Drilling Around Salt: Risks, Stresses, And Uncertainties

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DRILLING AROUND SALT: STRESSES, RISKS, UNCERTAINTIES

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ABSTRACT: Drilling around salt structures means coping with a wide range of stress and pore pressure conditions, sometimes over a relatively short vertical distance. Zones with exceptionally low σ_{hmin}, with open fractures, with overpressured fluids, or with exceptionally high σ_{HMAX} can be encountered. It is often possible to make semi-quantitative predictions of stress orientations and magnitudes based on the geological history of the salt structure emplacement, the general tectonic regime, and the displacement history of the sediments around the structures. For example, in the case of a diapiric structure that has pierced through overlying strata, the outward thrust placed on the sediments surrounding the dome shaft imprints the region surrounding the shaft with a highly compressive radial stress and a low tangential stress. These stress regimes not only affect drilling strategies and tactics around salt structures, they also affect completion approaches involving perforation placement, hydraulic fracture design, and horizontal well placement.

1. INTRODUCTION

Salt structures in extensional sedimentary basins are associated with large hydrocarbon deposits. Traps may be found in the anticlinal structures and normal fault blocks above piercement and non-piercing salt domes, in updip traps in upwarped and occasionally overturned strata that terminate against the salt dome flank in the piercement region, in gentle flank anticlines, or under salt tongues (Figs 1 & 2). Accessing these resources presents problems including massive lost circulation, fractured shale sloughing, serious gas cutting of mud, and so on. These problems are related to current stress state, gas migration, and rock properties and fabric alteration arising from large deformations. Issues during salt drilling are discussed elsewhere [1].

Initial drilling of an anticlinal structure above a Gulf of Guinea salt dome in the 1990's resulted in 92 lost drilling days because of an exceptionally low σ_{hmin} value, a MW window < 0.05 density units, and massive lost circulation that re-initiated at each attempt to continue advancing. Similar though less severe lost-time cases are reported wherever extensive drilling takes place around salt structures, and the magnitude of the problems are larger the younger and less consolidated the sediments.

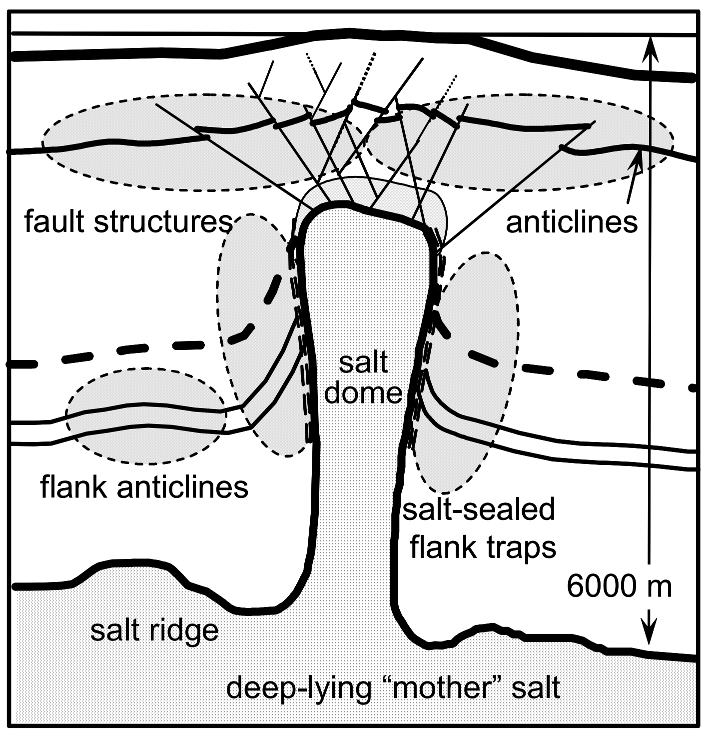

Figure 1: Shallow Salt Dome with Trap Locations

Salt dome growth is complex; structures may grow and punch through sediments (piercement), others develop while sediments are emplaced around them, others deform strata above so that thinned anticlines form, and so on. Even in "simple" stress conditions (e.g. pure extensional regimes for millions of years), salt ridges, domes, and isolated salt pods now unconnected to underlying sources of salt can form.

