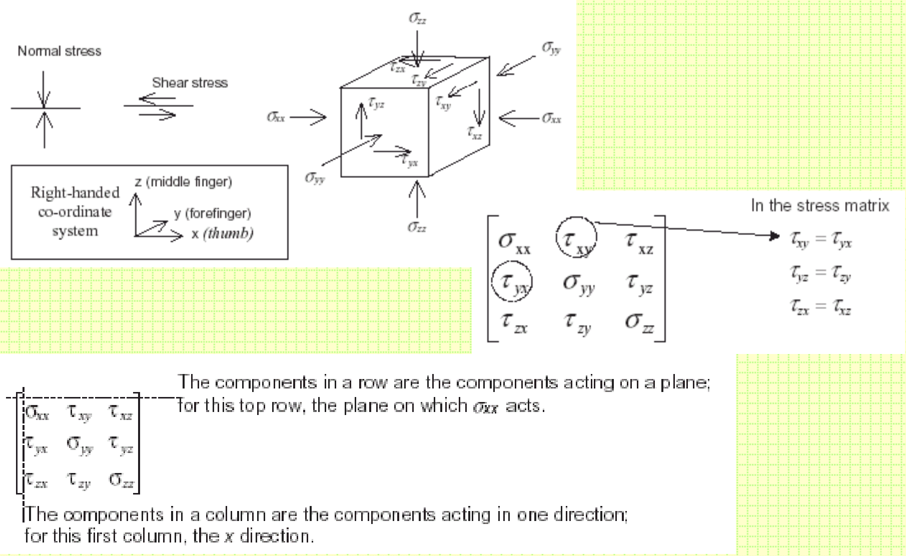
In situ stress

In situ stress - the components of stress tensor



In the stress matrix

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

$\tau_{xy} = \tau_{yx}$

$\tau_{yz} = \tau_{zy}$

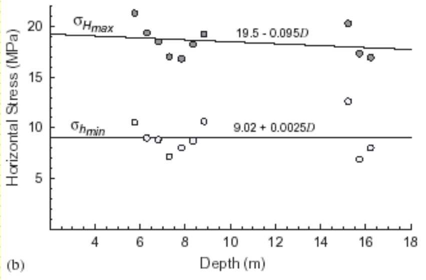
$\tau_{zx} = \tau_{xz}$

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

The components in a row are the components acting on a plane; for this top row, the plane on which σ_{xx} acts.

The components in a column are the components acting in one direction; for this first column, the *x* direction.

In situ stress



A 'pop-up' observed at a quarry site in granite in Southeastern Manitoba and the horizontal stress determined using the USBM Borehole Deformation Gauge in a vertical borehole.

(Quarry 'popup'. (b) Measured horizontal stress)

In situ stress

Stress is a concept fundamental to Rock Mechanics principles and applications:

- There is a pre-existing state in the rock mass and we need to understand it, both directly, and as a stress state applies to analysis and design.
- During rock excavation, the stress state can change dramatically. This is because rock, which previously contained stress, has been removed and the load must be redistributed.
- Stress is not familiar – it is a tensor quantity and tensors are not encountered in everyday life.
- Distribution of tectonic forces is also complicated by geological factors, with the added uncertainty in that there is no constraint on the total force, as is the case with gravity loads. Plate motions, interactions at plate boundaries and within plates are all driven by tectonic forces. The magnitude and orientation of the forces have changed over geological time; folds and faults created in response to forces from past epochs, volcanic intrusions, etc. may all have been involved in creating the current heterogeneous system that is now subject to the current tectonic regime.
- It is to be expected, therefore, that the magnitude and orientation of these forces may vary considerably within geological systems.

In situ stress

Thus, unlike other materials used in engineering design, rock is pre-loaded, by forces that are, in general, of unknown magnitude and orientation. The problem of design in rock is complicated further by the fact that structural features such as joints, fractures, and bedding planes can have an important influence on the ability of the rock mass to resist these forces, i.e. on the strength of the rock mass, as measured over the region, often large, that is affected by the structure. This could have an adverse influence on the stability of the engineering structure.

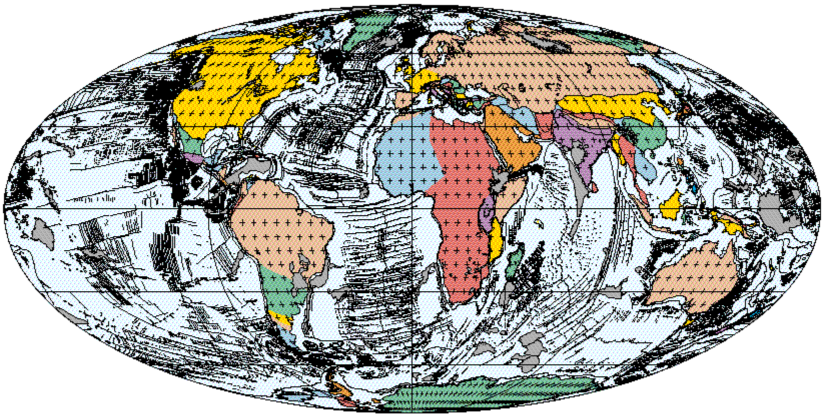
Stress conditions often may change significantly across structures such as faults, dyke contacts and major joints. Stiffer geological materials tend to attract stress, so that stress in say a dyke may be higher than in a rock such as quartzite in close proximity. These effects may influence the vertical stress to some extent.

The effect of topography on vertical stresses depends on the height of the hill or valley in relation to its width.

Many phenomena other than tectonics could result in high and unequal horizontal stresses, in particular near the ground surface.

Such phenomena include residual and thermal stresses, erosion, lateral straining, anisotropy, glaciation and deglaciation, topography, curvature of the Earth and other active geological features and processes. This is not to say that tectonic stresses do not exist, but simply that their contribution to the measured stress fields may not be as large as previously thought.

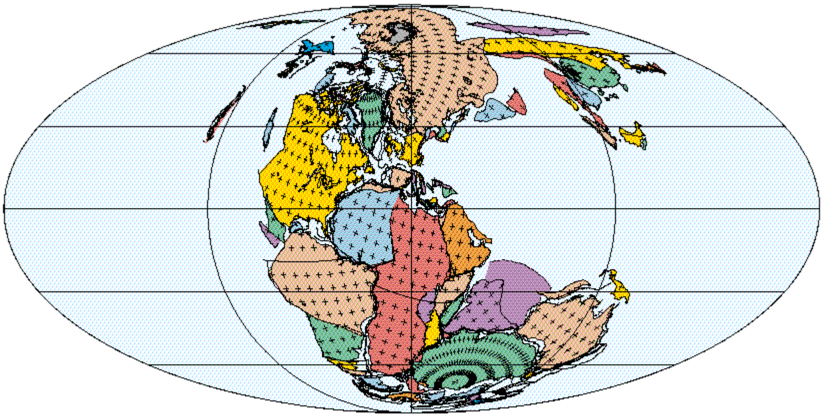
Global Plate Tectonics – Jurrasic to Present Day



0 Ma
Present Day

PLATES/UTIG
July 1999

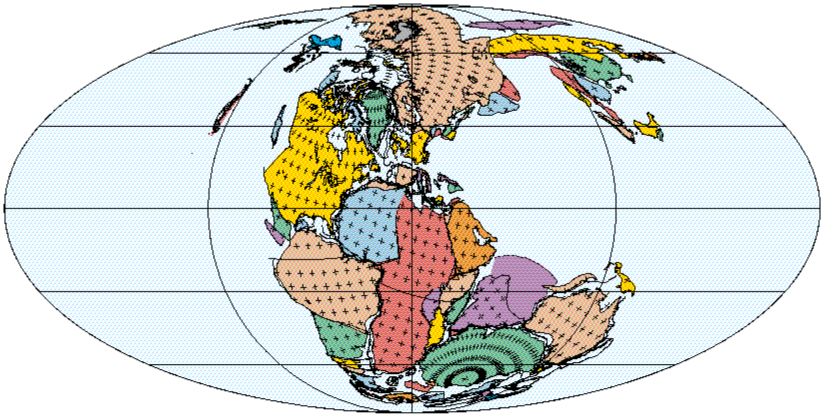
Global Plate Tectonics – Jurrasic to Present Day



200 Ma
Sinemurian (Early Jurassic)

PLATES/UTIG
July 1999

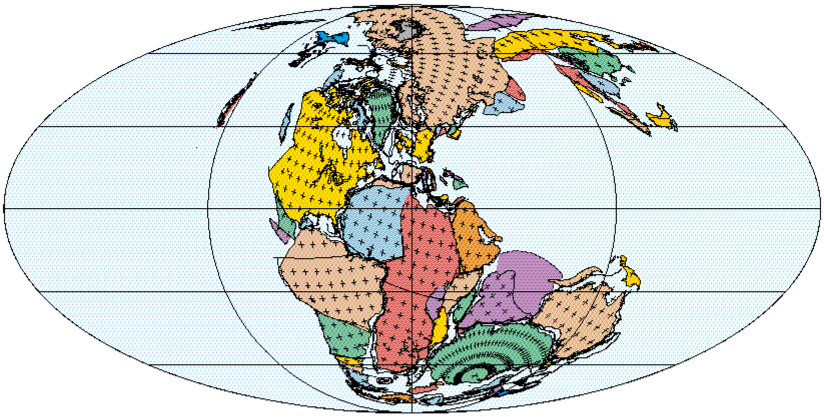
Global Plate Tectonics – Jurrasic to Present Day



190 Ma
Pliensbachian (Early Jurassic)

PLATES/UTIG
July 1999

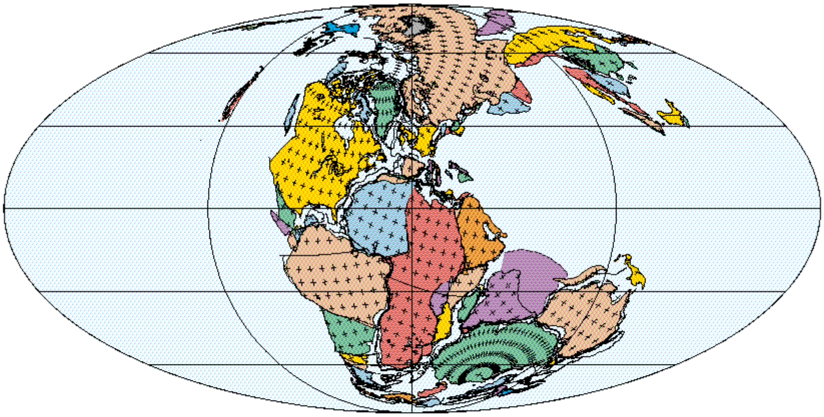
Global Plate Tectonics – Jurrasic to Present Day



180 Ma
Aalenian (Middle Jurassic)

PLATES/UTIG
July 1999

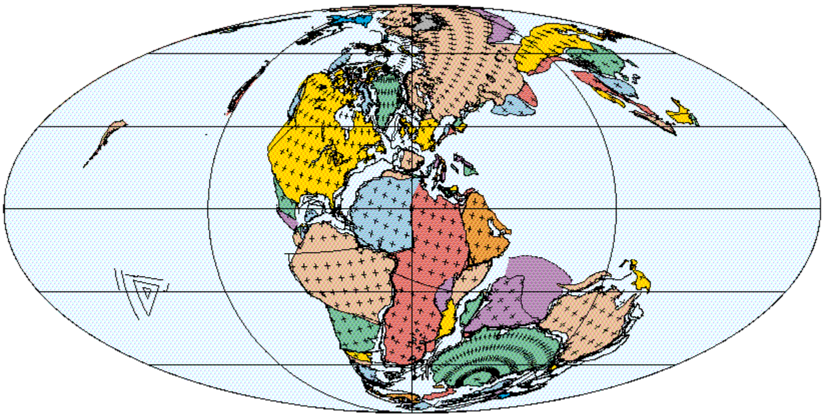
Global Plate Tectonics – Jurrasic to Present Day



170 Ma
Bajocian (Middle Jurassic)

PLATES/UTIG
July 1999

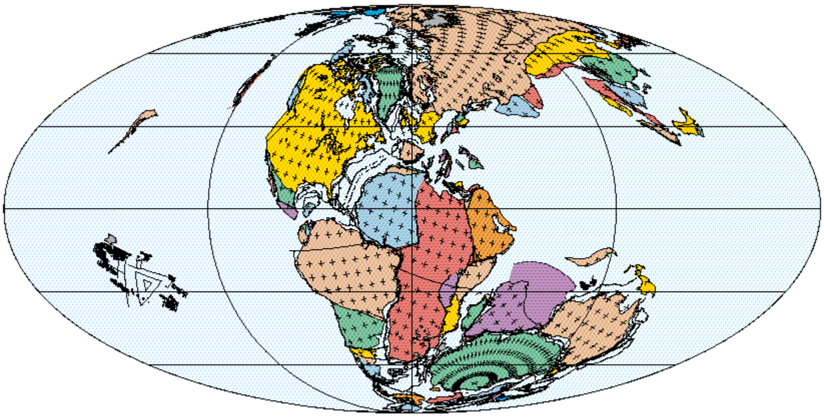
Global Plate Tectonics – Jurrasic to Present Day



