Journal of Structural Geology 32 (2010) 1061–1069

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Stress determination in active thrust belts: An alternative leak-off pressure interpretation

Brent A. Couzens-Schultz*, Alvin W. Chan

Shell International E&P, Inc., P.O. Box 481, Houston, TX 77001, United States

ARTICLE INFO

Article history:
Received 12 May 2009
Received in revised form
17 June 2010
Accepted 20 June 2010
Available online 25 June 2010

Keywords:
Stress
Stress determination
Thrust
Compression
Wellbore stability
Leak-off test

ABSTRACT

In thrust belts, fluid flow through critically stressed fractures will occur at pressures less than the overburden stress, which is the minimum stress. We propose that low leak-off pressures obtained in active thrust belts may result from this mechanism, leading workers to infer that apparent minimum stresses are 30–60% less than the overburden stress in some compressional settings. Traditionally, leak-off pressure data have been used to constrain the magnitude of minimum stress, assuming that the rock is dilating against the minimum stress during a leak-off test. In our new interpretation, we constrain the stress state by assuming that the leak-off test causes shear failure along pre-existing weaknesses rather than tensile opening. While this mechanism has been discussed in a small number of borehole stability and hydraulic fracture papers, it has not been directly applied to leak-off tests. We considered this interpretation because we observed that some leak-off tests imply an apparent contradiction between the stress states from the standard interpretation of leak-off tests versus the stress state inferred from geologic and geophysical evidence in tectonically active thrust belts. We present two examples with one in an onshore fold–thrust belt and one in a deepwater fold–thrust belt. Our new interpretation of stresses based on shear failure resolves the contradiction and also provides a constraint on the maximum horizontal stress in the fold–thrust belts.

1. Introduction

Leak-off tests are commonly used to interpret the minimum stress magnitude (Baumgartner and Zoback, 1989; De Bree and Walters, 1989; Sarda et al., 1992; Addis et al., 1998; Yamamoto, 2003; Zoback et al., 2003). The test is a routine procedure used to determine the pressure at which the exposed formation will fracture (the fracture pressure). It is performed with drilling mud, which is also the material that is circulated through the borehole during drilling. The mud is composed of a mixture of water or oil, clays, weighting materials and other chemicals that are used to control its properties including viscosity and density. Drilling mud prevents destabilization of the wellbore walls and is used to counteract the pressure of fluids inside the rock so that they cannot enter the wellbore. In an open borehole, if the mud density, or mudweight, needed to prevent either destabilization or fluid influx becomes large enough, it will exert a pressure that fractures the rock exposed in the shallow portion of the borehole. Setting borehole casing at regular intervals during the drilling process to isolate the shallower rock from the mudweight pressure prevents this fracturing.

When casing is set, a leak-off test (LOT) is performed to determine the fracture pressure at the base of the casing and thus, the upper limit to the mudweight for further drilling of the borehole before additional casing will need to be set. A LOT is a pumping pressure test, similar to a fracture test. After the casing is cemented in place, a few meters of open hole is drilled out below the casing. During the test, the well is shut-in and pressurized by drilling mud delivered through the drill pipe from a cementing pump set on the drill rig floor (Fig. 1a). The pressure in the open hole is the sum of the weight of the drilling fluid column and the pumping pressure. During pumping, pressure is measured at the surface and sometimes by a gauge that is placed on the bottom of the hole. Over time, or volume pumped, the mud pressure builds linearly as the mud column compresses and the casing and rock around the borehole expands elastically. When fluids begin to enter the surrounding rock from the borehole, or "leak-off", the pressure build-up will deviate from this linear trend (Fig. 1b). The point where this deviation occurs is known as the leak-off pressure (LOP). The LOP then dictates the greatest mudweight that can be used to drill the next section of open borehole.

Most commonly, casing is set and a LOT is performed in a low permeability mudrock. In these cases, the leak-off pressure is assumed to reflect either the opening of existing fractures in the

* Corresponding author. Tel.: +1 281 544 3272.
E-mail address: Brent.Couzens@shell.com (B.A. Couzens-Schultz).

0191-8141/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2010.06.013

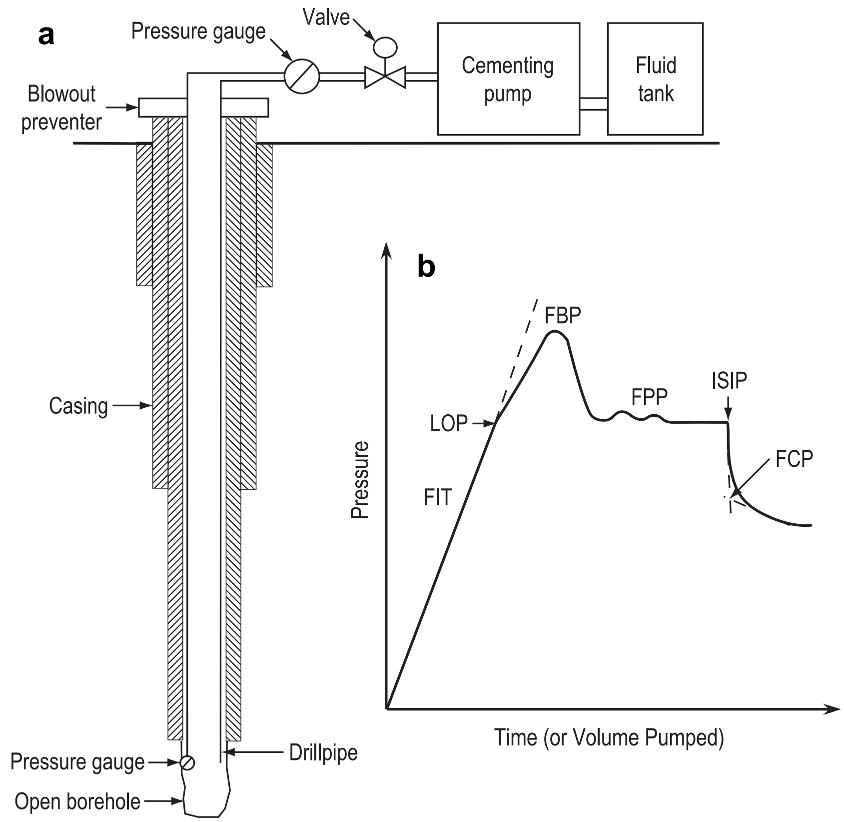

Fig. 1. (a) Schematic borehole configuration during a leak-off test (after Yamamoto, 2003). (b) Schematic extended leak-off test results (after White et al., 2002). The horizontal axis may be mud volume pumped in borehole or time up until shut-in. FIT = formation integrity test, which is a test that ends prior to leak-off. LOP = leak-off pressure. FBP = fracture breakdown pressure. FPP = fracture propagation pressure. ISIP = instantaneous shut-in pressure. FCP = fracture closure pressure.

rock, or the initiation of a new tensile fracture. Therefore, at leak-off, the mud pressure in the open borehole may represent the minimum stress in a fractured or weak formation, or the minimum stress plus the tensile failure strength of an intact borehole, which is controlled by local stresses around the borehole (Fig. 2a). Guidelines for interpreting LOT data often conclude that leak-off pressures in mudrocks can be used as reasonable estimate of the least principal stress (Baumgartner and Zoback, 1989; De Bree and Walters, 1989; Sarda et al., 1992; Addis et al., 1998; White et al., 2002; Yamamoto, 2003; Zoback et al., 2003). However, issues do exist with testing procedures, equipment, and interpretation that lead to uncertainties (Kunze and Steiger, 1991; Enever et al., 1996; Gjønnes et al., 1998; Raaen et al., 2006). To overcome these uncertainties, the LOT can be run further as an extended LOT (Fig. 1b) to determine a fracture closure pressure (FCP, Fig. 1b; Gaarenstroom et al., 1993), which is measured after pumping is stopped and drilling fluids are no longer propping open any existing or created fractures. The test can also be run multiple times (e.g., Yamamoto, 2003), and a consistent fracture closure pressure gives greater confidence in the minimum stress interpretation. However, due to the test duration and associated cost, simpler tests that run to only leak-off pressure are most common in the oil and gas industry. The data discussed in this paper includes some tests taken only to leak-off pressure and some extended tests taken through one cycle to fracture closure pressure (Fig. 1b).

