Oil & Gas Science and Technology – Rev. IFP, Vol. 54 (1999), No. 6, pp. 785-795

A Hydro-Geomechanical View of Seal Formation and Failure in Overpressured Basins

G. D. Couples[1]

1 Department of Petroleum Engineering, Heriot-Watt University, Edinburgh EH14 4AS - Scotland
e-mail: gary.couples@pet.hw.ac.uk

Résumé — Approche hydro-géomécanique de la formation des barrières d'étanchéité et de la fracturation dans les bassins en surpression — La formation de barrières d'étanchéité, et par conséquent le maintien de surpressions, est un phénomène physique courant auquel on peut s'attendre au cours de l'évolution normale d'un bassin actif ayant une séquence importante d'argiles. La perte d'étanchéité et la limitation de l'augmentation de pression qui en résultent (mécanisme de valve) constituent également un événement prévisible de ce phénomène. Les concepts hydro-géomécaniques, incluant la poro-élasto-visco-plasticité et les modèles discrets, permettent d'expliquer les processus de création de pièges et de perte d'étanchéité par rupture. Ces concepts rendent également prévisibles l'état de contrainte et le comportement des roches en surpression. Cette approche permet notamment d'intégrer les propriétés liées à la porosité (comme la perméabilité). Ces concepts permettent de développer des simulations qui peuvent être utilisées comme outils de prévision. Dans un bassin, les interactions entre le fluide et la roche peuvent alors être considérées comme un système autoorganisé, en considérant que la surpression et le déficit de compaction qu'elle induit retardent la création d'un espace de réarrangement mécanique et agissent donc comme un mécanisme négatif de rétroaction, qui ralentit la vitesse de chargement.
Mots-clés : surpression, mécanique des roches, modélisation de bassin, barrières d'étanchéité, poro-viscoplasticité, état de contrainte.

Abstract — A Hydro-Geomechanical View of Seal Formation and Failure in Overpressured Basins — *The formation of seals, and the consequent retention of overpressure, is a common and expected event during normal basin evolution in active basins that have a significant mudrock succession. Seal failure, and the resultant limitation to fluid-pressure increase (valve action), is also an expected process. Hydro-geomechanical concepts, including poro-elasto-visco-plasticity (PEVP), and discontinuum models, allow the processes of seal formation and failure to be explained, and predict the state of stress in, and behaviour of, overpressured rocks. Importantly, properties that relate to porosity (such as permeability) can be integrated with this approach. These concepts provide a capability to undertake simulations that can serve as predictive tools. The fluid/rock interactions in a basin can be viewed as a self-organizing system, in the sense that overpressure and the undercompaction it permits retard the creation of accommodation space, and hence act as a negative feedback mechanism that slows the loading rate.*
Keywords: overpressure, rock mechanics, basin modelling, seals, poro-viscoplasticity, stress state.

INTRODUCTION

Abnormal fluid pressures, representing the results of natural processes, are of both scientific and practical interest. In the petroleum industry, overpressures are a particular concern, and a number of research projects on this topic currently receive industrial support. Although a wide range of possible mechanisms have been suggested, compaction disequilibrium (interrupted compaction) due to fluid retention associated with permeability barriers ("seals") is interpreted to be one of the major causative processes in overpressure development (Grauls, this issue). Chemical effects may also have a potentially significant role in causing overpressure because of cementation (mass import) or grain shape changes leading to porosity losses. One argument in favour of a chemical role is the appreciation of rate effects during compaction (Schneider *et al.,* 1996). It is probable that a combined view will emerge, and that a future cycle of research will discover the relative roles and controls for the mechanical and chemical contributions to the compaction process.

However, for the present, I wish to concentrate only on the mechanical aspects of compaction. By doing so, I hope to illustrate that a hydro-geomechanical analysis can explain most of the relevant observations, including those indicating rate dependence. This is by no means an attempt to remove chemical effects from consideration! Indeed, it may well be that chemical processes underlie the rate effects that are known from rock mechanics testing, and there may be an inextricable linkage that cannot be separated merely for convenience. It may also subsequently be shown that chemical effects are otherwise important in basin evolution and overpressure development (beyond their possible role in rock mechanics), and, if so, they need to be properly addressed.

Before describing the hydro-geomechanical models that are the focus of this paper, it is worth noting the basic features of overpressured basins that need to be explained by any comprehensive theory that seeks to explain the relationship between compaction and overpressure in mud-rich basins (Fig. 1):

– There is a general decrease in porosity as a function of depth, but, importantly, there is variability in the observed porosity at any given depth (noisy plots). In some overpressured zones, porosity fails to decrease with depth, or the decrease is less than expected (under-compaction).
– The basin materials gain strength as they compact, and so there is a general relationship between porosity loss and increase in strength.
– In general, there is a relationship between porosity loss and permeability reduction, so mudrocks become less-permeable as they compact.
– Fluid pressure can increase rapidly with depth, producing a sharp "transition zone". This zone is notionally associated with the location of a seal, or cap. Observations indicate that it is not uncommon to have fluid pressures that are a significant fraction of the calculated lithostatic pressure (usually called σ_v).
– In a typical relaxed basin, it is generally inferred that the horizontal stresses (σ_H and σ_h) increase with depth, with a magnitude of +/–60% of σ_v. This relationship seems to hold until the depth at which a zone of overpressure is reached. In the overpressured zone, the horizontal stresses are interpreted to increase, and to be nearly equal to σ_v.

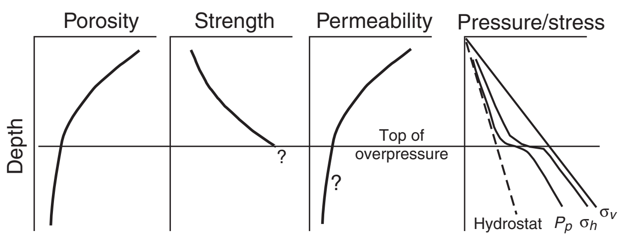

Figure 1

Primary material characteristics of subsiding basins. Porosity generally decreases with depth, but there is often a lot of scatter. In overpressured zones, porosity may not decrease (as rapidly) with depth. Strength generally increases with decreased porosity. See text for discussion of strength within overpressured zone. Permeability generally declines with porosity, but see text for discussion of values in overpressured zone. Pore pressure (P_p) and stresses (σ_h, σ_v) usually exhibit a linear increase with depth until top of overpressure. Within overpressured zone, P_p is elevated, and σ_h may approach the magnitude of σ_v.

