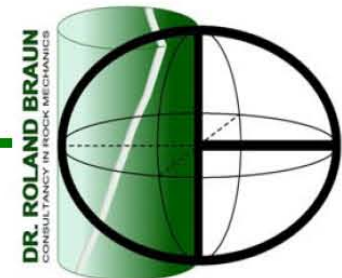# In situ stress and parameter determination using core samples

Ermittlung wesentlicher Gebirgsspannungen und –eigenschaften an Bohrkernen

7. Workshop Bohrlochgeophysik und Gesteinsphysik

Hannover im Oktober 2003

DR. ROLAND BRAUN
CONSULTANCY IN ROCK MECHANICS

INTRODUCTION:

PLANNING AND ROCK MECHANICS ANALYSIS

stability of underground openings (wellbores, caverns, tunnels etc.), sanding, perforations, frac operations, inflow conditions, seal sufficiency, strata compaction, in situ stresses and the changes in these during pore pressure variation, well-log calibration etc.

INPUT PARAMETERS REQUIRED

in situ stresses, elastic rock properties, rock deformation and strength, propagation of elastic waves, permeability etc.)
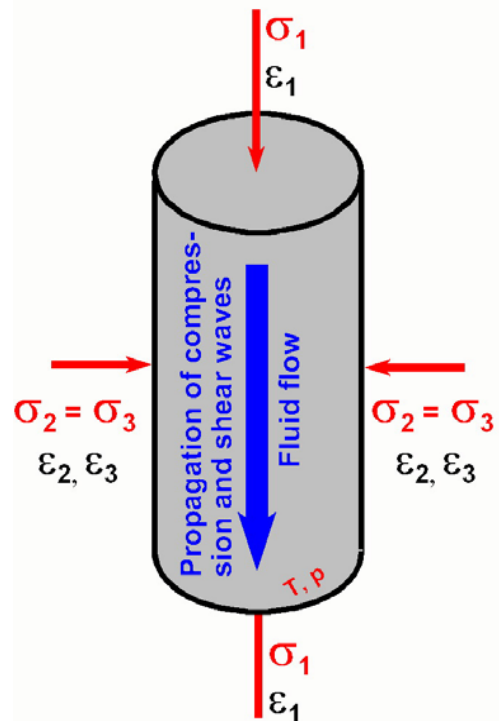
DETERMINATION OF THE PARAMETERS

in situ measurements (hydraulic fracturing, logging etc.), laboratory investigations on core samples
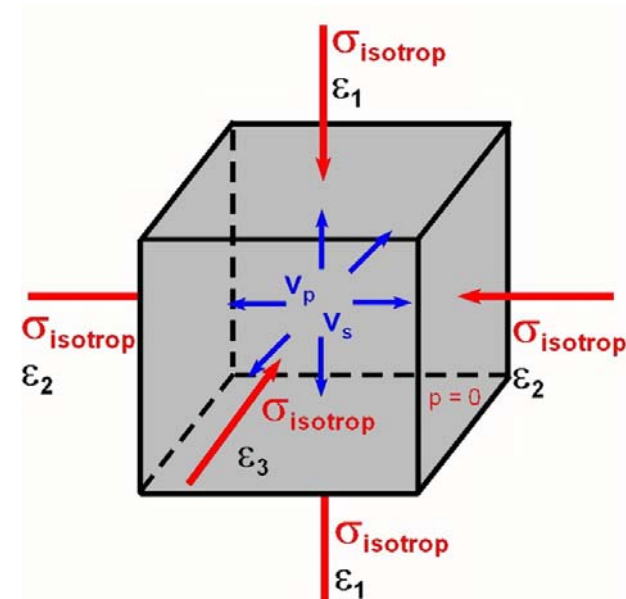
LABORATORY TESTING:

Compression/extension test on cylindrical rock samples (plugs)

RACOS®

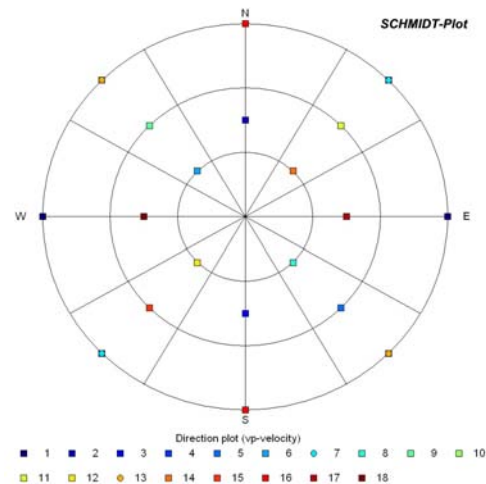(**R**ock **A**nisotropy **C**haracterisation **O**n **S**amples)

REQUIREMENTS FOR RACOS® TESTING:

Rock material

A section of core is required with approximately constant rock properties. Comparison of selected features of the sample with typical in situ characteristics can often be used for re-orientation.