In a deltaic basin on a passive margin, where both horizontal stresses are less than the overburden, it is assumed that during a LOT, any fracture that is generated will be approximately vertical and normal to the minimum horizontal stress and the LOP will reflect the minimum stress magnitude. In an active thrust belt setting, where horizontal tectonic compressive stresses are expected, the minimum stress is close to vertical. Therefore, we assume that any fracture generated during a LOT will be sub-horizontal and the LOP should be near overburden.

In a compressive system, it is possible that overburden is not exactly the minimum stress because the principal stresses in thrust systems can be rotated near active thrust faults or detachments (Hafner, 1951; Last and McLean, 1996). If the stresses are rotated, then the minimum stress will be less than the overburden pressure. To obtain an upper bound for how much less the minimum stresses could be, we examined the difference between the minimum principal stress and the overburden stress assuming the stress field is rotated 30°. The difference between the maximum and minimum principal stresses is a function of the frictional properties (e.g., Jaeger and Cook, 1979). If we assume that the rocks fail according to Byerlee's (1978) law and that the minimum stress is vertical, a simple Mohr Circle analysis shows that in a hydropressured compressional system the maximum stress can be two to three times greater than the minimum stress. Using a maximum to minimum stress ratio of two to three, simple stress ellipse geometry shows that the difference between the minimum principal stress and the vertical stress is about 10%. Therefore, including rotated compressive stress fields, we might expect all leak-off pressures in compressive settings to be between 90% and 100% of the overburden pressure.

However, drilling experiences reveal that the leak-off pressure in thrust belts can be much less than 90% of overburden, in some cases up to 60% less. This experience has lead to interpretations of normal fault and strike-slip stress regimes in these thrust systems (e.g., Last and McLean, 1996; Tutuncu et al., 2006; Lin et al., 2007). One explanation is that the current stress state in a fold and thrust belt has evolved to strike-slip conditions due to a stress drop

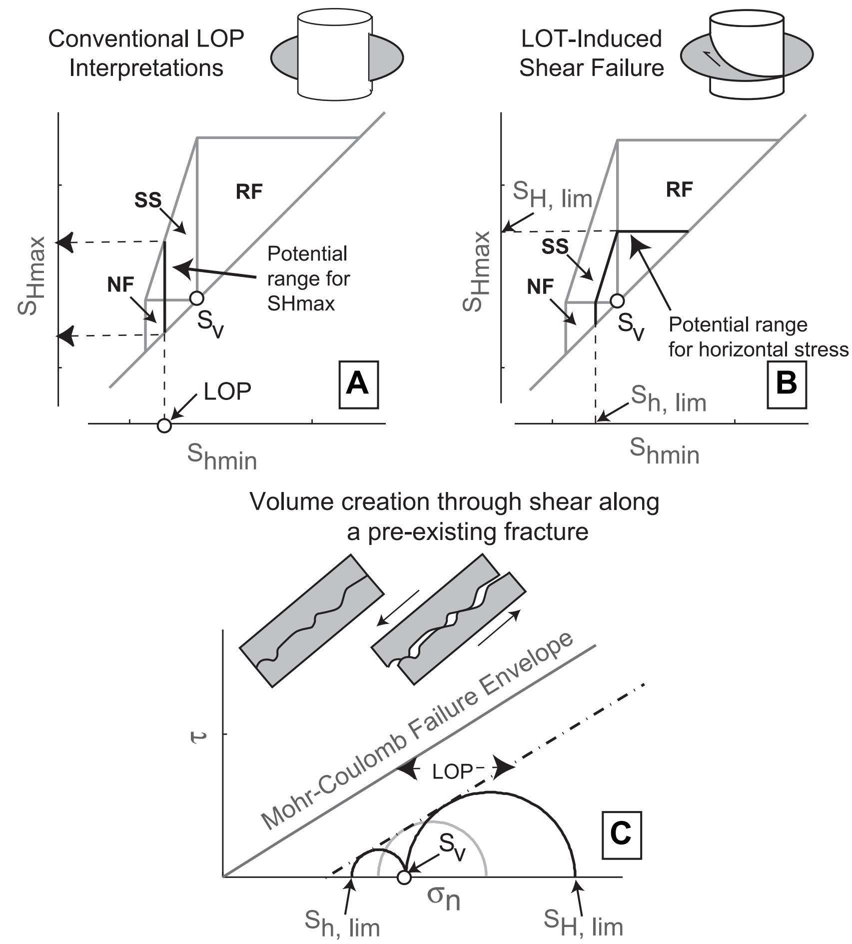

Fig. 2. We use the stress polygon (see Zoback et al., 1987) to constrain the range of possible stress state at a given depth. The lower bound of the polygon is the line where minimum horizontal stress ($S_{h\min}$) equals maximum horizontal stress ($S_{H\max}$). The left-sides and upper bound for the polygon are determined by frictional equilibrium for a given coefficient of internal friction (we use 0.6) such that shear failure will occur at stress states on those boundaries. Overburden stress (S_v), shown as the white circle, is used to divide the polygon into three zones: normal faulting (NF) if $S_{h\min} < S_{H\max} < S_v$, strike-slip faulting (SS) if $S_{h\min} < S_v < S_{H\max}$, and reverse-faulting (RF) if $S_v < S_{h\min} < S_{H\max}$. (a) Conventional interpretation of stress from LOP, where the range of possible stresses is shown by the thick black line. (b) Our new alternate interpretation of stress states in the case of shear failure on a pre-existing discontinuity during a LOT, where the range of possible stresses is shown by the thick black polygon. $S_{h,\ \lim}$ is the least possible minimum horizontal stress for the shear failure interpretation. $S_{H,\ \lim}$ is the greatest possible horizontal stress. (c) We constrain the stress state in (b) by assuming a frictional failure envelope and using the known S_v and LOP. The dashed line shows the failure criterion shifted by the LOP along the normal stress axis. The small black Mohr circle on the left shows the normal-fault stress case. The larger black Mohr circle on the right shows the reverse-fault stress case. A grey Mohr circle shows one of the possible strike-slip fault stress cases. Cartoon shows that shear failure may produce dilation in the deforming rock.

following deformation. However, most of these examples have clear geologic evidence for active compression supported by GPS motions, focal mechanisms, and/or growth sediments.