1 A "NEW" MATERIAL DESCRIPTION

The objective of this section of the paper is to outline a general material description that can be used for understanding the hydro-geomechanics of compaction, the action of seals, and how overpressure can affect the mechanical state of rocks. For this purpose, the treatment is necessarily at the macroscale, and microscale details are subsumed. The material description is developed from the knowledge gained from decades of laboratory testing of rock and soil deformation, along with the theoretical appreciation that has been derived from the laboratory observations. In this paper, I do not seek to make an argument that this material description *must* be adopted; instead, I seek to demonstrate that it is a plausible way to integrate most of the general knowledge that now exists, and therefore, that it is a practical tool.

1.1 Previous Knowledge

The vast majority of laboratory testing is described in a manner that might be called "Mohr-Coulomb failure". In this approach, yielding is depicted in a two-dimensional space, and a curvi-linear boundary limits the field of achievable states of stress (Fig. 2). In the usual depiction, the failures that occur (when the Mohr circle touches the sloping, linear portion of the criterion line) are nominally called brittle. Variations in state of stress, and material, produce different details of how the deformation occurs, and, to some extent, in the volume strain that is realized, but there is more consistency than difference in the large body of laboratory data arising from such tests. For granular rocks (e.g., sandstones, most carbonates, siltstones), brittle failure is usually characterized by grain breakage or grain-boundary sliding, and there is often substantial dilation produced during typical laboratory experiments.

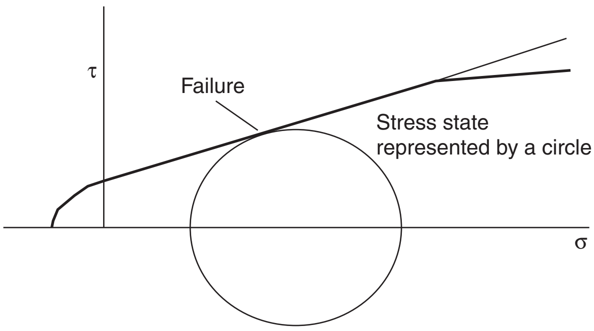

Figure 2

Classical Mohr-Coulomb representation of failure in normal stress (σ) and shear stress (τ) space. Note linear portion of failure envelope at lower values of normal stress, but flattening of slope of failure limit at high values of σ.

A different set of descriptors applies to deformations that occur as the Mohr circle touches the failure criterion at high mean stress. The constructed yield criterion in such a case is usually below the linear projection of data obtained at lower mean stresses, and many depictions show this stress-state boundary as nearly flat. The term ductile is often applied to such deformations, even though they may be produced by the same grain-scale phenomena as occur in the brittle field of failure. However, the volumetric strain is either neutral or compactional for these tests—in contrast to the usual dilational deformation associated with brittle fracture.

Theoretical rock mechanics has a long history of seeking to synthesize the results of laboratory testing. Important to this discussion is the work that has sought to apply plasticity to the range of results noted in the preceding paragraphs. Plasticity, of course, is distinctly focused on the yielding of materials. In a form appropriate for rocks, pressure-dependent or Coulomb-plasticity, has a graphical representation (Fig. 3) that is similar to that adopted in the Mohr-Coulomb perspective. However, in plasticity, a yield surface

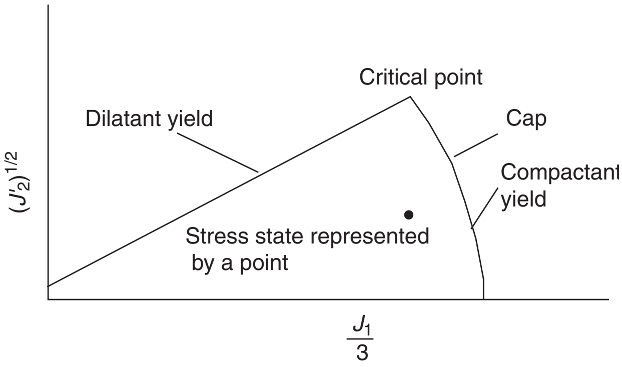

Figure 3

Example of Coulomb-plastic failure criterion (mean-stress dependent yield). J_1 is the first invariant of the stress tensor, so $J_1/3$ is the mean stress. J'_2 is the second invariant of deviatoric stress, and its square root represents the "differential stress". The axes of such plots are sometimes denoted as "*P*" and "*Q*", respectively. Note general similarity to Mohr-Coulomb failure depiction, except for "cap" representing compactional failure mode. Sometimes the dilatant portion is shown as a curved line, thereby avoiding the singularity at the critical point.

represents the locus of states at which yielding occurs. Invariants of the stress tensor are typically used as the primary parameters in the equations defining the conditions of yielding and form the axes of the resulting plots. States of stress plot as single points, rather than as circles, and there is no directional information (as can be achieved in a Mohr circle plot via the pole method).

Incremental dilatant and compactant volume strains at yield, as known from laboratory testing, are typically associated with either of two portions of the yield surface that are separated by what is usually referred to as the "critical point". The dilatant portion of the yield surface has an association with the classical, Mohr-Coulomb, brittle field, and the compactant portion of the yield surface, forming a "cap", is related to the "ductile" behaviour observed at higher mean stresses. Recent laboratory results (Fig. 4; Wong and Baud, this issue) provide comprehensive support for this general description.

