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A study of the design of inclined wellbores with regard to both mechanical stability and fracture intersection, and its application to the Australian North West Shelf

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Abstract

Knowledge of the in-situ stress field can be applied both in planning most stable drilling trajectories and also in maximizing intersection of the wellbore with open, natural, and hydraulically-induced fractures in the reservoir. Inclined wells drilled with the optimum drilling direction (azimuth) and deviation (from the vertical), at which the shear stress anisotropy around the wellbore wall is minimized, may be more mechanically stable than vertical wells in various stress regimes. Such mechanically stable trajectories may also maximize open fracture intersection. Combining the objectives of maximum mechanical stability and maximum open fracture intersection

- wells in an extensional stress regime should be highly deviated from vertical (at about 55–70°) and drilled along the azimuth of the least horizontal principal stress;
- wells in a strike-slip stress regime should be horizontal and drilled at 55–70° with respect to the major horizontal principal stress;
- wells in a compressional stress regime should be slightly deviated from vertical (at about 20–35°) and drilled along the azimuth of the major horizontal principal stress.

Application of this study to the Wanaea/Cossack field of the Australian North West Shelf, where the in-situ stress field has been constrained, suggests that the most stable drilling direction and that which maximizes potential intersection with any open fractures in the reservoir is horizontal, in the azimuth of the least horizontal principal stress, 005–010°N.

1. Introduction

Highly deviated, extended reach and horizontal wells have been widely recognized to offer great economic benefits through lower development costs, faster production rates, higher recovery factors, and the potential exploitation of naturally fractured reservoirs (e.g. Lang and Jett, 1990; Joshi, 1991). However, wellbore stability threatens to impede the realization of the benefits offered by new horizontal drilling technology. Hence an understanding of the problem, and analytical design capability to manage wellbore stability will help realise the full benefits offered by inclined well drilling technology. Knowledge of the in-situ stress field is a critical requirement for well design with regard to mechanical stability. The in-situ stress field also controls the orientation of open, natural and hydraulically-

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induced fractures (although the orientation of palaeo-fractures may have little relationship with the contemporary stress field), and the planning of inclined wells designed to exploit such fractures should also incorporate knowledge of the contemporary stress field.

Much progress has been made towards the determination of the orientation and magnitude of the in-situ stress in the crust, in particular, by hydraulic fracturing techniques including modified leak-off tests (e.g. Stock et al., 1985; Enever, 1988; Haimson, 1993), by borehole breakout analyses (e.g. Plumb and Hickman, 1985; Zoback et al., 1985; Haimson and Herrick, 1986; Barton et al., 1988; Guenot, 1989; Moos and Zoback, 1990; Hillis, 1991; Vernik and Zoback, 1992; Hillis and Williams, 1992, 1993a,b), by strain relaxation on oriented core expansion (e.g. Teufel and Warpinski, 1984; Teufel, 1993), and by measurement of passive acoustics during hydraulic fracturing (e.g. Wills et al., 1992). However, it is not the purpose of this paper to discuss the determination of the in-situ stress field, rather we aim to apply knowledge of the in-situ stress field to the design of inclined wells with regard to both mechanical stability and fracture intersection.

Once the orientation and magnitude of the in-situ stress field is constrained, the most stable inclined well trajectory can be designed. This is based on the concept that minimization of the stress anisotropy around the wellbore wall minimizes wellbore failure. Potential failure of deviated wells has been discussed extensively in the literature (e.g. Hiramatsu and Oka, 1968; Bradley, 1979; Aadnoy and Chenevert, 1987; Mastin, 1988; Baumgärtner et al., 1989). In this study, the concept of minimum stress anisotropy around the inclined wellbore wall using a shear stress measurement is introduced. An optimum combination of deviation angle and drilling direction which minimizes the shear stress anisotropy around the wellbore can be determined for any tectonic stress regime. It will be shown that, perhaps counter-intuitively, such well aligments may be more mechanically stable than vertical wells based on the commonly adopted Mohr-Coulomb failure criterion.

In order to maximize recovery from fractured reservoirs (whether the fractures are natural or induced), the wellbore should intersect the fractures at a high angle. This paper presents a strategy for determining which fracture directions are likely to be open (or to be opened in the case of induced fractures) on the basis of which orientations are subject to the least normal stress. In many situations the prefered orientation for maximizing fracture intersection is coincident with the most mechanically stable wellbore trajectory.

In applying this study to the North West Shelf of Australia, we will briefly review the contemporary stress field in the Wanaea/Cossack area of the North West Shelf, and discuss its implications for horizontal drilling. The Australian North West Shelf is rapidly becoming Australia's major oil producing region. Horizontal or highly deviated drilling activity has been seen in this region (McNicoll, 1991), and deviated wells such as North Rankin A-21 have been successful in terms of economic benefits and mechanical achievements (Scholes, 1992). However, oil companies operating in this region have experienced wellbore instability problems often associated with borehole breakouts. Such wellbore instability threatens to be the major impediment to the realisation of benefits offered by contemporary deviated drilling technology on the North West Shelf. Hence there is a need, in particular, for a better understanding of the mechanical stability of inclined wellbores.

