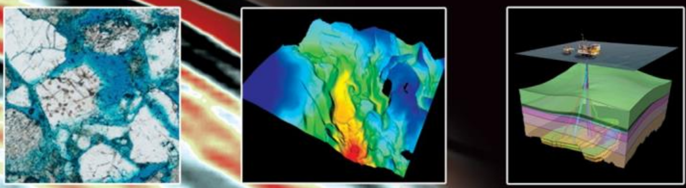

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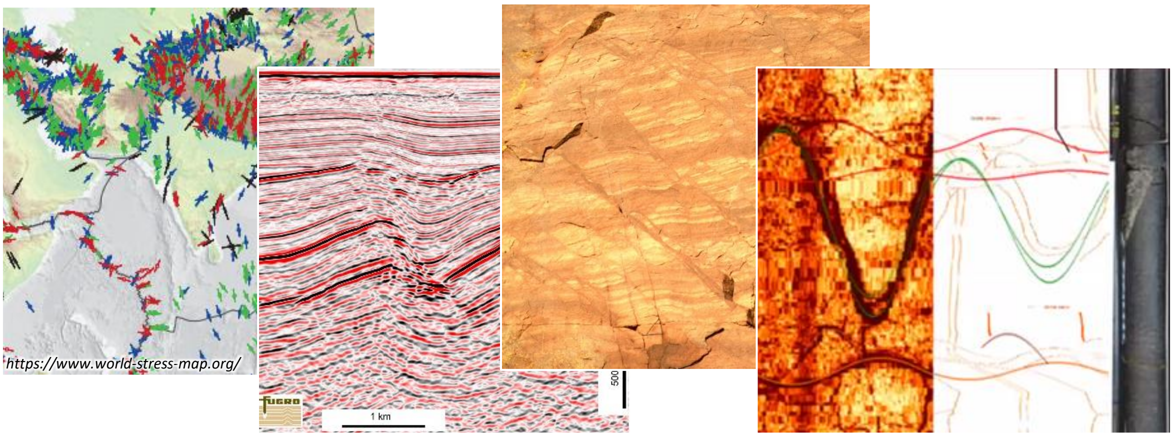
Abstract Book

Tectonic Stress: from the lithosphere to the wellbore

21-22 May 2024

The Geological Society, Burlington House, Piccadilly London



Understanding Tectonic stress, and associated strain, is of fundamental importance to many areas of the energy sector. Integrating tectonics and associated stresses is of key importance at all scales of and across all aspects of the value chain from early exploration, through development and production, as well as long term subsurface containment. From optimized reservoir management for fluid recovery, CCUS and waste disposal; geothermal reservoir performance; wellbore stability during drilling; or geoengineering for mining and surface hazard assessments; each require an understanding of the tectonic stresses and their implications for the viability and integrity (both near and long-term) of the project. From an academic perspective, tectonic stresses are a central component of understanding plate tectonics, basin geodynamics, and earthquake dynamics, linking plate diving forces with the resulting strain in the crust/ lithosphere.

This two-day event will bring together industry and academic groups to present and discuss the latest understanding of Tectonic Stress and how it applies to the energy sector. The organisers welcomes papers on the following themes: Plate tectonic driving forces; lithospheric stress and deformation; Measuring, monitoring and modelling stress; Reservoir geomechanics and fluid flow (inc. geothermal); Pore pressure, Operations and Wellbore stability; Seismicity (tectonic & induced) and earthquake hazards; Subsurface storage and the energy transition.

The meeting will also be followed by an optional 1.5-day field excursion to the South coast of England to look at the effects of far field stress in the Wessex Basin.

Convenors:

Woody Wilson
bp

Mark Ireland
Newcastle University

David McNamara
University of Liverpool

Myra Keep
UWA

Steve Dee
bp

Keynote Speakers include:

Oliver Heidbach
GFZ Potsdam

For further information please contact:

The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Email: energygroup@geolsoc.org.uk

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#EGStress24

Tectonic Stress: from the lithosphere to the wellbore

21-22 May 2024

In person at Burlington House and Virtual via Zoom

Provisional Programme

Day One	
08.30	**Registration**
09.10	**Welcome**
	Session One: Tectonic forces, Lithospheric Stress/Strain
09.20	**How strong is the upper continental crust?** James A Chalmers
09.40	**The constant-strength model of overpressured crust: Present-day strength-depth observations to 14km in the western Taiwan plate-boundary zone** John Suppe
10.00	**The Physics of Stress** Gary D Couples
10.20	**BREAK**
	Session Two: Measuring/ monitoring/ modelling Stress I
10.50	**KEYNOTE** **Recent Findings and Future of the World Stress Map Project** Oliver Heidbach
11.30	**Probabilistic stress reconstruction constrained by the orientation of fractures** Rivalta, E
11.50	**Tectonic stress evolution on the western margin of Central Africa between the Congo Basin and the Atlantic coast from fault-slip data analysis and paleostress reconstruction** Delvaux Damien
12.10	**Effect of time-dependent damage deformation on fault zone stress magnitude: field and experimental evidence** Mayukh Talukdar
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14.40	**Stress measurements for calibrating geomechanical models – Examples from the site selection process for a nuclear waste repository in northern Switzerland** Jean Desroches

15:00	**Calibration of geomechanical models – Examples from the site selection process for a nuclear waste repository in northern Switzerland** Karsten Reiter
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17.30-18.30	**Drinks Reception**

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08.30	**Registration**
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11.50	**Deciphering the modern stress field facies in Costa Rica and vicinity from earthquake focal mechanisms and GNSS support** Allan López
12.10	**Landslides, earthquakes and far field stress on a passive margin: Australia's North West Shelf** Myra Keep
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14.30	**KEYNOTE** **Mud Volcanoes: What They Tell Us About Stress and Pore Pressure** Mark Tingay
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15.20	**End of Conference**

Posters
Prediction of the recent crustal stress state of Germany – The SpannEnD Project Steffen Ahlers
Plio-Quaternary interaction between Adria and surrounding orogens: a Central-Northern Apennines perspective Paolo Pace
The Morphology of Induced Tensile Fractures in Boreholes: Lessons learnt from Scientific Drilling Mario Habermueller
The impact of tectonics on the geothermal resources distribution in the eastern Po Plain, northern Italy Dimitra Rapti
Slip-dilation tendencies and CFS within an oil-gas prospective basin in Costa Rica Allan López
New seismologic inversion method for absolute crustal stress and deep pore-fluid pressure Yi-Rong Yang

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ORAL ABSTRACTS
(In Programme Order)

Session One: Tectonic forces, Lithospheric Stress/Strain

How strong is the upper continental crust?

James A Chalmers

Geoligical Survey of Denmark and Greenland (GEUS), geusjac@yahoo.co.uk

A number of authors have suggested that the whole or upper crust has been folded. The folds formed are on the scale of hundreds of kilometres horizontally and hundreds of metres to a few kilometres vertically. Such folds may have formed in western Europe in the early Miocene.(Cloetingh & Burov, 2010). Similar folds in Scandinavia may have started at 22±1 Ma (Green et al., 2023). Cloetingh & Burov (2010) listed many other examples of folded continental crust with spatial wavelengths of a few hundred kilometres.