Plasticity theory was developed to solve problems in disciplines where the materials (mostly metals) do not have a strong dependence on mean stress. Some of the theoretical work that seems applicable in these original subject areas does not translate well into the geoscience domain. In particular, basic plasticity predicts post-yield flow by using what is called an "associated flow rule". This approach can be paraphrased as follows. When yield occurs, draw an outward-pointing vector normal to the yield surface at the point representing the state at yield. The orientation of this vector is transferred into a parallel space where the axes

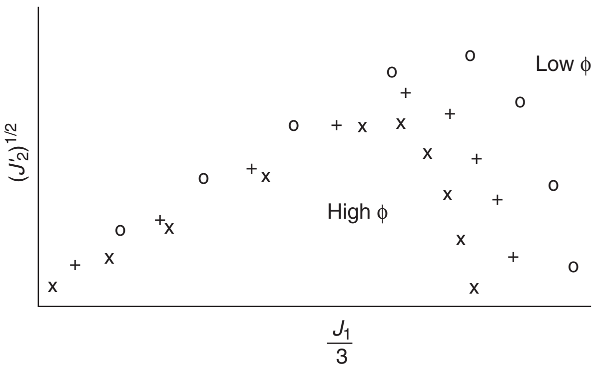

Figure 4

Schematic illustration of laboratory results for the yielding of porous sandstones (after Wong *et al.,* 1997). Low-porosity rock denoted by circles, medium-porosity rock by pluses, and high-porosity rock by crosses. Note linear, mostly dilatant behaviour at lower mean stress, and compactant response ("cap") at higher mean stress for each rock type. Refer to Figure 3 for descriptions of axes.

represent rates of strain increment. The strain increments are then used to calculate the deformation during a (virtual) time step. Unfortunately, this flow rule grossly over-predicts dilation (compared with what is observed for brittle deformations), and so "nonassociated flow rules" must be used, instead.

Another element of rock behaviour that is well-known from laboratory work is its dependence on loading rates. Rapid loading requires a higher stress difference to achieve the same strain than does a slower loading. Viscous models, whether Newtonian or power-law, are adopted by many in an attempt to simulate accumulated deformation. Of course, in a basin setting, it may be misleading to lump all rate-dependent changes together, but there is certainly a case for including rates within a material description.

1.2 PEVP

Mudrocks, and other basin sediments, are initially deposited with high porosities that are reduced during burial as grains/particles are rearranged or distorted and contained porefluids escape. This mechanical compaction during burial is a deformation that produces significant volumetric strains, and, as such, it should be considered in the context of yielding. Other deformations, for example those produced by tectonism, also can cause volume changes, and these examples of yielding also need to be addressed by any comprehensive material description.

Porosity has a critical role in determining the mechanical response of rocks. It is not merely an associated property that is affected by deformation, but it has the impact of a state variable. A more-comprehensive material description must, therefore, be linked with porosity in equal importance to the state of stress.

A framework that meets this requirement already exists in the domain of soil mechanics (and was applied to mudrocks by Jones and Addis, 1986). In a graphical fashion, the yielding of a soil can be depicted in a three-axis space where state variables—porosity (ϕ, or, alternatively, the void ratio), mean stress (σ_m, also denoted as J_1), and differential stress ($\Delta\sigma$, or more precisely, $\sqrt{(J_2)}$) govern yielding (Fig. 5). In mathematical terms, the yield surface is a function of these three variables: $Y = f(\phi, \sigma_m, \Delta\sigma)$. Yielding occurs when the calculated value of Y equals the value appropriate to that material. Yielding produces both distortional strain, and a derived volume strain (porosity change) that is either positive (dilatant), negative (compactant), or zero (volume-constant). Because of the way the yield surface varies ($\delta Y/\delta\phi \neq 0$), there must be a change in either the differential stress or the mean stress that is needed to cause yielding after an increment of deformation that causes a non-zero volumetric-change. In this sense, deformation of the material can create a "new material" that has different properties.

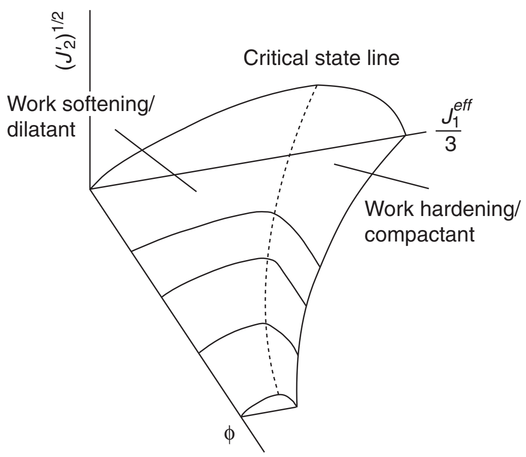

Figure 5

Representative poro-plastic yield criterion. Refer to Figure 3 for descriptions of axes; ϕ is porosity (alternatively, may be shown as void ratio). Depiction similar to that often used in soil mechanics; see also Jones and Addis (1986). The three lines crossing the yield surface represent the experimental data depicted in Figure 4.

I suggest that a similar approach can be used to integrate the key elements of rock behaviour that we know from laboratory testing (as summarized in the preceding section). For example, the data shown in Figure 4 represent (in a two-parameter projection) the yielding of otherwise-similar sandstones that differ only in their porosities (having similar grain size, similar roundness, and similar cement). In the laboratory, usually only a small range of porosity change is examined for any specimen, but, in nature, a sandstone evolves through a substantial range of porosity as it experiences mechanical compaction during burial, and as other deformations affect it. Adopting the framework initially created in soil mechanics permits this full evolution to be included within the material description. Other, "non-mechanical processes" that affect porosity (and hence strength), such as cementation, can be addressed by evolving the yield surface as a function of these events.

The concept of effective stress is well-known from laboratory rock mechanics work dating back for more than a third of a century (Handin *et al.,* 1963). In practice, rock mechanics data obtained under "dry" conditions is assumed to be applicable to an equivalent effective stress condition produced by a framework stress and a fluid pressure. I assume that the approach described herein can be similarly extended by replacing the σ_m parameter with σ_m^{eff}. This extension enables dry experiments to be included in the knowledge data base. If a persuasive argument can be made to overturn the fundamental validity of the effective stress principle (as opposed to a result that needs to be re-considered in the new framework), then the argument in this paper is invalidated.