160 Ma
Callovian (Middle Jurassic)

PLATES/UTIG
July 1999

Global Plate Tectonics – Jurrasic to Present Day



150 Ma
Volgian (Late Jurassic)

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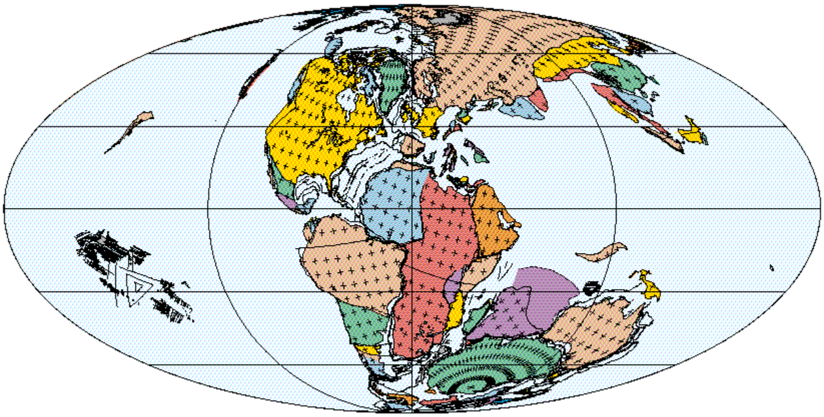
July 1999

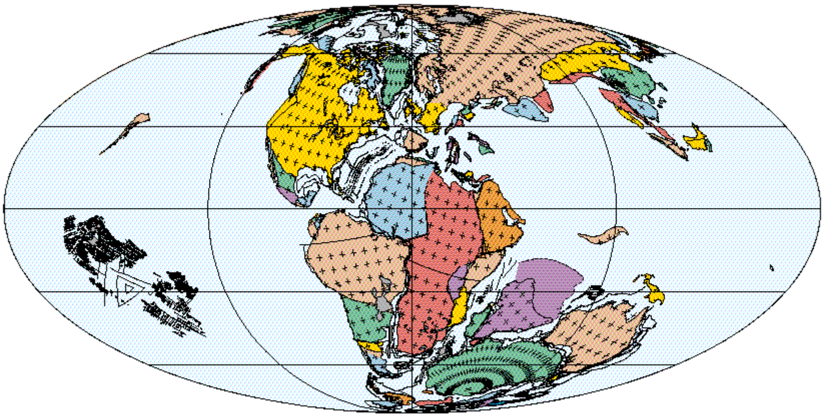
Global Plate Tectonics – Jurrasic to Present Day



140 Ma
Ryazanian (Early Cretaceous)

PLATES/UTIG
July 1999

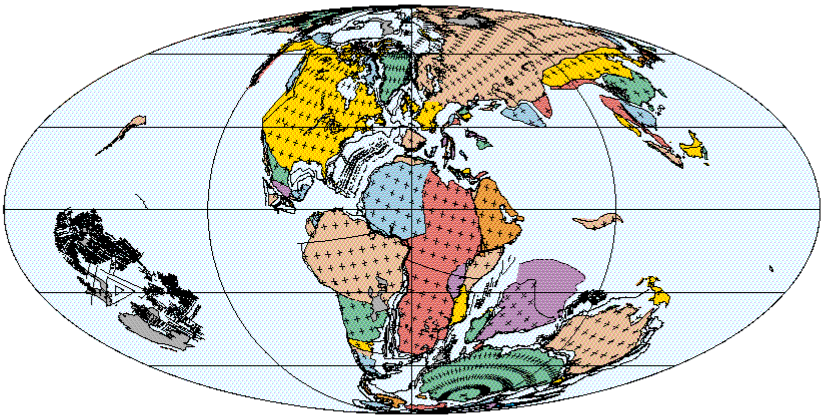
Global Plate Tectonics – Jurrasic to Present Day



130 Ma
Hauterivian (Early Cretaceous)

PLATES/UTIG
July 1999

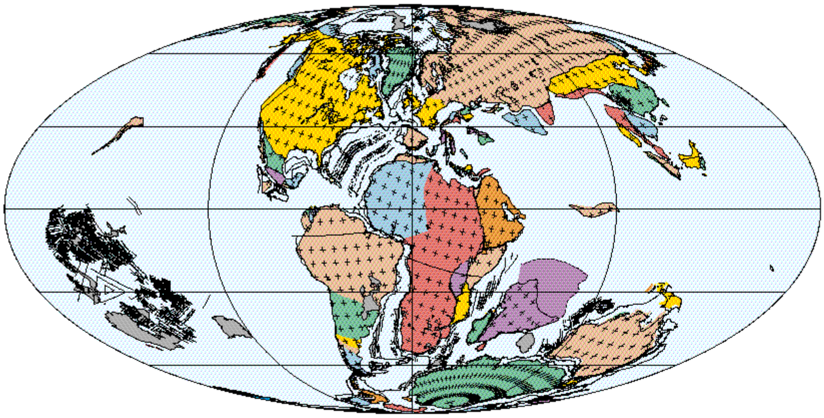
Global Plate Tectonics – Jurrasic to Present Day



120 Ma
Aptian (Early Cretaceous)

PLATES/UTIG
July 1999

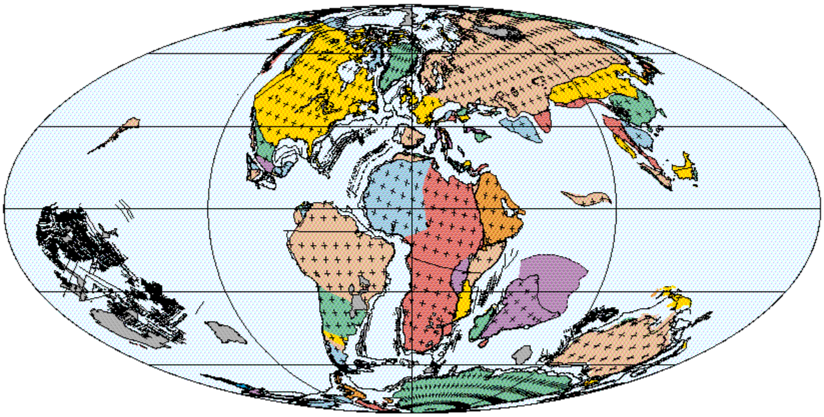
Global Plate Tectonics – Jurrasic to Present Day



110 Ma
Early Albian (Early Cretaceous)

PLATES/UTIG
July 1999

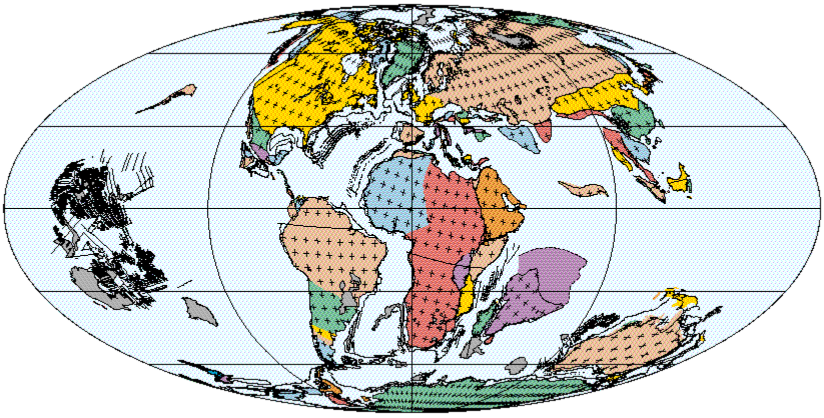
Global Plate Tectonics – Jurrasic to Present Day



100 Ma
Late Albian (Early Cretaceous)

PLATES/UTIG
July 1999

Global Plate Tectonics – Jurrasic to Present Day



90 Ma
Turonian (Late Cretaceous)

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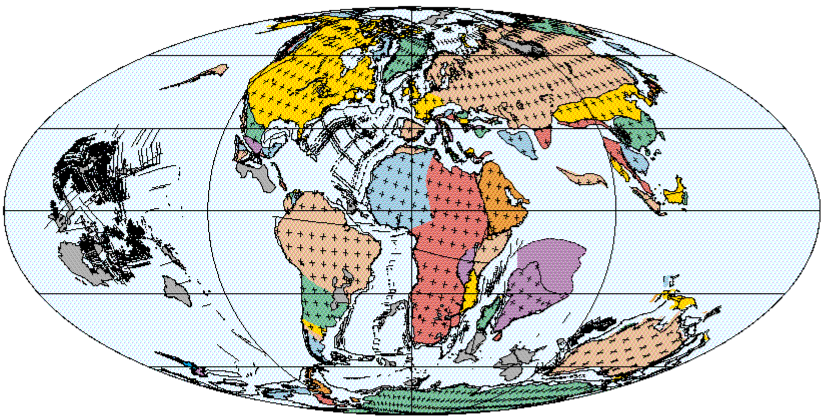
Global Plate Tectonics – Jurrasic to Present Day



80 Ma
Campanian (Late Cretaceous)

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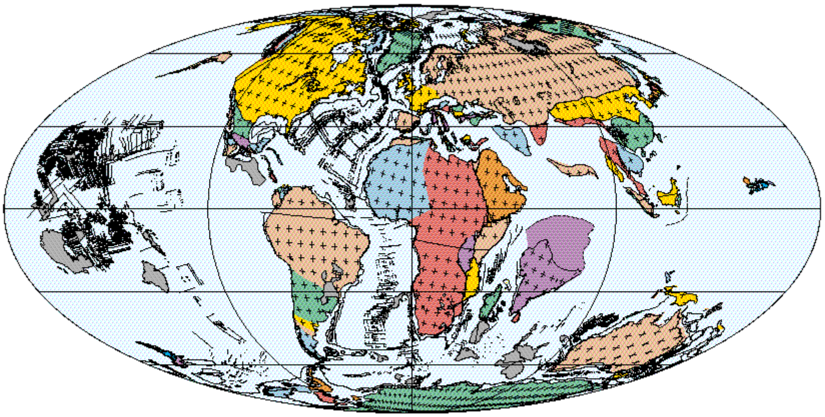
July 1999

Global Plate Tectonics – Jurrasic to Present Day



70 Ma
Maastrichtian (Late Cretaceous)

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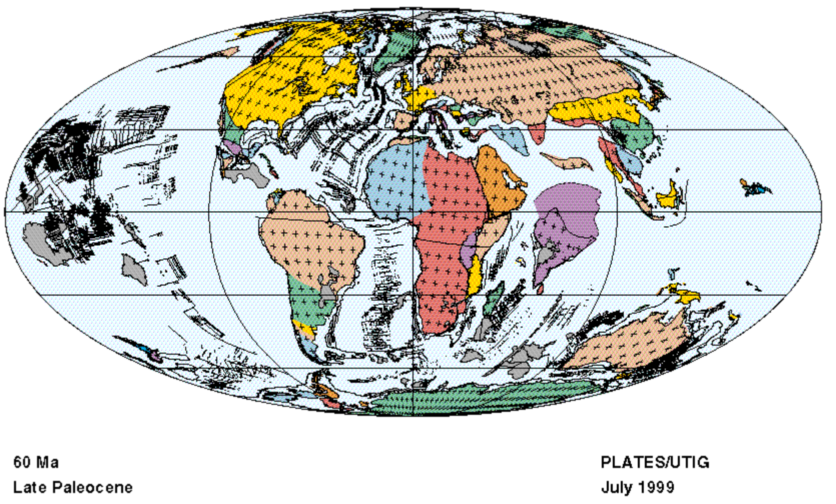
Global Plate Tectonics – Jurrasic to Present Day



60 Ma
Late Paleocene

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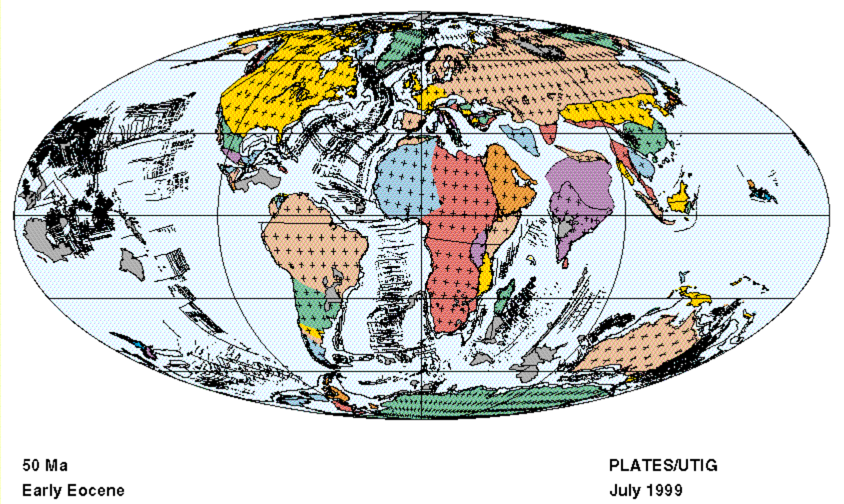
Global Plate Tectonics – Jurrasic to Present Day



50 Ma
Early Eocene

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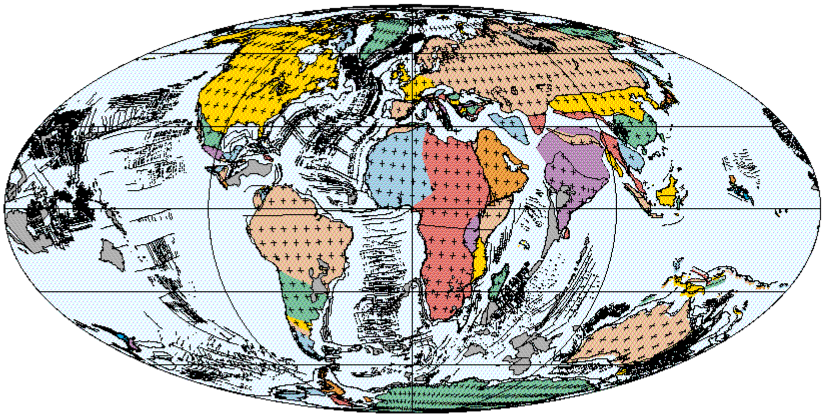
July 1999