Test orientations

The transmission directions for the compression and shear waves are chosen to ensure 3D coverage (18 directions on 6 rectangular blocks)
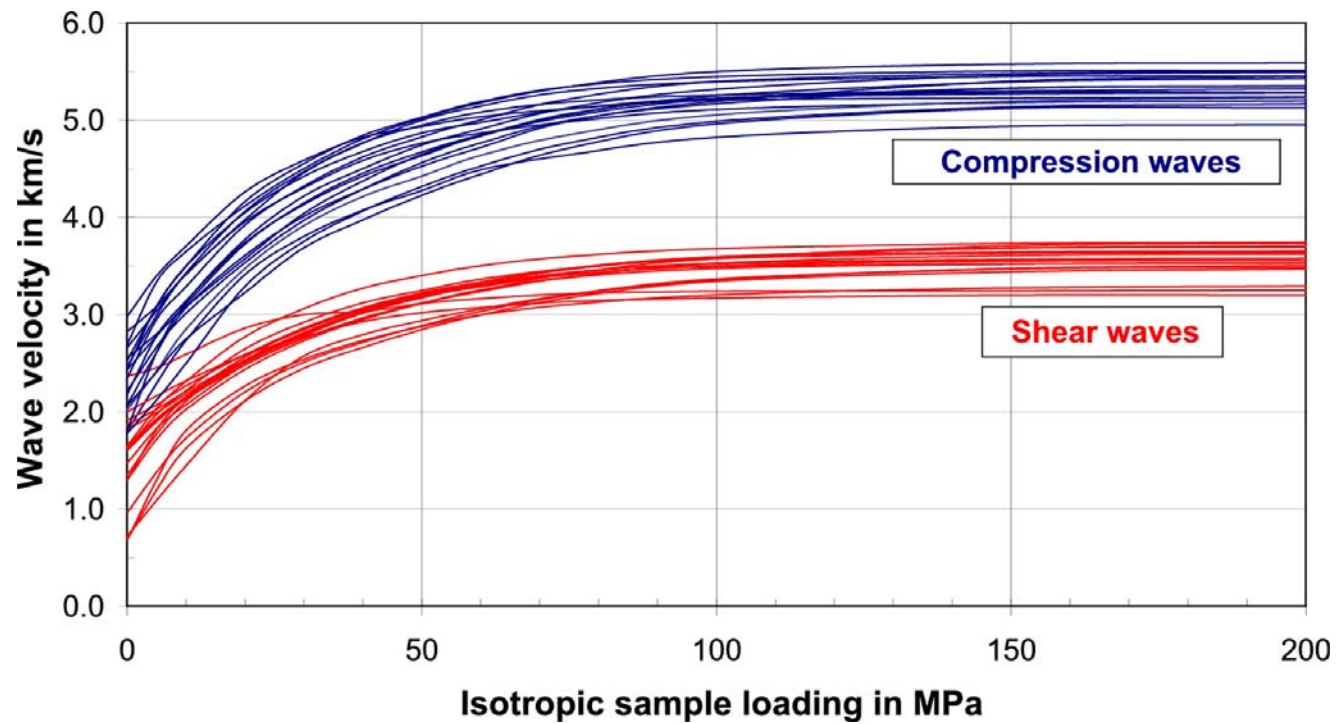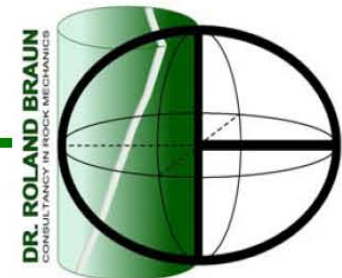
Preparation of the samples
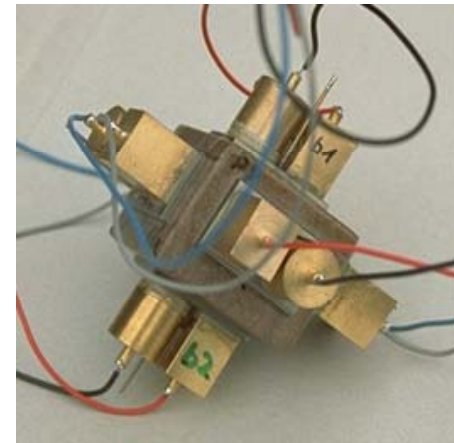
Pairs of compression and shear wave transducers are fixed to the block end faces. The surface of the completed sample is then sealed.
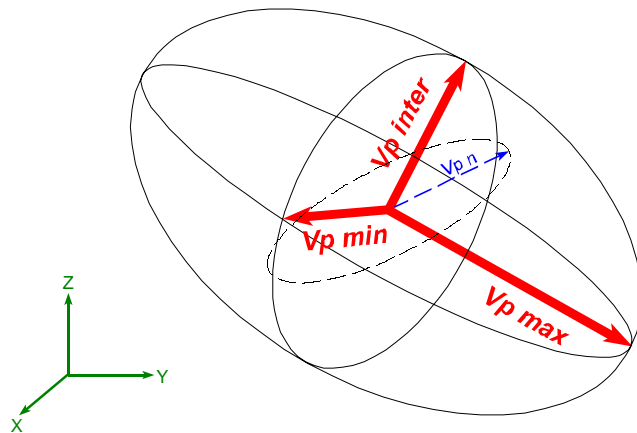
RACOS® - MEASUREMENTS:

The elastic wave velocities between the opposing end faces of each block are determined at several isotropic load levels.

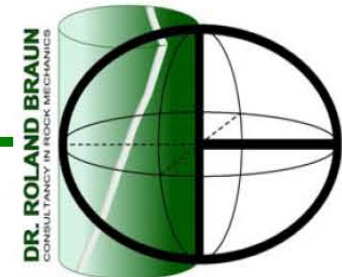# EVALUATION OF THE RACOS® - MEASUREMENTS:

Spatial anisotropy

Data points from RACOS® analyses are combined in 3D distributions described by symmetrical 2nd order tensors. The principal directions and magnitudes of the specific parameters are determined from the tensors.

## Statistical parameter evaluation

Statistical analysis is made of the deviation of the individual measurements from the values derived from the mean tensor. The results from all the valid measurement configurations are evaluated, in order to screen for random heterogeneities.

DERIVATION OF PARAMETERS FROM THE RACOS® - MEASUREMENTS:

Properties of the rock mass

In situ stress state
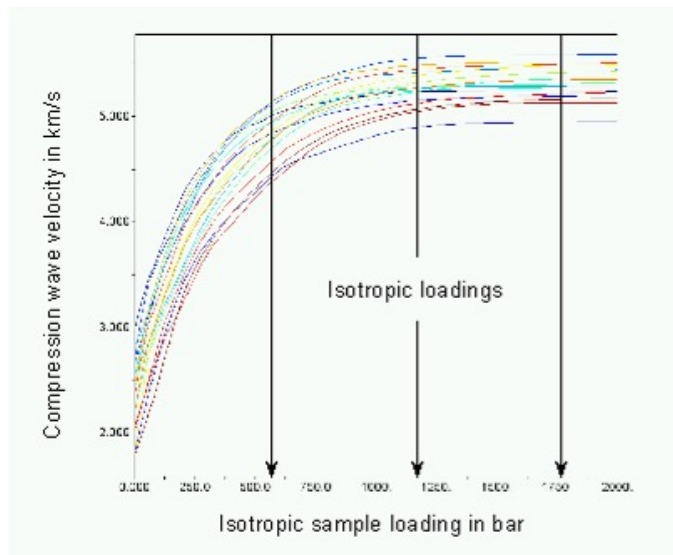
Evaluation of the anisotropy of the propagation velocities of elastic waves (seismic anisotropy) for selected isotropic loading condtions.
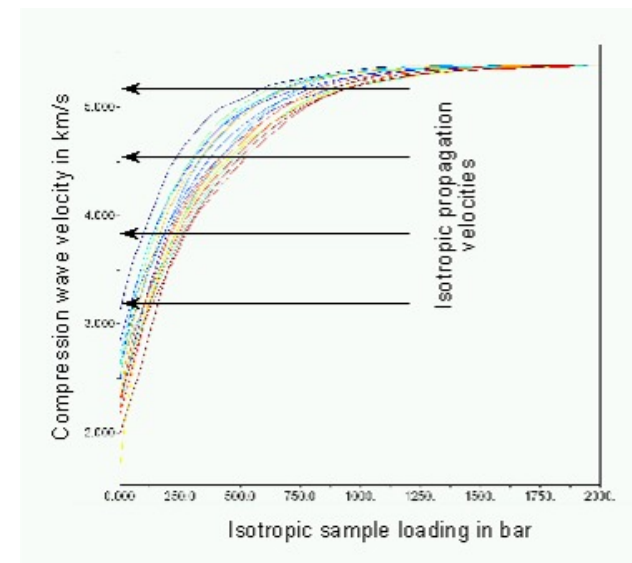
Evaluation of the loadings required to achieve selected isotropic propagation velocities (seismic isotropy).

