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Résumé de l'article

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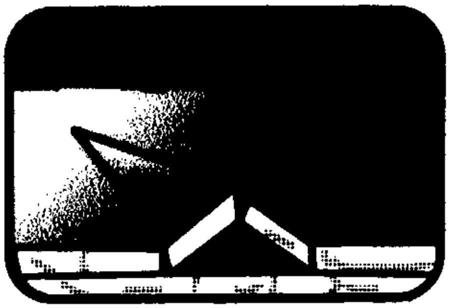

Petro Geoscience 2. *IN SITU* STRESSES IN SEDIMENTARY ROCKS (PART 2): APPLICATIONS OF STRESS MEASUREMENTS

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SUMMARY

This paper addresses the applications of *in situ* stress measurements in sedimentary rocks, with emphasis on Canadian case histories. Combined with other data, the measurements allow stress regimes in sedimentary basins to be characterized as attached or detached to underlying rocks. With information on stress orientations and relative magnitudes, hydraulic fracture propagation azimuths can be predicted, as can preferred flow directions in hydrocarbon reservoirs. If enough data are available to diagnose anomalous stress orientations in a basin, a number of significant geomechanical inferences can be made. Stress orientations, together with magnitudes, help assess the likelihood of serious borehole wall collapse during drilling, whereas stress magnitudes alone will help determine in which rock units hydraulic fractures will advance. Fluid production rates appear to be inversely related to stress magnitudes in coalbed methane deposits and it is likely that a similar situation exists with respect to conventional oil and gas reservoirs. Overpressuring mechanisms are particularly sensitive to stress magnitudes and *vice versa*, depending on the tectonic setting. Induced earthquakes may be triggered by changes in effective stress, a function of stress magnitude and fluid pressure.

Today's stress regimes give us a window into the recent geological past, and possibly the future, in that they are manifestations of the ongoing structural evolution of the earth's surface. Horizontal stress orientations appear to reflect both the present motions of tectonic plates and their overall geometry: in short, today's geotectonics. However, at least in sedimentary rocks, stress orientation measurements give minimal indications of remnant (past) stresses inherited from former regimes. Although stress magnitudes seem to be controlled largely by today's lithostatic loads and by contemporary tectonic compression, they also appear to involve components of remnant stresses derived from former loads (such as ice sheets), crustal rebound and a region's thermal history.

SOMMAIRE

Ce rapport addresse les applications des mesures des contraintes in-situ dans des sédiments, accentuant les exemples Canadiens. En combination avec d' autres données, les mesures permettent de charactériser les regimes de contraintes dans les bassin sédimentaires comme attachés ou détachés. Avec l'information des orientations et des grandeurs relatives des contraintes, on peut prédire les azimuths de propagation des fractures hydrauliques, de même les directions préférées d'écoulement dans les reservoirs d'hydrocarbures. Si on dispose de données suffisantes pour déterminer les orientations anormales des contraintes dans un bassin, alors il y a quelques inférences significatives à réaliser. Les orientations des contraintes, en concert avec les grandeurs, aident à estimer les possibilités pour le gauchissement sérieux des murs des puits de forage, puisque c'est seulement les grandeurs qui déterminent les formations dans lesquelles des fractures hydrauliques avanceront. La rapidité de production des fluides des dépôts de gaz d'huille semble être inversement reliée aux grandeurs des contraintes. Il est probable qu'une situation pareille existe dans les reservoirs conventionels de pétrole et de gaz. Les mécanismes de surpression sont particulièrement sensitifs aux grandeurs des contraintes et vice versa, dépendant de l'environment tectonique. Les tremblements de terres induits sont provoqués par des changements en contraintes effectives et par variations en pressions fluides.

Les régimes actuels de contrainte nous offrent une vision du passé géologique récent, et peut-être de l'avenir, parce qu'ils sont des manifestations de l'évolution structurale contemporaine de la surface de la Terre. Il est évident que les orientations des contraintes horizontales reflètent les mouvements actuels de plaques tectoniques et même leur géometrie, en bref, les géotectoniques d'aujourd'hui. Toutefois, au moins dans les roches sédimentaires, les mesures d'orientation des contraintes offre des indications minimales des contraintes rémanentes des régimes préexistents. D'autre part, quoique les grandeurs des contraintes paraissent être controllées largement par les charges lithostatiques actuelles et les pressions tectoniques contemporaines, ils semblent impliquer les contraintes passées et dérivées des charges préexistentes (glaces sur la terre), des retours élastiques de la croûte et de l'histoire thermale d'une région.

INTRODUCTION

In situ stress measurements are rarely of significant use on their own. When considered in the context of their geological setting, however, they can provide highly beneficial insights. Prior to the 1994 Winter Olympic Games in Lillehammer, Norway, investigations were undertaken to determine whether it would be feasible to excavate an underground ice hockey arena. The minimum required span was 60 m and the length 100 m. At the proposed site the thickness of gneiss cover varied between 40 m and 100 m. The first prerequisite was that the virgin near-surface horizontal stresses should be high enough to hold up the roof. Overcoring measurements showed that they were of the order of 4-5 Mega pascals (MPa). In combination with rock property tests, geological mapping and numerical modelling, these stress measurements showed that the proposed rink was feasible (Myrvang, 1993) and it was built. Obviously, economics played a role, as did the lack of large historical earthquakes in the area.

APPLICATIONS OF STRESS MEASUREMENTS IN SEDIMENTARY BASINS

Geomechanical Characterization of Basins

The most comprehensive application of stress measurements is to obtain enough of them to be able to characterize a basin in terms of its overall geomechanics, including the relationship between the sedimentary section and the underlying rocks (Bell, 1993).

Attached stress regimes are found in sediments that rest directly on another tectono-stratigraphic unit or on basement without any intervening intervals of low strength rocks that would give rise to mechanical detachment.Stress orientations in attached regimes exhibit the signature of the underlying rocks and, usually, the orientations are predictable over a wide region. Detached stress regimes occur in rocks that are separated from underlying units or basement by zones of geomechanical weakness across which anisotropic stress cannot propagate. Widespread intervals of halite that has flowed, or of overpressured shales, will detach the overlying rocks from basement, or from underlying rocks that are mechanically attached to basement. Weak subhorizontal faults also provide surfaces of detachment (Fig. 1). Detached stress regimes are likely to exhibit more randomly oriented horizontal stress orientations than attached regimes, although this is not always the case.

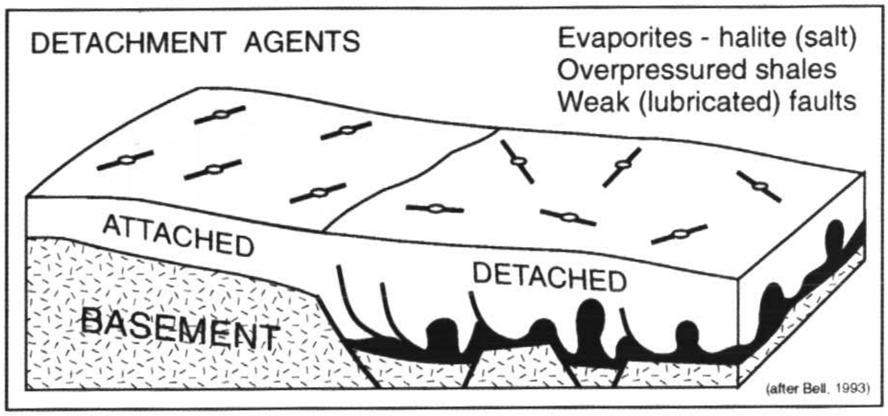

Figure 1 *Schematic diagram of stress regimes that are attached to basement (on left) and detached from basement (on right). Geomechanical detachment can be caused by evaporite layers or overpressured shales (shown in black) and weak sub-horizontal faults (Bell, 1993). Horizontal stress orientations (indicated by the thin bow tie symbols) tend to exhibit more azimuthal variation within detached regimes.*

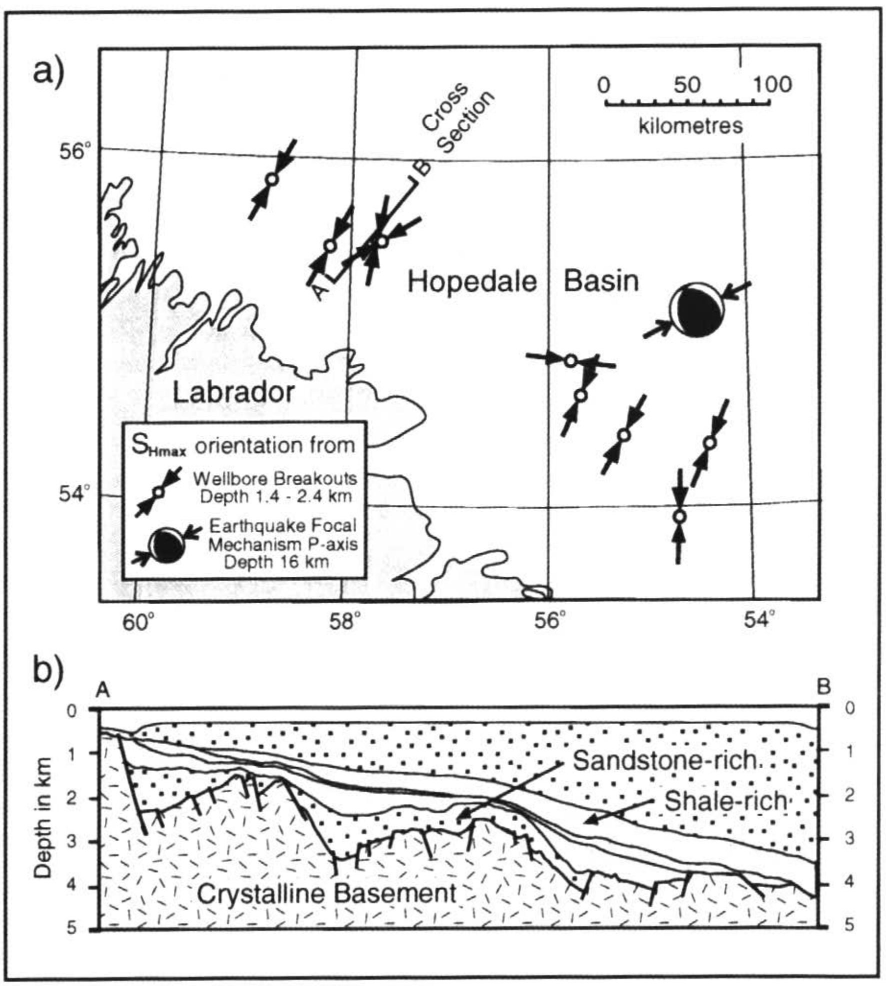

Figure 2 **(a)** *Map of the southern part of the Labrador Shelf, offshore eastern Canada, where* S_{Hmax} *orientations derived from breakouts within Mesozoic and Cenozoic sediments are compatible with the P axis calculated for an earthquake within basement, suggesting an attached stress regime for the sediments.* **(b)** *The cross section confirms that there are no potential detachment surfaces between the cover and basement in this part of the Labrador Shelf (after Bell, 1989a).*

Attached Stress Regimes

The southern Labrador Shelf provides a good example of an attached stress regime (Fig. 2). Faulted basement is overlain by Mesozoic and Tertiary clastic sequences that contain no evaporites or overpressured intervals. Breakouts in nine wells document a reasonable directional homogeneity of stress orientations with S_{Hmax} oriented NNE-SSW (Bell, (1989a). This is consistent with the 065° P-axis (Fig. 2) determined for a 1971 earthquake with epicentre at 16 km depth in basement (Hashizume, 1977).