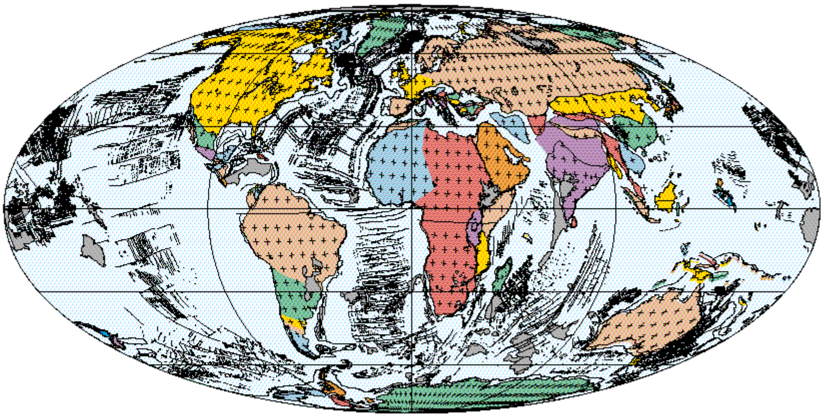
Global Plate Tectonics – Jurrasic to Present Day



40 Ma
Middle Eocene

PLATES/UTIG
July 1999

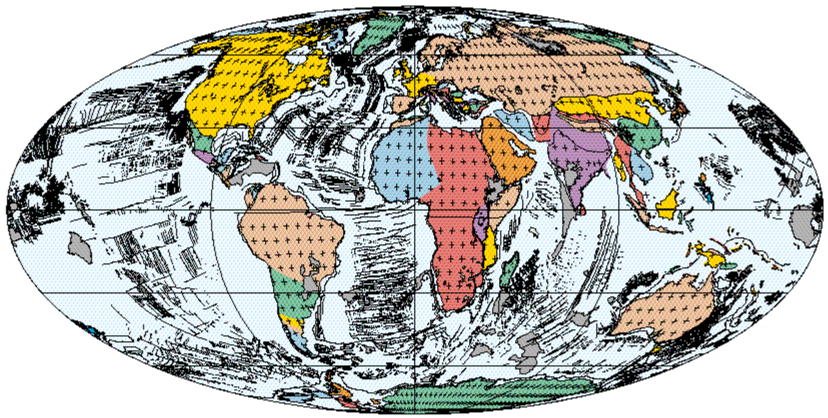
Global Plate Tectonics – Jurrasic to Present Day



30 Ma
Early Oligocene

PLATES/UTIG
July 1999

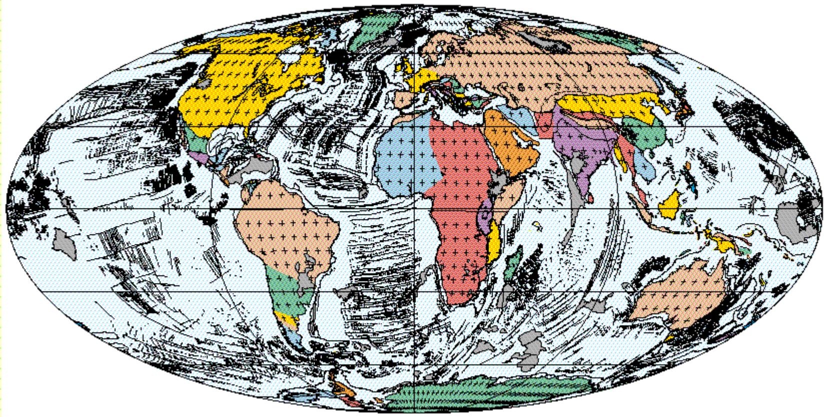
Global Plate Tectonics – Jurrasic to Present Day



20 Ma
Early Miocene

PLATES/UTIG
July 1999

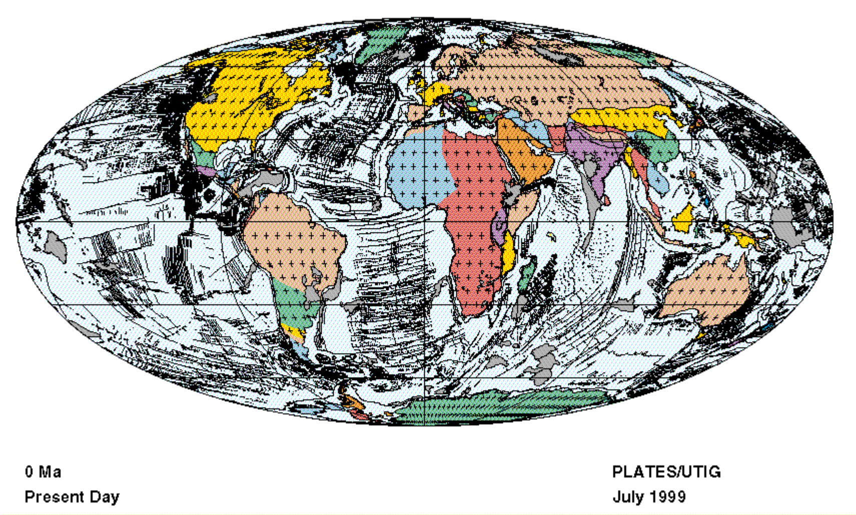
Global Plate Tectonics – Jurrasic to Present Day



10 Ma
Late Miocene

PLATES/UTIG
July 1999

Global Plate Tectonics – Jurrasic to Present Day



In situ stress – World Stress Map

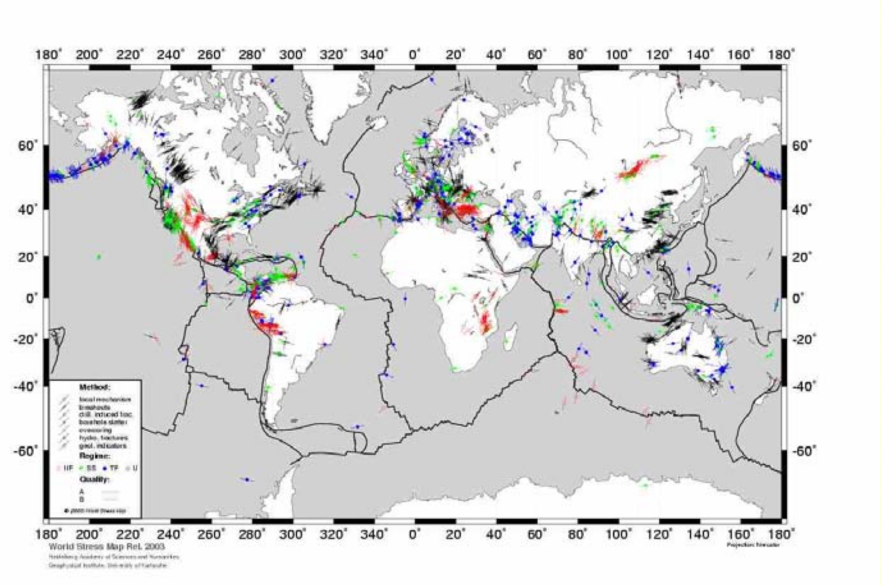
World Stress Map Project has now been working for more than 15 years on its data base.

Types of stress indicators. To determine the tectonic stress orientation different types of stress indicators are used in the World Stress Map.

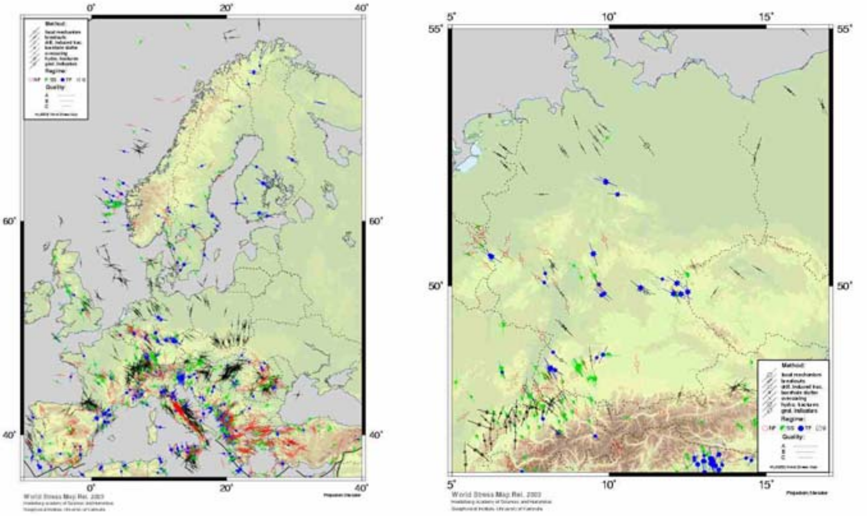
They are grouped into four categories:

- earthquake focal mechanisms (69%)
- well bore breakouts and drilling induced fractures (19%)
- in-situ stress measurements - overcoring, hydraulic fracturing, borehole slotter (8%)
- young geologic data (from fault slip analysis and volcanic vent alignments (4%)

