IN-SITU STRESSES IN ROCK MASSES: A GENERAL REVIEW

by
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ABSTRACT

The in situ *state of stress is a rock's point-to-point property that must be taken into consideration in every subsurface engineering activity. This has been realized to an increasing extent over the past 10 – 20 years. Good quality* in situ *stress information enhances the quality of engineering designs such as for mining, petroleum and geothermal production. In turn, good engineering designs will support the process of decision making in related industries. However, efforts are required to encourage the use and integration of this information into the engineering activities.*

This paper is basically a general review over the in situ *stress that encompasses various aspects, among others are: concept, causes/sources that generate it, influencing factors, the effect of scales, techniques for measuring it, and its distribution throughout the lithosphere. The review is supported by works and conclusions that have been made by various investigators in the past. The relative absence of the use of* in situ *stress information in petroleum engineering practices in Indonesia is also discussed. This includes the absence of demand upon the information, probable consequence, and the field cases that are likely caused by the absence.*

Apart from the importance of in situ *stress information shown by the review, it has also prompted the need to apply proper use of in situ stress information in relation to the corresponding engineering scales. Inappropriate measurement techniques assigned to an engineering problem, which corresponds to a certain scale, will certainly lead to a serious misprediction over the expected outcome. These all are hoped to provide operators in the industry a complete general view over the* in situ *stresses their importance.*

I. INTRODUCTION

The state of stress existing in a rock mass comprising part of the earth's crust prior to any construction work is referred to as the *in-situ* or primary state of stress. The knowledge of this state of stress is important for the planning of engineering projects in rock masses, such as for petroleum and geothermal wells, which require this information as an input parameter. In such engineering designs, the information is usually required to represent the boundary loading conditions for the problem to be solved.

For certain aspects of petroleum/geothermal engineering it has long been recognised that a knowledge over the magnitudes and principal directions of the *in-situ* stresses is important. In determining the most favourable injection/production pattern of enhanced oil recovery (EOR) past investigators (e.g. Donohue et al, 1968) have shown that oil recovery is sensitive to the orientation of natural fractures in reservoir. As described accurately by Kranz (1979), it has been postulated that directions of fracture propagation are largely governed by the state of *in-situ* stresses. Furthermore, the directions of the fractures are controled by degree of unequality of the stresses (e.g. Haimson and Fairhurst, 1967). The effect of stresses on propagation directions of fractures also affects other activities, such as drilling of horizontal wells (e.g. Schnerk and Madeen, 1990), hydraulic fracturing stimulation (e.g. Hubbert and Willis, 1957 for theoretical examination, and Hansen and Purcell, 1986 for laboratory investigation), and hot-dry-rock geothermal exploitation (e.g. Batchelor, 1982). Observations of wellbore instability by a number of investigators (e.g. Gough and Bell, 1981; and Hickman et al, 1985) have indicated that regions around wellbores fail in a pattern and manner strongly controled by the magnitude and orientation of the *in-situ* stress field.

Considering the importance of *in-situ* stress field, this paper presents a general review over various aspects of the stresses including the concept of stress, generation, factors influencing the state of stress, scale effects, and distribution of the stresses in the earth.

II. THE CONCEPT OF STRESS

All undisturbed rock masses in the earth contain non-zero components of stresses due to various physical processes including the deposition of overlying materials, confinement, tectonic activities, and previous stress history. The dynamic nature of the earth crust is apparent in the deformation of its lithosphere as manifest by mountain belts, continental rifts, rapidly subsiding basins, high plateaus, and deep oceanic trenches. In other words, every part of the earth's crust is subjected to an *in-situ* stress field.

Stress is defined (Crouch and Starfield, 1990) as a tensor property that varies from point to point. The concept of stress is used to explain the way in which forces are transmitted through a solid. If the point is imagined as an isolated body element (often considered as an elementary cube), it can be assumed that the forces from the surrounding material are transmitted through it. If the element is small enough, these forces are distributed more or less uniformly over each of its faces, even though not necessary equally in each direction.

Consider one of the elementary cube's faces as a plane which the force is applied. If the area of the plane is A, and the average force acting through it is denoted F, then the stress is given by the general equation

$$Stress = \frac{F}{A} \tag{1}$$

As the actual forces do not operate in a direction perpendicular to the plane, they also work in directions parallel to it, the force must be decomposed into a component F_n normal to the cross section and F_p parallel to the section.

$$\tau = \frac{F_n}{A} \quad \text{and} \quad \tau = \frac{F_p}{A} \tag{2}$$

The stresses are the *normal stress* and *shear stress*, respectively. The magnitude of each depends on the relative orientation of the surface and the force F.

Since the cube considered above has six faces in three orthogonal directions (x, y, and z), the stresses related to the surfaces normal to the axes are given a specific notation (Figure 1). For instance, the stresses operating on the surface normal to the x-direction are denoted σ_{xx}, τ_{xy}, and τ_{xz}, representing the normal stress, and the shear stresses in y- and z- directions respectively. This decomposition results in nine stress component related to one element:

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \tag{3}$$

The above expression which represents the state of stresses on an elementary cube element is called the *stress tensor*, as defined in Jaeger and Cook (1978): "A tensor is a quantity with magnitude, direction, and the plane of which the forces act". Considering the concept of symmetry among stress components, in which $\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$, and $\tau_{yz} = \tau_{zy}$, the matrix ends up in having only six independent components, leading to six independent observations.

Since the rock stresses are difficult quantities to measure, especially for rocks at great depths, the *principal stresses* are of special significance in relation to analysis for engineering purposes. A principal direction is defined as (Fjaer et al, 1992): "the direction in which shear stresses vanish, hence only normal stresses exist". The normal stresses that act parallel to the directions are called principal stresses. At this condition, a matrix with all off-diagonal components equal to zero represents the stress matrix shown above.