The central and eastern portions of the Western Canadian Sedimentary Basin are also interpreted as attached, despite the wide extent of Lower Devonian salt and evaporites (Fig. 3). Breakouts and other stress orientation indicators in numerous wells (Bell *et al.*, 1994) document directional homogeneity of the horizontal stresses on a regional scale (Fig. 3) and similar NW-SE directions have

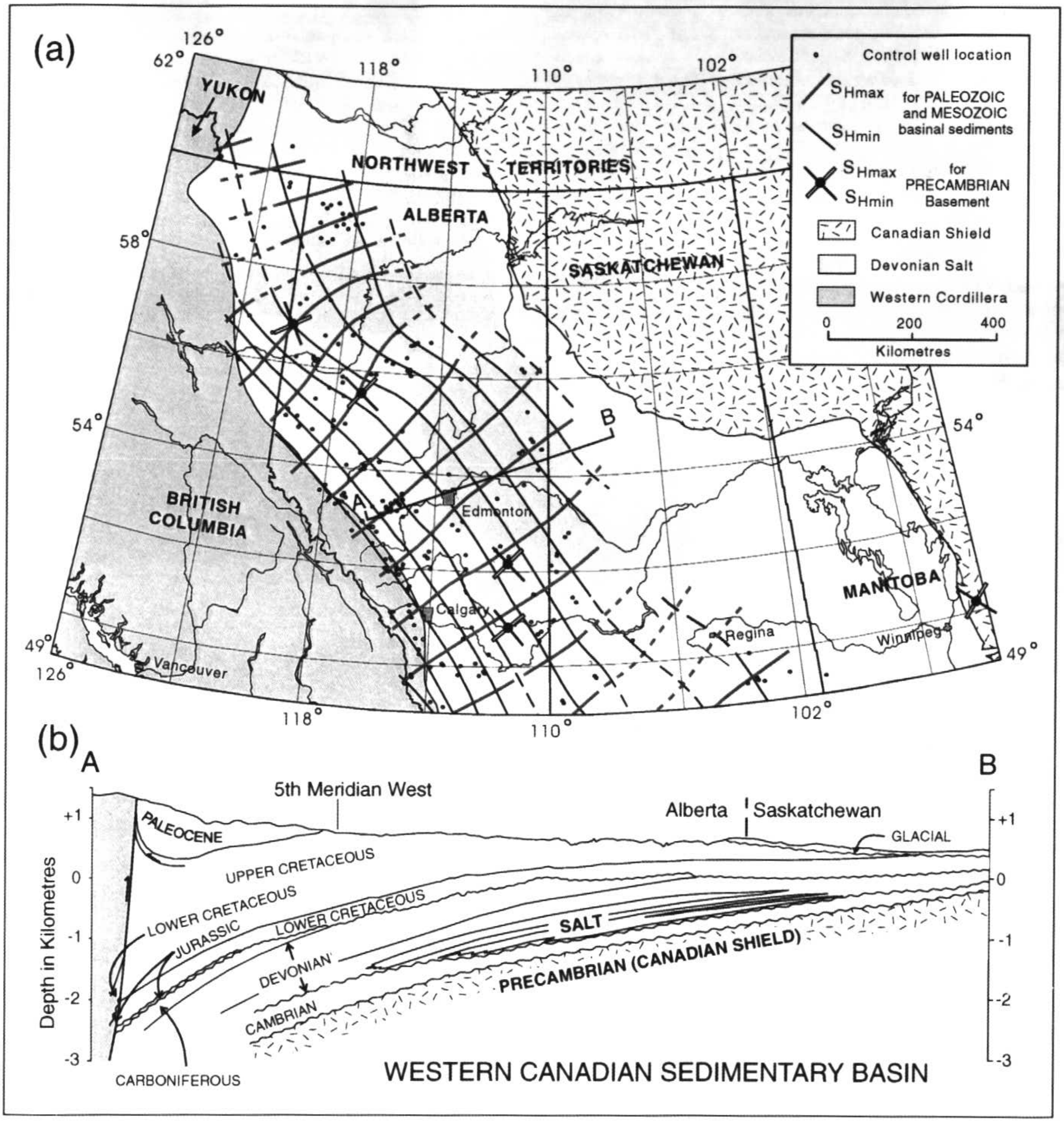

Figure 3 (a) *Stress trajectory map of the Western Canada Sedimentary Basin based largely on mean breakout azimuths from over 200 wells (Bell and McLellan, 1995). Note the similar Precambrian stress axes which imply that the axial and eastern part of basin is attached geomechanically to basement.* **(b)** *Simplified dip cross section through the Western Canada Sedimentary Basin. Note the undeformed Devonian salt; it does not appear to have acted as a detachment horizon.*

been obtained from the underlying crystalline basement and at Pinawa, northeast of Winnipeg (Fig. 3), on the western outcrop edge of the Canadian Shield (Herget, 1993). There are no indications of detachment within the salt-rich intervals. Exactly why this is so is not fully understood, but at least part of the reason is likely to be because the salt has never been involved in diapiric flow (Fig. 3), which would promote geomechanical detachment (Jackson and Vendeville, 1994). A similar but less well documented situation appears to exist in the Hudson Bay Basin (Bell and Wu, submitted).

Detached Stress Regimes

Figure 3 emphasizes the directional consistency of horizontal stresses in the Western Canadian Sedimentary Basin but, as Bell and Babcock (1986, Fig. 4) showed, there is less orientational consistency in the Rocky Mountain foothills. At the time that study was undertaken, the aim was to identify major populations of breakouts based on their orientations and little attention was paid to their structural setting. Recent work (Fig. 4) has shown that stress orientations can vary between thrust plates, implying that these form surfaces of detachment. Complex multi-level detachment on thrust faults is likely to be present along the western flank of the basin, as has been documented in the Jura Mountains of Switzerland (Becker *et al.*, 1987).

A more spectacular case of detachment appears to exist on the Scotian Shelf (Yassir and Bell, 1994). Mean breakout azimuths from 54 wells document rather regular horizontal stress trajectories in the Cenozoic and Mesozoic sequences, with S_{Hmax} oriented NE-SW (Fig. 5a). Since this coincides with the regional stress directions for the North American Plate (Zoback and Zoback, 1991), it is tempting to infer that the stress regime reflects basement stresses and that the Mesozoic and Cenozoic sequences are attached. This is probably true for the Lahave Platform, but does not appear to be likely downdip of the faulted hinge zone (Fig. 5a). Downdip of the hinge zone, two intervals of potential detachment are present: the Argo Salt, and overpressured shales of the Verrill Canyon and equivalent formations (Figs 5, 6). The Argo Salt has been involved in considerable diapirism; it is widespread and is buried to 15 kilometres depth or more. At these depths, it must be at temperatures in excess of 400° C according to well measurements (Reiter and Jessop, 1985) and subject to pressures (vertical stresses) of the order of 400 MPa (Fig. 6b). Under such conditions, halite would be virtually ductile and incapable of transmitting anisotropic stress (Yassir and Bell, 1994), so it is assumed that it serves to detach overlying sediments from the rocks below the

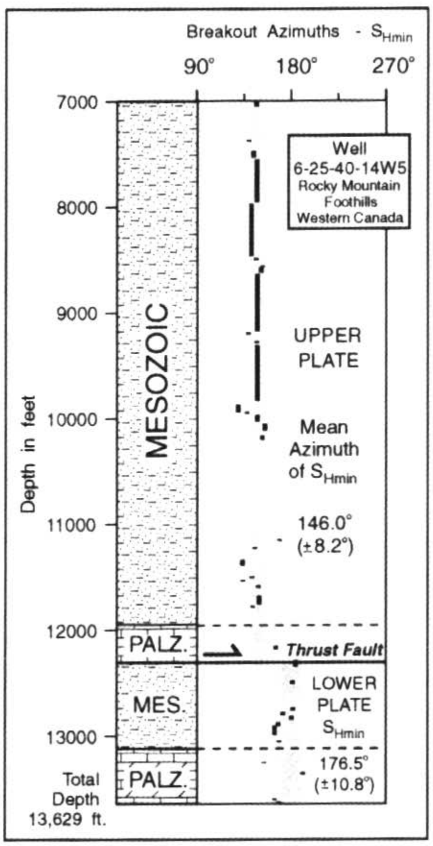

Figure 4 *Breakout orientations measured between 7000 and 13, 624 ft in the Amerada Shunda 6-25-40-14W5 well that was drilled in the overthrust foothills along the western margin of the Western Canadian Sedimentary Basin. Note that stress orientations change across the thrust fault at 12,298 ft, suggesting that this is a local surface of geomechanical detachment.*

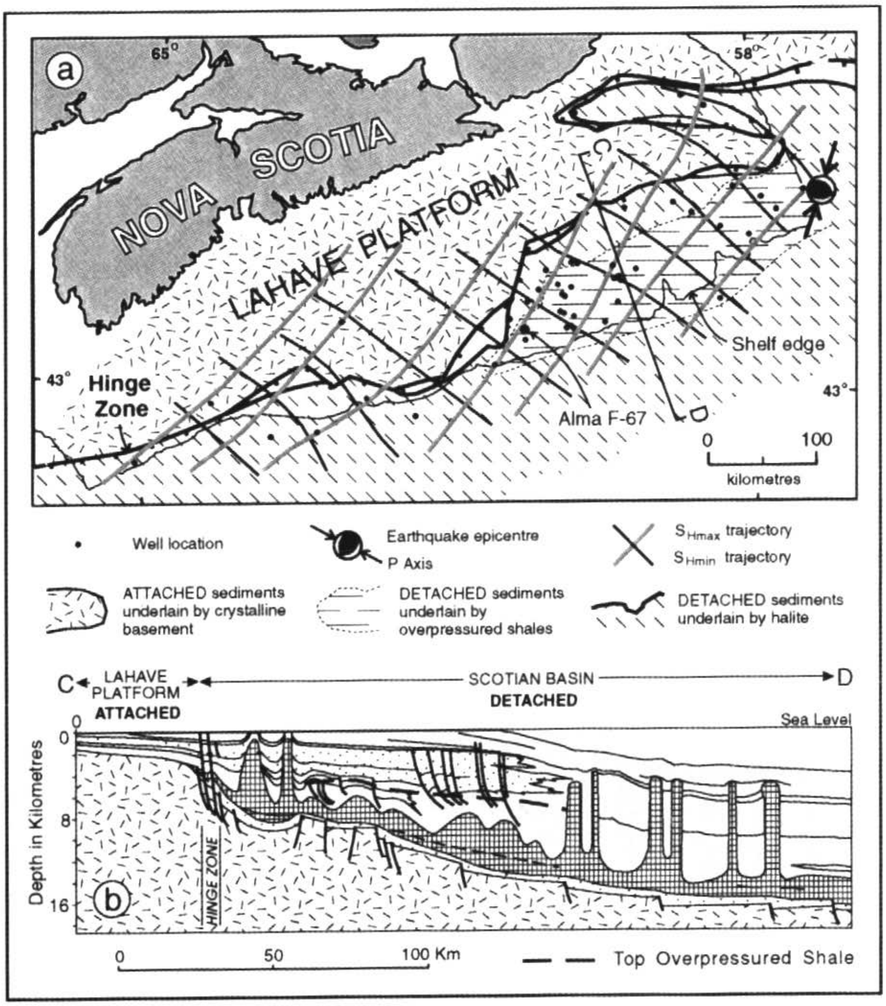

Figure 5 **(a)** *Stress trajectories derived from breakouts in 54 wells on the Scotian Shelf, offshore eastern Canada (Bell, 1990). The map delineates the inferred attached and detached stress provinces.* **(b)** *Cross section though the Scotian Basin showing the postulated attached stress regime above the Lahave Platform and the inferred detached sediments downdip of the Hinge Zone.*

salt. A second, more local, detachment is believed to occur within overpressured shales. Overpressures are encountered at depths ranging from approximately 2712 m to 5184 m (Wade, 1991) and the upper surface of overpressuring dips to the southeast. Pseudo-effective stress profiles (plots of leak-off pressure minus pore pressure *versus* depth) show that the overpressured shales are extremely weak (Fig. 6a). The mean downdip slope of the overpressures closely parallels breakout directions, suggesting that the stress regime of the overlying rocks represents their response to attempts to slide southeastwards. In other words, the horizontal component of the stress regime is an expression of the potential energy of the system.

The Jeanne d'Arc Basin on the Grand Banks of Newfoundland exhibits the same type of geomechanical profile with overpressured shales and diapiric salt overlying faulted basement. Stress orientations are anything but consistent (Fig. 7). Their apparent randomness may be due in part to fault deflections, as discussed below, but geomechanical detachment within overpressured shales or within salt is believed to be the main cause. Similar variability in horizontal stress orientation from well to well is observed in the offshore part of the Beaufort Basin (Courel and Bell, 1996). Detachment within overpressured shales is suspected in the Beaufort Basin, although the variable horizontal stress orientations may, in part, be a consequence of there being only small differences in the magnitudes of S_{Hmax} and S_{Hmin}.

Mapping Stress Orientations in Basins

Mapping horizontal stresses in a basin is a worthwhile endeavour. Ideally, the exercise will show how the stress trajectories vary across the basin and establish what are the regional, or expected, stress orientations in a particular area and, most importantly, what are the anomalous directions. Reliable horizontal stress orientation maps have been constructed for the Western Canadian Basin (Fig. 3), drawing largely on breakout analyses from more than 200 wells. In this basin, the mean breakout orientations are generally consistent between different stratigraphic levels in a single well and between adjacent wells (Fordjor *et al.*, 1983). There is no mappable distinction between the stress orientations obtained from Precambrian, Paleozoic or Mesozoic rocks, for example (Bell *et al.*, 1994; Bell, 1995). Moreover, the horizontal stress orientations implied by the breakouts are fully compatible with information from other indicators, so it is justifiable to combine directional stress information from all levels onto one map. Horizontal stress is used here in an approximate sense because breakouts can show that an inclined well is being subjected to lateral anisotropic stress, but they cannot sense if the principal stresses are aligned precisely perpendicular to the wellbore. In fact, we suspect that many "horizontal stresses" in the Rocky Mountain Foothills are slightly inclined, since there are indications from drilling-induced fractures that one of the principal stresses is not exactly vertical, but is affected by bed attitude and, possibly, topography (McCallum and Bell, 1995).