PROPERTIES OF THE ROCK MASS: *SEISMIC ANISOTROPY*

Direction and loading dependent elastic wave propagation
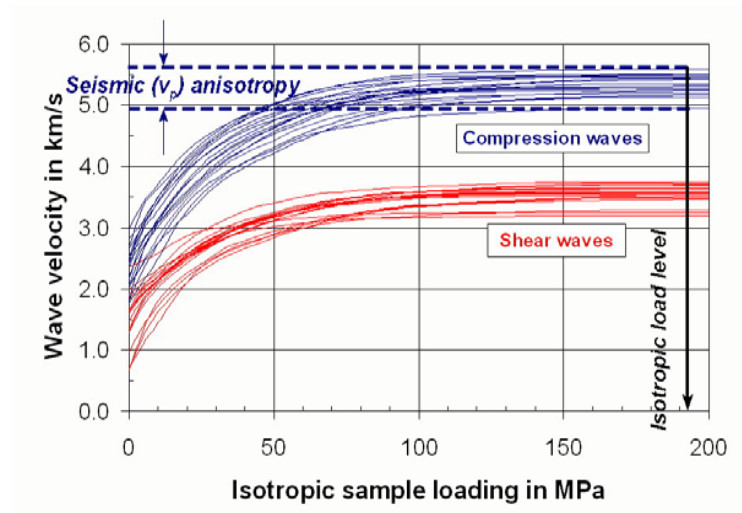
A first assessment of the rock anisotropy can be derived from the differing measured loading-dependent propagation velocities.

Principal propagation directions of compression waves

SCHMIDT plots show the geographical orientations of the parameters; in this example the seismic anisotropy.

PROPERTIES OF THE ROCK MASS: *ELASTIC CONSTANTS*

Deformation parameters
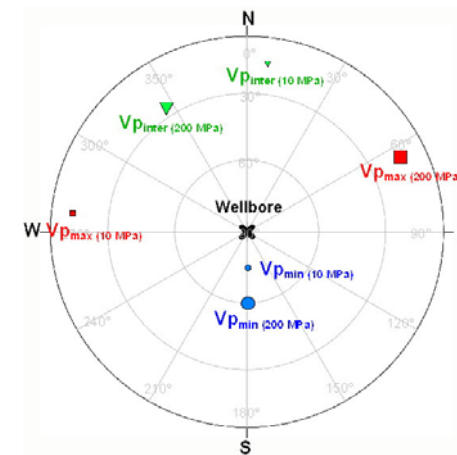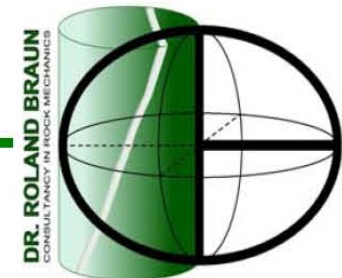
Stress – strain behaviour

Principal directions of dynamic YOUNG's modulus E

$$s_{ijkl} * n_j * n_k * \Delta_l = \rho * v^2 * \Delta_i$$
(CHRISTOFFEL equation)

$$\sigma_{ij} = s_{ijkl} * \varepsilon_{kl}$$

$$\varepsilon_{kl} = c_{ijkl} * \sigma_{ij}$$

Determination of the elasticity parameters **s** as a function of the wave velocity, its vibration and propagation directions (Δ, **n**) and the rock density ρ. Iteration is used to fit the solutions to the measured propagation velocities.

General linear relationship between stress σ and deformation ε for given loading.

In the SCHMIDT plot are shown the geographical orientations of the principal elastic parameters.
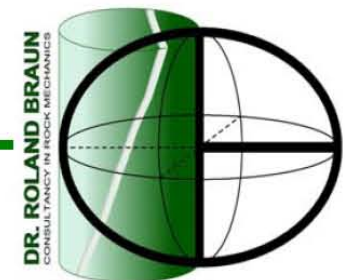
PROPERTIES OF THE ROCK MASS:
ANISOTROPY OF LOADING-DEPENDENT DEFORMATION
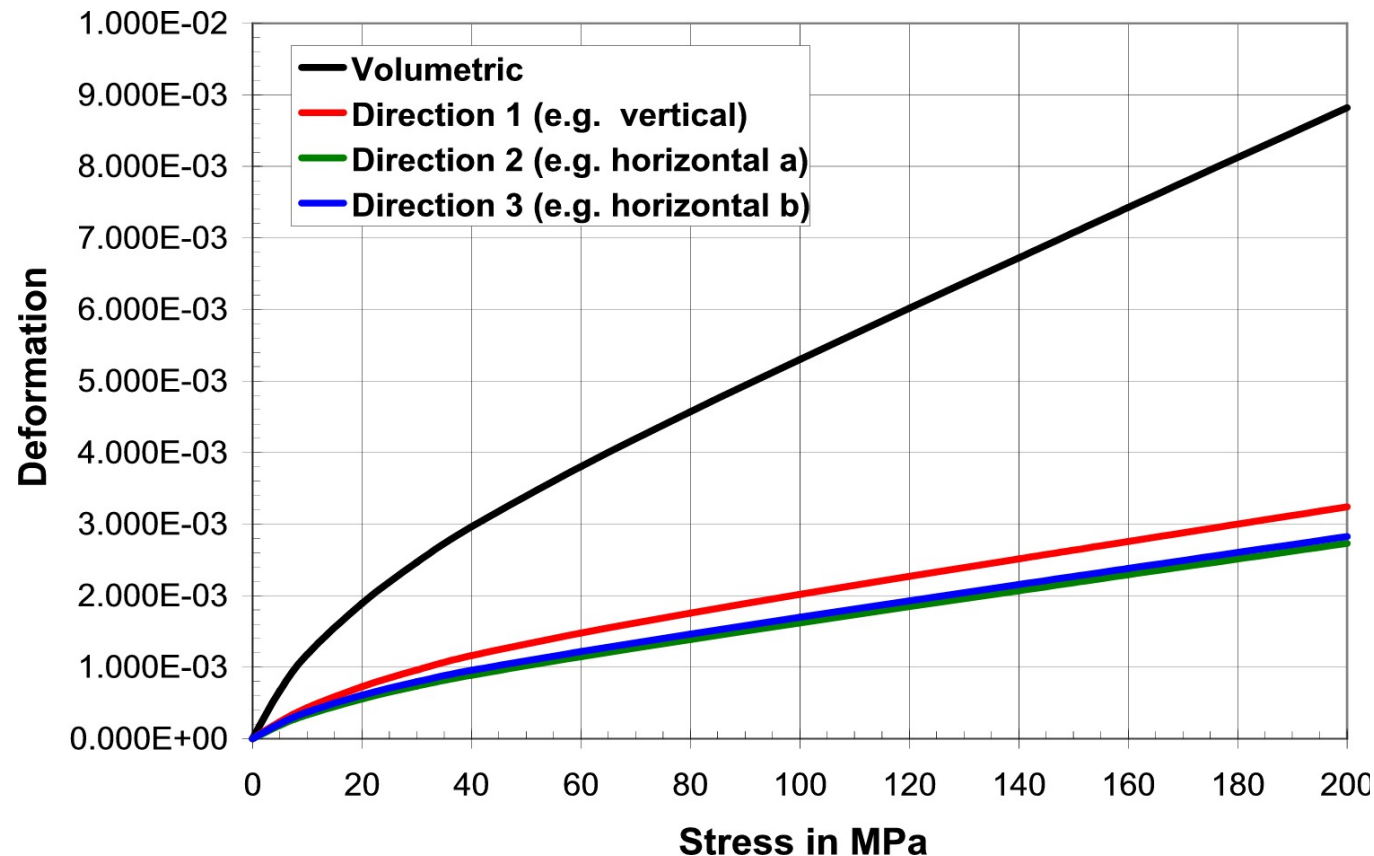
Determination of the loading-dependent deformation in various directions on the basis of the calculated elasticity parameters **c**.
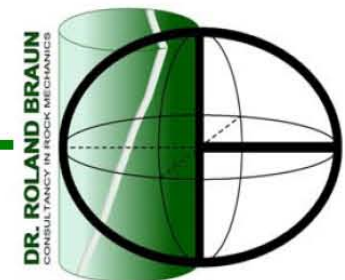
PROPERTIES OF THE ROCK MASS:

ANISOTROPY OF LOADING-DEPENDENT COMPRESSIBILITY

Determination of the volumetric and direction-dependent compressibility from tangents to the stress-strain curves.