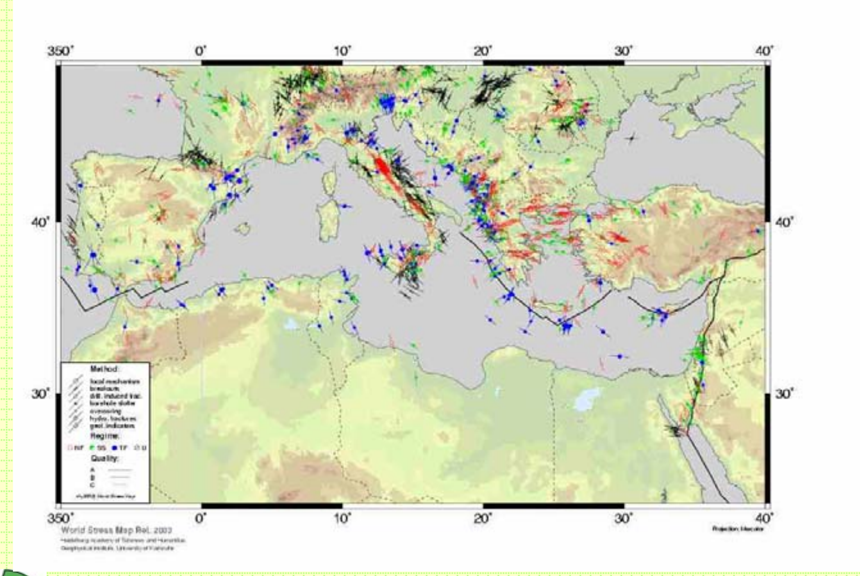
In situ stress – World Stress Map



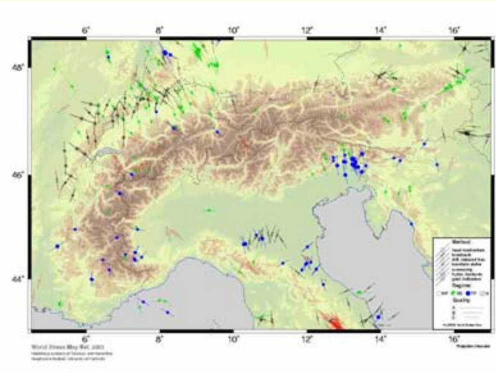
In situ stress – World Stress Map

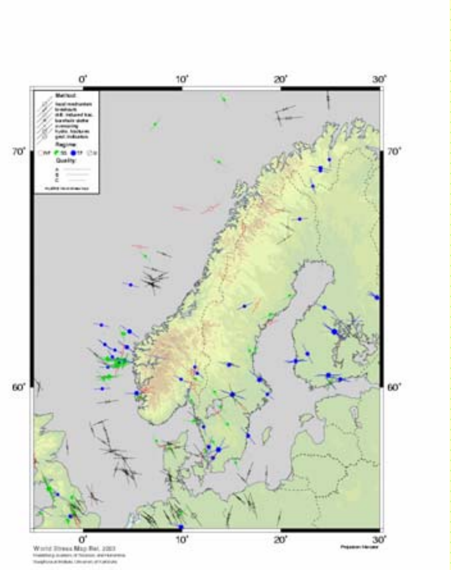


In situ stress – World Stress Map

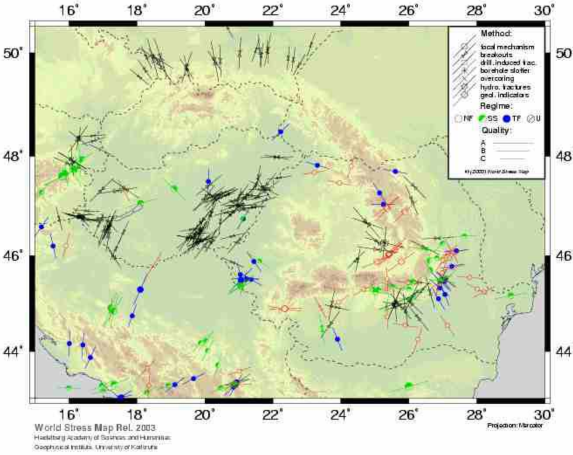


In situ stress – World Stress Map



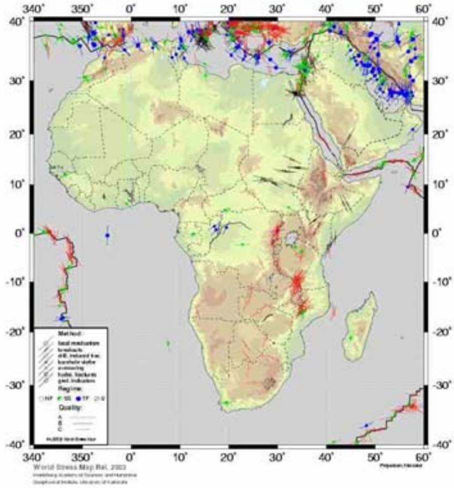


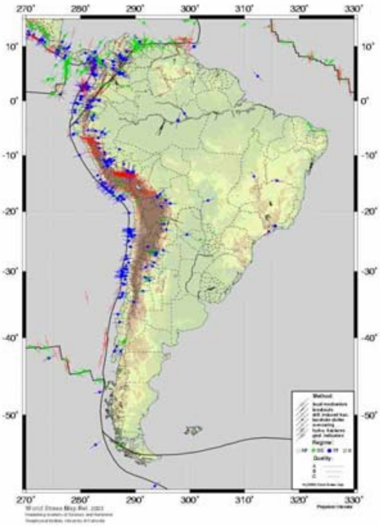
In situ stress – World Stress Map



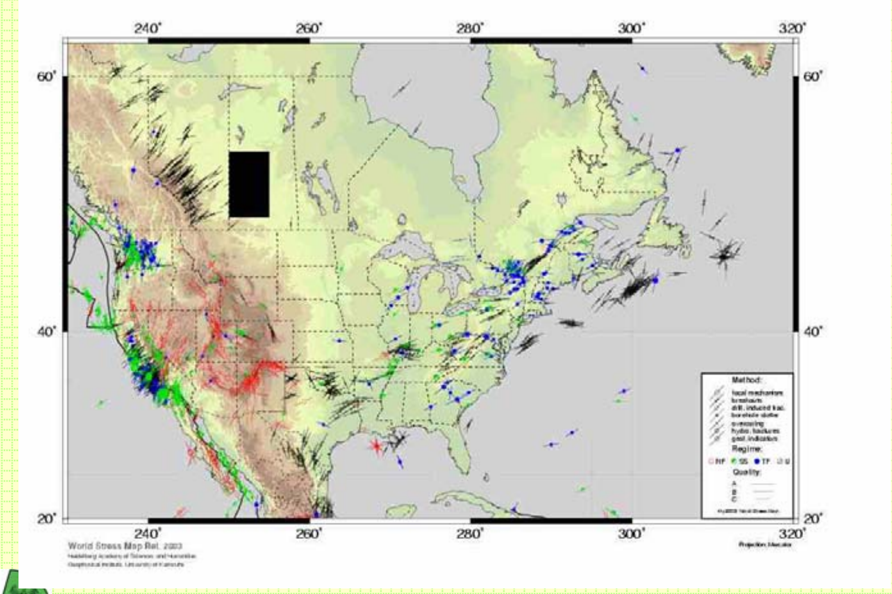
Poland, 2003
50 records,
(mainly borehole
breakouts)

In situ stress – World Stress Map

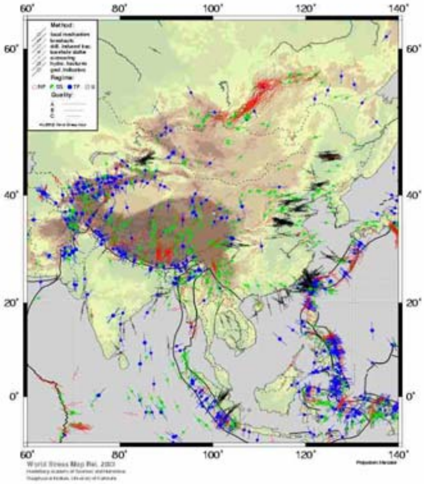


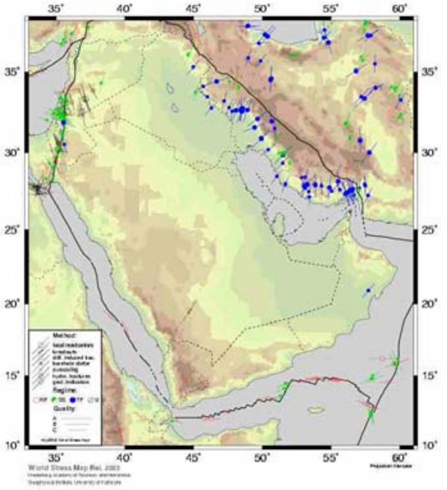


In situ stress – World Stress Map

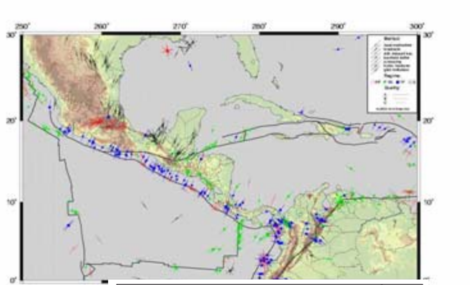


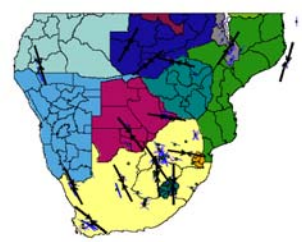
In situ stress – World Stress Map

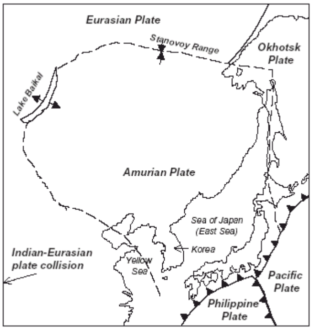


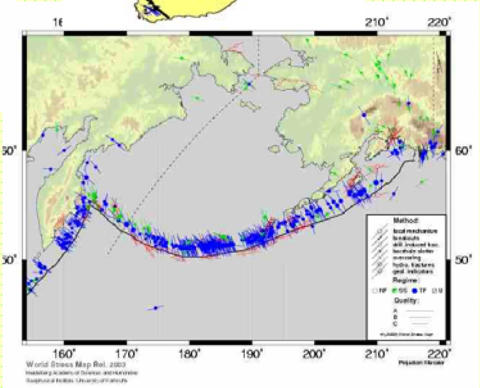


In situ stress – World Stress Map

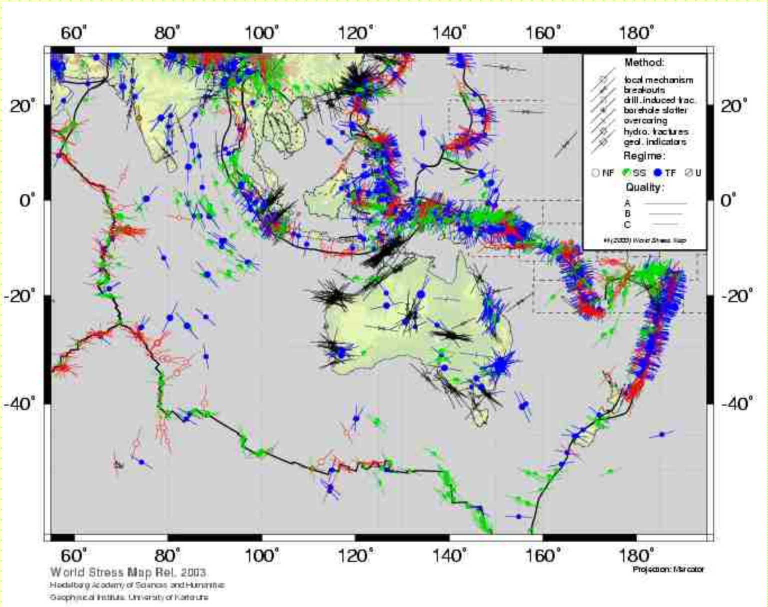




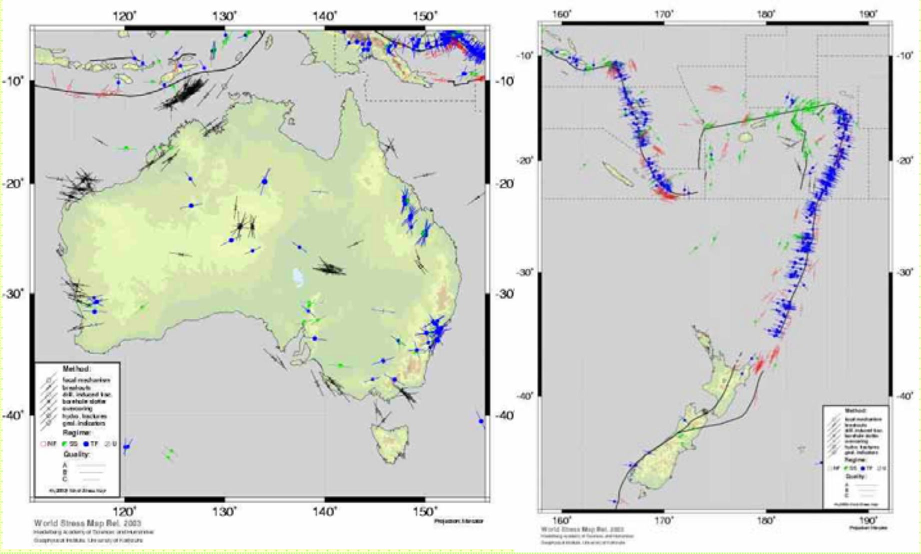




In situ stress – World Stress Map



In situ stress – World Stress Map



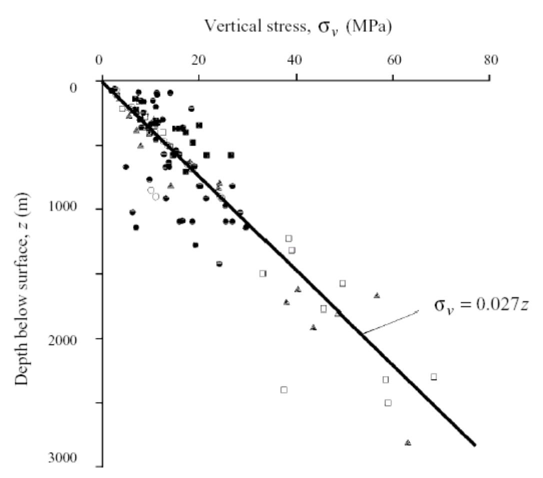
In situ stress – measurements

$$\sigma_v = \gamma \cdot z$$

σ_v - is the vertical stress,

γ – is the unit weight of the overlying rock,

z - is the depth below surface.



Measurements of vertical stress at various mining and civil engineering sites around the world confirm that this relationship is valid although, as illustrated above, there is a significant amount of scatter in the measurements.

In situ stress – measurements

The horizontal stresses acting on an element of rock at a depth *z* below the surface are much more difficult to estimate than the vertical stresses. Normally, the ratio of the average horizontal stress to the vertical stress is denoted by the letter *k* such that:

$$\sigma_h = k \cdot \sigma_v = k \cdot \gamma \cdot z$$

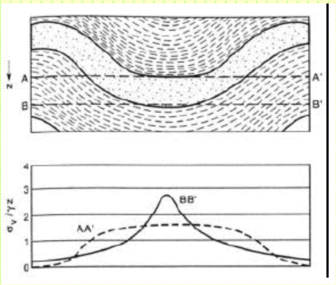
Terzaghi and Richart (1952) suggested that, for a gravitationally loaded rock mass in which no lateral strain was permitted during formation of the overlying strata, the value of *k* is independent of depth and is given by:

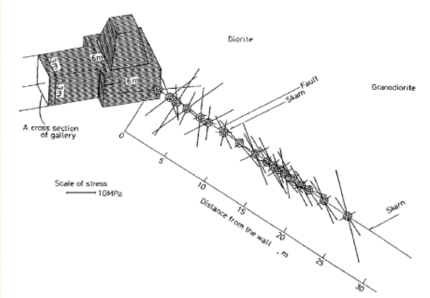
$$k = \frac{\nu}{1-\nu}$$

where ν is the Poisson's ratio of the rock mass. This relationship was widely used in the early days of rock mechanics but, as discussed below, it proved to be inaccurate and is seldom used today. Measurements of horizontal stresses at civil and mining sites around the world show that the ratio *k* tends to be high at shallow depth and that it decreases at depth. In order to understand the reason for these horizontal stress variations it is necessary to consider the problem on a much larger scale than that of a single site.

In situ stress

Stress conditions often may change significantly across structures such as faults, dyke contacts and major joints. Stiffer geological materials tend to attract stress, so that stress in say a dyke may be higher than in a rock such as quartzite in close proximity. These effects may influence the vertical stress to some extent. The effect of topography on vertical stresses depends on the height of the hill or valley in relation to its width.



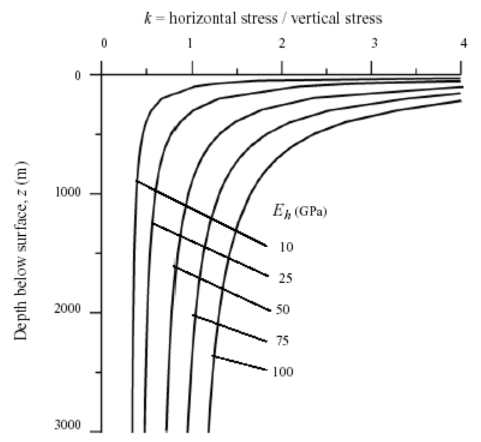


In situ stress – Sheory concept

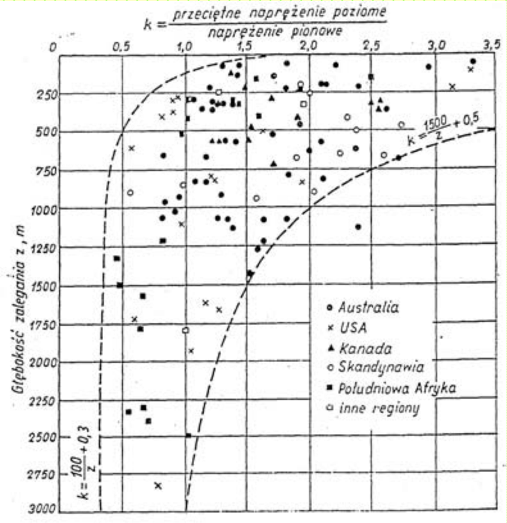
Sheorey (1994) developed an elasto-static thermal stress model of the earth. This model considers curvature of the crust and variation of elastic constants, density and thermal expansion coefficients through the crust and mantle. A detailed discussion on Sheorey's model is beyond the scope of this presentation, but he did provide a simplified equation which can be used for estimating the horizontal to vertical stress ratio k:

$$k = 0.25 + 7E_k\left(0.001 + \frac{1}{z}\right)$$

where E_h (GPa) is the average deformation the upper part of the earth's crust measured in a horizontal direction.