Despite these provisos, the map is a useful document. Some of its applications will be discussed in the following paragraphs. The fact that it can be constructed with such directional homogeneity from so many breakouts means that horizontal stress anisotropy is well de-

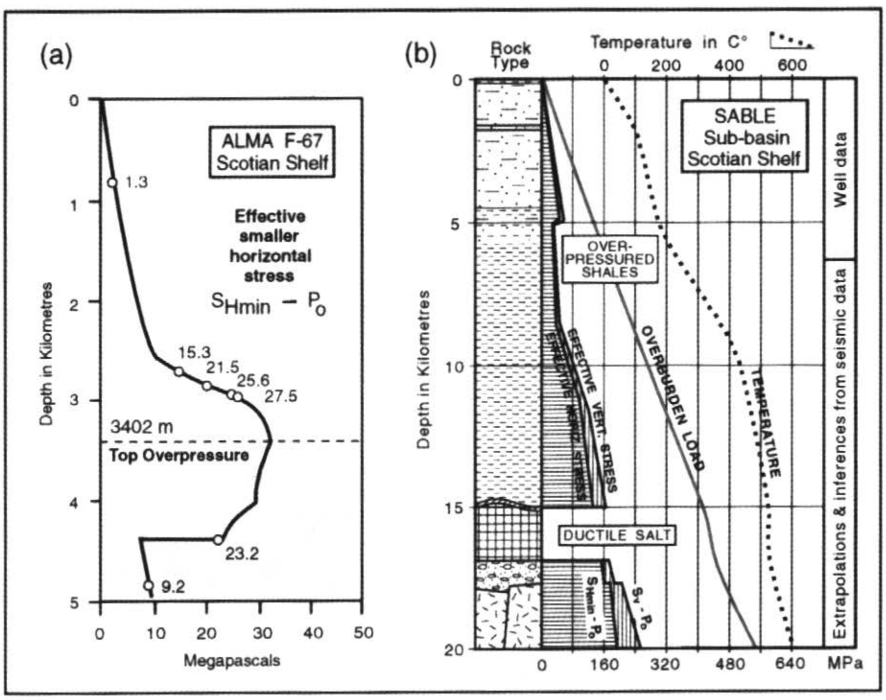

Figure 6 **(a)** *Effective stress profile at Alma F-67 (location shown in Fig 5a). Note the significant decrease in effective smaller horizontal stress within the overpressured zone. Gas has migrated into a shallow reservoir at Alma F-67, suggesting that pore pressures periodically rise high enough to "open" faults to fluids generated at depth. The value of 9.2 Mpa for the effective stress at 4873 m depth is a maximum estimate. The true figure is likely to be lower (Bell, 1989b).* **(b)** *A geomechanical profile for the central part of the Scotian Basin illustrating the two potential surfaces of detachment within overpressured shales and deeply buried halite (after Yassir and Bell, 1994).*

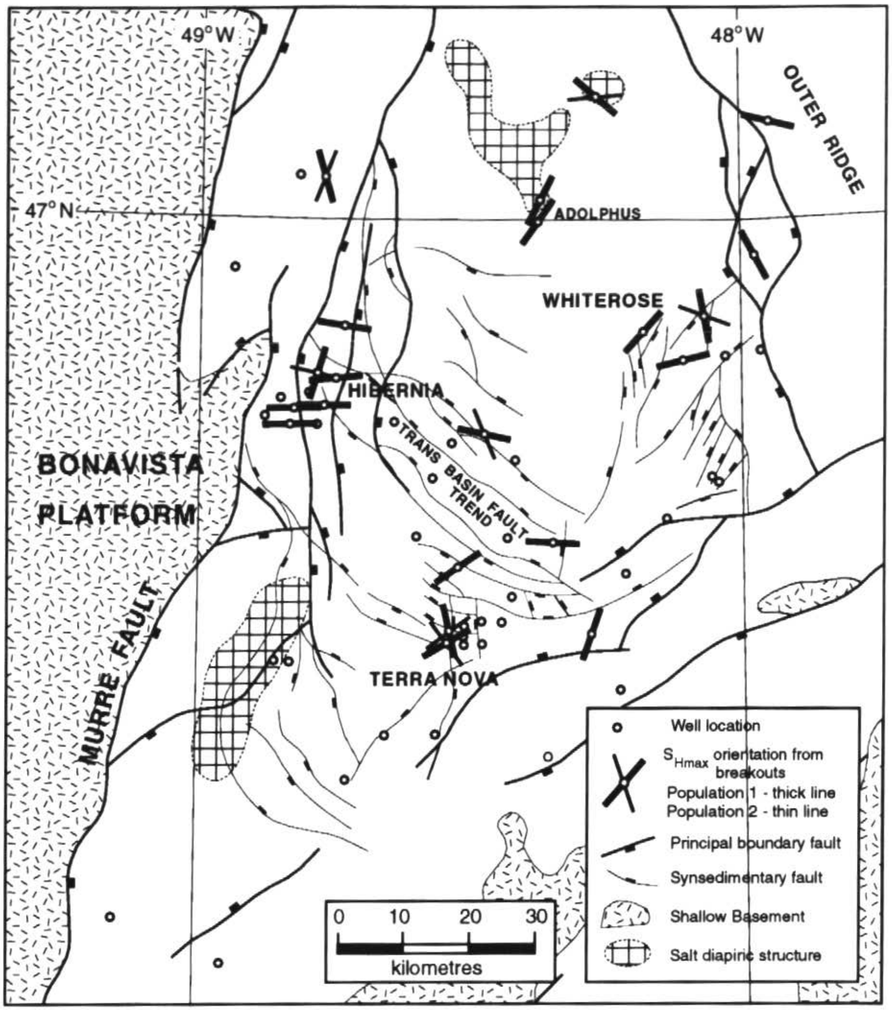

Figure 7 *A preliminary interpretation of horizontal stress orientations in the Jeanne d'Arc Basin of offshore Newfoundland. Most of the breakouts are oriented at high angles to the regional trend (NW-SE) and suggest local horizontal stress deflections related to the elastic properties of fault zones or to geomechanical detachment above overpressured shales and/or halite.*

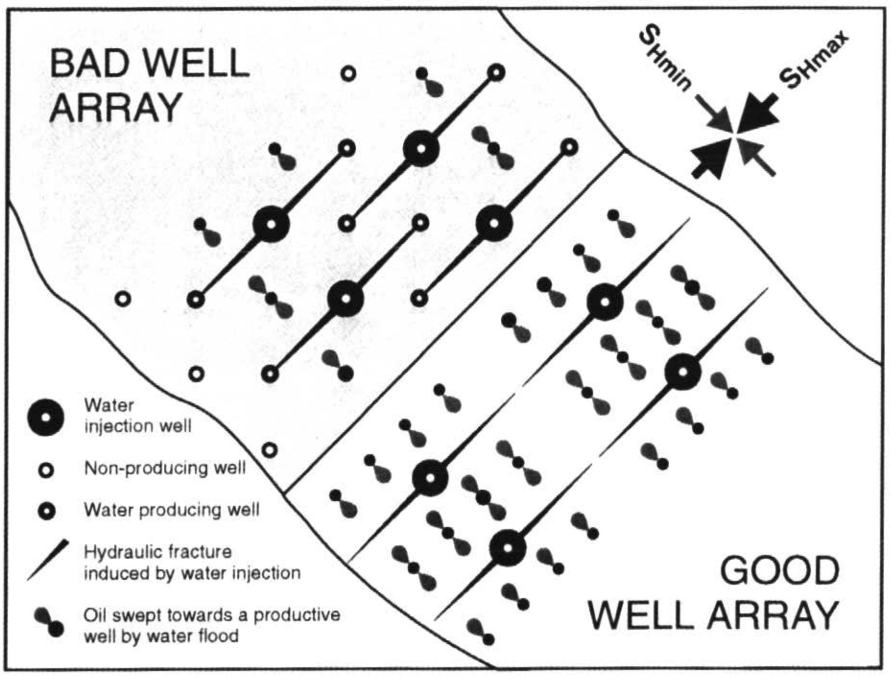

Figure 8 *Production well configurations in an idealized oil field where waterflooding promotes hydraulic fracturing. In the "bad" array, little oil is recovered because induced fractures connect water injection wells with intended production wells. In the "good" array, the induced fractures do not interconnect and distribute the injected water so that it drives oil towards numerous production wells (after Bell and Babcock, 1986).*

veloped. Overcoring measurements and hydraulic fracture calculations point to a maximum S_{Hmax}:S_{Hmin} ratio of around 1.5:1.0 in the western part of the basin (Kaiser *et al.*, 1982; Kry and Gronseth, 1983).

Hydraulic Fracture Propagation

Hydraulic fractures will propagate in the plane of the two largest principal stresses and perpendicular to the smallest principal stress (see Bell, 1996). Except at shallow depths (< 400m) on the eastern flank of the Western Canadian Basin, stress magnitude measurements demonstrate that the two largest stresses are S_{Hmax} and S_V. Hence, most hydraulic fractures that are induced in western Canadian wells will be vertical and will propagate parallel to the S_{Hmax} trajectories (Fig. 3). This has a bearing on the placement of vertical wells in secondary recovery projects (Fig. 8) and means that horizontal wells that are to be multiply fractured should have NW or SE trajectories to obtain perpendicular fractures (Fig. 9).

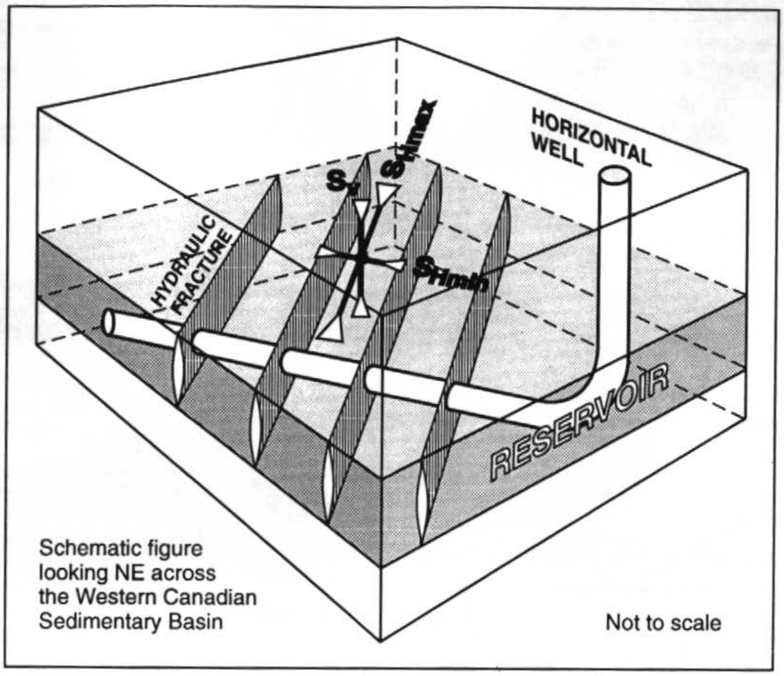

Figure 9 *Hydraulic fractures aligned parallel to* S_{Hmax} *induced from a horizontal well drilled parallel to* S_{Hmin} *(NW-SE in western Canada). This is the optimum trajectory for a well designed for multiple fracturing.*

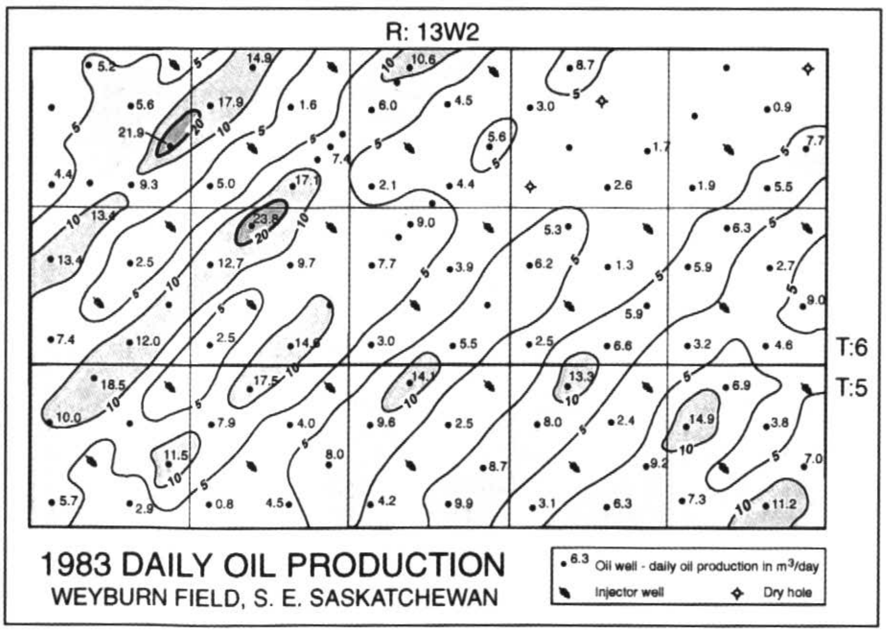

Figure 10 *Daily production rates at Weyburn (Wegelin, 1987) that may reflect stress-induced flow anisotropy in the reservoir.*

Principal Stress Orientations and Flow Anisotropy in Reservoirs

Comparative studies from hydrocarbon reservoirs around the world have shown that preferred flow directions are approximately aligned with S_{Hmax} (Heffer and Lean, 1991) or, in simple terms, fluids flow most easily through rocks at right angles to the direction of least compression. Surprisingly, preferred flow directions appear to be largely independent of depositional fabrics or of fracture geometry. This is an enormously significant finding since it affects the optimum locations for hydrocarbon production wells, as well as affecting how hydraulic head information should be contoured.

