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Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 80 (2005) pp. 87-103

Review of Methods of Measuring Stress and its Variations

Osam Sano[1], Hisao Ito[2], Atsuo Hirata[3] and Yoshiaki Mizuta[3]

[1] the Earthquake Research Institute, Univ. of Tokyo
[2] JAMSTEC
[3] Sojo Univ.

Abstract

Methods of measuring stress and its variations are briefly reviewed with particular interest in precise measurements at depth. Stress-relief methods are widely used techniques in the engineering field. Wireless strain-cells indicate the possibility of stress-relief methods for deep wells. However, elastic coupling of [rock＋mortar＋strain-meter] must be precisely estimated including thermal stress effects, before application to depth. The hydraulic fracturing method has been widely used in the geophysical field. However, serious suspicions about the interpretation of reopening pressure have also been raised in the past 20 years. As possible answers to these suspicions have been proposed recently, it is necessary to check past results again and cross-check the results of different methods. Non-hydrofracture methods are free from problems associated with the permeation of pressure fluid into artificial fracture and borehole wall. Furthermore, some non-hydrofracture methods do not need the assumption of principal stresses having a constant direction, which can be an advantage over hydrofracture methods for long-term observations of stress variations. Core-based and borehole-wall-fracture-based methods, unfortunately, cannot now be considered precise measurement methods. However, these methods have the potential to estimate stress, particularly at great depths.

Key words: stress, stress measurement, crustal deformation, earthquake prediction research

1. Introduction

Based on the national earthquake prediction research program, seismograph networks have been developed throughout Japan to make fundamental observations. The high-sensitivity seismograph network (Hi-net) and the digital strong-motion seismograph network (K-net and KiK-net) have been constructed by the National Research Institute for Earth Science and Disaster Prevention (NIED). These networks of seismometers are connected with other seismograph systems constructed by the Japan Meteorological Agency (JMA) and other institutes. Regarding crustal deformation, GPS-based control stations (GEONET) have been constructed by the Geographical Survey Institute (GSI). Using such a fundamental observation system, earthquake prediction research in Japan has clarified many important phenomena, e.g., asperities and non-asperities, seismic slips, and other time-dependent slips, and Niigata-Kobe Tectonic Zone (NKTZ).

Earthquakes are fracture phenomena in the Earth's crust. Stress fields in the Earth's crust have been considered to be one of the most important parameters measured in the history of earthquake prediction research. In a new national earthquake prediction research program [Hirata, 2004], the importance of determining the stress field has been noted [Council for Science and Technology, 2003].

In both the fields of engineering and Earth sciences, several stress measurement techniques have been proposed. The results can be seen in the World Stress Map Project [Zoback, 1992]. The results in

* e-mail: osano@eri.u-tokyo.ac.jp

Japan are presented in several review articles [Sugawara 1998, Mizuta, 2002, Ikeda and Omura, 2004; Yokoyama, 2004]. After Zoback [1992], the stress-state can be estimated from focal mechanisms (54%), breakouts (28%), fault slip (5.5%), volcanic alignments (4.1%), hydrofractures (4.5%), and overcoring method (3.4%). From focal mechanisms, we can estimate the direction of the principal stress and the stress change associated with earthquakes. Fault slip and volcanic alignments provide little information on the magnitude of stress, but do give information on the principal stress direction. Induced fractures associated with drilling boreholes provide information on the magnitude and the direction of principal stress at depths greater than approximately 3 km. The latter 2 techniques are the main methods for determining a complete stress field, namely the magnitude and the direction of principal stresses. These 3 techniques including breakouts are the main techniques for determining complete stress field, and magnitude and direction of principal stresses.

Associated with the depth of the seismogenic zone, we want to know the stress field deep underground, namely deeper than several kilometers. Unfortunately, there are limits to the depths boreholes can be drilled. Major deep boreholes can be found in oil fields. In Japan, the deepest wells are around 5 km. The deepest borehole on the Cora Peninsula in Russia is 13 km. The KTB in Germany is 10 km deep.

From the viewpoint of boring cost, a barrier exists at around 2 km in Japan. For boreholes shallower than 2 km, drilling technology developed for mining engineering is generally used. For a borehole deeper than 2 km, technology developed in petroleum engineering is usually employed.

Limitations on depth also apply to measurement techniques. For deep boreholes, stress concentration at the bottom of a borehole leads to tensile fractures in over-cores, known as core-disking, and over-coring techniques cannot easily be applied to such a depth. Stress concentration around the borehole wall leads to fracture, and hydrofracture techniques have depth limitations. In addition to depth limit, measurement techniques have their own basic problems from the viewpoints of the accuracy required for earthquake prediction research. The focus of this review article is to summarize the problems associated with the major methods, and present possible solutions.

2. Stress-relief method

Stress measurement methods can be classified into 4 groups from the viewpoint of measurement principle; namely, (1) stress-relief method, (2) borehole-wall fracturing methods, (3) core-based methods, and (4) methods based on drilling-induced fractures. The stress-relief method is one of the most widely used techniques in the engineering field. This method uses a strain-cell with built-in displacement transducers or strain gages to measure deformation of the borehole or strains in the borehole-wall during the over-coring process. To determine the state of external stress, it is necessary to correlate deformation or strain with the external stress tensor. In general, the strain-cell must be so compliant that the effects of the stiffness of the strain-cell are almost always neglected in the analysis.

There are many variations with respect to measurement parameters, namely, diametral deformation of the borehole [e.g., Leeman, 1959; Obert *et al.,* 1962; Crouch and Fairhurst, 1967; Niwa *et al.,* 1969; Suzuki, 1969], strains in the borehole wall [e.g., Leeman and Hayes, 1966; Hiramatsu and Oka, 1968], strains at the flat end of the borehole [e.g., Mohr, 1956; Leeman, 1971; Oka *et al.,* 1979], strains at the hemi-spherical end [e.g., Sugawara *et al.,* 1984; Sugawara and Obara, 1986], and strains at the conical end [e.g., Kobayashi *et al.,* 1987]. Strain cells in the field of Earth sciences can be found in Engelder [1993]. At the early stage of development, at least 3 boreholes were used to determine the 3-dimensional stress-state. However, only one borehole is known to be sufficient to determine the full components of the 3-dimensional stress tensor when more than 6 independent strain components of a borehole bottom are measured. This is one of the advantages over borehole-wall fracturing methods, in which one of the principal stresses is assumed to be vertical in conventional analyses.

Homogeneity and linear elasticity of rocks are always assumed. Isotropic elasticity is not always necessary [e.g., Amadei, 1983; Hirashima and Hamano, 1987; Amadei and Stephansson, 1997], but is almost always assumed. Conversion of strain to stress requires the elastic moduli of the surrounding rock. The reliability of the estimated stress is directly affected by the estimation of elastic moduli.

When differential stress is very high, the stress concentration at the wall and/or end of the borehole is consequently so high that the elastic moduli of the rock can be influenced by microfractures during and even after the drilling process [e.g., Katoh *et al.,* 1994 a]. This method cannot be applied easily under high differential stress conditions relative to strength.