In situ stress



Variation of average horizontal to vertical stress ratio with depth below surface

Brown & Hoek, 1978

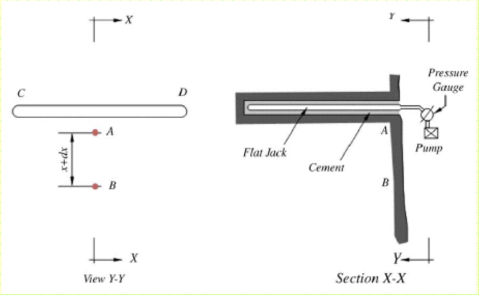
CHILE versus DIANE

Continuous
Homogeneous
Isotropic
Linearly
Elastic

Discontinuous
Inhomogeneous
Anisotropic
Non-Linearly
Elastic

In situ stress - Flat-jack

One of the earliest reported methods was based on the use of a flat-jack. An extensometer gauge is installed between the points A and B in the rock surface. This can be of various forms, but a (piano) wire tensioned between the two points was often used. The frequency of vibration of the wire is determined.



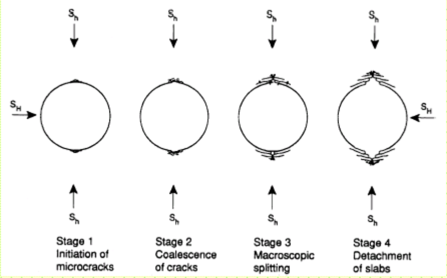
A slot is then cut into the rock as shown. The slot should be wide enough to completely relieve the stresses acting across the points A and B: This is accomplished by making the slot width equal to three times the distance from the slot to point B: The flat-jack is then inserted into the slot and cemented into place to ensure good contact with the faces of the slot. The jack is then pressurized until the distance AB is restored to the value measured before cutting the slot, as indicated by the frequency of the wire transducer. It is then assumed that the pressure in the jack is equal to the average normal stress that was acting across the slot before the slot was cut.

In situ stress - flat-jack – limitations & advantages

- The measurement assumes that the normal stress/pin deformation relation on unloading as the slot is cut is the same as the flat jack pressure/pin deformation relationship on pressurization, i.e. that the rock is elastic over the range of pin deformation.
- However, an important limitation of this technique is that it needs to be conducted on the surface of an excavation, in the region of maximum (and varying across the depth of the slot) stress concentration around the excavation. This is the region where the rock is most likely to be overstressed and develop some inelastic deformation.
- It seems likely, therefore, that there will be some hysteresis between loading and unloading paths, so that the pressure required to return the pins to their original spacing will differ from the stress released by cutting of the slot. Thus, the flat-jack pressure may not represent the in situ stress. This inherent shortcoming of stress determinations made on the surface of an excavation is a main reason why most techniques involved measurements at depth within a borehole.
- One advantage of this flat-jack method was that it allowed the use of a simple extensometer (i.e. placed between points A and B), and did not require the development of special tools and transducers that could be placed within a small borehole.

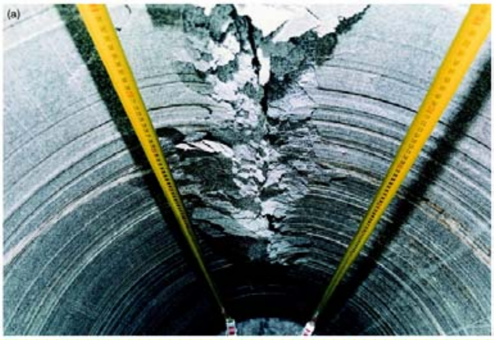
In situ stress – borehole breakouts

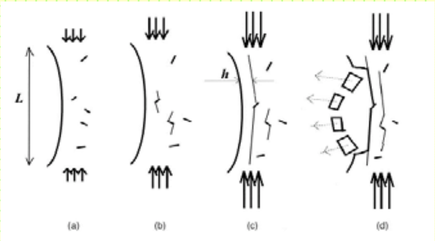
The stress concentrations that develop around a borehole in stressed rock can result in inelastic deformation, damage, and fall out of broken rock in the zones of maximum stress concentration. The hole develops an oval or elliptical shape. The major axis of the deformed (breakout) shape is taken to be coincident with the direction of the minimum secondary principal stress σ_2 with the maximum stress σ_1 orthogonal to it. However it is sometimes observed that the axes of the breakout may not pass through the centre of the borehole.

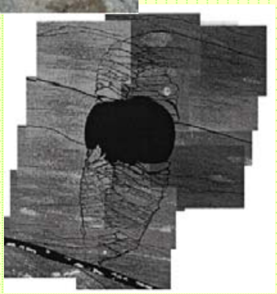


It is suggested that the asymmetry is a consequence of the stress distribution (influenced by the shear stresses) and a possible onset of damage in the rock ahead of the coring bit. This suggests that observation of asymmetric breakout may be an indication that the borehole does not coincide with a principal stress direction.

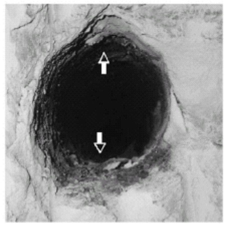
In situ stress – borehole breakouts

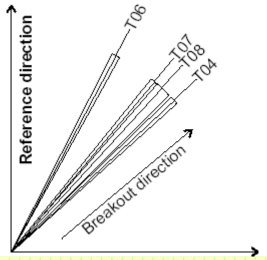


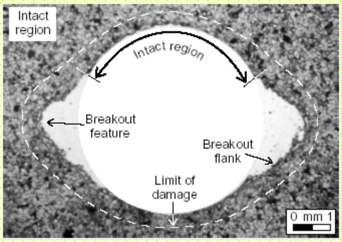


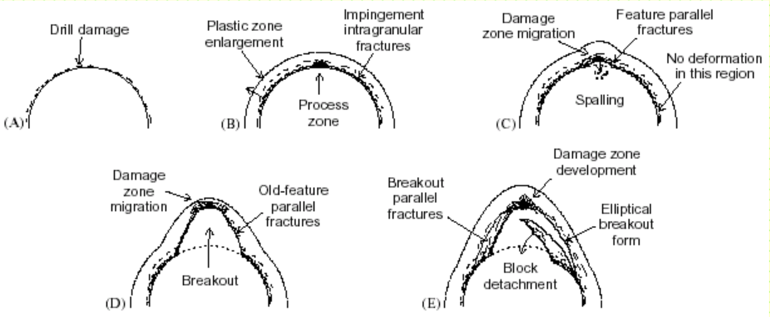


In situ stress – borehole breakouts

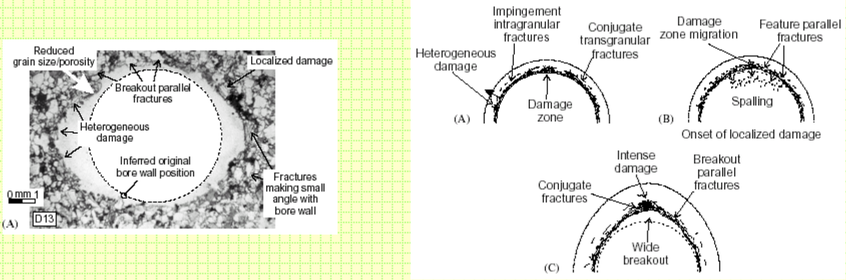








In situ stress – borehole breakouts



Progression of breakout development by combined extension and shear-mode cracking in Darley Dale sandstone. (A) Porosity closes, causing impingement fracture formation, migrating the ‘plastic’ zone into the wall rock. Fractures concentrate into damage zones. (B) Spalling initiates, creating a broad and shallow breakout feature. (C) The damage zone migrates into the wall rock creating breakout parallel fractures. Breakout growth occurs, but also hole enlargement in the orthogonal directions

In situ stress – borehole breakouts

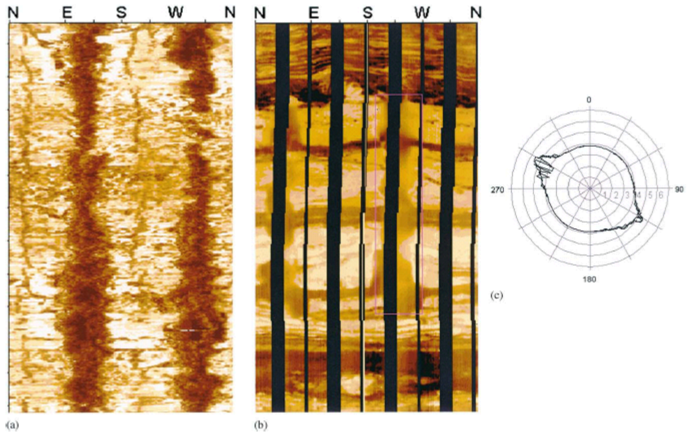
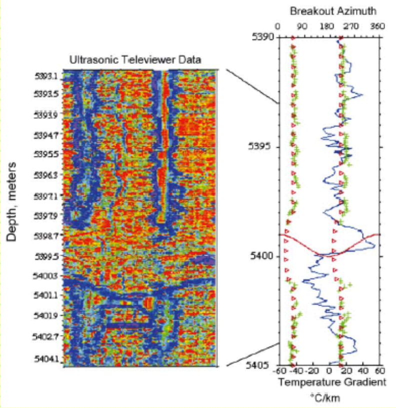


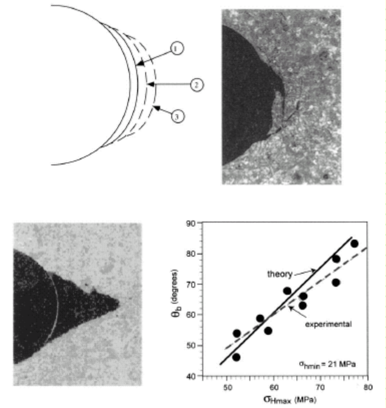
Image logs of a well with wellbore breakouts.

These are manifest as dark bands (low reflection amplitudes) on opposite sides of the well in ultrasonic televiewer image logs (UBI Well A) and out-of-focus zones on electrical imaging logs (FMI Well B). By making cross sections of Well A, it is possible to clearly identify wellbore breakouts as shown on the right.

In situ stress – borehole breakouts

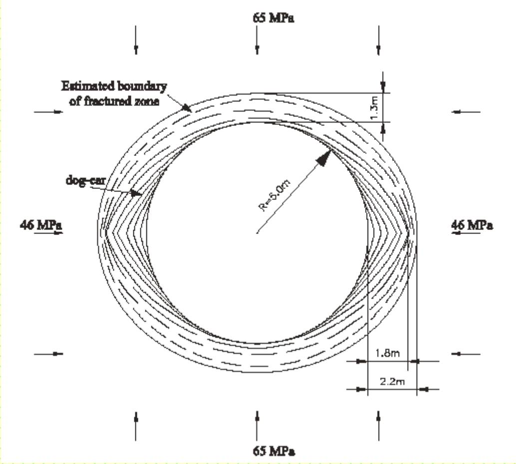


Rotation of wellbore breakouts near a fault in the borehole that can be modeled as the result of a perturbation of the stress field induced by slip on the fault.

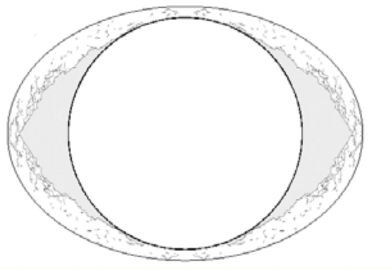


The theoretical growth of a breakout after initial formation. Note that the breakouts deepen but do not widen. The photographs of breakouts formed in laboratory experiments confirm this as well as the relationship between stress magnitude and breakout width.

In situ stress – borehole breakouts



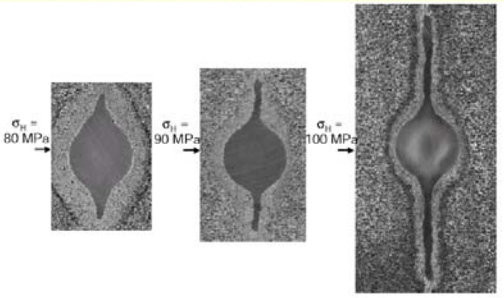
Sketch of the fracture pattern observed around 10-m diameter shaft



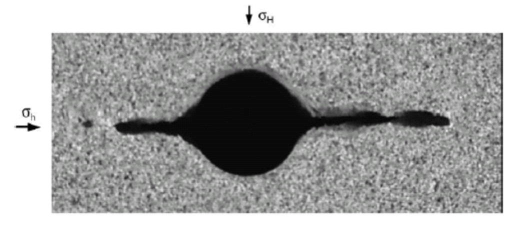
Simulated final fracture pattern obtained after removing 'loose blocks'. The ellipse cumscribing the damaged zone is indicated as well.

