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Desk Based Study and Literature Review of Diapirism in Plastic Clays and an analysis of the Critical state of Boom Clay

Minerals & Waste

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Cover Photograph

Valley bulging , River Ashop near Rowlee Bridge, Derbyshire, UK . (Photo: P. Hobbs)

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Foreword

This report is the product of a study by the British Geological Survey (BGS) into diapirism in plastic clays with particular emphasis on the Boom Clay and the geological disposal of higher activity radioactive waste/spent nuclear fuel in the Belgian context. This involved a desk study and literature review. A critical state analysis was undertaken to determine the probable driving mechanism in the formation of the observed diapirs and their likelihood of their formation in the future. A number of critical stress scenarios were modelled which demonstrate that the Boom Clay at a depth equivalent to the MOL laboratory (220m) is stable and that under *in situ* conditions is not close to failure in any of the scenarios examined. The final scenario, which attempts to model the diaper formation in the Boom Clay under the Scheldt River, shows that the clay is close to failure in this near surface situation.

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NIRAS/ONDRAF is preparing an initial Safety & Feasibility Case (SFC 1) for high-level and long-lived radioactive waste (to be completed by 2013) to demonstrate that geological disposal in poorly indurated (plastic) clays (using the Boom Clay as reference case and the Ypresian clays as an alternative) is a practical and safe disposal option to allow them to progress towards siting a repository. A significant part of the SFC 1 will be a geosynthesis report (edited by SCK-CEN and NIRAS/ONDRAF) to investigate the long-term stability of the Boom Clay. Beneath the Scheldt River, up-doming of the top of the Boom Clay (only at a few 10's of metres of depth) is observed in geophysical records and has been referred to as a 'diapiric' structure. NIRAS/ONDRAF has asked the British Geological Survey (BGS) to undertake an initial desk based study to review the literature on diapirism like processes in plastic clays, including the Scheldt River structure, and to discuss the relevance (or lack thereof) of this process in the context of a clay-based geological disposal system for radioactive waste.

NIRAS/ONDRAF has provided access to the dedicated literature on Boom Clay and Ypresian clays and the reported diapiric structures. BGS has undertaken a literature search of published international papers to supplement the information available from NIRAS/ONDRAF and to identify the geological processes that might give rise to diapirs in poorly indurated clays and ductile shales. This includes an assessment of the diapir-like structures observed in the Boom and Ypresian clays in the context of the information obtained from the wider literature search. The comprehensive literature search is focussed on material published in English.

The term diapir infers a density driven mechanism that moves material from depth to a shallower depth. The stress analysis undertaken shows that the formation of a "diapir" is highly unlikely at the depth of a repository due to the extreme changes in stresses required. The analysis has shown that a localised deformation as the result of the location of a river is more likely the cause of the creation of the features that have been inferred as being a diapir. These are not diapirs and are similar to valley bulging features seen, with the river banks acting similarly to valley sides and the bulge occurring in the bottom of the river.

A number critical stress scenarios have been modelled during the work reported here which demonstrate that the Boom Clay at a depth equivalent to the MOL laboratory (220m) is stable and that under *in situ* conditions are not close to failure in any of the scenarios examined. The final scenario, which attempts to model the diaper formation in the Boom Clay under the Scheldt River, shows that the clay is close to failure in this near surface situation.

1 Introduction

The Boom Clay in Belgium is a proposed radioactive waste disposal host rock for NIRAS/ONDRAF. Aspects of the plastic and plastic/brittle deformation of mudrock and clay formations, commonly referred to as ‘diapirs’, are examined and discussed with natural examples from the UK and abroad. Various geological conditions and processes may result in, and from, the deformation of mudrocks and clays including cambering, stress relief, artesian conditions. Depending on the properties of the materials involved these deformations may be plastic or brittle. In either case such deformations usually affect the integrity and engineering properties of the formation(s) affected. The report concludes with a desk study of the mechanisms of critical stress state failure of the Boom Clay to develop an understanding of the conditions under which the Boom Clay could deform in such a way as to form ‘diapirs’.

2 Desk Study

2.1 DIAPIRISM

2.1.1 Definition

The words **diaper, diapirism and diapiric** are derived from the Greek word *diapeirein*, meaning to pierce through (O'Brien, 1968). The term was introduced by the Romanian geologist M.L. Mrazek in the early 20th Century to describe folds with piercing cores in the Carpathian Mountains. Diapiric structures have however, been recognised and studied since at least the mid 19th Century (O'Brien, 1968). Notable recent contributions to the study of diapirism include O'Brien (1968), Findlater (1979) and Vendeville *et al.* (2000).

The simplest and most succinct definition of diapirism is provided by O'Brien (1968). He defines diapirism as '*a process in which earth materials from deeper levels have pierced, or appear to have pierced, shallower material'.* Diapirs have been identified across the earth, both onshore and offshore, at surface and below surface. They are most frequently found in tectonically active areas and/ or areas of high sedimentation. They may be composed of various materials such as evaporite (halite, gypsum, anhydrite, sylvite), shale, clay, mudstone, peat and serpentine. Diapirs may comprise a single material or be a composite of several.

2.1.2 Formation Mechanisms

Diapir formation has traditionally been attributed to 'Raleigh-Taylor instabilities' whereby weak, low-viscosity, less dense material rises through, and deforms, denser country rocks that are assumed to behave viscously and have negligible yield strength. However, current research no longer supports the Raleigh-Taylor instability mechanism and favours a mechanism whereby weak material rises through much stronger country rock, often requiring some form of tectonic deformation in order for the intrusion to overcome the strength of the country rock; either by directly reducing the strength of the country rock (e.g. tectonic extension or removal of overburden) or indirectly by increasing the pore fluid pressure within the material which forms the diapir (e.g. tectonic compression) (Vendeville, 2000). There are also non-tectonic mechanisms which may increase pore pressure, such as rapid sedimentation and fluid addition. Rapid sedimentation may prevent sediment dewatering and hence sediment compaction, consequently the load of the overburden is increasingly borne by the pore fluid rather than by grain contacts. Gases and liquids can be injected from adjacent fluid rich strata or may even be generated within the sediment by chemical and biological processes. If the egress of fluid from the sediment is less than the ingress or volume generated internally then the pore pressure will increase.

It is evident that diapirs can be formed by a variety of mechanisms depending on the geological setting and nature of source material and surrounding rock/sediment. For example, within the shallow subsurface sediments are less consolidated and subject to lower overburden stress, they will therefore be susceptible to widespread deformation caused by fluid injection from deeper sources. Whereas deeper sediment mobilisation, because the sediment is more indurated and subject to higher overburden stress, often requires significant tectonic forces coupled with large pore fluid overpressure in order to facilitate hydraulic fracture and critical state deformation (Van Rensbergen *et al.* 2003).

2.1.3 Clay diapirism

Clay diapirism, a specific form of diapirism, is the upward deformation and intrusion of plastic clay-rich sediments usually into, or through, more competent overburden; broadly speaking in the manner of intrusive magma. In some instances clay diapirs extrude fluidised mud at surface and are known as mud volcanoes. The active process often takes place during rapid sedimentation of fine-grained materials, for example on the sea bed, in glacial lakes and beneath prograding river deltas. The key feature being that the build-up of excess pore pressures in the clays and other fine-grained sediments is unable to dissipate during the addition of further sediment. The structures formed by this upward movement are seen as folding, faulting and doming. Diapiric features persist and become exposed in natural outcrops and engineered excavations. Mechanisms for the formation of clay diapirs also include valley formation (valley bulging) and other dynamic processes including cambering, pingos and scour hollows, fluid injection and possibly polygonal faulting. Sea-bed domes, ridges and troughs off the Norwegian coast, and elsewhere on the Continental Shelf, were attributed to clay diapirism caused by migrating gas (Hovland, 1990).

2.2 MUD VOLCANOES & MUD SPRINGS

Mud volcanoes are typically the surface expression of fluidized sediment injection and expulsion from over-pressured sediment layers in the subsurface (Rensbergen, 2003). It is important to recognize the difference between a mud volcano and a diapir. All mud volcanoes are associated with diapirs but not vice versa (Milkov, 2000). Mud volcanoes have been identified both onshore and offshore across much of the world, although the majority are located in convergent plate margins (Kopf, 2002).

Milkov (2000) postulates two key requirements for the formation of submarine mud volcanoes: high sedimentation rate and lateral tectonic compression. Plastic clay layers must also be present. He also identifies two different mechanisms for their formation. The first is the formation of a mud-volcano directly on top of a seafloor-piercing diapir, as a consequence of fluid migration through the body of the diapir. The second, and more common, mechanism is the formation of a mud volcano as a result of the rise of fluidized mud along faults and fractures. For deep-seated mud volcanoes Kopf (2002) recognized four common features (1) a connection with rapidly deposited, overpressured, thick argillaceous sequences of mostly Tertiary age parent beds; (2) the incorporated fragments of underlying rocks and other structural associations; (3) a relationship to regional tectonics and seismicity or to petroleum reservoirs; and (4) the presence or influx of gaseous and liquid fluids to facilitate diapiric intrusion and extrusion.

Mud springs are found in the UK at Royal Wootton Bassett, Wiltshire where the Ampthill Clay Formation is fluidized and breaks through to the surface (Bristow et al., 2000). These arise from artesian pressures within the underlying Corallian limestone, and bring Ampthill Clay Formation fossils to the surface (Reeves, et al. 2006). The Ampthill Clay Formation outcrops in Bedfordshire and consists of 10 to 20 m thickness of fossiliferous, pyritous, pale grey mudstone with occasional thin nodular cementstone bands. It is typically fissured, and may contain shear surfaces in the uppermost 1 – 2 m. Its plasticity classification is ‘high’ to ‘very high’ and the clay content is high at about 70 % (Reeves et al., 2006; Cripps & Taylor, 1981).

No evidence for mud volcanoes within the London, Boom or Ypresian clays has been found. However, mud volcanism has been identified in the North Sea. The most prominent is Håkon Mosby near the Norwegian-Barents-Svalbard continental margin. The formation mechanism is believed to be fluid expulsion from gas hydrate processes and mass wasting deposits (Kopf, 2002; Hovland, 1990).

Mud volcanoes may also be associated with liquefaction resulting from earthquakes.

2.3 GLACIAL PROCESSES

Basal processes beneath glaciers are multifarious and include the deformation of soft substrates. This is considered to be due to high basal pore pressures in areas of low bed permeability and/or rapid sliding on low competence sub-glacial layers (Benn & Evans, 1996; Boulton, 1996). These processes produce what are termed 'glacitectonite' and 'deformation till' which feature brittle fracture and fragmentation of the substrate, with some incorporation into the overlying till, shear deformation of the till layer, often with very large strains, and of the substrate accompanied by intermixing with the overlying deformed till (Boulton, 1996). Ice front features such as 'ice-push' and 'ice-squeeze' features may also produce comparable deformations of soft sediment.

Pingos are individual mounds or hill-like features produced under periglacial conditions by the build-up of ground ice and blistering of the ground surface (Hutchinson, 1980; Ballantyne & Harris, 1994; Berry, 1979). They are found actively forming today, for example in Canada, and can reach heights of several tens of metres and measure 100's of metres in diameter. The remnants of collapsed pingos have been identified in south-west Wales and East Anglia (Ballantyne & Harris, 1994), but also in central London (Berry, 1979), although some of these may be scour-hollows (Ellison et al., 2004).

Ground ice growth occurs because of the pressure gradient between the liquid and solid states of water, particularly within poorly-graded and silty soils. Thus considerable thicknesses of many tens of metres of ice develop locally thus uplifting the overburden. During warmer interstadial or interglacial times these structures collapse with the melting of the ice; the volume reduction on melting being greater than the original volume increase on freezing in the case of 'open system' pingos. This is because of re-sorting and consolidation of the sediment (Morgenstern & Nixon, 1971). An important observation is that not only the overlying, but also the immediate underlying, strata may be disrupted by this process presumably as a result of excess pore pressures below the melting ice (Hutchinson, 1980). Remnant pingos may remain undetected and affect sub-surface engineering structures in London (Hobbs et al., 2008). The disposition of Thames tributaries has been cited as evidence for fault blocks (deFreitas, 2007). The presence of 'pingos' and 'scour hollows', formed in the London Clay Formation, has also been connected with these fault block boundaries.

2.4 VALLEY BULGING

Valley bulging or valley rebound are terms used for a specific case of plastic and plastic/brittle deformation of strata. Here valley downcutting and the associated overburden stress removal have resulted in passive failure of formerly competent rocks and their subsequent upward deformation. This is rarely seen at outcrop but is distinguished by localised folding the geometry of which appears to relate to the valley floor rather than to regional tectonism. In order for these features to be viewed exposure has to have taken place as the features are not manifested at ground surface. This has been achieved in river banks, quarries and temporary engineering works such as dam cut-off trenches and tunnels. Whilst the process of valley bulging is driven by plastic deformation of clays and mudrocks, other lithologies may be entrained with the deformation and fractured in a brittle manner forming folds, faults and boudinage-like structures matching those resulting from tectonic stresses. Usually the greatest deformation is concentrated on the alignment of the valley's lowest point. This amounts, in its simplest form, to <u>buckling</u> when considering brittle failure and <u>extrusion</u> when considering plastic failure. These volume changes require that changes in the effective stresses are also occurring. The lateral component of deformation implied by this scenario is likely to manifest itself as flexural slip (Hutchinson, 1988) and may also be associated with cambering and landsliding on the valley slopes where they are sufficiently steep and the materials involved sufficiently weak.

The effects on the engineering behaviour of the materials in this deformation zone may be considerable. These include reduced shear strength, strength anisotropy, reduced bearing capacity and enhanced vertical permeability.