Because the treatment described here draws on plasticity theory, while also treating porosity (or void ratio) as a state variable, it should logically be called "poro-plasticity". However, this term has been used by others, both as a generic description of plasticity applied to porous materials, and as a specific "rheology" similar to the treatment developed above. Although the historical usage of the expression may be somewhat muddled, poro-plasticity is the appropriate term to describe the concepts summarized above.

There is no mention of deformation rate in the above material description. However, because we know this is an important consideration, I suggest that "poro-plasticity" be modified to become "poro-visco-plasticity" (meaning a rate-sensitive poro-plasticity). This can be accomplished by making the yield surfaces dependent on strain rate. In graphical form, this modification can be illustrated by showing separate yield surfaces for selected strain rates (Fig. 6). If there is a strong rate effect, the surfaces will be located a distance apart, but if rate effects are minimal, the surfaces may essentially overlie one another. Although the term "viscous" can be argued to have precise meaning(s), it can be used to mean a general rate effect, and that is how it is co-opted here.

Another element that needs to be addressed by a comprehensive material description is the behaviour of rocks when their state lies "underneath" (within) the yield surface. The term "poro-elastic" is used to describe elastic (recoverable) porosity changes associated with changes in fluid pressure, for rocks that are not yielding. These effects must be incorporated into the general material description, and, so there is, finally, poro-elasto-visco-plasticity (PEVP).

Note, however, that although a given state may be "inside" a yield surface for some strain rate, it may—as noted above—be "on", or above, a yield surface for a slower strain rate. Therefore, behaviour inside any given, rate-defined yield surface has both an elastic component for that given strain rate, and plastic strains accumulating at some slower rate. A more-complicated model may be needed to resolve these issues (e.g., different rules may apply in loading and unloading modes), but this paper is not the appropriate place to explore these details. The new, more-comprehensive material description—PEVP—is capable of reproducing the principal mechanical effects that we know from the laboratory, and can be used (see below) to explain the characteristics of basins as listed in the Introduction.

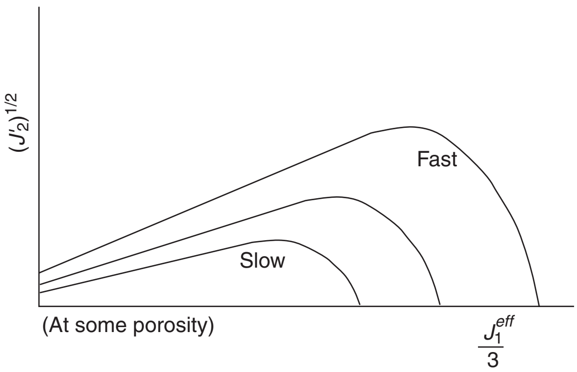

Figure 6

Slice (at arbitrary porosity) through suite of poro-visco-plastic yield surfaces drawn at three strain rates. Refer to Figure 3 for descriptions of axes. This plot suggests a significant rate dependence.

Rocks experience changes in important properties associated with any induced deformation. Intrinsic permeability is such a property, and one that is key to the subject of this paper. Such associated properties (but not state variables) can be treated in the new material description as attached functions. D'Onfro *et al.* (1994) illustrated this approach with a map relating incremental permeability change (plus, minus, neutral) produced by deformation to all points on the yield surface (a single strain rate, so not "visco" in the current context). Other properties, such as sonic velocity (for some given reference fluid content), thermal conductivity, etc., can be treated in a similar fashion. The justification for this approach is that these properties relate to the microscopic structure of the grains and the shapes of the pores, and since these are inherently included in the "porosity" state variable, it is reasonable to attach such incremental maps to the yield surfaces.

2 RAMIFICATIONS OF THE PEVP MODEL

2.1 Compaction, Seal Creation and Overpressure

Recent studies of mudrocks reveal a complex layered heterogeneity of primary particle types (and, hence, composition) in otherwise monotonous-looking sequences (Yang and Aplin, 1998). Other studies serve to relate such variations in material type to variations in material properties (for example, oedometer tests on different "muds" produce different rates of porosity loss). It might well be expected that a typical mud-rich basin will have a layer- (and lamina-) dominated arrangement of material types.

Given that basin materials are subjected to mechanical compaction as they are buried, and that the (evolving) mechanical properties are related to the composition and grain configuration, there is likely to be a layered arrangement to the mechanical parameters, and to the associated properties, of the rocks in a basin. Since permeability reduction is generally correlated with compaction (porosity loss), there will also be a layered arrangement to the permeability distribution. As a consequence, a typical basin probably has a very complex arrangement of small-scale flow units that evolve as they become buried and further compact, and as the porefluids contained in the basin seek to escape.

If subsidence is sufficiently rapid, and, therefore, produces a rapid loading, it is possible for the system of rock + porefluid to be forced into a nonequilibrium condition related to the inability of the system to dissipate the excess energy (by expelling porefluids) sufficiently quickly (Waples and Couples, 1998). The usual result of this situation is to create overpressure within the basin, from which it can be concluded that some particular layer(s) has/have reached a degree of compaction-induced permeability reduction that is adequate to retard fluid flow to a degree sufficient to sustain a fluid-pressure differential.

Likewise, if buoyant hydrocarbons become trapped, we can conclude that sealing capacity has been achieved. For such a two-phase system, the critical parameter is the capillary entry pressure, which is directly linked with the pore-throat size distribution, and, hence, to the same phenomena as is the reduction in intrinsic permeability. Since both of these types of evidence (overpressured porefluids and trapped hydrocarbons) are common in basins, it can be concluded that the formation of flow retarders/barriers (seals) is essentially inevitable in typical basins.