By implication, most reservoirs in the Western Canadian Basin are likely to exhibit a preference for NE-SW aligned fluid flow, parallel to S_{Hmax} (Fig. 3). At this time there is not much documentation of such behaviour, although several ongoing studies suggest it. Possible examples of the phenomenon occur in the Weyburn and Midale Fields in Saskatchewan, where oil is produced from the Mississippian Midale Formation and S_{Hmax} is oriented NE-SW (Bell *et al.*, 1994). At Weyburn, daily production rates indicate a pronounced NE-SW flow preference (Fig. 10), which Wegelin (1987) tentatively attributed to opening of NE-SW aligned fractures. Such fractures were identified in cores, but the majority were closed (A. Wegelin, pers. comm., 1987). However, in the adjacent Midale Field, numerous fractures occur in cores, and NE-SW flow anisotropy there is firmly documented by waterflood breakthrough and pressure tests (Beliveau, 1989), so it appears likely that the production behaviour at Weyburn is also largely controlled by open fractures. The stress regime may be the critical control for maintaining open fracture networks in both fields. Relative relaxation of uncemented fractures oriented at high angles to S_{Hmin} (NW-SE) would favour preferred fluid flow along a NE-SW axis.

Stress control over flow anisotropy has major implications for oil and gas field development. At the simplest level it implies that lateral flow into production wells will not be radial, but will be elliptical. The consequences for well placement are cartooned in Figure 11. It should be possible to drain a field with fewer wells, if they are located so as to respect flow anisotropy, rather than being sited on a NS-EW grid, as has been the historical practice in western Canada and many other producing basins. Happily, modern directional drilling techniques make it possible to take advantage of anisotropic flow to improve recovery from reservoirs that were originally drained by geographically-gridded wells. In undeveloped fields, such as Hibernia and Terra Nova, offshore of Newfoundland, where much of the development drilling will be directional, there are excellent opportunities to exploit stress-controlled flow anisotropy.

Anomalous Horizontal Stress Orientations and their Implications

The directional homogeneity of horizontal stress trajectories in western Canada and, for that matter, on the Scotian Shelf (Bell, 1990) and parts of the Grand Banks (Adams and Bell, 1991) is impressive, yet in all these basins there are local anomalous stress orientations. In western Canada, there is a 10-20° counterclockwise rotation of horizontal stresses in northern Alberta over the Peace River Arch basement high (Fig. 3). In the offshore basins of the Scotian Shelf and Grand Banks of Newfoundland, breakouts indicate that, locally, horizontal stresses are reoriented by as much as 90° (Bell, 1989b; Adams and Bell, 1991). Similar effects have been observed in the North Sea (Teufel and Farrell, 1990; Yale *et al.*, 1994) and around the San Andreas Fault (Mount and Suppe, 1987).

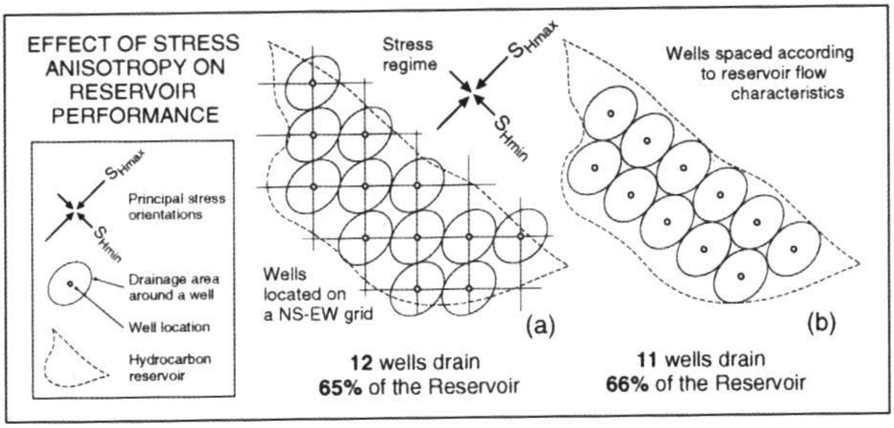

Figure 11 *Schematic representation of how stress-controlled flow anisotropy can affect hydrocarbon recovery from a reservoir that is being produced from vertical wells. In this simplified example, the axis of preferred fluid flow is aligned with* S_{Hmax} *(oriented NE-SW), so that the area drained by each well approximates a horizontal ellipse with the long axis oriented NE-SW. The flow preference means that well array* **(b)** *will be more productive and cheaper than well array* **(a)**.

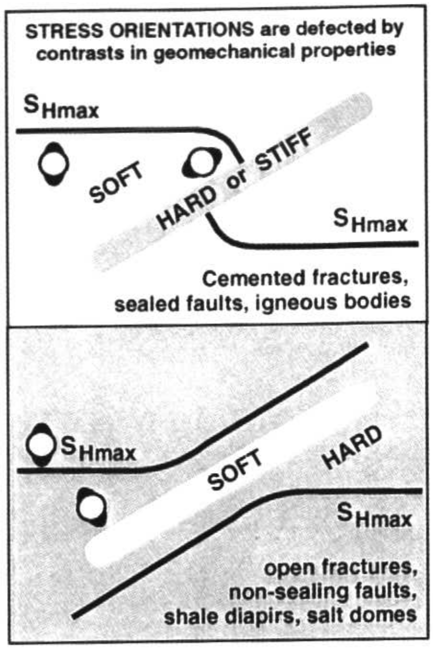

Figure 12 *Schematic plan view diagram showing how stress orientations can be bent by contrasts in geomechanical properties. Breakout axes are shown for vertical wells.*

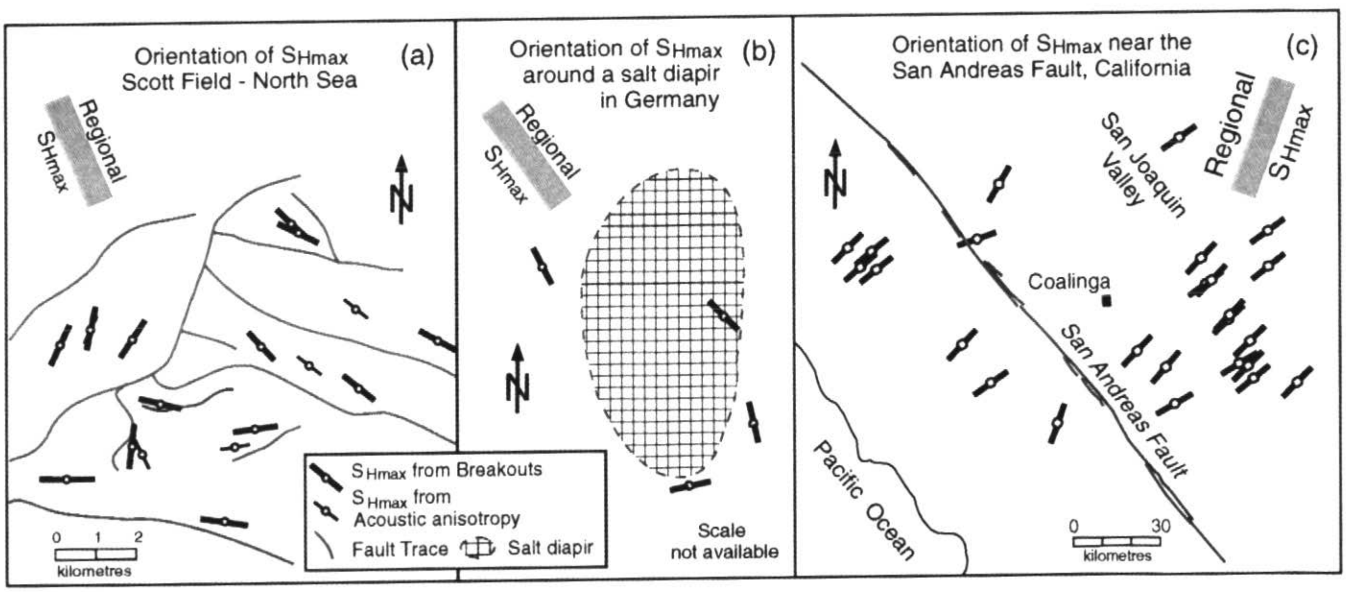

Figure 13 *Examples of stress orientations modified by elastic properties of rock units.* **(a)** S_{Hmax} *is deflected so as to parallel faults in the Scott Field, North Sea (Yale* et al., *1994), suggesting that the fault zones are "soft" relative to the surrounding rocks,* **(b)** *Close to the southern margin of a salt diapir in Germany,* S_{Hmax} *is deflected so as to parallel the edge of the "softer" salt body (Schneider, 1985),* **(c)** *As regional stress trajectories approach the San Andreas Fault,* S_{Hmax} *trajectories are deflected so that they are approximately perpendicular to the fault trace (Mount and Suppe, 1987; Zoback and Zoback, 1991).*

It is accepted that these anomalous orientations are the consequence of structure and/or of lateral variations in the elastic properties of rocks.

Principal stresses intersect free surfaces at right angles so if a geological structure, or part of one, acts as a free surface it will deflect a principal stress unless that stress happens to be oriented exactly perpendicular to the surface. How much horizontal principal stresses are deflected depends on the nature of the interface and the geomechanical property contrast (Zhang *et al.*, 1994). If stress trajectories "encounter" a zone that is relatively "harder" or stiffer than the surrounding rocks, they will be deflected so that S_{Hmax} intersects the interface at right angles (Figs. 12, 13). On the other hand, if the zone is relatively "softer," stresses will be deflected so that S_{Hmax} parallels the interface (Figs. 12, 13). It is not clear how far stress deflection effects can extend from property contrast interfaces. The degree of contrast is clearly a factor, as modelling indicates (*e.g.*, Bell and Lloyd, 1989). Breakout orientations (Fig. 13) imply that measurable effects around faults can extend at least 1 km (Yale *et al.*, 1994) and possibly to greater distances (Mount and Suppe, 1987; Zoback and Zoback, 1991). It is not clear whether a wide zone adjacent to the San Andreas Fault zone is rotating regional stresses because it is geomechanically "harder," or whether the breakouts are simply defining a separate stress province related to Pacific oceanic crust subduction. Most of the breakouts were identified in wells more than 5 km distant from the fault trace (Fig. 13c), so it would be unwise to use their mean azimuths to infer that the San Andreas Fault Zone is "harder" than the surrounding rocks.

If enough orientation data are available to define the regional stress orientations in a specific area, and anomalous directions are observed, they can be used to identify zones of open fractures and/or non-sealing faults (Bell *et al.*, 1992). This type of application should only be attempted in well-studied basins.

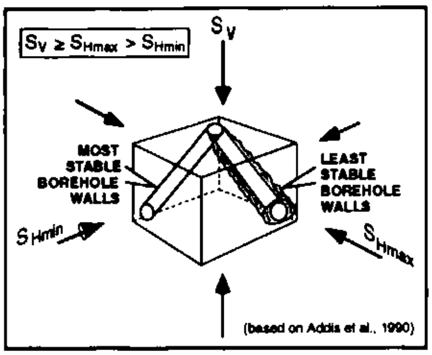

Figure 14 *Schematic diagram showing how borehole instability (wall caving) increases when a well is drilled parallel to the plane containing the largest difference in principal stress magnitudes. This situation is similar to what was encountered while developing the Panuke oil field, offshore eastern Canada.*

Assessing the Likelihood of Borehole Instability While Drilling

Weak sediments that are subject to high anisotropic stress are liable to be mechanically unstable around wellbores and to spall excessively (McLellan, 1994). In effect, the breakout mechanism operates when stress magnitude anisotropy perpendicular to the wellbore is high (Bell, 1996), hence the amount of spalling can be mitigated by orienting a well so that it is subject to a low degree of stress anisotropy in the specific regime in which it is being drilled. Raising the mud weight above pore pressure levels will exert a differential pressure on the borehole wall and thereby limit spalling (Zoback *et al.*, 1985), but care should be taken not to fracture the rock. Furthermore, it is worthwhile to limit the time that a well remains uncased, since borehole wall stability is often time-dependent.