In situ stress – borehole breakouts

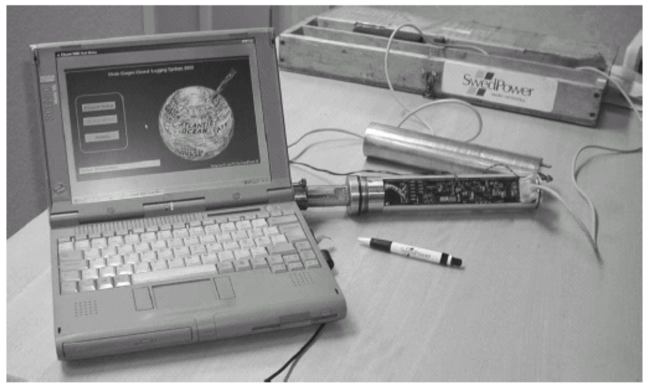
Borehole cross sections of specimens that underwent drilling while under the same minimum and intermediate far-field stresses (σ_h=50 MPa, σ_v = 60 MPa), but different maximum horizontal stresses (σ_H), showing the dependence of fracture-like breakout length on the far-field stress.



Typical cross section of a borehole breakout in high-porosity Berea sandstone. Note its narrow, tabular, fracture-like shape, aligned with the σ_h spring line, and consequently its counterintuitive orientation vis-a`-vis the σ_H direction.



In situ stress – overcoring - Borre probe



The Borre probe with logger connected to a portable computer for activation and data retrieval.

In situ stress – overcoring - Borre probe

This cell allows, in principle, the complete stress tensor to be determined from a single overcoring operation in one borehole. Strain gauge rosettes attached to the outer surface of a thin molded epoxy cylinder are bonded to the wall of the borehole at different orientations. Overcoring of the inner borehole induces strains in the gauges that are influenced by all of the in situ stress components. Resolution of the measured strains should yield the in situ stress tensor at the overcoring location. The method is used widely and is considered to be a valuable technique. Problems of improper bonding of the gauges to the rock are reported. Depending on the orientation of the hole, some of the components of the stress tensor may be small, so that measured values may be suspect. It is useful, once the stress tensor has been determined, to repeat the test - if possible, using a hole drilled at an orientation for which the stress components are all of substantial magnitude.

Characteristics of the most common soft overcoring cells

Instrument	No of active gauges	Measuring depths	Continuous logging	Borehole requirements
CSIR cell	12	Normally: 10–50 m, modified versions: up to 1000 m	No	38 mm pilot hole, usually 90 mm drillhole. Modified versions accept water
CSIRO cell	9/12	Normally: up to 30 m	Yes, via cable	38 mm pilot hole, usually 150 mm drill hole. Problems in waterfilled holes
Borre probe cell	9	Practised to 620 m. Tested for 1000 m	Yes, built in datalogger	36 mm pilot hole, 76 mm drillhole. Accepts water-filled holes

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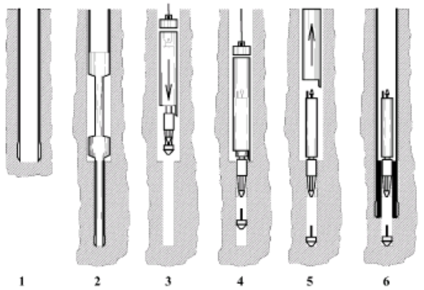
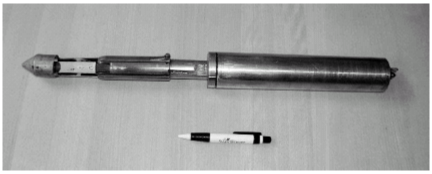
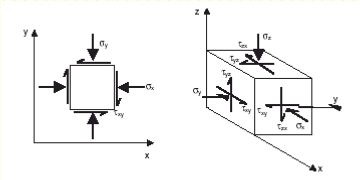
In situ stress – overcoring - Borre probe

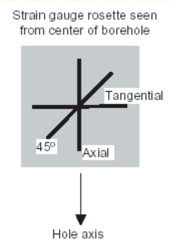


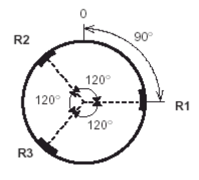


Principle of soft, 3D pilot hole overcoring measurements:
(1) advance +76mm main borehole to measurement depth, (2) drill +36mm pilot hole and recover core for appraisal, (3) lower probe in installation tool down hole, (4) probe releases from installation tool; gauges bonded to pilot-hole wall under pressure from the nose cone, (5) raise installation tool; probe bonded in place and (6) overcore the probe and recover to surface in core barrel.

In situ stress – overcoring - Borre probe





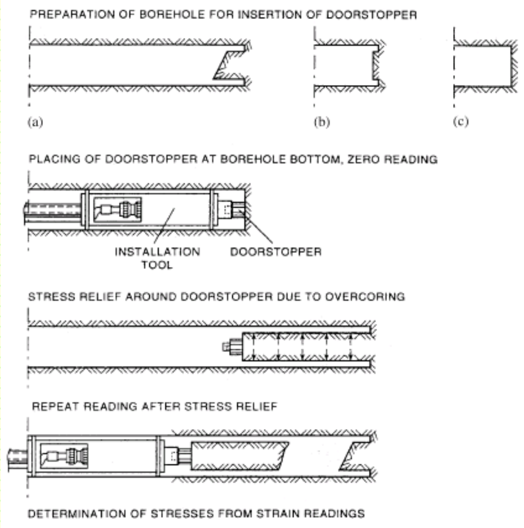


Evaluation of rock stress measurements by means of overcoring requires the assumption of ideal rock behaviour (CHILE behaviour). During field measurements, one strives to take measurements only when the above conditions are satisfied. However, because these conditions are seldom met completely in rock masses, errors are introduced. Also, even when seemingly ideal conditions apply, some scattering of the results always occurs. These errors may be quantified in terms of accuracy, i.e., how close a particular measurement result is to a true or accepted value, and precision, i.e., how close two or more measurements are to each other.

In situ stress – overcoring - doorstopper

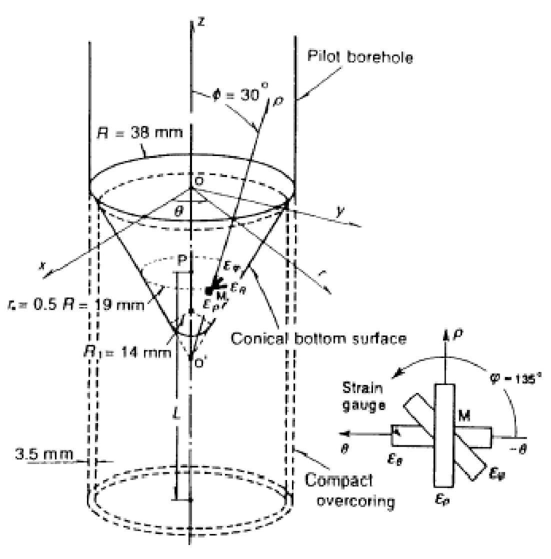
Doorstopper methods have been developed and practised for more than 20 years worldwide.

The Doorstopper cell is attached at the polished flat bottom of a borehole. Hence, it does not require a pilot hole. After the cell has been positioned properly at the end of the borehole and readings of the strain gauges have been performed, the instrument is overcored. During overcoring, the changes in strain/deformation are recorded.

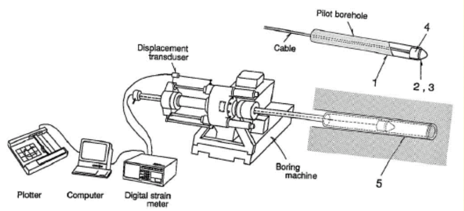


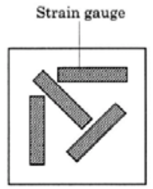
In situ stress – overcoring - doorstopper

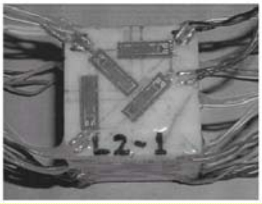
The hemi-spherical or conical strain cell is attached to the hemi-spherical or conical bottom of the borehole. It also do not require a pilot hole. After the cell has been positioned properly at the end of the borehole and readings of the strain gauges have been performed, the instrument is overcored. During overcoring, the changes in strain/deformation are recorded.



In situ stress – overcoring - doorstopper



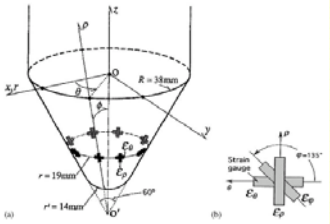




- Using a hemispherical or conical strain cell for measuring rock stresses, a borehole is first drilled. Its bottom surface is then reshaped into a hemispherical or conical shape using special drill bits. Thereafter, the strain cell is bonded to the rock surface at the bottom of the borehole.
- The latest version of the conical strain cell, equipped with 16 strain components, has been successfully tested.
- Measurements with the conical borehole technique have been made mostly in Japan. This technique has been found to be a useful method for measuring rock stress in a single borehole and in various rock types.

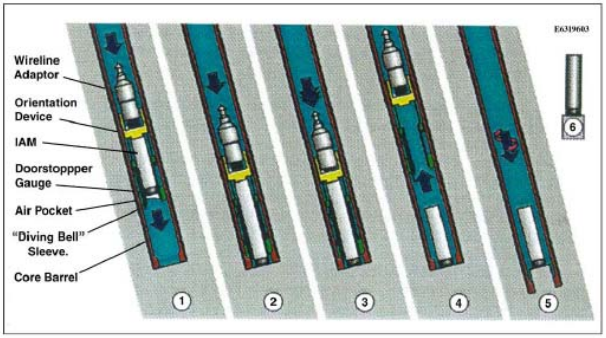
In situ stress – overcoring - doorstopper

- Leeman indicates that a doorstopper technique was used as early as 1932 to determine stresses in a rock tunnel below the Hoover Dam in the United States, and also in Russia in 1935. Leeman developed a cell with strain gauges that could be cemented on the bottom of 60mm boreholes and overcored. The cell is often referred to as CSIR (Council for Scientific and Industry Research) Doorstopper and has been used for measurements in 60 m deep boreholes. The CSIR Doorstopper is 35mm in diameter and at the base of the gauge a strain rosette consisting of 3 or 4 strain gauges is cemented. The cell is pushed forward by compressed air and glued at the base of a drill hole. Reading of the strain gauges is taken before and after overcoring of the cell. Hence, they do not require a pilot hole.
- A modified doorstopper cell called the Deep Doorstopper Gauge System (DDGS) has been developed lately. The DDGS was designed to allow overcoring measurements at depths as great as 1000m in subvertical boreholes.



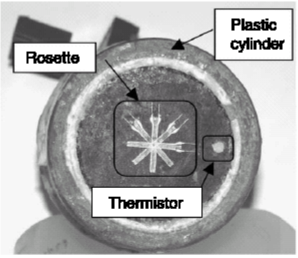
In situ stress – overcoring - doorstopper

The device utilises an Intelligent Acquisition Module, a remote battery-powered data logger that collects and stores strain data during stress measurement tests.

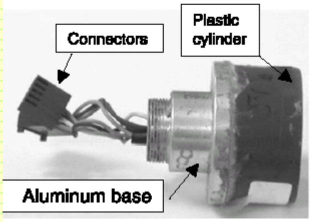


Installation of the DDGS: (1) After attening and cleaning of the bottom, the instruments are lowered down the hole with the wire line cables. (2) When the DDGS is at the bottom the orientation of the measurement is noted in the orientation device and the strain sensor is glued.(3) The IAM and Doorstopper gauge are removed from the installation equipment. (4) The installation assembly is retrieved with the wire line system. (5) The monitoring and overdrilling start, the strain change in the bottom is measured by the time. (6) When overdrilling is completed, the core is taken up and a bi-axial pressure test done to estimate the Young's modulus.

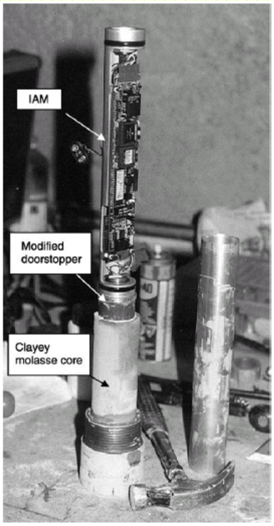
In situ stress – overcoring - doorstopper



(a) Front view



(b) Side view



In situ stress – overcoring - doorstopper

Successful measurements have been performed in Canada - borehole depths as great as 518m (943m depth from surface), where both hydraulic fracturing and triaxial strain cells were not applicable at depths deeper than 360m because of the high stress situation.

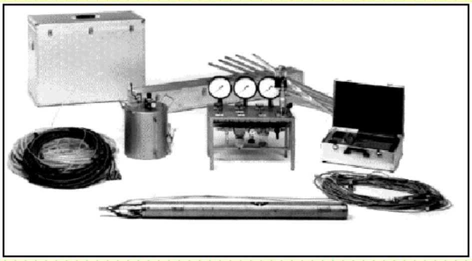
An advantage for the Doorstopper, as well as the conical or spherical methods, is that they do not require long overcoring lengths, i.e. only some 5 cm, as compared to the pilot hole methods (at least 30 cm).

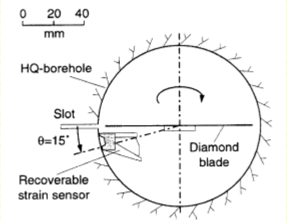
As the methods do not require a pilot hole there are also better possibilities for successful measurements in relatively weak or broken rock, as well as in rocks under high stresses in which core discing is common. Compared to triaxial cells, a Dorrstopper measurement requires less time, and 2–3 tests can be conducted per day.