2. Stress field around an arbitrarily orientated borehole

Anderson (1951) argued that the three principal stresses would usually be oriented vertically and horizontally, because the Earth's surface is a free surface. This has since been confirmed by numerous in-situ stress measurements (Obert, 1967; Greiner, 1975; Gysel, 1975), and is further supported by the vast majority of intraplate crustal earthquake focal mechanisms (Zoback et al., 1989). Therefore, it is assumed that the principal stresses in the upper few kilometers of the Earth's crust act in the vertical and two orthogonal horizontal directions.

An analytical solution to the stress field around an arbitrarily oriented borehole, based on the assumption and that the rock is isotropic and behaves like a linear elastic material, has been provided by Faihurst (1968), Hiramatsu and Oka (1968), Bradley (1979), Aadnoy and Chenevert (1987), Mastin (1988), Baumgärtner et al. (1989), and Qian and Pedersen (1991). The following is a summary of the theoretical basis and coordinate system used in this paper.

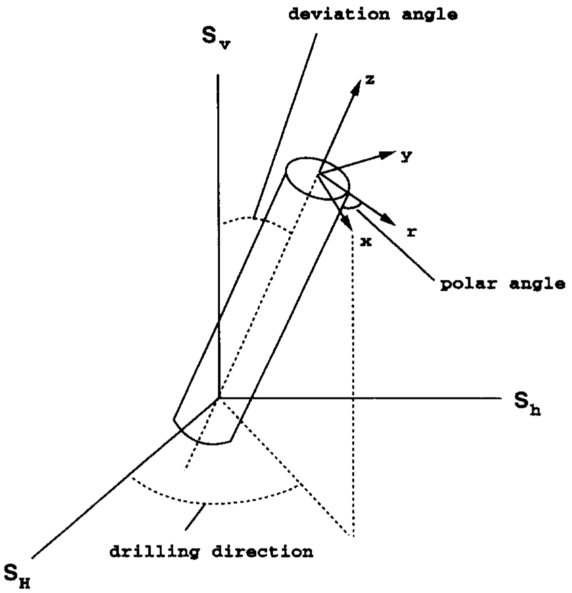

Fig. 1. Borehole orientation and the coordinate system used in this study (from Baumgärtner et al., 1989), in which $S_v=\sigma_v$, $S_H=\sigma_H$, $S_h=\sigma_h$, drilling direction $=\alpha$ and deviation angle $=\beta$.

For an arbitarily oriented borehole, the rotation of the stress tensor from the global (in-situ) coordinate system to a local borehole coordinate system (Fig. 1) is given by (Baumgärtner et al., 1989):

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix} = \begin{Bmatrix} \sin^2\beta & \cos^2\beta\cos^2\alpha & \cos^2\beta\sin^2\alpha \\ 0 & \sin^2\alpha & \cos^2\alpha \\ \cos^2\beta & \sin^2\beta\cos^2\alpha & \sin^2\beta\sin^2\alpha \\ 0 & -\sin\alpha\cos\alpha\sin\beta & \sin\alpha\cos\alpha\sin\beta \\ -\sin\beta\cos\beta & \sin\beta\cos\beta\cos^2\alpha & \sin\beta\cos\beta\sin^2\alpha \\ 0 & -\sin\alpha\cos\alpha\cos\beta & \sin\alpha\cos\alpha\cos\beta \end{Bmatrix} \begin{Bmatrix} \sigma \mathrm{v} \\ \sigma \mathrm{H} \\ \sigma \mathrm{h} \end{Bmatrix} \tag{1}$$

From these equations, the stress field at the wall of the borehole is given by:

$$\sigma_r = \Delta P \tag{2}$$

$$\sigma_\theta = (\sigma_x+\sigma_y) - 2(\sigma_x-\sigma_y)\cos2\theta - 4\tau_{xy}\sin2\theta - \Delta P \tag{3}$$

$$\sigma_{z'} = \sigma_z - 2\nu(\sigma_x-\sigma_y)\cos2\theta - 4\nu\tau_{xy}\sin2\theta \tag{4}$$

$$\tau_{\theta z'} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta) \tag{5}$$

$$\tau_{r\theta} = 0 \tag{6}$$

$$\tau_{rz'} = 0 \tag{7}$$

where the symbols are as given in Table 1.

Based on the above equations, the effective principal stresses on the borehole wall (which are orthogonal to each other) in the local borehole coordinate system can be expressed by:

$$\sigma_1 = \frac{1}{2}(\sigma_\theta+\sigma_{z'}) + \frac{1}{2}\sqrt{(\sigma_\theta-\sigma_{z'})^2+4\tau_{\theta z'}^2} \tag{8}$$

$$\sigma_2 = \frac{1}{2}(\sigma_\theta+\sigma_{z'}) - \frac{1}{2}\sqrt{(\sigma_\theta-\theta_{z'})^2+4\tau_{\theta z'}^2} \tag{9}$$

$$\sigma_3 = \sigma_r \tag{10}$$

3. "Stable" drilling direction and deviation angle

In order to define an optimum drilling direction and deviation angle, an effective parameter R_s, called shear stress anisotropy around the wellbore wall, is introduced here and defined by:

$$R_s = \frac{\tau_{oct}(\max) - \tau_{oct}(\min)}{\tau_{oct}(\min)} \tag{11}$$

where τ_{oct} is the octahedral shear stress, defined by (Jaeger and Cook, 1969, p. 24):

$$\tau_{oct} = \sqrt{\frac{1}{9}[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2]}$$

The octahedral plane has a normal equally inclined to the principal stress axes, and it is so-called because it is parallel to a face of an octahedron with vertices on the principal axes (Jaeger and Cook, 1969, p. 23).