Recent development drilling at the Panuke oil field on the Scotian Shelf provides a good illustration. The production plan called for inclined wells to be drilled approximately in the plane of the vertical principal stress, S_V, and the larger horizontal stress, S_{Hmax}. Since the largest difference in principal stress magnitudes on the Scotian Shelf is probably between S_{Hmin} and S_V (Bell, 1990), these well trajectories determined that the resolved stresses acting normal to the wellbores would be significantly different in magnitude (Fig. 14). Combined with the low strength of the Cenozoic shales,

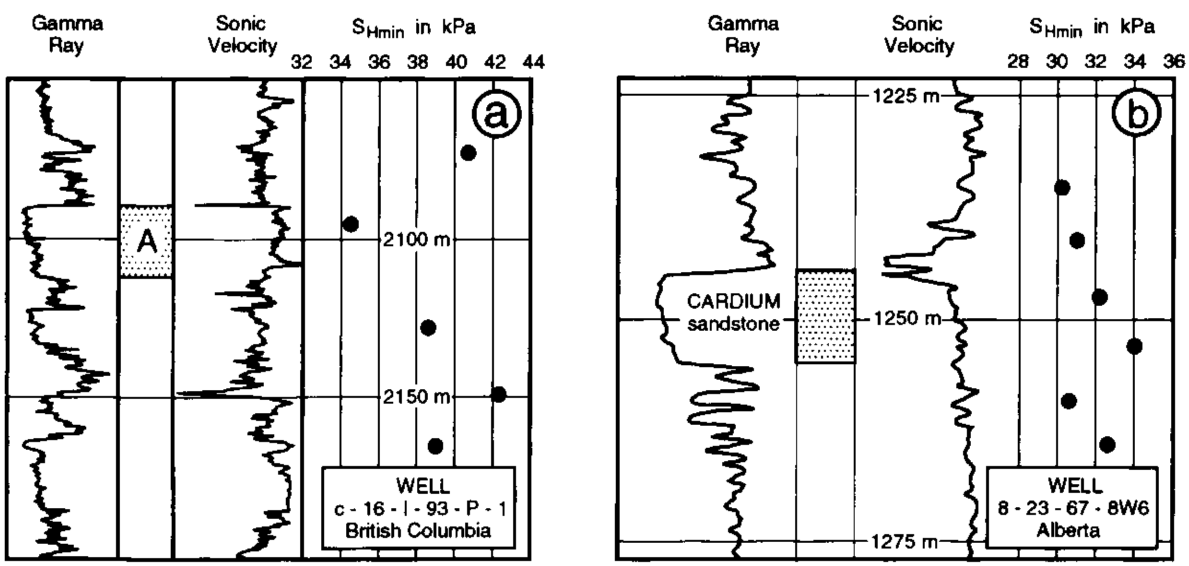

Figure 15 (**a**) S_{Hmin} *magnitudes measured in a well in northeastern British Columbia (Kry and Gronseth, 1983). A hydraulic fracture within Sandstone A would be confined to that unit, provided the fracturing pressure was greater than 34.5 and less than 38.6 MPa.* (**b**) S_{Hmin} *magnitudes measured at Wapiti, Alberta (McLellan, 1988). To fracture the Cardium sandstone, a pressure greater than 34.0 MPa would be required, which exceeds the stresses acting on the enclosing rocks, so hydraulic fractures would not be confined to the sandstone. This would be undesirable if the enclosing rocks were water-bearing.*

this situation led to excessive borehole wall collapse in the upper parts of the wells. Since redirecting wells was not feasible, given the placement of the drilling platform and the geometry of the Panuke oil field, the weight of the drilling mud was raised and this increased borehole stability to a degree. A better geomechanical solution would have been to drill directional wells at right angles to the chosen trajectories (Fig. 14).

Borehole instability can be anticipated by modelling the situations likely to be encountered during drilling. The necessary calculations require stress orientations and magnitudes. For consolidated sediments in onshore settings, the vertical stress, S_V, increases with depth at approximately 25 $kPa \cdot m^{-1}$ or 1 $psi \cdot ft^{-1}$, and the smaller horizontal stress, S_{Hmin}, averages 70 - 80% of S_V. In such cases, the larger horizontal principal stress is generally between 120% and 160% of S_{Hmin}. If greater precision is needed for assessing potential borehole instability, stress magnitude measurements will have to be made.

Hydraulic Fracture Confinement

Many hydrocarbon reservoirs can be stimulated into greater production by hydraulic fracturing which augments their existing permeability and improves fluid flow through them. Invariably, however, hydrocarbon-bearing intervals abut water-bearing strata so, to avoid producing water, the fractures must be confined to the targeted rocks and should not extend upward or downward into the water-bearing units. This can be achieved if the target reservoir is under lower stress than the rocks above and below it. In such cases, fractures can be propagated at pressures that exceed the smallest principal stresses acting on the reservoir rocks, but which are lower than the smallest principal stresses acting on the enclosing units. Figure 15a portrays an ideal situation for fracturing Sand "A," where S_{Hmin} is the smallest principal stress (Kry and Gronseth, 1983). Provided fractures were propagated at pressures greater than the S_{Hmin} value for Sand "A" and lower than the S_{Hmin} values for the enclosing shales, the fractures would be contained within the reservoir and could be kept open with a suitable proppant material, such as coarse sand. Exactly the opposite situation prevails at Wapiti (Fig. 15 b), where the Cardium Formation sandstone reservoir is more highly stressed than the siltstones and

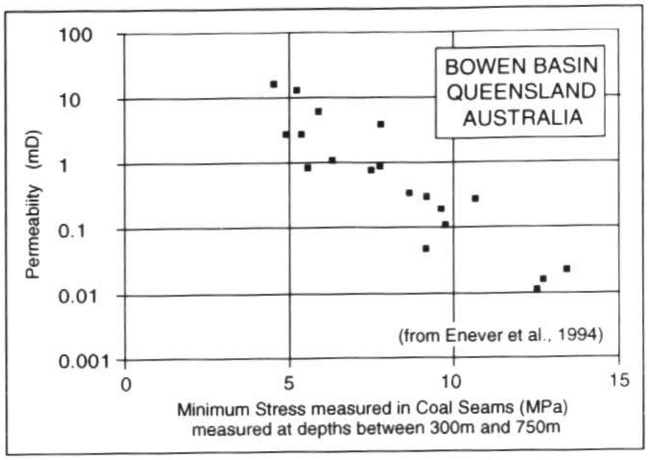

Figure 16 *Inverse log-normal relationship between stress magnitudes and permeability (coalbed methane productivity) in coals in the Bowen Basin of Australia (Enever* et al.*, 1994).*

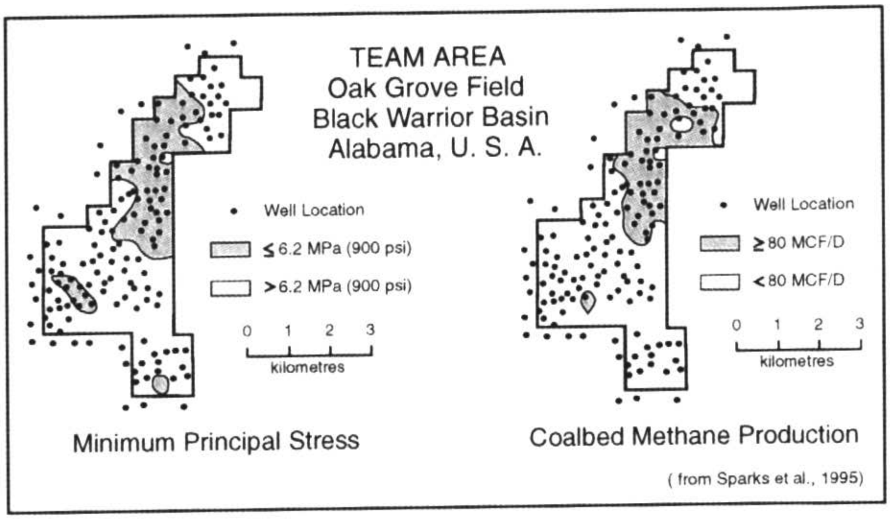

Figure 17 *Relationship between in situ stress and gas production from coal in the Mary Lee Group (depth ca. 700 m) in the Black Warrior Basin, Alabama (Sparks* et al.*, 1995). Note that productivity is greatest where the* in situ *stress is the lowest.*

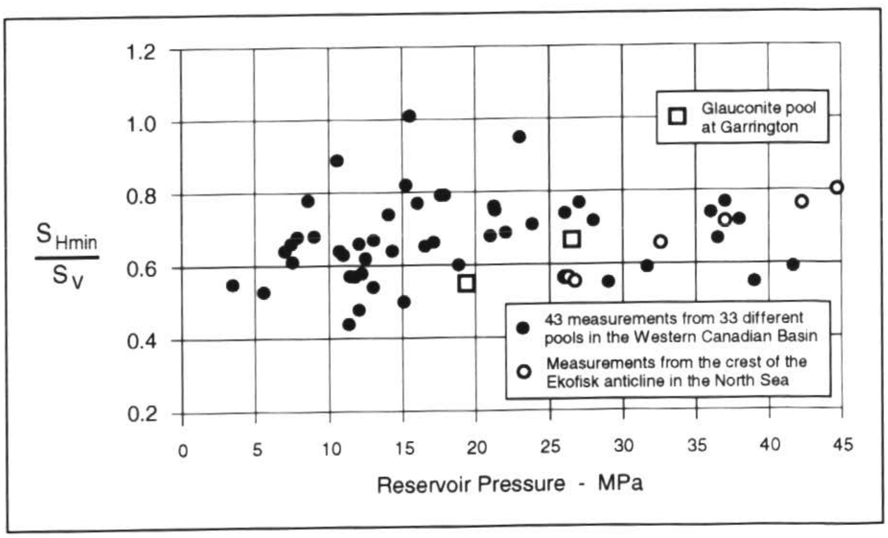

Figure 18 *Plot of reservoir pressures versus S_{Hmin}/S_V showing how reductions in reservoir fluid pressures lower horizontal stress magnitudes. This is clearly illustrated by measurements made on the crest of the Ekofisk anticline (Teufel* et al.*, 1991). Similar relationships exist in western Canada, as indicated by the data from the Glauconite pool at Garrington, although the picture appears to be less clearcut when data from 34 pools are plotted on the same graph as shown here.*

shales above and below it (McLellan, 1988). In order to fracture the Cardium sandstone, pressures exceeding the stress acting on the sand would be required, and since these exceed the stresses acting on the abutting siltstones and shales, the fractures so created would propagate into them with ease. Moreover, any injected proppant would be likely to come to rest in fractures in the underlying siltstone and shale sequence rather than within the "targeted" reservoir, so that maintaining open hydraulic fractures in the sandstone might not be feasible. These examples illustrate the value of making successive stress magnitude measurements across stratigraphic intervals in which hydraulic fracturing is contemplated.

Hydrocarbon Production and Stress Magnitudes

There is an emerging appreciation that stress magnitude exerts a significant control on reservoir permeability and therefore on the rates at which fluids will flow out of permeable rocks (Fig. 16). Methane production rates from coal beds exhibit approximately log normal relationships to S_{Hmin} magnitudes (Enever *et al.*, 1994; Sparks *et al.*, 1995). This relationship can be demonstrated areally in the Black Warrior Basin of Alabama (Fig. 17).

Coal beds generally are highly fractured and their permeability will be particularly susceptible to lateral compression, but experimental studies (Konechny and Kozusnikova, 1996) suggest that the same effects are likely to be felt by conventional hydrocarbon reservoirs, fractured or non-fractured. Their "sweet spots" probably can be defined in part by areas of low horizontal stress magnitudes, which is why it is important to map the lateral variations in stress magnitudes. Potentially, these could be as important as sedimentary facies in designing optimal recovery scenarios in some reservoirs. However, demonstrating relationships between hydrocarbon production rates and horizontal stress magnitudes is difficult because most oil and gas fields are not produced under natural open flow conditions and, usually, there is little stress magnitude data available.

What can be more easily shown is that, when hydrocarbon production lowers reservoir pressures, horizontal stress magnitudes decline. This is particularly well illustrated at Ekofisk in the North Sea (Teufel *et al.*, 1991) and can also be documented in western Canada (Fig. 18). Reduction of virgin stresses by fluid removal, and hence reservoir pressure decline, is a major concern when one is attempting to assess lateral variations in horizontal stress magnitudes, if parts of the data set come from depleted reservoirs. This is often the case when the stress magnitude data are derived from mini-frac or fracture treatments used to stimulate wells. These procedures are usually undertaken to raise production rates that have declined owing to depletion and reduced reservoir pressures (drawdown), so the horizontal stress magnitudes that are measured are lower than the virgin stress magnitudes for the area (Salz, 1977).

Stress Magnitudes and Overpressures

As discussed in Part 1, a hydraulic fracture is initiated when injected fluids raise pressures rapidly by artificial means to levels that are higher than the least principal stress acting on a rock (Bell, 1996). On the other hand, there are numerous natural examples of overpressures (pore pressure greater than hydrostatic) that are associated with elevated horizontal stresses (*e.g.*, Bell, 1990; Gaarenstroom *et al.*, 1993), suggesting that hydraulic fracturing does not necessarily occur if the fluid pressure rise takes place over a period of time. There is much discussion as to what the relationship means, and which is the chicken and which is the egg. Engelder and Fischer (1994) attributed the increases in S_{Hmin} magnitudes observed in the Scotian Shelf and North Sea to time-dependent poroelastic behaviour (deformation of lithified porous rock containing pressurized fluids) triggered by rises in pore fluid pressure. Yassir and Bell (1996) reached a similar conclusion for the Scotian Shelf, but proposed that increases in horizontal stress may actually promote overpressuring in the Beaufort Basin.

