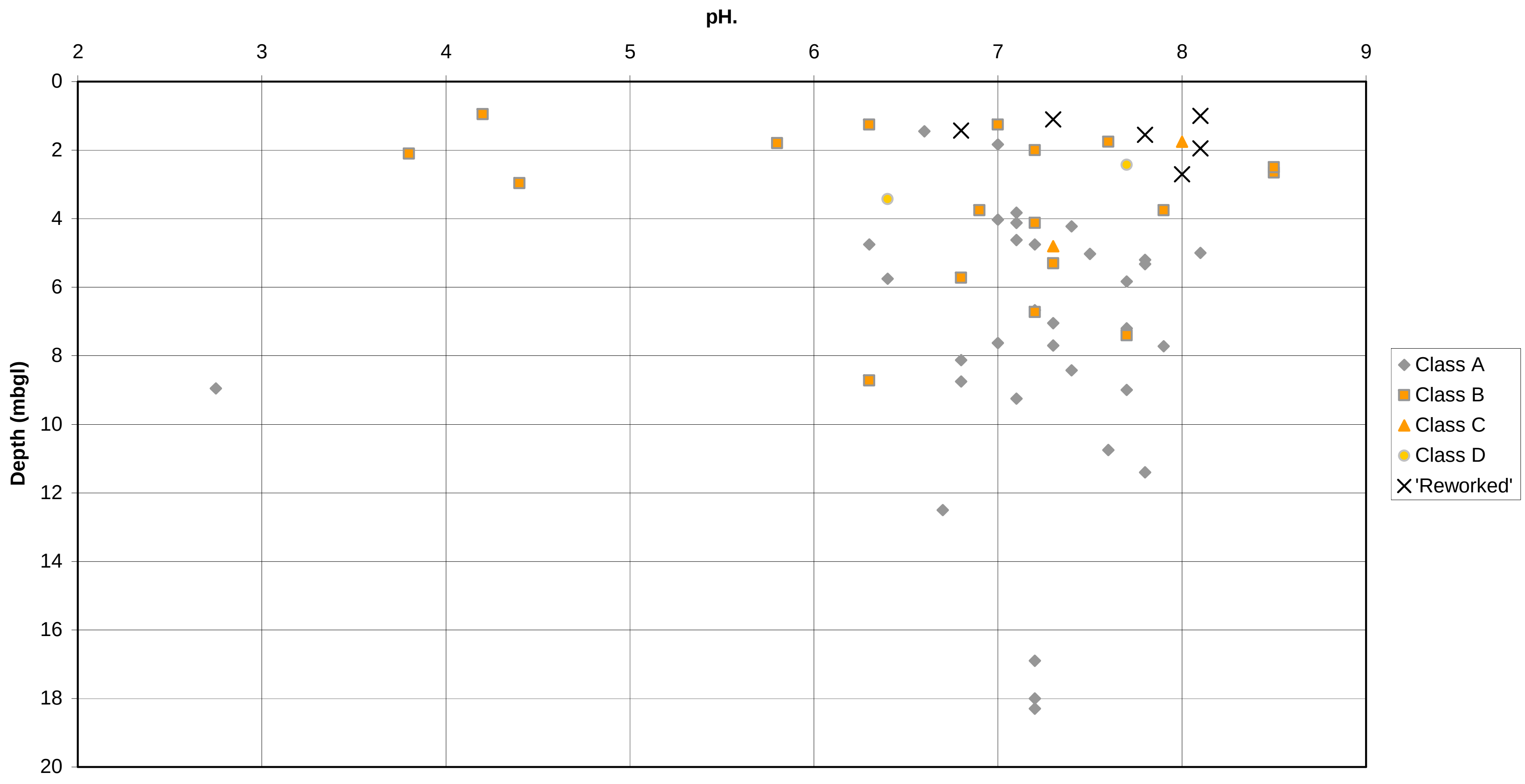


Whitby Mudstone Formation, cohesion by weathering class
Cohesion (kPa)
0
100
200
300
400
500
600
700
800
Depth (mbgl).
0
5
10
15
20
25
30
35
Class A
Class B
Class C
'Reworked



Whitby Mudstone Formation - Total Sulphate - Weathering Class
Total Sulphate (%).
0
0.5
1
1.5
2
2.5
Depth (mbgl)
0
2
4
6
8
10
12
14
16
18
20
Class A
Class B
Class C
Class D
'Reworked'