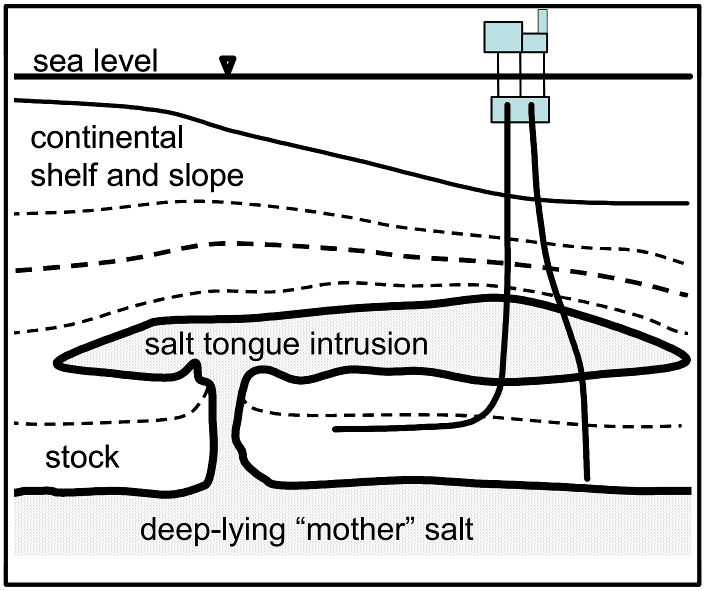

Figure 2: Drilling Beneath Salt Tongues in Deep Water

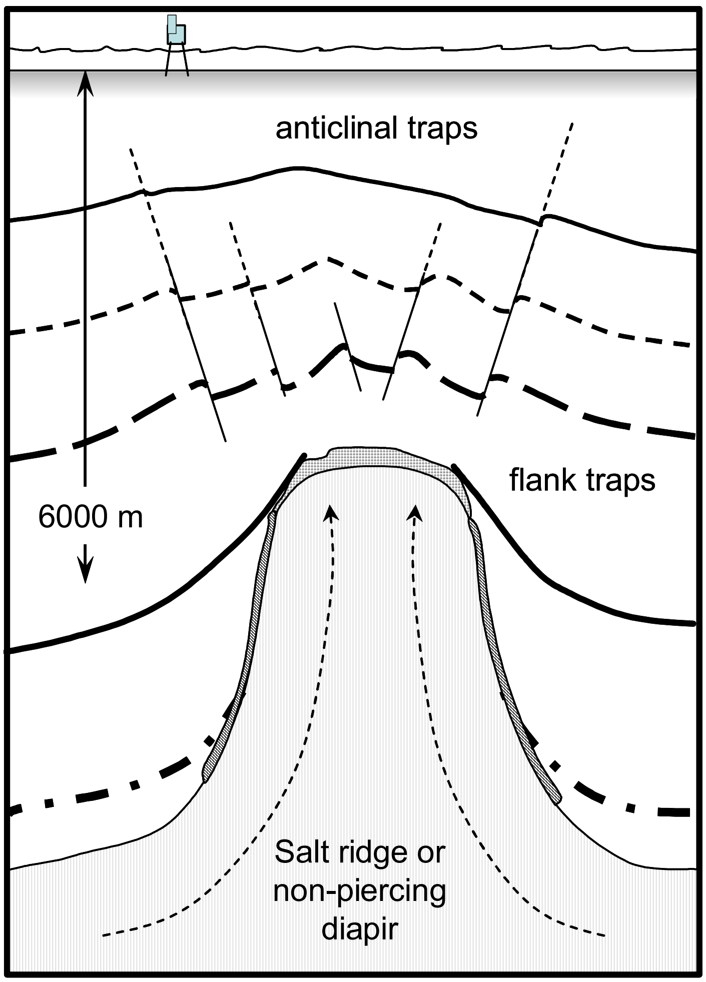

Figure 3: Deep Salt Diapir with Overlying Anticlinal Traps

In listric fault conditions such as the Gulf of Mexico (GoM), offshore equatorial West Africa and eastern South America, salt tongues linked to deep salt deposits through a “stock” can form (Fig 2), much like laccolith structures observed in igneous rocks. These structures have recently become exploration targets because of better sub-salt seismic imaging.

In thick sedimentary salt beds, mobilization can be observed at all stages of deformation, such as in the Kungurian Salt in the Pre-Caspian Basin. Diapirs, broad domes, ridges, and other structures can be found above the Permian age Kungurian, all of which have resulted in large deformations of the non-salt rocks and often generating local traps [2]. Below the salt, large unusual overpressured sulfur rich reservoirs exist (Tengiz and Kashagan fields).

In compressional belts, bedded salts can be tectonically affected, generating thrust fault thickened salt, as seen in west Appalachian foreland salt structures (New York and Pennsylvania), in New Brunswick, Iran, and elsewhere.

Understanding stress fields and rock fabric around salt structures helps to guide drilling practices. This leads to savings and large risk reduction because uncertainty is minimized and problems can be anticipated and managed proactively.

2. SALT STRUCTURE FORMATION

2.1. Stress Regimes, Buoyancy

Full-scale diapirs and salt tongues are invariably associated with crustal extensional strain regimes and salt buoyancy as the driving force. Extensional regimes can be horst-graben structures, of which the Central Graben of the North Sea is typical (though there are elements of strike-slip displacement among blocks), or open-to-the-sea passive continental margins such as the Nova Scotia, West Africa or GoM regimes, often associated with listric faulting (down-to-the-sea or growth faults).

The driving force for diapirism is self-reinforcing stress imbalance arising from overburden stresses acting perturbations in the source salt and maintained by salt buoyancy ($\rho = 2.16$ compared to host rocks $\rho = 2.35 - 2.6$). Creep-activating force imbalance is sustained by continued sedimentation during dome growth, stress transmission from depth upward through the column of salt as the result of viscous flow, and the removal of the overlying strata by erosion as they are uplifted. Salt reacts as a viscous liquid over geological time and cannot sustain shear stresses; in an effort to return to an isotropic stress condition, it creeps; if driving forces are sufficient, the salt distorts the overlying rocks, pierces through them, and rises through the sediments. At the surface, erosion removes the additional vertical stress that arises because of the upwarping of the sediments, helping sustain the driving forces. The result is a domal structure that can even grow as a narrow vertical salt finger rising from great depth, piercing through non-salt strata, and arching the overlying. Buoyancy and mushrooming effects at the top of domes imply that there is some continued stress transmission through the salt body, so that the vertical stress gradient through the salt structures is closer to 21 kPa/m, whereas in the surrounding country rock it is 23-25 kPa/m. Diapirism ceases when frictional resisting forces in surrounding rocks can sustain the imbalanced buoyancy forces.

The ability of overlying strata to "resist" forces by developing curvature, stress arching and frictional resistance is difficult to quantify. To some degree, non-salt strata also creep; sandstones and limestones lose porosity through pressure solution, a form of time-dependent behavior. However, indurated non-salt strata react largely in a brittle-frictional manner to the large deformations associated with salt structure emplacement.

It is likely that lateral stress magnitudes control vertical propagation of a domal structure, whereas the density instability generates the necessary driving force. Continued lateral sedimentation combined with erosion above the upwarping crest also seem necessary for continued salt diapirism, and it appears that extensional stress regimes ($\sigma_{hmin} = \sigma_3$) are needed for full dome emplacement.

In contrast, compressional stress regimes generate salt pillows and arrays of ridges (e.g. southern North Sea [3]), as well as salt-cored anticlines (potash ores in Clover Hill, New Brunswick), but these almost never develop into buoyant diapirs that independently pierce surrounding rocks. Rather, it can be seen that the surrounding rocks' bedding structures tend to conform more closely to the shape of the salt without piercement. Furthermore, in compressional regimes, rocks are denser and much more competent than in extensional regimes, thus a much larger force would be needed to deform these "beams" of overburden rock to allow true diapirism.

It is useful to examine results of large-strain numerical modeling of diapiric structures using viscoelastic creep of material penetrating into frictional or frictional-ductile rock masses. Figures 7.11 to 7.16 of Barnichon (1998) are interesting, as are other results [4, 5, 6, 7].

2.2. Salt Diapirism as Slow Hydraulic Fracture

The higher lateral stresses in a compressional regime restrict the efficacy of salt buoyancy for the same reason that natural or induced hydraulic fractures change attitude as they rise through the country rock. In other words, salt emplacement can be viewed as slow hydraulic fracture emplacement.

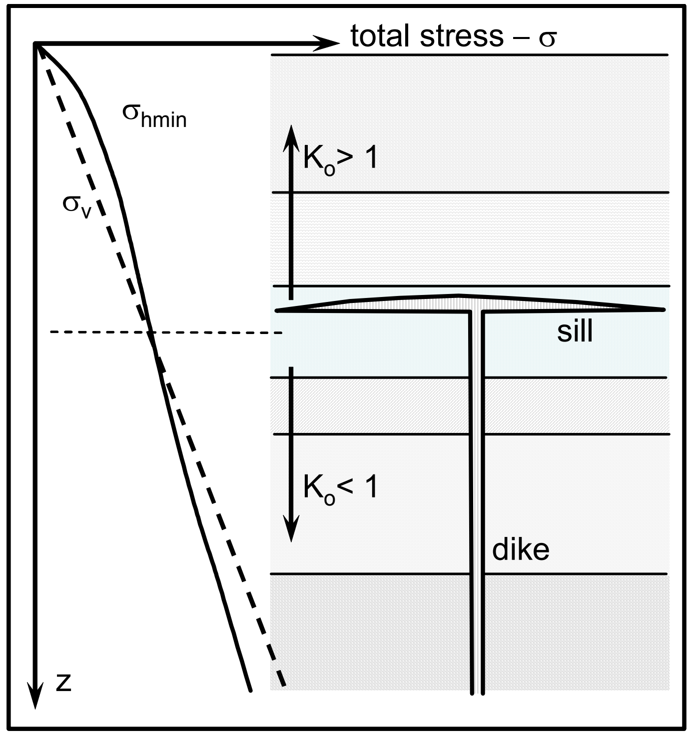

Figure 4: Intrusions as Hydraulic Fractures

Fig. 4 shows typical behavior of a rising low-viscosity (basaltic) dike. When the dike rises to the point where $\sigma_v = \sigma_3$, it becomes energetically easier to lift the overburden, rather than to part it vertically. Because shear stresses are diminished through creep, the stress state in salt approaches hydrostatic conditions ($\sigma_1 = \sigma_2 = \sigma_3$), but the surrounding rocks can sustain a shear stress indefinitely through frictional resistance. Hence, the surrounding rocks almost always behave in a frictional-brittle manner, generating fault structures (excepting soft muds, which also evidence diapirism if pore pressures are elevated so that $\sigma' \sim 0$ and frictional strength is thus minimal [8]).