Relationships between pore pressures and horizontal stresses are cartooned in Figure 19. The pressure/depth profiles (a) and (b) have been drawn on the assumption that there is no lateral strain, in other words, that the rocks cannot expand sideways. In such a situation:

$$S_h = [(\upsilon/1-\upsilon)\ (S_v - P_o)] + P_o$$

where υ is Poisson's Ratio and S_h is the mean horizontal stress $(S_{Hmax} + S_{Hmin})/2$.

The pore pressure/depth profiles that this relationship generates are interesting. Rapid burial of normally pressured rocks beneath a perfect seal gives rise to

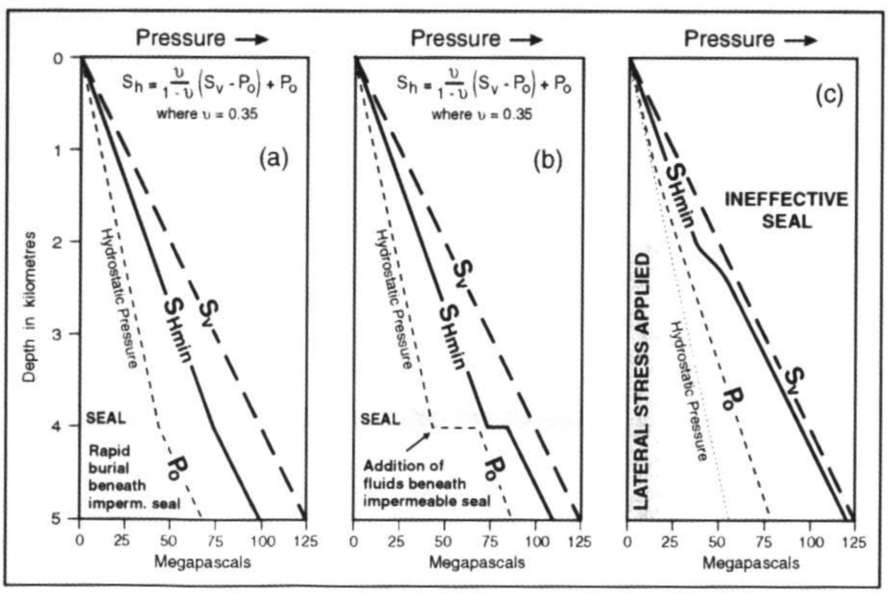

Figure 19 *Simulated pore pressure and horizontal stress profiles:* **(a)** *A seal is created at 4000m. Rapid burial follows, so that the fluids below the seal cannot equilibrate with those above it. Pore pressures and horizontal stress increase in tandem with the overburden gradient, producing mild overpressuring.* **(b)** *Fluids are added beneath the seal at 4000m so as to raise pore pressure by 25 MPa over a thin vertical interval and this increases the horizontal stress by 11.5 Mpa. The result is significant overpressuring and a corresponding step in the S_h/depth profile.* **(c)** *In this example, the horizontal stress is raised tectonically by lateral compression. If the system were sealed, the pore pressures and horizontal stresses would converge to lithostatic pressures. However, if the system leaks, as shown here, horizontal stresses could be raised to lithostatic levels, but the pore pressure would not keep pace and the overpressuring would be mild.*

overpressuring which increases gradually with depth, but there is no sharp increase in the gradient (Fig. 19a). On the other hand, if fluids are added beneath a perfect seal, sharp buildups of overpressures occur and there are corresponding but smaller buildups of the horizontal stresses (Fig. 19b). This combination of fluid pressure/depth and stress/depth profiles is characteristic of the Scotian Shelf, and is attributed to gas generation at depth in that basin (Yassir and Bell, 1996).

A rather different situation exists in the outer shelf part of the Beaufort Basin. There S_{Hmin} approaches S_V in magnitude at relatively shallow depth, yet overpressure buildup is not rapid with depth and the levels reached are less than those measured beneath the Scotian Shelf. The observed fluid pressure/depth and stress/depth profiles could arise if lateral stress were applied to the rocks so as to raise the smaller horizontal stress to lithostatic stress levels (S_V). If perfect seals were present, the pore pressure would reach lithostatic levels as well and the rocks would attain an isotropic, essentially fluid, condition. However, if the system leaked, maintaining high overpressures would not be possible and the overpressuring observed would increase with depth, but the increase would be mild (Fig. 19c), as is observed in the Beaufort Basin. It is believed that this overpressuring is due to lateral tectonic compression of a permeable rock column, an interpretation which is compatible with structural and rock property data. It is difficult to envisage how the addition of fluids could raise the horizontal stresses to their observed levels, unless the volumes concerned were gigantic and were being injected at relatively shallow depths. Comparative profiles for the Scotian Shelf and Beaufort Basin are shown in Figure 20.

These examples show that it should be possible to infer the dominant controlling mechanism of overpressuring by examining how the horizontal stress magnitudes vary with the pore pressures and by reference to the pressure/depth profiles of both these parameters. Overpressuring appears to raise horizontal stresses in certain geological settings whereas, in others, it is a rise in the horizontal stresses that generates the overpressures!

Triggered Earthquakes (Induced Seismicity)

Injection of fluid chemical wastes into a 3.7 km deep well in the Rocky Mountain arsenal began in 1962 and was followed by an apparently related increase in seismicity in the Denver area (Healy *et al.*, 1968). Because of this, pumping was halted in 1966, but the earthquakes continued with the largest (Richter magnitude 5.5) occurring in 1967. Over the course of the injection program reservoir pressures were raised by 12 Mega pascals (MPa). Subsequently, Raleigh *et al.* (1976) demonstrated that increases and decreases in fluid pressures can, respectively, trigger and diminish, induced earthquake occurrence.

Naturally-occurring earthquakes involve rapid failures on fault surfaces which release crustal stress, so it is not surprising that human interventions that modify pre-existing stress regimes can induce such events. It should be emphasised that the human interventions are only triggers; the "gun" has been cocked by natural forces, and our activities have merely "hurried Nature along." Changes in applied load or fluid pressures that shift a pre-existing stress regime to a failure mode will trigger earthquakes. Simpson (1986) has classified the crustal responses by invoking the well-known Mohr circle diagram and the following discussion is drawn from his paper.

The stresses acting on a rock mass

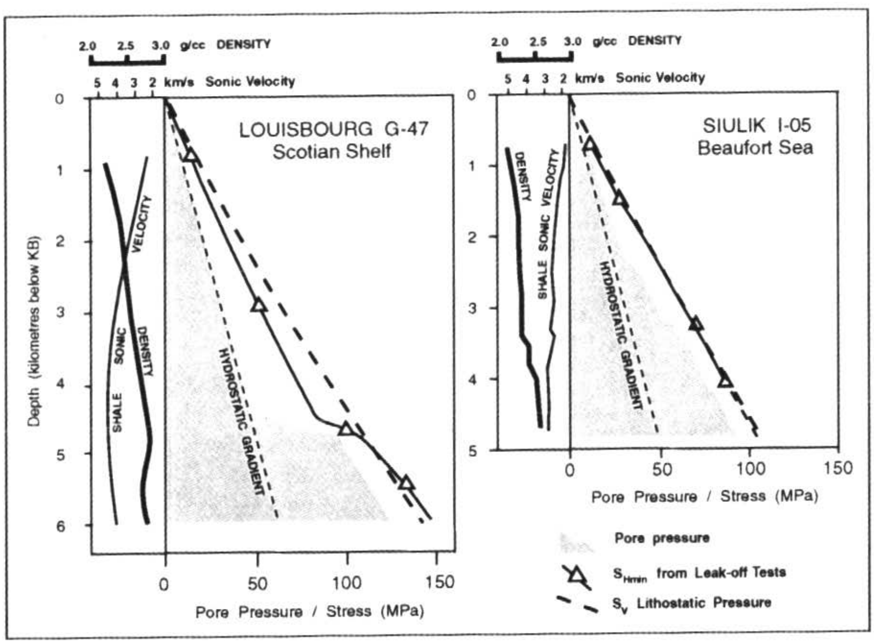

Figure 20 *Pressure/depth profiles for Louisbourg G-47 (Scotian Shelf) and Siulik I-05 (Beaufort Basin) modified from Yassir and Bell (1996). Note the similarity of the Louisbourg pore pressure and S_{Hmin} profiles to Figure 19b, suggesting that fluid additions are responsible for the overpressures below 4500m. The Siulik profiles resemble Figure 19c, suggesting that lateral stresses are the major overpressuring mechanism, which is also supported by the semi-continuous increase with depth of density and shale sonic velocity. The more gradual build-up of overpressuring at Siulik, compared to Louisbourg, is probably due to fluid leakage.*

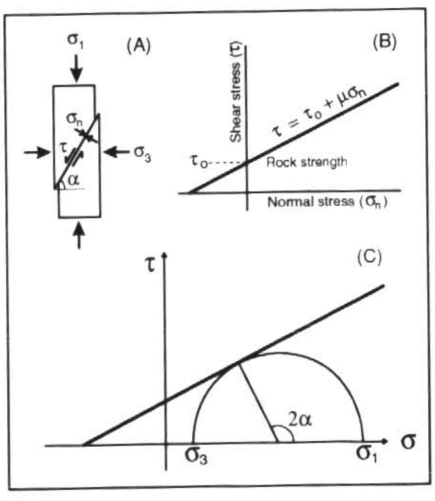

Figure 21 **(A)** *Failure in a rock mass compressed by maximum (σ_1) and minimum (σ_3) principal stresses will occur on a plane containing the intermediate stress (perpendicular to the page), at an angle α to σ_3. Note the resolved normal (σ_n) and shear stress (τ).* **(B)** *Coulomb's Law for failure (= earthquake incidence) in dry rock, graphing the relationship between the normal stress (σ_n) and the shear stress (τ).* **(C)** *The Mohr-Coulomb failure criterion applies when the circle containing maximum (σ_1) and minimum (σ_3) principal stresses intersects the failure curve defined in (B). This degree of stress anisotropy promotes shear failure in dry rocks of strength τ_o. (Figure modified from Simpson, 1986).*

are specified with respect to three orthogonal principal stresses which, in decreasing magnitude, are labelled: σ_1, σ_2 and σ_3. Compressional failure will occur along a plane containing the intermediate stress, σ_2, and will be independent of the value of σ_2 (Fig. 21a). Thus, to evaluate failure criteria, one need only consider the maximum and minimum principal stresses, σ_1 and σ_3, and resolve these into a shear component (τ) and a normal component (σ_n) along a plane other than that incorporating σ_1 and σ_3. According to the Mohr-Coulomb criterion, a dry rock will fail when $\tau = \tau_o + \mu\sigma_n$, where τ is the shear stress required for failure on a specific plane, τ_o is the rock strength, σ_n is the normal stress across that plane, and μ is the coefficient of friction on the surface (Fig. 21b). If the rock is porous and contains fluids, the failure criterion becomes $\tau = \tau_o + \mu(\sigma_n - P_o)$, where P_o is the pore pressure. The Mohr circle is a convenient method of resolving principal stresses into normal and shear components (Fig. 21c). A circle is drawn so that the values σ_1 and σ_3 define its diameter along the normal stress axis. This circle is the locus of normal (σ_n) and shear stress (τ) components on planes at an angle α to σ_3. Adding the Coulomb failure criterion to the Mohr circle diagram defines the condition for failure; this will occur when the circle becomes tangent to the failure envelope. The point of tangential intersection determines the angle 2α, and indicates the orientation of the plane on which failure (*i.e.*, earthquakes) will occur (Figure 21c).

Earthquakes will not occur if the largest and smallest principal stresses acting on the rock body are of such magnitudes that the Mohr circle does not intercept the failure envelope of the rock. It can be appreciated readily that changing the magnitudes of, or the ratio of the differences between, σ_1 and σ_3 could lead to failure (earthquakes). Figure 22 illustrates some of the conditions under which earthquakes can be triggered.

The simplest mechanism involves the removal of overlying loads by quarrying or mining. If the rocks concerned are subject to such high horizontal stresses that the minimum principal stress is vertical, removing overburden will reduce it and increase the difference between S_{Hmax} and S_V. This would extend the diameter of the Mohr circle as shown in Figure 22a, so that the circle might intercept the failure curve of the rock mass. Should the reduction in vertical stress be this great, shear failure in the form of thrust faulting may well occur, possibly explosively. Rock bursts in mines represent small triggered earthquakes and even quarry floor pop-ups (Fig. 10, Bell, 1996) have been reported to occur explosively (J. Wallach, pers. comm., 1992).

Injecting fluids into a porous rock in the subsurface increases the reservoir pressure and hence reduces the effective stress (Fig. 22b). If the reservoir pressure is raised sufficiently and rapidly enough to override poroelastic effects, shear fracturing in the plane of the intermediate principal stress can occur and trigger earthquakes. Micro-earthquakes have been recorded in a number of subsurface reservoirs (Grasso *et al.*, 1992) in settings compatible with this mechanism.

Earthquakes triggered by impounding bodies of water in surface reservoirs or dammed lakes involve processes that involve elasticity, compaction and diffusion (Bell and Nur, 1978; Simpson, 1986). However, at the simplest level, this is a loading phenomenon (Fig. 22C) whereby the vertical stress is increased until shear fracturing occurs and generates earthquakes. Such induced seismicity occurs preferentially where σ_1 is vertical.