From the viewpoint of cost, it has to be noted that the stress-relief method requires the borehole to be drilled at least twice, which is one of its disadvantages compared to borehole-wall-fracture methods. This disadvantage has been partly overcome by employing a pilot hole as shown in Fig. 1. Before setting strain-cells, the borehole is drilled in an over-core size. Then, a pilot hole is drilled from the bottom of the borehole. In the next step, the strain-cell is set in the pilot hole, and then the borehole is drilled to the size of over-core again. In spite of using a pilot hole, time is still required to replace the drilling head, which can be crucial for a very deep well. This disadvantage may be overcome using the down-hole exchange technique for the drilling head.

Stress-relief methods require many analogue signal lines from the strain-cell to the electronic measurement system on the ground surface, because strains or deformations in more than 6 independent directions have to be measured. This is another disadvantage of a deep well. This disadvantage can be overcome using wireless strain-meters [Hallbjorn *et al.,* 1990; Leite *et al.,* 1996; Yamauchi *et al.,* 2004; Sakaguchi, 2004; Katoh and Tanaka, 2004].

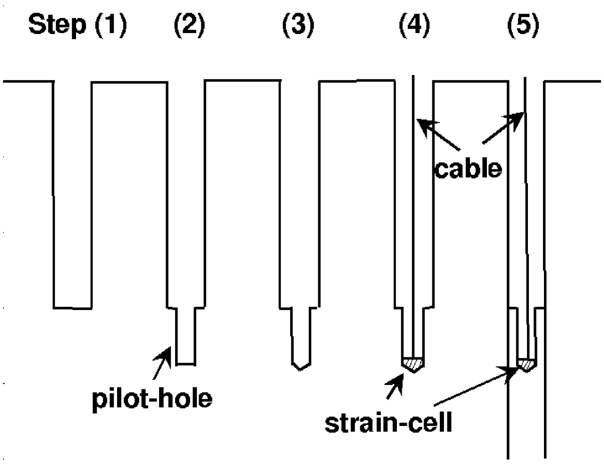


Fig. 1. General procedure of over-coring method. In step 1, a borehole is drilled to the depth of the measurement position with a scale of over-core size. In step 2, a pilot hole is drilled, and in step 3, the bottom of the pilot hole is ground to a semi-spherical or conical shape for borehole bottom measurement. In step 4, a strain-cell is embedded inside the borehole or glued to the bottom. In step 5, the pilot hole is over-cored.

Some sort of adhesive must firmly attach the strain-cell to the wall or end of the borehole, and must be very compliant at the same time. For vertical boreholes, it is sometimes difficult to find appropriate adhesives that can be applied in water. When measuring strains at the borehole bottom, it is also difficult to find an appropriate technique to remove slime and debris at the bottom of a deep vertical borehole. Ishii and Yamauchi [1998] employed a highly sensitive borehole strain-meter developed for measuring very small strains in the Earth's crust [Ishii *et al.,* 1997]. Their system can be applied to depths of more than 1000 m [Ikeda *et al.,* 2001; Ishii *et al.,* 2004; Yamauchi *et al.,* 2004]. An appropriately prepared mortar mixture is used for fixing the strain-meter to the borehole wall with slight compression. The stiffness of the mortar compound is not negligible in this case. Stress in the over-cored rock cannot be relieved completely, because of residual stress. The accuracy of the estimated stress depends on the estimation of elastic coupling of the [strain-meter + adhesives + rock] system [e.g., Duncan Fama and Pender, 1980; Hirashima *et al.,* 1990; Kikuchi *et al.,* 1991; Sano *et al.,* 2004]. Eccentricity when setting the strain-meter also affects the results [Hirashima *et al.,* 1990]. It is noted that their method still has a possibility of being used to estimate the stress-state of deep vertical boreholes and temporal changes with much higher resolution than other strain-cells used in the engineering field.

In very deep wells, borehole walls tend to be severely damaged by drilling (e.g., later section), which significantly changes the stiffness of the surrounding rock, stress distribution around the borehole, and permeability. Furthermore, the stress distribution around the borehole might also be influenced by thermal stress due to the temperature difference between the rock and the mud-water used for drilling. A precise estimation of elastic coupling is necessary under such conditions.

3. Hydraulic fracturing method

Hydraulic fracturing was developed as a stimulation method for oil fields in petroleum engineering. This technique was researched as a potential method for determining in-situ stress at depth in laboratory and field tests [e.g., Haimson and Fairhurst, 1967; Haimson, 1968; Zoback and Zoback, 1980; Cornet, 1982; Tsukahara, 1983]. Using the hydraulic fracturing method, drilling the borehole once is sufficient, and no information on the elastic moduli is needed. Furthermore, in principle, only a flexible hose for hydraulic power is needed. This is of great significance in earthquake prediction research where stresses at depths of several kilometers are of interest. In the field of the Earth sciences, therefore, the hydraulic fracturing method has been used to measure stress-state at depth.

In general, a hydraulic pump, a flow meter, and a pressure transducer are usually set on the ground surface. At the down-hole, double-packer is used for sealing the pressure fluid. In the conventional analysis, one of the principal stresses assumed is vertical. As shown in Fig. 2, hoop stress, $\sigma\theta$, on the borehole wall due to maximum horizontal stress and minimum stress, S_H and S_h, is given by the solution of Kirch [1898]. In the assumption of linear and isotropic elasticity of a homogeneous impermeable material, hoop stress is given by

$$\sigma_\theta = 3S_h - S_H - 4(S_h - S_H)\sin^2\theta, \qquad (1)$$

where θ is the angle of the point to the direction of maximum principal stress. The increment of tangential stress due to internal pressure is equal to $-P$ at any point on the wall surface. For permeable rocks under water pressure, poroelastic terms can also be added in Eq. (1).

Fig. 3 shows a typical pressure/time curve observed in a hydraulic fracturing procedure. By injecting fluid at a constant flow rate, the internal pressure increases to break the borehole wall in the direction of the maximum horizontal stress when the minimum tangential stress reaches the tensile strength of the rock. The pressure at the formation of the fracture is called breakdown pressure, *Pb*. In

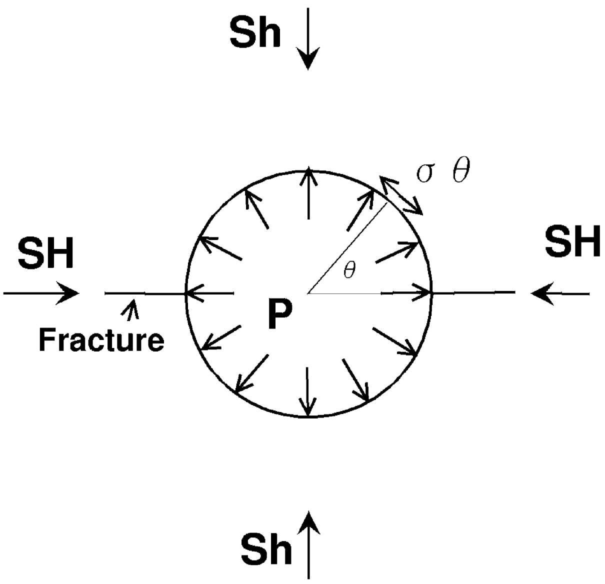


Fig. 2. Principle of hydraulic fracturing method. Stress concentration around a circular hole was introduced by Kirsch [1898]. Hoop stress on the borehole wall is minimized at the intersection points of the borehole wall and the axis of maximum compressive principal stress. When hoop stress reaches the tensile strength of the rock, fractures are formed, in general, bi-laterally in the direction of the maximum compressive stress. The magnitudes of maximum stress and minimum stress are determined by the conditions for fracture initiation, fracture re-opening, and fracture closure.