We consider two examples where leak-off pressures are significantly less than overburden pressure, while other evidence points to a compressive stress field. The two examples create a picture that suggests a potential conflict between stresses interpreted from hydraulic leak-off tests and stresses interpreted from geologic and geophysical indicators. Our intention is to present an alternative interpretation of LOT data that would reconcile such a conflict. Our hypothesis is that, in some cases, the LOT results reflect shear on pre-exiting weaknesses rather than tensile opening and that in those cases the LOT data does not reflect minimum stress conditions. The difference between LOT with tensile failure and those with shear failure is most evident in compressive settings, where large differential stresses favor shear failure, but we believe that the effect can be observed in all tectonic settings.

An example may be the recent results from the Nankai accretionary prism drilling project. There, some LOT data and fracture tests suggest minimum horizontal stress is less than overburden stress (Kano et al., 2009; McNeill et al., 2009), but borehole breakout and drilling induced fractures suggest that minimum horizontal stress is at or above overburden stress (Chang et al., 2009). As a result, Chang et al. (2009) proposed that stress variation is not gradual, but abrupt. We propose that instead of an abruptly changing stress state, the stress is compressive everywhere with overburden as the minimum stress. In our proposed interpretation, the LOT and fracture tests are reflecting shear failure instead of the minimum stress.

While we generally focus on the interpretation of leak-off tests, we believe that the concept presented is of significant interest to any geologist working on understanding stress magnitudes in tectonic settings. Our hypothesis, should it be correct, offers an opportunity to constrain the magnitude of the maximum horizontal stress in active thrust belts. Until now, the understanding of stress magnitudes in thrust systems has been problematic. Workers modeling thrust systems only have relative stress magnitudes, but, magnitudes are important when constraining rock properties, compaction state, fluid flow, etc. (e.g., Dula and Crook, 2007; Yardley and Couzens, 2007). As a result, the implications of this hypothesis should be of interest to anyone attempting to mechanically model compressive systems (e.g., Erickson, 1995; Jamison, 1996; Luo et al., 2006; Dula and Crook, 2007; Stockmal et al., 2007). In addition, our hypothesis can easily be expanded to any *in situ* stress state, making it of interest to anyone building a geomechanical model in a tectonically active setting, be it for understanding compaction history, fluid flow, seal capacity for hydrocarbons or CO_2 sequestration, reservoir production modeling, or any of a number of other applications and investigations (e.g., Tingay et al., 2005). Our hope is that structural geologists participating in these types of investigations will look for ways to verify or discount our hypothesis using other information such as strain distributions and history, compaction data, or other rock properties that reflect the stress state that a rock has experienced.

2. Hypothesis for shear interpretation of leak-off pressure

We will now present our hypothesis for the analysis of cases where LOT data conflict with other information about stress or deformation state in a rock volume. Often LOT data are ignored as "bad" because they do not match the expected results. This behavior is commonly the case when the pressure during testing deviates from a linear trend early, giving the graphed pressure vs. volume a curved shape rather than a long linear build-up (Fig. 1b). We propose that this effect can be due to reactivation of a fracture system or discontinuity by shear failure (Fig. 2). Similar to the concept of determining hydraulic conductivity of critically stressed fractures (e.g., Zoback and Healy, 1992), we propose that the fluid loss associated with these 'abnormal' leak-off tests occurs along some pre-existing plane of weakness that is or becomes hydraulically conductive during the testing procedure. In contrast to the typical methodology of identifying critically stressed fractures for a known stress state, our interpretation utilizes the observed leak-off pressure along with a given fracture or fault orientation to invert for the background stress state.

The plane of weakness is a permeable, pre-existing joint or fault where fluid entry is not blocked by mudcake formation. Mudcake forms as a sheath along the borehole wall where water-based mud fluid invades a permeable formation and leaves suspended particulates behind. Assuming little or no mudcake formation, when borehole fluid pressure is increased, fluids will penetrate the fractures or discontinuities and interact with the regional stress field in the host rock. Because we assume that fluids can enter the permeable discontinuity, we do not need to consider wellbore-wall stress effects. This approach is similar to the standard LOT interpretation that assumes minimum stress is simply related to opening existing fractures. As pore pressure from the borehole fluid increases in the fracture system, the fracture is, in our case, induced to fail in a shear mode due to relatively large differential stress. The shear failure would create mixed mode fractures, opening up volume in the nearby rock (Fig. 2c).

Fig. 2c illustrates the inversion of background stress from leak-off pressure assuming shear failure along an optimally oriented pre-existing plane of weakness as the failure mechanism. Because we are focused on tectonically active settings in this paper, we constrain our analysis to an optimally oriented fracture or discontinuity, which is likely to be present in an actively deforming setting. The method, however, may be expanded to consider non-optimally oriented discontinuities. We utilize the Mohr–Coulomb shear failure criterion as the yielding criterion for its simplicity (other criteria can be used if needed). Our calculations are in total stress. In a Mohr diagram, the Mohr circle that represents the *in situ* stresses acting on a fault plane will shift along the normal stress axis towards smaller stresses as pore pressure increases until the Mohr circle contacts the failure criterion. Because the differential stress is unaffected by the pore pressure increase, the size of the Mohr circle remains the same (Twiss and Moores, 1992). Typically, the amount of fluid pressure needed to induce shear failure along a discontinuity is calculated based on the failure criterion required for slip and the given stress state, which determines the size and position of the Mohr circle (e.g., Eq. (1) in Finkbeiner et al. (2001)). This amount of fluid pressure is equal to the shift along the normal stress axis required to place the Mohr circle in contact with the failure criterion (e.g., Twiss and Moores, 1992). In our scenario, we have reversed the workflow. We use the observed leak-off pressure as the fluid pressure required to induce shear together with the failure criterion and then invert for the Mohr circles to determine the range of possible *in situ* stress states. Unlike the forward model, which gives a critical pressure for slip on a fracture, the inversion yields a family of Mohr circles in contact with the shear failure criterion, and hence a family of stress states consistent with shear failure on a pre-existing fracture.

For simplicity, if vertical stress is one of the principal stresses, the family of Mohr circles will be bounded by a lower limit, which is the smallest that the minimum horizontal stress can be for any possible solution, $S_{h,\lim}$ (left Mohr circle on Fig. 2c), and an upper limit, which is the largest that the maximum horizontal stress can be for any possible solution, $S_{H,\lim}$ (right Mohr circle on Fig. 2c). The two limits can be determined from the two Mohr's circles where each circle has the vertical stress as a principal stress and is in tangential contact with the shifted failure criterion. Graphically, since we know the vertical stress, we shift the failure criterion line to greater normal stresses (dashed line, Fig. 2c) and then determine the two limiting Mohr circles (black circles, Fig. 2c), each of which terminate at the value of the vertical stress. The lower limit will be a normal faulting case, where both horizontal stresses are less than the vertical stress and can be expressed as:

$$S_{h,\lim} = S_v - \frac{2(S_v - (LOP - C_0/\mu))\sin\phi}{(1+\sin\phi)} \tag{1}$$

The upper limit will be a reverse-faulting case, where both horizontal stresses are greater than the vertical stress. It can be expressed as:

$$S_{H,\lim} = S_v + \frac{2(S_v - (LOP - C_0/\mu))\sin\phi}{(1-\sin\phi)}, \tag{2}$$

where C_0 = cohesion, S_v = vertical stress, and μ = coefficient of friction = $\tan(\phi)$.