A number of measurements could describe the stress anisotropy around the wellbore, e.g. using the mean principal stress, the maximum principal stress (e.g. Mastin, 1988) or the octahedral shear stress as proposed. Intuitively, a measurement of the stress anisot-

Table 1
Nomenclature

$\sigma_x,\sigma_y,\sigma_z,\sigma_{yz},\sigma_{xz},\sigma_{xy}$	= Stress tensor in the borehole cartesian coordinate system (MPa)
$\sigma_H,\sigma_h,\sigma_v$	= Effective major and minor horizontal principal and vertical stresses, respectively (MPa)
$\sigma_r,\sigma_\theta,\sigma_z,\sigma_{\theta z},\sigma_{r\theta},\sigma_{rz}$	= Stress tensor in the borehole cylindrical coordinate system (MPa)
α	= Angle between σ_H and the projection of the borehole axis onto the horizontal plane (°)
β	= Angle between the borehole axis and the vertical direction (°)
θ	= Polar angle in the borehole cylindrical coordinate system (°), shown in Fig. 1
ΔP	= Excess fluid pressure in the borehole (i.e. mud pressure less pore pressure in the formation) (MPa)
ν	= Poisson's ratio
$\sigma_1,\sigma_2,\sigma_3$	= Effective maximum, intermediate and minimum principal stresses in the borehole cylindrical coordinate system (MPa)
τ_{oct}	= Octahedral shear stress (MPa)
$\tau_{oct(max)}$, $\tau_{oct(min)}$	= Maximum and minimum octahedral shear stress (MPa)
R_s	= Shear stress anisotropy
c'	= Rock cohesive strength (MPa)
μ	= Coefficient of internal friction = tan ϕ where ϕ is the angle of internal friction
C_0	= Uniaxial rock compressive strength (MPa)
T	= Rock tensile strength (MPa)
n_h	= Ratio of the effective minor horizontal principal stress to the effective vertical stress
n_H	= Ratio of the effective major horizontal principal stress to the effective vertical stress
$\sigma_{1rockfailure}$	= Evaluated rock strength (MPa)
P_p	= Pore pressure in the rock formation (MPa)
$\sigma_{1borehole}$	= Maximum principal stress at borehole wall (MPa)
σ_{eff}	= Effective failure stress (MPa)
σ_n	= Normal stress acting on a fracture plane (MPa)
k_v,k_H,k_h	= Directional cosines of normal vector on the fracture plane

ropy should incorporate all stress factors which influence or control wellbore mechanical stability. The octahedral shear stress is considered the most useful on the basis of: (1) the increasingly recognized fact that the octahedral shear stress τ_{oct} is an important factor controlling the stress level at failure, as shown by experiments (e.g. Mogi, 1971, 1972; Steiger and Leung, 1988, 1989); (2) the conventional von Mises failure criterion for rocks (e.g. Bradley, 1979; Woodland, 1990), in which the octahedral shear stress is considered to be the controlling rock stress at failure; and (3) the effective strain energy failure criterion (Wiebols and Cook, 1968), which has been shown to be most consistent with results of laboratory rock strength tests (Paterson, 1978; Hoek and Brown, 1980; Brady and Brown, 1985; Takahashi and Koide, 1989), and the elastic distortional strain energy is in fact directly proportional to the octahedral shear stress (Jaeger and Cook, 1969, p. 118).

The shear stress anisotropy R_s as defined in Eq. (11) is a function of the effective principal stress ratios $n_h = \sigma_h/\sigma_v$ and $n_H = \sigma_H/\sigma_v$, the Poisson's ratio (ν) of the material, and the effective well pressure ΔP. So for given Possion's ratio and effective well pressure, R_s can be uniquely determined from the deviation angle from the vertical (β) and the drilling direction (α) in a specified $n_h = \sigma_h/\sigma_v$ and $n_H = \sigma_H/\sigma_v$, which solely define the tectonic stress regime, according to Andersonian faulting mechanics (Anderson, 1951). For instance, $n_h < n_H < 1$ indicates a normal faulting stress regime, while $n_h < 1 < n_H$ points to a strike-slip faulting stress regime, and $1 < n_h < n_H$, a reverse faulting stress regime. Therefore, a critical stable condition can be determined once the tectonic stress regime is known (i.e. the orientation and magnitudes of σ_H and σ_h).

The "stable" configurations, as given by an optimum deviation angle (β) from the vertical and the drilling direction (α) with respect to the azimuth of the maximum horizontal principal stress, of deviated wells in various tectonic stress environments are defined to be those in which the stress anisotropy as defined in Eq. (11) around the wellbore wall is minimized.