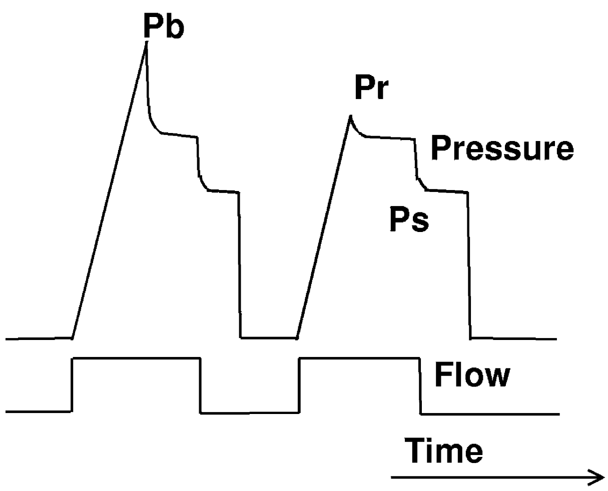


Fig. 3. Schematic of hydrofracturing procedure. The borehole is pressurized at a constant flow rate. When fractures are formed, a sudden pressure drop is always observed. The peak pressure is called the breakdown pressure (Pb). The fractures extend at a constant flow rate. When the valve for flowing water is closed, the pressure decreases to a constant level called the shut-in pressure (Ps). Ps is known to be equal to the stress component normal to the fracture. After complete closure of the fractures, the borehole is pressurized again to re-open the fractures. Several re-loading cycles are performed in conventional hydraulic fracturing procedures as shown in Fig. 5.

the next step, a valve connected to the hydraulic system is closed and the internal pressure decreases rapidly to a value called the shut-in pressure, *Ps.* Based on *Pb* and *Ps,* the magnitudes of maximum and minimum stresses can be determined using the 2 equations below.

$$Pb = 3S_h - S_H - Pp + St, \quad (1)$$

and

$$Ps = S_h, \quad (2)$$

where *Pp* and *St* are pore pressure term and tensile strength, respectively.

At the early stage of development, breakdown pressure was used for interpretation, for which tensile strength had to be known. However, in the interpretation of the tensile fracture, we sometimes have to consider the poroelastic process and modify Eq. (1) [Haimson and Fairhurst, 1967; Haimson, 1968]. Furthermore, no unique modification can be found easily for all kinds of rock [Detounay *et al.,* 1989; Shmitt and Zoback, 1989]. Measuring tensile strength requires core-boring, which increases cost. Moreover, natural fractures sometimes prevent tensile strength from being obtained precisely. Instead of *Pb,* the reopening pressure, *Pr,* was proposed by Bredehoeft *et al.* [1976] and has been generally used. In this case, the Eq. (1) is modified to

$$Pr = 3S_h - S_H - Pp, \quad (3)$$

The reopening pressure can be determined from the sudden change along the pressure/time curve in the reloading cycle. However, a sudden drop like that shown in Fig. 2 cannot always be observed, and the reopening pressure is defined by the departure from linearity of the pressure/time curve under constant flow-rate conditions. Employing *Pr,* the hydraulic fracturing method can be applied many times at the same points on the borehole wall. This suggests that stress variation can also be estimated using the same fractures produced by the former procedures.

As has been mentioned in the history of stress-relief techniques, conventional over-coring methods are difficult to apply to deep vertical boreholes. As the hydraulic fracturing method is almost free from the difficulties associated with over-coring methods, this method has been widely used in the field of Earth sciences. However, the reopening pressure was frequently been found to be very close to the shut-in pressure [Evans *et al.,* 1989; Lee and Haimson, 1989; Cheung and Haimson, 1989]. Fig. 4 is an example of this phenomenon. These field results suspiciously suggest that the stress ratio, $(S_H + Pp)/S_h$, is almost equal to 2.0 at many places around the world at any depth. Lee and Haimson [1989] collected many hydrofracture results for many rock types in the USA, Canada, France, China, and Japan, and raised questions as to the detection of *Pr* and *Ps.* In the history of the hydraulic fracturing method, many improvements have been proposed for determining both *Pr* and *Ps.*

Scholz [2000] and Scholz [2002] suggested that a similar stress ratio could be controlled by the frictional strength of the preferentially oriented fault for which the friction coefficient was assumed to be around 0.65. Although Scholz's explanation seemed to resolve the argument, several uncertainties in data interpretation remain. Including questions solved in the past, the main questions are summarized below.

(a) Due to permeation of injected fluid into surrounding rocks, the water pressure often does not stay constant, even after shutting the valve for water injection, and it is difficult to determine *Ps* in such cases.

(b) The pressure/time curve is sometimes extremely non-linear, and the departure point from the linearity of the pressure/time curve is sometimes vague.

(c) Under high differential stress conditions, the fracture might not close completely.

(d) Measurement of stress variations for the same fracture requires the condition that the direction of the principal stress does not change over time, which cannot always be fulfilled in long-term observations.

(e) Water pressure inside the fracture when the reopening conditions are fulfilled is still inconclusive.

(f) The argument that a departure from linearity does not suggest the beginning of reopening but reopening of the whole fracture is still controversial.

Regarding questions (a) to (c), several proposals have been successfully considered, and have been employed in test and data interpretation. Question (d) is only associated with estimations of long-term stress variations. Questions (e) and (f) have still not been conclusively answered.

Regarding question (a), fluid pressure does not often stay constant, but decreases exponentially [Detournay and Cheng, 1988; Detournay *et al.,* 1989] in contrast to the idealized form shown in Fig. 3. This kind of pressure decrease can be generally considered to be due to water leaks through natural fractures intersecting the sealed section of the borehole and/or artificial fracture. Mizuta *et al.* [1987] suggested a possible flow from the sealed section to both upper and lower sides of the borehole through an artificial fracture parallel to the borehole axis. In these cases, instantaneous shut-in pressure, *ISIP,* defined by the flexure point in the pressure/time curve can be used as *Ps.*

Regarding question (b), Hickman and Zoback [1983] classified the observed pressure/time record into the 3 types shown in Fig. 5, and satisfactorily explained the differences in terms of external stress conditions, namely

$$\mathrm{Pb} > Pr > Ps = S_h \text{ or } 2S_h - \mathrm{Pp} > S_H \quad (4)$$

$$\mathrm{Pb} > Ps = S_h > Pr \text{ or } 2S_h - \mathrm{Pp} < S_H \quad (5)$$

$$Ps = S_h > \mathrm{Pb} > Pr. \quad (6)$$

σ_N in Fig. 5 expresses normal stress on the fracture surface and can be expressed by
$\sigma_N = ((S_H + S_h)/2 - \mathrm{Pp})(1 + R^2/r^2) - ((S_H - S_h)/2)(1 + 3R^4/r^4) + \mathrm{Pp} - PR^2/r^2$.
In addition to the above 3 cases, we have to consider case (7) corresponding to question (c), namely,

$$Pr < 0 \text{ or } 3S_h - \mathrm{Pp} < S_H \quad (7)$$

In case (4), hoop stress at the mouth of the fracture is larger than S_h when the reopening conditions are satisfied. Once the fluid penetrates into the fracture, the fluid tends to permeate throughout the fracture more easily than in other cases. In cases (5) and (6), *Pr* is smaller than S_h. The additional increase in fluid pressure is required for fluid penetration into the whole fracture, even after reopening. In case (7), the fracture remains open even under unloaded conditions, and reopening cannot be defined.

