Influence of poroelastic behavior on the magnitude of minimum horizontal stress, S_h, in overpressured parts of sedimentary basins

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ABSTRACT

In many sedimentary basins of the world the minimum horizontal stress, S_h, is greater in overpressured zones than in normally pressured zones at equivalent depths. A common explanation is that the frictional slip on listric normal faults keeps the difference between vertical stress, S_v, and S_h within certain bounds, and the difference is smaller under lower effective stress (i.e., higher pore pressure, P_p). However, in the overpressured parts of the central North Sea graben, United Kingdom, and the Sable subbasin of the Scotian Shelf, Canada, conventional friction envelopes underestimate the magnitude of S_h. These data instead indicate that S_h increases at a rate proportional to but less than the rate of increase of P_p, a condition consistent with a P_p-induced deformation of the rock called poroelastic behavior. This paper argues that, whereas friction may govern S_h in normally pressured basins, poroelastic behavior is responsible for the unusually high S_h in the overpressured parts of these same basins. Data on the P_p and S_h gradients from these basins suggest that $\Delta S_h/\Delta P_p \sim 0.7$.

INTRODUCTION

Many deep sedimentary basins on continental margins have zones of abnormally high pore pressure starting at depths between several hundred metres and 4 km. In these same basins, petroleum industry data on the magnitudes of both pore pressure, P_p, and the minimum horizontal stress, S_h, are extensive. A common thread in these data is that S_h varies as a function of P_p (e.g., in the Gulf Coast region of the United States, Brunei, the Maracaibo region, Venezuela [Breckels and van Eekelen, 1982], the Scotian Shelf of Canada [Bell, 1990], and in the North Sea [Gaarenstroom et al., 1993]). In all cases, $\Delta S_h < \Delta P_p$.

One explanation for the correlation between S_h and P_p in sedimentary basins is that rock friction acts as a governor, limiting differential stress, $\sigma_d = S_v - S_h$ (Zoback and Healy, 1984). The idea is that in actively subsiding basins dominated by normal faulting, the vertical stress, S_v, increases by sedimentary loading until σ_d becomes large enough to initiate frictional slip on listric normal faults. Slip will act to laterally compress sediments of the basin, thereby increasing S_h and decreasing σ_d. The value of σ_d at which frictional slip occurs is governed by the frictional strength of the faults (i.e., coefficient of friction, μ) through the equation

$$\sigma_d = 2\mu(\sigma_n - P_p), \tag{1}$$

where σ_n is the normal stress across the fault zone and $\sigma_n - P_p$ is the effective normal stress across the fault zone. An increase in P_p causes a decrease in effective normal stress; thus, slip occurs at a smaller σ_d. Equation 1 predicts that S_h is relatively higher in overpressured parts of sedimentary basins.

In many sedimentary basins, the most complete record of S_h comes from leakoff tests, which are used by petroleum engineers to gauge the amount of pressure (i.e., mud weight) an open hole can maintain without causing a hydraulic fracture. Leakoff pressure is measured in a short length of open hole drilled after a string of casing is cemented in the well. If the cement seal is good, leakoff starts when a crack in the open hole allows flow into the surrounding rock. Once flow takes place, pumping is stopped, the well is shut in, and another pressure reading—the instantaneous shut-in pressure or ISIP—is recorded. Data on the ISIP, a measure of the S_h, suggests that leakoff pressure overestimates S_h by <5% (Bell, 1990).