For practical purposes principal stresses are often presented by a set of symbols, σ_1, σ_2, σ_3 with a convention that $\sigma_1 > \sigma_2 > \sigma_3$ regardless of their directions. It is the rule rather than an exception that the real principal stresses, which are perpendicular to each other, are parallel or at least sub-parallel to either horizontal or vertical directions dependent on the relative magnitudes of the local gravitational and horizontal forces.

Stress is measured in the SI unit Pa (=Pascal = N/m^2), or non-SI units bar, atmosphere, psi, or dynes/cm^2.

III. GENERATION OF *IN SITU* STRESSES

The natural stresses accumulated in the lithosphere are the results of deformation activities over a long period of time. Turcotte and Oxburgh (1976) suggested that stresses can accumulate in the lithosphere for $10^6 - 10^9$ years. It is now recognised that there are number of mechanisms leading to the accumulation of stress in the lithosphere.

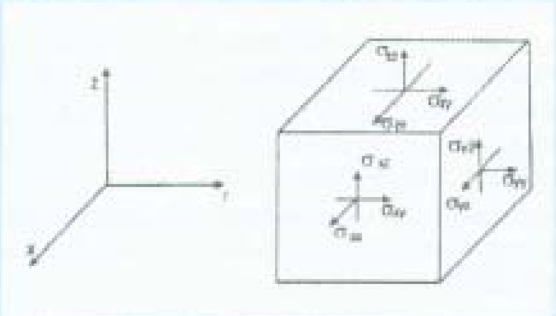

Figure 1
An elementary cube with its stress components

Bott (1982) divided the stress sources into two main categories that are referred to as *renewable* and *non-renewable* types. In one hand, stress sources of a renewable type are those which persist as a result of the continued presence or re-application of the causative boundary or body forces, even though the strain energy is being progressively dissipated. The two main examples are stress systems arising from plate boundary forces and isostatically compensated surface loads. On the other hand, stress sources of non-renewable types are those, which can be dissipated by release of the strain energy initially present. In reality, each of these stress sources contributes to the *in situ* state of stress and it is difficult to distinguish the contribution of a particular source. In other words, the actual stress at any point in the lithosphere is a result of a combination of superimposed stress systems, which may be dependent on the position of the point under consideration relative to the position of the sources.

A. *Renewable Stress Systems*

As earlier implied the renewable stress systems are characterized by their ability to maintain the continuity of the strain energy supply, which itself is fed by the action of boundary or body forces and is relieved at approximately the same rate by tectonic activities. The followings are some examples of renewable stress systems.

1. Plate boundary stresses

The basic hypothesis of plate tectonics is that the earth's crust is broken into a number of rigid plates. It has been long accepted that these crustal plates are always in a state of movement relative to each other in response to forces applied to their boundaries which result in the plates being stressed (e.g. Sykes and Sbar, 1973). It is also argued that the strained plates are relieved in about the same rate by the resistance to motion which cause earthquakes, frictional and viscous loss of energy, etc (i.e. the "antagonism" principle, as discussed by Scheidegger, 1979). Furthermore, Engelder (1993) proposed that the stress distribution within the plates depends critically on whether the plates are driven by forces on their edges or by underlying drag of mantle convection current on the base of the lithosphere. Under such circumstances, it has been concluded that stress fields within the lithosphere arise from the balance of forces driving (i.e. plates' edge forces) and resisting (i.e. underlying mantle's drag forces) plates motion.

The various types of driving and resistive forces which may act on plates have been summarized by Forsyth and Uyeda (1975):

a. Ridge push force

A force which is generated as the result of mid-oceanic ridges spreading (Figure 2). Bott and Kuznir (1984) reported that the average stress caused by this mechanism is about 20 – 30 MPa.

Figure 2
Forces acting on lithospheric plates (from Forsyth and Uyeda, 1975) RP = ridge push SU= trench suction SP=slab pull MD=mantle drag CD=continental drag SR=slab resistance CR=colliding resistance TR=transform-fault resistance

b. Slab pull force

This mechanism acts at subduction zones (e.g. McKenzie, 1969). Figure 2 shows the mechanism as the result of the oceanic plate subduction. The higher density of the cool, downward-moving slab in the subduction zones create a negative buoyancy of the sinking plate.

c. Trench suction force

At the subduction zone, a seaward migration of the trench may create a gap between plates, as suggested by Elsasser (1971). The created gap can result in a lack of support which in turn can create a tension force. Bott and Kuznir (1984) reported a probable magnitude of about 20 MPa.

d. Mantle drag

A result of viscous coupling between the lithosphere and the more viscous asthenosphere. Mantle drag can be either a driving or a resisting force depending on the direction of the mantle convection currents on the base of the lithosphere. Arguably, mantle drag provides the greatest resistance to the plate movements.

e. Continental drag

An additional drag force caused by the difference in theological properties of the asthenosphere under the ocean and continents (Engelder, 1993).

f. Slab resistance

A resisting force as a result of the drag of the subducting plate on the asthenosphere.

g. Colliding resistance

A resistive force generated as a result of frictions between oceanic and continental plates at the subduction zone.

h. Transform-fault resistance

A resistive force resulted by faulting at plates boundary.

2. Gravitational stresses

A force that is generated by the weight of overlying materials (Figure 3). Ideally, if the overlying rocks are assumed to be homogeneous, isotropic, and linearly elastic, the gravitational/vertical stress can be related to horizontal stress by (Wittke, 1991):

$$\sigma_H = \frac{\nu}{1-\nu}\ \sigma_v \qquad (4)$$

where ν, σ_H, and σ_v are Poisson ratio, major horizontal stress, and vertical stress, respectively. Note that the σ_H could be either σ_1 or σ_2, whereas σ_v be either σ_1, σ_2, or σ_3. Equation (4) suggests that since n values for common rocks are between 0.15 – 0.25 (Fjaer et al, 1992) it is likely that σ_H is always less than σ_v. However, it is often found that horizontal stresses are measured as larger than the vertical ones (e.g. Brown and Hoek, 1978). This fact can be treated as an evidence that shows the superimposed nature of the stress systems, as well as the effect of transversely isotropic condition frequently exhibited by sedimentary rocks (even with the same n values), as shown by Amadei et al (1987) in their investigation.