If diapirism is a slow hydraulic fracture, it is theoretically feasible to have diapir growth even though there is no rock density difference, providing that σ_{hmin} is less than the driving hydrostatic stress in the salt. For example, in an active normal fault regime, the lateral stress gradient is usually 20-30% less than the vertical stress gradient, which is controlled by the rock density. We also note that in conventional hydraulic fracture use in the oil industry, highly viscous fluids and high pressures generate short, fat fractures (e.g. frac-and-pack operations). In the limit, an extremely viscous material such as salt (or viscous felsic magma) does not generate planar structures, but ovoid shapes (a short, fat fracture).

In a low-viscosity fluid, pressure is transmitted over great distances, but in salt, the effect of the pressure from below (i.e. the buoyancy force) likely diminishes with distance because the slow nature of the creep processes means that small amounts of shear stress can be sustained for extended time periods during active diapirism.

In a natural extensional stress field that is horizontally isotropic ($\sigma_{hmin} \approx \sigma_{HMAX} < \sigma_v$), gravitational instabilities generated by density differences should lead to roughly circular dome cross-sections, whereas in strongly anisotropic horizontal stress cases ($\sigma_{hmin} << \sigma_{HMAX}$), salt structures should display some elongation normal to the σ_{hmin} direction. If salt ridge instabilities are being generated, these should be aligned normal to the regional minimum stress. It appears that such effects are common (such as the salt ridge at depth that is the source of the Five Islands domes in southern Louisiana), but of course the high viscosity of the salt tends to keep the ellipticity of structures modest.

If salt can be viewed as a hydraulic fracture, what happens as salt continues to rise through the sediments? In denser sediments in an extensional stress regime such as the on-shore parts of the GoM, mushrooming of the salt dome top, often generating overturned strata beneath the salt lip, takes place. However, at the relatively shallow depths where groundwater dissolution is important and where the distance to the mother salt is great (perhaps with no significant viscous stress connection exists anymore), this effect leads to a limited extent cap.

Consider the generation of salt tongues, farther out in the GoM where the continental slope exists. It is accepted that these tongues are linked to the mother salt by a relatively wide stock (Fig 2), and the formation of salt tongues has been likened to a "salt glacier" effect. If salt emplacement can be viewed as a slow hydraulic fracture, then one can postulate that vertical rise continues until it is easier for the salt to creep and extend horizontally. We suggest that GoM-type listric fault structures are evidence of this behavior. When the listric fault décollement zone (which is under less rock overburden farther out in the GoM) is encountered by a rising diapiric structure, the regional condition $\sigma_v < \sigma_h$ is "sensed" by the salt, and the propagation direction becomes horizontal (Fig 5). This assumes that the listric mechanism is active and strong enough to sustain the stress condition, allowing the salt tongues to propagate laterally, much like viscous lava or diapiric mud spreads laterally as it slowly extrudes at the surface when continuously fed from below. Note that the "roll-over" shape of the listric fault dictates that there must be a principal stress field rotation with depth, and that there must be, around the décollement zone, a region where $\sigma_h > \sigma_v$.

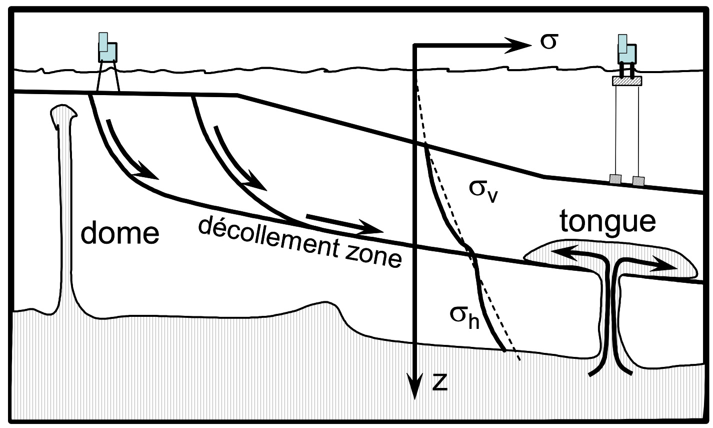

Figure 5: Stress Fields, Salt Structures, Listric Faults

To the writers' knowledge, a detailed synthesis of LOT, FIT and other stress data has not yet been undertaken for the salt tongue region of the GoM. This would help in deconvolving the emplacement mechanism, and proving or disproving the hypothesis on tongue development presented here.

2.3. Diapirism and Regional Stresses

Diapirism driven by gravitational force imbalances arising from density differences can only form in regimes of crustal extension, and these occur in two typical cases:

- In continental margin basins that are "open-to-the sea", so that normal (extensional) faulting occurs, and the lateral stresses are maintained at low values regionally (at the basin scale). Typical cases are found in onshore and shallow offshore sediments in the Gulf of Mexico and offshore Nova Scotia.
- In cases where continental drift forces generate crustal extension, characterized by normal fault

regimes ($\sigma_v = \sigma_1$) and horst-graben structures, or, less commonly, in strike-slip regimes where ($\sigma_v = \sigma_2$). The Central Graben region of the North Sea is a classic example, where the underlying Zechstein salts can be mobilized into domes, leading to oilfields such as Ekofisk and Valhall.

3. STRESSES AROUND SALT DOMES

Stress distributions around salt domes are complex and depend on the mode of emplacement and formation. If large compressional or extensional strains were applied to surrounding rocks, in all likelihood they will have a fabric that reflects that strain (deformation) history through plasticity processes (irreversible deformations, fracturing…).

The mechanics of salt dome emplacement imply that the regional stresses have been altered at the scale of perhaps 10-20 km, whereas the domes have diameters of 1-3 km. For a radial distance of several times the dome diameter in all directions, the stress orientations and relative magnitudes have been affected by the displacements associated with the dome. At greater distances, >4-5 dome diameters, the field stresses apparently revert to the regional values.

Nevertheless, if it is clear that a subsequent tectonic event has overprinted the stress field and the salt structure has been inactive since the overprint, the current stress state may not reflect the relict fault structure. It is important to state that this is a basic caveat in all stress history deconvolution attempts: the most recent large tectonic event may have overprinted the previous stress history, so that the fault and deformation fabric stored in the rocks may be misleading. Nevertheless, in the great majority of cases, it is clear which stress field is currently dominant.