Whitby Mudstone Formation - pH - Weathering Class



APPENDIX D4

Summary shrink-swell data by Formation

Summary shrink-swell data by Formation

FORMATION	MEMBER	LOCATION	NMC (%)	PD (Mg/m3)	LL (%)	PL (%)	PI (%)	%CLAY (%)	LS (%)	LI	1-D Swell Strain (%)	3-D Swell Strain (%)	Ac
Scunthorpe M.	Frodingham Ironstone	Conesby Quarry	18.4	2.83	51	24	27	46.8	14	-0.21			0.58
Scunthorpe M.	Barnstone Limestone	Barnstone quarry	9.3	2.65	36	22	14	12	8	-0.91			1.17
Scunthorpe M.		Flixborough Quarry	16.2	2.85	60	23	37	5.8	12	-0.18			6.38
Scunthorpe M.		Flixborough Quarry 2		2.7	46	17	29	29.1	11				1.00
Scunthorpe M.		Norton Bottoms	16.7	2.82	60	25	35	34.4	13	-0.24			1.02
Scunthorpe M.		Whisby Quarry	19.7	2.64	53	22	31	35	12	-0.07			0.89
Blue Lias	Porthkerry	Aberthaw	24.1	2.71	39	20	19	15.7	8	0.22			1.21
Blue Lias		Bishops Cleeve 2	22.8	2.72	48	20	28	49.2	9	0.10			0.57
Blue Lias		Bishops Cleeve 1	21.6		46	23	23	33.2	9	-0.06	0.69	2.68	0.69
Blue Lias		Lake View	14.1	2.75	33	17	16	12.8	7	-0.18			1.25
Blue Lias		Southam	28.2	2.77	57	22	35	53.7	10	0.18	0.4	2.76	0.65
Blue Lias		Station	16.3	2.65	30	20	10	2	6	-0.37			5.00
Blue Lias		Stowey	30.5	2.69	65	29	36	59.3	16	0.04	1.47	0.66	0.61
Charmouth M.	Belemnite Marl	Black Ven	7.6	2.76	36	17	19	3.7	8	-0.49			5.14
Charmouth M.	Black Ven Marl	Black Ven	21.4	2.64	52	28	24	41.3	12	-0.28			0.58
Charmouth M.	Shales-with-Beef	Black Ven	11.1	2.69	50	25	25	5.8	11	-0.56			4.31
Charmouth M.		Blockley 1	23.9	2.65	55	23	32	39.1	12	0.03	0.36	1.78	0.82
Charmouth M.		Blockley 2	21.4	2.7	56	22	34	42.3	9	-0.02			0.80
Charmouth M.		Conesby Quarry 2	23.3	2.66	61	23	38	35.1	13	0.01			1.08
Charmouth M.		Dimmer 1	31.2	2.64	57	23	34	53.7	13	0.24	0.48	2.22	0.63
Charmouth M.	Green Ammonite Bed	Seatown	20.8	2.79	58	24	34	38.3	12	-0.09			0.89
Dyrham		Robins Wood Hill 2	17.5	2.7	46	25	21	27.3	12	-0.36			0.77
Dyrham	Eype Clay	Seatown	11.6	2.71	54	23	31	20.6	12	-0.37			1.50
Redcar M.		Robin Hoods Bay	16.4	2.66	34	15	19	23.9	10	0.07			0.79
Cleveland I.		Kettleness	10.9	2.63	41	23	18	96.1	10	-0.67			0.19
Marlstone R.		Robins Wood Hill 3	19.3	2.73	45	25	20	22.9	8	-0.29			0.87
Marlstone R.		Edgehill	42.9	3.24	55	36	19	15	10	0.36			1.27
Marlstone R.		Hornton	29	3.4	47	31	16	0	9	-0.13			
Whitby M.		Brixworth	20.5	2.79	55	28	27	1.7	9	-0.28	0.19	6.08	15.88
Whitby M.	Alum Shale	Ravenscar 2	19.9	2.69	41	25	16	62.4	9	-0.32			0.26
Whitby M.		Runswick Bay	4.4	2.75	32	18	14	31.6	8	-0.97			0.44
Whitby M.		Sidegate Lane 1	16	2.83	61	26	35	1.7	14	-0.29	6.04	12.47	20.59