The calculated "stable" conditions for an extensional (normal faulting) stress regime show that the

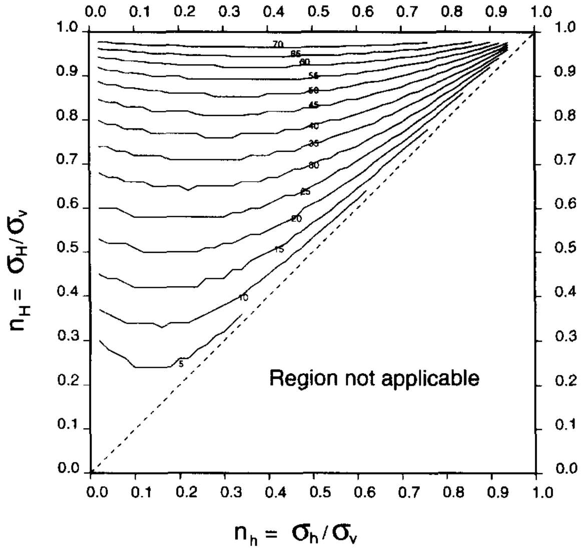

Fig. 2. Deviation angle from the vertical in normal faulting stress regime with $\Delta P=0$ and $\nu=0.25$, at which the stress anisotropy around the well wall is minimized. The drilling direction (α) is equal to 90° for all cases, unless explained otherwise in the text.

stable drilling direction should always be parallel to the azimuth of the minimum horizontal principal stress σ_h, and the optimum vertical deviation angles (Fig. 2) depend on the ratios of the horizontal principal stresses to the vertical stress. In general, the deviation angle is controlled by both n_H and n_h. The larger the stress ratio n_H, the higher the deviation angle required for maximising stability. At a given n_h, the deviation angle increases with n_H. However, at any given $n_H(\geq 0.5)$, the deviation angle does not change greatly for $n_h \leq 0.4$. In addition, for some cases where both horizontal principal stresses are equal in magnitude, vertical wells ($\beta=0°$) would be most stable in terms of stress anisotropy around the borehole. When $n_H=1$, the well should be drilled horizontally (i.e. $\beta=90°$). The stress anisotropy, associated with the "stable" condition, is generally less than 15% (without excess fluid pressure in the wellbore), which can be further reduced by using a much finer interval of the vertical deviation angle during calculation (1° interval is used in this study). However, for $n_h > 0.2$, the stress anisotropy is always less than 5%.

The calculated "stable" conditions for a strike-slip stress regime suggest that the deviation angles should be always 90° (horizontal wells), and the drilling directions (α) (Fig. 3) with respect to the azimuth of σ_H are controlled by the ratios of the horizontal principal stresses to the vertical stress. The larger the stress ratio n_H, the lower the angle of drilling direction required for maximizing stability. At a given n_h, the drilling direction decreases with the increase of n_H. However, at a given n_H, the drilling direction only changes slightly for $n_h \leq 0.6$. When $n_h=1$, the well should be drilled along the azimuth of σ_H (i.e. $\alpha=0°$). In general, the calculated minimum stress anisotropy is less than 20% (without excess fluid pressure in the wellbore), which once again can be further reduced by using a much finer interval of the drilling direction during calculation (1° interval is used in this study). However, for $n_h > 0.4$, the stress anisotropy is always less than 5%.

The calculated "stable" conditions for compressional (reverse faulting) stress regime suggest that the stable drilling directions should be always parallel to the azimuth of the maximum horizontal principal stress σ_H. The deviation angle from the vertical (Fig. 4) depends on the ratios of the horizontal principal stresses to the vertical stress. In general, the deviation angle is controlled by both n_H and n_h. At a given n_h, the deviation angle increases with the increase of n_H. However, at a given n_H, the deviation angle decreases steadily with the increase of n_h. In addition, for some cases where both horizontal principal stresses are equal in magnitude, vertical wells ($\beta=0°$) would be most sta-

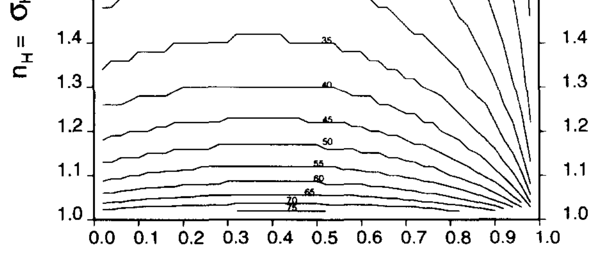

Fig. 3. Drilling direction with respect to σ_H in strike-slip faulting stress regime with $\Delta P=0$ and $\nu=0.25$, at which the stress anisotropy around the well wall is minimized. The deviation angle (β) is equal to 90° for all cases.

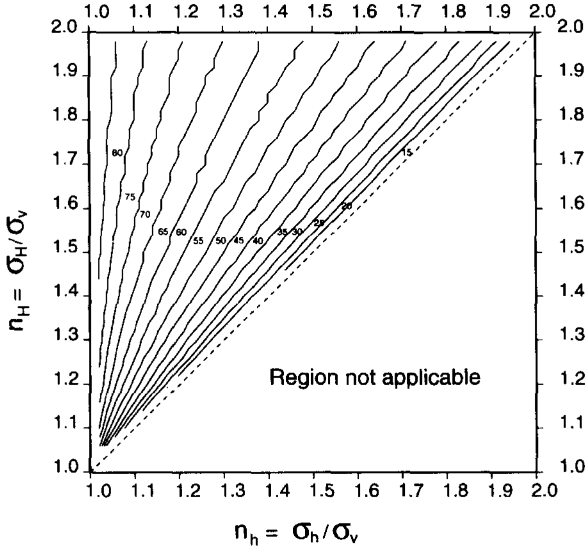

Fig. 4. Deviation angle from the vertical in reverse faulting stress regime with $\Delta P=0$ and $\nu=0.25$, at which the stress anisotropy around the well wall is minimized. The drilling direction (α) is equal to 0° for all cases, unless explained otherwise in text.

ble in terms of stress anisotropy around the borehole. When $n_h=1$, the well should be drilled horizontally (i.e. $\beta=90°$). The calculated minimum stress anisotropy is less than 1% (without excess fluid pressure in the wellbore) for all cases.