By using leakoff-pressure data from Howard and Fast (1970), Zoback and Healy (1984) pointed out that conventional friction envelopes (i.e., $\mu = 0.6$) provide reasonable lower bounds for S_h in normally pressured parts of the Gulf Coast region of the United States. The same may be said for data on S_h from the central North Sea graben, United Kingdom, and the Sable subbasin of the Scotian Shelf, Canada, where a friction envelope set at $\mu = 0.6$ defines a lower bound for S_h (Figs. 1A, 2A). However, in the central North Sea graben at depths below 3000 m where P_p is higher, a friction of $\mu = 0.6$ underestimates S_h (Fig. 1A). Likewise, below 5000 m in the Sable subbasin of the Scotian Shelf, S_h calculated from a friction of $\mu = 0.6$ does not match the leakoff data (Fig. 2A). For the theory of frictional slip to hold in the deeper, overpressured parts of basins, μ must be considerably less than that found in shallower, normally pressured parts of sedimentary basins. Laboratory data give no indication that μ is reduced in rocks at higher pore pressures (Byerlee, 1967), although the presence of clay may have some effect on friction (Morrow et al., 1992). An alternative explanation for high S_h in overpressured sedimentary basins is found in poroelastic behavior.

POROELASTIC BEHAVIOR

The variation of S_h as a function of P_p is described by the theory of poroelasticity, a theory designed to explain how a lithified, porous medium-like rock deforms when pore space is filled with fluid and pressurized (Biot, 1941; Kümpel, 1991). According to the theory of poroelasticity, a dilation ΔV of the rock with initial volume V is induced by an increase in pore pressure, ΔP_p, according to the equation

$$\frac{\Delta V}{V} = \alpha\beta\Delta P_p, \tag{2}$$

where ΔV is controlled by the Biot coefficient of effective stress, α, and the compressibility of the rock, β (Detournay et al., 1989). Assuming that volume strain is zero where the compressibility β is $(1/V)(\Delta V/\Delta P_c)$, equation 2 may be rewritten as

$$\Delta P_c = \alpha\Delta P_p, \tag{3}$$

where P_c is the confining pressure (Segall, 1992). For $\alpha < 1$, a change in P_p causes a smaller change in P_c. An exact equation may