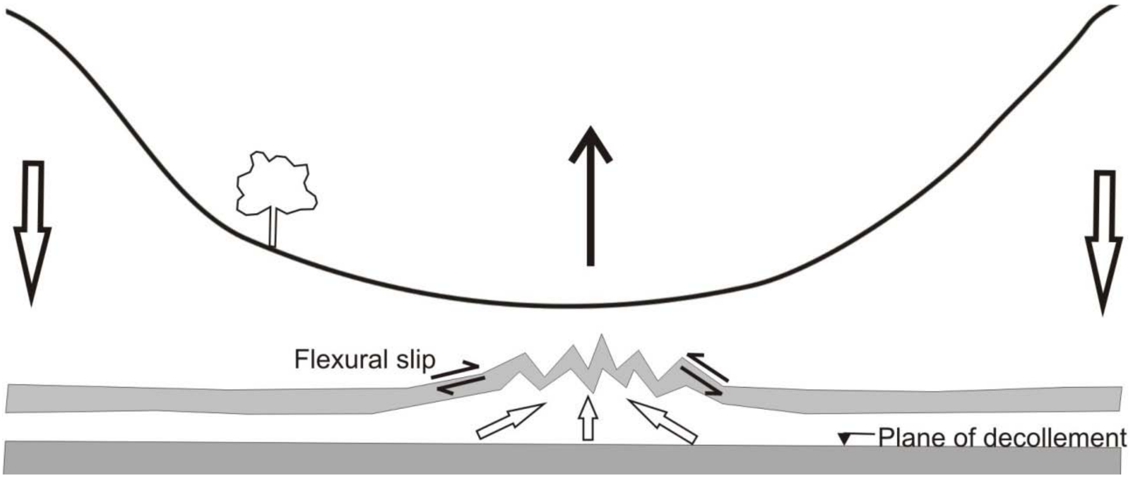


Figure 1 Schematic showing the main features of valley bulging

Instances of natural valley bulging in the UK are relic features which are assumed to date from the time of recent glaciations where rapid downcutting of rivers, for example meltwater or glacial lake overflow channels, occurred and periglacial conditions produced excess pore water pressures and strength reduction of clay formations. Early recognition of the phenomenon of valley bulging was given by Hollingworth et al. (1944) for ironstones and mudstones in Northamptonshire, UK, revealed in quarry faces. They described valley bulging in the following terms “in their simplest form anticlinal uprises of the material composing the valley floor. Such a structure may be a simple or compound fold or a series of discontinuous elongated domes”. Horswill & Horton (1976) referred to valley bulging structures observed during dam construction in the Gwash Valley. Empingham, Rutland, UK, and made the connection between valley bulging and cambering (section 2.5). A distinction was drawn by Hutchinson (1988) between the type of valley bulging associated with cambering and that associated with valley rebound alone. A short review of cambering and valley bulging in the UK was carried out by Parks (1991).

Figure 2 Valley bulging (chevron folding) in river bank in upper Bowland Shale Formation (formerly Edale Shales) overlain by Head, River Ashop near Rowlee Bridge, Derbyshire, UK [414750,389150] Photo: P. Hobbs

At Rowlee Bridge, Derbyshire, UK, the Bowland Shale Formation (uppermost Edale Shales underlying folded Mam Tor Sandstones), of Upper Carboniferous age, is seen facing upstream on the southern bank of the River Ashop (Figure 2). The distinctive folding is believed to be the result of valley bulging of the relatively soft underlying Edale Shales. This is overlain by undeformed Head deposits. Extensive landsliding is present on the northern valley side, with minor drapes of Head on the southern. Downstream the River Ashop flows into Ladybower Reservoir where valley bulging structures were also seen.

Figure 3 Valley bulging in stream section in Upper Purbeck Beds, River Dudwell, Heathfield, E. Sussex, UK [559500,120500] BGS Photo P006797

An example is shown in Figure 3 where small scale folding is seen in interbedded shelly limestones and mudstones of the Durlston Formation (Purbeck Group), formerly Upper Purbeck Beds, of marginal freshwater, brackish and marine origin.

Figure 4 Valley bulging in stream section in Wadhurst Clay Formation, Clay's Wood, Frant, Hampshire, UK [560500,134500] BGS Photo: P210209

A further example of valley bulging is shown in Figure 4. Here, similar small scale folding, but perhaps with a greater element of plastic deformation, is seen in Wadhurst Clay Formation clays and mudstones. The Wadhurst Clay Formation consists of a dark grey, heavily faulted and jointed, over-consolidated silt /clay and clay shale, of ‘intermediate’ to ‘high’ plasticity. Lenses of calcareous sandstone up to 3 m thick, and subordinate sandstones, siltstones, clay-ironstones, and lignites, are also found within it. It forms the central unit of the Hastings Group, the basal part of the Lower Cretaceous Wealden Group. It was formed in brackish and freshwater lacustrine and fluvial environments (Reeves et al., 2006).

Another example from the Wadhurst Clay Formation is shown in Figure 5. Here at Freshfield Lane Brickworks, Danehill, Sussex, UK, vertical bedding is seen in the core of a valley bulge where, in this most intensely deformed part, the shales have undergone plastic flow and thin hard beds of limestone and clay ironstone have been stretched out to produce a boudinage-like effect. Small, tight folds (right centre) are present and some of the hard beds in the left of the picture may be repeated by large isoclinal folds. Oxidation (brown colouration) has penetrated the more permeable beds to differing extents.

Figure 5 Valley bulging in Wadhurst Clay Formation at Freshfield Lane Brickworks, Danehill, Sussex, UK [538500,126500] BGS Photo: P210151

When exploring for the construction of the Ladybower Reservoir, Derbyshire, UK, several crumples within the alternating sequence of shale and grit had been discovered at some distance upstream from the centre line of the dam. During construction one large deep-seated crumple within the carboniferous strata was encountered towards the centre of the valley. The main aspect of interest of the Ladybower crumple is its depth. The trench was carried down to 175ft (53m) at which stage the crumple was dying out and fissures practically closed. At the Derwent and Howden Dams the crumples extended only to 70-75ft (21 – 23m)(Figure 6) and at the Goyt Valley to 90ft (27.5m). No doubts were expressed when the paper was published that the depth of the structure at Ladybower was due to the surrounding hill height and the steep slopes in comparison with the other sites mentioned, producing excessive valley creep.

The crumples, which occur throughout the Derwent and Ashop valleys, were due to the strata in the hillsides and at the bottom of the valleys which consisted of a succession of beds of shale and sandstone. The theory suggested was that the weight of the hillside had compressed the shale and caused it to flow into the valleys where it had obtained relief from the intense pressure by crumpling up the strata. In the case of the Ladybower dam site the process had gone a little further and the folds had become an over thrust fault. It is noted that the relative movement of the strata was very much less at 200 ft (61m) below the surface than at the surface, thus distinguishing it from an ordinary geological fault.

Figure 6 Valley bulging features exposed at the Derwent Dam cut-off trench, Derbyshire, UK

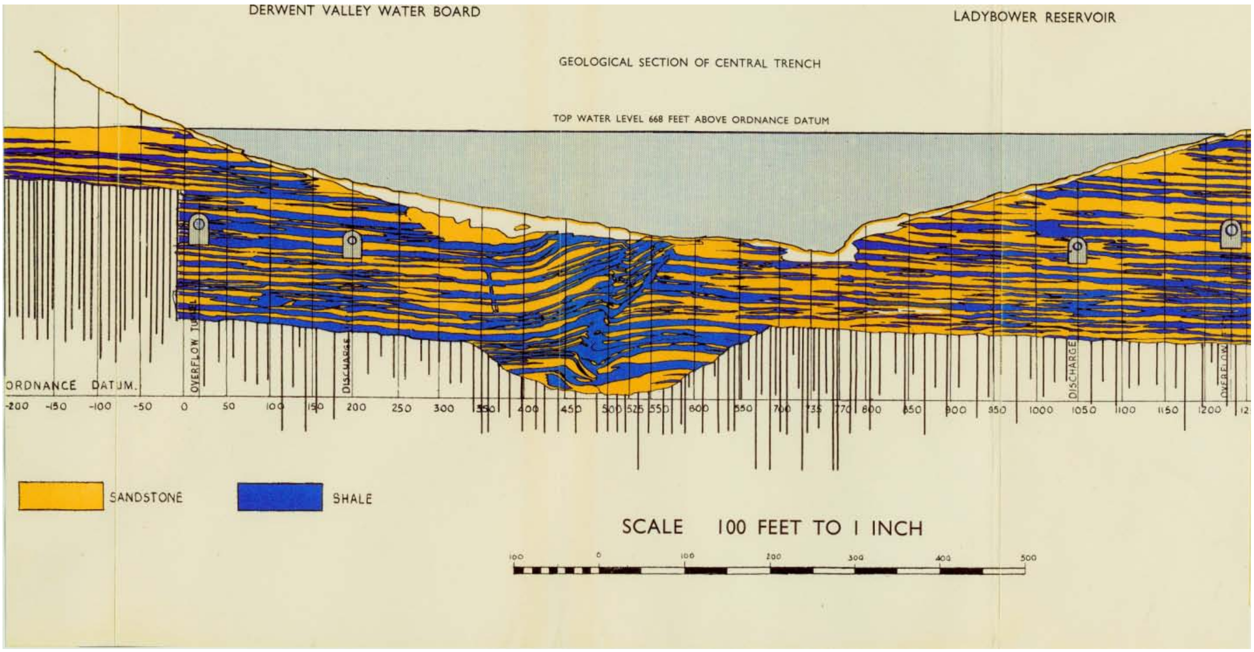


Figure 7 Schematic of the Derwent Valley Dam cut-off trench, Derbyshire, UK

2.5 CAMBERING

Cambering is a mass movement process whereby a strong caprock layer overlying a weak, 'extruding' clay layer, at the edge of a plateau or hilltop, is subject to a gradual downslope movement. This often involves 'hinging' or 'slumping' downward and subsequent gradual break-up of the caprock into blocks, which then become available for involvement in landslides on the slope. One effect of cambering is to give an exaggerated impression at outcrop of caprock thickness, and conversely a reduced impression of underlying stratum thickness.

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. In some cases, gulls may be 'bridged', that is they occur only in the lower beds of the caprock, particularly where the caprock is thick and well bedded, and thus are not visible at surface. Such gulls occur in the Great Oolite Group and to a lesser extent in the Inferior Oolite Group. In some cases the Great Oolite Group gulls have developed into a complex network of distinctive orthogonal 'gull caves' deep within the hillside (Self, 1985; Self, 1995, Hobbs & Jenkins, 2008). These are unusual in cambered terrain, and are distinct from the more common solution caves found in limestone terrain.

Various models developed for cambering were reviewed by Parks (1991) and Hutchinson (1991). The most likely sequence of events, according to Parks, based on observations at Empingham Dam (Horswill & Horton, 1976) is as follows:

1) Valley-bulge development caused by stress-relief during rapid river downcutting (glacial melt-water, river capture?)

2) Melting of the ground ice contained within the slope creating excess pore pressures (Stevenson & Gaunt, 1971),

3) Downslope creep / extrusion of the softened plastic clay substrate.

Ice and snow in the form of overburden were dismissed as the primary drivers of cambering by Vaughan (1976); giving as evidence the fact that the morphology and likely overburden of ice were inconsistent. The most commonly quoted morphology for cambering is the simple 'drape' profile shown in Figure 8. This profile features progressive forward tilting combined with subsidence of the caprock blocks into the underlying extruding clay formation. One of the features of the drape profile is that as blocks become separated, the underlying (and in some cases the overlying) clay material extrudes into the gap created. The drape may develop further to produce the 'dip and fault' structure shown in Figure 9. Here the dip of the bedding in individual detached cap-rock blocks is increased.

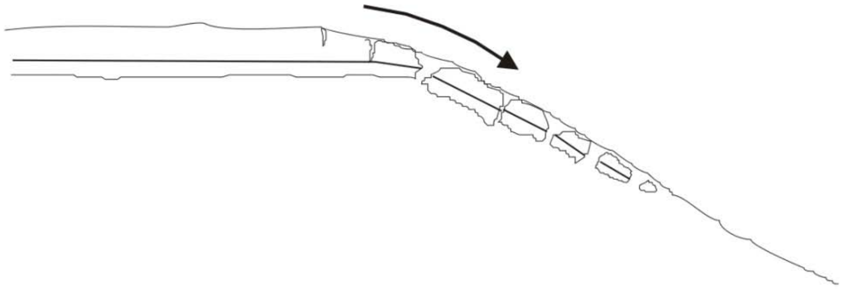


Figure 8 Cambering - simple 'drape' profile

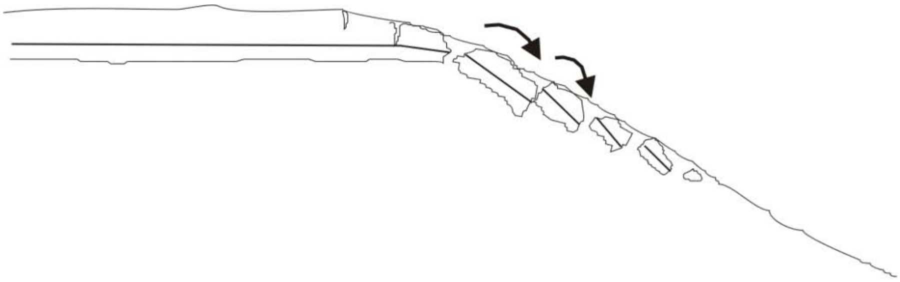


Figure 9 Cambering – 'dip and fault' profile

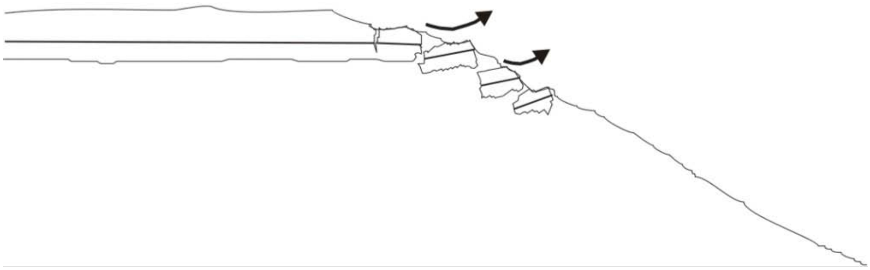


Figure 10 Cambering - back-rotation profile

An alternative back-rotation profile is shown in Figure 10. This occurs when individual cambered blocks are subject to rotational landsliding. Such processes were probably separated in time from the cambering itself, and being active have probably tended to degrade the original cambered profile.