Eq. (3) is obtained from the assumption that the fracture closes completely before the reloading procedure, and that the loading pressure does not act just before reopening. However, many observations suggest that the residual aperture of the induced fracture cannot be negligible for rocks [Zoback *et al.,* 1977; Cornet, 1982; Durham and Bonner, 1994]. When the fluid pressure acts on the surfaces of the mouth of a fracture before reopening, Eq. (3) should be modified by substituting *Pr* into *Pp* as

$$2Pr = 3S_h - S_H. \quad (8)$$

This is question (e) mentioned above.

Through a numerical simulation, Hardy and Asgian [1989] showed that the pressure fluid should permeate easily into the fracture, even for an initial aperture of 3 μm, and the aperture should be enlarged by the penetration of fluid. Based on a simulation, Hardy and Asgian [1989] concluded that Eq. (8) was more appropriate than Eq. (3). Also Ito *et al.* [1999] suggested using Eq. (8) instead of Eq. (3), based on a similar simulation result. In the reloading process, if the residual aperture is sufficiently large for fluid to permeate instantaneously throughout the fracture, the reopening pressure can even be the same as the shut-in pressure, because the shut-in pressure is known as the smallest pressure required to keep the fracture open. Regarding this argument, the suggested method presented by the International Society for Rock Mechanics (ISRM) only notes that "*The flow rate should be sufficiently high to prevent fracturing fluid percolation into the closed fracture before the actual mechanical fracture opening* " [Haimson and Cornet 2003].

Based on experimental results for a granitic rock mass, Pine *et al.* [1983] considered reopening pressure as a measure of minimum horizontal stress, namely

$$Pr = S_h. \quad (9)$$

Ito and Hayashi [1993] numerically showed that the conventional *Pr* could be equal to *Ps* by considering that the pressure fluid permeates the fracture deeply before reopening. Eq. (9) corresponds to question (f) mentioned above, and seems to answer the question as to why the reopening pressure is frequently found to be very close to the shut-in pressure. Although questions (a) to (e) are associated with accuracy, question (f) is a fundamental problem. If Eq. (9) is true, we can obtain very little information on S_H from a hydraulic fracturing test.

The permeation process of fluid into a fracture is not simple, but is influenced by the residual aperture and the length of the fracture. For a relatively short fracture with a large aperture, fluid pressure immediately acts throughout the fracture [Hardy and As-

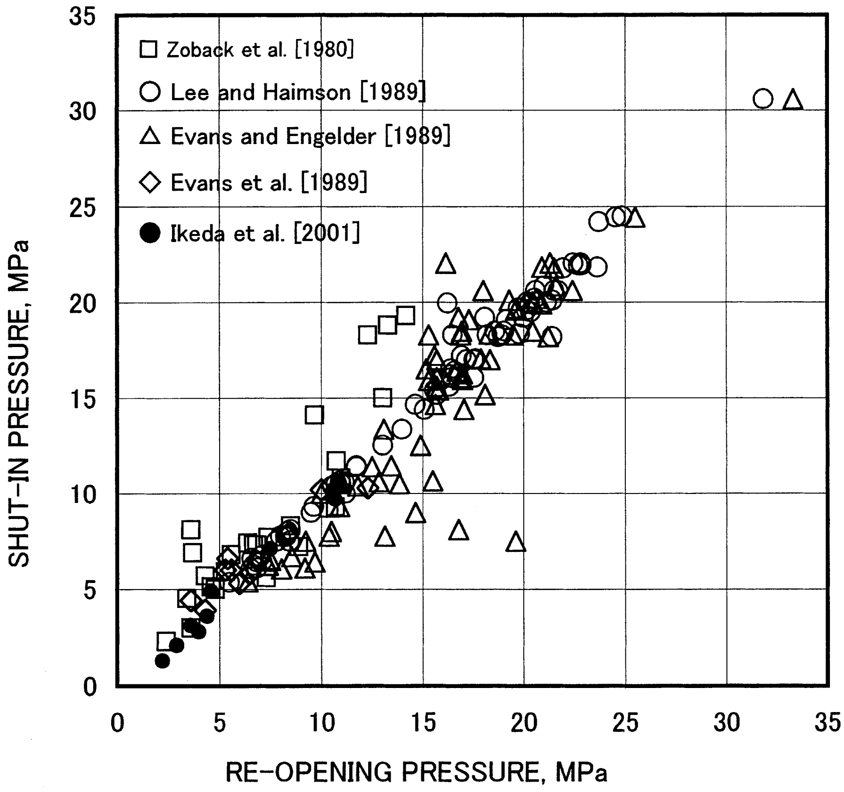


Fig. 4. An example of the relationship between the re-opening pressure (Pr) and the shut-in pressure (Ps) obtained in the U.S.A., Canada, and Japan. Many results indicate the relationship, Pr=Ps, which suspiciously shows that $(S_H+Pp)/S_h$, is equal to 2.0 at any depth around the world.

gian, 1989]. In contrast, for a long fracture with a small aperture (e.g., 1μm), fluid pressure acts only in the neighborhood of the mouth of the fracture at first, and permeates gradually into the fracture. In the latter case, Eq. (9) cannot be applied. Based on a numerical simulation, Rutqvist *et al.* [2000] suggested that the above 3 equations, (3), (8), and (9), might be true for fractures with extremely small apertures, medium-sized apertures, and sufficiently large apertures, respectively.

Through a numerical simulation, Ito *et al.* [1999] pointed out that the true reopening pressure should be much lower than the reopening pressure defined in a conventional way. In general, numerical simulations in past articles [Hardy and Asgian, 1989; Ito *et al.*, 1993; Ito *et al.*, 1999; Rutqvist *et al.*, 2000] suggest that water permeates at a lower pressure than conventional reopening pressure, and the conventional *Pr* is affected by flow rate. Besides, Ito *et al.* [1999] suggest that the conventional *Pr* should also be affected by water volume in the pressurizing system. When the constant flow rate is so small that the pressure gradient in the fracture is negligible, temporal variations of pressure are given by Ito *et al.* [1999], namely

$$dP/dt = Q/(dVc/dP + C) \tag{10}$$

where Q, Vc, and C are flow rate, volume change due to fracture opening, and compliance of the system, respectively. The departure from linearity of the pressure/time curve can only be observed when the magnitude of dVc/dP increases to a level as large as C. Considering the plausible sizes of dVc and C in Eq. (10), they suggest that the conventional *Pr* could only be detected when the water permeated a fracture several times longer than the borehole radius. This result explains why the conventional *Pr* is almost equal to *Ps*. They also proposed the use of a high-stiffness hydraulic fracturing system instead of the very compliant conventional hydraulic fracturing system.