B. *Non-renewable Stress Systems*

Some investigators have shown that large stresses can be generated by non-renewable stress systems. Bott (1982) suggested that the initial strains caused by such systems could be as high as 1 % or more. However, because of their non-renewable nature, they can probably be relieved substantially by transient creep and brittle fracture over a relatively short period of geological time or perhaps even engineering time.

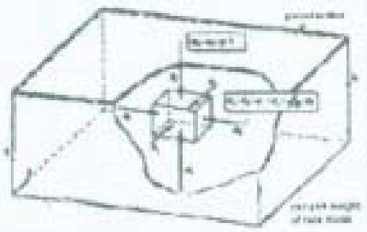

Figure 3
Overburden loading due to dead weight with isotropic and elastic behaviour (from Wittke, 1991)

The most commonly known non-renewable stress systems are:

1. Bending stress

Risen by flexure of the lithosphere as a result of uncompensated loading and downbending at subduction zones (see Figure 2) and occurs on the concave side of the bend and tension on the convex side. Walcott (1970) presented a possibility of 500 MPa, whereas Turcotte et al (1978) even suggested a more fantastic figure of 1,000 MPa compression at the lower part of the zone. These large forces are quickly dissipated by the ductile flow regime that probably prevails at that part.

2. Membrane stress

Generated by changes in radius of curvature of a plate as it moves towards the equator or towards the pole. Turcotte (1974) showed that this stress might reach magnitudes up to 100 MPa.

3. Thermal stress

Collisions and movements of the tectonic plates can increase the temperature in the subduction zones. These temperature changes give rise to thermal stresses. Such stresses are liable to have most effect on the oceanic lithosphere as it cools after a period of time and later heats up again during subduction. House and Jacobs (1982) showed that a maximum stress of 600 MPa can be generated through this mechanism. Despite large, enough to generate earthquakes, its role in tectonic deformation is probably limited because of discontinuous temperature changes.

IV. FACTORS INFLUENCING *IN-SITU* STATE OF STRESS

In general, measurements of *in situ* stress fields are made inside boreholes, on outcrops, on internal surfaces of underground cavities or on samples. Most of the measuring techniques intentionally disturb the state of stress in the rock and then measure the consequent deformations, usually by assuming homogeneous, isotropic, continuous, and lienearly elastic. Under such circumstances various investigators (e.g. Batchelor and Pine, 1986 and Montgomery and Ren, 1981) reported local variations in *in situ* stress fields that differ significantly from the regional stress fields, depending on the volume of rocks being tested. In general, the factors influencing this variation are related to the heterogeneity of rock properties and geometry of the rock's body. The following examples have been proven as influencing factors:

A. *Inhomogeneity of Elastic Properties*

Inhomogeneity in elastic properties is the most important factor in deviating regional *in situ* stress fields. This statement comes from an understanding that it is the elastic properties (e.g. Poisson ratio, bulk modulus, and shear modulus) that govern the relationships between stress and strain. Inhomogeneity in these properties can modify stress distribution in the rock body initially loaded by 'far' stress fields at its boundary.

The main causes of the inhomogeneity are recognised as variations in lithology and local structures. Szymanski and Harper (1979) presented an example of variation in stress orientations derived from stress-relief measurements made in a strata formed by a sequence of quartz sand, shale, and graywacke intraclasts, with variation in elastic properties. They concluded that local heterogeneity in a sedimentary sequence can cause variability of results (i.e. major stress' magnitudes and directions), as indicated by directions of the arrows, even though the measurements may be only short distance apart.

B. *Anisotropy*

A medium is called anisotropic if its properties vary with direction, even though they might be uniform at all points throughout the medium (homogeneous). Crampin et al (1984) suggested five possible sources of anisotropy: lithologic variation (differences in lithification of the same rock, for instance), rock structure (laminated sedimentary rocks), aligned cracks, aligned cristals, and direct stress.

In a manner similar to inhomogeneity in elastic properties, any anisotropic deformations may also change the magnitudes and directions of stresses within a rock medium. As proven by Amadei et al (1987) horizontal stresses as results of Poisson effect from the overlying rock masses can be modified by presence of transverse anisotropy in rocks.

C. *Inelasticity*

Many materials deviate from elasticity at high stress levels, elevated temperatures, or under prolonged loading. The deviations can take the form as: an incomplete instantaneous recovery of strain as the loading stress is removed, a change in strain with time under constant load, a change in stress with time under constant deformation, or a variation of mechanical properties with temperature. This behaviour is termed inelastic or viscoelastic (Obert and Duvall, 1967).

In a given condition in which a rock material starts to deviate from elasticity, it tends to react to an applied stress in a manner termed time-dependent deformation (a deviation from the linear Hooke's law). An example is provided by Wawersik and Stone (1986) that while conducting a hydrofracturing test in Salado rock salt formation in New Mexico they found that the virgin *in situ* state of stress is isotropic (lithostatic condition, $\sigma_1 = \sigma_2 = \sigma_3$). They concluded that the hydrofracturing result does not represent the true *in situ* state of regional stress field because the test's pressure reponses are strongly influenced by the rock's creep behaviour.

D. *Natural Cracks*

There is some evidence that natural cracks (e.g. fractures, joints, and microfissures) exist and interconnected to considerable depths (Brace, 1972; 1980), at least in the brittle uppermost 10 – 20 km of the earth's crust (Crampin and Atkinson, 1985). The existence of cracks in the earth's crust has also been established by the fact that water permeates into the fractures (Fyfe et al, 1978), as was also proved by Nekut et al (1977) when during their conductivity survey they found that conductivities of rocks down to a depth of 20 km are quite similar in magnitudes to the conductivities of moist rocks of similar types in laboratory. This implies the existence of liquid filled cracks at those depths.