PROPERTIES OF THE ROCK MASS:

ANISOTROPY OF LOADING-DEPENDENT PORE PRESSURE EFFECTIVENESS

Determination of the coefficient of pore pressure effectiveness (extended BIOT coefficient) as a function of the loading-dependent rock compression moduli and the rock matrix compression in various directions.
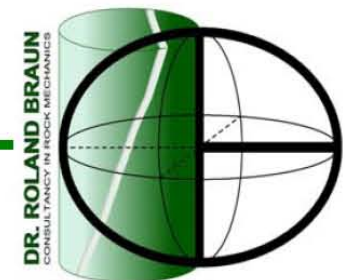
PROPERTIES OF THE ROCK MASS:

ANISOTROPY OF LOADING-DEPENDENT ROCK PARAMETERS

Deformation relationships, which can be derived for any chosen set of mutually perpendicular directions, together with the data on seismic anisotropy, can also be used to make qualitative assessments of preferred flow directions, strength anisotropy etc.

PROPERTIES OF THE ROCK MASS:

ANISOTROPY OF LOADING-DEPENDENT ROCK PARAMETERS

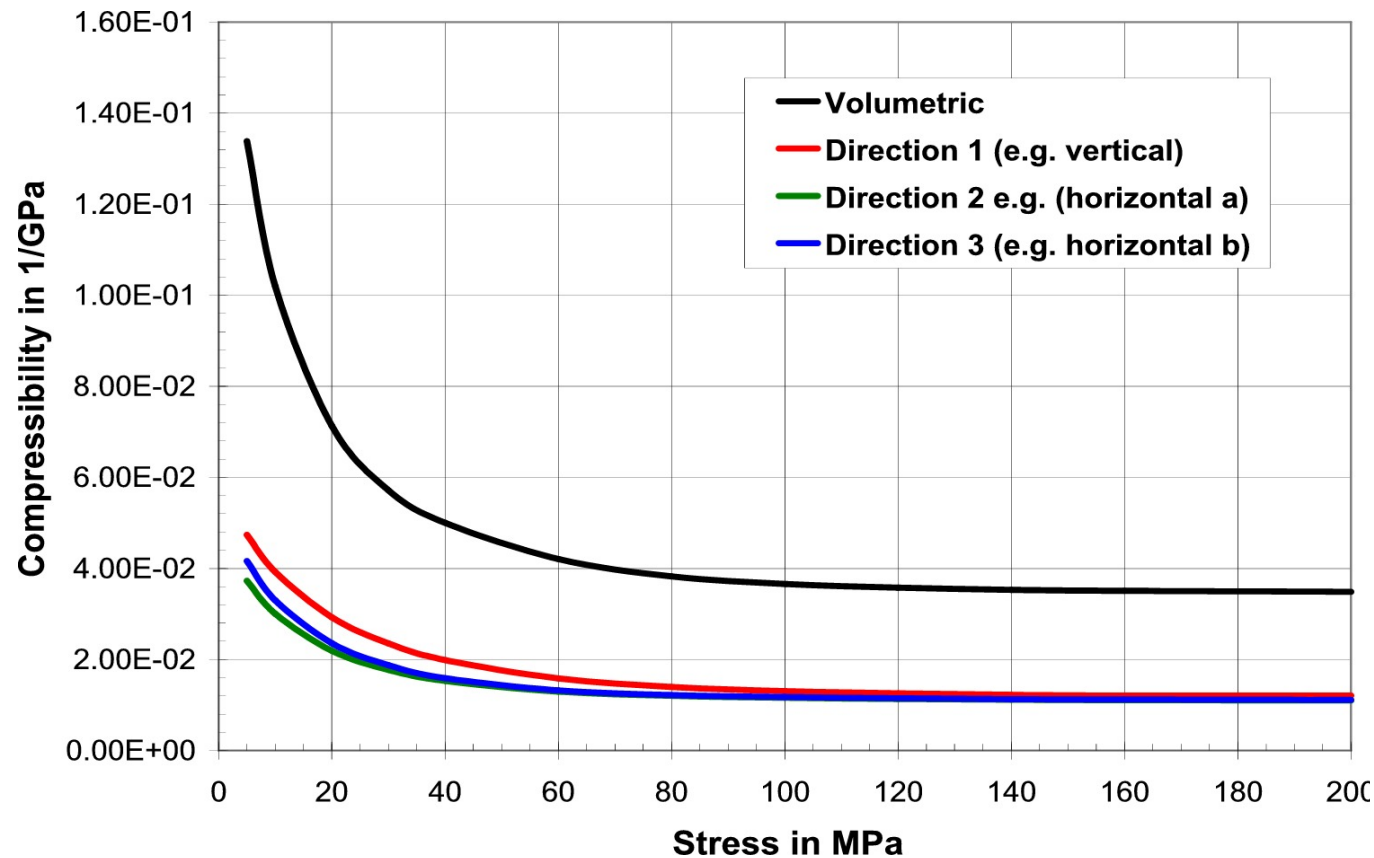| Deformation	Compressibility	Coefficient of pore pressure effectiveness