The periglacial model described by Parks (1991) is based in part on the fact that cambering, unlike landsliding, is inactive in the UK; that is, the process ceased following periglaciation. This would tend to discount any idea that cambering is purely a stress-relief process. Hutchinson (1991) and Parks (1991) point to ground ice formation and melting as essential factors in the development of cambering. Melting of periglacial ground ice tends to occur from both above and below. This tends to give the remaining body of ice a profile running parallel with the valley slope, and hence encourages the development of simple cambering (Figure 8). Several cycles of ground ice formation/melting would tend to disrupt this pattern, and final melting would initiate landslipping (Figure 9 and Figure 10).

During the heyday of Northamptonshire ironstone quarrying in the late 19th and early 20th C, exposures of cambering and associated valley bulging were visible. However, these have now been infilled and are no longer visible (Cooper, 2007). Weak horizons within the Whitby Mudstone Formation in the UK have contributed to the processes of cambering, valley bulging, and landsliding, for example in Northamptonshire, Rutland, UK (e.g. Empingham Dam) and the Cotswold escarpment, UK (e.g. Bredon Hill, Broadway Hill, Leckhampton Hill) where it is overlain by Inferior Oolite limestones (Reeves et al., 2006). Cambering is also found in the area around the city of Bath, UK where descriptions of the 'dip & fault' mechanism include the upward extrusion of the underlying strata between individual cambered blocks; in effect clay diapirism (Chandler et al., 1976; Forster et al., 1985; Hobbs & Jenkins, 2008).

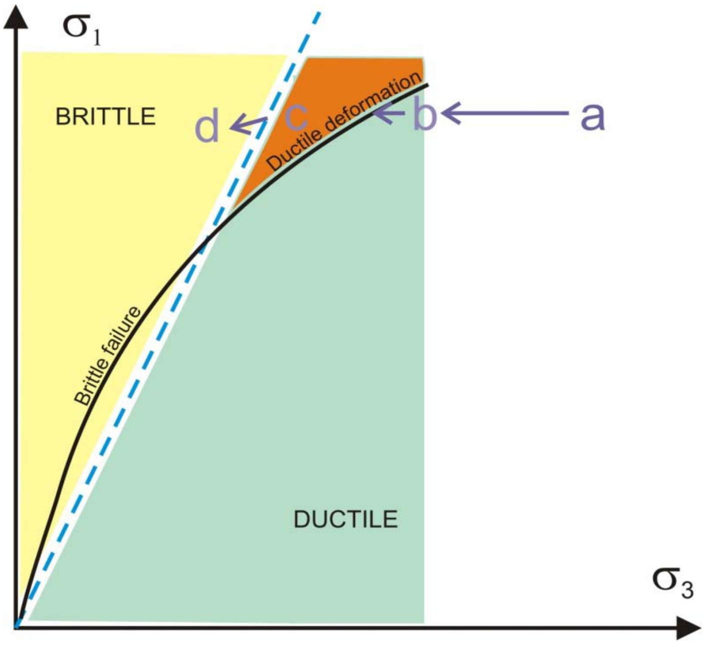


Figure 11 Brittle/ductile transition model for weak substrate deformation and failure (adapted from Poulsom, 1995) *Note:* refer to text for explanation

A key pre-requisite for cambering to take place is the mobility of a weaker substrate. In the Bath area these are represented by the Fuller's Earth Formation mudstones which underlie the Great Oolite Group limestones, and the Lias Group mudstones and sandstones which underlie the Inferior Oolite Group limestones. The means by which a weaker substrate to the cambering rock-mass becomes mobile is a topic which has received little attention in the literature. One contribution was from Poulsom (1995) who described a process of brittle/ductile transition to explain the large-scale coastal displacements at Portland, Dorset and Ventnor, Isle of Wight, UK. Whilst these well-known landslide complexes are not entirely a function of cambering, the process proposed does hold some interest for the likely genesis of today's Bath slopes. Poulsom (1995) related lateral stress relief to principal stress-paths within the clay substrate using pre-critical-state soil mechanics terminology. A brittle/ductile transition boundary defined by the principal stress equation (dashed blue line in Figure 11):

$$\sigma_1 = 2\sigma_3$$

where: σ_1 is vertical stress and σ_3 is horizontal stress was derived from Barton (1976). In the same figure the strength envelope for the clay is shown as a black curve. The proposed sequence of (geological time-scale) events as a point within the rock mass would have been approached by the valley side is as follows (letters refer to Figure 11 and the geology to Figure 12):

a) Initially, lateral stress (σ_3) exceeds vertical due to the over-consolidated nature of the clay deposit. This places an example point within the clay layer at point 'a'. Points at other positions within the clay layer would be located elsewhere on the right side of the graph. (The Fuller's Earth Formation mudstones and clays are lightly over-consolidated, so this offset may be small. The Lias Group mudstones are generally heavily over-consolidated which would tend to give a larger offset).

b) As the valley side approaches, the lateral stress (σ_3) at the example point reduces whilst the vertical stress (σ_1) remains constant. The clay layer is within the ductile zone but below the failure envelope (i.e. intact). Deformation does not occur.

c) With closer proximity to the valley side, parts of the clay layer are within the zone of ductile deformation and have begun deforming and thinning. This allows the process of cambering of the overlying limestone to initiate. As the limestone is a brittle material, tension cracks (gulls) develop and the limestone blocks subside or rotate. However, the clay layer does not fail catastrophically as the ductile deformation zone is characterised by strain-hardening behaviour. Rather, a process of clay creep leads to gull widening and progressive lateral movement of the limestone blocks.

d) As lateral stress decreases further, the clay layer enters the brittle zone by crossing the blue line. As this is characterised by strain-softening behaviour, shear strength reduces to a residual value and displacements tend to concentrate in one or more shear surfaces at levels of common principal stress. At this point vertical stress has also decreased somewhat due to progressive thinning of the clay layer. As the overburden, and hence σ_1, within the clay layer is greatest at its base, the principal shear plane tends to develop here (Poulsom, 1996) and a deep-seated landslide is formed. Increased pore pressures would tend to reduce strength further and initiate shear failure at some point within the clay mass.

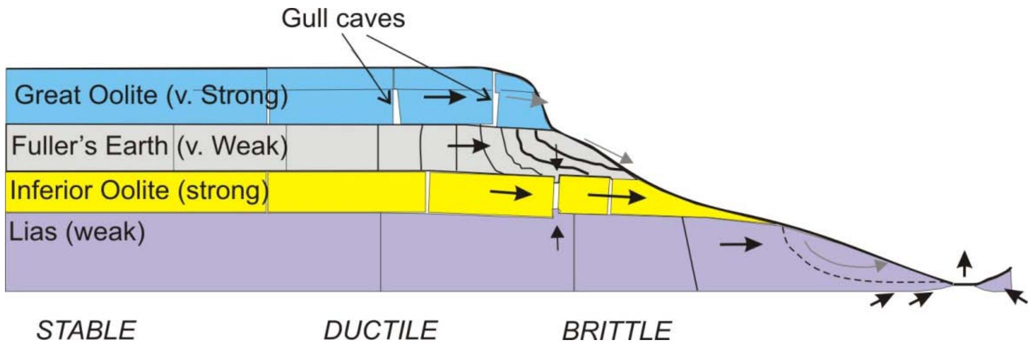


Figure 12 Processes of cambering, gull cave formation and valley bulging in Bath area (Hobbs & Jenkins, 2008)

2.6 POLYGONAL FAULTING

Polygonal faulting is a relatively recently recognised phenomenon that was made possible by the advent of 3D seismic surveying. Whilst 2D seismic surveys could only show evidence of randomly oriented faults, 3D surveys were able to show that these randomly oriented faults partially or fully intersected to form broad polygonal patterns when viewed from above. Polygonal faults share many of the same features as tectonic normal faults, they are planar to listric with dips of between 30-70° and typical throws of between 10-100 m. They are often found to have an irregular strike orientation, rather than one of parallel and sub-parallel dips and strikes (although regional tectonics, slopes and basement topography can exert some influence). They are frequently found in passive tectonic basins and are dominantly confined to very fine-grained sediments (Cartwright *et al*, 2003; Goulty, 2008). Polygonal faulting has also frequently been found in association with intense folding and diapirism. The exact relationship between polygonal faulting and diapirism is poorly understood. There is great debate as to whether polygonal faulting is created by diapirism or whether polygonal faulting itself is responsible for diapiric structures where they are found together.

Many mechanisms have been proposed for polygonal faulting. The three most favoured mechanisms include density inversion (Raleigh-Taylor instabilities) (Henriet *et al*, 1991), syneresis (Cartwright *et al*, 2003), and gravitational loading (or low coefficient of friction)

(Goulty, 2008). Hernriet *et al.* (1991) proposed that density inversion occurred due to under-compaction and over-pressuring of a self-sealing clay body being overlain by normally compacted material. The gravitational instability caused by the lower density (and lower viscosity) fluid underlying a higher density (and higher viscosity fluid) coupled with decrease in shear strength caused by the over-pressurisation results in mass sediment movement in the shape of regular spaced upwellings (cuspate anticlines and diapirs). Essentially the density inversion mechanism coupled with over pressuring is responsible for both diapirism and polygonal faulting. Density inversion mechanisms have also been proposed by others as an explanation for polygonal faults encountered elsewhere in the world (Cartwright *et al*, 2003; Goulty, 2008). Syneresis is the contraction of a gel accompanied by the expulsion of water without evaporation. Cartwright *et al.* (2003) propose that fully saturated clays in a gelatinous state will spontaneously contract. This contraction results in tensional forces occurring throughout the clay thereby creating the lateral strain required for normal faulting. There are also a number of other proponents for this mechanism (Cartwright *et al*, 2003). Gravitational loading or low coefficient of friction is proposed by Goulty (2008) as the most likely mechanism for polygonal faulting. He proposes that normal gravitational loading of sediment with pre-existing faults is sufficient to cause failure without having to invoke extensional forces or over-pressure. Essentially the residual shear strength on an existing fault plane is low enough that additional sedimentation is all that is required to induce failure of the underlying sediment (Cartwright *et al*, 2003; Goulty, 2008). Overall volume decrease produced by endogenous brittle-ductile deformation, combined with minor external forces, is proposed by Dehandschutter *et al*. (2005) to explain intraformational faulting in the Boom Clay at depths up to 200m. This was based on an analysis of fault zone structure and fabric.

As yet there does not appear to be a definitive explanation and the academic debate is likely to continue for some time. A full review of polygonal faulting and its relationship to diapirism is beyond the scope of this desk study report.

2.7 DIAPIRISM IN RUPELIAN AND YPRESIAN CLAYS

2.7.1 Boom Clay

The underground research facility high activity disposal experimental site (HADES), is located in the Boom Clay at 223 m below the SCK·CEN site, where several diapirs and up-arching structures, related to post-Miocene relaxation of the clay, have been detected in the upper part of the formation at 10's of metres depth. The Boom Clay Formation is between 40m and 50m thick in the vicinity of Antwerp. These diapiric structures have only been identified in the Scheldt River valley using mainly geophysical methods (Wartel, 1980; Henriet, 1992; Henriet *et al.* 1986; Laga, 1966; Missiaen et al., 2002); the scouring of the Scheldt possibly influencing this relaxation process. Mertens et al (2003) stated that the exclusive relationship between the diapirs and the river valley strongly suggests that the diapirs were formed by valley bulging.

Henriet *et al.* (1983) speculated that low p-wave velocities observed within the Boom Clay may be due to the presence of sediment gas, and that an organic rich layer within the Boom clay may be the source of this gas. They go on to speculate that the gas may accentuate or even cause the clay diapirism observed within the Boom Clay in the Antwerp region. A methane eruption was reported by Henriet *et al*. (1983) during their investigation. No other records have been identified which link fluid injection to clay diapirism in the Boom Clay. However, large mud diapirs, up to 100 km long and 40 km wide, have been observed in the Hordaland Group (Eocene to Early Miocene age deposits) in the North Sea. The formation of these diapirs is attributed to the injection of gas, oil and formation water from underlying Cretaceous strata (Løseth *et al*, 2003).

Mertens *et al.* (2003) have identified orthogonal tension joint sets within the Boom Clay in the Antwerp area of Belgium. Neither the burial/uplift history of the clay nor regional tectonic stresses can account for the negative horizontal stress required for the formation of tension joints. Instead it is proposed that clay shrinkage as a result of dewatering is the driving mechanism. Van Rensbergen *et al*, (2003) speculate that these tension joints may represent an outcrop example of the early stages of a polygonal fault system. While Mertens *et al.* (2003) do not offer a reason for the clay dewatering, Van Rensbergen *et al*, (2003) speculation that these tension joints may initiate polygonal fault system, lends support to the syneresis hypothesis being part of the mechanism for polygonal faulting. Mertens *et al.* (2003) also calculate that the maximum depth below which no tension joints can occur within the Boom Clay in the Antwerp area is 40-50 m.

Diapirism within the Boom Clay Formation is likely due to valley bulging. It is debatable whether there is any input from polygonal faulting or over-pressurisation from gas. Regardless of the formation mechanism it is unlikely that diapirism will occur in the Boom Clay Formation below a depth of 50m.