While a choice of $\nu=0.25$ is adopted for the above calculations, a change of the Poisson's ratio by ± 0.1 has a minimal effect on the stress field of deviated wells, and the tested range of Poisson's ratio from 0.15 to 0.35 covers most of sedimentary rocks. Therefore, the selected value of Poisson's ratio is not critical for this study.

The above analysis for the determination of optimum drilling direction and deviation angle has been based on the assumption that the orientation and magnitude of the in-situ stress field is known. It should be mentioned here that the in-situ stress measurements in boreholes or on cores are often affected by a number of factors, such as the pore pressure in the rock formation. For example, pore pressure shows significant natural variation, and is often affected by the infiltration of drilling mud into the surrounding rock formation, so that the true in-situ (far-field) stress field is often difficult to constrain accurately. In particular estimation of the major horizontal principal stress is generally not as good as the other two (vertical and the least horizontal) principal stresses which can be calculated from integrating the density log over depth, and from directly measured shut-in pressure in hydraulic fracturing tests, respectively. However, as we have shown above, our design approach to optimize the mechanical stability of inclined wellbore does not critically depend on the accuracy of the in-situ stress field, since slight variations or errors in the estimated principal stress field do not change significantly the optimum design angles of the inclined wellbore.

4. Wellbore stability

In the previous section, the drilling direction and deviation angle which minimize the shear stress anisotropy around the inclined wellbore in different stress regimes have been discussed. In order to gain a better understanding of the stability of the deviated wells, one needs to consider borehole failure due to breakouts. Borehole breakouts are spalled regions centred on the azimuth of the least circumferential stress, and are formed by compressive shear failure due to a large difference between the radial stress and the circumferential stress (e.g. Bell and Gough, 1979; Gough and Bell, 1981, 1982; Bell and Babcock, 1986).

Based on the commonly adopted Mohr-Coulomb failure criterion (Fjaer et al., 1992, ch. 2), it is possible to quantify the likelihood of borehole breakouts. In the Mohr-Coulomb theory, the greatest and the least principal effective stresses are assumed to control failure, that is, rock will fail if:

$$C_0+q\sigma_3=\sigma_1 \tag{12}$$

where σ_1 and σ_3 are the effective maximum and minimum principal stresses, respectively. C_0 is the uniaxial compressive strength and $C_0=2c'(\sqrt{\mu^2+1}+\mu)$, and $q=(\sqrt{1+\mu^2}+\mu)^2$.

A measure of the borehole stability can be made by defining an effective failure stress as:

$$\sigma_{\mathrm{eff}}=\sigma_{1_{\mathrm{rockfailure}}}-\sigma_{1_{\mathrm{borehole}}} \tag{13}$$

where σ_{eff} is the effective failure stress, $\sigma_{1_{\mathrm{rockfailure}}}$ is the rock strength evaluated using Eqs. (1–10), (12), and $\sigma_{1_{\mathrm{borehole}}}$ is the maximum principal stress at the point on the borehole wall under consideration, calculated by using Eqs. (1–10). A positive value of the effective failure stress indicates a stable condition, and a negative value indicates an unstable or failed condition. The

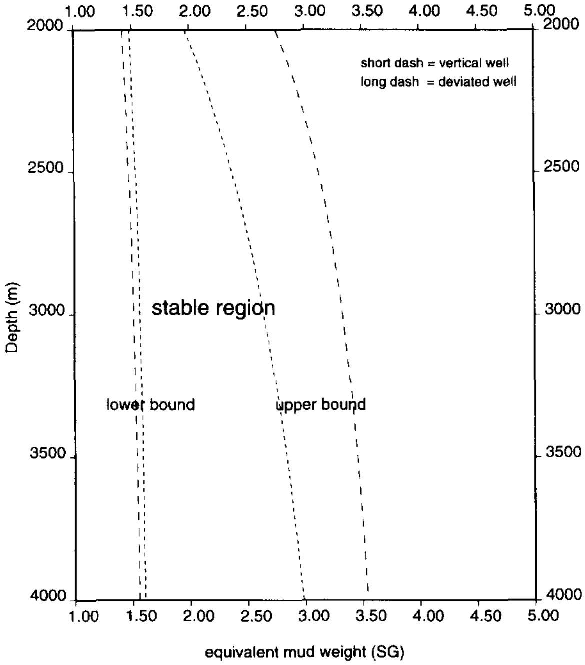

Fig. 5. Mud weight stability profile, in which the tectonic stress regime is normal fault type, indicated by extensional stresses at both horizontal directions with the major horizontal principal stress $\sigma_H = \sigma_v - 5$ MPa and the minor horizontal principal stress $\sigma_h = \sigma_v - 15$ MPa. The vertical stress σ_v is calculated using a rock density of 2.5 g/cm^3. The rock strength parameters are: $C_0 = 20$ MPa (uniaxial compressive rock strength), $\mu = 0.6$ (coefficient of internal friction), Poisson's ratio $\mu = 0.25$, and $T = 0$ (tensile strength). The deviated well alignment is given by the optimum set of drilling direction and deviation angle ($\alpha = 90°$ and $\beta = 50°$) in Fig. 2 for the stress ratios n_H and n_h at depth 3000 m, as defined by the input tectonic stress field. The pore pressure within the depth range under consideration is assumed to be hydrostatic.

definition of the effective failure stress, Eq. (13), is similar to that of Bradley (1979) except we use the maximum principal stress instead of the octahedral shear stress. Because we are concerned with compressive brittle failure, it is appropriate to adopt the Mohr-Coulomb criterion for rock failure prediction.