Determination of the loading-dependent deformation in various directions on the basis of the calculated elasticity parameters **c**.
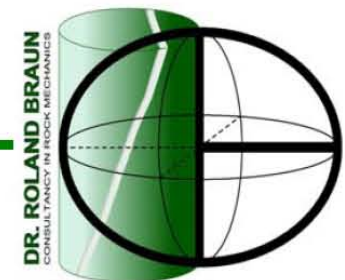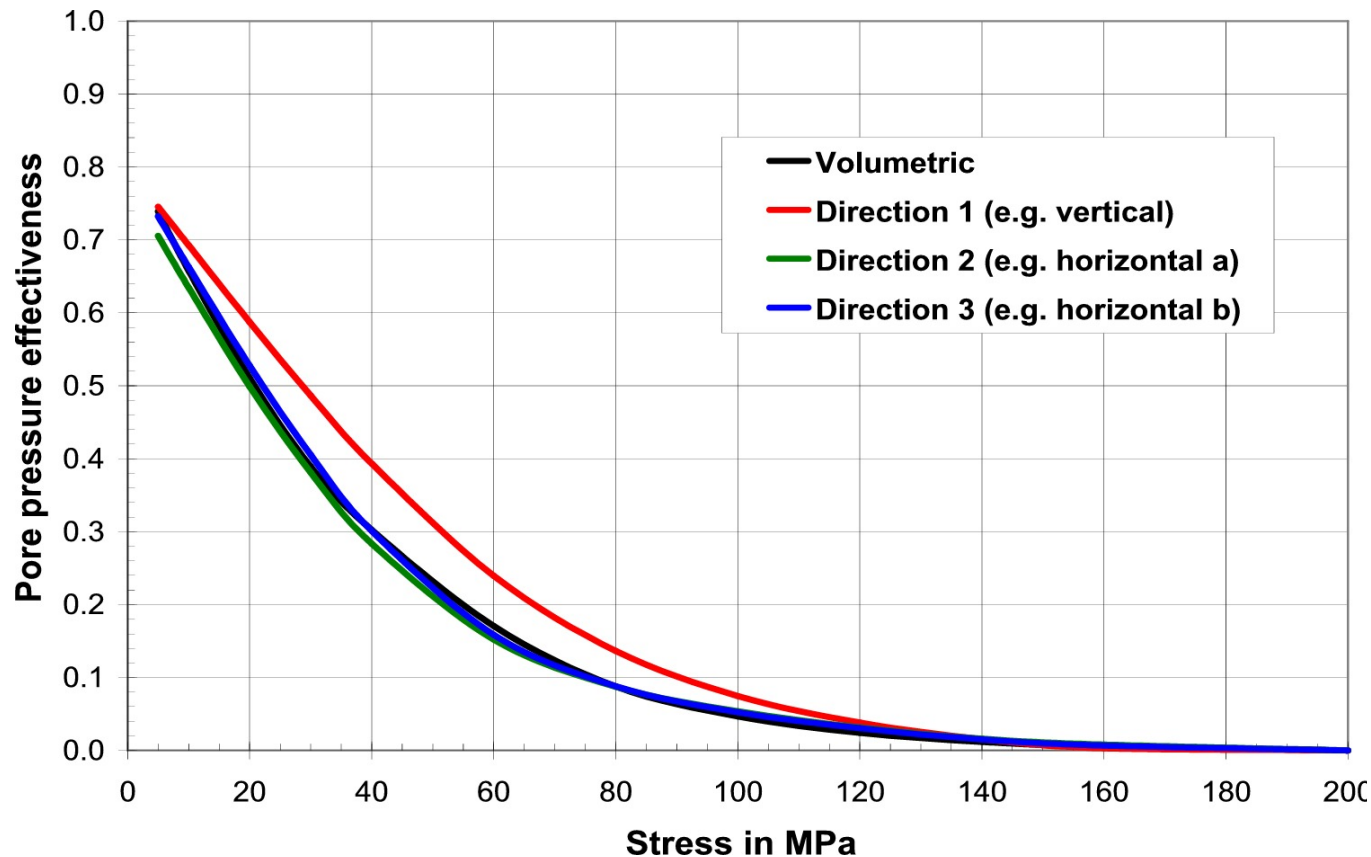
Determination of the volumetric and direction-dependent compressibility from tangents to the stress-strain curves.

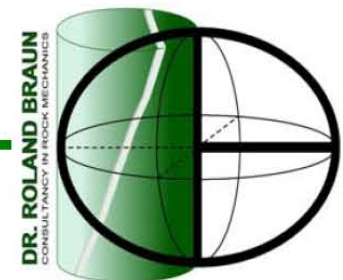Determination of the coefficient of pore pressure effectiveness (extended BIOT coefficient) as a function of the loading-dependent rock compression moduli and the rock matrix compression in various directions.
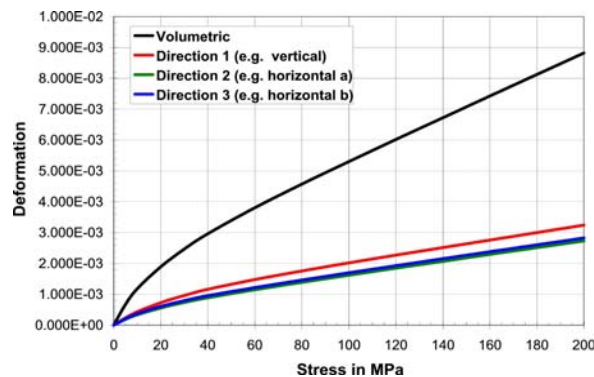
Deformation relationships, which can be derived for any chosen set of mutually perpendicular directions, together with the data on seismic anisotropy, can also be used to make qualitative assessments of preferred flow directions, strength anisotropy etc.
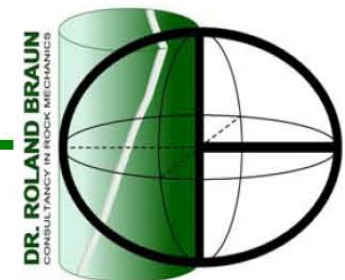
IN SITU STRESS STATE: *EFFECTIVE STRESSES*
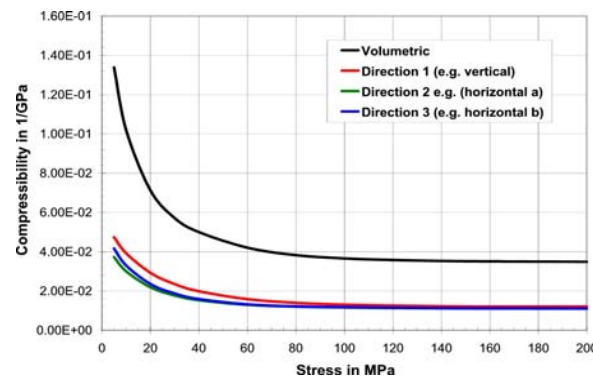
Determination of the effective in situ stress from the compression wave velocities
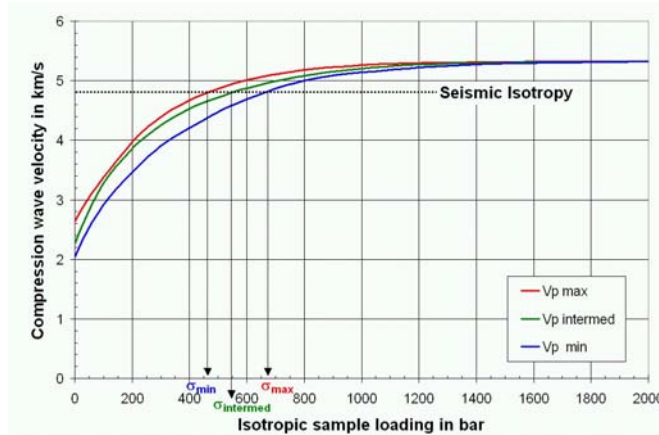
Any seismic anisotropy can be more or less eliminated by applying an appropriate triaxial loading. The tensor for this loading contains the information on the magnitudes and orientations of the sought for effective in situ stress condition. This loading tensor is determined from velocity tensors which only contain information on the changes in the rock properties related to loading or unloading (without influences from rock fabric, sampling and preparation etc.)