2.7.2 Kortrijk Formation

The Kortrijk Formation is the same age as the London Clay Formation and is considered to be a facies lateral variation. Deformations in the Kortrijk Formation are widespread, having been observed all over the Southern Bight of the North Sea, from the Belgian coasts to the Thames estuary. A striking feature is that these deformations are closely bound to the Ypresian clays: they do not affect the Palaeocene basement and fade out in the overlying Ypresian sands. Henriet *et al* (1982) identified several features of clay tectonics in seismic lines undertaken in the southern Bight of the North Sea. This included festoon-like sequences of cuspate anticlines often developing into diapirs within Palaeogene strata. The Kortrijk Formation was characterised by intense block faulting, randomly dipping faults (later identified as polygonal faults by Cartwright *et al* 2003), and diapirs 100 – 200 m wide and between 2 – 10 m in amplitude. Henriet *et al.* (1988) postulated that the basic mechanism of Ypresian clays tectonics fitted a model of a Rayleigh-Taylor gravitational instability, caused by density inversion in a self-sealing clay body. Abnormal pore fluid pressures may have contributed to the sediment flow by acting as a lubricant, decreasing the sediment shear strength. The dissipation of abnormal pore fluid pressures could have happened by a process of progressive hydraulic fracturing or locally by the development of diapiric drainage pipes over rising clay wave crests. Some brittle deformations suggest some additional processes of stress and strain evolution such as a compacting clay body. Henriet et al. (1982) indicate that diapirs are present at the base of infilled palaeo-valleys. However, they do not state that this association is exclusive, thereby implying that diapirs occur elsewhere. Also, the term ‘valley bulging’ is not used, although this appears to be a contributory mechanism in the case cited.

Surface features such as diapirs piercing Quaternary palaeovalley fills and slide structures with apparent growth faulting behaviour in Quaternary times may argue in some cases for a reactivation of inherited deformations. However, the randomly oriented faults identified by Henriet *et al.* (1982) have since been identified as polygonal fault systems (Henriet *et al*, 1991; Cartwright & Lonergan, 1996; Goulty, 2008). Cartwright (2003) asserts that where polygonal faults are closely spaced and grouped into sets with similar strikes and dip direction, fault-related folds combine to create alternating synclinal and anticlinal structures. This is different to many other authors who speculate that it is the folds themselves, created by density inversion, which are responsible for the formation of the polygonal faults (Cartwright *et al*, 2003). This therefore brings a great deal of uncertainty as to the exact formation mechanism of the diapiric structures within Kortrijk Formation, and whether they are indeed formed by Raleigh Taylor instabilities or are instead related to the Polygonal Faulting which itself may be formed by Rayleigh-Taylor instabilities, syneresis or even gravitational loading.

2.7.3 London Clay

Berry (1979) identified diapiric structures occurring at the base of deep depressions within the London Clay Formation. Berry (1979) proposed that these depressions were 'scour hollows'. Henriet et al. (1982) used this as evidence of land based diapiric structures within the London and Kortrijk Formations. Hutchinson (1991) contested the proposition that the depressions could wholly be attributed to scour, and that the lower parts of the hollows at least were formed by the collapse of pingos. Hutchinson (1991) suggested that the diapiric rises were likely due to artesian pressure in strata underlying the London Clay facilitated by unloading produced by scouring. As a consequence, the diapirism is confined to the feather-edge of the London Clay (i.e. less than approximately 35 m) where it is thin enough to be susceptible to hydraulic uplift from below. Hutchinson (1991) postulated that the scouring and following hydraulic uplift would have most likely occurred in the late stages of cold periods, when the London Clay was unfrozen and rivers were swollen with melt-water. Increased pore pressures would also be generated by the progressive thawing of permafrost. The precise relationship between the pingos and diapirism is not explained.

It should be noted that diapiric structures in scour hollows/collapsed pingos are not confined to London Clay, but also include diapirs of Woolwich and Reading Formations (Lambeth Group) and Cretaceous chalk; the chalk (and possibly the Woolwich and Reading Formations) requiring frost shattering by deep permafrost in order to render it capable of mobilisation.

Whilst isolated valley bulging features themselves have not been positively identified in the London Clay Formation, Whiteman and Kemp (1990) reported a diapir within the London Clay, 1m wide with 1m amplitude, below a linear depression structure identified as a gull. Gulls are large linear depression found on valley sides which are formed by periglacial cambering. Whiteman and Kemp also reported that similar structures had been observed in Great Waltham Quarry and elsewhere in the Chelmsford area in Essex, UK.

3 Deformation and critical state concepts

Roscoe et al. (1958), proposed the critical state theory of soils, which provides a unified model of behaviour where stress states and volume states are interrelated. Gerogiannopoulos & Brown later modified this theory in 1978, to account for the brittle or work-softening behaviour of rocks. Shah (1997) also showed that further modification is required to the classical critical state model to account for the tensile strength of rocks, as soils are assumed to have zero tensile strength.

The *state* of shale subject to a simple stress field is defined by its position in the effective stress (p') – differential stress (q') – specific volume (v) parametric space. A change in state can be represented as a *path* within the p' - q' - v space. The projection of this change in the p' - q' space is referred to as the *stress path*. The deformation path can be used to describe fully the deformation history of the rock and can be used to infer certain aspects of the deformation, such as whether it is drained or undrained, etc. Thus a complex deformation history can be represented and described by critical state theory.

A model is proposed where an isotropic soil yields, i.e. passes from purely elastic to elastoplastic behaviour, at a critical specific volume ($v_c = 1 + e$; where e is the voids ratio). Yielding or shear slipping is considered to occur as a combination of effective stress (σ'_1, σ'_2, σ'_3) and specific volume (v_c) coinciding with a state boundary surface. Experimentation has shown that when sheared, a deforming rock will tend towards criticality, a state where large shear distortions will occur without any further changes in p', q', or v (Roscoe & Burland, 1968a; Schofield & Wroth, 1968). The critical state line (CSL) is the locus of all possible critical states in the p' - q' - v parametric space. Figure 13 shows a soil yield surface, which can be split into three distinct surfaces: the tension, Hvorslev, and Roscoe surfaces. The normal consolidation (NCL) and critical state (CSL) lines bound these surfaces, which are geometrically and, to a degree, physically equivalent to a Mohr-Coulomb type failure surface for porous rocks (Jones *et al.*, 1987; Loe *et al.*, 1992).

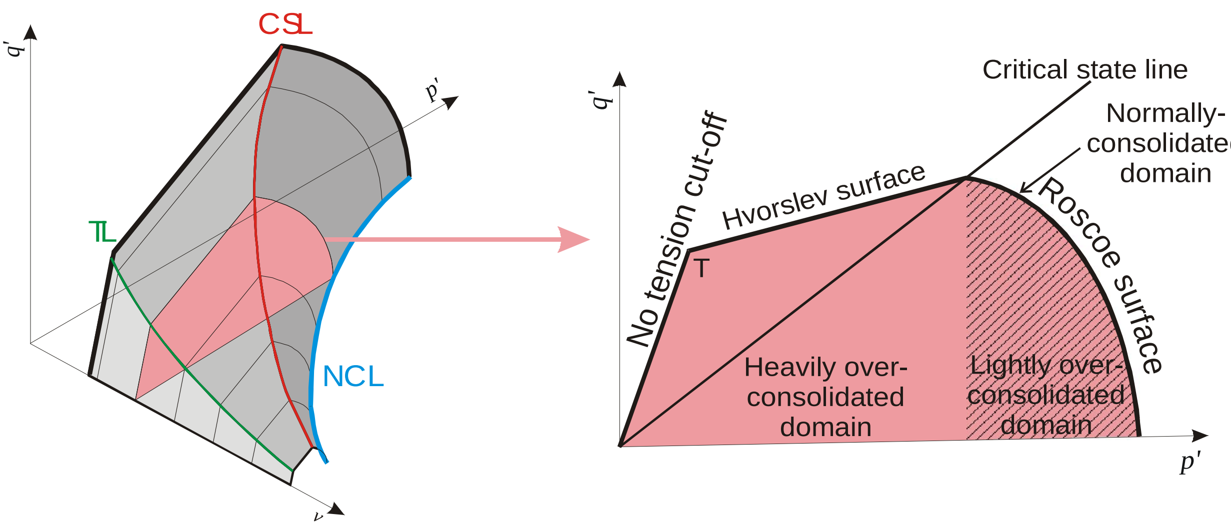


Figure 13 The critical state model of soil mechanics, showing the relationship of the tension line (TL), normal consolidation line (NCL) and critical state line (CSL). These lines bound the Hvorslev and Roscoe surfaces in the p′ - q′ space.

During consolidation under isotropic stress the volume change path will move along the NCL, which is in the plane of zero deviatoric stress (i.e. when stress in all directions is equal). The volumetric strain during consolidation is considered to have elastic (recoverable) and plastic (non-recoverable) components (Scholfied & Wroth, 1968). Figure 14 b-d shows the paths a material would take in drained (reducing volume path $C \rightarrow D$) and undrained (constant volume path $C \rightarrow U$) tests. Yield occurs at U_1, D_1, U_2, D_2, U_3, and D_3; in the p' - q' - v space this line represents the CSL. On unloading, deformed sediments will only recover the elastic component of deformation; plastic deformation by definition is non-recoverable.

3.1 CRITICAL STATE THEORY AND REAL SEDIMENTS

There are many examples within the literature of studies on soils and clays that demonstrate the validity of critical state theory and the use of the Cam-clay derived models; including: Adams & Wulfsohn (1997), Cotecchia & Chandler (2000), Diaz-Rodriguez *et al.* (1992), Kirby (1994) Kirby & O'Sullivan (1997), Maâtouk *et al.* (1995), Mitchell (1970), Petley (1999), Tavenas & Leroueil (1977), and Wheeler & Sivakumar (1995). Kirby & O'Sullivan (1997) clearly show how successfully the modified Cam-clay critical state model, with only five material property parameters [M, slope of the critical state line; λ, slope of the normal consolidation line; k, slope of the elastic line; E, *elastic modulus* ; and η, *Poisson's ratio*], reproduces non-linear soil deformation behaviour in four dimensions.

The simplistic model of critical state theory is complicated in rocks by features that are generally absent in soils. The concepts of, and relationships between, consolidation and shear are quantitatively valid for clays, fine carbonates, and sands where grain size and angularity do not cause dilatation during shear. For coarse angular grained clastic sediments the critical state concept must be modified to incorporate hardening associated with dilatant shear. Pore volume increase is minimal if high porosities are maintained, and as structure becomes more densely packed the dilatation effects become more pronounced. Yield surface form is unaltered, although deformation paths for dilatant materials will be more complex. Shear deformation is complicated at low stresses by elastic stiffness created by intergranular bonding. Studies show a consistent deformation style irrespective of sediment type and strength (Jones, 1994; Vaughan, 1985). Chalk shows a marked behaviour change with increased stress that is more complex than the ideal critical state behaviour; similar features have been observed in bonded mudrocks, carbonates, and sand (Jones, 1994).

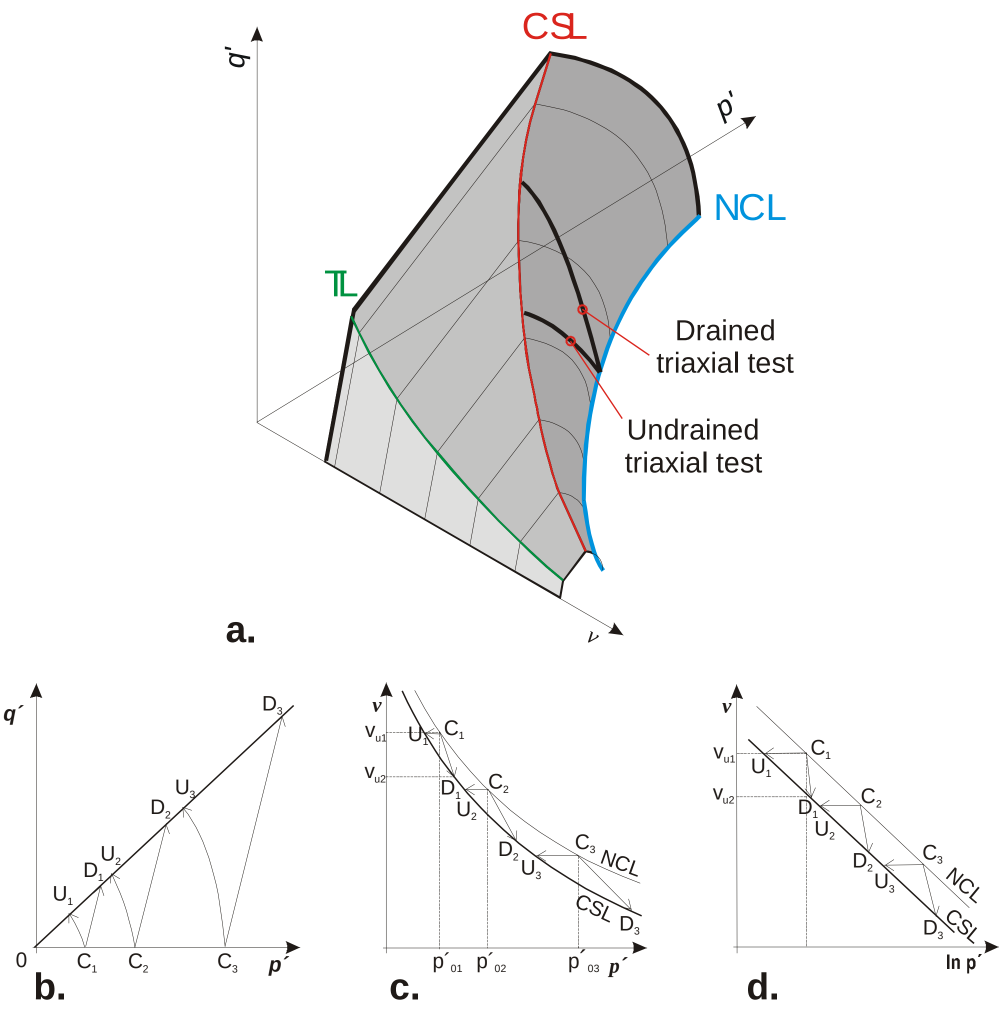


Figure 14 The critical state model of soil mechanics in detail. a) The state boundary surface for a particulate sediment (after Atkinson & Bransby, 1978). b-d) p′ - q′ - v plots of triaxial test results for drained (D) and undrained (U) tests. The stress path for all tests tends towards the critical state line where critical state deformation continues.

