Borehole Geomechanics in Petroleum Exploration and Development: From Controlling Wellbore Stability to Predicting Fault Seal Integrity

Introduction

Few in the Australian oil patch were familiar with the term 'borehole breakout' when David Lowry alerted PESA Journal readers to this phenomenon (1990, v.17, p. 43-44). Ten years later, few are unfamiliar, with breakouts having been reported in every Australian basin subject to significant drilling activity. This change witnesses the dramatically increased awareness of borehole geomechanics in the Australian oil patch that has developed over the last decade. One driver for this increased awareness has been the increasing quality and use of borehole imaging tools, and the geomechanical information yielded by these tools. Furthermore, borehole geomechanics has applications that are particularly significant for, although by no means restricted to, deviated wells. Hence the increased incidence of deviated drilling has been another driver. That significant fundamental research on the origin of crustal stresses and their application in the oil patch has been undertaken in Australia, both in the universities and at CSIRO, has been another driver for the uptake of borehole geomechanics in the Australian oil patch over the last decade. This article provides a contemporary snapshot of borehole geomechanics in the oil patch, addressing specifically, the methodology of in situ stress determination, and some key applications of knowledge of subsurface stresses.

Initially, breakouts gained prominence as a drilling problem responsible for stuck pipe, lost time, and even lost holes. However, utilising the breakouts themselves to help ascertain the in situ stress field has led to drilling strategies that minimise such wellbore stability problems. More recently, there has been rapidly growing recognition that the in situ stress field controls both natural and induced fluid flow in the subsurface, impacting on:

- reservoir flooding and drainage patterns;
- hydraulic fracture stimulation;
- fluid flow in naturally fractured reservoirs, and;
- seal integrity of fault-bound prospects.

Knowledge of the in situ stress field can optimise exploration and development strategies pertaining to these issues. Hence the applications of borehole geomechanics have grown from their early roots in wellbore stability to a wide range of exploration and field development issues.

Borehole Geomechanics: Determining the In Situ Stress Tensor

Assuming that the vertical stress ($\sigma_z$) is a principal stress, the full stress tensor is constrained by the orientation of the other two principal stresses, i.e. the maximum and minimum horizontal stresses ($\sigma_h$ and $\sigma_v$ respectively), and by the magnitude of all three principal stresses.

The orientation of the horizontal stresses is given by the orientation of borehole breakouts and drilling-induced tensile fractures commonly seen on borehole image logs such as Schlumberger’s FMI (Formation MicroImager: resistivity image) and UBI (Ultrasonic Borehole Imager: sonic image), and Baker Atlas’ STAR II (Simultaneous Acoustic & Resistivity Imager). In vertical wells, the long axis of breakouts is oriented in the $\sigma_h$ direction, and drilling-induced tensile fractures strike in the $\sigma_v$ direction (Figures 1 & 2). Breakouts occur where the circumferential stress acting around the wellbore wall exceeds the compressive strength of the rocks forming the wellbore wall (Figure 1). Failure of intersecting, conjugate shear planes leads to pieces of rock breaking off the wellbore wall. The central pad on Figure 2 shows both breakout (poorly resolved zone of low resistivity), and, at the periphery of the breakout, the fracturing of the wellbore wall that precedes breakout formation.

Vertical stress magnitude can be determined from the weight of the overburden, which is given by inte-grating density log data that have been carefully edited for bad hole conditions. It is imperative to determine the site-specific $\sigma_h$ magnitude, and not to use the commonly applied value of 1 psi/ft (22.6 MPa/km), because the 1 psi/ft value may be in error by as much as ±30% at different depths in different basins.

Ideally, horizontal stress magnitudes are determined from hydraulic fracture-tests. Such tests are not performed in petroleum exploration wells. However, leak-off tests, which resemble the first part of a hydraulic fracture test, are routinely undertaken. The lower bound to leak-off pressures is widely considered to give a reasonable estimate of $\sigma_h$. An improved estimate of $\sigma_h$ may be obtained from extended leak-off tests, a procedure for which has been developed by Jim Enever of CSIRO based on extensive experience with hydraulic fracture testing in the mining industry (APPEA Journal, 1996, v. 36, p. 528-535). An extended leak-off test is simply a leak-off test in which several cycles of pressurisation of the wellbore are undertaken in order that repeatable fracture closure pressures (a better estimate of $\sigma_h$ than leak-off pressures) can be obtained. Under ideal circumstances, an extended leak-off test can also help constrain $\sigma_h$ magnitude.

The most difficult parameter of the in situ stress tensor to constrain is $\sigma_v$. The occurrence, or indeed non-occurrence, of breakouts and drilling-induced tensile fractures can constrain $\sigma_v$ if rock strength is known. The change in azimuth of breakouts or drilling-induced tensile fractures...
It is worth emphasising that the only two key pieces of non-standard data that should be acquired during drilling to help constrain the in situ stress field are a good quality leak-off, or preferably extended leak-off test and an image log (preferably both resistivity and sonic). Given the very wide significance of in situ stress data outlined below, operators should give serious consideration to acquiring these data as standard practice.