Stress change with depth in a formation
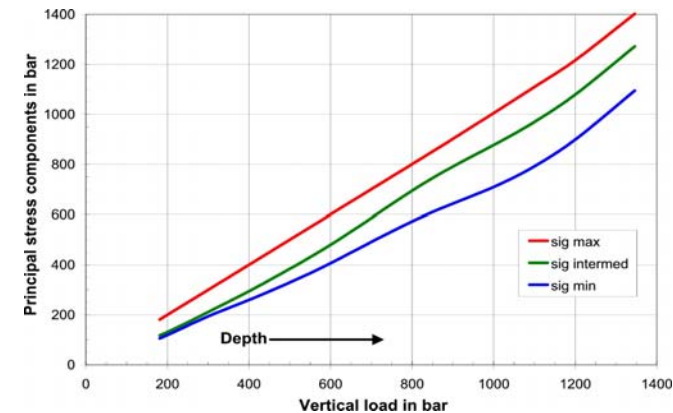
On the basis of determinations at various stress levels the changes in situ stresses with depth can be calculated.
The vertical component of this is the effective overburden pressure.
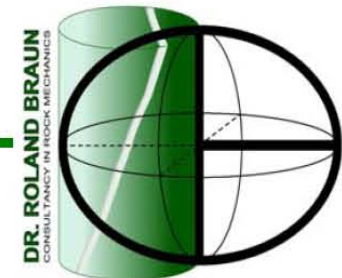
IN SITU STRESS STATE:

Determination of the effective overburden stress

1.5 m m

Microfractures

Stress-Magnitude — Azimut [°] — Dip [°]

Maximum

Median

Minimum

Loads (vs) in selected direction
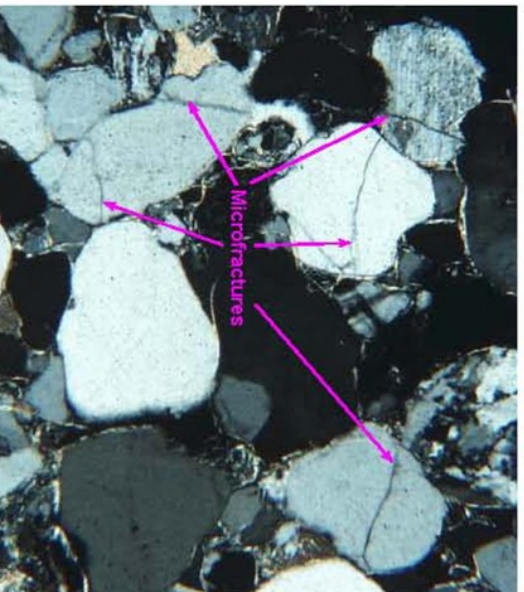
Most of the changes in the rock result from its removal from the rock mass, with the resulting unloading from the in situ loading condition. These changes produce anisotropies additional to those of the primary rock fabric. The stress changes can cause macroscopic failures (bursting, core discing etc.) and / or microscopic effects (microcracks, loosening etc.). Appropriate triaxial loadings can cancel these additional anisotropies.
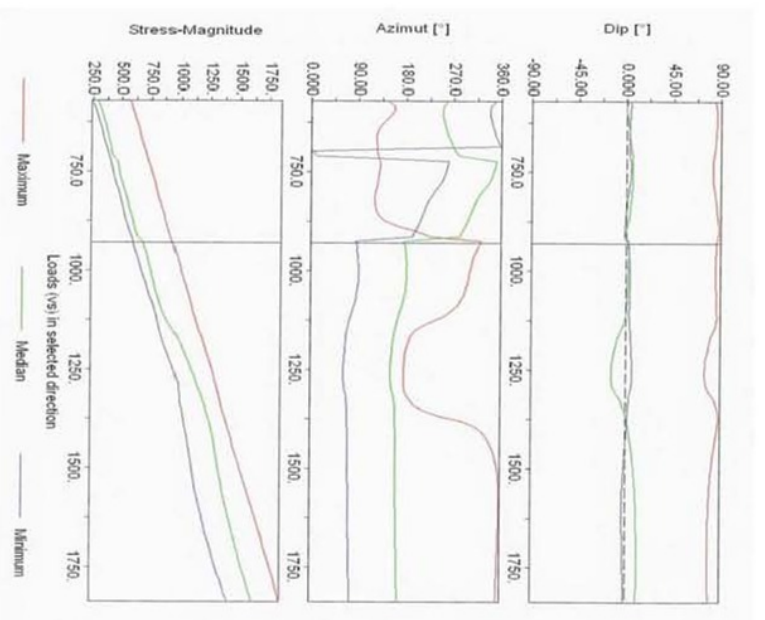
With the opening or the closure of fractures there are generally changes in the propagation characteristics of elastic waves. In most cases, this is clearest for shear waves, which change their polarization, and therefore their splitting, as a result of the structural alteration. This leads to changes in the eigen-values and eigen-vectors of the specific tensors. These changes are used to identify the point of appearance or disappearance of the seismic anisotropies resulting from the coring.
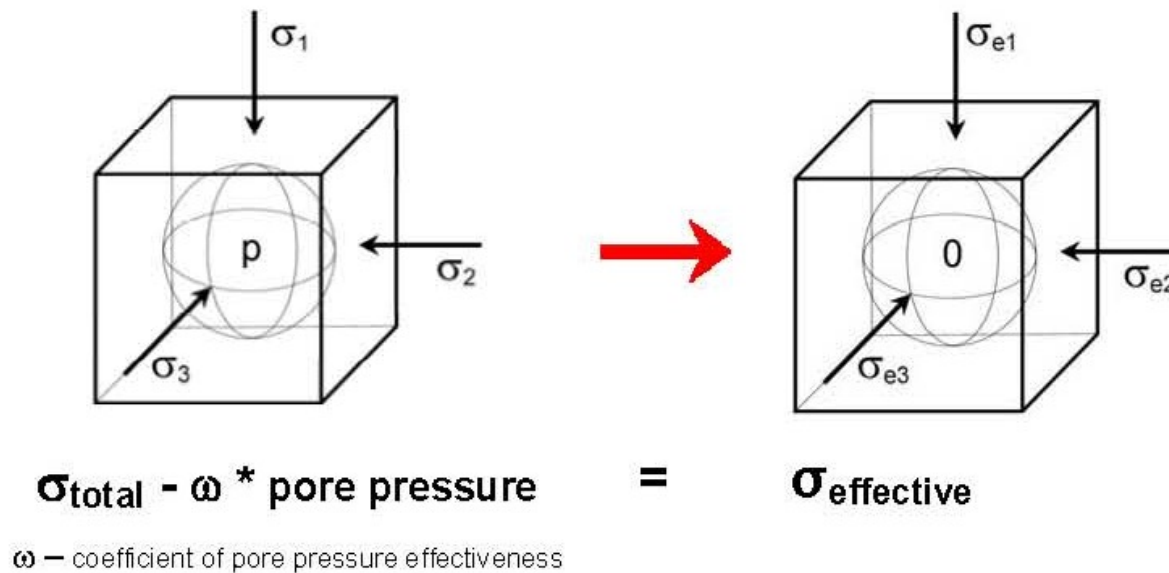
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IN SITU STRESS STATE: *EFFECTIVE STRESS / TOTAL STRESS*

$$\sigma_{total} - \omega * \text{pore pressure} = \sigma_{effective}$$

ω — coefficient of pore pressure effectiveness

Deformation and strength of porous rocks both depend on the combined effect of all the loadings (total in situ loading and pore pressure) and this is generally expressed as the effective loading. The total stresses, as required for frac planning, can be obtained directly from the effective stresses determined with RACOS® and the corresponding coefficient of pore pressure effectiveness.