How can the hydro-geomechanical perspective (PEVP) be used to explain this "inevitable" formation of seals? Imagine a structurally-simple, flat-lying basin that is actively subsiding and becoming filled with a very large number of layers (or laminae) of mudstone and sandstone (Fig. 7). Assume that each layer/lamina of mudstone has a (slightly) different original composition, such that, at any time in the basin history, there exists a vast number of individual materials that have nested yield surfaces. Each set of yield surfaces describes the state of its layer, as well as predicts its subsequent deformation at every point in time. Each layer is also, at each point in time, characterized by a particular intrinsic permeability (and other properties) that is the product of its original composition and its compaction history.

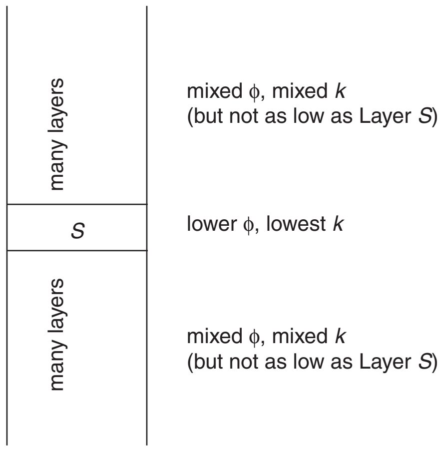

Figure 7

Schematic drawing showing the situation at the time that first sealing layer (lamina) becomes effective. ϕ is porosity, k is (intrinsic) permeability. No scale shown.

Now let us focus on a particular layer (called "*S*") that, in its depth region, has developed the lowest permeability at some stage in the basin evolution. At the next increment of (sufficiently-rapid) loading (which, in this simple case, of mechanical processes only, is produced by sedimentation at the top of the succession), layer *S* retards the upwards escape of porefluids from the dewatering layers below. If loading continues, then the layers beneath can no longer continue normal compaction because they cannot fully expel their excess porefluids, and their porosities and permeabilities no longer decline with increasing depth as quickly as before (limited fluid escape does occur, of course). In the terms of PEVP, the layers beneath layer *S* cease yielding because the point representing their state of stress moves away from the yield surface (or, in reality, perhaps, to a slower strain-rate yield) because of the change in effective mean stress (Fig. 8).

Above layer *S*, the layers can continue to expel porefluids (because they are in a "drained" region), and, hence, they continue to compact. As a consequence, their permeabilities

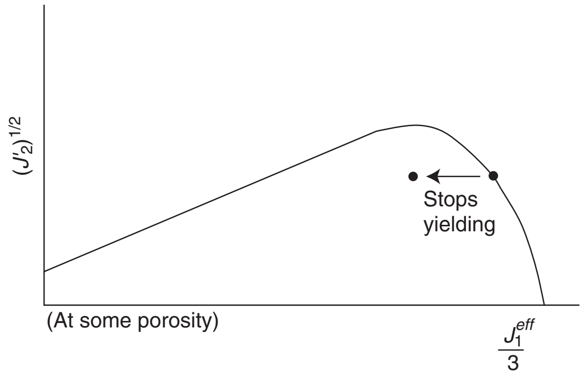

Figure 8

Slice (at arbitrary porosity and strain rate) through poro-visco-plastic yield surface. Stress point initially indicating compactional yield, but yielding ceases as point moves "inside" yield surface because of increasing pore pressure. Refer to Figure 3 for descriptions of axes.

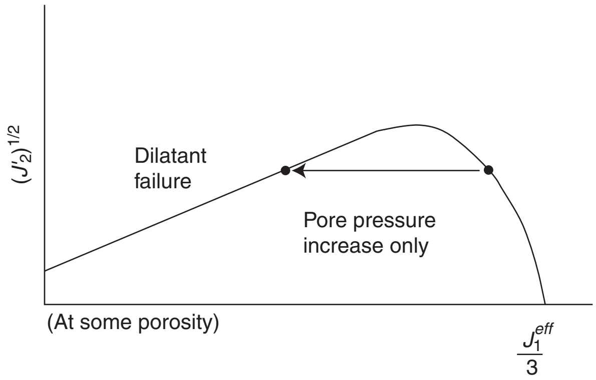

Figure 9

Slice (at arbitrary porosity and strain rate) through poro-visco-plastic yield surface for rocks lying above layer *S* (as in Fig. 7). Stress point initially indicating compactional yield (adding to capacity of seal interval). Large increase in pore pressure moves stress point to conditions that produce dilational failure (ignoring poro-elastic stress changes), and hence limit the capacity of the seal. Refer to Figure 3 for descriptions of axes.

are reduced (in line with their reduced porosity) while their strength is increased. The lowered permeabilities, and the resulting reduction in fluid movement, mean that these now-better-compacted layers subsequently become part of the seal, and the total seal capacity (in terms of differential pressure) is increased. The growing strength of the upper seal layers also contributes to the increase in seal capacity by resisting seal failure (see below). In the sense described here, seal creation is a process that involves positive feedback, but it is dependent on the "right" set of circumstances occurring.

2.2 Seal Failure

It is clear that excess fluid pressures in basins, and, particularly, those beneath seals, do not build indefinitely, but that they are, instead, limited in magnitude by some means. Thus, seals have only a certain capacity, and seal failure is identified with a yielding of the rocks that constitute the seal. Because the focus here is on the capacity of the seal to retain high-pressure fluids, the failure that is of interest must be one where permeability is increased (if it decreased, then even-higher pressure differentials could be realized). Notionally, such an increase in permeability will allow fluids to flow, and so it permits an increment of added fluid pressure to be "absorbed" by the system. Another type of failure that could increase permeability, and be associated with the inability to retain fluids, is a change in the rock-framework mechanics.