At low consolidation stresses, mudstones and sandstones reach the state boundary in an intact bonded condition. Stresses beyond the state boundary can be supported until interception of the peak strength envelope occurs resulting in shear failure. A stress drop is experienced from peak strength to residual strength, as the newly formed shear fracture can no longer support loads above the state boundary. These observations have been shown experimentally in sandstones and mudrocks (Leddra et al., 1993; Leddra et al., 1992; Petley et al., 1992).

What occurs at intermediate and high consolidation stresses is difficult to observe in many rock types as pervasive disaggregation renders test material an incohesive powder. Dissagregation means materials cannot support stresses above the CSL. At the critical state, shear deformation is pervasive and accompanied by grain sliding and rotation.

The critical state concept and yield surface provide a powerful and effective framework in which all aspects of porous sediment deformation and evolution can be described and interrelated. Complex burial and stress-porosity histories can be described using this concept.

3.2 MODIFICATION OF THE CRITICAL STATE MODEL

The critical state model described above, incorporating Hvorslev and Roscoe surfaces, has been shown to inadequately model certain geomaterials, especially in the Hvorslev region (Byerlee, 1967; Cuss, 1999; Hudson and Harrison, 1997; Maltman, 1994a; Ohnaka, 1973; Schofield, 1998; Wong et al., 1997). This is primarily due to the complications introduced by lithification and general rock-forming processes. Some researchers have chosen to replace the state boundary surfaces by more general failure criteria, which may be either theoretical (mathematically derived) or empirical (experimentally derived). It can be argued that the empirical approach is more appropriate and useful, however calibration demands accurate deformation data under known conditions that may not exist or be prohibitively expensive to obtain.

Many failure criteria exist that can be used to modify the critical state model. On the “dry side”, the Griffith-type, modified Griffith-type (McLintock & Walsh, 1962), Hoek-Brown (Hoek & Brown, 1980), Mohr-Coulomb, non-linear Mohr-Coulomb, or Khan empirical failure (Wong et al., 1997) can be used to modify the no-tension and Hvorslev regions. Fewer options are available for the "wet side". The empirical elliptical cap model of DiMaggio & Sandler (1971) has been successfully applied to porous sandstone by Teng-fong Wong and co-workers (Wong et al., 1997; Zhu et al., 1997; Zhu and Wong, 1997a; Zhu and Wong, 1997b) and by others (Cuss, 1999; Cuss & Rutter, 2003).

3.3 CRITICAL STATE MODEL FOR ARGILLACEOUS MATERIALS

Figure 15 summarises the features observed for shale deformation in terms of the critical state model and the dilatancy boundary in the $p' - q'$ space, but could easily be expanded into the $p' - q' - v$ critical state space.

Within the domain below the state boundary surface, permeability and porosity reduction is essentially independent of deviatoric stress (Zhu & Wong, 1997b). Prior to yield, porosity reduction will be elastic as pore space reduces as grains elastically deform. Porosity will also reduce as pre-existing damage (i.e. fractures) elastically close.

On the dry side, stresses above the idealised Hvorslev-type surface are achievable due to the strength of lithified shale. Brittle failure occurs at a deviator given by a brittle failure criterion, e.g. the Hoek-Brown failure criterion, and deformation progresses towards the idealised Hvorslev-type surface, which corresponds to the residual strength envelope. Considerable dilatancy is observed during this stage of deformation as a shear fracture is formed in shale. The further ‘left’ of the dilatancy boundary, i.e. at low effective mean stresses, the more dilatant deformation is. Critical state mechanics shows that further deformation progresses towards the critical state where deformation is isovolumetric. During this progression, shale work hardens as the further granulation of material within the shear band becomes more difficult to disaggregate. Dilatancy hardening may also be present under undrained conditions. The reduction in porosity along the fracture leads to a significant reduction in permeability (a self sealing process). Permeability will reach a minimum at the critical state.

On the wet side, deformation always results in contractancy of the bulk material. This leads to a reduction in porosity by the processes of compaction/consolidation and cataclasis. Intracrystalline plasticity may also contribute to a lowering of porosity. This results in a reduction in permeability, which further reduces as deformation progresses up the Roscoe-type surface towards the critical state. The further ‘right’ of the dilatancy boundary, i.e. at high effective mean stresses, the more contractive deformation is and the higher the degree of permeability reduction. The extreme case is the stress path that coincides with the NCL. Here plastic volumetric strains are largest and the decline in permeability is most marked.

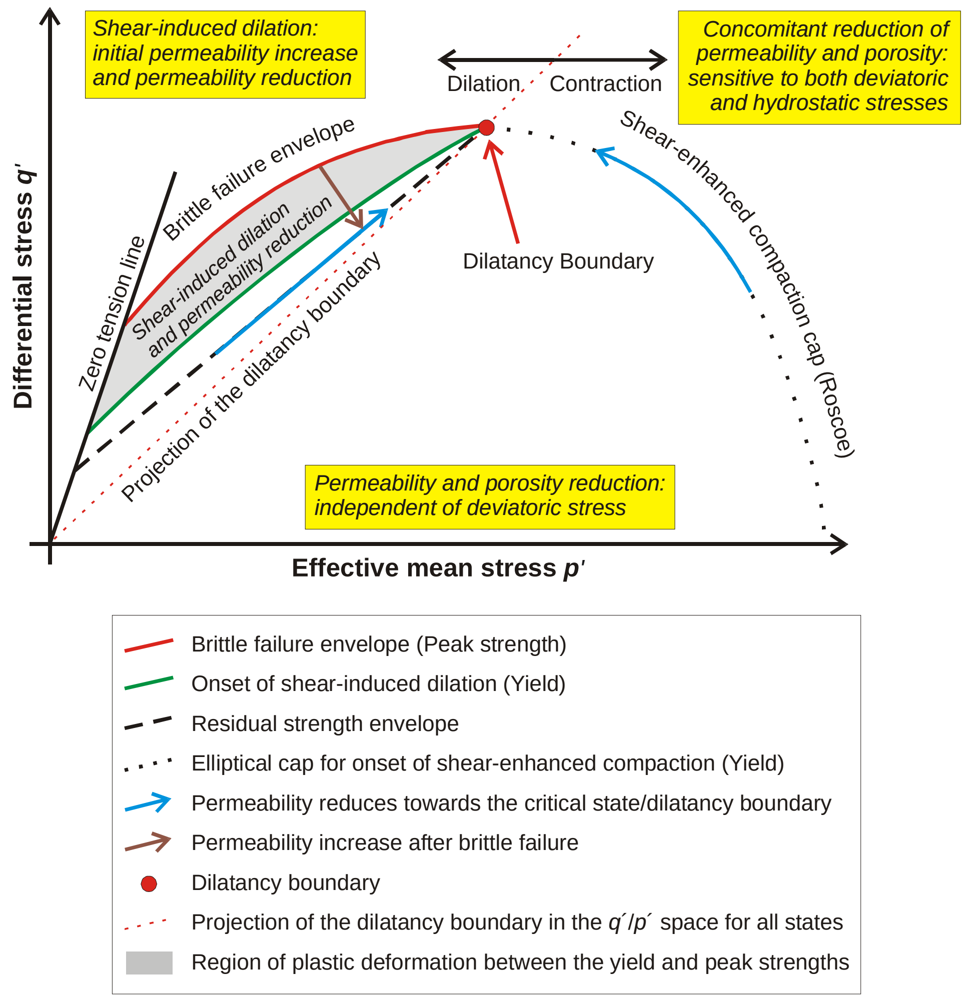


Figure 15 The role of the dilatancy boundary in shale sealing as shown in the p′ - q′ space. Modified from Zhu & Wong (1997b).

A thorough knowledge of the dilatancy boundary is required in order to predict the likely mode of deformation and forecast the effect of deformation on the capacity of the rock to impede fluid movement.

It can be seen that the disposal of waste in a geological repository is favourable under “wet” conditions. As long as pore pressure is not raised, which would lower effective mean stress, induced deformation under these conditions will result in a more effective self-sealing of discontinuities such as faults and fractures. The construction of a waste site will inevitably alter the local stress field, and as rocks at depth can be viewed as approaching a state of limiting equilibrium[1], deformation and yield are likely. Since permeability enhancement by dilation can be ruled out in “wet side” sediments, deformation and yield of these host materials will pose no special problems in the context of fluid flow and radionuclide transport.

Lithified shale at shallow depths is over-consolidated, and thus deformation will tend to be on the “dry side”. There seems little doubt that shales that lie substantially to the left of the dilatancy boundary, will be subject to strong dilation and permeability enhancement during repository development or disturbance by external factors such as seismicity. Self-sealing may no longer be effective in rocks which are heavily over-consolidated and prone to shear-dilatancy.

[1] In many regions, the upper crust is subject to shear stresses approaching the frictional strength of favourably orientated faults (Engelder, T. (1993). *Stress regimes in the lithosphere*: Princeton, NJ, United States, Princeton Univ. Press, 457 pp.). This results in a state of limiting equilibrium within the crust with everywhere at the point of failure according to Byerlee’s rule.

3.4 SETTING UP A CSSM MODEL FOR BOOM CLAY

The critical state soil mechanics model is made of the zero-tension line, the Hvorslev surface and the Roscoe surface. The Hvorslev surface is given by:

$$q = hp' + (M - h)\exp\left[\frac{(e_a - e)}{\lambda}\right]$$

Where h is the soil constant = 0.47, M is the slope of the critical state line = 0.81, e_a is the intercept of the CSL with p' = 1 MPa = 0.88, λ is the slope of the normal consolidation line = 0.18, and e is voids ratio = 0.68. Therefore the Hvorslev surface can be defined as:

$$q = 0.47\,p' + 0.34\exp\left[\frac{0.88 - e}{0.18}\right]$$

The Roscoe surface can be given by:

$$q = p'M\sqrt{\left[\frac{p_c^{'}}{p} - 1\right]}$$

Where M is the slope of the critical state line = 0.81 (Horseman et al., 1993) and p'_c is the pre-consolidation stress = 6 MPa.

Figure 16 shows the critical state model for Boom Clay as defined from the data of Horseman et al., 1993.

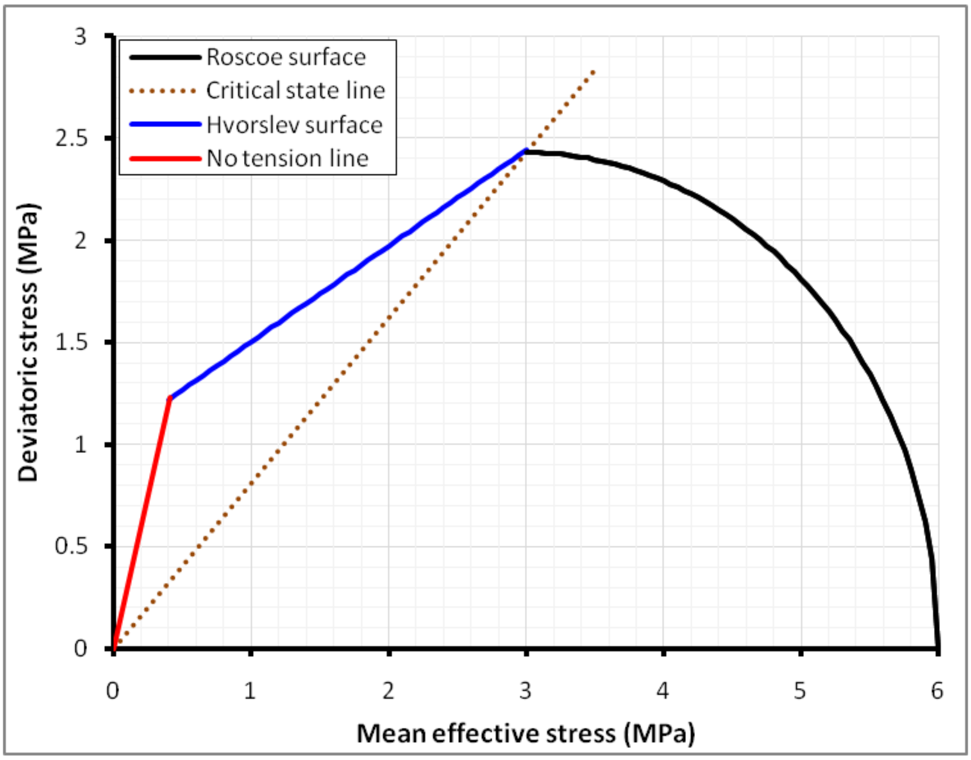


Figure 16 The critical state soil mechanics model for Boom Clay.

3.5 STRESS STATE AT MOL

Figure 17 shows the stress state observed at Mol, where vertical stress (σ_V) = 4.6 MPa; the maximum and minimum horizontal stress components (σ_H & σ_h) = 4.1 MPa; and pore-water pressure (P_p) = 2.5 MPa. This shows that the Boom Clay at depth is stable and far from a state of stress where deformation will be initiated. A change in stress-state, such as a stress concentration created around the periphery of a tunnel opening, is required in order to initiate deformation. Total and effective stresses are plotted. It should be noted that the law of effective stress has been assumed, where effective stress is simply total stress minus the pore-water pressure.