IN SITU STRESS STATE: *PALEO-STRESS COMPONENTS*
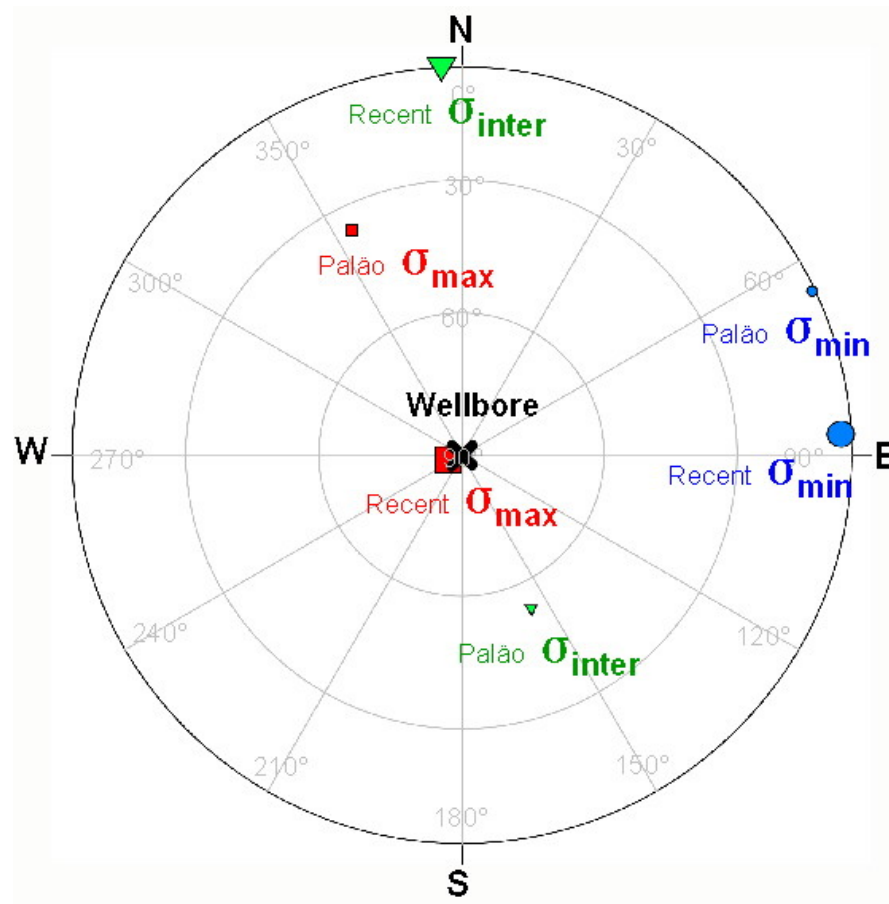
The core sample may have anisotropies (not resulting from the fabric and/or coring and sample preparation) in addition to those resulting from the release from the recent stress field. These may result from earlier loadings or changes in the in situ stresses and can be referred to paleo-stress conditions. In the SCHMIDT plot are shown the geographical orientations of a recent and a paleo stress state.

IN SITU STRESS STATE: *TECTONIC STRESS COMPONENTS*

$$[\sigma_{tectonic}] = [\sigma_{effective}] - [\sigma_{deformation}]$$

The effective in situ loadings result from the deformation and lateral constraint conditions during geological changes in the overburden thickness, from pore pressure effects and possibly from tectonic influences. When there are multiple samples, the constancy of the direction of tectonic action can be used in extended evaluations of the in situ loadings.

IN SITU STRESS STATE: *STRESS COMPONENTS*

Effective stress / total stress

$$\sigma_{total} - \omega * pore\ pressure = \sigma_{effective}$$

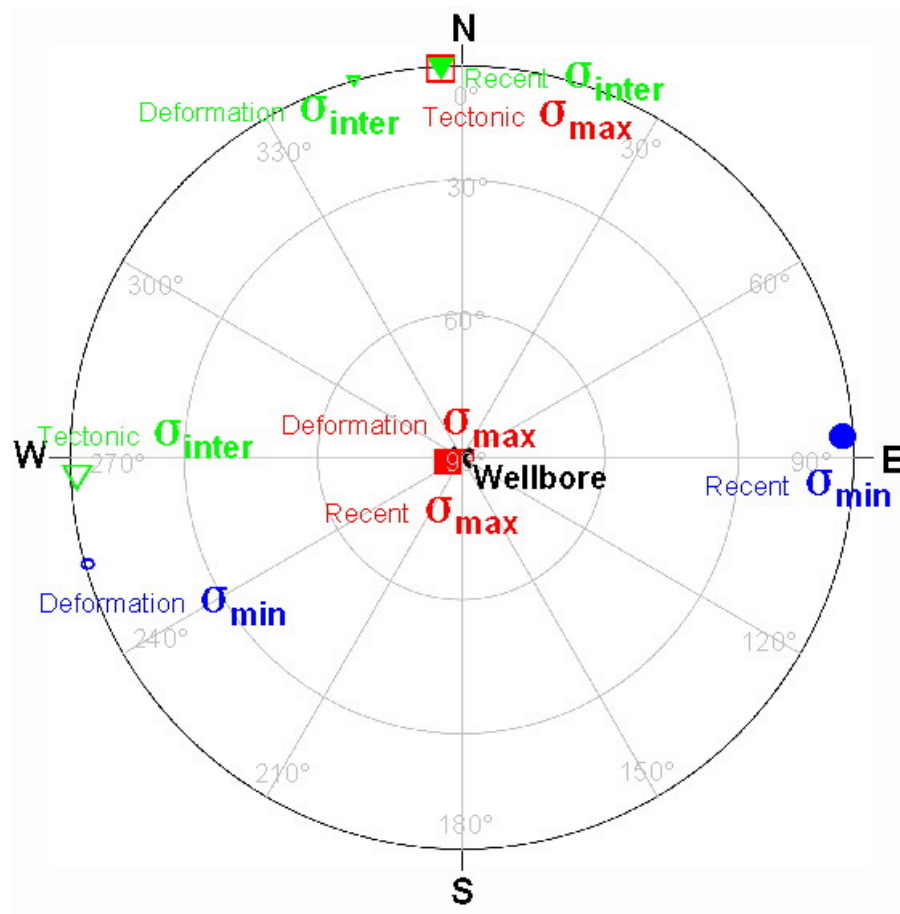ω – coefficient of pore pressure effectiveness

Deformation and strength of porous rocks both depend on the combined effect of all the loadings (total in situ loading and pore pressure) and this is generally expressed as the effective loading. The total stresses, as required for frac planning, can be obtained directly from the effective stresses determined with RACOS[®] and the corresponding coefficient of pore pressure effectiveness.

Paleo-stress components

The core sample may have anisotropies (not resulting from the fabric and/or coring and sample preparation) in addition to those resulting from the release from the recent stress field. These may result from earlier loadings or changes in the in situ stresses and can be referred to paleo-stress conditions. In the SCHMIDT plot are shown the geographical orientations of a recent and a paleo stress state.