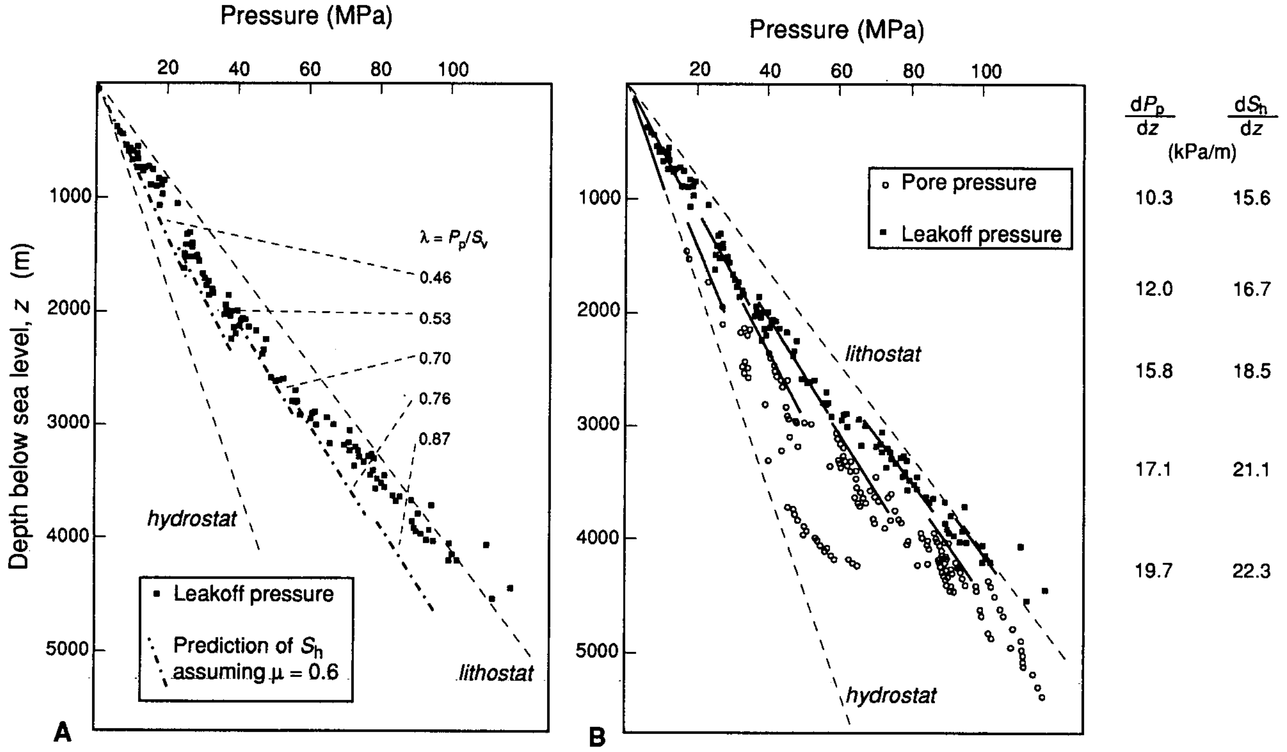

Figure 1. A: Compilation of leakoff-pressure data from throughout central North Sea graben plotted as function of depth. Data are from Marnock, Skna, Erskine, Puffin, Franklin, and Heron fields of central graben. Friction envelopes are shown for μ = 0.6 and pore pressures at λ = 0.46 (hydrostatic), 0.53, 0.70, 0.76, and 0.87. B: Compilation of pore-pressure and same leakoff-pressure data from throughout central North Sea graben plotted as function of depth. Straight lines are hand-fit to pore- and leakoff-pressure data to estimate the gradients of each throughout five depth intervals within central North Sea graben. Data taken from Gaarenstroom et al. (1993).