**Borehole Geomechanics: Applications**

The remainder of this article illustrates some of the key applications of in situ stress data with reference to the in situ stress tensor at approximately 2.8 km depth in the Penola Trough, Otway Basin, South Australia. The stress tensor there is given by:

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\begin{align*}
\sigma_h &: 46 \text{ MPa}; \\
\sigma_v &: 64 \text{ MPa}; \\
\sigma_H &: 82 \text{ MPa}; \\
\text{\textit{\(\sigma_H\) orientation: 156°N, and;}} \\
\text{pore pressure} &: 28 \text{ MPa}.
\end{align*}
\]

This stress tensor was determined using the techniques outlined above, including an extended leak-off test that was undertaken by Origin Energy, in collaboration with the authors, for the purpose of improved \(\sigma_h\) determination. For further details on the determination of the in situ stress field of the Penola Trough, and for a more extensive discussion of fault seal issues in the area, see Jones et al. (2000, APPEA Journal, v. 40, p. 194-212).

**Borehole Stability**

Perhaps counter-intuitively, a vertical wellbore is the most prone to breakout-induced instability in a strike-slip stress regime (i.e. \(\sigma_H > \sigma_v > \sigma_h\)), such as that of the Penola Trough (Figure 3). The extensive breakout development seen in vertical wells in the area is a consequence of this stress regime. Any deviated wellbore is more stable than a vertical wellbore in this environment, and hence lower mud weights can be used in deviated than in vertical wells (Figure 4). Horizontal wells drilled towards 150-160°N (i.e.}
σ_H direction) are the most stable. Wells drilled in less optimal trajectories require a higher mud weight to prevent breakouts developing (Figure 4).

Depending on rock strength, underbalanced drilling may be an option in such an environment, particularly in wells deviated at high angles towards 150-160°N. In areas prone to formation damage, or mud losses into natural fractures, wellbore stability analysis such as that presented is a critical tool for assessing the viability of underbalanced drilling.

Figure 5 illustrates the maximum mud weight that can be run without exceeding the fracture gradient, and thus causing mud losses, in the stress environment of the Penola Trough. Again it is perhaps counter-intuitive that the vertical well can sustain the least mud overbalance without fracturing. Combining the propensity for breakout and fracture development, the safe mud weight envelope for vertical wells is very tight in this stress environment, whereas a wider mud weight envelope can be tolerated in horizontal wells.

In Situ Stress and Fluid Flow in Hydrocarbon Reservoirs
There are numerous studies demonstrating the control of the in situ stress field on subsurface fluid flow, especially in hydrocarbon reservoirs, the most extensive being those of Kes Heffer (BP). Preferential directionality of reservoir floods in the σ_H direction has clearly been demonstrated by Heffer, based on data from some 80 fields in North America, North Sea, continental Europe, Middle East and China (water, surfactant/polymer and gas floods). Using half a million well pair histories, Heffer also demonstrated that rate correlations between injector and producer well pairs are best developed in the σ_H direction. Similarly, at the geological timescale, his study of 423 faults in the North Sea revealed that non-sealing faults (those across which there is no change in the hydrocarbon-water contact) are strongly preferentially aligned in the σ_H direction.

Reservoir Flooding and Drainage Patterns
Hydraulic fractures induced by reservoir flooding may be responsible for the observed directionality of reservoir floods and well pair rate correlations. Hydraulic fractures open normal to the minimum principal stress (σ_min in most basins), hence they are generally vertical and strike parallel to σ_H. The recognition of such can aid the efficient planning of flooding operations. In order to maximise sweep efficiency in flooding operations, injector-producer pairs should not be aligned in the σ_H direction. If injector-producer pairs are so aligned, injected fluids tend to flow directly from the injection well to the production well, bypassing much of the reservoir. If injectors are aligned in the σ_H direction, flooding fluids from the injectors rapidly link up, forming a ‘curtain’ that sweeps hydrocarbons to producing wells, which should be offset from the injectors in the σ_H direction.

Reservoir drainage is anisotropic and sensitive to the in situ stress field, even in reservoirs not subject to fracture stimulation, perhaps because of stress-sensitive natural fractures and/or micro-fractures. Again the recognition of such can help optimise plans for field development (Figure 6).

Hydraulic Fracture Stimulation
Where hydraulic fracturing is undertaken to stimulate low permeability reservoirs, the in situ stress field is the critical...
control on the nature of the induced fracture, controlling not only fracture orientation but also fracturing pressure and fracture height/containment. A full discussion of the influence of in situ stresses on hydraulic fracturing is beyond the scope of this article. However, the issue of fracture stimulation from deviated wells has received considerable attention, some of it potentially misleading, and is briefly discussed herein.