Earthquakes can also be triggered by fluid removal if this alters the horizontal stresses sufficiently to cause rupture. Segall (1989) has developed an elegant poroelastic model which accounts for normal faulting around the margins of oil fields and for reverse faulting above or below a zone of fluid extraction (Fig. 23). Most earthquakes that are induced by fluid removal involve one or other of these mechanisms.

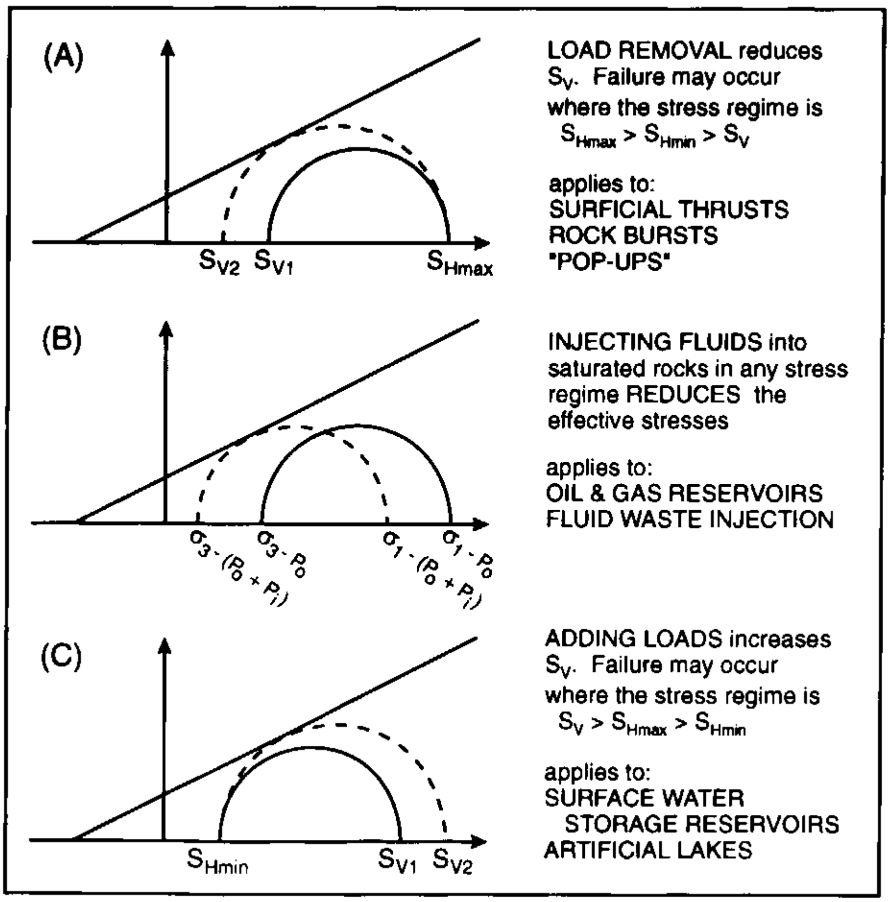

Figure 22 *Mohr-Coulomb representation of conditions in which human intervention can trigger earthquakes by inducing shear failure in highly stressed rocks. The original condition is portrayed by solid lines; the modified situation by dashed lines. In* **(A)** *and* **(C)**, S_{V1} *is the original vertical stress and* S_{V2} *is the modified vertical stress. In* **(B)**, P_o *is the original pore fluid pressure in a subsurface porous rock, whereas* P_i *is the pressure due to fluid injection, so that the modified pressure becomes* (P_o+P_i). *Reductions in the effective stresses* (σ-P_o), *"displace" the Mohr circle to the left. Earthquakes will be triggered in situations where initially the magnitudes of the largest and smallest principal stresses and the difference between them are such that the Mohr circle does not intercept the failure curve but where human intervention (removing loads, injecting fluids, adding loads) modifies conditions so that the circle intercepts the failure curve. Figure modified from Simpson (1986).*

This discussion emphasizes that induced earthquakes are most likely to be triggered by human activities where the stress magnitudes and the principal stress anisotropy are high, so that relatively small changes in subsurface pressures will promote failure. These conditions are met along the western margin of the Western Canada Sedimentary Basin, where production activities have induced earthquakes at Rocky Mountain House (Wetmiller, 1986) and near Fort St. John (Horner *et al.*, 1994). Small earthquakes also occur at shallow depth in those regions of North America that were subjected to Pleistocene and Holocene ice loading (Wu and Hasegawa, 1996).

Lateral Variations of Stress Magnitudes

There is no substitute for a succession of measurements of S_{Hmin} in a single well. Horizontal stresses vary in magnitude in relation to the mechanical properties of the rocks being compressed. A more ductile interval will experience less horizontal stress than a more brittle unit at a comparable depth (Fig. 15) and, ideally, an S_{Hmin}/depth profile should show details of that degree of stress variation.

Successive stress magnitude measurements in specific wells (*e.g.*, Warpinski, 1989) illustrate the danger of extrapolating horizontal stress gradients to depth from single readings, or of trying to map lateral variations in stress magnitudes from scattered measurements. Despite these problems, mapping horizontal stress magnitudes within a basin is a worthwhile objective (see Fig. 17) because of the regional information it imparts to oil company operators who are planning to fracture reservoirs or to drill deviated wells to deplete them. Figure 24 is a preliminary interpretation of S_{Hmin} variation across the Western Canada Sedimentary Basin, based on the limited information that is currently available. Constructing this type of map is fraught with problems related to the paucity of good stress magnitude data and the difficulties in interpreting less reliable measurements (Bell, study in progress).

The map shows horizontal stress magnitude gradients increasing southwestwards across the basin towards the overthrust Rocky Mountains. This is not an unexpected configuration, since the well-documented NE-directed Mesozoic and early Cenozoic thrusting in the Rocky Mountains and the Foothills indicates that high horizontal stresses existed along the western margin of the basin during the Laramide orogeny, so lateral tectonic stresses may become greater closer to the mountains. The pattern could also be an artifact of Late Tertiary uplift and erosion, however. Organic maturation data indicate that the thickness of eroded sediments (missing overburden) increases southwestward (Nurkowski, 1984; Majorowicz *et al.*, 1990). If the rocks have not completely equilibrated with respect to the former loads above

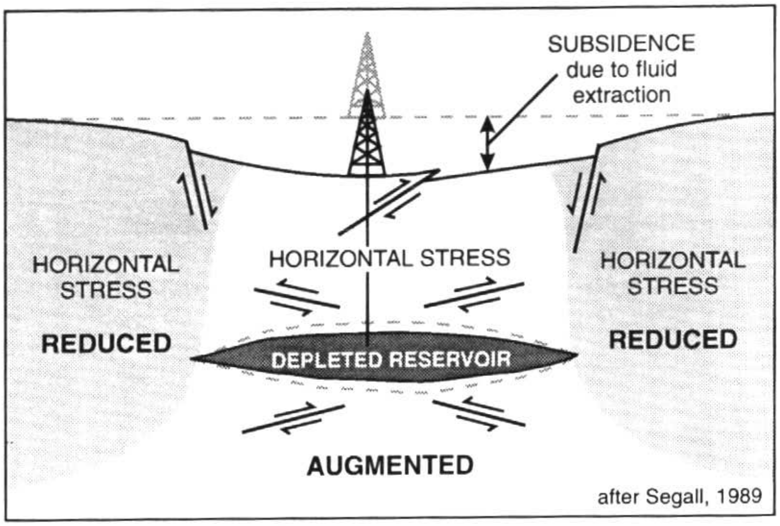

Figure 23 *Schematic cross section showing changes in the stress regime caused fluid withdrawal from an oil field. The net effect is to decrease the horizontal stresses acting around the edge of a field (grey zone) and to increase them above and below it (white zone). As a result, normal faults may develop on the flanks of fields, especially if subsidence is significant, whereas reverse faulting may occur above or below depleted reservoirs.*

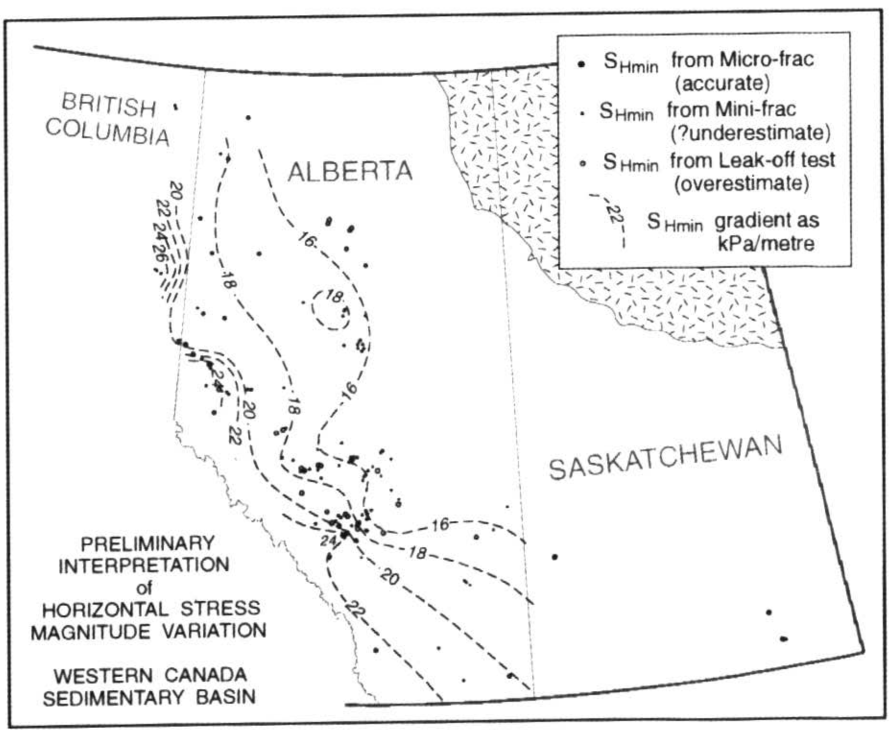

Figure 24 *An interpretation of S_{Hmin}/depth gradients across part of the Western Canada Sedimentary Basin. The following limitations apply: (1) the map relies largely on stress magnitude inferences from mini-frac measurements made in reservoirs where virgin fluid pressures have been reduced, hence far field stress magnitudes may have been lowered; (2) one measurement per well is typical, so results from different levels in geographically-grouped wells have been combined to give local stress/depth profiles; (3) most of the stress measurements were made in Mesozoic sandstones.*

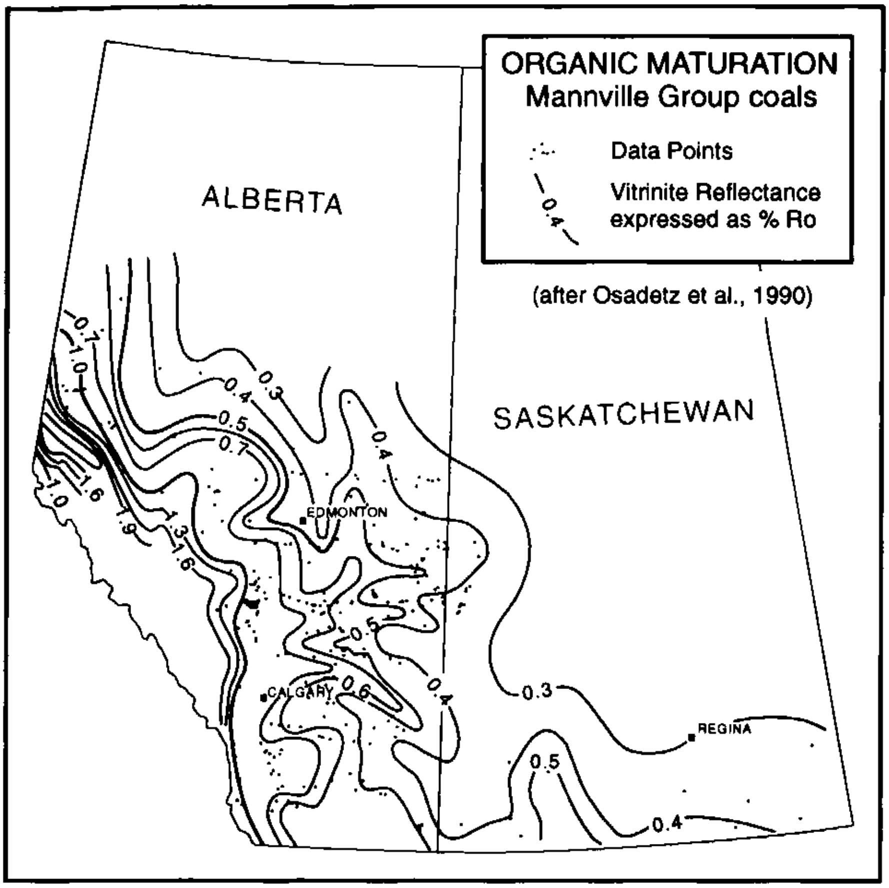

Figure 25 *Mannville Group organic maturation levels (Osadetz* et al., *1990) expressed as vitrinite reflectance in oil (% Ro). The map configuration bears no relationship to heat flow patterns and appears to represent the effects of heat transferred by moving fluids, probably along fractures induced by palaeostress regimes!*