If these structures are folds, they must have formed as strong crustal layers separated by weak layers. The strong layers will start to buckle sinusoidally if the horizontal compressive stress on them approaches their maximum yield strength. Calculations of the buckle wavelengths for crustal-scale folds show that they would be in the range 200-300 km if the fold was formed from a 20 km thick upper crust alone. If 40 km thick whole crust were involved, the wavelength would be 350-500 km. These figures are comparable to those observed by Cloetingh & Burov (2010).

Horizontal compressive stresses within Europe in the early Miocene arose from three different sources

- The collision of the Adria (Italy/south Austria) continent with the European continent at 35 Ma initiated northward-verging overthrusting in the Alps (Pfiffner, 2014). The static presence of the mountains and their root could generate a horizontal compressive stress of around 100 Mpa.
- The Iceland plume became active at 23 Ma after a period of dormancy after 35 Ma. The static presence of Iceland generates a horizontal compressive stress of around 100 Mpa (Bott, 1991).
- As Iceland plume material moved outwards at the base of the lithosphere, it formed the V-shaped ridges to the SW of Iceland. If we assume that the outflow was symmetrical, then pressure from the outflow towards Europe would have generated poiseuille flow in the asthenophere. The poiseuille flow would have generated horizontal stress on the European lithosphere by drag on its base. It is difficult to quantify coupling between the poiseuille flow and the lithosphere, so it is difficult to estimate the combined amounts of compression from Iceland. It is unlikely, however, to have been of the order of 1 GPa or more.

The addition of the stresses from Iceland at 23 Ma to those existing from the Alps since 35 Ma would have put the European crust within a vice. Whether that is enough to initiate folding depends on the strength of the crust.

The horizontal stresses calculated above are insufficient to fold the European crust if the commonly-published calculated Yield-Strength Envelopes (YSEs) are accurate. There is general disagreement about the strength of the lower crust; the so-called jelly sandwich versus crême-brulée models; see Jackson (2002) and Burov (2006). There appears, however, to be general agreement that the maximum differential strengths of upper continental crust under compression are in the range 900 to 1500 MPa (e.g. Burov *in* Schubert & Watts, 2009). This strength is far greater than the combined horizontal compression available from the sources discussed in the previous two papragraphs.

The calculations of YSEs, however, make a number of assumptions about the conditions in the upper crust. Brace & Kolstedt (1980), however, noted that the level of pore pressure has great influence on crustal stress levels. I cite "For example, the stress drops from its maximum possible value when the rocks are dry ... to zero when the pore pressure is equal to the lithostatic pressure ..., that is, when the total stress is hydrostatic and equal to the vertical stress. What is known about pore pressure level at depth? Unfortunately, almost nothing, so that this parameter is almost totally unconstrained at this time."

There are few direct tests of stress in the upper continental crust. One of the few is the measurement of differential stress (σ_1-σ_3) in the KTB main borehole in southern Germany (Zoback & Harjes, 1997). They measured (σ_1-σ_3) increasing to 190 MPa at a depth of 7.7 km.The maximum differential stress was extrapolated by Zoback & Harjes (1997) to be 250 MPa at a depth of around 11 km, much less that the calculated maximum differential stress shown by e.g. Burov (2011) (see figure). The differential stresses found in the KTB main borehole are, however, comparable to those combined compressive stresses that Europe may be subject to from the Alps and Iceland.

It seems possible, therefore, that the commonly calculated YSEs for the upper crust may show its strength to be too high and that maximum strength of the upper continental crust may be in the range of 200-300 MPa. Folding of the whole crust can occur if this is the case.

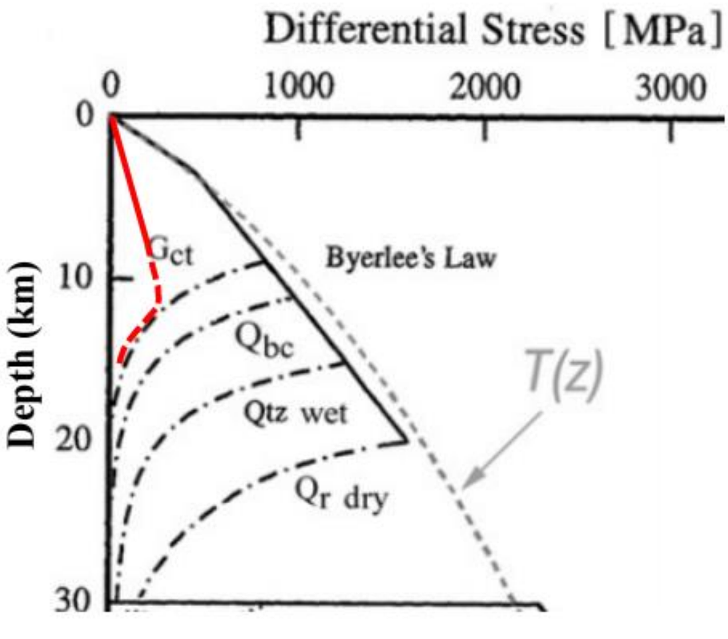

Figure: Comparison of calculated YSE in the upper crust (Burov (2011) (black and white) with measured failure stresses in KTB borehole; southern Germany (red lines) (from Zoback & Harjes, 1997).

Solid red line: actual measurements
Dashed red line: extrapolation.

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The constant-strength model of overpressured crust: Present-day strength-depth observations to 14km in the western Taiwan plate-boundary zone

Yi-Rong Yang[1], **John Suppe[2*]** Kaj M. Johnson[3], Tai-Tien Wang[1], En-Chao Yeh[4], Fu-Shu Jeng[1]
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Crustal-strength and its depth dependence and heterogeneity play key roles in the mechanics of the lithosphere. The classic view is a strong pressure-dependent brittle upper crust, overlying a weak temperature-dependent ductile lower crust. However, this view assumes hydrostatic pore-fluid pressure, which does not hold in weak overpressured tectonic environments, as is best documented from borehole and seismic-velocity measurements in sedimentary basins. The extent and nature of fluid-pressure weakening outside of sedimentary basins remains poorly known and controversial given the lack of deeper direct measurement of strength and fluid pressure within deforming regions. Here we present new observations that strength is low and nearly constant down through the brittle-ductile transition in the active Taiwan arc-continent collision, in agreement with overpressure predictions. We determine a high-resolution 1D strength-depth profile in western Taiwan using seismologic stress-inversion methodologies based on perturbations of the stress field by the M7.6 Chi-Chi earthquake. This 1D profile to 14 km depth in metasedimentary basement agrees with borehole fluid pressure measurements in the overlying western Taiwan basin to its base at ~5.5 km depth and shows a reduction of integrated crustal strength by a factor of 4–5 relative to hydrostatic predictions. We deduce that overpressured fluids focus plate-boundary deformation into the upper crust, weakening plate-boundary crust, and transferring loads to the mantle lithosphere.

The Physics of Stress

Gary D Couples: Institute of GeoEnergy Engineering, Heriot-Watt University, Edinburgh, Scotland g.couples@hw.ac.uk

The concept of stress is intimately linked to the abstract idea of the continuum. A continuum is imagined to be an ideal material within which all physical responses are independent of size. That idealisation is reasonably good for some materials, such as many metals, and the mechanical framework developed for continuum mechanics has served very well in a wide range of practical applications – for suitable materials. But material understanding, of the physical interactions and responses in porous media, such as with geomaterials, has been held back by over-reliance on the assumption that continuum principles can be assumed to apply.