3.1. Stresses and Faults Above Salt Domes

Detailed seismic mapping of overlying strata for several domes in the British Sector of the North Sea (Central Graben region) shows radial and polygonal fault patterns, reflecting the extensional strains that the dome emplacement enforced on the overlying rocks [9]. Although syneresis (general shrinkage) is thought to be important, a uniform extensional strain in all directions will give the same pattern. For example, when clay dries on a flat surface, syneresis polygons develop. However, when a brittle material on a membrane is extended in all directions (isotropic extensional strain), polygons also develop. Above salt dome the evidence is clear that a region of general extensional strain develops, and this can lead to polygonal structures as well as the more common arrays of radial and circumferential normal faulting.

Figure 6 shows radial and arctuate circumferential faulting patterns above a salt dome in the GoM [10]. This pattern of large-scale discontinuities indicates that both the radial and tangential stresses were the least principal stresses at times in the dome emplacement, confirming general extensional stain conditions in the materials above the salt dome.

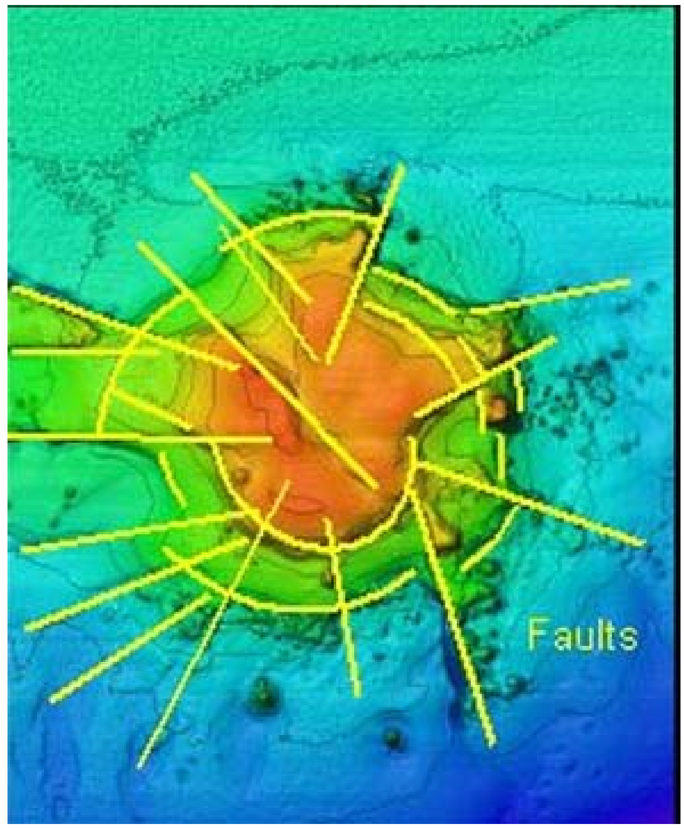

Figure 6: Salt Dome in the GoM with Interpreted faults [4]

Figures 1 & 3 show typical normal faulting structures in cross-sectional view above domes that are classified as piercement structures. Above domes that are deep and have no shallow piercement structure, or gentle pillow structures at depth [11], normal faults are also almost always observed. Even if a dome has not been active for millions of years, the same general extensional regime above the dome can be assumed to apply because of rocks' ability to sustain differential stresses for geological time.

If a dome has been recently active, one may assume that the horizontal stresses in the region above the dome are close to the limiting state of stress. This implies that faults are at or close to the limiting condition for a friction angle of about $\phi' \approx 30°$, a reasonable assumption for the frictional strength of a fault. Also, if the faulting intensity is large and there is no evident seal, it is likely that the pore pressures are hydrostatic, leading to the following conditions:

$p_o \sim \gamma_w \cdot z$ (symbols defined in Symbology section)

$\sigma'_1/\sigma'_3 \sim (1 + \sin\phi')/(1 - \sin\phi') \approx 3.0$ for $\phi = 30°$

These relationships permit an estimation of the stress state. For example, consider a case in 500 m of water, z = 2000 m, with a mean rock density of 21 kN/m^3. The vertical stress is (500·10 + 1500·21) or $\sigma_v \approx 36.5$ MPa, $p_o \approx 20$ MPa, and the lowest possible value of σ'_3 (= σ'_{hmin}) is ⅓(36.5 – 20), or about 6 MPa. Therefore, one may assume that the minimum lateral <u>total</u> stress, σ_{hmin}, which is the fracture pressure p_F, ≈ (20 + 6) ≈ 26 MPa.

However, as has been pointed out in the geological literature, if the two horizontal stresses are far from equal (e.g. $\sigma_{hmin} = \sigma_3$, $\sigma_{HMAX} = \sigma_1$), salt domes tend to form elongated structures and the overlying fault structure is accordingly distorted anisotropically.

3.2. Stress and Faults on Dome Flanks

Below the top of the salt structure, against the flanks of the dome, the strains associated with the emplacement of the salt have been dominated by radial compression. It is likely that the principal stress direction is horizontal and oriented radially ($\sigma_1 = \sigma_{HMAX} = \sigma_r$). Because an outward expansion against the country rock also has the effect of extensional circumferential strain, the minor stress in this region is horizontal and oriented circumferentially ($\sigma_3 = \sigma_{hmin} = \sigma_\theta$), and the intermediate stress is vertical ($\sigma_v = \sigma_3$). Generally, σ_{HMAX} is radial for some distance out from the dome, so that the trace of the major principal stresses radiates radially from the dome centre but is increasingly influenced by the regional stresses, so that at some distance the initial stress fields dominate.

In the geological literature, radial dike swarms around igneous intrusions such as Spanish Peaks in the Raton Basin, South Colorado, the Sweetgrass Hills near the Alberta border in Montana, and others, testify to the lowering of σ_θ because of the strains imposed by the rising igneous stock. We surmise that the outward strain in salt dome emplacement, or in salt pillow development, lead to stress conditions approximately similar.

Figure 7 is an attempt to demonstrate the overprinting of a regional linear stress field with a smaller-scale radial stress field.

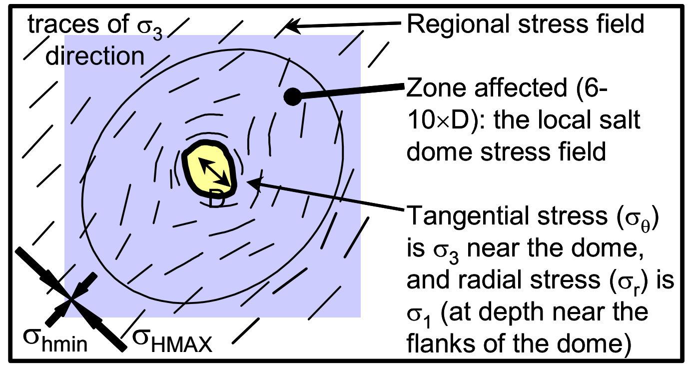

Figure 7: Stress Field Perturbation by Salt Diapirism

Attempts to see this pattern in stress data from the Gulf of Mexico and the North Sea are of course severely restricted by the paucity of published data of a sufficient density to allow direct inferences [12]. The data compilation by Zerwer [13] hint at such effects, but the interpretation of a pattern such as in Figure 7 remains conjectural, if logical.