Cracks as a source of discontinuity in rocks play an important role in disturbing rock's mechanical behaviour, as well as the stress pattern applied on it. Crack geometrical characteristics namely orientation, spacing, aperture, roughness, and fillings are factors that determine the result. Brady et al (1986), in their numerical modelling, found that geometry and connectivity of the cracks pattern can lead to high stress concentrations at crack tips (Figure 4). If these 'locked-in' stresses occur naturally in the field, there is a possibility that a stress measurement will measure a field that is different from the true regional stress field. Crack's

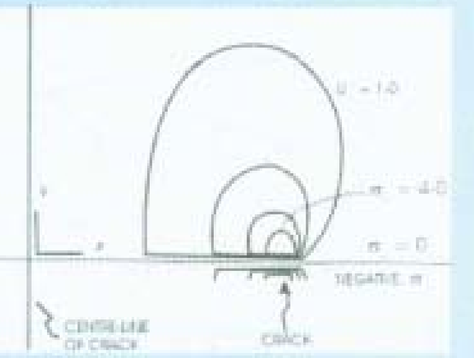

Figure 4
'Locked-in' stresses at the tip of a crack (from Brady et al, 1986)

decoupling effect is also thought as an important factor in disturbing stress field. This was observed by Brown et al (1986) when they conducted an experiment using a large fractured block of gneiss, with a number of vertical boreholes drilled in it used for observation, which is exposed to various applied stresses.

E. *Topography*

Topography can have a significant influence on the *in situ* state of stress, especially in positions close to rough ground surface (mountains, valleys, etc). Warpinski and Teufel (1991) put that in some extreme cases, the principal stresses are reoriented by as much as 45°. The *in situ* stress modifications due to topography variation diminish as the distance from the surface increases. At these positions, the overburden stress acts vertically and increases with depth.

F. *Geological Structures*

The cause of stress redistribution due to geological structures is by and large the structure boundary (in effect, changes in elastic properties). Carlsson and Christiansson (1986) found that there is a tendency for stress directions to be parallel to an adjacent structure, whilst Martin and Chandler (1993) in their stress characterization study reported that stress orientations can rotate significantly when geological structures such as thrust fault are crossed.

G. *Presence of Residual Stresses*

The existence of residual stresses in rock has been recognised for at least 200 years (Gentry, 1973), but only during a few past decades has it been given much attention. Residual stress is defined as a component of stress stored in a material after the application of the stress source is lifted (Engelder, 1993). Residual stress is regarded as a fundamentally active stress, since it is related to stored strain energy, but is associated with zero surface tractions. Basically, there are two factors that can generate residual stresses in material: a change in energy level such as a stress load and/or a temperature change, and heterogeneity of the material arising from variability of the material's constituent property. This heterogeneity could be variations in elasticity behaviour, inelasticity, temperature expansivity, anisotropic grain orientation, or the presence of discontinuities along which slip can occur. With the factors highlited above, it is not difficult to understand that variations in relaxation also take place during a relief of loading (e.g. stress relief after faulting). These variations result in 'locked-in' stresses that have orientations and magnitudes, hence the potential to disturb the true regional stress field.

V. SCALE EFFECTS IN ROCK MASSES

The fact that the state of an *in situ* stress field is very much affected by various factors implies its dependency upon dimensions of rock volumes involved in investigation or measurement. Figure 5 illustrates the changing texture of rock volumes with the increasing of their size. In the smallest volume, the behaviour of rock properties is largely governed in grain scale and can be regarded as an intact rock. By increasing the specimen size, the texture of the specimens becomes variable with the introduction of discontinuities at different pattern levels. When these specimens are subjected to similar test condition aimed at measuring the stresses, the results could be different eventhough all specimens are taken from the same rock body. This characteristic, which is a function of size, is called *scale effect*. A qualitative diagram illustrated in Figure 6 shows the influence of scale effect on rock property.

Figure 5
Representation of scale effects
(from Cunha, 1990)

From the diagram shown in Figure 7, it is obvious that the data scatter converges at a size beyond which the test results become independent of the specimen size. This volume, which is the smallest volume that can be considered as representing the behaviour of the entire rock mass, is called *representative elementary volume* (REV). At volumes greater than the REV, all inhomogeneities exist in the rock body are 'averaged' and all tests conducted will give reasonably consistent results (Hudson and Cooling, 1988). The REV varies from one rock mass to another, depending on the inhomogeneity scales within the rock mass (i.e. the material's intrinsic properties and the discontinuity network).

A. *Potential of Scale Effects on Stress Measurements*

Measured *in situ* stresses are certainly complicated by the presence of inhomogeneity at different scales. The com-

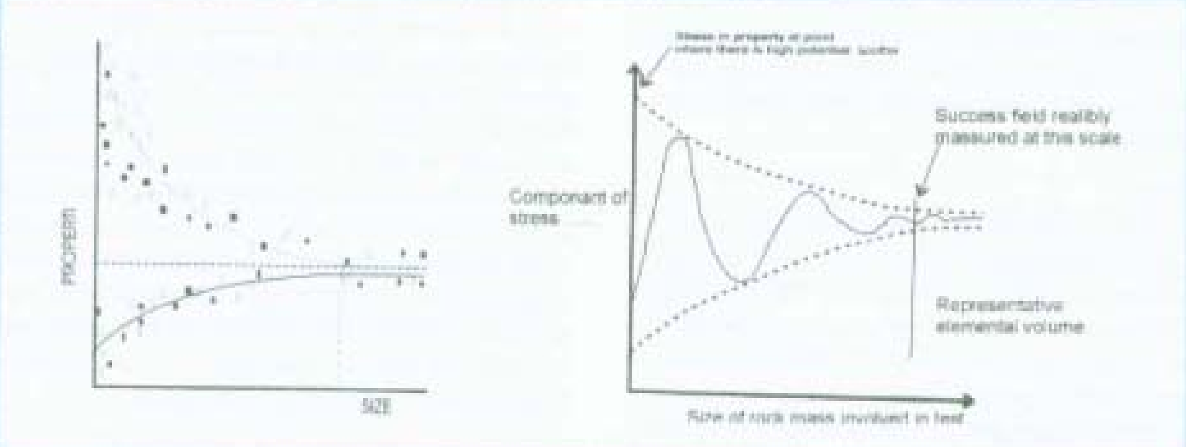

Figure 6
Scatter of rock property due to scale effects (from Cunha, 1990)