Geoscientists have long appreciated that rocks and soils are composites – such as the assemblage of transported grains, partially stuck together by added mineral cements, that characterise many sedimentary rocks. Over the last two decades, advances in imaging technology have provided 3D images of the realistic micro-textures of such rocks. New approaches enable the extraction of micro-scale models of the arrangements of the pore space, and models of the connected skeleton of the rock. Process simulations of fluid movement, operating on the micro-scale model domain of the pore system, enable the derivation of a macro-scale 'property', such as the multi-phase fluid permeability. These *ab initio* approaches are now being extended to the topic of thermo-hydro-mechanical process interactions (10.1007/s40948-022-00484-1). These methods provide insight into the complex ways that the micro-scale, multi-connected continuum, i.e. the rock skeleton, interacts with fluid pressure, and with the thermal state.

Perhaps the most important point arising from this approach is the realisation that the micro-scale stress states that exist within the rock skeleton are not uniform. They differ: states in the connecting elements in the solid skeleton network (the 'rods'), are not the same as the states within the larger solid elements (the 'junctions'). The micro-scale arrangements of rods, junctions, and fluid-filled pore space, mean that the exposed faces of the rods are directly loaded by the fluid pressure, and the local stress components inside the rods are different to the stress components in the junctions. Thus, the external manifestation of the potential mechanical energy stored within the skeleton – which can be called the bulk stress state – has no simple relationship with the complexity of the micro-scale states. Importantly, the macro-scale responses of a porous rock do not provide a means to identify the micro-scale reality. It is incorrect to assume that the micro-scale is the same as the macro-scale. In terms of the physical state in a porous rock, the use of the continuum idea is wrong, and often harmful.

Models of a porous rock, where the pore space and solid skeleton are explicitly captured, reveal complex interactions between macro-scale thermo-hydro-mechanical (THM) changes. Coefficients of interaction terms, such as between pressure and stress, are dependent on the full set of situation constraints. The state dependencies of the coefficients differ from those that might be asserted from continuum thinking, or from the types of lab experiments that are routinely employed. Moreover, the interactions reveal energy transformations, between THM state changes, that cannot be back-inferred from the continuum perspective. This complexity is readily understood when the micro-scale model is used to examine the question of the conditions needed for a crack to open or close. This analysis (URL above) reveals a significant energy-budget discrepancy during the response from one macro-scale state to another, if only the before-after state parameter changes are considered.

Thus, a full energy formulation is needed for THM changes. One significant outcome of that approach is the realisation that the usual formula for vertical stress (rho x density x thickness) is phenomenologically incorrect. This expression defines the gravitational specific (volume-linked) energy at a subsurface point. The actual macro-scale vertical stress at some depth does in fact depend on the material properties, and the resulting distribution of vertical stresses in a layered rock system do not exhibit a monotonic increase with depth. The physics of stress has long been misunderstood as a consequence of over-reliance on continuum principles being simplistically applied to rock materials, and by the false conclusion that the potential energy formula defines vertical stress.

Session Two: Measuring/ monitoring/ modelling Stress I

KEYNOTE - Oliver Heidbach

Recent Findings and Future of the World Stress Map Project

Oliver Heidbach[1,2] Mojtaba Rajabi[3], Moritz Ziegler[1,4], Karsten Reiter[5], and the WSM Team

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The need to describe the crustal stress field has been recognized from a wide range of geodisciplines. Furthermore, to meet the climate goals the resulting energy transition and the associated phase-out of fossil forms of energy will result in an intensified usage of the subsurface and modified utilisation concepts will place new demands on the integrity and long-term stability of subsurface operations. Thus, crustal stress data and geomechanical models for continuous predictions of the stress field in larger volumes will become more important.

Stress data were already raised in the 30s of the 20th century using surface relief methods, followed by flat jack and borehole relief methods in the 50s, and hydraulic fracturing to measure the least principal stress in the 70s. Another source of stress information was established with the interpretation of borehole breakouts as stress indicator in the late 70s. Furthermore, with the expansion of global seismological networks in the 60s to detect nuclear weapons tests globally and the advent of the Global Digital Seismograph Network in the 70s the number of earthquake focal mechanism solutions has increased since. These developments and the wide range of stress indicator from engineering, geological and geophysical methods resulted 1986 in the initiation of the World Stress Map (WSM) project. The key project scientists Mary-Lou and Mark Zoback developed the backbone of the WSM, which is the quality ranking scheme. It allows comparability of the various stress indicator that sample the rock stress on very different scales. One of the objectives of the WSM project was to investigate if plate tectonics is the key control of the orientation of maximum horizontal stress S_{Hmax} in the Earth crust. This was confirmed with the first release of the WSM database in 1989. The approximately 3600 quality-ranked data records showed indeed that there is a positive correlation of absolute plate motion and the first-order pattern of the S_{Hmax} orientation [*Zoback et al.*, 1989].

Since than the number of WSM data records has increased steadily and the upcoming WSM database will provide over 70,000 data records. In particular data from thousands of newly analysed boreholes in the past years revealed that there are significant rotations of the S_{Hmax} orientation confirming the earlier hypothesis that 2nd order effects resulting from lateral rock stiffness and density contrasts can result in horizontal stress rotations [Heidbach et al., 2007]. The figure with the WSM also shows a zoom into an intraplate setting in NW Australia where a S_{Hmax} rotation of >60° on spatial scales <100 km is observed. Other areas, however, show a tremendously stable S_{Hmax} orientation even though the structural setting seems to be similar to the areas where large rotations occur. These observed stress rotations are important constraints for large-scale 3-D geomechanical models [*Rajabi et al.*, 2017].

We also see stress rotations on a meter scale within a borehole when a fault is crossed (see Fig. 1). Faults have also been postulated to change the S_{Hmax} orientation laterally, but so far even with high density datasets that cover areas with faults we cannot identify rotations on kilometre scales that are caused by faults. Fault-induced rotations seem to be localized in the fault core and its surrounding damage zone with a width of 10s or a few 100s of meters. This is confirmed with recent comprehensive studies using generic 3-D geomechanical models [*Reiter et al.*, in press] and 3-D models of potential siting areas for a deep geological repository for high-level radioactive waste in Switzerland. The latter fit very well a unique dataset of high-quality horizontal stress magnitude data derived from Micro-Hydraulic Fracture and Sleeve Re-Opening tests [Desroches et al., 2024], but clearly shows that the effect of faults is localized and small in comparison to other stress changes that result from variability of rock stiffness.