Similar stress calculations for the limiting possible stress state in the region around the salt stock can be attempted, but there remains substantial uncertainty. Assuming z = 4000 m and $\gamma_m \sim 24$ kN/m^3, $\sigma_v = \sigma_2 \sim 96$ MPa is calculated. Assume that pore pressure is $p_o \sim 55$ MPa (moderately overpressured), and that the rock is at the limiting condition for strike-slip faulting with a $\phi' = 30°$. This gives an indeterminate condition for solving the equation $\sigma'_1/\sigma'_3 = \sigma'_{HMAX}/\sigma'_{hmin} \sim 3.0$, as there are no explicit constraints on either of them. However, σ'_{hmin} can be no less than ⅓($\sigma_v - p_o$), giving a lower bound value for $\sigma_{hmin} = 55 + 0.33(96 - 55) \approx 69$ MPa. (In this case, σ_{HMAX} is essentially the same value as σ_v.)

If there are LOT data available, the calculation of possible limits can be constrained. For example, if $p_F = 75$ MPa (= σ_{hmin}), then the maximum value of σ_{HMAX} can be calculated to be 115 MPa.

It is not likely that an effective stress ratio of $\sigma'_1/\sigma'_3 \sim 3.0$ can be sustained indefinitely at depth where rocks are hotter, somewhat ductile and subject to diagenetic processes. This condition would only be possible when the dome stock was actively pushing against the surrounding rocks, and we believe that a value of $\sigma'_1/\sigma'_3]_{max}$ = 2.0 to 2.5 is more reasonable to estimate the stress limits for σ_{HMAX} in these conditions. There is also the effect of the basal salt, which “detaches” the stress fields from the deep underlying rock, and probably allows adjustments and movements of the deeper rocks with less faulting than would otherwise be expected.

Finally, it is worth noting that if a stress field is locally perturbed by outward expansion of a stock, there must be a gradient of stresses toward the farfield, and in extensional basins, a stress field rotation such that the principal stress direction changes from $\sigma_v = \sigma_1$ above to $\sigma_v = \sigma_2$ on the flanks, with a transition in between.

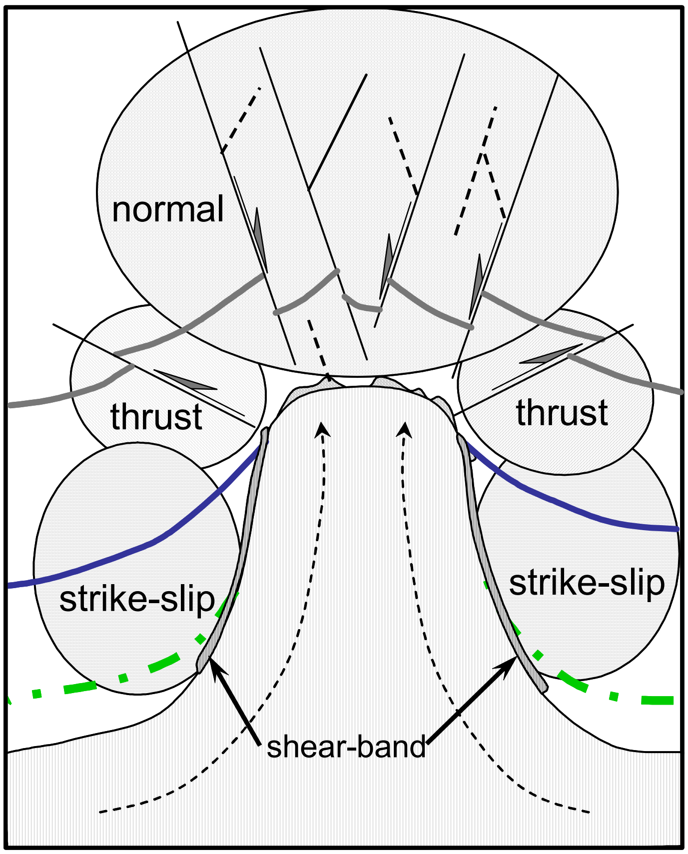

Figure 8: Generalized Stress Regimes around a Dome

Figure 8 is a generalized view of faulting regimes (stress regimes) around a dome that has “pushed” outward in all directions against the surrounding rock. Because of the elastoplastic nature of faulting processes the extent of these stress regimes and the stress contrast magnitudes depend on the magnitude of plastic deformations imposed on the country rock, and it is not simple to determine this value. Particularly at the shoulders and upper flanks of the dome, the relative amounts of plastic deformation, diagenesis (porosity loss), bedding plane slip and sedimentary accretion are difficult to determine.

3.3. Stress Regime on the Shoulders of the Dome

Off the crest of a domal structure, because of the radially outward deformations and the geometry, there is a region where thrust faulting is the predominant stress regime (e.g. [5]).

In this region, stress limit estimates can also be made, but only assuming that σ_v is indeed a principal stress, which may not be the case because of the altered trajectories as the dome rises (Figure 9). This diagram also shows the reason why erosion is deemed necessary for continued diapirism: if the vertical load concentration on the diapir becomes too large, it will suppress vertical extension.

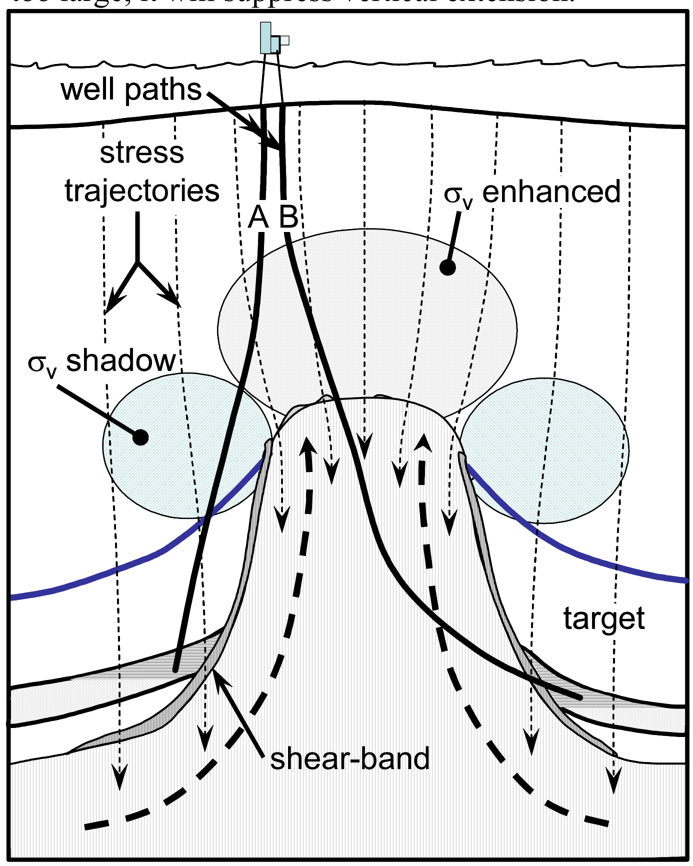

Figure 9: Principal Stress Trajectories around a Dome

In the thrust area, $\sigma_v = \sigma_3$, and σ_r (outward) is σ_1, leaving $\sigma_\theta = \sigma_2$. Assuming p_o = hydrostatic, stress limits in this region can be estimated. Suppose that the salt dome is just onshore, the thrust region is at a depth of 2500 m and γ_m òf the overburden is 2.25;σ_v ~ 55 MPa, p_o ~ 25 MPa, therefore the upper limit for σ_{HMAX} can be calculated to be 115 MPa. However, it is unlikely that such high stresses would be sustained, and in general, the development of clear thrust fault elements around a salt dome or near the advancing front of a salt tongue is rare. Nevertheless, in this region, the stress regime is that associated with thrusting, $\sigma_v = \sigma_3$.