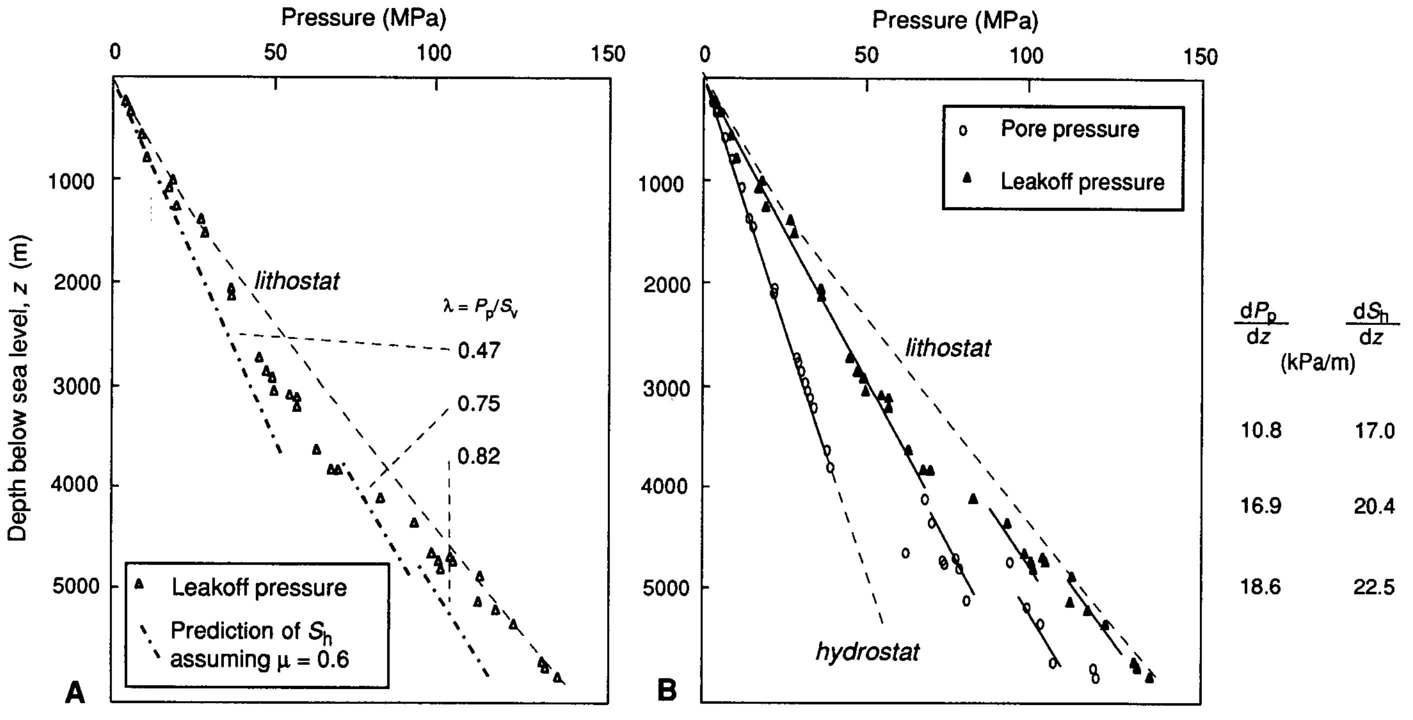

Figure 2. A: Compilation of leakoff-pressure data from 11 wells in Sable subbasin of Scotian Shelf, Canada, plotted as function of depth. Friction envelopes are shown for μ = 0.6 and pore pressures at λ = 0.47 (hydrostatic), 0.75, and 0.82. B: Compilation of pore-pressure and same leakoff-pressure data from Sable subbasin of Scotian Shelf, Canada, plotted as function of depth. Straight lines are hand-fit to pore- and leakoff-pressure data to estimate the gradients of each throughout three depth intervals on Scotian Shelf. Data taken from Bell (1990).

be derived for $\Delta S_h/\Delta P_p$ by using the equation for total horizontal stress under uniaxial strain conditions:

$$S_h = \frac{\nu}{1-\nu}S_v + \alpha\frac{1-2\nu}{1-\nu}P_p, \tag{4}$$

where ν is the drained Poisson ratio. Rewriting equation 4, we find that

$$\frac{\Delta S_h}{\Delta P_p} = \alpha\frac{1-2\nu}{1-\nu}. \tag{5}$$

EFFECT OF A P_P DRAWDOWN

Poroelastic behavior is most easily demonstrated in the pressure drawdown records from oil and gas fields. An interesting set of drawdown data comes from the McAllen Ranch field in south Texas, where S_h was measured in the same stratigraphic horizons before and after drawdown (Fig. 3). Six data points taken at depths between 3.2 and 3.8 km indicate that $\Delta S_h/\Delta P_p$ varies between 0.37 and 0.62. More recent drawdown data from the Ekofisk field in the North Sea indicate that in some situations $\Delta S_h/\Delta P_p$ is as high as 0.8 (Teufel et al., 1991). The point here is that because of poroelastic behavior, a P_p drawdown causes a decrease in S_h and an increase in σ_d without the action of friction or the addition of overburden.

The effect of a P_p drawdown is also evident in a Devonian section of the Appalachian basin. A plot of S_h vs. depth, z, shows a steplike decrease in S_h at the base of the Rhinestreet Formation (Fig. 4). This steplike decrease in S_h is interpreted as a poroelastic relaxation during the bleeding off of abnormally high P_p once found below the Rhinestreet (Evans et al., 1989b). At the heart of this interpretation is the assumption that at the time the Appalachian basin was overpressured, S_h was higher than it is today. Evidence for an ancient, abnormally high pore pressure within the Appalachian basin comes from joint-surface morphology that is consistent with natural hydraulic fracturing (Lacazette and Engelder, 1992), compactional strain comparable to the strain in overpressured basins (Oertel et al., 1989), and fluid-inclusion data (Srivastava and Engelder, 1991).