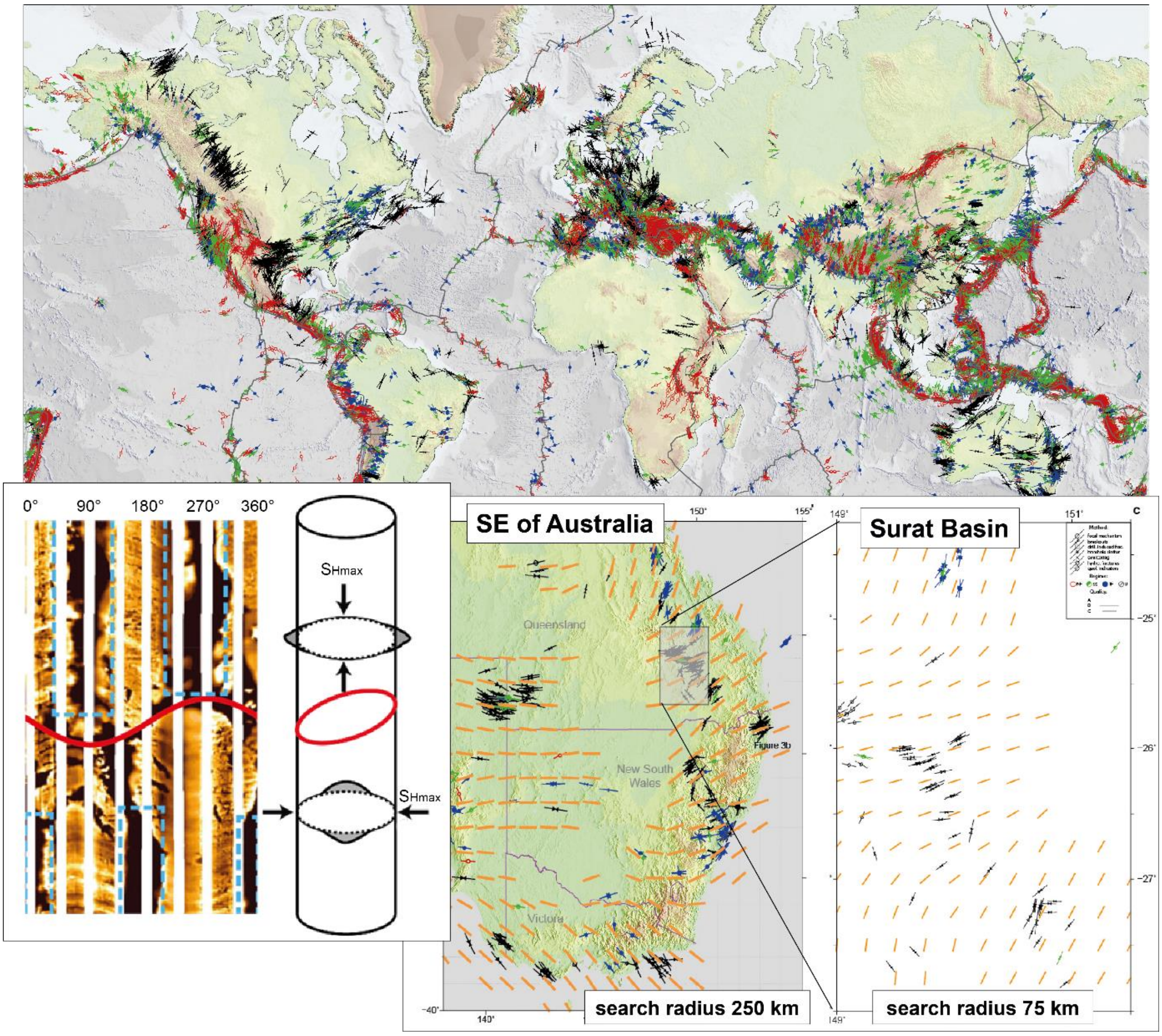

Figure 1. World Stress Map with A-C quality data records. Lines indicate orientation of maximum horizontal stress S_{Hmax}, symbols specify the type of stress indicators and colours mark the stress regime with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). Stress map of SW Australia shows a stress rotation of >60° on spatial scales <100 km, orange lines show mean S_{Hmax} orientation on a regular grid. Image log shows a S_{Hmax} rotation on a meter scale due to a fault derived from borehole breakout zone (blue boxes).

Quo Vadis WSM? Even though, the WSM database is growing, stress data will always be sparse, unevenly distributed, and incomplete as most methods do not provide data of all components of the 3-D stress tensor. So far, the WSM compiles systematically only quality-ranked data records of the S_{Hmax} orientation. However, for the calibration of geomechanical models, stress magnitude data are essential. Therefore, the WSM will expand towards stress magnitude data using the German stress magnitude database that is based on a dedicated quality ranking scheme as a blueprint [*Morawietz et al.*, 2020]. Furthermore, the WSM will provide a long-term repository for the complementary World Pressure Map project which aims at a global compilation of pore pressure data using new quality ranking scheme as well. These developments are currently accompanied with a new WSM website, and a new database infrastructure based on postgreSQL, with a user web-interface. Even though the demand of 3-D geomechanical models will certainly increase, the backbone of these are quality-ranking stress data in an open access database.

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Probabilistic stress reconstruction constrained by the orientation of fractures

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The elastic stress field in geothermal environments is often heterogeneous in both space and time due to several dynamic processes occurring at different spatial and time scales contributing to the build up and relaxation of stresses. While the regional stress field is typically spatially uniform and changes slowly over time, other factors such as the movement of hydrothermal fluids, injection of magma or faulting induce localized stress changes in the surrounding rocks. Moreover, surface loading and unloading may be cause of large stress changes, especially in volcanic areas where large volcanic edifices may be created or destroyed in relatively short periods of time (e.g. Clair et al., 2015).

These distinct contributions may be estimated through modelling but it is challenging to assess their relative weight when evaluating the overall stress field. Here we propose a procedure to infer in a probabilistic manner the stress field in a geothermal or volcanic area. The procedure works by firstly evaluating the different individual contributions via numerical modelling, and then optimizing their relative weights so that the orientation of tensile and shear fractures match with the overall stress field. We tested a two-dimensional version of this approach in the area of Campi Flegrei caldera, Italy, using as constraints the location of the eruptive vents (Rivalta et al., 2019) and, more recently, developed a numerical framework to bring the method to three-dimensions (Davis et al., 2019, 2020, 2021, Mantiloni et al., 2021, 2023). We also tested the forecasting power of our procedure on analogue laboratory experiments and synthetic scenarios.

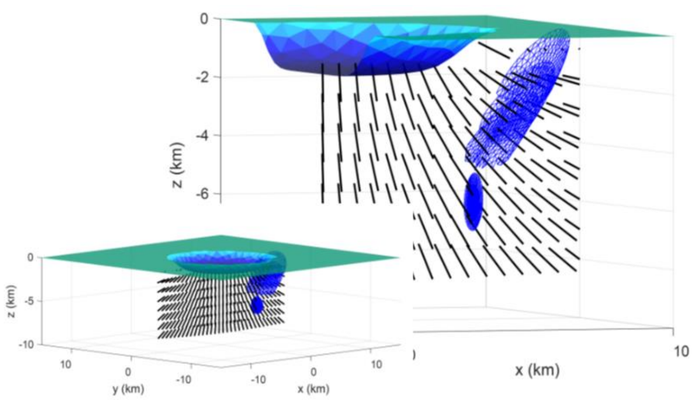

Figure 1: Example of stress model and hydrofracture propagation. The negative topography at the top represents a caldera or a cauldron-shaped basin. The Black segments are directions of the least compressive stress axis. The meshed surfaces represent different stages of propagation of a magma-filled dyke or hydrofracture.

Tectonic stress evolution on the western margin of Central Africa between the Congo Basin and the Atlantic coast from fault-slip data analysis and paleostress reconstruction.