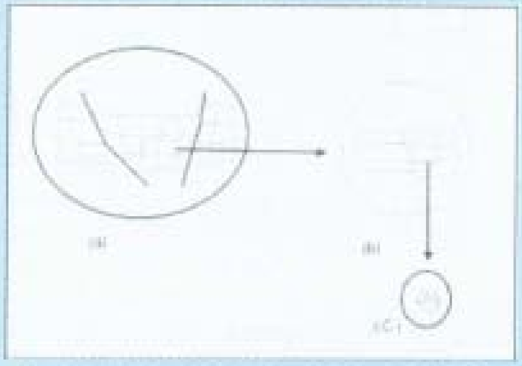

Figure 7
A rock mass with different levels of heterogeneites (adapted from Cuisiat and Haimson, 1992)

mon approach used in rock mechanics is to justify the assumption that stresses in rock mass are continuous. This assumption is also applied in stress measurements, and any stress tensors defined at any points are assumed not to involve any heterogeneity and its corresponding scale dependency. Considering different scales that characterize the most common *in situ* stress measurement techniques (Table 1) different results might be produced by the techniques. At this point the concept of REV provides the best explanation over the potential inconsistencies caused by rock inhomogeneities.

Cuisiat and Haimson (1992) pointed out that rock structure is too complex to model all the heterogeneities separately. The heterogeneity in a real rock mass is usually formed by various levels of heterogeneities ranging from grain-size to the size of a major fault. Figure 7 illustrates a rock mass containing heterogeneities at different levels. In large scale (Figure 7a) the heterogeneity is provided by a pair of faults which confine a regularly jointed rock mass. Between these two faults, the jointed rock mass can be considered as a homogeneous medium, analogous to a continuous medium. At lower level (Figure 7b) the joints provide heterogeneity and the medium in between them may be considered continuous. At the smallest level (Figure 7c), the irregularities in grain size, shape, mineral constituents, orientations and cementation material provide the heterogeneity. In this case, the inner parts of the grains are considered homogeneous.

In accordance with the concept of REV, the fact that a real rock can have several levels of heterogeneity, it can be put that the concept can be extended so that each level of heterogeneity in a rock mass has its own REV (and also a smallest dimension that causes the measurement scatter), from micro-level up to macro-level. Nevertheless, the 'true' REV that represents the regional *in situ* stress field is determined by the macro-level heterogeneity.

B. *Different Scales of Required* In Situ *Stress Information*

Various activities in subsurface engineering are affected by the need for information regarding *in situ* state of stresses. However, the scale on which knowledge of the stress is necessary can vary considerably from one area of interest to another, and from one specific case to another. In problems related to earth science such as plate tectonics, the *in situ* stress information required must represent a very large volume of rock mass under consideration. On the other extreme, stress information required for wellbore stability analysis is limited to several tens of cubicmeters (Aadnov et. al, 1987).

As presented earlier, scale effect exists because a rock mass containing heterogeneities behaves differently at different scales. Consequently, stress measurements made at different scales can give different magnitudes and orientations (Figure 8). Thus, there is a coexistence between the scales of *in situ* stress information required by various areas of interest at different scales and the fact that the information of *in situ* stress provided by the measurement techniques is variable at different scales. This leads to a consideration underlining the need to acquire *in situ* stress information that represent the size of rock masses involved in the problem. Therefore, any *in situ* stress measurement plan has to be set up according to the size of the problem, despite the fact that information from other methods of different scales is also valuable. Schematically, this is illustrated by the layout in Figure 9. The figure implies that heterogeneity description of the surrounding rock masses plays an important role in determining every *in situ* stress measurement programmes.

For the purpose of problem solving in petroleum and geothermal engineering, techniques presented in Table 1 (and Figure 10) can be used as guidance. For instance, *in situ* stress field for problems such as wellbore stability and design of hydraulic fracturing for stimulation can be sufficiently provided by "micro" and "meso" techniques such as overcoring and hydraulic fracturing. On the other hand, if the information is required for predicting the general directions of natural fractures in petroleum and/or geothermal reservoirs, additional "macro" techniques will be useful, while a total reliance over "micro" techniques can lead to misleading conclusions. Technique selection is therefore a neccessity for useful output.

VI. THE DISTRIBUTION OF *IN SITU* STRESSES

A. *Stress Regimes in the Lithosphere*

The knowledge that stresses in the earth's crust cannot exceed the strength of rock shows the active role played by rock strength as a governor for the state of stress in the lithosphere. In general, the governors for earth stress include three types of mechanisms leading to failure of intact rocks, namely crack propagation, shear rupture, and ductile flow. Furthermore, existing joints or shear fractures can slip if they are subjected to large shear tractions, hence providing an additional governor for lithospheric stresses. This mechanism (called fractional slip) can also occur in ductile flow, even though the distinction between ductile shear and ductile flow is not as clear as the distinction between slip of existing cracks and the brittle failure of intact rock by shear rupture. The abundance of both brittle and ductile structures evidence in outcrops, and the recognition that they behave differently when subjected to tractions have lead to the postulate that stresses in the lithosphere vary from point to point depending on the deformation mechanism that govern the stress-deformation process. The four stress regime groups based on these mechanisms are (Engelder, 1993): *crack propagation*, *shear rupture*, *frictional slip*, and *ductile flow* (Figure 11).