In situ stress – doorstopper - pluses & minuses

- Like the Doorstopper, a small length of the rock is required for overcoring.
- For the conical cell, the stress relief is achieved at an overcoring distance of 70mm and then the strains remain at constant values.
- Hemispherical or conical strain cells have mostly been used in Japan and successful applications have been reported in the literature.
- The disadvantage with the doorstopper is, however, that measurement at one point only enables the stresses in the plane perpendicular to the borehole to be determined.
- Furthermore, the end of the borehole must be flat which require polishing of the hole bottom.
- Disadvantages with the conical or hemispherical cell are that they require preparation of the borehole bottom, either in the form of a cone or as a sphere.
- Another limitation is their poor success in water-filled boreholes.

In situ stress – Borehole Slotter





The borehole slotter consists of a contact strain sensor, which is mounted against the wall of a large diameter borehole. Thereafter, three slots, 120 apart, are cut into the wall. A small, pneumatically driven saw cuts the slots. Each slot is typically 1.0 mm wide and up to 25 mm deep. Tangential strains induced by release of tangential stresses by the slots are measured on the borehole surface. It is based on the theory of linear elastic behaviour of the rock and uses the Kirsch solution for stresses and strains around a circular opening.

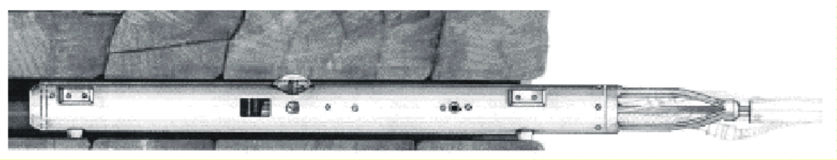
In situ stress – Borehole Slotter

The borehole slotting stress measuring method is based on the principle of local stress relief. A half moon shaped radial slot is cut into the borehole wall by means of a small diamond–impregranted saw.

Before, during and after slotting the change of tangential strain is measured at the borehole surface in the vicinity of the slot were practically full stress relief occurs. A specially developed recoverable strain sensor measures the tangential strain.

At the selected test location down the hole a minimum of six slots are cut. Three cuts at 120° apart are made 10 cm away from the first set and rotated 30°. The six slots and the corresponding strain relief for each slot constitute a single test.

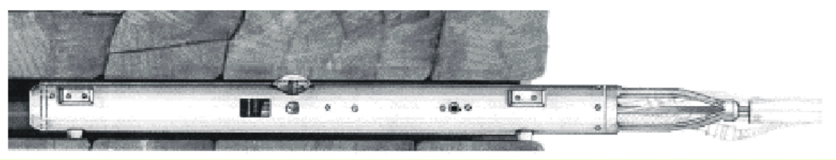
In general, good agreement has been found between stress measurements with the borehole slotter and measurements with other techniques.



In situ stress – Borehole Slotter

From this output the magnitude and the direction of the major and minor stresses in the plane normal to the borehole axis can be determined. When evaluating the borehole slotter readings, the theory of linear elasticity, in particular the KIRSCH solution for the problem in a circular hole (borehole) in a stressed plate is employed to transfer the strain readings into stresses. This means that the elastic constants of the rock (Young’s modulus E and Poisson’s ratio) must be known.

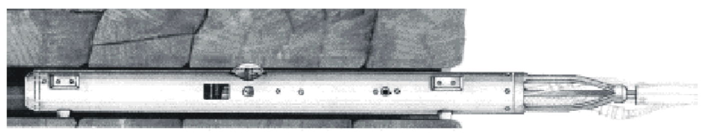
By means of 3 independently orientated 2-D stress measurements (in three independently orientated boreholes) it is possible to determine the 3-D in-situ Principal Stresses.



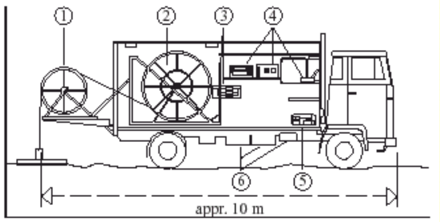
In situ stress – Borehole Slotter

Suitable for diamond drilled boreholes of 95 – 103 mm

- No over-coring
- Fully recoverable probe, maximal depth 30 m (standard)
- Dry boreholes of any inclination; no preparation
- Particular economy: One 2-D stress measurement in only 40 minutes: 10 stress measurements in a single 8 hour shift
- Extreme measurement density of up to 10 measurements per borehole meter allows delineation of geological and technical stress profiles
- Instantaneous control of the measurement during testing and adjustment of the measuring strategy
- Measurements in three independently orientated boreholes allows determination of the in-situ 3-D Principal Stresses.



In situ stress - HF & HTPF

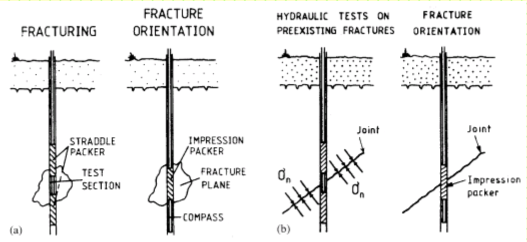


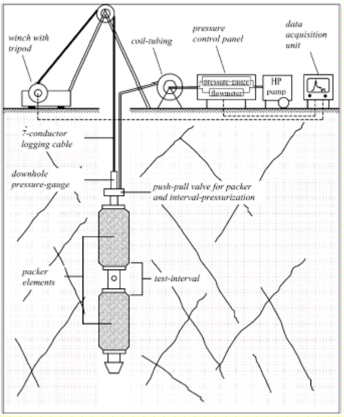
Example of equipment for hydraulic fracturing and HTPF rock stress measurements: (1) guidewheel for multihose on adjustable working platform, (2) drum for 1000m multihose, (3) flow meter manifold and manifold for control of fracturing flow and packer pressure, (4) data registration equipment, signal amplifier, chart recorder and portable PC, (5) high pressure water pump and (6) 400 l diesel fuel tanks, hydraulic pump and tank

There exist two stress measurement methods that use hydraulics as an active method to stimulate the rock surrounding a borehole and hence to determine the stress field.

These methods are hydraulic fracturing and HTPF. Both methods use the same type of equipment, including straddle packers, impression packers and high-pressure pumps to generate high-pressure water during either the formation of new fractures or reopening of pre-existing fractures. Fig. 2 presents an example of equipment that is used for both hydraulic fracturing and HTPF measurements.

In situ stress - HF & HTPF

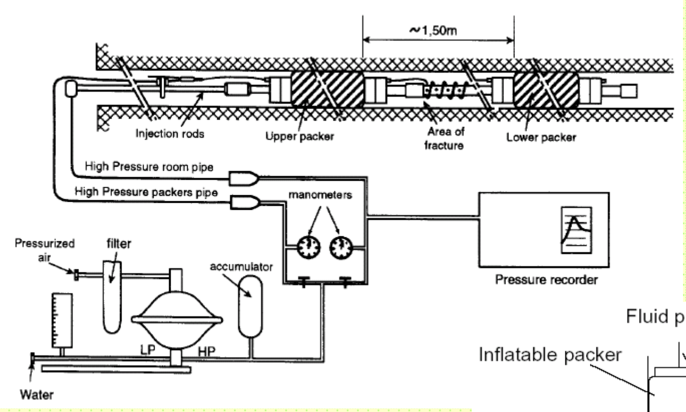


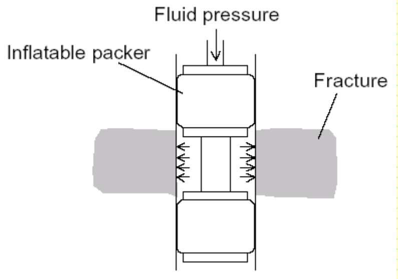


The term hydraulic fracturing is used for fluid injection operations in sealed-off borehole intervals to induce and propagate tensile fractures in borehole wall rock. It was first applied in the oil industry to stimulate productivity from low permeable oil-bearing formations (1940). In the beginning of the 1960s it was proposed to derive the state of stress from such hydraulic fracturing operations.

The classical concept for the interpretation of hydraulic fracturing pressure records was developed by Hubbert and Willis in 1957.

In situ stress - HF & HTPF





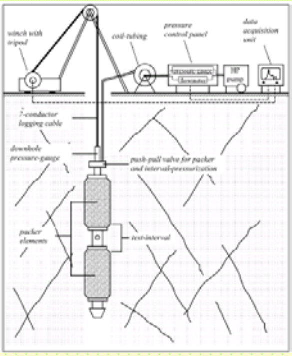
In situ stress - HF & HTPF

The following points should be noted with respect to HF:

- There is no theoretical limit to the depth of measurement, provided a stable borehole can access the zone of interest and the rock is elastic and brittle.
- Classical interpretation of an HF test is possible only if the borehole axis is parallel to one of the principal stresses and is contained in the induced fracture plane. The initiation of 'en echelon' fractures may indicate that the borehole axis is not along a principal stress. Excessive deviation invalidates the classical method of interpretation of test results.
- Principal stress directions are derived from the fracture delineation on the borehole wall under the assumption that fracture attitude persists away from the hole.
- Evaluation of the maximum principal stress in the plane perpendicular to the borehole axis assumes that the rock mass is linearly elastic, homogeneous, and isotropic. It involves considerations of pore pressure effects, often difficult to ascertain, and requires an assessment of the rock tensile strength.

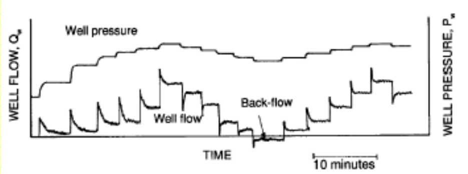
In situ stress - HF & HTPF

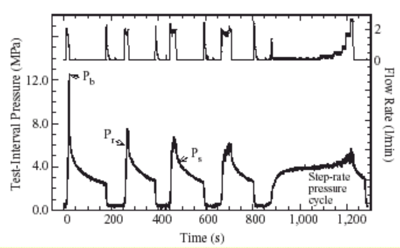
A section, normally less than 1m in length, of a borehole is sealed off with a straddle packer. The sealed-off section is then slowly pressurised with a fluid, usually water. This generates tensile stresses at the borehole wall. Pressurisation continues until the borehole wall ruptures through tensile failure and a hydrofracture is initiated. The fracture plane is normally parallel to the borehole axis, and two fractures are initiated simultaneously in diametrically opposite positions on the borehole periphery. The hydrofracture will initiate at the point, and propagate in the direction, offering the least resistance. The fracture will therefore develop in a direction perpendicular to the minimum principal stress. -scanner or a borehole televiewer.



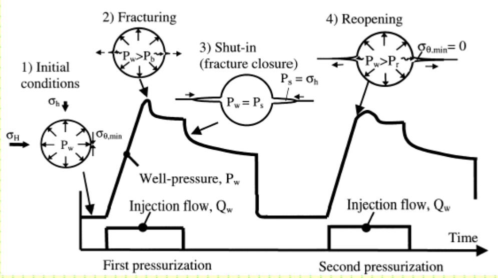
The orientation of the fracture is obtained from the fracture traces on the borehole wall – it coincides with the orientation of the maximum horizontal stress, in a vertical or sub-vertical hole where it is assumed that one principal stress is parallel to the borehole. The fracture orientation may be determined either by use of an impression packer and a compass or by use of geophysical methods such as a formation micro-scanner or a borehole televiewer.

In situ stress - HF & HTPF





Pressure – up to 100 MPa



$$\sigma_h = P_s$$

$$\sigma_H = R_r + 3\sigma_h - P_b$$

In situ stress - HF & HTPF

- In its conventional form, the method is 2D: only the maximum and minimum normal stresses in the plane perpendicular to the borehole axis are established. For a vertical borehole, these components are the maximum and minimum horizontal stresses. Since the principal stress directions in tectonically passive and topographically at areas are usually close to horizontal and vertical, it can often be assumed that the components measured in a vertical borehole are two of the principal stresses.
- Hydraulic fracturing is an efficient method for determining the 2D stress field, normally in the horizontal plane, and is therefore suitable at the early stages of projects when no underground access exists. Due to its efficiency, it is especially advantageous for measurements at great depth. . The method is also not significantly affected by the drilling processes. Hydraulic fracturing normally includes large equipment, which requires space. Furthermore, the theoretical limitations normally imply that the measurements should be done in vertical holes. Hence, the method is most suited for surface measurements in vertical or sub-vertical boreholes.
- Applied packer presssure – 2-4 MPa

In situ stress - HF & HTPF

- The hydraulic fracturing method allows a direct measurement of the least stress in the plane perpendicular to the borehole axis, which is normally the least horizontal stress, σ_h and the accuracy is good (±5%). The maximum horizontal stress is calculated from equations including a failure criteria and parameters evaluated from the field pressure data. The accuracy is less good for the maximum horizontal stress (B710– 20% or more). It is shown that the general theory for calculating the major horizontal stress from the hydraulic fracturing suffers from uncertainties in the assumptions—a continuous, linearly elastic, homogenous, and isotropic rock together with the fracture reopening. It is probable that the major horizontal stress, determined from hydraulic fracturing, may be somewhat underestimated when the major principal stress divided by the minor principal stress is close to, or higher than, a factor of 3.
- Classical hydraulic fracturing requires sections in the borehole free from fractures. These sections should be at least a few meters long so that the induced fractures do not interact with existing ones. Hydraulic fracturing may be difficult to apply with an acceptable success rate in rock domains with very high stresses, such as when core discing is indicated in the core from core drilling. Geological features, such as foliation planes in gneissic rock, may also affect the possibilities of success as they act as weakness planes and thereby may control the direction of the initiated fracture.