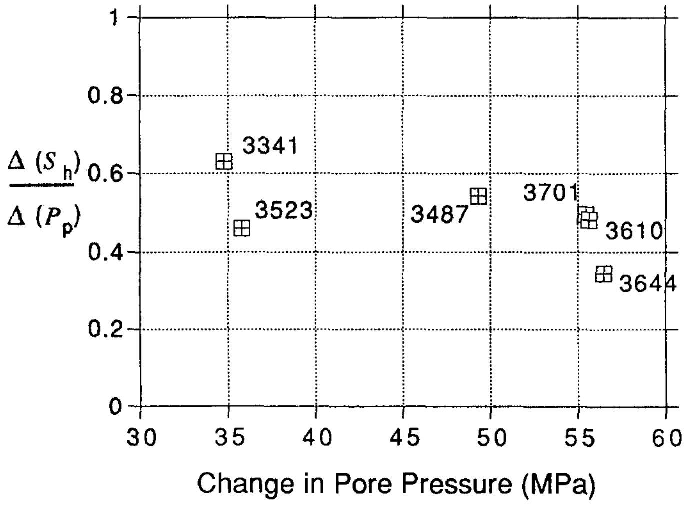

Figure 3. Plot of $\Delta S_h/\Delta P_p$ vs. ΔP_p in McAllen Ranch field, south Texas. Depth of each datum is indicated in metres. Data taken from Salz (1977).

EFFECT OF AN INCREASE IN P_P

The correlation between increases in P_p and S_h is apparent in pore-pressure and leakoff-pressure data from the central North Sea graben, United Kingdom, and the Sable subbasin of the Scotian Shelf, Canada. The central North Sea graben is normally pressured to depths of 2000 m or more depending on location (Fig. 1B). Below 4000 m in pre-Cretaceous reservoirs, P_p may exceed 90% of S_v (Gaarenstroom et al., 1993). The Scotian Shelf is normally pressured down to 4000 m, below which, in the Upper Jurassic section, P_p may exceed 80% of S_v (Fig. 2B) (Bell, 1990). Leakoff pressures, as a proxy for S_h, increase with P_p and approach the lithostat in both the North Sea and the Scotian Shelf of Canada. As pointed out above, frictional slip does not readily explain the relatively high leakoff pressures.

Unlike the P_p drawdown data from the McAllen Ranch and the Ekofisk field where S_h and P_p before and after drawdown are known, Figures 1 and 2 give no direct indication of the effect of pressurization. These figures, however, can be used to estimate $\Delta S_h/\Delta P_p$ assuming that the normally pressured section gives an accurate indication of S_h and P_p that might have been present in the overpressured sections prior to pressurization. In Figures 1B and 2B, we estimate the pore-pressure and leakoff-pressure gradients for various depths in both the North Sea and the Scotian Shelf. These gradients are determined by hand fitting a line to the data. For the pore-pressure data, the hand-fit line was placed at the upper bound. Because the leakoff data overestimate S_h by a few percent, we placed the hand-fit line through the middle rather than at the upper bound of the leakoff data. Pore- and leakoff-pressure gradients are plotted to calculate $\Delta S_h/\Delta P_p$ for the two basins (Fig. 5). $\Delta S_h/\Delta P_p \sim 0.7$ for both basins, a slightly lower number than that derived by using Teufel et al.'s (1991) data from the Ekofisk field.