3.4. Stresses and Well Trajectories

Now that the stress regimes have been outlined in general, it is possible to sketch qualitative stress distributions for different well trajectories (A and B in Figure 9).

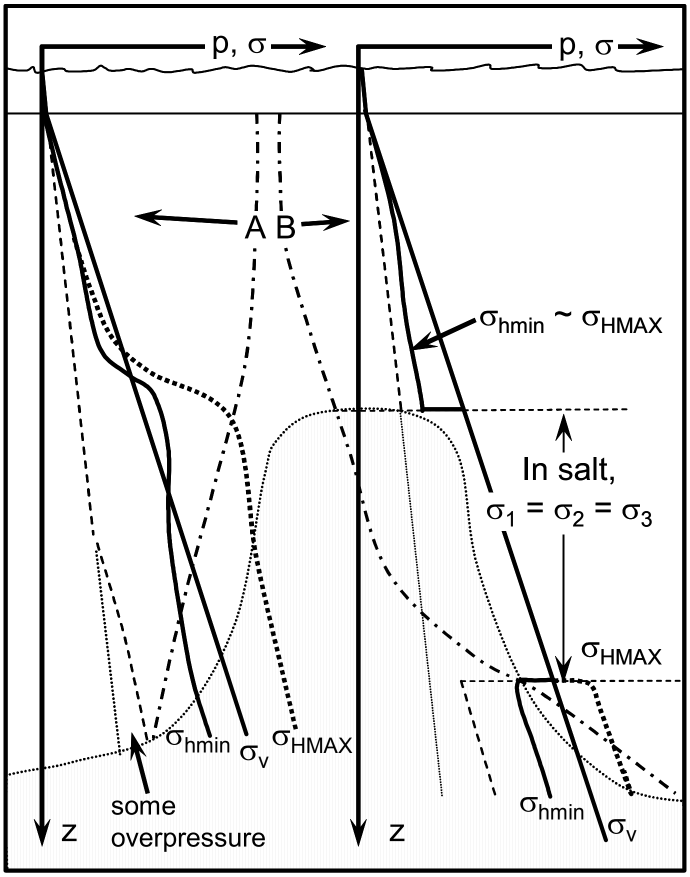

Figure 10: Stress Plots for Different Well Trajectories

Well trajectory A has a lesser risk of lost circulation in the supradome region, but a greater risk of wellbore instability if the thrust stresses are large. Well trajectory B avoids the thrust zones and regions of high stress gradients, but must be drilled through the worst of the lost circulation zone directly above the dome, through a creeping material, and also must exit from salt into country rock with a sudden increase in shear stress. Deciding which path is overall the least risky depends on using available data (logs, LOT…) to quantify these stress plots, rock fabric condition estimates, and previous experience in the region.

4. ROCK CONDITION AND FABRIC

Because of the wide variety of rock types and conditions encountered, because of the large plastic strains and faulting that have been imposed on the surrounding rocks because of dome emplacement, and because of diagenesis, increasing depth, the possible existence of overpressure, and other factors, specifying the geomechanical properties of the non-salt rocks is problematic. Nevertheless, despite difficulties in making valid generalities for such complexity, a few significant general trends can be outlined here, mainly with respect to shales:

- The non-salt rocks around salt domes in the North Sea, below the top of the salt dome and adjacent to the "shoulders" or the dome, tend to be dense but fractured.
- Relatively speaking, the rocks above the salt dome where piercement has not taken place are far less dense, less fractured and less cemented than sediments later from the stock of the dome.
- One may expect more jointing and fracturing in the areas of more intense deformation associated with the piercement of the dome through the overlying strata.
- Proportionately, shale strata are far more common that sandstones and carbonates (>80% of the non-salt rocks encountered), and are also the most problematic for borehole stability.
- In situ, under confining stress, the general strata stiffness is high if computed from seismic data. In terms of static behavior, however, massively deformed rocks around a salt dome may have a wide variety of "static" properties, depending on fabric, stress state, and pore pressure.
- Undeformed or slightly deformed shales in the gentle upwarped anticlinal zone above deeper-seated salt domes tend to be laminated, of low to intermediate stiffness, and susceptible to delamination and sloughing along bedding surfaces, perhaps because of bending slip. They may be overpressured (e.g. Ekofisk), in which case they are of substantially higher porosity and ductility than normally pressured shales.
- The stiffness and strength of all lithotypes except salt increase with depth: deeper rocks are denser (lower porosity), having been compacted more; they are generally better cemented; and, they are under higher confining stress, which gives them both higher stiffness and higher frictional strength (excepting cases of high overpressure, where depth-trends are violated).

Two critically important shale properties are the geochemical sensitivity and the state of rock fracturing. These factors are always to a degree uncertain for most materials encountered during drilling, and around a salt dome they can change substantially over a short distance. Fracture intensity in cores can, at present, only be assessed reliably in cores, which are almost never taken in shale. There appears to be no way of easily assessing fracture density, aperture and conductivity with standard geophysical techniques at present, though multiple spacing quadrupole sonic logs can give some quantitative insight into fracture intensity.

The condition of the strata overlying a salt dome depends to a considerable degree on the competence of the overlying sediments at the time of the dome emplacement. If the sediments were ductile, thick shale sequences can retain their sealing characteristics, even though there are through-going normal faults. On the upturned strata against the dome flanks and also in the supradome sediments, extensive fracturing appears common, even though the fractured shale may occasionally still act as an effective hydrocarbon trap because the fractures are closed by stress.

5. SPECIFIC DRILLING RISKS

5.1. Shallow Well Sections above Domes

Above domes, lateral extension causes low fracture gradients, as low as 13-14 kPa/m in sandstone stringers surrounded by softer shales, which in turn are often geochemically reactive (smectitic), or of high ductility. These conditions lead to increased risk if isolated sandstone bodies charged with gas are encountered. If a sand lens is fault sealed, high pressures arising from deeper gas can be preserved indefinitely (Fig. 11).