In-between these two limiting stresses, shown as a grey circle on Fig. 2c, lies a series of Mohr circles that represent strike-slip faulting conditions, where the vertical stress is intermediary and the Mohr circle is defined by the minimum and maximum horizontal stresses. This family of Mohr circles can then be translated and represented as a new constraint in a stress polygon (Fig. 2b) commonly used in stress characterization studies (Zoback et al., 1987). On the stress polygon, the line defined by $S_{H,\lim}$ is the horizontal constant S_H line in the reverse-fault field. The line defined by $S_{h,\lim}$ is the vertical constant S_h line in the normal fault field. The sloping line in the strike-slip field is defined by the stress states represented by all the possible Mohr circles in-between the limiting ones shown in Fig. 2c. Similar to currently used stress interpretation, when combining the new stress constraint with independent observations from conventional wellbore breakouts or drilling induced tensile failure analysis, an *in situ* stress state can be inferred.

One distinct characteristic of our alternate approach is the capability to constrain the magnitude of the maximum horizontal stress for a reverse-faulting environment. While the traditional interpretation involving a mode I tensile fracture may accurately measure the minimum principal or vertical stress in a reverse-faulting stress regime, it will only reconfirm the magnitude of the overburden without providing additional information on the magnitude of the two horizontal stresses. If shear reactivation along a pre-existing plane of weakness is the cause of the fluid loss during the testing procedure, the 'abnormal' test results may be considered as a rare opportunity to characterize the maximum horizontal stresses in compressional settings.

The idea that drilling fluid can reactivate pre-existing features is not new. It has been discussed largely in terms of borehole stability rather that LOT results (e.g., Maury and Sauzay, 1989; Addis et al., 1993). When a well is drilled, a mechanical balance is achieved to prevent breakouts and drilling induced fractures. In certain situations, that mechanical balance may also consider a third, less discussed, phenomenon, shear displacement of pre-existing weak structures (Addis et al., 1993). This analysis is similar to induced seismicity by fluid injection, where pressure build-up can induce shear movements. In many cases when drilling difficulties in open holes are not mitigated by in increasing mudweights, clays and borehole chemistry are usually considered to be the problem. However, reactivation of faults by high mudweights is a potential alternative explanation (Maury and Sauzay, 1989). Reactivated fractures that slip in shear failure are difficult to document, still, they have been observed by borehole televiewer data (Héloit et al., 1989). Using borehole-imaging data, a perspective view of the borehole, deformed by small shear slippage on a fracture, can be constructed to relate the movement direction to the orientation of *in situ* stresses (Héloit et al., 1989).

Existing fracture models have been modified to quantify the influence of *in situ* state of stress, fracture friction angle, wellbore pressure, mud invasion in the fracture plane, and fracture orientation on the shear stability of the fracture (Atkinson and Thiercelin, 1995, 1997). These models show that fracture reactivation is likely to occur and depends on orientation of the wellbore and fracture. The models demonstrate that the reactivation could be used for stress determination as suggested by Héloit et al. (1989).

Hydraulic fracturing for well stimulation also shows that shear failure along pre-existing weak zones can occur and that volume for fluid loss from the borehole can be created by this mechanism (Chipperfield et al., 2007). Volume creation, or shear dilation, is important because that is what is used to recognize failure on the volume–pressure plots that are used to interpret LOT data (i.e., the departure from a linear pressure-time trend on Fig. 1b). For water fracture treatments, technologies known by various names, such as low proppant, no-proppant, or proppant-free rely on the process of shear dilation (Hossain et al., 2002). The basic argument is that once shear begins to occur, the fracture walls are displaced, creating asperities and natural mismatches that effectively prop the fracture system open (Fig. 2c).

Our approach to the analysis of LOT results for the case of a reverse-fault regime can be applied to all stress regimes as well as reactivation along any arbitrarily oriented fault. It is also applicable to any test or event that is related to measuring minimum stress, such as mini-frac tests, dynamic formation integrity tests, or lost-circulation events during drilling.

3. Examples from active thrust belts

3.1. Camisea, Peru

The Camisea gas field is located in the Peruvian Andes foreland (Fig. 3), where the main structures are thrust faults and fault-related folds (Shaw et al., 1999). In the context of possible evidence for present-day deformation in the region, the authors are not aware of any GPS data to document present-day shortening in the area. A micro-earthquake survey documented reverse-fault focal mechanisms approximately 100 km to the west of the Camisea area in the Andean foothills (Dorbath et al., 1986).

A borehole stability analysis study was conducted to assess drilling risks for the development of the Camisea gas field, where the current tectonic environment is characterized by active thrusting toward the northeast (Tutuncu et al., 2006). The structure of the field is characterized by a series of imbricate thrust sheets, which are bounded towards the foreland by backthrusts to form a triangle zone (Fig. 3). Two prospects (Prospect P and Prospect S) are located in a thrust sheet bound by the frontal backthrust. A third prospect, Prospect C, is located in an imbricate thrust sheet behind the frontal structure.

For the borehole stability study, the magnitude of the overburden pressure was obtained by integrating the bulk density over the depth interval in two wells in the area. Formation pressure tests indicate the absence of any overpressured interval (Tutuncu et al., 2006). Breakouts were observed (Tutuncu et al., 2006, their Fig. 1) and can be used to constrain the stress state. Details about the mechanical properties used to interpret the breakouts can be found in Tutuncu et al. (2006).

In this setting, we would expect overburden to be the least principle stress. However, two different LOT responses were observed at Camisea (Fig. 4, Table 1). At the Prospect S and Prospect C wells, the leak-off tests exhibit a linear build-up and LOP is consistent with the overburden being the minimum stress. Combined with the breakout data, the stress state at Prospect S is constrained to a set of reverse-fault stress states (Fig. 4a). At the Prospect P well, the extended LOT shows a shorter linear build-up and, as a result, a LOP substantially smaller than the overburden pressure (Fig. 4b). Tutuncu et al. (2006) interpreted the variability in LOP data as a reflection of the variations in minimum horizontal stress in the area. The lowest LOP is from Prospect P and is located closer to the main thrust fault underlying that structure as compared to the location of the LOP data from Prospect S and Prospect C relative to the main thrust fault underlying those structures. From this observation, Tutuncu et al. (2006) surmised that a stress drop, possibly related to motion on the underlying thrust fault for those structures, locally changed the stresses to strike-slip conditions. Instead, we suggest that the two different LOT responses may reflect two different failure mechanisms during leak-off. In the case of the Prospect S and Prospect C tests, the LOP reflects the traditional interpretation of tensile failure and minimum stress is therefore close to overburden pressure. Breakout data from Prospect S can then be used to constrain the stress state within the compressional field (Fig. 4a, black ellipse). In the case of the Prospect P test, we propose that the LOP reflects shear failure and does not reflect minimum stress. Using the data from Tutuncu et al. (2006), we determine a set of stresses at Prospect P (Table 1) that is consistent with shear failure during leak-off (Fig. 4b, thick black polygons). The maximum horizontal stress possible, determined from Eq. (2), is 51.9–58.7 MPa depending on the frictional sliding coefficient used (Table 1). With this interpretation, the breakout data at Prospect P constrain the maximum horizontal stress to the compressive field (Fig. 4b, white ellipse), not the strike-slip field (Fig. 4b, black ellipse). The new stress interpretation at Prospect P is then consistent with the stress field predicted at prospect S using a traditional LOT interpretation and the breakout data (Fig. 4a, Table 1). While this result is permissive of our hypothesis, it is not conclusive and down-hole data demonstrating shear offset after the LOT is not available.