Delvaux Damien1, Boudzoumou Florent2, Miyouma Timothée2, Nkodia Hardy2

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The evolution of tectonic stress on the western margin of Central Africa during Mesozoic and Cenozoic has been investigated from fault-slip data analysis and paleostress reconstruction in the rapids of the Congo River at the outlet of the Pool Malebo between Kinshasa (Democratic Republic of the Congo) and Brazzaville (Republic of the Congo). We measured 1146 brittle fractures in the Inkisi arkosic sandstones of early Paleozoic age. They were inverted for tectonic stress and assessed to four successive paleostress stages. The obtained tectonic stress states are interpreted in function of the possible sources of stress originating from the Gondwana plate boundary and from the African plate boundary after its separation from South America. The first paleostress stage is related to the Gondwanide subduction orogeny at the southern margin of Gondwana in late Permian-early Triassic. The second and third paleostress stages are attributed respectively to late Santonian (83-85 Ma) and late Maastrichtian (70-66 Ma) basin inversion events. Those are already recorded in Northern Africa and related to differential opening of the Central and South Atlantic and to the convergence between Africa-Arabia and Eurasia along the Tethyan plate margins. The last paleostress stress stage is related to the late Aptian to recent mid-Atlantic ridge-push forces. It is still active as indicated by the stress inversion of regional earthquake focal mechanisms.

Effect of time-dependent damage deformation on fault zone stress magnitude: field and experimental evidence

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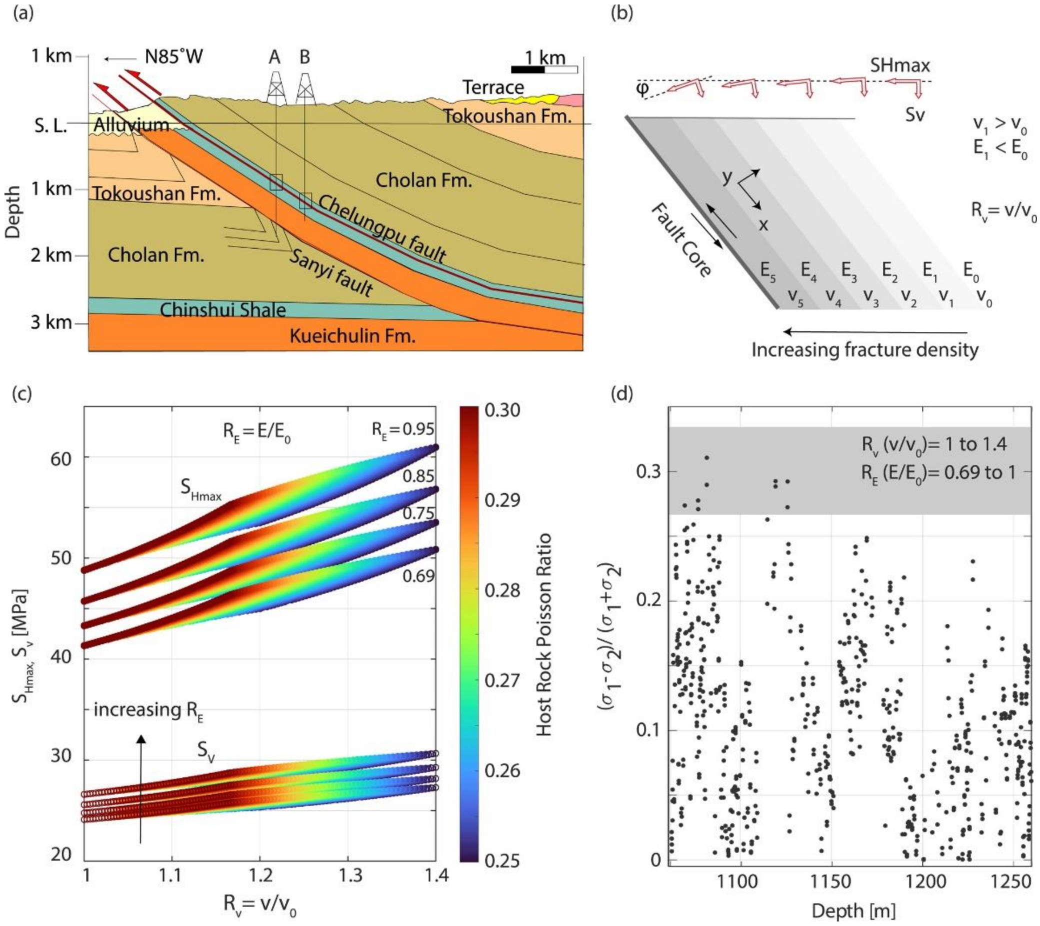
Forces in the Earth's crust define the stresses acting on faults that drive earthquakes. Tracking how stress accumulates due to plate motion and is released due to fault slip has been a central topic in the study of earthquake mechanics and associated seismic hazards. Previous analyses of data collected from the Taiwan Chelungpu-fault Drilling Project (TCDP), following the 1999 Chi-Chi earthquake, resulted in inconsistent estimates of post-earthquake stress. This study included reviews of previous measurements, laboratory experiments, and analyses of borehole data to reconsider the stress state after the Chi-Chi earthquake. We show that the stress state varied along the TCDP borehole due to lithologic and fault-related changes in mechanical properties, which explains why past studies indicated significant variability. We also estimated pre-earthquake stress by calculating the stress change caused by the Chi-Chi earthquake and subtracting it from the post-earthquake stress. Our pre-earthquake stress estimate suggests that the stress before the Chi-Chi earthquake was low in magnitude compared to the frictional strength of shallow crustal rocks (Talukdar et al., 2022). Comparing the estimated pre- and post-earthquake stress magnitudes of the damage zone and host rock shows that the maximum principal stress is lower and the minimum principal stress is higher at the depth interval between 1050-1250 m, which corresponds to the damage zones of the Chelungpu fault. An elastic plane strain model with fault-parallel layers of varying elastic properties shows that stress rotation due to reduced elastic stiffness cannot explain the low differential stress magnitude in damage zones. Since fault zone material is not significantly weaker than the host rock, this suggests that fault shear stress was relaxed within the damage zone due to time-dependent deformation. Borehole log data also show more time-dependent ductile deformation in damage zones compared to the host rock (Talukdar and Sone, 2024).

To quantify the time-dependent deformation, we experimentally measured the creep deformation of artificially fractured rocks. TCDP core samples were fractured by impacting in a Split Hopkinson Pressure bar at strain rates analogous to those experienced by a natural damage zone during sub-shear to super-shear rupture. Samples were impacted at different strain rates to create a range of damage intensities which would increase towards the principal slip zone. We then subject the samples to constant stress hold stages in a triaxial apparatus to measure the creep deformation of the rocks. With increased damage, the creep deformation increased. This increase in creep with damage is attributed to the higher compaction of fracture volume, as also observed from microstructural observations. Next, we modelled the volumetric strain of the specimens using a Perzyna viscoplasticity law that employs the Modified Cam Clay model as the yield criterion (Haghighat et al. 2020). The model fits the experimental data well, but we observed trade-offs between parameters, which means that the experimental data can be fit equally well using different sets of constitutive parameters. The viscoplastic model shows that highly damaged specimens with greater fracture volume and higher creep deformation have higher elastic and inelastic compliance. Due to the high density of microfractures in highly damaged specimens, the overall resistance to flow of the specimen is low, leading to low apparent viscosity of the material. Conversely, intact samples have high viscosity. Recorded velocity data during these experiments demonstrated that damaged rocks exhibit time-dependent velocity recovery analogous to those observed in the field. Such time dependent mechanical healing of fault damage zone materials after fault reactivation has implications for reservoir productivity, as fracture closure can cause production decline. Studying the long-term ductile properties of damaged rocks is also important to ensure the long-term safety and stability of underground storage caverns in fractured rocks.