If we first consider the case of fluid pressure that is increasing in isolation from any other events, PEVP provides a straightforward illustration of the primary process (Fig. 9). If we imagine that the seal under consideration is composed of those rocks located above layer *S* in Figure 7, then, by the arguments presented above, those rocks are continuing to compact and contribute to the seal interval, making it grow in thickness. This mode of yielding plots on the cap portion of the yield surface, and serves as a starting point for this analysis. If there is now an "external" increase in porefluid pressure (brought about by slow flow through the seal), the stress point simply moves to the left because of the reduction in effective mean stress, but with no change in "stress difference" (ignoring any stress changes associated with poro-elastic effects). If the pore-pressure increase is large enough, the stress point can contact the yield surface on its dilatant portion. Once located there, this point can "oscillate" on and off the yield surface as small variations in fluid pressure are associated with buildups and leak-offs. The macroscopic, continuum material description (PEVP) is not suited to a study of the details of that process; instead, a discontinuum approach is required. The oscillating conditions predicted for seal failure represent a pseudo-steady state, and it is only possible if the escaping fluids can move away.

Tectonism can also move the stress point and cause seal failure (Fig. 10). If fluid pressure is not changing, then the required movement of the point must be due to an overall reduction in mean stress, but the "differential stress" can vary —becoming either larger or smaller. One way to achieve the necessary reduction of mean stress is by uplift. Other means can be related to flexure, or to other deformation styles,

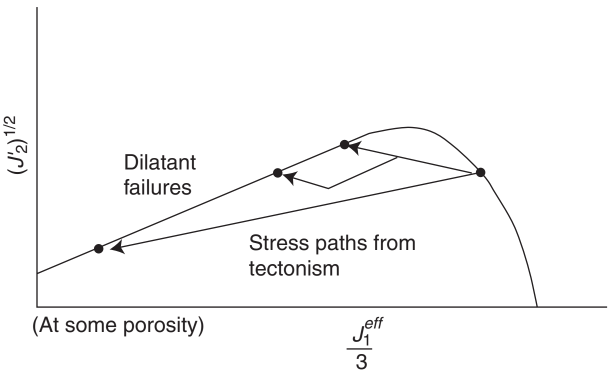

Figure 10

Slice (at arbitrary porosity and strain rate) through poro-visco-plastic yield surface for rocks lying above layer *S* (as in Fig. 7). Stress point initially indicating compactional yield (adding to capacity of seal interval). Tectonic processes can move stress point to conditions that produce dilational failure (ignoring poro-elastic stress changes), and hence limit the capacity of the seal. Lowest path might represent simple uplift, while other paths indicate possible complexities. Refer to Figure 3 for descriptions of axes.

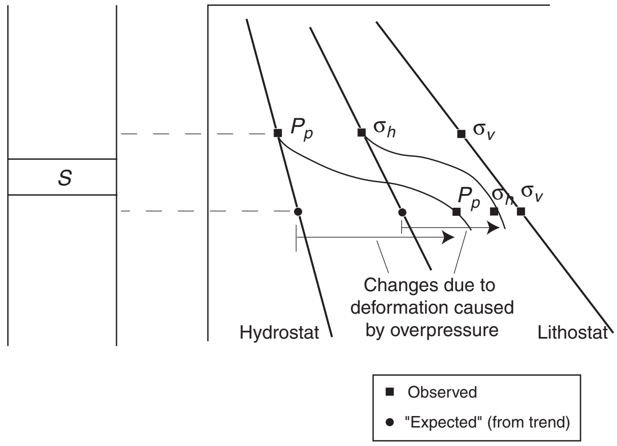

Figure 11

Portion of typical pressure/depth plot (right) in region of seal "*S*" (indicated in rock column on left). In overpressure zone, expected values of pore pressure and horizontal stress would lie on projection lines, but high fluid pressure beneath seal, and associated deformation, have caused both values to increase significantly. See text for details. No scale shown.

where there is spatial heterogeneity in the produced stress state (Couples *et al.,* 1998). Of course, combinations of fluid-pressure change and tectonism may well represent the normal situation.

2.3 Stress State in the Overpressured Zone

In a typical setting, the overpressured zone lies beneath the seal and consists of a rock + porefluid system in which the pore pressure is greatly elevated. As noted in the Introduction, the horizontal stress and the pore pressure are both considerably elevated as compared to their values in rocks only a short distance away, lying above the seal. Considering an idealized system in which the seal and transition zone are very thin, these changes can be highlighted (Fig. 11). The argument that I wish to make is that these changes are brought about by the fluid-pressure increase, and by the consequence this has on the rock mechanics.

Let us ignore any stress changes due to poro-elastic effects. Remembering that stress is a reaction (a dependent variable), the problem is to explain a large increase in σ_h (the minimum horizontal stress) as the pore pressure is increased (due to retention by the overlying seal), while the stress difference and the effective mean stress both become smaller (Fig. 12a). The change in stress difference *must* be associated with yielding (and not with external loads) because the situation described is common to many basins.

A probable stress path (Fig. 12b) initially follows the scheme described above for seal failure. Simple pore-pressure increase moves the stress point to the left. However, when the stress point contacts the yield surface, fluid pressure is not released (in contrast to the situation during seal failure), *because this deformation is occurring within a sealed region.* Yielding, therefore, continues, and the stress point "tracks" along the yield surface. Because this section of the yield surface is nominally associated with work-softening (Couples and Lewis, 1999), the stress point moves towards lower "differential stress" while fluid pressure continues to increase (effective mean stress decreases). The weakening rock framework is able to support less of the total system load, and the remainder is transferred to the fluid, thereby further increasing its pressure and (potentially) representing a positive runaway feedback.