Hydraulic fractures generated in wells deviated in the $\sigma_h$ direction tend to be transverse to the wellbore, because induced fractures are oriented normal to $\sigma_h$ (Figure 7). In wells deviated towards $\sigma_h$, hydraulic fractures tend to be axial (Figure 7). It has thus been suggested that hydraulically fracturing wells deviated in $\sigma_h$ direction affords optimal reservoir drainage per well. The authors urge caution in this approach, because hydraulic fractures tend to form axial to the wellbore in the immediate vicinity of the wellbore, and only in the far-field (several wellbore diameters distant) are they normal to the minimum principal stress. Hence fractures formed in wells deviated in $\sigma_h$ direction may twist from axial to transverse as they propagate away from the wellbore. Such fracture twisting may lead to a loss of hydraulic conductivity, and indeed to an inability to proppant beyond the twisted zone. The planning of hydraulic fracture stimulation from deviated wells should include careful analysis of fracture orientation in both the near- and far-field, and the key issue may be to minimise the propensity for fracture twisting.

**Fluid Flow in Naturally Fractured Reservoirs**

The relationship between natural subsurface fluid flow and in situ stress is due to the focusing of fluid flow along planes suitably oriented to be tensile or shear fractures within the in situ stress field. Pre-existing natural fractures in these orientations tend to be open and transmit fluids. Hence, although pre-existing natural fractures may have a wide variety of orientations, those suitably oriented to be tensile or shear fractures within the in situ stress field tend to be open and hydraulically conductive (Figure 8). Deviating wells in the $\sigma_h$ direction maximise the probability of intersection with such fractures, and in many fractured reservoirs, such as the Austin Chalk, drilling in the $\sigma_h$ direction is the key to obtaining commercial production rates. The authors do, however, note that not all natural fractures are stress-sensitive and where fractures are partially cemented, or the rocks indurated, significant production may come from natural fractures that are not optimally oriented within the in situ stress field. Nonetheless, in the absence of a well-constrained, and clearly preferentially oriented pre-existing natural fracture set, deviating in the $\sigma_h$ direction optimises intersection with open natural fractures. Hence in the Penola Trough, where there have been minor recoveries of oil from fractured basement, wells designed to take advantage of this play should be deviated towards 060-070°N (or 240-250°N).

It is clear from the above that in a strike-slip stress environment like that of the Penola Trough, different imperatives may lead to different decisions on deviation direction. Wells deviated towards 150-160°N are least prone to breakout, and may be fracture stimulated without twisting-type problems occurring, but are poorly oriented to intersect open natural fractures. Borehole geomechanics provides the requisite data from which to make informed decisions about deviation direction, given the key imperatives for a well. In many cases, especially offshore, deviation direction may be driven by the need to access a particular reservoir compartment, and may not be open to selection. However, if such trajectories are, for example, non-optimal with respect to wellbore stability, more aggressive mud weights should be planned, and the significance of such with respect to the ultimate objective of the well, e.g. in terms of formation damage, can be assessed.

**Seal Integrity of Fault-Bound Prospects**

Open natural fractures may be desirable in tight reservoirs, but such open natural fractures may also provide conduits for seal breaching, especially in fault-bound prospects. The same principles used to predict which fracture orientations are likely to be open and productive in the reservoir can be used to predict fracture orientations likely to be associated with seal breaching. Seal breaching due to fault/fracture reactivation is a key exploration risk factor in the Otway Basin, and indeed in a number of other Australian basins. Planes in hot colours in Figure 8 are suitably oriented within the in situ stress field of the Penola Trough to act as tensile and shear fractures, hence these planes are at the greatest risk of reactivation and associated seal breach. These data can be transposed onto a fault map to risk fault segments with respect to the likelihood of seal breach due to reactivation (Figure 9). Such provides a tool for pre-drill assessment of the likelihood of seal breach due to structural reactivation subsequent to hydrocarbon charge.

**Developments**

The greatly increased awareness of borehole geomechanics in the Australian oil patch over the last decade has been the result of increased quality and use of borehole imaging logs, of increased application of deviated drilling, and of fundamental research carried out in the Australian universities and CSIRO. The next decade is likely to see further expansion in the application of borehole geomechanics which the authors predict will be driven by continued improvement in borehole imaging tools, and by yet more case studies of the importance of in situ stresses in subsurface fluid flow. Key areas of ongoing research are likely to be in the evolution of the stress tensor with time as fields are developed and reservoir pressures decline, and in stress modelling. The latter is already a growth area with recognition of the significance of in situ stresses at the wellbore driving a demand for improved stress prediction prior to drilling.

A public domain database of in situ stress data for the Australian Continent, and further information on the origin, determination and application of in situ stresses can be found on the web at www.ncpgg.adelaide.edu.au/asm.