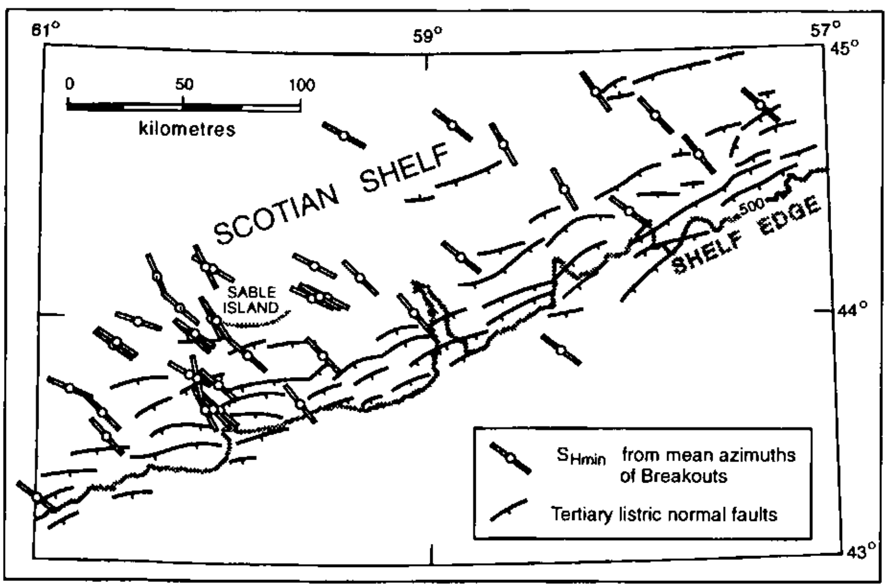

Figure 26 *Map showing the traces of Tertiary listric normal faults compared to the mean breakout azimuths that are diagnostic of today's horizontal principal stresses on the Scotian Shelf. Note that the breakouts are not aligned exactly perpendicular to the fault traces, as would be expected if the faults had evolved in today's stress regime. It would appear that the horizontal stresses have rotated anticlockwise since the faults developed.*

them (Carlsson and Olsson, 1982; Herget, 1988), horizontal stress magnitudes would be larger closer to the mountains at common depths, thereby giving rise to higher S_{Hmin}/depth gradients.

The map also shows a significant salient in the southern part of Alberta, where S_{Hmin}/depth gradients are markedly lower than to the northwest and southeast. Despite the variable precision of the available S_{Hmin} measurements, this salient is real and it coincides areally with a region of relatively high organic maturity of Lower Cretaceous coals (Fig. 25). This areal correspondence implies a genetic relationship: either decreasing lateral compression increases organic metamorphism or, what is more likely, increased heating raises the rocks' ductility and thereby decreases the amount of lateral stress they can transmit. If this is true, and intuitively it appears to be reasonable, the present day stress magnitudes in western Canada are, in part, a function of former thermal processes, since the organic metamorphism levels were achieved prior to Late Tertiary erosion and uplift (Majorowicz *et al.*, 1990). Interestingly, no significant production-triggered earthquakes have been reported in the low stress salient.

Contemporary Stresses and Geotectonics

Today's stress regimes represent contemporary tectonics, the latest stage in upper crustal structural development of the Earth, so that understanding them sheds light on what went on before, namely Tertiary geotectonic evolution. An example of such an application involves the Scotian Shelf, where the majority of the Tertiary-aged listric normal faults are not aligned with today's horizontal principal stresses (Fig. 26), implying that S_{Hmax} stress trajectories have rotated in an anticlockwise direction since the faults were initiated (Yassir and Bell, 1994). Contemporary horizontal stress orientations appear to be related to the subsurface topography of overpressuring on the Scotian Shelf, so the inferred modification of the stress regime may be related to the 3-D spatial development of overpressuring.

Horizontal stress magnitudes in certain areas of the Beaufort Sea are so high that they suggest that parts of the basin are now under significant lateral compression (Fig. 20). This is not readily apparent from regional cross sections which show little obvious deformation of the Early Miocene unconformity and the younger strata (Fig. 27). What may be occurring is that the stress regime is currently changing and that renewed regional compression has begun recently.

CAUSES OF VARIATIONS IN CRUSTAL STRESSES IN SEDIMENTARY BASINS

This topic properly requires book-length treatment, so what follows is a very cursory review. Deviatoric stresses, namely principal stresses of unequal magnitude, are largely phenomena of the upper part of the Lithosphere, the brittle varnish of the Earth, although they must characterize contemporary subduction zones, and have existed formerly where seismic reflectors dipping at a low angle now intersect the upper Mantle. Surfaces such as the Flannan Reflector, north of Scotland (McBride *et al.*, 1995), and the well-imaged reflector beneath the Superior Province in the Canadian Shield (Calvert *et al.*, 1995), are thought to represent the scars of ancient subduction zones.

The major component of any stress regime is gravitational in origin, but lithostatic loading does not account for horizontal stress anisotropy, or for the directional homogeneity of horizontal stresses across large parts of the Earth's surface (Zoback *et al.*, 1989). For that, organized lateral compression is required. Gough *et al.* (1983) suggested that this is transferred to the upper crust by basal shearing of the lithosphere against the convecting asthenosphere. Zoback and others (1989) have drawn attention to the close correspondence of S_{Hmax} orientations and absolute plate motions for some, but not all, of the Earth's tectonic plates (North America, South America, Europe). Cloetingh and his co-workers have modelled the effects of geotectonic plate shape and the forces acting at their edges. They have obtained reasonably detailed fits between modelled and measured stress orientations for the Indo-Australian plate, which does not exhibit obvious correspondences between S_{Hmax} orientations and plate motion directions (Cloetingh and Wortel, 1986). Richardson (1992) modelled the torque acting on each plate due to ridge push forces and demonstrated a strong correlation with absolute plate motions, which suggests that there is a causal relationship between regional intraplate stresses and the ridge push forces that originate along ocean-spreading axes.

Most published stress orientations are measurements of contemporary compression. This is clear when the measurements involve the responses of a reasonably large body of rock as they do for breakouts, hydraulic fractures and earthquakes, or when the measurements are made in rocks with fabrics that permit rapid stress release, such as a clastic sediments. Remnant stresses, on the other hand, can be stored in crystalline rocks with interlocking grain fabrics and may be detected if the measurements involve small volumes of the rock. Thus, some overcoring measurements may generate stress orientations that contain paleostress directional components. This is difficult to demonstrate because overcoring is frequently performed within a few metres of irregularly excavated free surfaces that readily deflect regional stress orientations. Hence, excavation geometry, rather than relict stresses, may be the cause of many "anomalous" orientations. As Adams (1995) has shown, overcoring measurements in central and eastern Canada exhibit great variability in horizontal stress orientation. Many overcoring measurements are not compatible with the directionally homogeneous populations of breakout and hydraulic fracture orientations.

Stress magnitudes are a function of the lithostatic load (Jaeger and Cook, 1979). In the case of the vertical stress

$$S_V = \rho g z$$

where ρ is the density, g the gravitational constant and z the thickness of overburden. A component of horizontal compression in sediments, proportional to Poisson's Ratio, is also related to the lithostatic load. Assuming no horizontal displacement

$$(S_{Hmax} + S_{Hmin})/2 = \upsilon/(1-\upsilon)S_V + P_o$$

where υ is Poisson's Ratio and P_o is pore pressure. However, measured magnitudes of horizontal principal stresses usually do

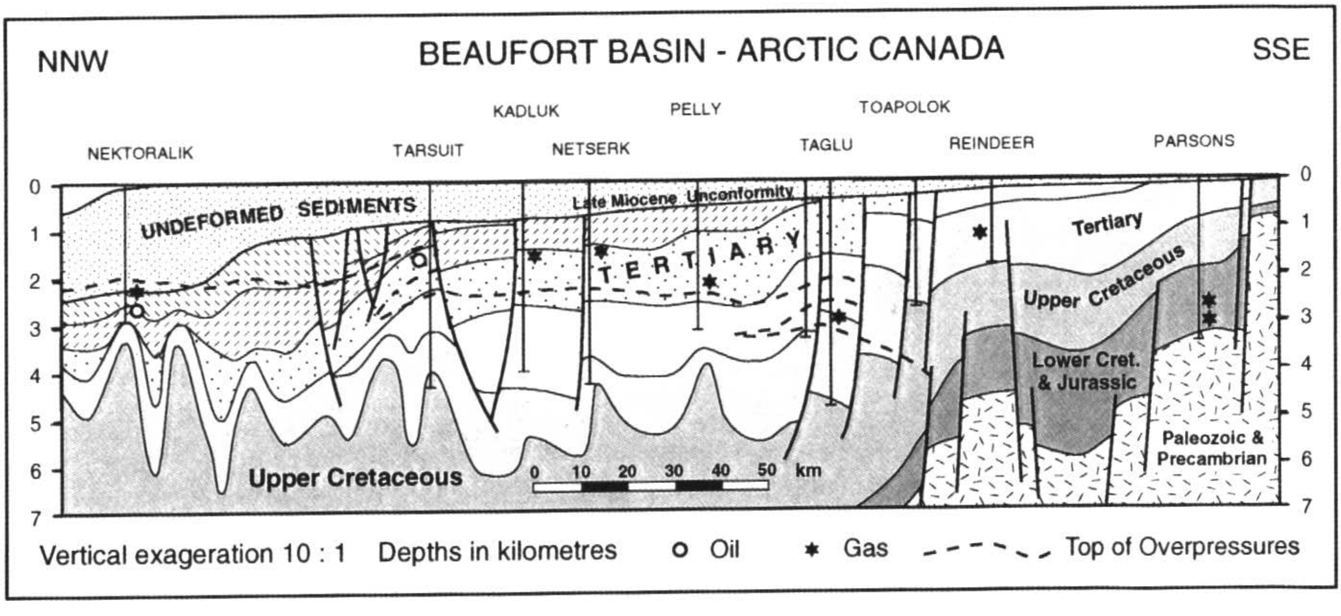

Figure 27 *Cross section of the central part of the Beaufort Basin (after Dixon* et al., *1985). Note the lack of obvious signs of post-Early Miocene compressional tectonics despite the high horizontal stresses documented by leak-off tests.*

not agree with the lateral pressures calculated from this equation. Horizontal stress magnitudes are higher in many locations, but in some they appear to be lower, so additional factors must be involved.

The major source of additional lateral compression is generally considered to be tectonic stress and, for much of Canada, this mechanism is a good candidate. In addition, the rapid removal of overburden can result in near-surface high horizontal stress relative to the vertical stress (Herget, 1988). Depending on the Poisson's Ratio of the rocks involved, and assuming that no lateral movement (relief) occurs, between 50% and 75% of load-generated horizontal stresses can be retained when the load is removed (Carlsson and Olsson, 1982), whereas the vertical stress will adjust almost immediately to load reduction. An additional source of high horizontal stresses at shallow depth in formerly depressed regions is the rebound process itself which, in theory, can generate near-surface horizontal compression of several megapascals provided there is no lateral relief of stress (P. Wu, pers. comm., 1996). These two mechanisms are thought to contribute to the abnormally high horizontal stresses documented by leak-off tests in Hudson Bay wells (Bell and Wu, in prep.) and to the shallow stress regime in the tar sands of eastern Alberta. To depths of the order of 300 metres, induced fractures in the tar sands are horizontal (Nicholls and Luhning, 1977), which indicates that both horizontal principal stresses exceed the vertical stress magnitude near the ground surface. As discussed above, it appears that thermal events can reduce horizontal stress magnitudes by increasing rock ductility.

In summary, stress measurements in sedimentary rocks will normally record today's horizontal stress orientations and involve no directional distortions arising from paleostresses. By contrast, there is growing empirical evidence that horizontal stress magnitudes may contain paleostress components, namely geological memories of former upper crustal events.

CONCLUDING REMARKS

Parts 1 and 2 of this review have illustrated the nature of *in situ* stress and how to measure and use *in situ* stress information in sedimentary basins. The coverage is not all-inclusive. There is no discussion of how stress measurements contribute to coal mining practices, especially with regard to safety in underground workings. Nor has much mention been made of the strain relief methods of stress measurement (overcoring), which are widely used in crystalline rocks. The emerging applications of shear wave splitting (Crampin, 1987) also have not been addressed. This is pre-eminently a tool for detecting rock fabric anisotropy at scales ranging from the upper mantle to hydrocarbon reservoirs and even core samples. In many settings the diagnosed rock anisotropy reflects contemporary stress orientations, but these need to be established independently.

I hope that the two papers demonstrate the increasing importance of in-situ stress data in understanding the geomechanics of sedimentary basins. In the past, we have rightly been concerned with temperature, aware that the thermal treatment a rock receives can affect its ability to generate hydrocarbons and its capacity to retain them. Less emphasis has been placed on pressure, perhaps partly because of its insignificant role in controlling diagenesis. There has been limited appreciation in many circles that stress anisotropy is the rule rather than the exception. The flood of new stress measurements continues to cause earth scientists to revise their viewpoints and to provide tools to improve the recovery of subsurface resources.

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