It is recognised that in the upper portion of the lithosphere, joints are so common that it is appropriate to recognise it as having a separate stress regime. A joint is known as a crack in rock along which there is no significant shear displacement. Therefore, there is no indication that joint is created as a result of large boundary tractions. In general, it is believed that joint is initiated as a result of propagation of pre-existing microscopic flaws such as microflaws and pores. Some efforts have been devoted to explaining the

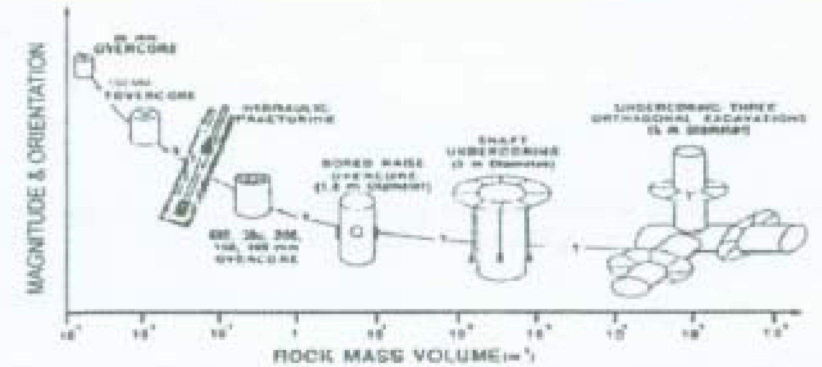

Figure 8
In situ stress measurement techniques at various scales (from Cunha, 1990)

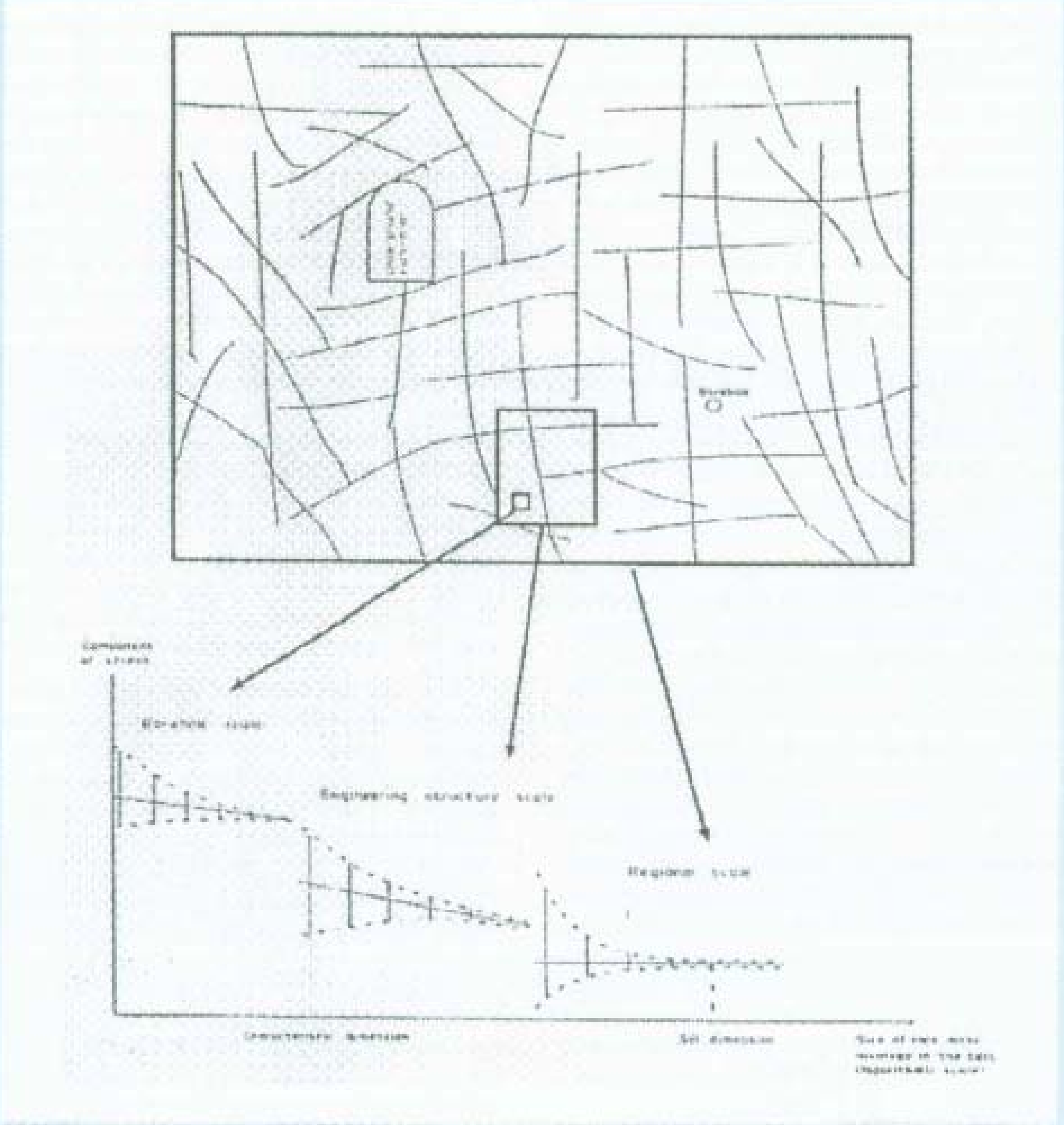

Figure 9
In situ stress information, different problem scales, different scales of stress are required (from Cuisiat and Haimson, 1992)

creation of rock joints. One possible explanation is found in the poroelastic behaviour (Biot, 1941) which is responsible for the generation of a net tensile stress across the pre-existing microflaws, and consequently generating *crack propagation*. This process is continued when the rock system is subjected to elevated pore pressure.