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Session Three: Measuring/ monitoring/ modelling Stress II

Quantification of in situ stress onshore UK

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Faults and fractures slip in response to changes in stress or fluid pressure, and these changes can be natural or anthropogenic. Estimating the likelihood of fault slip for a given change in loading is critical for safe geological storage and energy extraction in faulted and fractured rocks, as well as effective communication of risks to policy makers, investors, and the public. Widely used measures of fault and fracture stability include slip (T_s) and dilation (T_d) tendency, and fracture susceptibility (S_f, the change in fluid pressure to push effective stress on a fracture to failure). These measures are simple functions of *in situ* stress, fracture orientation and, for fracture susceptibility, rock properties. These parameters are always uncertain, and critically, they are uncertain to different degrees: for example, while the vertical stress can often be tightly constrained from wireline density log data, the maximum horizontal stress is generally much harder to quantify from any source.

In this presentation, I review the state of knowledge of stress magnitudes and orientations across the UK (onshore) from publicly available data. The uncertainties in the magnitudes of the principal stresses and the orientation of the maximum horizontal stress (S_{Hmax}) remain significant, especially when viewed at the scale of individual prospects or projects. For example, the possible range of orientation of S_{Hmax} has huge consequences for T_s, T_d and S_f on fracture systems targeted for geothermal energy in the Lower Carboniferous Limestone, and on faults in reservoir and caprock formations targeted for carbon dioxide sequestration. Uncertainty in the variation of stress with depth has consequences for deeper geothermal systems too, such as the faulted granites in Cornwall: the in situ stress regime is believed to be strike-slip, and yet the focal mechanism of a recent induced seismic event is more consistent with a normal fault regime.

Our current knowledge of the stress tensor beneath the UK, especially onshore, is not fit for purpose. The combination of a paucity of publicly available data and the uncertainties therein is hindering progress in decarbonization (geothermal energy, CO_2 sequestration), and the energy transition more generally. We need a renewed and sustained collaborative effort to:

- collect more data, in terms of stress magnitudes and orientations at a range of sites, lithologies and depths across the UK;
- develop new tools and methods to enable real-time in situ stress monitoring to assess the possibility of localised stress transients;
- build a publicly available and maintained UK stress model; and
- collate, measure and publish rock mechanical properties for the major formations of interest.

The energy transition and decarbonization are urgent and essential tasks: we will only be successful if we manage to balance public perceptions of risk with the technical challenges inherent to the exploitation of faulted rock. To accomplish both, we need to do a much better job of reducing the uncertainties in the mechanical data.

Use of shear wave splitting to investigate stress field orientation

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For many countries, such as the UK and EU, geological carbon storage is an essential component of plans to reach net zero emissions targets by 2050. In response, there has been a significant increase in assessments of deep geological storage sites, such as depleted oil and gas fields and saline aquifers. In addition to geological carbon storage, disposal of low-level radioactive waste is also being considered in engineered subsurface repositories. Net zero plans also require new energy storage facilities such as salt caverns or depleted gas fields, for storage of compressed air, natural gas and hydrogen.

Robust risk management strategies are implemented across these sectors. Existing methods for modelling containment risk can be transferred to evaluate new subsurface storage sites. However, prospective sites can be located far away from traditional oil and gas exploration areas. This can limit the data available to undertake stress analysis to support projects, despite the existence of open-source information from the World Stress Map.

To address these issues the Stress Histories and Reservoir Properties Project (SHARP Storage) was established. SHARP is a collaboration between 16 research institutions and companies under the Accelerating CCS Technologies (ACT3) Programme. The project aims to understand and reduce the uncertainties related to subsurface CO_2 storage containment risk by characterising in-situ stress and its evolution.

One aspect of this is to examine the role that new datasets can play in stress field characterisation. In the past 10 years, the number of broadband seismic stations deployed in the UK has increased significantly. This increase improves the viability of passive seismic methods, such as shear-wave splitting, to characterise the sub-surface. Shear-wave splitting can be used to measure seismic anisotropy, which can then be used to interpret the orientation of the horizontal stress components affecting the subsurface. We have measured shear-wave splitting for stations across the UK using data acquired between 2018-2022.

Seismic anisotropy has been used to determine stress orientations within boreholes using wireline tools. However, data from surface seismic stations and downhole geophones are not typically combined with borehole stress observations. This limits the value of the data for characterising the stress field at a range of depths.

This presentation focuses on two sites in the UK, in Surrey and Lancashire. We examine shear-wave splitting measurements at both sites and compare S_{Hmax} interpreted from shear-wave fast polarisation direction to nearby borehole data. This ongoing work shows the potential for seismic anisotropy, measured using shear-wave splitting, to aid in subsurface stress field determination.