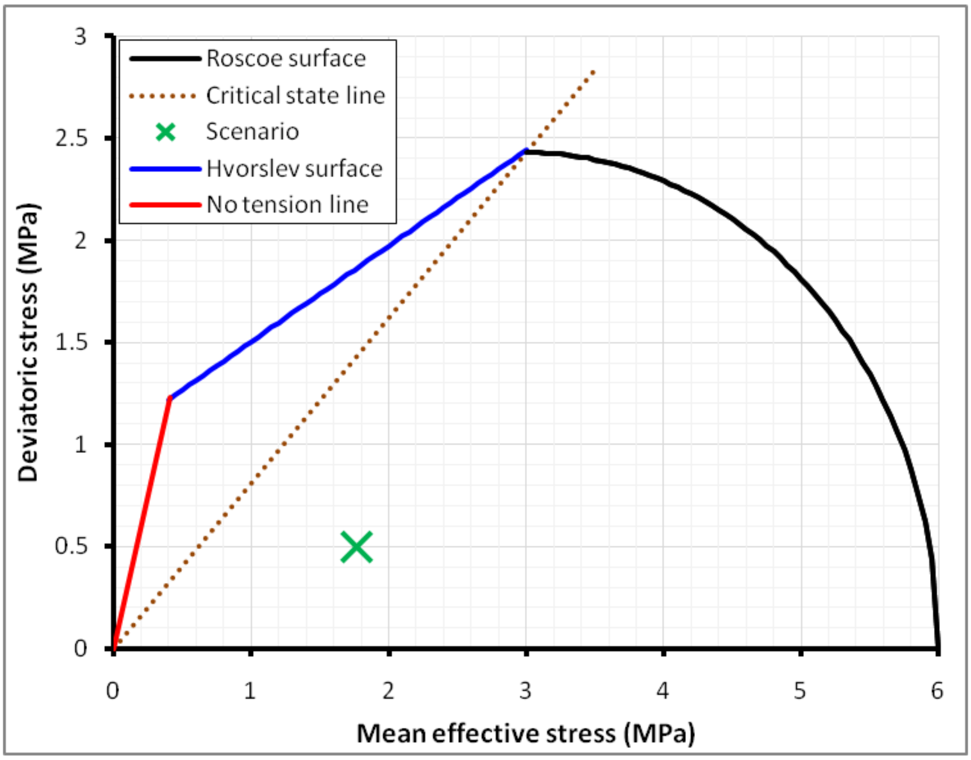


Figure 17 The critical state soil mechanics model for Boom Clay at Mol showing the current state of effective stress. The location of the effective stresses point shows that Boom Clay is stable at depth and plastic deformation would require a significant change in stress, such as a concentration of stress around a tunnel opening.

4 Stress state scenarios analysis for the Boom Clay

The following sections introduce a number of scenarios that could potentially occur. For each, the stress state at Mol is given as the starting stress state as this is the most reliable data available. The critical state model is defined from the data described above, the stress state is determined from the two components of horizontal stress (σ_H and σ_h), vertical stress (σ_v) and pore-water pressure (P_p). From the starting stress, the stress state was altered until the failure envelope was intercepted, giving the required stress to initiate failure and the nature of failure expected; be it ductile, brittle or tensional.

The approach adopted has been simplified to using a single failure envelope in the $q-p$ space and not the full CSSM surface in the $q-p-v$ space. This is due to a lack of data on the behaviour of Boom Clay during deformation in terms of void ratio.

Given the limitations of the above simplification, the approach adopted gives a relative stress required in order to initiate failure at the depth of a repository and the likelihood of a clay diapir to form.

4.1 SCENARIO 1 – EXHUMATION

The simplest form of stress change long term is the exhumation of the repository, which will reduce the vertical stress component. In this scenario σ_v has been reduced to 0.2 MPa, whilst horizontal stresses have remained unchanged at 1.9 MPa and pore pressure has reduced to zero. This creates the failure shown in Figure 18 . [σ_v = 0.2 MPa; σ_H & σ_h = 1.9 MPa; P_p = 0 MPa; estimates].

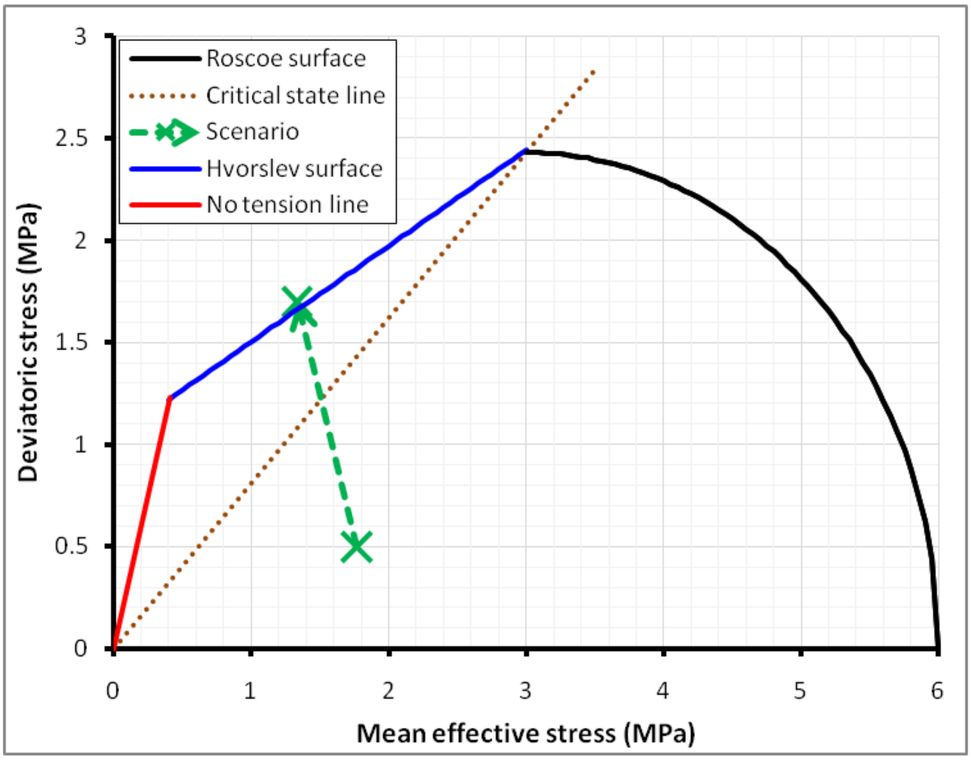


Figure 18 The critical state soil mechanics model for Boom Clay showing the scenario for exhumation on deformation.

- ✓ Failure is initiated
- × Failure mode is brittle, which is unlikely to be a mechanism in the formation of clay diapirs.
- × Requires a very rapid rate of exhumation, which has not occurred in recent geological time and is unlikely to occur in the near future. Rapid exhumation is required in order to lower the vertical stress component without seeing any alteration to the horizontal stresses. Given time Boom Clay deforms to create relatively hydrostatic stresses ($\sigma_v = \sigma_H = \sigma_h$) and large differential stresses are unlikely to persist.

Given the observations above, exhumation is unlikely to the mechanism that formed clay diapirs and is unlikely to form them in the long-term storage within a repository.

4.2 SCENARIO 2 – ELEVATED PORE PRESSURE (P_P)

Another simple scenario is the formation of over-pressure in pore-pressure. In order to create failure pore-pressure has to increase to 4.1 MPa, whilst σ_v, σ_H and σ_h remain unchanged; giving pore pressure a value equal to the horizontal stresses. This creates the failure shown in Figure 19 [σ_v = 4.6 MPa; σ_H & σ_h = 4.1 MPa; P_p = 4.1 MPa].

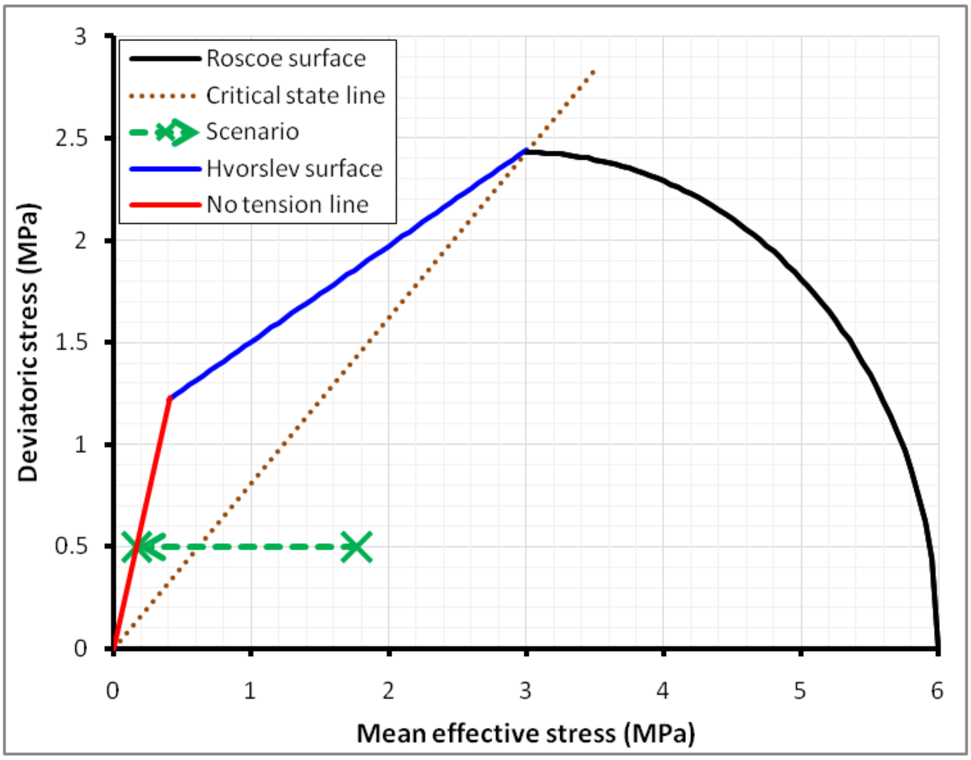


Figure 19 The critical state soil mechanics model for Boom Clay showing the scenario for increased pore-pressure on deformation.

- ✓ Failure is initiated in the extensional regime, which could be a mechanism in the formation of a clay diaper.
- × This degree of over-pressure is not observed in the Boom Clay at other locations and it is unlikely to have pore pressure so high that it creates an effective horizontal stress of zero at depth.
- × Vertical stress is greater than horizontal stress and so the initiated deformation would result in movement horizontally and not vertically; diapirism requires vertical movement of material.

The raising of pore-pressure alone is not likely to create a clay diaper and is unlikely to be the sole factor in initiating deformation.

4.3 SCENARIO 3 – INCREASED LATERAL LOADING

It is possible to create failure through the increase in lateral load, which would increase both σ_H and σ_h. In order to initiate failure σ_H and σ_h have to increase to 7 MPa. This creates the failure shown in Figure 20 [σ_v = 4.6 MPa; σ_H & σ_h = 7 MPa; P_p = 2.5 MPa].

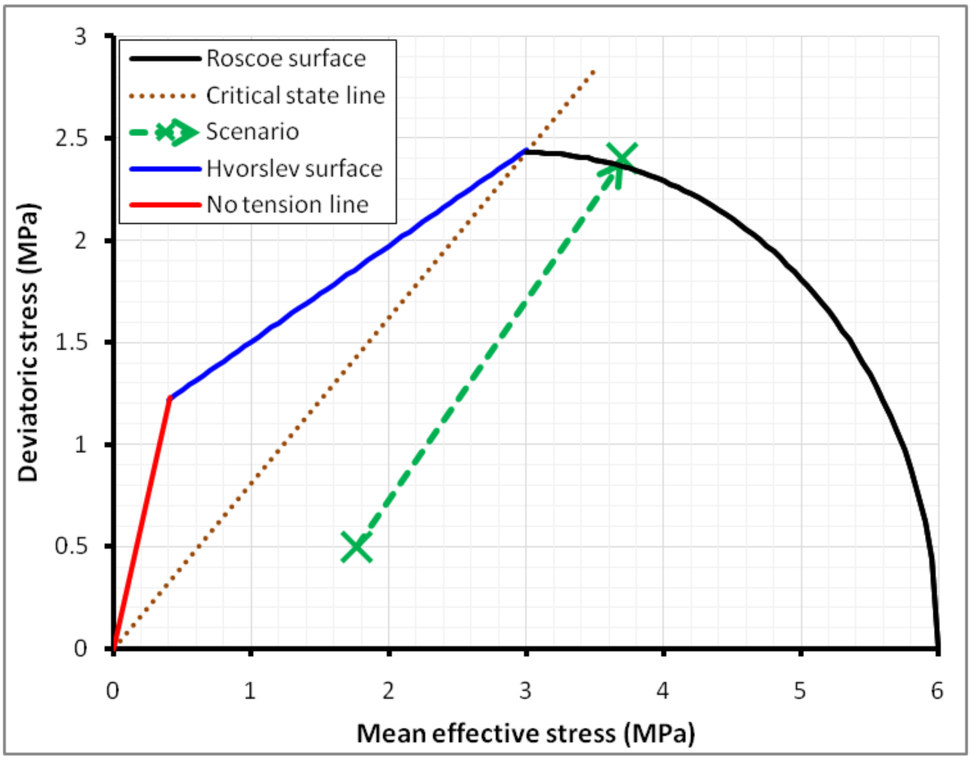


Figure 20 The critical state soil mechanics model for Boom Clay showing the scenario for increased lateral loading on deformation.

- ✓ Ductile deformation is initiated and as the horizontal stresses are greater than the vertical stress induced deformation will result in movement vertically.
- × A high lateral load is required and there are few scenarios of how this would form geologically. High lateral loads can be formed by deep valleys, i.e. valley bulging, however in the area of study the topography is unlikely to create such high lateral loads.
- × High differentials of stress are unlikely to be sustained due to the plastic nature of Boom Clay, therefore differential stresses of 2.4 MPa are unlikely to persist.

The increase of lateral load at the depth of a repository is unlikely and therefore this mechanism is unlikely to create clay diapirism at depth. It is possible that increased lateral loads can be created by valleys, but in this locality this is unlikely to be the mechanism that formed the features interpreted as clay diapirs.