3.2. A deepwater fold-thrust belt

Several offshore fold belts have recently been explored (e.g., Rowan et al., 2004). We examine a well recently drilled into one of these thrust folds (Fig. 5). Due to the proprietary nature of the well,

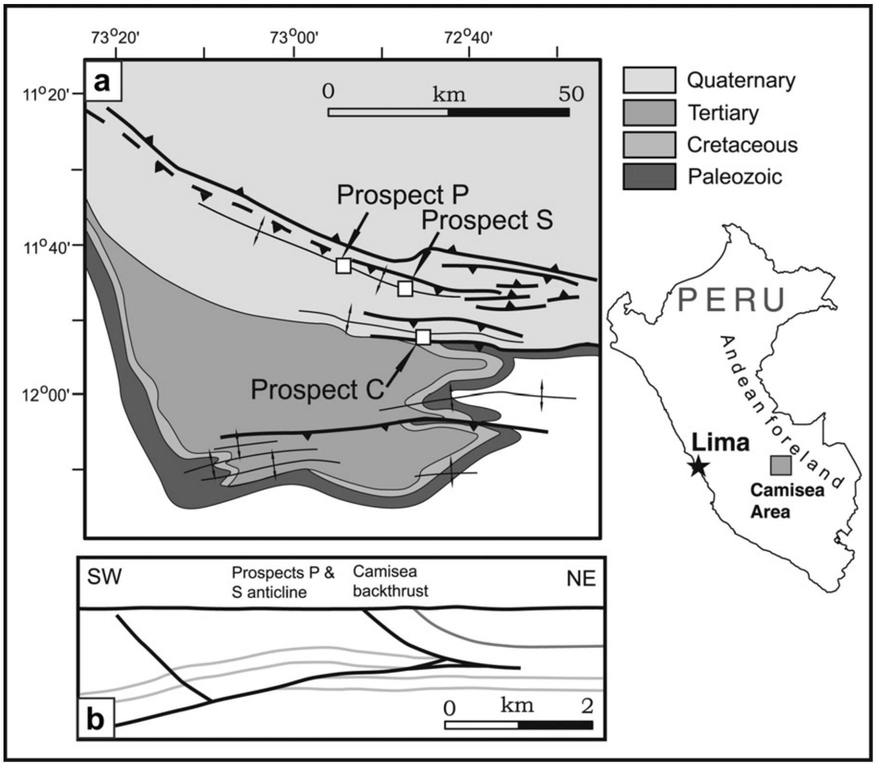

Fig. 3. Map showing the structures in the Camisea field, Peru with the location of the Prospect S, Prospect P and Prospect C wells (courtesy of A.N. Tutuncu et al., 1998 unpublished report). Location within Peru is indicated by the box shown on the map of Peru. Faults are shown in thick black lines and anticlines axes in thin black. (b) A schematic cross-section located to the SE of Prospect S with thrust faults shown in black.

we cannot divulge its location. However, we can provide information to develop an argument for present-day compressional stresses that explains not only the observed LOP data, but also changes in borehole shape, shear velocity anisotropy and reservoir porosity distribution.

In the shallow portion of the fold where normal faults are observed, we expect a normal faulting stress state (Fig. 5). The normal faults die out with depth toward an inferred neutral surface that is crossed by the well. Beneath that surface, we observe: (1) compressional mesostructures in whole core taken from the well, such as small cataclastic faults with reverse offsets through silt layers; (2) rocks that appear overcompacted for their present-day vertical effective stress based on three observations, (a) lower than expected porosity in sands, (b) a larger number of vertical

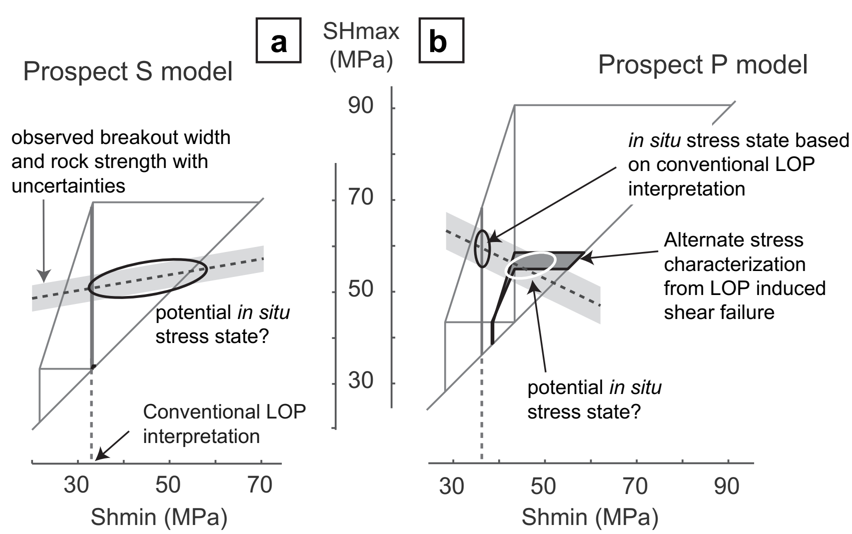

Fig. 4. Stress polygon plots showing two different LOT responses in the Camisea field, Peru. (a) The stress polygon at a LOT point in the Prospect S well, where the LOP is approximately equal to the overburden pressure. (b) The stress polygon at a LOT point in the Prospect P well, where the LOP is substantially less than overburden pressure. On both plots, the vertical line shows the traditional LOT interpretation; black lines with the dark grey shading show our alternative interpretation in (b). The light grey band with the dashed centerline shows the stresses implied by observed breakouts at each location (Tutuncu et al., 2006). The black ellipse on each plot shows stress states that are compatible with the breakout data and traditional interpretation of the LOT. The white ellipse shows stress states at Prospect P that are compatible with the breakout data and our alternative interpretation of the LOT that involves shear failure.

Table 1
Constraints on stress and calculation of the maximum horizontal stress, S_H, at the Camisea prospects (Figs. 3 and 4) and the deepwater foldbelt prospect (Figs. 5 and 6). Extended leak-off tests were run at the Camisea prospects. Tests for the deepwater foldbelt (DWFB) were run only to leak-off pressure (Fig. 1).

Well	S_v (MPa)	LOP (MPa)	Mu	SH, lim (Eq. (2))[a]	Interpreted S_H, (MPa)	Figure	Remarks
Camisea, Prospect S	33.3	33.0	N/A	N/A	50.5–55.0	Fig. 4a	LOT in foldbelt with minimum stress as S_v. S_H constrained by borehole breakout data.
Camisea, Prospect P	43.4	36.2	0.6	58.7	51.9–58.7	Fig. 4b	Interpreted S_H range based on shear failure during LOT.
Camisea, Prospect P	43.4	36.2	0.4	51.9	51.9–58.7	Fig. 4b	Interpreted S_H range based on shear failure during LOT.
DWFB shallow LOT	18.6	17.6	N/A	N/A	N/A	Fig. 5 (shallow point)	No data available to constrain S_H. Probable normal fault stress environment.
DWFB deep leak-off line	39.9	34.9	0.6	50.5	45.8–50.5	Fig. 6	Leak-off pressure projected to reservoir depth shown on Fig. 5. Interpreted S_H range based on shear failure during LOT.
DWFB deep leak-off line	39.9	34.9	0.4	45.8	45.8–50.5	Fig. 6	Leak-off pressure projected to reservoir depth shown on Fig. 5. Interpreted S_H range based on shear failure during LOT.