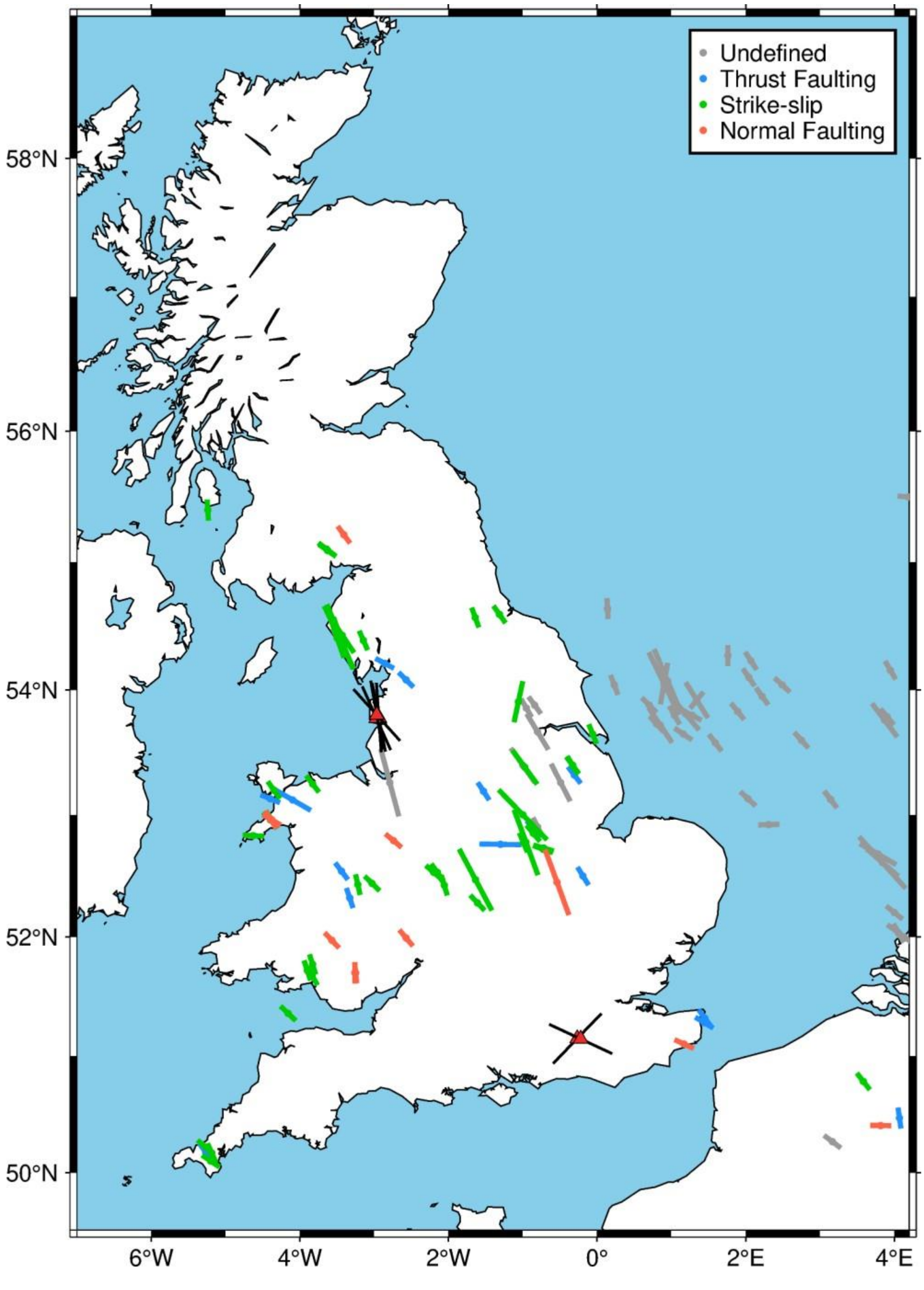

Figure 1. Shear-wave splitting measurements (black bars) averaged at suitable seismic stations (red triangles) in Lancashire and Surrey. Also shown is the publicly available World Stress Map dataset for the UK (Kingdon et al., 2022). For the stress measurements, the interpreted stress regime is indicated by bar colour for strike-slip (green), normal faulting (orange), thrust faulting

(orange) and undefined (grey).

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Three-dimensional numerical modelling of drilling-induced tensile wall fractures

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Drilling-induced tensile fractures (DITFs) form due to stress concentrations around a wellbore (Fig. 1a). In vertical wells the fractures are typically parallel to the largest horizontal far-field stress (σ_H) and normal to the least horizontal far-field stress (σ_h). Discrimination of DITFs from natural fractures or from induced hydraulic fractures can be difficult due to ambiguous geometric signals in borehole image logs. Misinterpretation of such features can cause serious errors in the characterisation of fractured reservoirs or in the calibration of geomechanical models. Hence, understanding the mechanics of DITF formation, the resulting fracture geometry and their continuation into the far-field is of interest for subsurface characterisation. In tectonically active regions, DITFs frequently develop in strike-slip faulting regimes. This can be illustrated by plotting the Hubbert-Willis fracture initiation criterion on a plot of maximum vs. minimum horizontal stress together with the so-called stress polygon that delimits possible stress states in a rock mass that is in a Rankine limit state which satisfies the Coulomb yield criterion, with $K_a = (1 - \sin\phi)/(1 + \sin\phi) = 1/K_p$ being the earth pressure coefficients (familiar from the soil mechanics literature) and $\phi = \text{atan}\mu$ the friction angle (Fig. 1b).

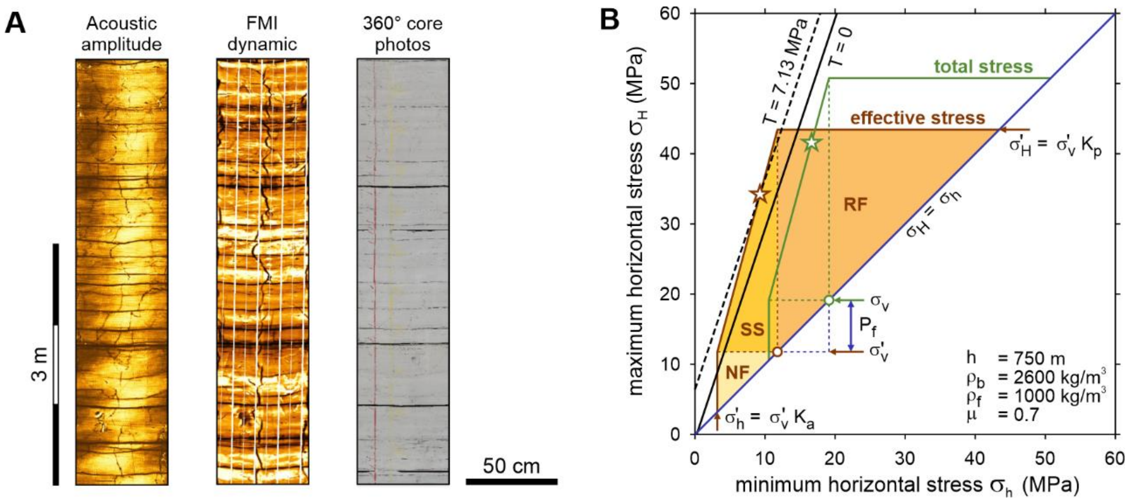

Figure 1. (A) Borehole image logs (BHIs) and core photos from NAGRA's well STA2-1, showing complex geometries of induced tensile fractures at the borehole wall. Note absence of fractures in the core photos. (B) Stress polygon constructed using the parameters given (h = depth; ρ_b = bulk density; ρ_f = pore fluid density; μ = friction coefficient), together with the Hubbert-Willis-criterion ($P_b = 3\sigma_h - \sigma_H + T - P_f$, with P_b = breakdown pressure, T = tensile strength, P_f = pore fluid pressure) using a mud density of 1100 kg/m^3. The three triangular fields cover possible stress states in a normal faulting (NF), strike-slip (SS) and reverse faulting (RF) tectonic stress regime. The stars denote the state of stress considered in the present analysis. The initiation of DITFs is expected when the tensile strength of the wall rock is lower than the critical value indicated (T = 7.13 MPa).

The initiation and propagation of tensile wall fractures is numerically modelled using the Distinct Element Method (DEM) software *PFC3D*, which implements the so-called Rigid Body Spring Network (RBSN) lattice model. Rigid blocks are convex polygons, that interact with each other and can be bonded at their contacts; these bonds fail when the effective normal stress exceeds the bonds' tensile strength, which corresponds to micro-fracture of the rock. Coalescence of these micro-cracks leads to the formation of macroscopic fractures. The model is a hollow cylinder with an inner radius R = 8.1 cm ('standard' 6.375-inch diameter hole) and an outer radius ten times the hole radius (Fig. 2a). The hollow cylinder model has a height equal three times the hole radius and periodic boundary conditions are used normal to borehole axis resulting in plane strain conditions. The propagation of DITFs is modelled by gradually increasing the mud density, and hence the wellbore pressure, from an initial value of 1100 kg/m^3 in increments of $\Delta\rho_m$ = 10 kg/m^3 towards a finite value of 1300 kg/m^3. Model results at three different drilling mud densities are shown in Figure 2c, where each 'micro-crack' is coloured for aperture. It is straightforward to apply this modelling approach to more complex scenarios, for example to situations where the borehole axis is not parallel to one principal stress direction or when mechanical layering is present. Results of such scenarios are presented at the conference.