4.4 SCENARIO 4 – CHANGE IN VOID RATIO

During the current study stresses are considered in terms of the q – p space and void ratio has been simplified to be constant. However, it is possible to show what would occur if stresses remained constant whilst void ratio changes. Figure 21 shows that the change in void ratio results in the change of the size of Roscoe surface; the surface is shown to reduce, which would occur if void ratio increases.

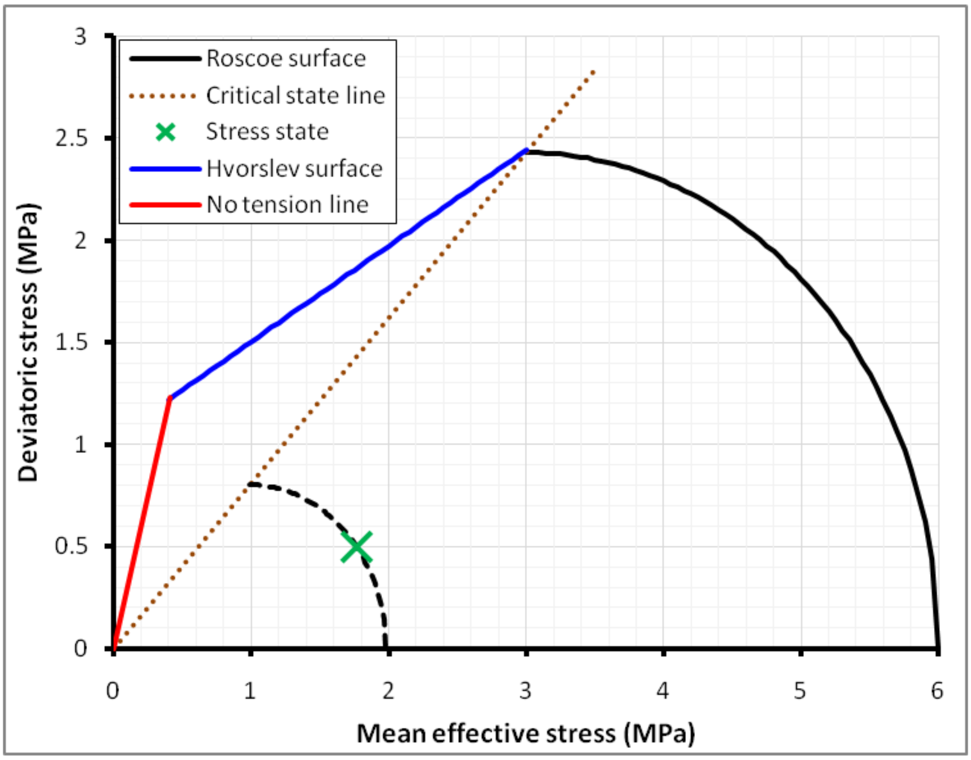


Figure 21 The critical state soil mechanics model for Boom Clay showing the scenario for reduced void ratio on deformation.

- ✓ Failure is initiated in the form of ductile deformation; as expected for the formation of clay diapirs.
- ✓ Rock creep is a mechanism that could result in the change in size of the failure envelope.
- × A reduction in the envelope requires void ratio to increase. This is unlikely unless the material takes on water and the pore space dilates.

It is difficult to define a geological explanation that would result in no change of load on the Boom Clay whilst the material undergoes an increase in void ratio.

4.5 SCENARIO 5 – REDUCTION IN ONE HORIZONTAL STRESS

It is possible to create failure through the reduction of one of the horizontal stresses, whilst vertical stress and the other horizontal stress remains unchanged. In order to initiate failure σ_h would have to decrease to 2.9 MPa. This creates the failure shown in Figure 22 [σ_v = 4.6 MPa; σ_H = 4.1 MPa; σ_h = 2.9 MPa; P_p = 2.5 MPa].

- ✓ Failure is initiated with a minimal change in stress.
- × Failure mode is brittle, which is unlikely to be a mechanism in the formation of clay diapirs.
- × Vertical stress is still the greatest stress direction, therefore deformation will result in movement in the horizontal direction, which would not create a clay diaper.

This scenario requires only a small change in one horizontal stress component, but the deformation will still be horizontal and so this case is not likely to create a clay diapir at depth.

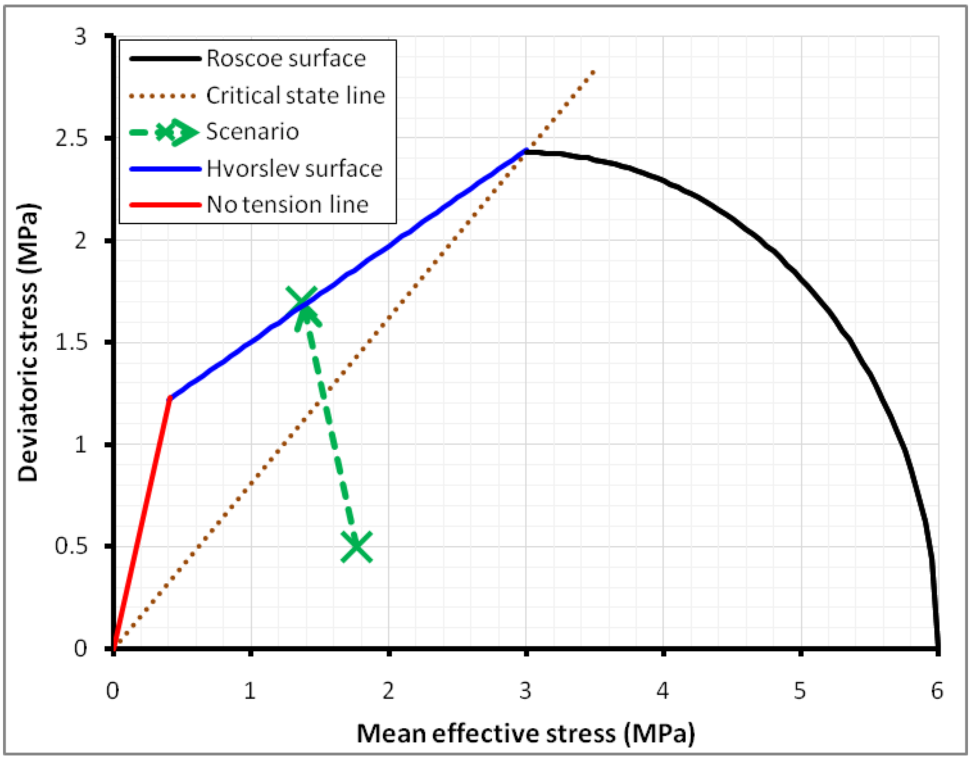


Figure 22 The critical state soil mechanics model for Boom Clay showing the scenario for the reduction in one horizontal stress on deformation.

4.6 SCENARIO 6 – NEGATIVE PORE PRESSURE

Failure of Boom Clay is possible through the inclusion of negative porewater pressures. The opening of a repository will result in dehydration of the Boom Clay and in the years following closure negative porewater pressure in the form of suction will be evident. In order to initiate failure a negative porewater pressure of 1.7 MPa is required, as shown in Figure 23 [σ_v = 4.6 MPa; σ_H & σ_h = 4.1 MPa; P_p = -1.7 MPa].

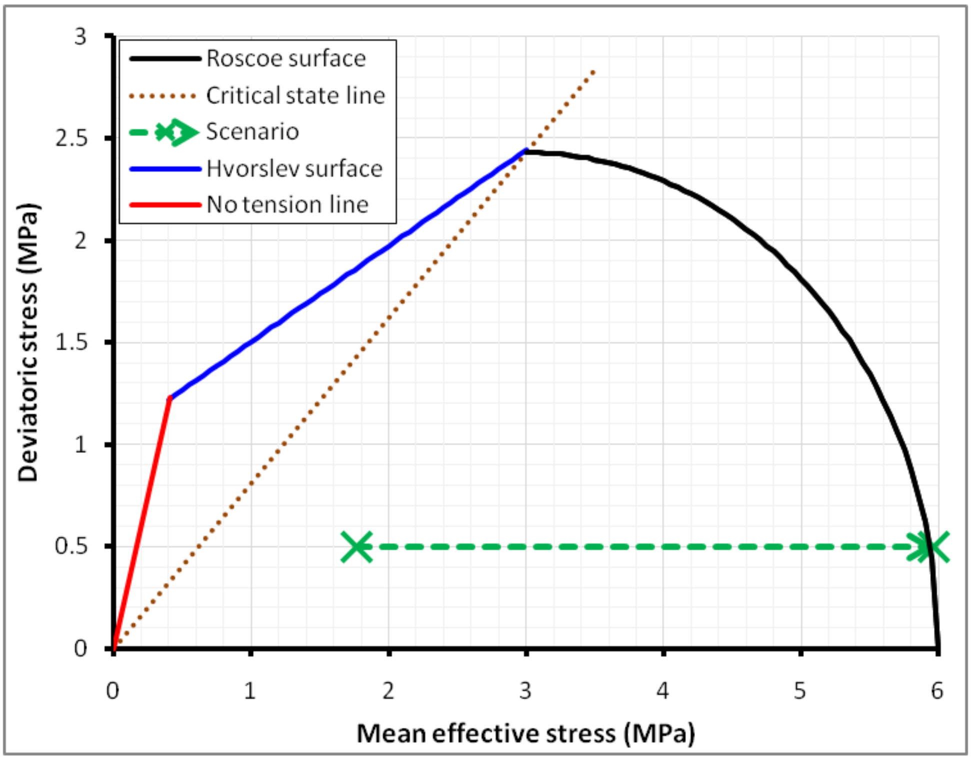


Figure 23 The critical state soil mechanics model for Boom Clay showing the scenario for negative pore pressure (suction) on deformation.

- ✓ Ductile failure is initiated
- ✓ Suction will be created by the opening of a repository and the dehydration of the Boom Clay
- × Whilst suction will be created by the opening of the repository, the scale of the pressure is unlikely to be as great at 1.7 MPa.
- × There is little evidence of natural negative porewater pressures in the Boom Clay.

Negative porewater pressures are likely to be the consequence of the opening of repository infrastructure. However, the magnitude of this stress is unlikely to be sufficient to initiate failure of the Boom Clay at depth. The lack of field evidence for natural negative porewater pressures at shallow depths means that this mechanism is not likely to be the sole driving force behind the formation of the features that have been interpreted as being clay diapirs.

4.7 SCENARIO 7 - SWELLING

Failure of Boom Clay is possible through the inclusion of swelling pressure. Figure 24 shows that a swelling pressure of 4.1 MPa is required in order to initiate failure for the in situ stress conditions for Boom Clay at Mol. [σ_v = 4.6 MPa; σ_H & σ_h = 4.1 MPa; P_p = 2.5 MPa; P_{swell} = 4.1 MPa].

- ✓ Ductile failure is initiated
- ✓ An increase in water content could result in the formation of swelling pressure
- × High swelling pressure of 4.1 MPa required to initiate failure, whereas published values for swelling pressure of the Boom Clay are 0.92 MPa.
- × Deformation is horizontal as vertical stress is still the greatest stress component.

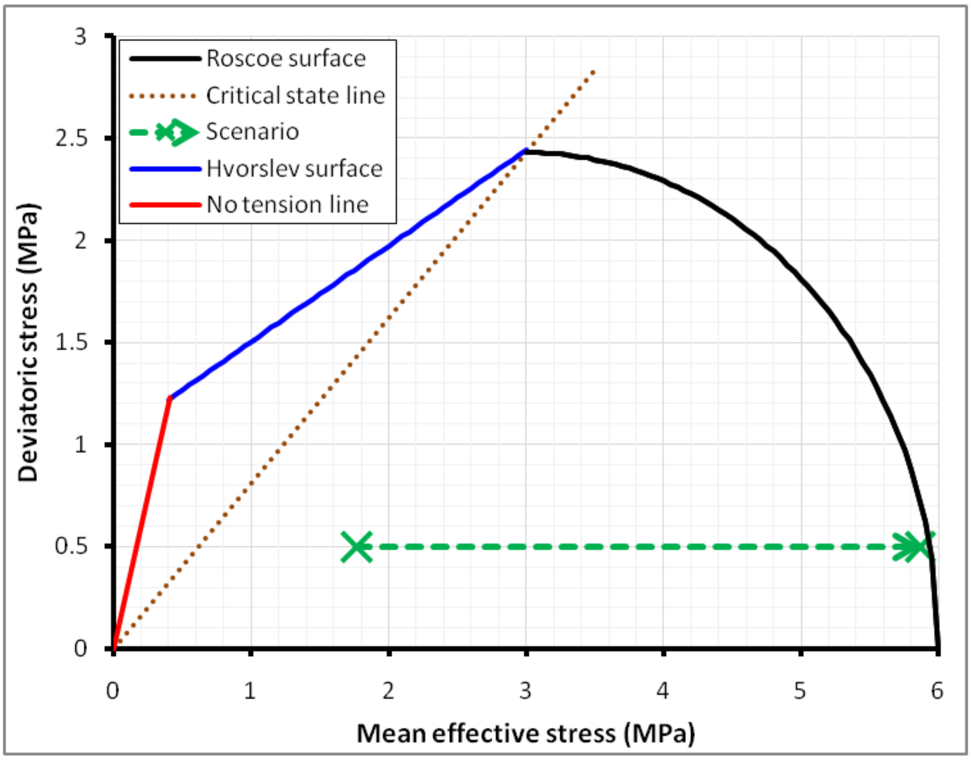


Figure 24 The critical state soil mechanics model for Boom Clay showing the scenario for swelling on deformation.

As a diapir needs to flow vertically, swelling pressure has to be formed at the same time as a reduced vertical stress component, as seen in Figure 25[σ_v = 2.4 MPa; σ_H & σ_h = 4.1 MPa; P_p = 2.5 MPa; P_{swell} = 4.1 MPa].

- ✓ Ductile failure is initiated
- × High swelling pressure and requires a reduction in vertical stress.