Based on the concept of the effective failure stress as defined in Eq. (13), the lower limit for the mud pressure (mudweight) can be calculated, i.e. the minimum mud pressure required to avoid compressive shear failure, for a given well alignment (i.e. drilling direction and deviation angle). On the other hand, to avoid hydraulic fracturing and associated fluid loss caused by high mud weight, the upper limit for mud pressure can be calculated based on the assumption that hydraulic fracturing occurs when the minimum effective principal stress becomes tensile and equal to rock tensile strength T. Such rock strength can be derived from the unconfined compressive strength (i.e. $T = C_0/12$, based on the extended Griffith criterion), or as directly measured by the extended leak-off test. For previously fractured rocks, $T = 0$, and this value is used in the following calculations in order to provide a lower limit on the estimated upper bound mud weight.

Wellbore stability charts are presented in terms of equivalent mud weight against well depth since it is the mud weight that drilling engineers can effectively monitor and use to control wellbore stability (e.g. Steiger and Leung, 1989; Addis et al., 1993; Tan et al., 1994). The calculated mud weight stability profiles bounded by the lower and upper limits for various tectonic stress regimes are shown in Figs. 5, 6 and 7. Wellbore stability can be improved by inclined wells if an optimum drilling direction and deviation angle are adopted, as demonstrated by the fact that the equivalent mud weights in the optimum deviated wells are lower than vertical wells for controlling compressive failure, and higher than vertical wells for avoiding tensile failure (Figs. 5–7). Perhaps surprisingly, deviated wells may be

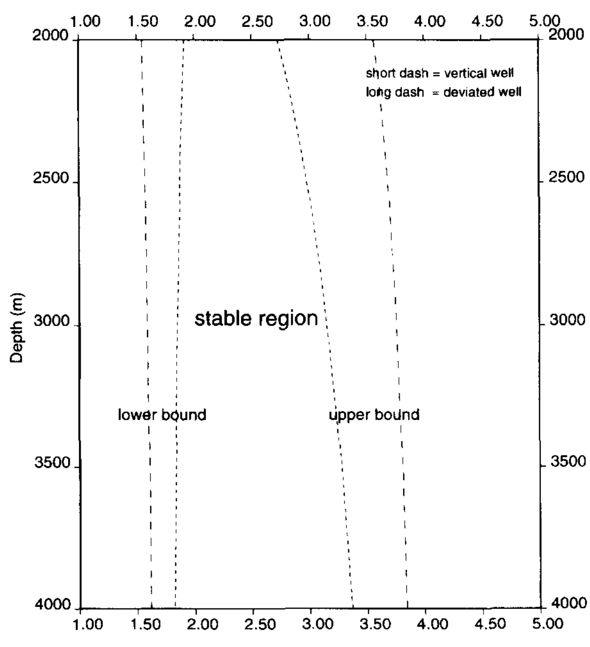

Fig. 6. Same as in Fig. 5 except that the stress regime is strike-slip with $\sigma_H = \sigma_v + 10$ MPa and $\sigma_h = \sigma_v - 5$ MPa, and the well aligment is given by $\alpha = 30°$ and $\beta = 90°$.

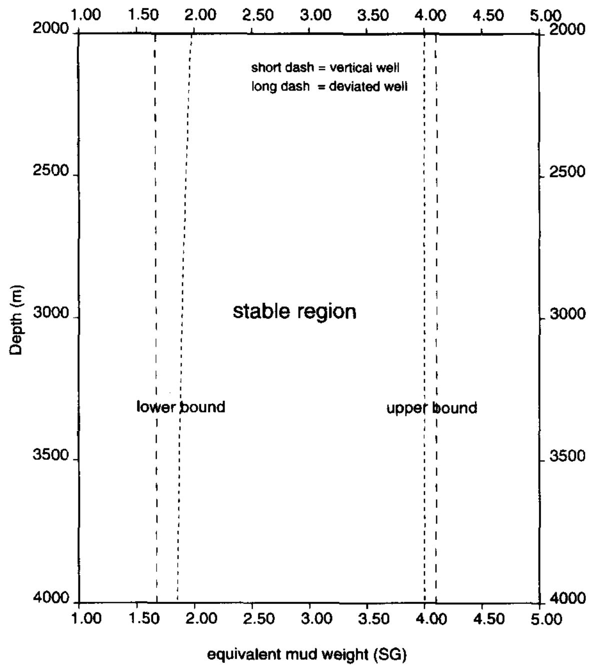

Fig. 7. Same as in Fig. 5 except that the stress regime is in reverse with $\sigma_H = \sigma_v + 15$ MPa and $\sigma_h = \sigma_v + 5$ MPa, and the well aligment is given by $\alpha = 0°$ and $\beta = 60°$.

more stable than vertical wells, especially in the strike-slip stress regime.

As for rock spalling associated with plastic failure, we have also shown that improvement of wellbore mechanical stability could be achieved by adopting an optimum drilling direction and deviation angle as described in this paper (details have been described in Zhou et al., submitted).