In general, the crack propagation regime of the lithosphere is characterized by a low differential stress, σ_d (=σ

$- \sigma_3$) and pore pressure at or above hydrostatic pressure. In this condition, any pressure elevation is likely to form new joints.

The generation of a primary *shear-rupture* in an intact rock is dependent upon its brittle strength. Thus, the creation of shear-rupture follows brittle failure criterion (e.g. Jaeger and Cook, 1978). Unlike joints, it is indicated that shear-ruptures are not commonly found over broad regions, even in tectonically active areas where shear fractures are sometimes less common than might be expected (Engelder, 1993). The limited distribution of primary shear fractures illustrates the point that regional σ_d is often not large enough to initiate shear ruptures. This is partly due to the process of *frictional slip*. As mentioned earlier, the earth's crust contains discontinuities such as joints, shear fractures and faults. Because of the pervasive nature of these discontinuities, a build up in earth stress is generally relieved by fractonal slip long before σ_d becomes high enough to shear intact rocks. It is stress relief by fractional slip that makes primary shear rupture such a local phenomenon. In other words, this stress regime is characterized by frictional strength of the sliding crack surfaces as the major governing factor. As reviewed by Scholz (1990), frictional strength is controled by parameters such as roughness, hardness, temperature, and ductility.

In *ductile flow* stress regime, stress distribution is largely governed by rocks' ductile strength. Temperature and confining pressure have fundamentally different effects on brittle and ductile strength. Ductile strength, in terms of deviatoric stress, is almost unaffected by confining pressure whereas brittle strength increases with the rise of confining pressure. On the other hand, temperature has a large effects on ductile behaviour such as dislocation motion, whereas brittle strength shows little dependence on temperature (Heard, 1963). Because of this behaviour towards temperature and confining pressure, ductile flow regime is characterized by low σ_d in the lithosphere. Consequently, the ductile flow regime in the lithosphere is more commonly found in the warmer temperature-dominated ductile deformation zones. Transition between brittle and ductile flow stress regimes is usually marked by a gradual drop of σ_d (Tullis and Yund, 1977).

Limits of the stress regimes can be defined in terms of the maximum σ_d. Engelder (1993) defines the limits of the stress regimes by plotting σ_d versus vertical effective stress (i.e. depth). Figure 12 illustrates the plot of the four stress regimes.

B. *Global Stress Map*

Many efforts have been made in different parts of the world in order to map the *in situ* stress distribution. Examples of continentwide compilation include Zoback and Zoback's (1980) stress map of the United States; Fordjor's et al (1983) map of Canada; Klein and Barr's (1986) map of Northwest Europe. Example of world stress map is presented by Zoback et al (1989) who compiled a global database of contemporary *in situ* stresses in the upper lithosphere (Figure 12). Note that arrows on the map represent the direction of major horizontal stress (σ_H).

When compiling the stress data for the global stress map (Figure 12) Zoback et al (1989) concluded that the net plate-boundary forces responsible for moving the tectonic plates dominate the stress distribution in the plate interior. This implies that the knowledge of the state of relative movements of the plate is valuable in order to obtain a

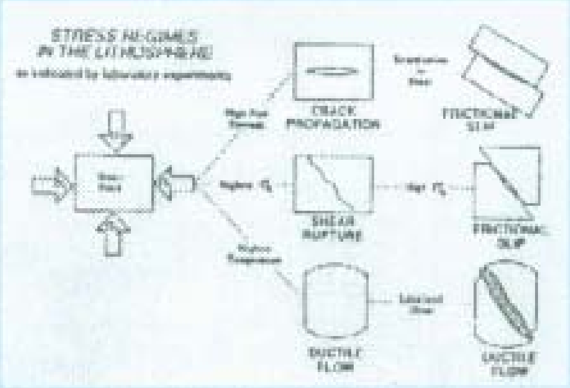

Figure 10
The definition of stress regimes in the lithosphere based on the general types of failure encountered in laboratory experiments (from Engelder, 1993)

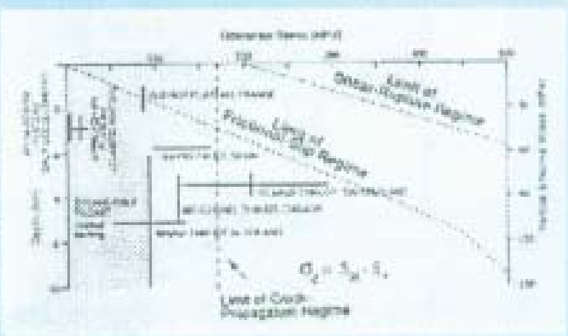

Figure 11
Approximation of d limits of stress regimes in the upper crust, with some. Examples of d vs depth plots (from Engelder, 1993)