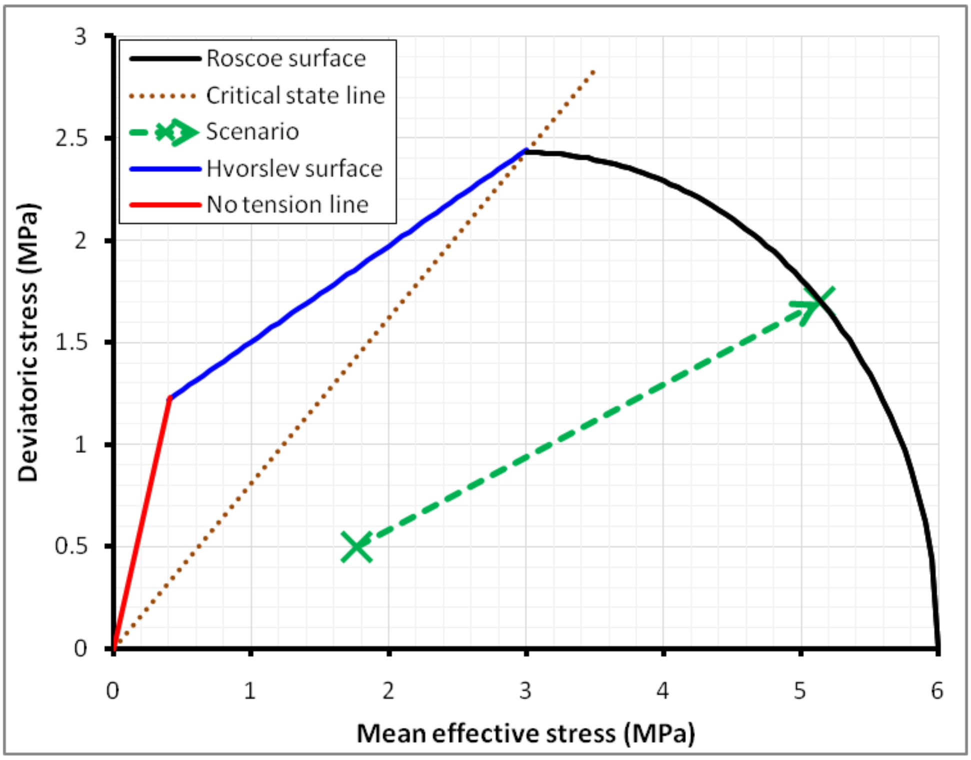


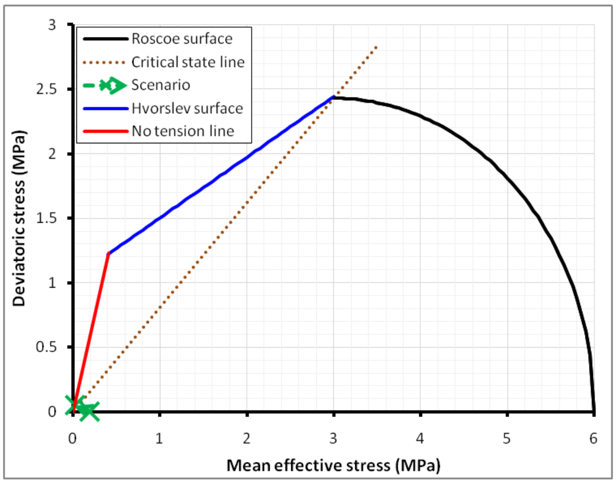
Figure 25 The critical state soil mechanics model for Boom Clay showing the scenario for swelling on deformation; this scenario would result in vertical movement of Boom Clay.

Swelling can occur by the Boom Clay taking up water; however, the magnitude of stresses created are likely to be insufficient to initiate deformation and the formation of a clay diapir at depth. However, the inflow of water at a shallow depth and near a river, such as where clay diapirs have been suggested, could result in the formation of swelling pressures. Therefore swelling may have been a contributing factor in the formation of the clay diapirs interpreted at shallow depths, but are not likely to form at depth and as the result of the construction of a repository.

4.8 DIAPIRISM IN BOOM CLAY

The scenarios above have looked at the likelihood of deformation in the Boom Clay at depth, either at the repository depth or at shallower depths. This scenario looks at the stresses that are likely at the depth of the inferred clay diapirs. Figure 26 shows the state of stress estimated for Boom Clay at the shallow depth. [σ_v, σ_H & σ_h = 0.2 MPa; P_p = 0.01 MPa; estimates].

- ✓ Very close to failure
- × Deformation is not created and is difficult to initiate.



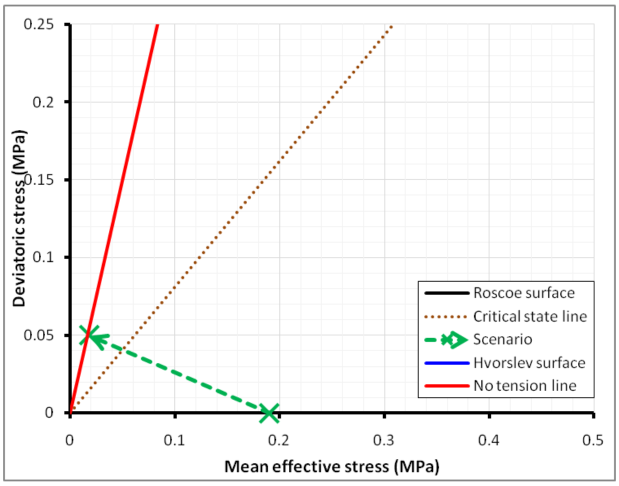


Figure 26 The critical state soil mechanics model for Boom Clay showing the scenario for deformation seen at shallow depths at the locations of clay diapirs.

4.9 POSSIBLE EXPLANATION FOR CLAY “DIAPIR” FORMATION IN THE SCHELDT RIVER

The scenarios above show the sensitivity of Boom Clay to the changes in different stresses. Figure 27 shows the proposed mechanism for the formation of the interpreted clay diapirs. The downward cutting of the river through the overlying 5m moraine and 5m of the clay formation results in a stress instability. Through the 10 metre column of water (ρ = 1 g/cc) 0.098 MPa of vertical load is created. At the same 10m depth either side of the river 0.18 MPa of vertical load is created. This results in a differential of vertical stress and will drive horizontal movement of material towards the river as shown. The river in this area is tidal so water column in the channel is of variable depth as the tides ebb and flow thus the calculation above reflects the minimum of differential in vertical stress which occurs at high tide. At low tide the vertical load created on either side of the river will be greater than the 0.18 MPa calculated above.

This explanation is plausible as being the cause of the formation of the inferred clay diapir at shallow depths. It explains why it is not possible to initiate the formation of such features at depth and it can be stated with a degree of certainty that the observed features only form at shallow depths.

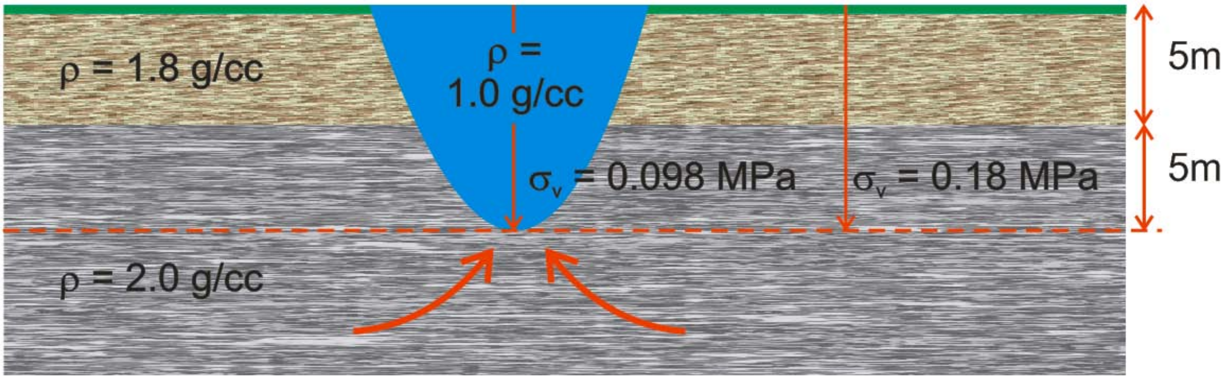


Figure 27 Possible explanation of the stresses driving the creation of clay diapirs in Boom Clay.

4.10 OTHER MECHANISMS

The analysis above based on the critical state soil mechanics approach is a purely mechanical analysis. There are additional mechanisms that potentially could change the stress state or location of the failure envelope. These include:

- **Density** – The term diapir implies a density driven feature. It is possible that buoyant forces cause a material to move if it is able to do so. The interpreted diapir features have not been sampled and it is not known whether their bulk density is different than the surrounding material.
- **Mineralogy** – As above, it is not known if the mineralogy of the diapir features differs from the surrounding material. Differences in mineral content could result in localised deformation.
- **Geochemistry –** As above, it is not known if the pore fluid geochemistry (gas content, water content, inclusion of brine) is different. Variations in geochemistry could result in localised deformation.
- **Creep –** Deformation can occur at stresses below the failure envelope when creep (time-dependent deformation) is involved. There is insufficient data to do a thorough creep analysis as data would be required for both the host rock and the “diapir” material.

5 Conclusions

There is evidence of a general relationship between the degree of induration of a clay sediment and levels of stress relief associated with, for example valley formation. In the glacial and periglacial palaeo-environments of Northern Europe conditions existed for stress relief sufficient to mobilise the plastic deformation of the clay-rich layers within a sedimentary sequence. Away from these environments the normal processes of valley formation and erosion may provide sufficient stress relief to mobilise younger and hence less indurated sediments.

The prerequisites for the process of post depositional clay diapirism are:

1. The presence of clays capable of plastic deformation

2. The removal of overburden stress sufficient to promote plastic deformation
3. The development of excess pore water pressures sufficient to promote plastic deformation

The key factor here appears to be the relative levels of factors 1 & 2 above. For example, the Namurian shales of Rowlee Bridge whilst being indurated have nevertheless been subject to clay diapirism, the reason being that the local stress relief factors are sufficiently great to induce plastic deformation. Further south, for example in Northamptonshire and Bath, younger, less indurated or non-indurated clay formations are subject to similar clay diapirism but resulting from smaller levels of stress relief.

There is probably a link between periglacial permafrost thawing and the development of a 'plane of décollement' (Hutchinson, 1988). This effectively defines a lower limit to deformation and may represent the depth limit of permafrost. A good documented example of this is the Marlstone Rock Bed at the Empingham Dam cut-off trench (Horswill & Horton, 1976).

The strength contrasts associated with bedded sequences of alternating lithologies (for example mudstones and limestones) may also be a factor in the development of clay diapirism, and valley bulging in particular. This interbedding appears to be a common feature in most examples of UK valley bulging. This may be due to both strength and permeability contrasts between beds, resulting in plastic deformation which in turn produces bedding-plane slip, brittle failure of the interbeds and their entrainment in the plastic material. Some form of 'marker' bed, often a thin limestone or sandstone, is useful in identifying the detailed structures within valley bulging; these being frequently obscure within the clays themselves.

The <u>relevance</u> of clay diapirism to a clay based geological disposal system for radioactive waste lies in the following features associated with it:

1. Joints and fractures
2. Enhanced vertical permeability,
3. Reduced strength,
4. Disrupted fabric affecting density,
5. Disrupted thermal properties,
6. High pressure fluids

It would appear that the mechanism for diapir formation is different for each of the three formations being studied, probably due to their regional/tectonic setting and recent Quaternary history. Depth of burial and proximity to external migratory fluids are also key determinants.

The following conclusions are made regarding the individual clay formations:

The <u>London Clay Formation</u>: Diaprism is connected with periglacial conditions. Within London the dominant driving mechanism appears to be the overpressuring of underlying formations (Woolwich & Reading Formations) (Hutchinson, 1991). Elsewhere, cambering has been identified as a causal factor for diapirism within the London Clay Formation.

The <u>Kortrijk Formation</u>: Extensive diapirism has been identified in the Southern North Sea by geophysical methods. Initially Raleigh-Taylor instability was proposed as a driving mechanism (Henriet et al., 1991), possibly with valley bulging as a contributory mechanism in some cases. However, following the identification of polygonal faulting associated with diapirism several conflicting mechanisms have been proposed. Foremost amongst these are syneresis and low residual strength (Cartwright et al., 2003; Goulty, 2008). The relationship between diapirism and polygonal faulting is poorly understood at the moment.

The <u>Boom Clay Formation</u>: The driving mechanism for diapirism in the Boom Clay appears to be valley bulging. This is based on extensive geophysical investigations in the Schelde River estuary (Verschuren, 1992, Wartel, 1980). However, Henriet et al (1983) suggest diapirism may also be associated with over-pressurisation from methane, possibly produced from within the Boom Clay itself.

The term diapir infers a density driven mechanism that moves material from depth to a shallower depth. The stress analysis undertaken shows that the formation of a “diapir” is highly unlikely at the depth of a repository due to the extreme changes in stresses required. The analysis has shown that a localised deformation as the result of the location of a river is more likely the cause of the creation of the features that have been inferred as being a diapir. These are not diapirs and are similar to valley bulging features seen, with the river banks acting similarly to valley sides and the bulge occurring in the bottom of the river.

The critical stress scenarios modelled during the work reported here demonstrate that the Boom Clay at a depth equivalent to the MOL laboratory (220m) is stable and that under *in situ* conditions are not close to failure in any of the scenarios examined. The final scenario, which attempts to model the diaper formation in the Boom Clay under the Scheldt River, shows that the clay is close to failure in this near surface situation. However, it also shows that it would be difficult to initiate such failure as modelled. This suggests that other factors, such as the physical properties of the clay and its saturation, have been affected by the near surface position and, perhaps, by past climatic regimes. No data on the physical properties of the clay in locations where diapirism has been observed are available. If such information was available further modelling could be undertaken to refine our understanding.

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