5. Fracture intersection

Deviated drilling has led to the exploitation of naturally fractured reservoirs, the intergranular porosity of which would not permit their economic exploitation, such as the Austin Chalk and Bakken Shale of USA (e.g. Kulch, 1990; Fritz, 1991). In order to maximize recovery from a fractured reservoir, wells should be inclined at a high angle to the fractures. Hence a pre-drilling assessment of open fracture orientation is a crucial development parameter. The existence and orientations of fractured zones can be detected using downhole seismic shear wave anisotropy and borehole televiewer or imager data (e.g. Martin and Davis, 1987; Queen and Rizer, 1990; Winterstein and Meadows, 1991; Toksoz et al., 1992). However, knowledge of the stress field and failure mechanisms can also indicate most likely open natural (and induced) fracture directions.

There are two key modes of fracture initiation: compressive shear failure and tensile failure. Based on the Mohr-Coulomb theory, compressive shear fracturing will occur in one or a pair of conjugate planes which are parallel with the direction of the intermediate principal stress, and are both oriented at an angle less than 45° to the direction of the maximum principal stress. Assuming that one principal stress is vertical, the common types of faulting are illustrated in Fig. 8a–c. Many laboratory tests on common sedimentary rocks such as sandstones have revealed that the angle of failure plane with respect to the orientation of the maximum principal stress is generally in the range of 20 to 35° (Fjaer et al., 1992, ch. 3). The type of shear fracturing is dependent on the relative values of the principal stresses, according to the Mohr-Coulomb failure criterion. So in a normal fault stress regime a high-angle (with respect to the horizontal plane) fracture zone occurs, whereas a low-angle fracture zone occurs in a reverse fault stress regime, and a vertical fracture zone in a strike-slip fault stress regime.

Tensile failure occurs when pore pressure in the rock formation is sufficiently high such that (Anderson, 1951):

$$Pp \geq \sigma_3 + T \tag{14}$$

provided $\sigma_1 + 3\sigma_3 < 4P_p$ (symbols are listed in Table 1). The plane of such tensile failure (open fracture) is perpendicular to the axis of σ_3, so that in an extensional or strike-slip environment tensile open fractures are vertical and parallel to the azimuth of σ_H, and in a compressional environment they are horizontal (Anderson, 1951; Jaeger and Cook, 1969). The initiation and orientation of hydraulically-induced fractures are the same as those for natural tensile fractures described above; however, in order to initiate a hydraulically-induced fracture the pore or fluid pressure is artificially increased.

The orientations of natural fractures need not to be related to the contemporary in-situ stress field. Natural fractures may have been created in a palaeo-stress regime different to the contemporary stress field. However, if natural fractures are in an orientation inconsis-

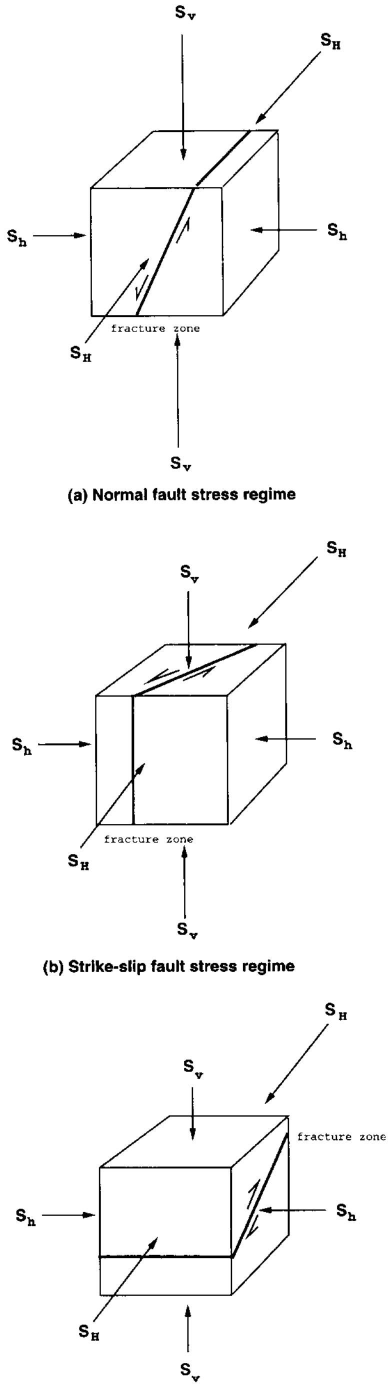

Fig. 8. Natural open fracture zone orientations with respect to the in-situ principal stresses in various stress regimes (adopted from Anderson, 1951), in which $S_v = \sigma_v$, $S_H = \sigma_H$, and $S_h = \sigma_h$. For simplicity, only a single fracture plane resulted from compressive shear failure is illustrated.

tent with the contemporary in-situ stress field, they are not likely to remain open and hence will tend to be non-productive (Martin and Davis, 1987; Hillis and Williams, 1993b). Any change of stress regimes from the palaeo-stress field to the contemporary stress field is likely to cause fracture closure by the increase of normal stress on the fracture plane. Therefore, the only productive naturally fractured reservoirs are likely to be those in which fracture orientation is consistent with that which a newly initiated fracture would have in contemporary stress field.