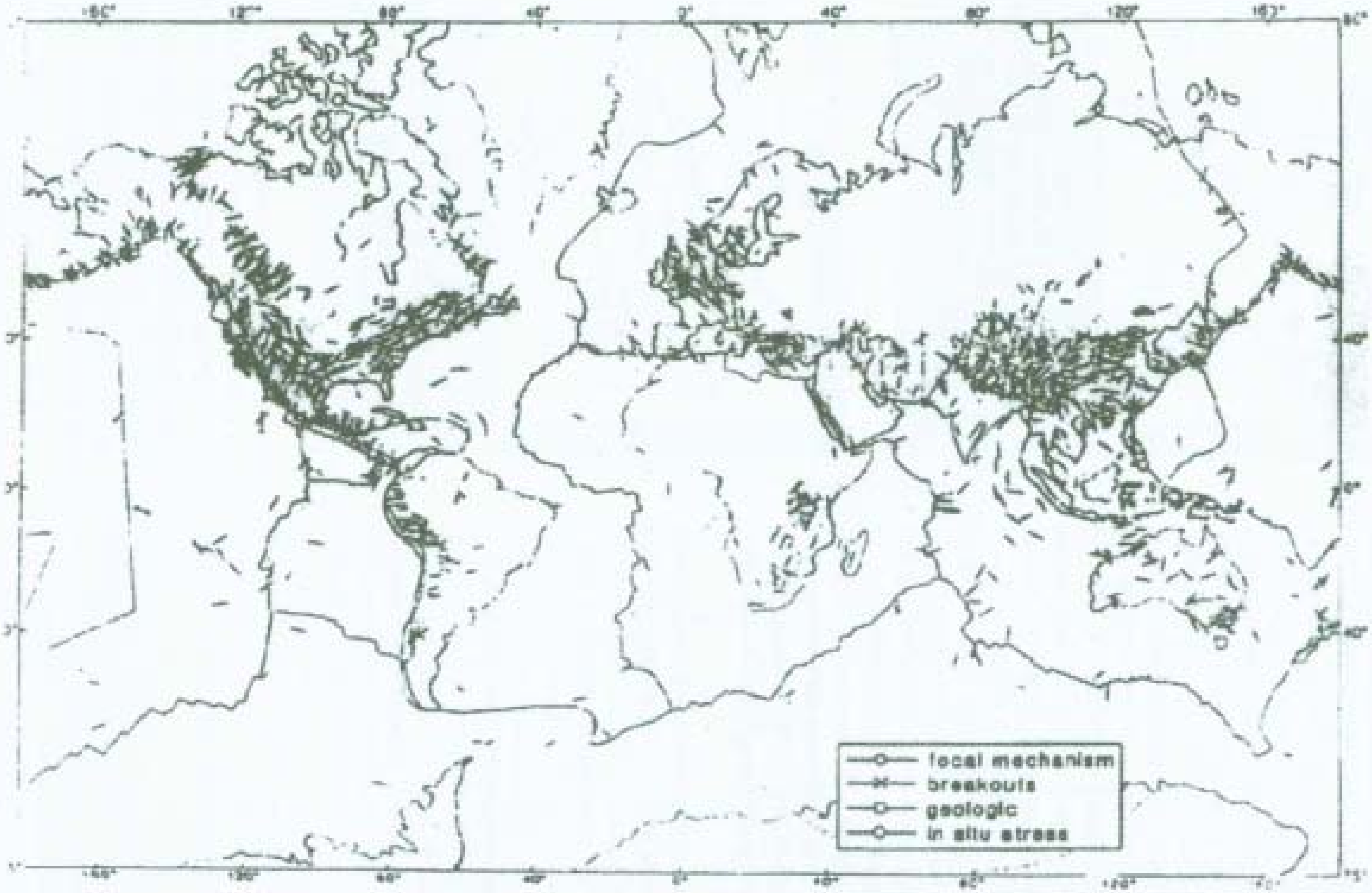

Figure 12
Global stress map (from Zoback et al., 1989)

broader view of *in situ* stress distribution, especially in studying regional stress fields. However, the stresses described in the map are just statistical results. They should be inadequate to meet the demand for various engineering designs at smaller scales, since geologic structure and properties of the rock masses are very complicated.

C. Case History: Indonesia's Oil and Gas Industry

The global map in Figure (12) exhibits in a marked clarity the absence of data from Southeast Asia in general, and especially Indonesia from which not a single data appears. It is not clear to the author whether the absence reflects Zoback and friend's lack of access to the data or indeed a genuine rarity. The author is convinced that no major mining activities in Indonesia prevail without any attempts to survey the *in situ* state of stresses, considering the utmost importance of the data for safety concerns. However, the reverse is probably true for the petroleum industry in Indonesia. To author's experience, most operators or individuals in the industry hardly realize the importance of incorporating the information of *in situ* stresses to their engineering activities.

At least there are three factors that indicate the absence of general awareness over the importance of *in situ* stress data.

1. The almost total lack of consideration over the information when petroleum engineering practices is to be the question. In studying or simulating reservoir future performance the incorporation of the data, even when it is regional scale in nature, is rarely practiced. As acknowledged, the local *in situ* stress field may affect the reservoir rocks' degree of permeability anisotropy. Similarly, very little attention is given to the matter in a preliminary study devoted for assessing the possibility of establishing a waste CO_2 underground disposal scheme in Natuna.
2. The occurrence of some examples in the field. The occurrence of borehole breakouts and sand problems in many cases in Indonesia is rarely linked to their corresponding local *in situ* stress fields. Likewise, leakage of drilling mud to the surface through generation of fractures on borehole wall (a case in Aceh province) is probably partly caused by an absence of proper preliminary wellbore stability study. No reliable wellbore stability study results can be yielded without proper knowledge regarding the local *in situ* stess field.
3. The absence of demand from operators in Indonesia's oil and gas industry. This is also reflected from the absence of services for *in situ* stress measurement offered by any core labs companies in Indonesia. This is not the case for oil and gas industries in advanced regions in which the information has been treated as equal to other input parameters.

VII. CONCLUSIONS

From the review on the *in situ* state of stress a set of conclusions has been drawn:

1. The fact that *in situ* stresses are a point-to-point property has led to a conclusion that every part of petroleum reservoirs, as well as every subsurface construction, is influenced by the *in situ* state of stresses.
2. The complexity of geological aspects in Indonesia supports the postulate that underlines the neccessity to obtain information concerning the local *in situ* stress field vis-à-vis the total reliance upon information of merely the regional *in situ* stress field.
3. The integration of accurate *in situ* stress information into petroleum engineering practices has to be further encouraged, considering the prevailing negligence and the ensuing problems that are often encountered.
4. It is important to acknowledge the stress regime that prevails in an area that is planned to have subsurface engineering carried out. This is to provide a general idea about how rocks will behave upon the disturbace of the *in situ* stress field by the engineering activities.

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