Based on the arguments in the preceding paragraph, PEVP predicts that overpressured rocks can be "at yield", and very weak, with important implications for drilling efficiency and safety. Simultaneously, other rocks in the overpressured section may not reach their yield surfaces, and so may not experience such large stress changes. For the rocks that do fail, I suspect that this deformation will often be expressed as multiple sets of small faults or shears. Could the blocks so-delineated be almost "floating" in a matrix of porefluid? It seems that it might be possible for the blocks to continue to be squeezed by the high-pressure porefluids, and this situation is very like the "hydraulic shrinkage" process described by Miller (1995). Depending

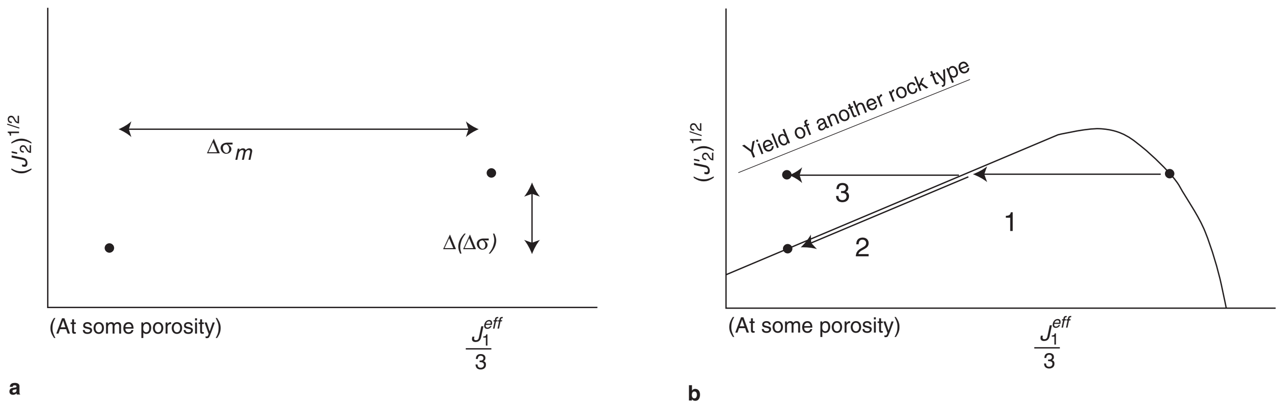

Figure 12

Explanation of state changes in overpressured zone brought about by increased pore pressure and deformation.
a: top-right stress point represents the expected state (refer to Fig. 11), while the lower-left point indicates the observed state. Note change in mean stress ($\Delta\sigma_m$) and change in differential stress ($\Delta(\Delta\sigma)$). This situation cannot be the product of simple pore pressure increase without deformation.
b: stress paths: 1 represents increase in pore pressure sufficient to cause yielding; 2 represents work-softening yield inclosed system; 3 is possible "nonyield" path for interbedded "strong" rocks (no change in "differential stress"). Refer to Figure 3 for descriptions of axes.

on the spacing of the deformation, a wireline tool might detect a lower bulk density, or a seismic investigation might sense a lowered velocity, and these data could be used to infer a state of undercompaction that did not exist (if the rocks were previously well-consolidated). Other processes, such as chemical dissolution (Wilkinson *et al.,* 1997), may also operate in these zones but not in the same fashion in other places within basins. The physical conditions within an overpressured zone can create situations that are unfamiliar, and therefore difficult to predict from normal experience.

An interesting corollary to this analysis is that it allows speculation about the nature of the deformation in rocks that were once part of an overpressured zone in a basin, but that have since become normally-pressured. Such situations will eventuate in all formerly-overpressured basins as they become less active, and as pressures dissipate by fluid flow through the low-permeability rocks that once served as seals. The progressive yielding of overpressured rocks, as suggested in the preceding paragraph (to produce the strength reduction), should leave evidence in terms of deformation features. If it affects mudrocks, faulting may be difficult to recognize, but if there are varying lithologies, it may be more apparent. The arrays of faults interpreted to occur in "tiers" in some mud-dominated basins (e.g. Cartwright and Lonergan, 1996), and other "unusual" fault systems (Henriet *et al.,* 1991), might be examples of the features—perhaps even reactivated slightly after/during overpressure release.

2.4 A Self-Organizing System

If undercompaction occurs as a consequence of the development of overpressure, then the sea-bed of the evolving basin will fail to subside as rapidly as it otherwise would have. In a muddy depositional setting, it is easy to imagine that a positive sea-floor anomaly might be associated with a reduced sediment accumulation at the time of the overpressure. Such locally-reduced deposition translates into a reduction of the loading rate (compared with other sites). The lesser loading provides an opportunity for the basin + porefluid system to bleed off excess fluid pressure (e.g., recover), which, because of the resulting compaction (delayed from earlier times), will subsequently produce an increase in subsidence, and then an increase in loading as thicker sediments accumulate there. This arrangement of feedback paths is essentially that which is needed to identify a self-organizing system. It may be that paleo-depositional anomalies could be used as indicators of paleo-pressure.

3 DISCUSSION

In the argument presented above, it is suggested that a seal interval might be a composite of multiple layers in which the further compaction of the upper layers adds to the integrity of the seal. Are there other arrangements that also produce an effective fluid barrier? Do soft and stiff layers work together to produce a robust ensemble that has both strength and low overall permeability? Are weak layers necessary to absorb any deformation that occurs in the stronger layers? If the layers that are immediately above an initial seal layer are already compacted, will the seal interval continue to develop? Do the systems jump from one level to another? Do multi-tiered overpressure systems indicate compaction plateaus? Obviously, there is considerable potential for an investigation of the processes of seal formation.

A key development that will enable that investigation is to construct a suitable simulator. Original material distributions could be drawn from repetitive depositional examples (annual, up to climatic cycles), or from data gathered from mudstone sequences, or from pseudo-random data generators. Specific cases, as suggested above, could be created to explore the importance of patterns of layers, and, indeed, of the details of compaction history. The overall goal of such studies would be to provide methods with which to interpret the probability of seal formation, and estimate its capacity and integrity, in a particular basin setting. The rate effects included in PEVP will certainly be important, especially to address the questions concerning loading rate.

Further Work

The PEVP material description is firmly rooted in meso- and macroscopic observations, and its main application will always be in the area of macroscale simulations. In contrast, there are exciting developments in poro-plasticity at the microscale where thermodynamics principles are being used to create first-principles rheological models (Dormieux and Maghous, this issue; Boutéca and Guéguen, this issue). There is certainly potential for integrating these two specialist areas.