Tectonic stress components
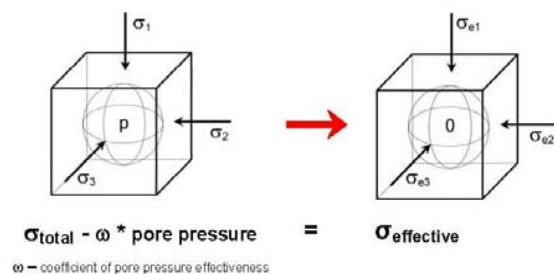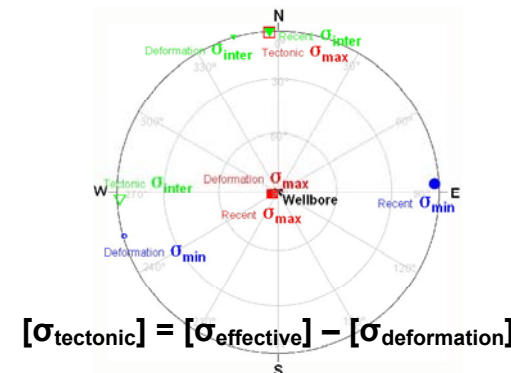

$$[\sigma_{tectonic}] = [\sigma_{effective}] - [\sigma_{deformation}]$$

The effective in situ loadings result from the deformation and lateral constraint conditions during geological changes in the overburden thickness, from pore pressure effects and possibly from tectonic influences. When there are multiple samples, the constancy of the direction of tectonic action can be used in extended evaluations of the in situ loadings.
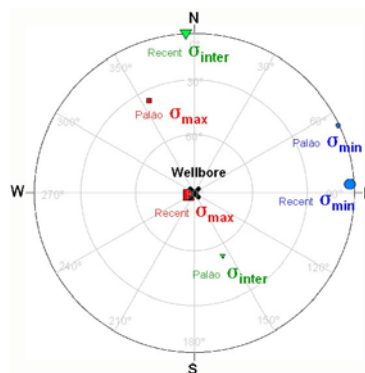

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Rock mass analyses using RACOS®
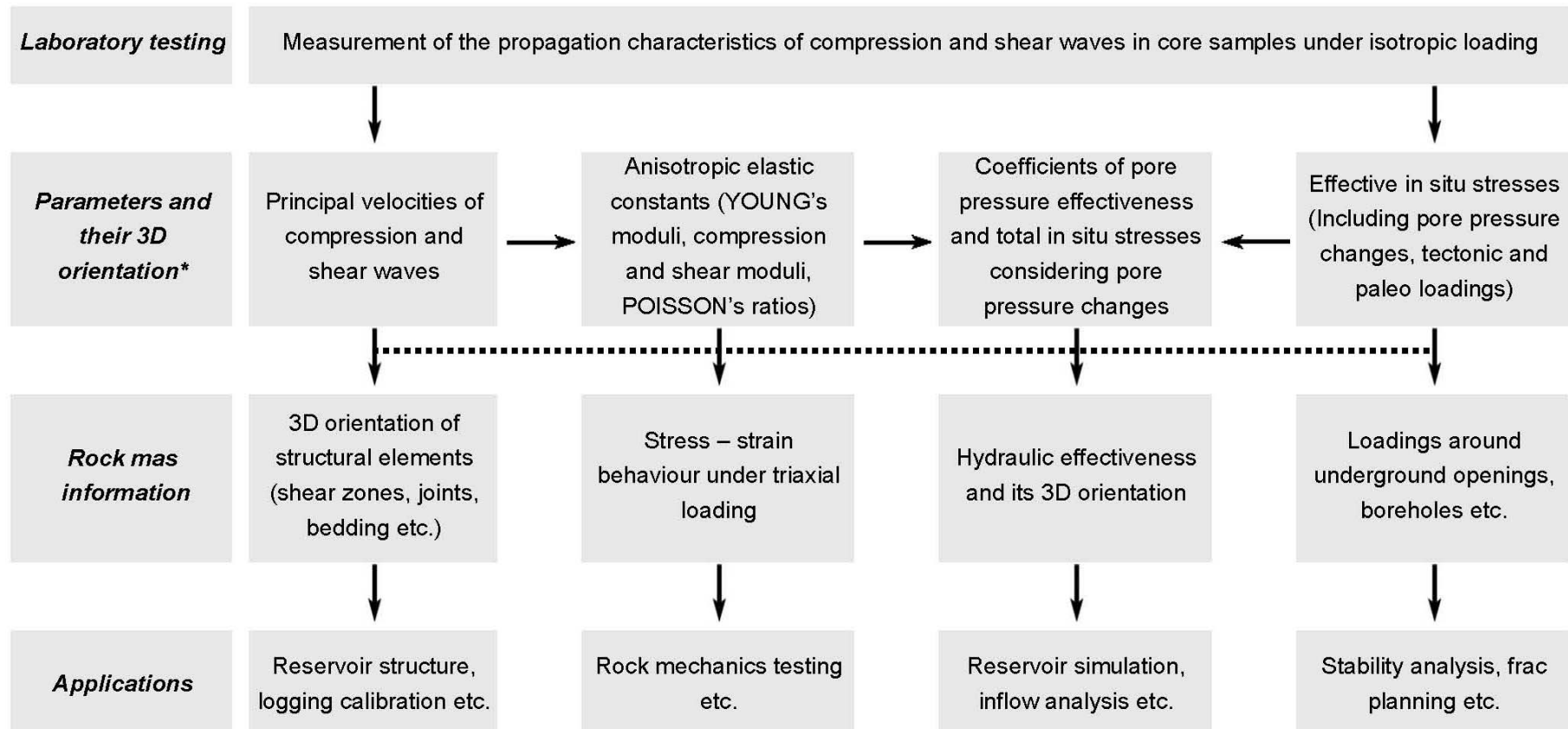
Laboratory testing	Measurement of the propagation characteristics of compression and shear waves in core samples under isotropic loading			
Parameters and their 3D orientation*	Principal velocities of compression and shear waves	Anisotropic elastic constants (YOUNG's moduli, compression and shear moduli, POISSON's ratios)	Coefficients of pore pressure effectiveness and total in situ stresses considering pore pressure changes	Effective in situ stresses (Including pore pressure changes, tectonic and paleo loadings)
Rock mas information	3D orientation of structural elements (shear zones, joints, bedding etc.)	Stress – strain behaviour under triaxial loading	Hydraulic effectiveness and its 3D orientation	Loadings around underground openings, boreholes etc.
Applications	Reservoir structure, logging calibration etc.	Rock mechanics testing etc.	Reservoir simulation, inflow analysis etc.	Stability analysis, frac planning etc.

* The analyses are not just for single directions, but provide complete 3D information.

Summary:

- **The comprehensive new analysis system, which has been presented, enables in situ stresses and rock mass properties to be determined. The analysis system, called RACOS®, is based on measuring the 3D propagation behaviour of shear and compression waves in samples from rock core.**

- **The complete 3D magnitudes and orientations of in situ stress components are derived from these measurements using special analytical and numerical techniques.**

- **The in situ properties, which can be determined in 3D with RACOS® analyses include the stress-strain parameters, elastic constants and the effectiveness of pore pressure.**

- **From a complete analysis for a location, assessments can also be made of the in situ structures and preferred flow directions, of critical loading orientations, and of the existing loading-dependent 3D rock behaviour**

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