Judging from the numerical simulation results

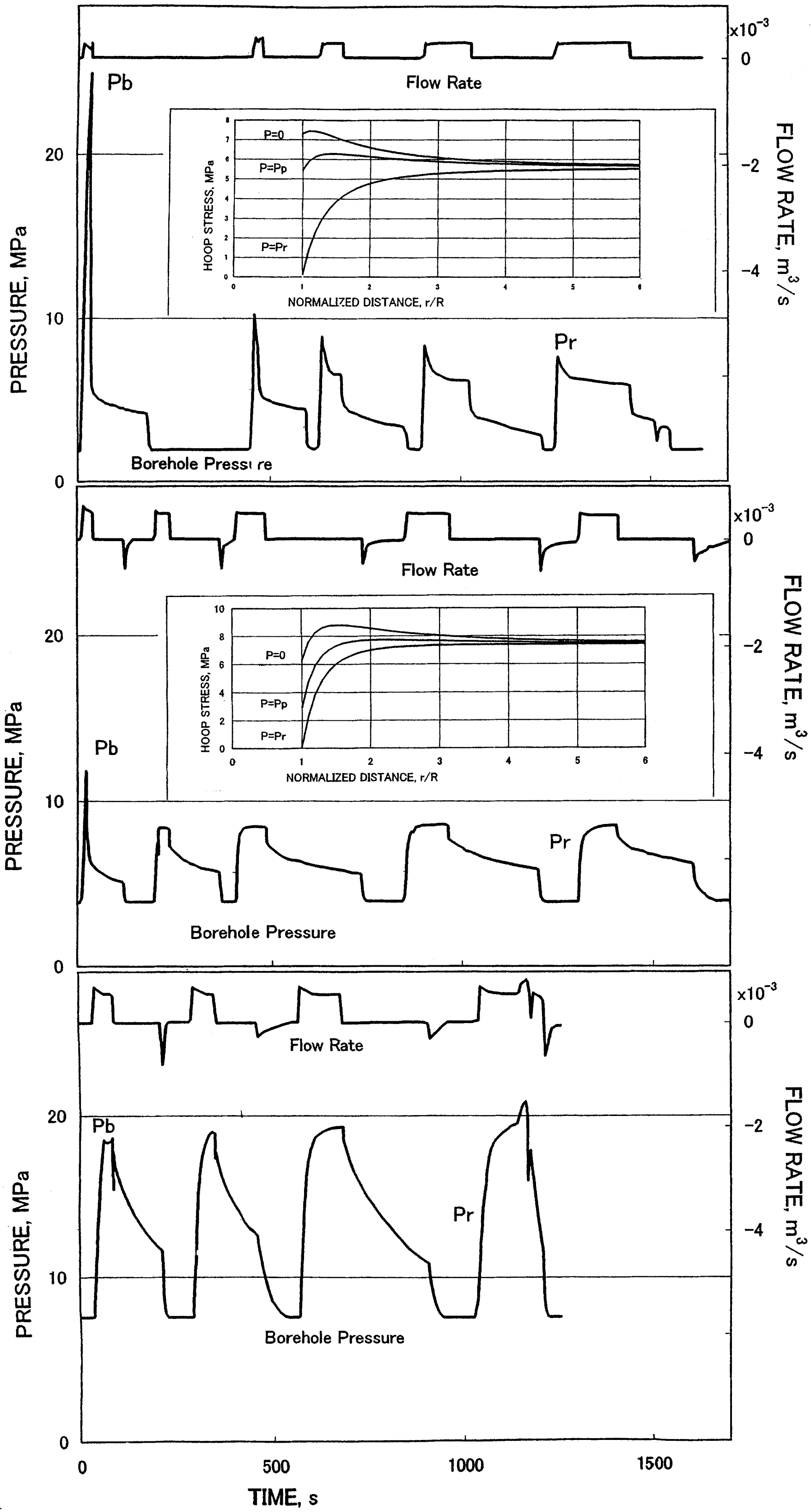


Fig. 5. Typical pressure/time curves of hydraulic fracturing tests. The figures after Hickman and Zoback [1982] are modified by adding hydrostatic pressure to borehole pressure. (a), (b), and (c) correspond to the results at depths of 185 m, 338 m, and 751 m, respectively. In each figure, the flow rate and the borehole pressure are shown at upper and lower sides, respectively. In (d) and (e), calculated hoop stress is plotted against distance from borehole axis.

[Hardy and Asgian, 1989; Ito *et al.,* 1993; Ito *et al.,* 1999; Rutqvist *et al.,* 2000], it is plausible that the fracture initiates to open at the true reopening pressure, being lower than the conventional reopening pressure. It is also plausible that water permeates deep into the fracture at the conventional reopening pressure. Regarding question (f), the high-stiffness hydraulic fracturing system may be a solution. However, it is still not certain whether or not the conventional Pr is completely free from the influence of S_H. Regarding questions (e) and (f), experimental evidence is necessary to resolve arguments.

In the hydraulic fracturing procedure, fractures inclined to the borehole axis are sometimes formed due presumably to natural fractures. Equations based on 2-dimensional analysis cannot be applied to the interpretation of data for such inclined fractures. However, these data may be available in an interpretation by using 3-dimensional analysis [Cornet and Vallete, 1984; Mizuta *et al.,* 1987; Baumgartner and Rummel, 1989; Burlet *et al.,* 1989]. From these interpretations, 3-dimensional stress-state can be determined by hydraulic fracturing for a single borehole experiment. However, it might sometimes be difficult to find natural fractures in sufficient numbers in different directions within the limited range of the depth in a single borehole.

When S_V is the minimum stress, further extension of the vertical fracture might rollover horizontally. When S_V is the minimum stress and the S_h is nearly equal to S_H, the artificial fracture is sometimes formed horizontally [e.g., Evans and Engelder., 1989]. In such cases, it is difficult to determine both S_h and S_H.

For rocks having anisotropic elasticity, Eq. (1) has to be modified. The tangential stress due to internal pressure is no longer equal at any point [Lekhnitskii, 1968]. Furthermore, due to the combined effects of anisotropic elasticity and anisotropic tensile strength, the probability is that fracturing similarly might occur widely within a borehole wall. In deep wells, e.g., deeper than 3 km, drilling-induced fractures tend to occur due to stress concentration around the borehole, and sealing with double packer tends to be difficult.

4. Non-hydrofracturing method

Two kinds of non-hydrofracturing method have been proposed. One is classified as the sleeve fracturing method [Stephansson, 1983; Serata and Kikuchi, 1986; Ljunggren and Stephansson, 1986; Sugawara *et al.,* 1987; Mizuta *et al.,* 1988]; the other is classified as the borehole-jack method [De la Cruz, 1977; Azzam and Bock, 1987; Yokoyama and Nakanishi, 1997]. These methods have similar advantages over the stress-relief method as the hydraulic fracturing method. In addition, loading fluid does not penetrate surrounding rocks. Hence, these methods are free from the problems associated with the penetration of pressure fluid in the hydraulic fracturing method. Furthermore, as pressure fluid is restricted within the loading jack or sleeve, the loading system can easily be made compact and set at the down-hole, which can be an advantage over the hydraulic fracturing method, particularly in deep wells. In hydraulic fracturing, the pressure drops just after formation of the fracture as shown in Fig. 3. In contrast, in non-hydrofracturing, as the fluid pressure does not directly act on the fracture surface, the pressure has to be increased to further extend the induced fracture. This is a disadvantage over the hydraulic fracturing method, because pressurizing system has to be more resistant to higher pressures than the hydrofracturing system.