To justify the claim that natural fractures are likely to remain productive only if the orientations of such fractures are consistent (i.e. parallel to one of the principal stress axes) with the contemporary stress field, consider the normal stress across a fracture plane in a stress field. Following Anderson (1951), and taking the present principal stress axes as the reference axes, the normal stress an acting on the plane is given by (Jaeger and Cook, 1969, p. 27)

$$\sigma_n = k_v^2 \sigma_v + k_H^2 \sigma_H + k_h^2 \sigma_h \tag{15}$$

where k_v, k_H and k_h are the directional cosines of the normal vector on the plane, and are connected by the relation:

$$k_v^2 + k_H^2 + k_h^2 = 1$$

It follows from Eq. (15) that the normal stress is greatest where k_v, k_H and k_h are all non-zero, i.e. the strike of the fracture plane is not parallel to one of the principal stress axes. In addition, it can be easily shown that: (1) σ_n reaches a minimum value of σ_h in both normal and strike-slip fault stress regimes where the fracture plane is vertical and strikes along the azimuth of σ_H; (2) σ_n reaches a minimum value of σ_v in a reverse fault stress regime where the fracture plane is horizontal.

In order to exploit naturally, or hydraulically-induced, fractured reservoirs the wellbore should be oriented at a high angle (orthogonal) to open fractures. It follows that in order to maximize recovery from fractured reservoirs wells in both extensional and strike-slip stress regimes should be drilled horizontally along the azimuth of σ_h, and in a compressional stress regime wells should be drilled vertically.

Combining the implications of the contemporary stress field for wellbore mechanical stability with those for fracture intersection, it is suggested that:

- wells in an extensional stress regime should be highly deviated from vertical (at about 55 to 70°) and drilled along the azimuth of σ_h;
- wells in a strike-slip stress regime should be horizontal and drilled at 55° to 70° with respect to σ_H;
- wells in a compressional stress regime should be slightly deviated from vertical (at about 20 to 35°) and drilled along the azimuth of σ_H.

It is also concluded that solutions to the problems of mechanical stability and fracture intersection can be mutually consistent, particularly in both the extensional and the strike-slip stress regimes where $0.9 \leq n_H \leq 1.1$ as indicated by Figs. 2 and 3, and in the compressional stress regime where n_H is close to n_h (Fig. 4).

6. Application to the North West Shelf of Australia

Borehole breakout studies from the North West Shelf of Australia have shown that the azimuth of σ_H is oriented roughly NE–SW in the Vulcan area of Timor Sea, and that it rotates about 45° clockwise to E–W in the Barrow–Damiper area (Hillis, 1991; Hillis and Williams, 1992, 1993a) (Fig. 9). This pattern of stress orientation is consistent with the results from finite element modelling of the intraplate stress field of the Indo-Australian plate (Cloetingh and Wortel, 1986; Zhou et al., 1994; Coblentz et al., submitted). Modified leak-off tests carried out at Cossack-2 and 3 and Wanaea-4 show that the stress regime in the Wanaea/Cossack field is on the boundary between extension and strike-slip (Hillis and Williams, 1993a; see Enever, 1988, for further discussion of the modified leak-off test).

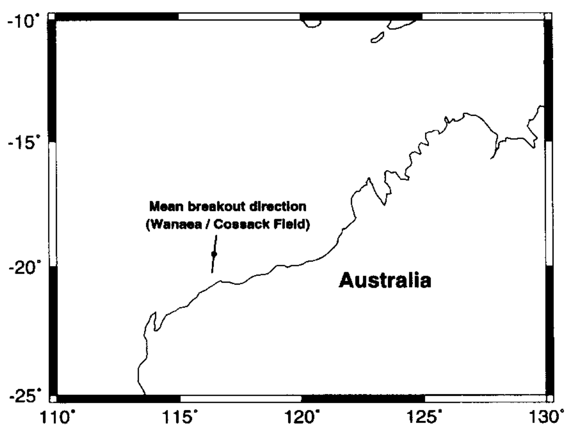

Fig. 9. Location of study area showing the mean borehole breakout orientation in the Wanaea/Cossack Field of Barrow–Dampier area in the North West Shelf of Australia.

Combining the above data on the contemporary stress field with the results of this stduy suggests that wells in the Wanaea/Cossack area should be drilled horizontally along the azimuth of σ_h, which is the mean breakout orientation of 005–010°N, for both maximum mechanical stability and maximum recovery from any fracture systems in the reservoir.

7. Conclusions

In this paper an integrated approach for the analysis of both mechanical stability of inclined wellbores and optimization of their intersection with open fractures has been presented. Wellbore stability can be significantly improved by adopting an optimum deviation angle and drilling direction at which the shear stress anisotropy around the inclined wellbore wall is minimized. Based on the commonly adopted Mohr-Coulomb failure criterion, and the assumption that rock surrounding the well can be reasonably described as linearly elastic and isotropic, predictions from mud weight stability profiles show that, contrary to intuitive expectation, in a highly anisotropic horizontal stress field (usually a strike-slip environment) inclined wells may be more stable than vertical wells, given selection of the correct drilling direction and deviation angle. This is consistent with an independent study on the mechanical stability of inclined wellbores (Tan et al., 1994). It has also been shown that the drilling direction and deviation angle which maximizes open natural or hydraulically-induced fracture intersection is consistent with that required for maximizing mechanical stability in both the extensional and the strike-slip stress regimes where $0.9 \leq n_H \leq 1.1$, and in the compressional stress regime where n_H is close to n_h.

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