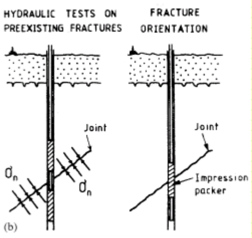
In situ stress - HF & HTPF

The following points should be noted with respect to HTPF:

- There is no theoretical limit to the depth of measurement, provided a stable borehole can access the zone of interest.
- The method assumes that isolated pre-existing fractures, or weakness planes, are present in the rock mass, that they are not all aligned within a narrow range of directions and inclinations, and that they can be mechanically opened by hydraulic tests. When the straddled interval includes multiple fractures, it is necessary to verify that only one single fracture has been opened, for the opening of pre-existing fractures change the local stress field.
- Fractures used in stress computations are delineated on the borehole wall under the assumption that their orientation persists away from the hole.
- For a complete stress tensor determination, the method requires a theoretical minimum of six tests, each conducted on pre-existing non-parallel fractures; but additional tests are recommended in order to correct for uncertainties. However, when combined with HF tests, only three–four HTPF results are necessary for the maximum horizontal and vertical stress components determination.
- The method is valid for all borehole orientations. It is independent of pore pressure effects and does not require any material property determination.
- It assumes that the rock mass is homogeneous within the volume of interest. When tested fractures are distant from one another by more than 50 m, a hypothesis on stress gradients is required.

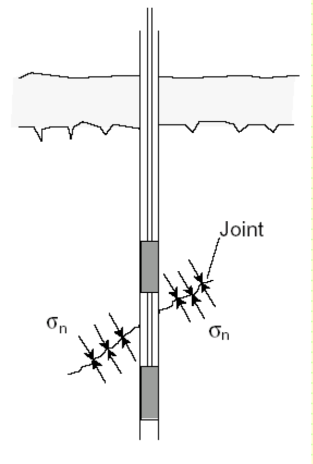
In situ stress - HF & HTPF

- The HTPF method has been practised for some 15 years. Instead of inducing new fractures in intact rock, the HTPF method is based on the re-opening of existing fractures found in the borehole wall and thereby determining the normal stress across the fracture plane. Depending on assumptions made regarding the stress field, the HTPF method allows either a 3D or 2D determination of the stress state. A 3D determination requires a larger number of fractures to be tested.
- When conducting HTPF tests, it is of importance that the fracture tested is of a size at which the normal stress can be assumed to be uniform and the geometry of the fracture must be planar. The HTPF method relies only on four field parameters; test depth, shut-in pressure, dip and strike of the tested fracture.
- The shut-in pressure is equivalent to the normal stress acting across the fracture plane. Given these parameters for a sufficiently large number of fractures with different strike and dips, either the 2D or 3D stress state can be determined.



In situ stress - HF & HTPF

Theoretically the 2D solution requires at least six different fractures to solve the problem. In practise some redundancy, however, is required. For successful measurements, it is suggested that at least 10–12 isolated, pre-existing fractures with different strikes and dips are found and tested in the borehole wall within the depth interval of interest. The 3D alternative of the HTPF method includes less assumptions on the stress field but requires a larger number of fractures to be tested. In the 3D alternative the vertical stress does not have to be a principal stress. Theoretically, 12 unknowns exist in the system of equations. In practise, it is suggested that at least 18–20 successful tests are obtained to resolve the 3D stress field.

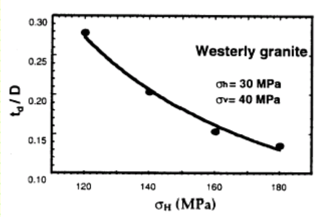


In situ stress - HF & HTPF – pluses & minuses

- As compared to classical hydraulic fracturing, the method has the advantages of less limitations as regards geological features.
- Nor does the method require determination of the tensile strength of the rock and it is independent of pore pressure effects.
- As long as a variation in strike and dip of the existing fractures exists in the rock mass, neither weakness planes such as foliation planes nor core discing should cause any problems in obtaining successful measurements.
- The method is more time consuming than hydraulic fracturing as the down-hole equipment must be positioned at the exact location of each discrete fracture to be tested.
- This requires good accuracy in the depth calibration. A drawback, compared to hydraulic fracturing, is also that no preliminary results can be obtained until all field-testing has been completed, field data evaluated and those data processed using computer codes.

In situ stress – Core discing

The pre-loaded nature of rock masses has consequences in rock stress observation. The process of boring of holes to obtain cores results in stress concentrations directly at the coring bit/rock interface. As the core is formed, the annular groove causes the in situ stresses to be redistributed, creating high-induced stresses across the core. This can result in damage (irrecoverable strains and microcracks) to the core. If the in situ stresses are high, and the rock brittle, this can result in 'core discing'— the core is produced in the form of thin 'poker chips'. The thickness of the chips decreases as the stress intensity increases; in extreme cases, the discs can become so thin that they have the appearance of milles feuilles, or flaky pastry. Observation of discing in cores is often taken as evidence of high stress zones in the rock.



Example of relation between disc thickness t_d (normalised by core diameter) and σ_H for given σ_h and σ_v

In situ stress – Core discing

The following minimum information is needed for the interpretation:

- the tensile strength of the rock,
- Poisson's ratio of the rock,
- the uniaxial compressive strength of the rock,
- the mean disc spacing,
- the shape of the fracture (morphology) and
- the extent of the fracture in the core.

The confidence of the interpretation can be increased considerably if the same information can be achieved from both normal coring and overcoring at the same depth level. In practice, core discing can only be used as an indicator for estimation of rock stresses. When core discing occurs, one can of course also conclude that rock stress concentrations are higher than the rock strength. Such information, obtained already during the drilling stage, is of course valuable and a guide for further decisions.

In situ stress – Core discing

In brittle rocks it has been observed that discing and breakouts usually occur over the corresponding lengths of core and borehole. The thinner the discs the higher the stress level. However, the formation of discs depends significantly on the properties of the rock and the magnitude of the stress in the borehole axial direction. In addition, the type and technique of drilling, including the drill thrust, can significantly affect the occurrence of discing. It is therefore unlikely that observation and measurements of discing will be successful in quantifying the magnitudes of in situ stresses.

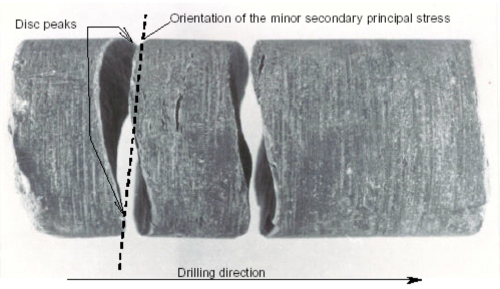
Core discs symmetrical with respect to the core axis

If the discs are symmetrical about the core axis, as shown in figure above, then it is probable that the hole has been drilled approximately along the orientation of one of the principal stresses.

In situ stress – Core discing

Nevertheless, the shape and symmetry of the discs can give a good indication of in situ stress orientations (Dyke, 1989).

A measure of the inclination of a principal stress to the borehole axis can be gauged from the relative asymmetry of the disc. For unequal stresses normal to the core axis, the core circumference will peak and trough as shown in figure next to text. The direction defined by a line drawn between the peaks of the disc surfaces facing in the original drilling direction indicates the orientation of the minor secondary principal stress.



Core discs resulting with unequal stresses normal to the core axis

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In situ stress – Core discing

Non-symmetrical core discing, indicating that the core axis is not a principal stress direction

Lack of symmetry of the discing, as shown in figure above, indicates that there is a shear stress acting across the borehole axis and that the axis is not in a principal stress direction.

In situ stress – Acoustic emission

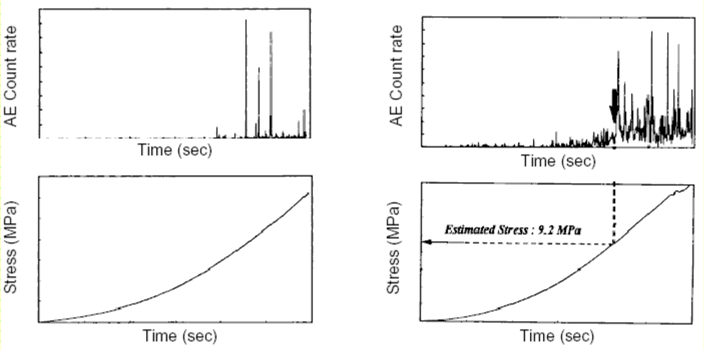
Kaiser (1953) observed that when the stress on a polycrystallised metal was relaxed and then reapplied, there was a significant increase in the rate of acoustic emission when the previous maximum stress level was exceeded. This phenomenon has become known as the Kaiser effect. Goodman (1963) observed a similar effect in rocks. It appears that Kanagawa et al (1976) were the first to make use of the phenomenon to estimate in situ stresses.

Hughson and Crawford (1986) demonstrated experimentally that, from a sample of rock extracted from a stressed environment, it was possible to determine the magnitude of the maximum stress to which the rock had been subjected, as well as how much more stress it could withstand before becoming unstable.

The Kaiser effect method involves the drilling of small secondary, orientated cores from the original core removed from the stressed environment. The original core must be orientated so the directions of secondary coring are known in relation to this original core orientation.

In situ stress – AEKE

The secondary cores are prepared with the required end flatness and parallelism, and then subjected to uniaxial compressive stress whilst the AE from the rock are monitored using sensors attached to the core.



a) First Loading

b) Second Loading

On a plot of the applied stress vs. the AE, the KE change point is at the position on the curve where the slope of the plot noticeably increases. As the KE changes in AE rate, the stress corresponds with the previous maximum stress to which the rock had been subjected. If a sufficient number of secondary cores are tested, the full three dimensional in situ state of stress may be determined.

In situ stress – AEKE

The KE does not occur abruptly at a precisely definable point, but within a transitional zone. The position and abruptness of this zone varies for different types of rock materials, and with the magnitude of the previous stress relative to the strength of the rock. The transition zone becomes large and indistinct if the maximum stress exposure time was brief.

The stress “memory” reduces over time, and hence it is necessary to carry out the tests within a relatively short time after removal of the original core. The length of the “memory” appears to depend on the type of rock. Kurita and Fujii (1979) conclude that no significant recovery of the KE occurs within one month of removal from the stressed environment. Friedel and Thill (1990) found that the effect was retained for a period of up to at least 5 months. Other researchers have noted very much shorter retention periods, for example, several hours (Goodman, 1963), one to five days (Yoshikawa and Mogi (1981), three days (Boyce, 1981). These limitations are contradicted by the results of Seto et al (1998), who obtained satisfactory results for in situ stress determinations on cores that had been removed almost two years previously. Their results agreed to within 10% of values determined by other methods.

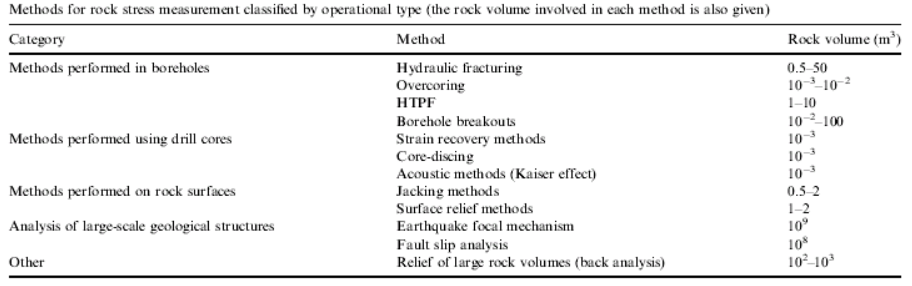
In situ stress – AEKE - considerations

- It gives a direct measure of stress. It is not dependent on the measurement of strain and the subsequent calculation of stress from strain, which requires the assumption of a relationship between stress and strain for the rock as well as measurement of the deformation properties of the rock. All of these factors can introduce errors.
- The full three dimensional in situ state of stress may be determined.
- Use can be made of original core obtained for other purposes, such as exploration, making the method cost effective.
- Core obtained remotely can be used, and therefore the method is applicable to greenfield sites, before any excavations have been made, as well as to operating mines.
- Since small secondary cores are used for the tests, many tests can be carried out using a limited length of original borehole core. Again this makes the method cost effective, with a large number of results being able to be obtained at relatively low cost. The more the number of cores tested, the greater the confidence in the results obtained.

In situ stress – AEKE - considerations

- The necessary accurate and sensitive sample preparation and testing activities are carried out in the laboratory. This therefore obviates field based testing errors that are common in the often harsh mining environment. Interference with production mining operations is also reduced or eliminated.
- At this stage it is not known what effect fracturing of core, induced during the drilling process, will have on the application of the method. Applications to date in a mining environment have been at relatively shallow depth, and therefore generally at stress levels well below the strength of the rock. It is therefore possible that application in the deep level gold mines may be problematic. However, stress magnitudes of close to 100 MPa have been determined in mine pillars in Australia (Villaescusa, 2001), and this indicates optimism for the use of the method at high stress levels.

In situ stress - measurements



Methods for rock stress measurement classified by operational type (the rock volume involved in each method is also given)

Category	Method	Rock volume (m^3)
Methods performed in boreholes	Hydraulic fracturing	0.5–50
	Overcoring	10^{-3}–10^{-2}
	HTPF	1–10
	Borehole breakouts	10^{-2}–100
Methods performed using drill cores	Strain recovery methods	10^{-3}
	Core-discing	10^{-3}
	Acoustic methods (Kaiser effect)	10^{-3}
Methods performed on rock surfaces	Jacking methods	0.5–2
	Surface relief methods	1–2
Analysis of large-scale geological structures	Earthquake focal mechanism	10^9
	Fault slip analysis	10^8
Other	Relief of large rock volumes (back analysis)	10^2–10^3

Representative volume involved in the rock stress measurement