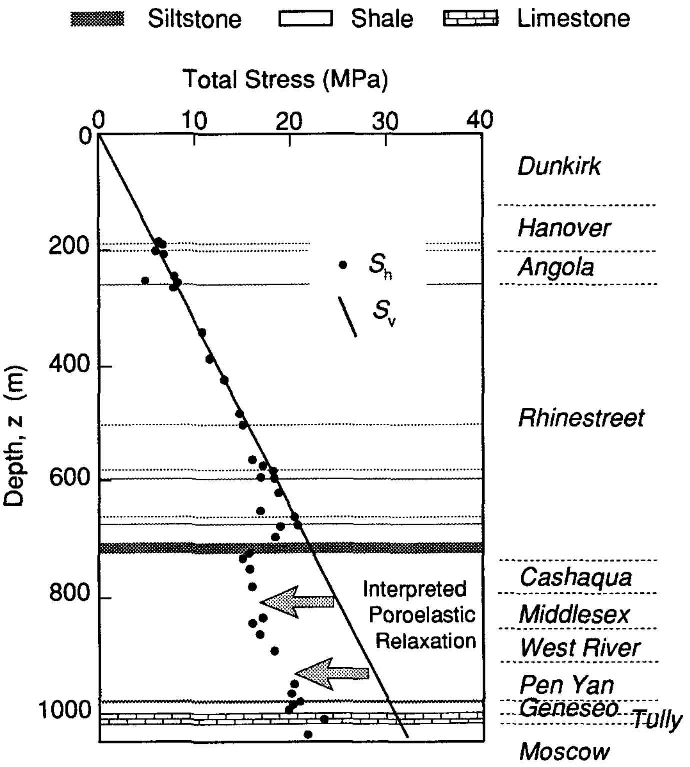

Figure 4. Plot of minimum horizontal, S_h, and vertical, S_v, stress in Wilkins well, South Canisteo, New York. Upper Devonian stratigraphic section of Appalachian basin is listed. Data taken from Evans et al. (1989a).

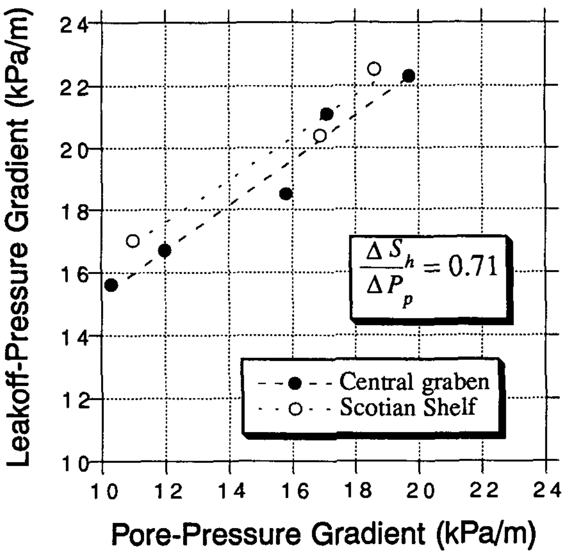

Figure 5. Plot of pore-pressure gradient and leakoff-pressure gradient for central North Sea graben, United Kingdom, and Sable subbasin of Scotian Shelf, Canada.

DISCUSSION

Although poroelastic behavior is another explanation for the magnitude of S_h in overpressured parts of sedimentary basins, friction still plays a role as a governor for S_h. This is suggested by the coincidence between the friction envelope and S_h in normally pressured parts of basins. Perhaps it is fair to suggest that friction sets the background level of stress at shallow depths and during periods of active listric normal faulting. Any increase in S_h due to poroelastic behavior starts from a friction-controlled value of S_h in the normally pressured part of the basin.

Although a poroelastic response makes physical sense for short time scales during which uniaxial-strain behavior applies, how can a poroelastic response apply over millions of years during which changes in vertical stress and horizontal strain are both likely? The answer is found in considering one mechanism by which abnormal pressures are generated: the conversion of kerogen to hydrocarbon. This is a dynamic mechanism for abnormal pressure that keeps pace with leakage through seals. Such pressures are maintained on a short-term basis without regard to the previous strain history or change in overburden load and thus qualify to drive a geologically short term poroelastic response.

CONCLUSIONS

The friction envelope defining the lower bound of S_h in sedimentary basins underestimates S_h within overpressured parts of the central North Sea graben, United Kingdom, and the Sable subbasin of the Scotian Shelf, Canada. This result triggered a search for another mechanism controlling S_h in the presence of abnormally high fluid pressure. Herein we have proposed that poroelastic behavior provides a more self-consistent explanation for the depth variation of S_h in the overpressured parts of these same basins.

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