In order to be used in simulations, PEVP needs to be parameterized. In doing this it is important to bear in mind the data that is, and will be, available from laboratory testing. The parameterization also needs to have phenomonological significance (e.g., the material constants should derive from the thermodynamic work noted in the preceding paragraph). It is also necessary to keep in mind how the material description is to be implemented within a simulator. Meeting all of these goals simultaneously will be challenging.

Although the sloping "planar" portion of the yield surface is often associated with dilatancy, this relationship may be only partial. Possibly, it is largely fortuitous because of the way that much laboratory testing has been undertaken. It may be that incremental dilation/compaction at yield is another "property" that must be calibrated from experiments.

If PEVP is to be used in a practical fashion, the material parameters need to be calibrated from suitable rock materials, as do the associated properties (e.g., permeability, conductivity, velocity). If dilation/compaction is an associated property (as suggested above), instead of a material constant, then this characteristic will also require further investigation. A substantial quantity of laboratory data is already available for many rocks, but it is likely that mudrocks are inadequately studied, in general.

CONCLUSIONS

Poro-elasto-visco-plasticity synthesizes a large body of existing knowledge concerning the yielding of rocks. Importantly, PEVP incorporates porosity as a state variable, so that yielding in this material description can explicitly address volume strains and their consequences, such as permeability changes. The formation of seals in an active basin is an entirely expected process, given the variability of mudrock successions. Seals represent an initial fluid barrier that grows via positive feedback. Seal failure is explained as a natural event that follows on from the development and evolution of seals, thus making it possible to undertake an integrated analysis of the formation and failure of seals, and their operation as pressure valves. Rocks within an overpressured zone beneath a seal are likely to be in a state of failure and to contain abundant distributed deformation.

ACKNOWLEDGMENTS

I thank Dave Weinberg, Philip Ringrose, and Jim Somerville for helpful reviews of this manuscript. My thinking on this subject has benefited from numerous discussions with a large number of colleagues, and I acknowledge both the pleasant and animated examples of these interactions. A special thanks is due to Mike Fahy in this regard.

REFERENCES

Boutéca, M. and Guéguen, Y. (1999) Mechanical Properties of Rocks: Pore Pressure and Scale Effects. *Oil & Gas Science and Technology, Rev. IFP,* **54**, 6.

Cartwright, J.A. and Lonergan, L. (1996) Volumetric Contraction During the Compaction of Mudrocks: a Mechanism for the Development of Regional-Scale Polygonal Fault Systems. *Basin Research,* **8**, 183-193.

Couples, G.D. and Lewis, H. (1999) A Poro-Plastic Material Description. *Bulletin des centres de recherche,* Elf, in press.

Couples, G.D., Lewis, H. and Tanner, P.W.G. (1998) Strain Partitioning During Flexural Slip Folding. In *Structural Geology in Reservoir Characterization,* Coward, M.P., Daltaban, T.S. and Johnson, H. (eds.). Geological Society of London, Special Publication, **127**, 149-165.

D'Onfro, P., Fahy, M. and Rizer, W. (1994) Geomechanical Model for Fault Sealing in Sandstone Reservoirs. *American Association of Petroleum Geologists, Annual Convention Official Program,* **3**, 130-131.

Dormieux, L. and Maghous, S. (1999) Poroelastic and Poroplastic Behaviour at Large Strains: Application to Compaction Modelling. *Oil & Gas Science and Technology, Rev. IFP,* **54**, 6.

Grauls, D. (1999) Overpressures: Causal Mechanisms, Conventional and Hydromechanical Approaches. *Oil & Gas Science and Technology, Rev. IFP,* **54**, 6.

Handin, J. Hager, R.V., Friedman, M. and Feather, J.N. (1963) Experimental Deformation of Sedimentary Rocks under Confining Pressure: Pore Pressure Tests. *American Association of Petroleum Geologists Bulletin,* **47**, 717-755.

Henriet, J.P., De Batist, M. and Verschuren, M. (1991) Early Fracturing of Palaeogene Clays, Southernmost North Sea: Relevance to Mechanisms of Primary Hydrocarbon Migration. In *Generation, Accumulation and Production of Europeís Hydrocarbons,* Spencer, A.M. (ed.). EAPG Special Publication **1**, 217-227.

Jones, M.E. and Addis, M.A. (1986) The Application of Stress Path and Critical State Analysis to Sediment Deformation. *Journal of Structural Geology,* **8**, 575-580.

Miller, T.W. (1995) New Insights on Natural Hydraulic Fractures Induced by Abnormally High Pore Pressures. *American Association of Petroleum Geologists Bulletin,* **79**, 1005-1018.

Schneider, F., Potdevin, J.L., Wolf, S. and Faille, I. (1996) Mechanical and Chemical Compaction Model for Sedimentary Basin Simulator. *Tectonophysics,* **263**, 307-317.

Waples, D.W. and Couples, G.D. (1998) Some Thoughts on Porosity Reduction—Rock Mechanics, Overpressure and Fluid Flow. In *Basin Modelling: Practice and Progress,* Duppenbecker, S.P., and Iliffe, J.E. (eds.). Geological Society of London Special Publication, **141**, 73-81.

Wilkinson, M.W., Darby, D., Haszeldine, R.S. and Couples, G.D. (1997) Secondary Porosity Generation During Deep Burial Associated with Overpressure Leak-off: Fulmar Formation, UKCS. *American Association of Petroleum Geologists Bulletin,* **81**, 803-813.

Wong, T.F. and Baud, P. (1999) Mechanical Compaction of Porous Sandstone. *Oil & Gas Science and Technology, Rev. IFP,* **54**, 6.

Wong, T.F., David, C. and Zhu, W. (1997) The Transition from Brittle Failure to Cataclastic Flow in Porous Sandstones: Mechanical Deformation. *Journal Geophysical Research,* **102**, 3009-3025.

Yang, Y. and Aplin, A.C. (1998) Influence of Lithology and Compaction on the Pore Size Distribution and Modelled Permeability of some Mudstones from the Norwegian Margin. *Marine and Petroleum Geology,* **15**, 163-175.

Final manuscript received in July 1999