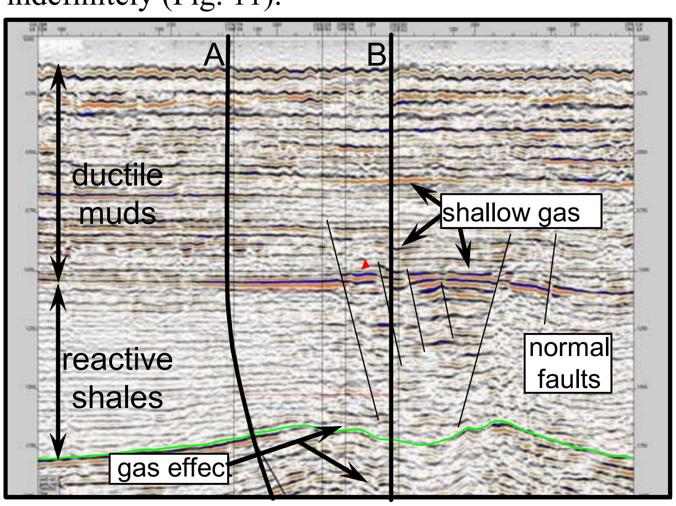

Figure 11: Conditions High above a Diapir: Seismic Section

Above salt domes, "gas clouds" are common because of the extensional strain; low σ_{hmin} leads to upward gas migration through fracturing. Simultaneous blowout and lost circulation conditions can be encountered, as well as the problem of severely gas-cut drilling fluids. In reactive shales drilled with WBM, there is usually a time lag (e.g. several days because of diffusion and thermal processes) before instability starts; this leads to a desire to drill as fast as possible and set casing. In regions above domes with gas clouds, high ROP in fractured shales with gas leads to serious gas-cutting, and it is often impossible to sustain the penetration rates that would otherwise be possible. Hence, risk management in these areas involves optimization of ROP to minimize costs while managing risks arising from mud gassing.

Excessive gas cutting is often dealt with by circulating out the gas-cut mud while penetration is temporarily suspended. This may lead to exacerbation of the problem because of excessive cooling, especially if circulation is rapid and if there is heat exchange through a tall riser. Cooling reduces σ_θ around the wellbore; this allows shale fractures to open. This facilitates communication with more fractures containing gas-charged fluids, so that it becomes difficult to reduce the gas content to a safe value. It may be more suitable to heat the drilling mud, for instance, through heat exchange with hot oil produced in another well. This strategy of increasing mud T to increase σ_θ is used in some parts of the southern North Sea above domal structures.

Because lost circulation risks are high and cuttings volumes large in shallow drilling in the supradome region, companies use WBM (water-base mud) because of cost. In regions away from salt domes, and in smaller diameter drill holes, OBM would be favored to cope with the ductile reactive shales.

Also, setting large diameter casing too shallow in an attempt to cope with such issues removes an important security casing needed for deeper drilling, therefore there is an incentive for the casing shoe to be located as deep as possible.

Fig. 11 also demonstrates a simple yet effective risk-reduction approach in exploration around domes: trajectory A avoids the worst of the gas cloud that would be encountered in trajectory B. Furthermore, well path A avoids the normal faulting region, meaning that the value of p_F is likely to be higher, and a longer open hole section can be sustained before setting casing string. A clear view of the expected fabric and stresses can directly affect the siting of production platform facilities to take advantage of the more favorable stress and gas conditions away from the crest of the structure.

5.2. Deeper Well Sections above Domes

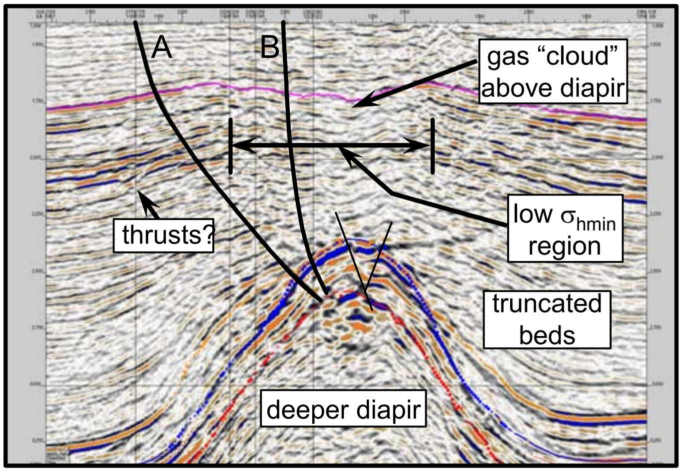

Fig 12: Drilling Trajectories Near Salt Domes

Similar strategies to reduce risk in the deeper parts of dome region drill holes can be envisioned. Fig 12 (continuation of Fig 11) shows well A approaching the targets from the side, rather than directly through the gas cloud and the region of low σ_{hmin}. In general, a deviated trajectory can result in the saving of one casing or liner in such cases, with reduced risk of gas cutting problems. The decision must be based on the cost of the additional time spent drilling versus the potential cost of an "event", with carries the risk of a sidetrack or setting a casing shoe too shallow.

In the case of deeper drilling, the chances of encountering overpressures increases, and if the upper shoe is in a region of low σ_h, an extra liner section has to be installed.

5.3. Traversing Shallow Depleted Zones

Because salt structures can have vertical extents of several thousands of metres, in many cases shallow depleted zones must be traversed before accessing reserves at depth along the deeper flanks of the salt structure. Again, lost circulation and blowouts present risks, and because deeper targets are being accessed from existing surface assets (platforms), there are practical limits to well trajectories.

Risk management in these cases means reducing the number of casing strings required to traverse the depleted zone. Avoidance through use of an in-salt trajectory is advised where possible ("B" in Fig 10), as this means that the high stress contrast regions on the shoulders do not have to be penetrated, reducing on average the need for one casing string.

Drilling through a depleted zone with WBM with a high content of lost circulation material (LCM) is a technique to avoid an extra casing (or expanded liner). As the low σ_h zone is penetrated, fractures open and are packed with LCM, generating a wide aperture, which increases σ_θ for a zone around the borehole, creating a "stressed skin" (Fig 13). To reduce risk, use of a WBM, maintaining low ECD, and proper LCM content and type design are vital.