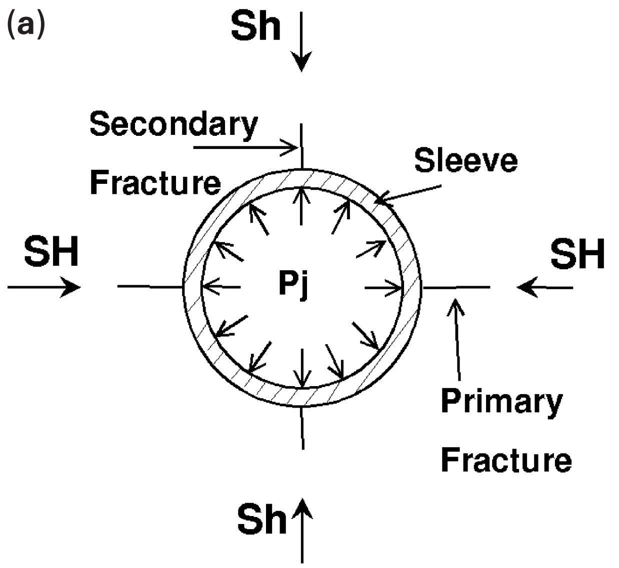
4-1. Sleeve Fracturing method

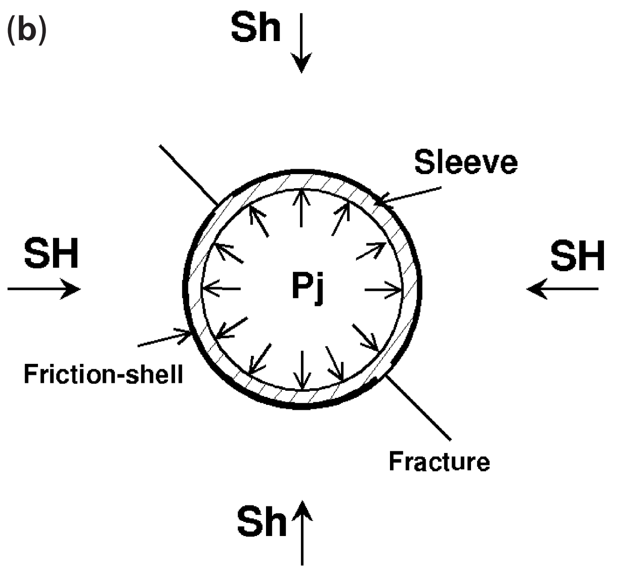
Using this method, the borehole wall is loaded though a urethane sleeve by the internal fluid pressure. In the first loading process for a double-fracturing method (named by Sakuma *et al.* [1989]), the first fracture is formed on the borehole wall as shown in Fig. 6a. The first fracture is parallel to the maximum horizontal compressive stress. As fluid pressure increases, the fracture continues to increase gradually. In response to further loading, a second fracture is formed perpendicularly to the first one. Similar to the hydraulic fracturing method, reopening pressures for both fractures are used to determine the 2 principal stresses within the horizontal plane [e.g., Amadei and Stephansson, 1997], namely

$$P_{n1}=3S_h-S_H \quad (8)$$

$$P_{n2}=3S_H-S_h \quad (9)$$

where P_{n1} and P_{n2} are reopening pressures of the first fracture and the second fracture, respectively. The reopening pressures can be estimated from a sudden change in the stiffness of the rock. However, it is





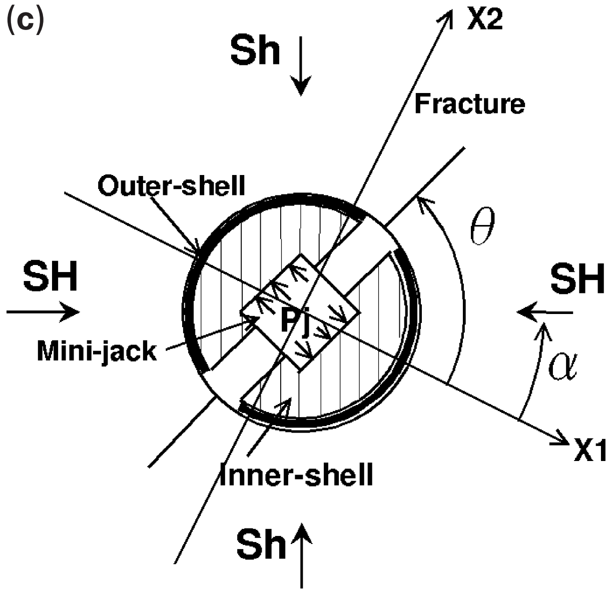


Fig. 6. Schematics of (a) double-fracturing method, (b) single-fracturing method, and (c) borehole-jack fracturing method. These methods are free from the problems associated with permeation of pressure fluid in the hydraulic fracturing method. In the double-fracturing method, the borehole wall is loaded with a urethane-sleeve. The primary and secondary fractures are formed parallel to SH and Sh, respectively. The magnitudes of SH and Sh are calculated from the reopening pressures of the two fractures. The single fracturing probe has two friction-shells between the borehole wall and the urethane sleeve. The borehole-jack fracturing probe has simple mini-jack and loading platens. The modified borehole-jack probe has inner shells and outer shells. In the latter two methods, fractures are formed in arbitrary directions determined by the orientation of the shells. At least three fractures in different directions are needed to estimate the direction and the magnitudes of the principal stresses.

often difficult to find any sharp change in the slope of the curve, particularly for hard rocks, which brings uncertainties in the estimated stress [e.g., Serata *et al.,* 1992]. Furthermore, the second fracture is not always formed perpendicularly to the first one, particularly in relatively weak rocks [Mizuta, 2002]. It is also noted that the assumption of a constant direction of principal stress is needed for the determination of temporal variation of the stress-state using the same fractures in the preceding measurements.

The single-fracturing method or Serata probe [Serata, 2002] is an improvement over the double-fracturing method. Using this method, the borehole wall is loaded through the friction-shell being cut in the opposite side. The fracture is formed in this direction as shown in Fig. 6b. In contrast to the double-fracturing method, the direction of the fracture is not determined by external stress but by the position of the cut in the friction-shell. Three unknown parameters are the magnitude of the maximum horizontal stress, the minimum horizontal stress, and their directions. After creating the fracture, the pressure for reopening the fracture is measured. Three fractures with different directions are required to determine 3 unknown parameters. The interpretation is similar to the borehole-jack method, and is shown later.