N/A – Not applicable because the LOT is not controlled by shear failure.
[a] $S_{H,\,\mathrm{lim}}$ – the maximum horizontal stress predicted for a compressive stress environment assuming negligible cohesion and shear failure during the LOT.

grain-to-grain contacts as compared to normally compacted sediments at a similar VES, and (c) higher measured shale densities as compared to normally compacted sediments at a similar VES, all of which implies an additional 750–900 m of burial even though no geologic evidence exists to indicate that such erosion and denudation of the existing geologic sequence occurred; (3) shear velocity splitting in sands with the fast direction normal to the fold axis; (4) an elliptical borehole from caliper data showing the long-axis parallel to the fold core. These observations, coupled with the structural setting of a fold–thrust belt, the current shortening direction observed, and the current tectonic maximum horizontal stress direction, both of which are at 90° to the fold axes indicates a present-day reverse-faulting stress state.

Three LOTs from a well were taken in the shallow section (Fig. 5). The pressures from these tests are just below the overburden pressure. Conventionally, this would mean that the minimum stress is near overburden and either the stress state is nearly isotropic or it is a reverse-fault stress state. Yet, this upper portion of the geologic sequence is where we observe normal faults and the rocks are normally compacted.

Two additional LOTs from the same well were taken in the anticlinal fold core and show LOPs substantially less than the overburden pressure (Fig. 5). Conventional interpretation of LOPs would infer that the minimum stress is horizontal and that the stress state is either a normal fault or strike-slip environment. Yet in this section, we observe no normal faults and the rocks are over-compacted with respect to their current vertical effective stress. Furthermore, the LOT data are likely in a location that experienced maximum horizontal compression. They are in the core of what appears to be an episodically active fold that has periods of quiescent deposition across it followed by onlapping deposition during and after fold growth.

On Fig. 6, we show two interpretations of the stress state at the depth of one of the reservoir units (Fig. 5, grey bar). First, the thick grey line shows the possible stress states if the LOTs represent minimum stress, resulting in either a normal or strike-slip fault

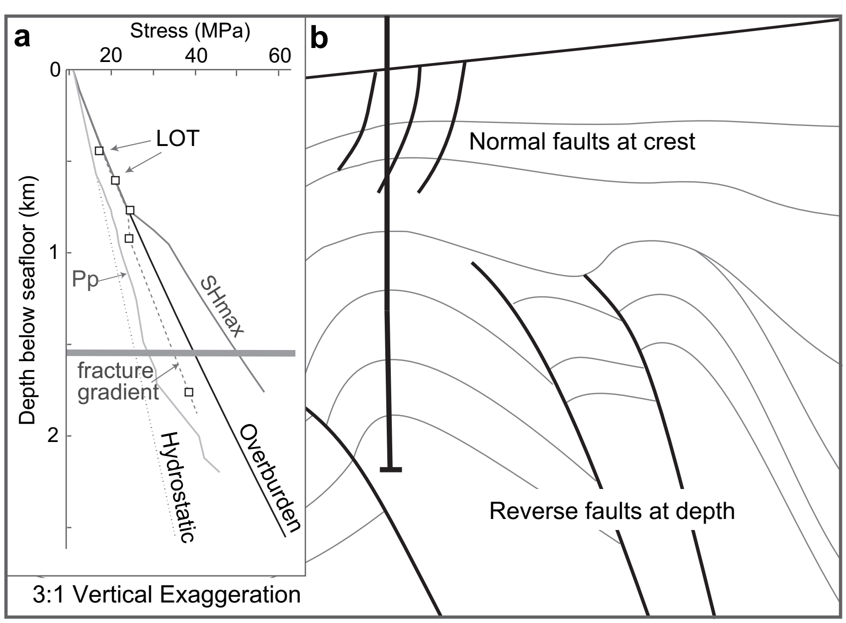

Fig. 5. Schematic cross-section and stress profile through a well in a deepwater fold belt. Pp = pore pressure. Squares are LOT data points with the three shallowest being formation integrity tests. S_{Hmax} is based on our alternate interpretation of the two deep LOT points. The horizontal grey bar shows the depth for the analysis shown in Fig. 6.

stress state interpretation. Second, we show the possible stress states assuming our shear failure mechanism as two thick black lines for a range of values for sliding friction of 0.4 and 0.6, which are thought to be appropriate because they bracket the range for the mudrocks in the area (quartz-rich silts to illite-rich shales; e.g., Lockner and Beeler, 2002). In addition, based on laboratory measurements, mudrocks in the area have friction angles near 0.4 to 0.5. Our alternative shear-failure mechanism predicts a set of stresses that spans the normal, strike-slip and reverse stress state fields (Fig. 6). Using Eq. (2), we predict the maximum horizontal stress to be between 45.8 and 50.5 MPa, or 5.8 to 10.5 MPa over overburden (Table 1).

Unfortunately, we do not have any direct, post-LOT, evidence of shear in the wellbore. We do, however, observe that the wellbore is slightly deformed from a circular shape. To test possible stress states, we can ask the question of whether or not we should observe borehole deformation in a normal-fault stress, strike-slip fault stress, or reverse-fault stress state. To do that, we used an in-house wellbore stability program named STABOR. STABOR is a finite element solver designed to evaluate the elastic and plastic strain distribution around a wellbore induced by the drilling operation. The program considers the mechanical rock properties of the host formation, far-field *in situ* stress, pressure information and well trajectory to calculate the mudweight required to prevent onset of wellbore instability. The modeled elastic and plastic strains are compared with calibrated critical strain values to determine the range of mudweights that can be used without encountering wellbore deformation. The results are shown in a borehole stability plot as a function of applied mudweight, which is a 2D cross-section schematic of the strain condition in the near wellbore region (e.g., Fig. 6). On these plots, medium grey areas show where the formation is predicted to remain intact without encountering plastic yield. The light and dark grey areas show the predicted areas around the wellbore where irreversible plastic flow would have occurred, and as a result the borehole would no longer be circular. The difference between the dark and light grey areas is whether the modeled plastic strain is within (light grey) or exceeds (dark grey) the allowed threshold for stable drilling operations.

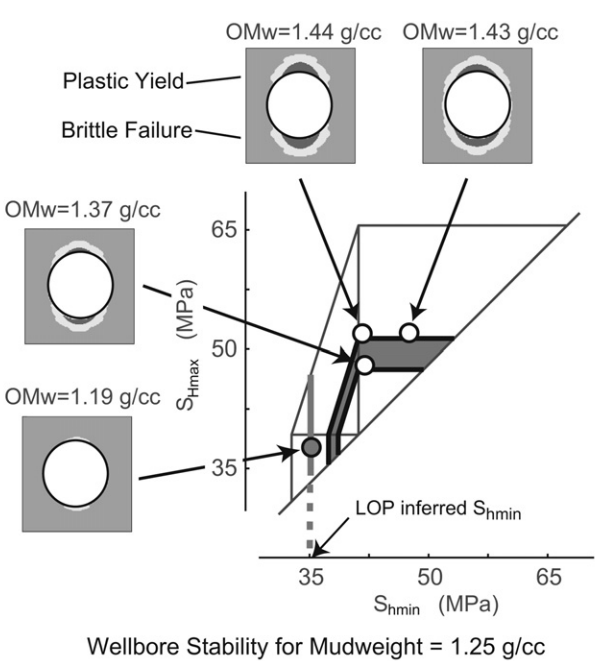

Fig. 6. The stress polygon for the depth shown in Fig. 5. The dark grey vertical line shows the traditional LOT interpretation and thick black lines show our potential alternative interpretation. A borehole stability model was run at each circle using Shell's in-house software, STABOR. The 2D schematics show the resultant strain conditions around the borehole for each stress state. See text for further discussion of the borehole stability plots and results. *OMw* = Optimal mudweight needed to drill the borehole at the given stress conditions.