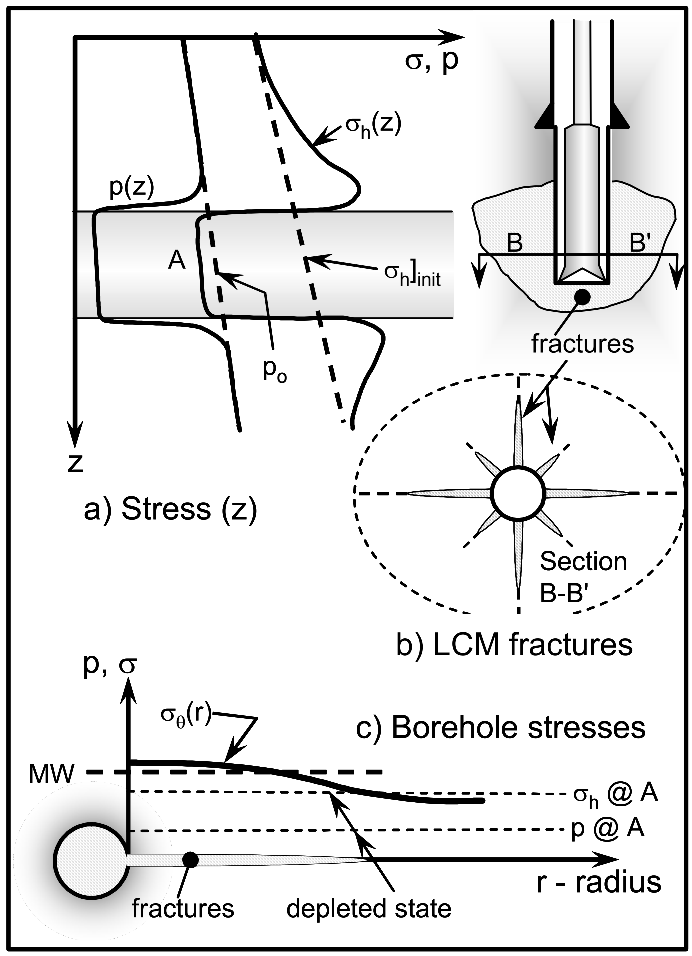

Figure 13: LCM can help Develop Higher σ_θ Values

5.4. Risk Management and Effects of Temperature, LCM

LOT values are presented in Fig 14 for trajectories off the crest of a dome (A in Figs 11 - 12). The solid line for overburden gradient (σ_v/z) was calculated by integration of several density logs on off-set wells. This is a case of a deeper-seated diapir that has distorted overlying sediments, but has not caused such intense faulting as to allow pressures to dissipate and return to hydrostatic. The shallow LOT values are relatively low, but do not correspond to a full normal faulting effective stress ratio of 2.5 – 3.0, likely because of ductility (LOT values are measured in shales and shallow shales are ductile, with low friction angles), but also because of gas charging which has kept all stresses more elevated than expected. Once z = 1.7 km is reached, p_F is essentially equal to σ_v. This confirms that the condition $\sigma_v \approx \sigma_3$ has been reached in the zone where thrusting would be expected.

Perhaps the most valuable information is that retesting of LOT values on shallow shoes, after several days of drilling advance, showed that the LOT values had risen appreciably, from SG 1.44 to 1.67 in one case. This arises because of two phenomena:

- Higher in the hole during drilling, heating occurs, increasing σ_θ, and increasing the peak pressure on a LOT (although the post-peak pressure will remain closer to original σ_3).
- Fracture plugging with mud solids, LCM and drill chip fragments also increase σ_θ near the wellbore, increasing the peak LOT pressures.

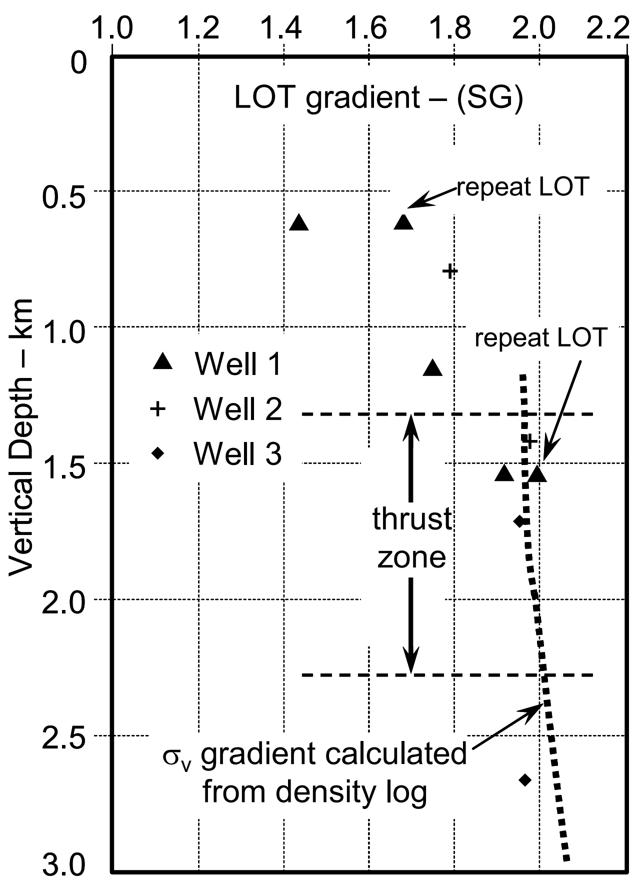

Figure 14: LOT Stresses for the Salt Dome Example

These increases in LOT provide a quantitative tool for helping to manage risk. Because fracturing risk is always near the shoe (except in cases of pressure reversion), it is possible to take advantage of local σ_θ increases at the scale of the wellbore

5.5. *Drilling the Fractured Shale Zones*

Salt dome are surrounded by strata that were distorted by highly differential stress fields, leading to shear and tensile fractures. As shales are more deeply buried, mineral transitions such as smectite → illite + SiO_2 + H_2O generate large shrinkage effects so that massive σ_h loss takes place. Because shale has high cohesion, the failure mode is tensile when $\sigma_h \approx p_o$, and intensely fractured quartz-illite shale is thereby generated.

There are several interrelated mechanisms associated with drilling stiff fractured shale. First, because MW > p_o, fractures open initially. At the bit, there is also a cooling shrinkage effect of up to 25-30°C [14, 15], and this causes loss of σ_θ of as much as 10-30 MPa (depending on stiffness and thermal expansion coefficient). These fractures are most effectively plugged if a carefully designed LCM is maintained in the drilling fluid. Also, mentioned above, one may heat the mud, which tends to close fractures that intersect the borehole, but excessive heating can increase σ_θ until shale sloughing is a serious problem, particularly in stiff shales (high modulus), and fractured quartz-illite shales tend to be stiffer than ductile smectitic shales.

6. OBSERVATIONS AND CONCLUSIONS

Strategies for risk reduction in drilling around salt structures involve assessing a number of risks (borehole instability, sharp stress gradients, gas-cutting of drilling fluids through fractured shale, lost circulation, sudden transition to overpressure…) and addressing these risks with the following tactics:

- Cooling or heating the drilling fluid, each of which may be appropriate in different well trajectories and rock fabric conditions;
- Increasing or decreasing the rate of fluid circulation, which affects ECD, cooling/heating rates and the flushing through of mud gas;
- Maintaining substantial amounts of LCM in drilling fluids, particularly for fractured shale

drilling, depeleted zone traversal, and for coping with a low LOT at the shoe;

- Increasing ROP (e.g. for reactive shales and WBM) or reducing the ROP (e.g. to control gas cutting in large holes in fractured shale); and,
- Adjusting trajectories to avoid dangerous zones by going through the salt or coming at the target from a distance away from the dome structure.

The sediments around a salt dome have been massively disturbed, hence the following risk factors must be quantitatively evaluated:

- Pore pressure and stress state prognoses must be made, based in part on the domal displacement fields and expected stress orientations.
- Distorted and folded shale and other strata have experienced fracturing and bedding plane slip, and thus have low tensile strength, gas charging, etc. Such zones should be mapped with seismic methods, offset well data, MWD, experience… .
- Above the dome crest and shoulders, highly fractured shales are often gas-charged and close to a normal faulting condition. Lost circulation and mud gas-cutting are serious issues.
- In drilling through salt to avoid poor conditions, boreholes exit through a zone of highly sheared sediments that may present stability problems.

7. SYMBOLOGY

p_o in situ pore pressure

ρ density (~1.03 for sea water)

γ_m, γ_w unit weight ($\rho\cdot\mathbf{g}$) of rocks, water, generally mean values

ϕ' effective stress friction angle of rock

σ, σ' stress and effective stress (subscripts 1,2,3 for major, intermediate and minor stresses)

σ_r, σ_θ radial and tangential stresses, with respect to the geometry of a salt intrusion body

σ_v, σ_{hmin}, σ_{HMAX}, vertical, horizontal earth stresses (often assumed to be principal stresses)

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