4-2. Borehole-jack based fracturing method

A borehole-jack was originally a tool for measuring rock stiffness in boreholes [e.g., Goodman *et al.*, 1970]. Using this kind of tool, the borehole wall can be fractured for measuring rock stress [de la Cruz, 1977]. With this loading type, a mismatch of the radius of curvature of the loading plate and the borehole wall is sometimes critical, particularly for hard rocks. If the radius of curvature of the plate is larger than that of the borehole, induced fractures are likely to be created at the contact of either edge of the loading plate. In contrast, if the radius of curvature is small, a load is applied along the line contact of the borehole wall, and fractures tend to form at the center of the loading platens. Using the borehole-jack fracturing method modified by Mizuta *et al.* [2004], the contact angle of the platens in the half space of the borehole is broadened from around 90 degrees [De la Cruz, 1977; Azzam and Bock, 1987; Yokoyama and Nakanishi, 1997] to 160 degrees as shown in Fig. 6c. A combination of loading shells and loading platens is proposed to reduce the probability of corner edge fractures. In contrast to the sleeve fracturing methods, any fracture detection system can be attached directly to the borehole wall for the borehole-jack system. De la Cruz [1977] employed a strain-relaxation-sensor for detecting fracture formation. Azzam and Bock [1987] and Mizuta *et al.* [2004] employed a tangential strain sensor (TSS) or crack-opening-displacement (COD) sensor.

Using this method, a load is applied in a distributed form along the borehole wall. Similar to the single-fracture method, 3 fractures in different directions are necessary to determine 3 parameters, i.e., the magnitudes of the maximum horizontal stress,

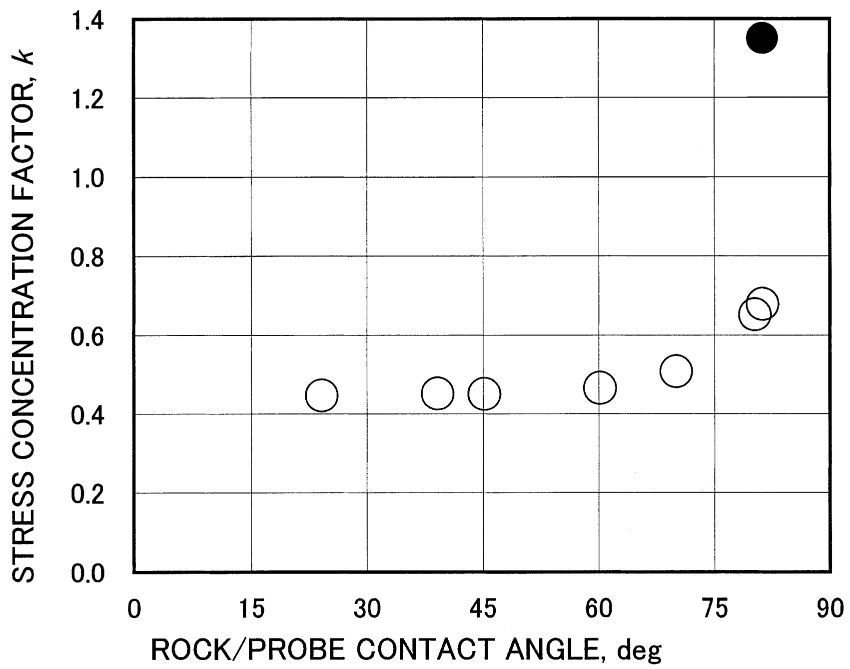


Fig. 7. For the newly designed borehole-jack stress probe, the stress distribution on the borehole wall is influenced by the elastic coupling of the probe/borehole contact. The stress concentration factor defined by ratio, hoop stress at the mouth of the fracture, and jack pressure, is plotted against the rock/probe close contact angle. The results shown by open circles indicate the stress concentration factor for the continuous coupling from the left-hand edge to the right-hand edge through the apex of the outer shell (see Fig. 6c). The result shown in the solid circle shows the result assuming a very thin space around the apex of the shell. The solid circle indicates the highly effective loading condition. However, the concentration factor might fall to almost half of the solid circle, if the coupling conditions are not the same as designed conditions. Hence, we may use the coupling conditions as shown in solid circle only in the fracturing process, but we have to use the coupling conditions shown by open circles for the re-opening procedures.

the minimum horizontal stress, and their directions. The normal stress acting on the borehole wall can be expressed as a sinusoidal distribution with borehole-jack fracturing method, while the normal stress is constant throughout the borehole wall with the single-fracturing method. The distribution of shear force is similar with these 2 methods [Mizuta *et al.,* 2004].

For stress determination using both borehole-jack and single-fracturing methods, the fracture is assumed to reopen when the tangential stress on the borehole wall at the mouth of the fracture reaches zero, namely

$$3S_h - S_H + 4(S_H - S_h)\sin^2(\theta-\alpha) - P_o - kPj = 0 \quad (11)$$

where θ and α are directions of fracture and maximum principal stress, respectively. The constant, k, is the system dependent coefficient. Pj is the internal pressure of the borehole jack or the sleeve. When the borehole wall is loaded in at least 3 different directions to get 3 Pj for 3 different θ, the parameters, S_H, S_h, and α can be solved. It is noted that the pore pressure term in Eq. (11) is explicitly defined, while this term is ambiguous with hydraulic fracturing method as mentioned above.

For the borehole-jack fracturing system, the elastic coupling between the borehole wall and the loading shell (and/or loading platen) is an important factor influencing the above stress concentration factor, k, particularly for hard rocks. The contact angle of the loading-shell and borehole-wall is one of the most important factors. The results of a numerical simulation of the influence of contact angle to the coefficient, k, are shown in Fig. 7 where open circles indicate the results for continuous close coupling of the whole shell (or platen), and the solid circle indicates the result for the case without contact around the top of the platen. The stress concentration factor is significantly affected by the contact angle, particularly at about 80 degrees. In such a case, the unintended change in the coupling conditions can be a cause of large errors in the estimation of reopening pressure. However, for contact angles less than 60 degrees, the stress concentration factor is only slightly influenced by the coupling, which should be important for precise measurements.

5. Core-based method

Several stress measurement methods have been introduced using core samples [e.g., Amadei and Stephansson, 1997]. One of the advantages of these methods is technical, in that no additional field procedures except drilling core samples are required. The methods are called acoustic emission (AE) method [e.g., Kurita and Fujii, 1979; Kanagawa *et al.,* 1981], differential strain curve analysis (DSCA) method [e.g., Strickland and Ren, 1980; Dey and Brown, 1986], deformation rate (DR) method [e.g., Yamamoto *et al.,* 1990], and anelastic strain recovery (ASR) method [e.g., Warpinski and Teufel, 1981; Ito *et al.,* 1997] methods. The AE method is based on the Kaiser effect [Kaiser, 1953], that is, the phenomenon whereby the acoustic emission occurs just after exceeding the former stress level in a reloading cycle. DSCA method is based on an analysis for determining the aspect ratio distribution of preexisting cracks in rocks [Simmons *et al.,* 1974; Siegfried and Simmons, 1978]. DR method is based on a change in the slope of the stress/strain curve at a point of the former stress level. ASR method is based on the anelastic strain change after stress-relieved by drilling. These methods can be candidates for a severe environment such as very deep boreholes where other stress measurement techniques cannot easily be applied. Although discussions on these methods can be found in the literature [e.g., Amadei and Stephansson, 1997; Yamamoto, 2004], the basic link between the observed data and the stress-state remains vague. Time-dependent crack extensions under residual stress could be responsible for such anelastic strain changes. Residual tensile stress in relatively stiff grains of heterogeneous materials can be a cause for microcracking [e.g., Katoh *et al.,* 1994b]. Although the physical mechanism and the link to external stresses have not been explicitly clarified, these core-based methods would be among the important techniques in the "Integrated Stress Measurement Strategy" employed in the KTB project [Brudy, *et al.,* 1997].