Standard interpretation of the LOT in the fold core of this example implies a normal fault or strike-slip fault stress condition (grey vertical line on Fig. 6). In this condition, we model the borehole to be stable and it should retain its original circular shape (bottom left borehole cross-section in Fig. 6). Using our shear interpretation of the LOT in the fold core, where maximum horizontal stress is interpreted to be between 45.8 and 50.5 MPa (dark grey shaded area between the black polygon lines on Fig. 6), the models predict that the borehole should be deformed, consistent with the caliper observation. This result is not proof, but it supports our hypothesis that the stresses are compressive and our interpretation that the LOT is reflecting the stress state through shear rather than tensile opening.

4. Conclusions

Our hypothesis is that leak-off pressures sometimes reflect shear failure on fractures or discontinuities rather than tensile fracture failure and therefore do not always represent the minimum principal stress. The hypothesis predicts that leak-off sometimes occurs at pressures significantly less than minimum stress. Often tests with lower leak-off pressures have been dismissed as inaccurate or "poor" data. Sometimes they were used to argue for a stress state that is incongruous with other information. We suggest that these data can be used differently to constrain the stress state in a way that is potentially consistent with all other data. In compressive settings, we propose that these data also offer a rare chance to constrain the maximum horizontal stress magnitude. Understanding the maximum horizontal stress magnitude is an important parameter for mechanical models in compressive geologic systems. Such models are used for understanding compaction, fluid flow, seal capacity for hydrocarbons or CO_2 sequestration, or reservoir production modeling.

In thrust belts, we observe both leak-off test data that supports vertical stress as the minimum stress and data that argues for much lower minimum stress in the same setting. For example, at the Camisea gas field, both leak-off pressures near the overburden pressure and much less than the overburden pressure are observed. Using our hypothesis, we suggest that leak-off pressures at overburden will be seen where tested rock is intact and failure occurs by opening horizontal tensile fractures. Whereas leak-off pressures substantially less than overburden pressure are observed where tested rock includes pre-existing fractures or discontinuities that will fail in shear mode.

We emphasize that our alternate interpretation does not replace traditional methods for interpreting leak-off pressure data. It is simply an additional option to consider. Determining when to assume shear failure is dependent on the interpreter's understanding of the subsurface geology. We would apply the shear failure method for determining stress when leak-off pressure is less than expected. However, other explanations for a smaller leak-off pressure should be ruled out when possible.

We believe that much evidence suggests that leak-off pressures are not always reflective of minimum stress, however, it is possible that our interpretation and hypothesis is incorrect. If the lower leak-off pressures do reflect a minimum stress, several implications arise. First, the compressive stresses that create fold–thrust belts would not be long-lived stresses, but instead the stress must dissipate in short time periods. The dissipation may be associated with a stress drop after motion on a thrust (e.g., Wu et al., 2009).

Furthermore, the compressive stresses must build rapidly. Otherwise, we would expect to observe them in active thrust systems. Given the mixture of results for leak-off tests in nearby locations, it is in our view, simpler to argue that we do not always measure minimum stress during a leak-off test. Our conclusion is reinforced by the observation that we calculate maximum horizontal stress magnitudes that are consistent with what is expected from observed breakout data.

Acknowledgements

The authors thank Shell International E&P, Inc. for permission to publish this work. We also thank Tony Addis, Neil Braunsdorf, L. Taras Bryndzia, Lori Hathon, Matt Hauser, Joel Ita, Thomas Kocher, and Scott Wilkins for their constructive suggestions and technical challenges during the preparation of this manuscript. We thank Bill Dunne, Peter Flemings and Mark Zoback for constructive reviews that enhanced the quality of this manuscript.

References

Addis, M.A., Hanssen, T.H., Yassir, N., Willoughby, D.R. and Enever, J., 1998. A comparison of leak-off test and extended leak-off test data for stress estimation, SPE/ISRM 47235. In: Proceedings SPE/ISRM Eurock 98, Trondhiem, 131–140.

Addis, T., Boulter, D., Roca-Ramisa, L., Plumb, D., 1993. The quest for borehole stability in the Cusiana Field, Colombia. Oilfield Review 5 (2–3), 33–43.

Atkinson, C., Thiercelin, M., 1995. The interaction between the wellbore and pre-existing fractures. International Journal of Fracture 73, 183–200.

Atkinson, C., Thiercelin, M., 1997. Pressurization of a fractured wellbore. International Journal of Fracture 83, 243–273.

Baumgartner, J., Zoback, M.D., 1989. Interpretation of hydraulic fracturing pressure-time records using interactive analysis methods. International Journal of Rock Mechanics and Mining Sciences 26, 461–470.

Byerlee, J., 1978. Friction of rocks. Pure and Applied Geophysics116, 615–626.

Chang, C., Lin, W., McNeill, L.C., Moore, J.C., Conin, M., 2009. Constraining *in situ* stress tensor in the Kumano forearc basin, Nankai, based on borehole wall failure analysis. AGU Fall 2009 Meeting Abstracts T21C-1832.

Chipperfield, S.T., Wong, J.R., Warner, D.S., Cipolla, C.L., Mayerhofer, M.J., Lolon, E.P., and Warpinski, N.R., 2007. Shear dilation diagnostics: a new approach for evaluating tight gas stimulation treatments, SPE 106289. In: Proceedings, Hydraulic Fracturing Technology Conference, College Station, TX.

De Bree, P., Walters, J.V., 1989. Micro/Minifrac test procedures and interpretation for *in situ* stress determination. International Journal of Rock Mechanics and Mining Sciences. Abstract 26, 515–521.

Dorbath, C., Dorbath, L., Cisternas, A., Deverchere, J., Diament, M., Ocola, L., Morales, M., 1986. On crustal seismicity of the Amazonian foothill of the central Peruvian Andes. Geophysical Research Letters 13, 1023–1026.

Dula, F., Crook, T., 2007. Kinematic and Mechanical Models of Complex Deformations: Towards a Coupled Solution. In: Geological Society of America Abstracts with Programs, vol. 13 128.

Enever, J.R., Yassir, N., Willougby, D.R., Addis, M.A., 1996. Recent experience with extended leak-off tests for in-situ stress measurements in Australia. Australian Petroleum Production and Exploration Association Journal 36, 528–534.

Erickson, S.G., 1995. Mechanics of triangle zones and passive-roof duplexes: implications of finite element models. Tectonophysics 245, 1–11.

Finkbeiner, T., Zoback, M., Flemings, P., Stump, B., 2001. Stress, pore pressure and dynamically constrained hydrocarbon columns in the South Eugene Island 330 field, northern Gulf of Mexico. American Association of Petroleum Geologists Bulletin 85, 1007–1031.

Gaarenstroom, L., Tromp, R.A.J., de Jong, M.C., Brandenburg, A.M., 1993. Overpressures in the Central North Sea: implications for trap integrity and drilling safety. In: Parker, J.R. (Ed.), Geology of Northwest Europe: Proceedings of the 4th Conference, pp. 1305–1313.