6. Drilling-Induced-Fracture method

When the overburden stress is much smaller than the horizontal stresses, the boring core is sometimes fractured horizontally with almost equal lengths. This is called a core-discing. Stress estimation has been discussed in the literature [Sugawara *et al.,* 1978; Ishida and Saito, 1989; Dyke, 1989; Haimson and Lee, 1995].

For deep wells, such as deeper than 3 km, borehole walls tend to be damaged due to compressive stress concentration. When the pressure of the mud-water mixture used for drilling fulfills fracture conditions similar to hydrofractures, tensile fractures are formed at the point of minimum stress concentration [Stock *et al.,* 1985; Brudy and Zoback, 1993]. From a technical point of view in drilling, the physical properties of mud-water mixture are important to prevent such fractures. A fracture zone in response to high compressive stress is known as wellbore breakout, borehole breakout, or simply breakout [e.g., Zoback *et al.,* 1985; Barton *et al.,* 1988]. The central point of the fracture zone indicates the direction of the minimum horizontal stress, S_h. The maximum horizontal stress, S_H can be estimated through an interpretation of the size of the fractured zone [Bell and Gough, 1979; Hottman *et al.,* 1979; Tsukahara, 1990; Moos and Zoback, 1990]. It is extremely difficult to use the hydraulic fracturing method for such a fractured wall. Under such conditions, a combination of induced fracture and breakout is generally employed. Brudy *et al.,* [1997] used the hydraulic fracturing method up to a depth of 2 km. For borehole deeper than 3 km, they employed the integrated stress measurement strategy [Brudy *et al.,* 1997], in which all data obtained by any available method were combined to estimate the stress state.

7. Other Factors Influencing the Reliability of Measurements

From the viewpoint of accuracy, we have to consider the effects of the heterogeneity of rocks from microscopic to macroscopic scales. Heterogeneity can be a cause of stress variations from space to space. Regarding a relatively small scale, a statistical treatment can be found in Hudson and Cooling

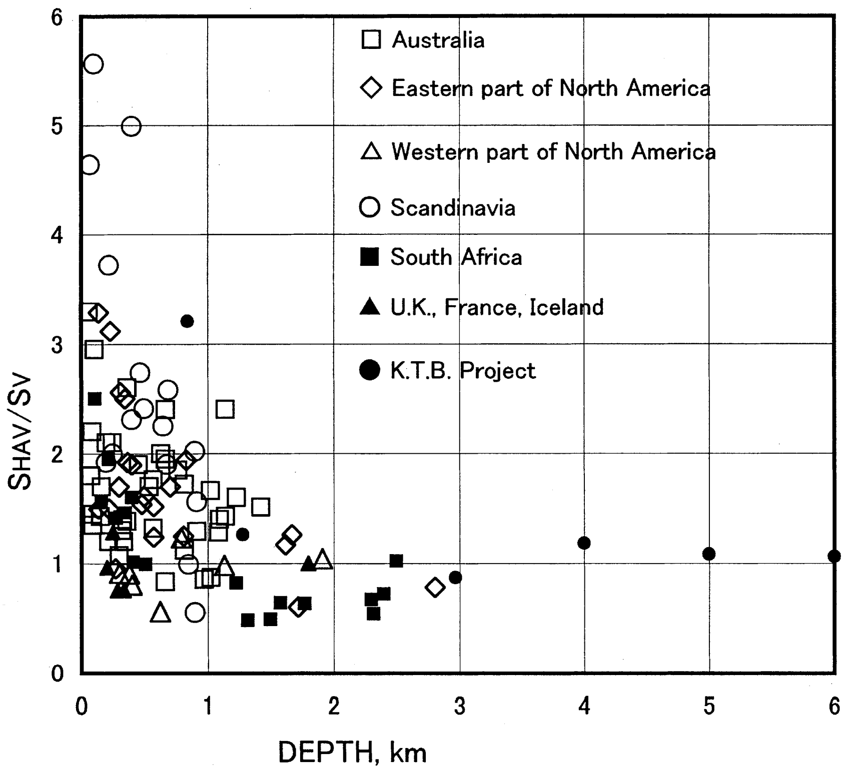


Fig. 8. Ratio between mean horizontal stress (S_{HAV}=(SH+Sh)/2) and overburden stress (Sv) increases ground surface approaches. Based on the figure of Brown and Hoek [1978], KTB result [Brudy *et al.,* 1997] is added. In the original figure, data for North America were classified in two groups, data in Canada and those in the U.S.A. In this figure, the data for North America are classified into data for the eastern and western parts of the North American continent.

[1988]. An example of numerical estimations of the far field stress-state from the observed pin-point stress-state in a heterogeneous medium of several kilometers in scale can be found in Mizuta [2004]. Heterogeneity can also be a cause of residual internal stress [e.g., Friedman, 1972; Voight, 1974; Voight and St. Pierre, 1974]. We also have to consider some disturbances. One of the disturbances is the topographic effect on measurement results [e.g., Engelder, 1993; Amadei and Stephansson, 1997]. Another is known as an abnormal increase in the S_h/S_V ratio or $(S_h+S_H)/S_V$ ratio near the ground surface as shown in Fig. 8, where S_H, S_h, and S_V are the maximum horizontal stress, the minimum horizontal stress, and the vertical stress [e.g., Engelder, 1993]. This disturbance may be explained by a theory proposed by Goodman [1980] or a completely different theory proposed by McCutchen [1982]. Given the present knowledge on the origins of this kind of disturbance, we cannot easily compare measured stress at different points at different depths. Fortunately, this disturbance decreases considerably at points deeper than 500 m in Japan [Yokoyama, 2004].

8. Conclusion

The methods of measuring crustal stress and its variations are briefly reviewed with particular interest in precise measurements at depth. The advantages and the disadvantages of these methods, and the problems in their interpretation are pointed out. The stress-relief methods are among the most widely used techniques in the engineering field. Wireless strain-cells indicate the possibility of stress-relief methods for deep wells. However, elastic coupling of [rock+mortar+strain-meter] must be precisely estimated including thermal stress effects, before application to depth. The hydraulic fracturing method has been used widely in the geophysical field. However, suspicions about the reopening pressure in hydrofractures have to be clarified to determine the stress state precisely. Non-hydrofracture methods are free from the problems associated with permeation of pressure fluid into artificial fracture and borehole wall. Furthermore, non-hydrofracturing methods with a single fracture do not need the assumption of a constant direction of principal stresses over time, which can be an advantage for long-term observations of stress variations. The core-based methods and the borehole-wall-fracture-based methods cannot, unfortunately, now be considered to be precise. However, these methods have the potential to estimate stress, particularly at great depths.

This study was partly supported by the Earthquake Research Institute cooperative research program (2004-W-02).

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(Received February 24, 2006)
(Accepted March 10, 2006)