Gjønnes, M., Cruz, A.M.G., Horsrud, P., Holt, R.M., 1998. Leak-off tests for horizontal stress determination? Journal of Petroleum Science and Engineering 20, 63–71.

Hafner, W., 1951. Stress distributions and faulting. Geological Society of America Bulletin 62, 373–398.

Héloit, D., Etchecopar, A., Cheung, P., 1989. New developments in fracture characterization from logs. In: Maury, V., Fourmaintraux, D. (Eds.), Rock at Great Depth, Rotterdam (Balkema), pp. 1471–1478.

Hossain, M.M., Rahman, M.K., Rahman, S.S., 2002. A shear dilation stimulation model for production enhancement from naturally fractured reservoirs. Society of Petroleum Engineers Journal 7, 183–195.

Jaeger, J.C., Cook, N.G.W., 1979. Fundamentals of Rock Mechanics, third ed. Chapman and Hall, New York.

Jamison, W.R., 1996. Mechanical models of triangle zone evolution. Bulletin of Canadian Petroleum Geology 44, 180–194.

Kano, Y., Ito, T., Lin, W., Flemings, P.B., Boutt, D.F., Doan, M., McNeill, L.C., Byrne, T., Saffer, D.M., Araki, E., Eguchi, N.O., Takahashi, K., Toczko, S., Scientists, E., 2009. Hydraulic fracture measurements at site C0009 of IODP expedition 319, NanTroSEIZE. AGU Fall 2009 Meeting Abstracts, T21C-1833.

Kunze, K.R., Steiger, R.P., 1991. Extended leak-off tests to measure *in situ* stress during drilling. In: Roegiers, J.-C. (Ed.), Rock Mechanics as a Multidisciplinary Science, Rotterdam (Balkema), pp. 33–44.

Last, N.C., McLean, M.R., 1996. Assessing the impact of trajectory on wells drilled in an overthrust region, SPE 30465. Journal of Petroleum Technology 48, 620–626.

Lin, W., Yeh, E.-C., Ito, H., Hung, J.-H., Hirono, T., Soh, W., Ma, K.-F., Kinoshita, M., Wang, C.-Y., Son, S.-R., 2007. Current stress state and principal stress rotations in the vicinity of the Chelungpu fault induced by the 1999 Chi–Chi Taiwan earthquake. Geophysical Research Letters 307, 5. L16307.

Lockner, D.A., Beeler, N.M., 2002. Rock failure and earthquakes. In: Lee, W.H.K., Kanamori, H., Jennings, P.C., Kisslinger, C. (Eds.), International Handbook of Earthquake and Engineering Seismology, 81A, pp. 505–538.

Luo, X., Liu, L., Li, X., 2006. Overpressure distribution and pressuring mechanism on the southern margin of the Junggar Basin, northwestern China. Chinese Science Bulletin 51, 2382–2390.

Maury, V.M., Sauzay, J.M., 1989. Rupture de puits provoquee par glissement sur faille: cas vecu mecanisme, remedes, consequences. In: Maury, V., Fourmaintraux, D. (Eds.), Rock at Great Depth, Rotterdam (Balkema), pp. 871–880.

McNeill, L.C., Saffer, D., Byrne, T., Araki, E., Eguchi, N.O., Takahashi, K., Toczko, S., Hayman, N., Huftile, G., Moore, J.C., Lin, W., Ito, T., Doan, M., Flemings, P.B., Kano, Y., Boutt, D.F., Conin, M., Sacks, A., 2009. *In situ* stress and deformation patterns across the Nankai Mumano basin and forearc: results from IODP expedition 319. AGU 2009 Fall Meeting Abstracts NH34A-06.

Raaen, A.M., Horsrud, P., Kjørholt, H., Økland, D., 2006. Improved routine estimation of the minimum horizontal stress component from extended leak-off tests. International Journal of Rock Mechanics & Mining Sciences 43, 37–48.

Rowan, M.G., Peel, F.J., Vendeville, B.C., 2004. Gravity-driven foldbelts on passive margins. In: McClay, K.R. (Ed.), Thrust Tectonics and Hydrocarbon Systems, vol. 82. American Association of Petroleum Geologists Memoir, pp. 157–182.

Sarda, J.P., Detienne, J.L., Lassus-Dessus, J., 1992. Recommendations for microfracturing implementations and the interpretation of micro- and pre-fracturing. Revue de l'Institute Francais du Pétrole 47, 179–204.

Shaw, J.H., Bilotti, F., Brennan, P.A., 1999. Patterns of imbricate thrusting. Geological Society of America Bulletin 111, 1140–1154.

Stockmal, G.S., Beaumont, C., Nguyen, M., Lee, B., 2007. Mechanics of thin-skinned thrust-and-fold belts: insights from numerical models. In: Sears, J.W., Harms, T.A., Evenchick, C.A. (Eds.), Whence the Mountains?: Inquiries into the Evolution of Orogenic Systems: a Volume in Honor of Raymond A. Price. Geological Society of America Special Paper, vol. 423, pp. 63–98.

Tingay, M., Muller, B., Reinecker, R., 2005. Understanding tectonic stress in the oil patch: the world stress map project. The Leading Edge 24, 1276–1282.

Tutuncu, A.N., Geilikman, M., Couzens, B., van Duyvenboode, F., 2006. Integrated wellbore-quality and risk-assessment study guides successful drilling in Amazon jungle. Geophysics 71, E99–E105.

Twiss, R.J., Moores, E.M., 1992. Structural Geology. Freeman and Company, New York.

White, A.J., Traugott, M.O., Swarbrick, R.E., 2002. The use of leak-off tests as a means of predicting minimum in-situ stresses. Petroleum Geosciences 8, 189–193.

Wu, H., Zoback, M.D., Ma, K., Hickman, S., 2009. Observations and modeling of co-seismic stress changes in the M7.6 Chi–Chi earthquake Taiwan – apparent evidence for complete stress drop on a small fault patch. AGU 2009 Fall Meeting Abstracts, T21D-1856.

Yamamoto, M., 2003. Implementation of the extended leak-off test in deep wells in Japan. In: Sugawra, K. (Ed.), Proceedings of the Third International Symposium on Rock Stress, Rotterdam (Balkema), pp. 225–229.

Yardley, G.S., Couzens, B.A., 2007. Pressure Modelling: Where It All Goes Wrong. AAPG Search and Discover Article #90066. American Association of Petroleum Geologists Hedberg Conference, The Hague, Netherlands.

Zoback, M.D., Barton, C.A., Brudy, M., Castillo, D.A., Finkbeiner, T., Grollimund, B.R., Moos, D.B., Peska, P., Ward, C.D., Wiprut, D.J., 2003. Determination of stress orientation and magnitude in deep wells. International Journal of Rock Mechanics and Mining Sciences 40, 1049–1076.

Zoback, M.D., Healy, J.H., 1992. *In situ* stress measurements to 3.5 km depth in the cajon pass scientific research borehole: implications for the mechanics of crustal faulting. Journal of Geophysical Research 97, 5039–5058.

Zoback, M.D., Mastin, L., Barton, C., 1987. In-situ stress measurements in deep boreholes using hydraulic fracturing, wellbore breakouts and stonely wave polarization. In: Stefansson, O. (Ed.), Rock Stress and Rock Stress Measurements, Proceedings of Conference in Stockholm. Centrek Publ., Lulea, Sweden, pp. 289–299.