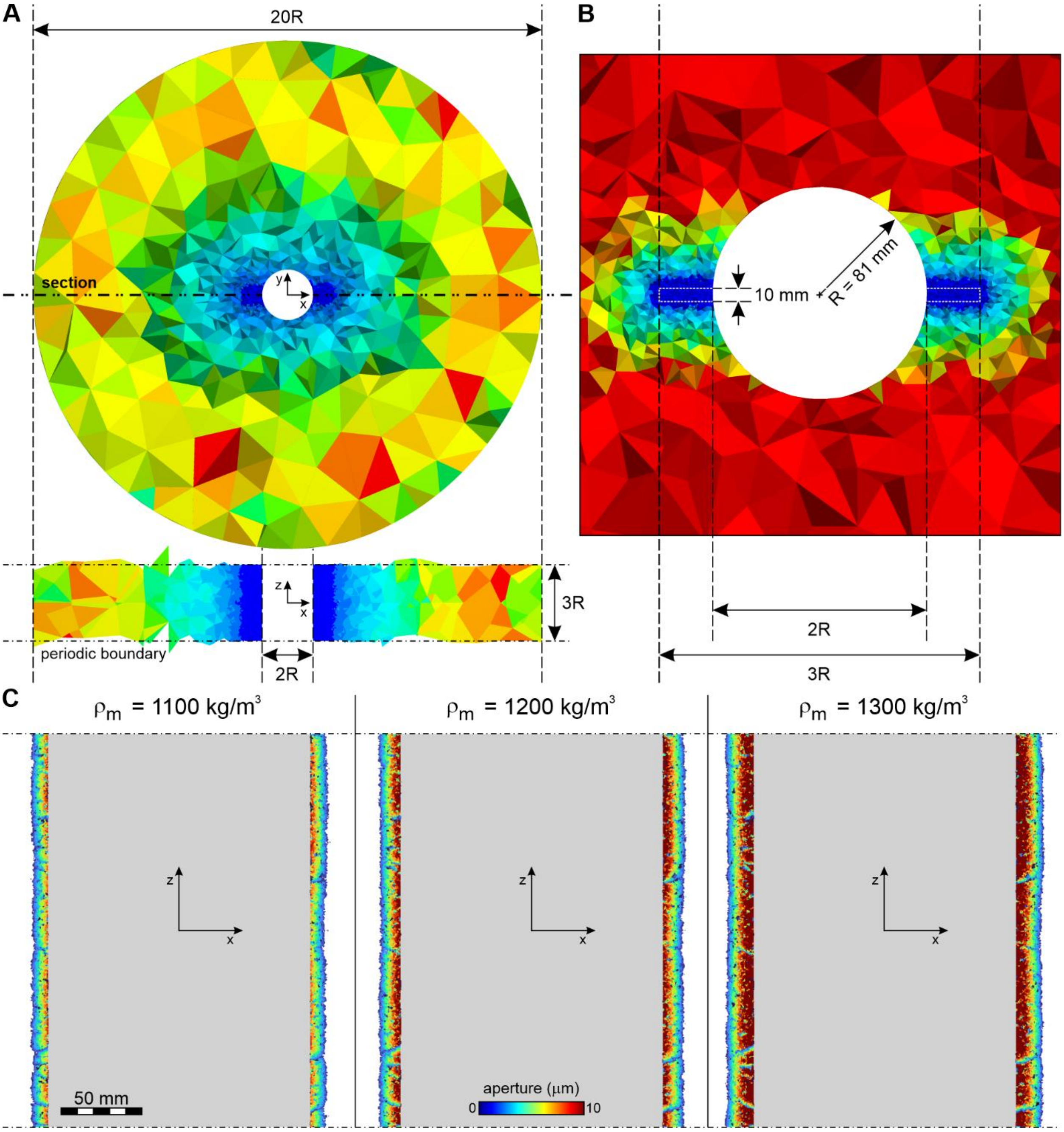

Figure 2. Rigid Body Spring Network (RBSN) model of drilling induced fractures. (A) Hollow cylinder model, with elements coloured for maximum length. (B) Close-up of central region illustrating refinement of the volume where fractures are expected. (C) Model results, with 'micro-cracks' coloured for aperture, at three different drilling mud densities ρ_m.

Stress measurements for calibrating geomechanical models – Examples from the site selection process for a nuclear waste repository in northern Switzerland

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Abstract for poster/presentation

Estimating the current state of stress in the earth's crust has many applications ranging from scientific studies to the safe design and operation of projects dealing with the subsurface. There is a renewed focus on such projects to mitigate climate change, be it geothermal projects, energy storage, or disposal of CO_2 or spent fuel from the nuclear industry. The state of stress is a key input to establishing the risk profile of such projects, generally to ensure the stability of the subsurface during and after operations.

The desired knowledge of the state of stress depends on the project, with the most demanding ones requiring a full 3-D description of the state of stress (direction and magnitudes) over the entire lithological column from the basement to a depth close to the surface. In such cases, it is now customary to build complex 3-D geomechanical models that provide a complete description of the state of stress throughout the modelled region.

Even with the best effort to describe the geological structure, the rheology of the rock, the distribution of pore pressure and that of discontinuities (faults and fractures), geomechanical models can provide a quasi-infinite number of realisations of the state of stress because the tectonic loading is typically unknown. There is therefore a need to calibrate geomechanical models with stress measurements, both in terms of stress orientation and stress magnitude.

Various strategies have been devised for such calibrations. One of the issues encountered during the calibration process is that stress measurements might sample the variability of the subsurface that is not explicitly represented by the geomechanical model. Another one is that stress measurements typically report only one best estimate of the minimum stress, without any uncertainty attached to it. In order to cater for these issues, powerful calibration strategies have been devised based on Bayesian frameworks (e.g. Lecampion and Li, 2010). Strategies around stress measurements, however, can also be applied to further make the calibration process more robust.

As part of the search for a site for the disposal of radioactive waste, three candidate sites in Switzerland were explored. The comprehensive exploration programme included the creation of site specific geomechanical numerical models, which are described more extensively in Reiter et al., 2024. An intensive campaign of measurements of the horizontal stress magnitudes (Desroches et al. 2023) was carried out in 8 deep boreholes using Micro-Hydraulic Fracturing (MHF) and (dry) Sleeve Re-opening (SR) tests (Fig.1): out of 139 successful MHF tests, 121 estimates of the magnitude of the minimum horizontal stress and 65 estimates of the magnitude of the maximum horizontal stress were obtained.

Based on the experience of this extensive campaign, key learnings related to measuring stresses are highlighted, especially with the view of calibrating a geomechanical model:

- Extensive planning needs to be performed to select the desired location of stress measurements – e.g. to prioritize tests during the campaign to provide best located calibration points given the importance of formation stiffness;
- The stress measurement protocol needs to be tailored and adapted in real-time to ensure that the MHF test will yield a "far-field" stress estimate;
- The interpretation of the test must rely on multiple cycles and multiple stress estimates and provide a range for the magnitude of the minimum horizontal stress instead of a single value;
- Addition of SR tests is key to the calibration process as it provides magnitudes of the maximum horizontal stress that are untainted by the hydraulic fracturing process
- MHF / SR tests provide stress estimates at the metre scale and thus sample the formation variability at that scale. Care must be taken to reconstruct that variability for optimum model calibration.

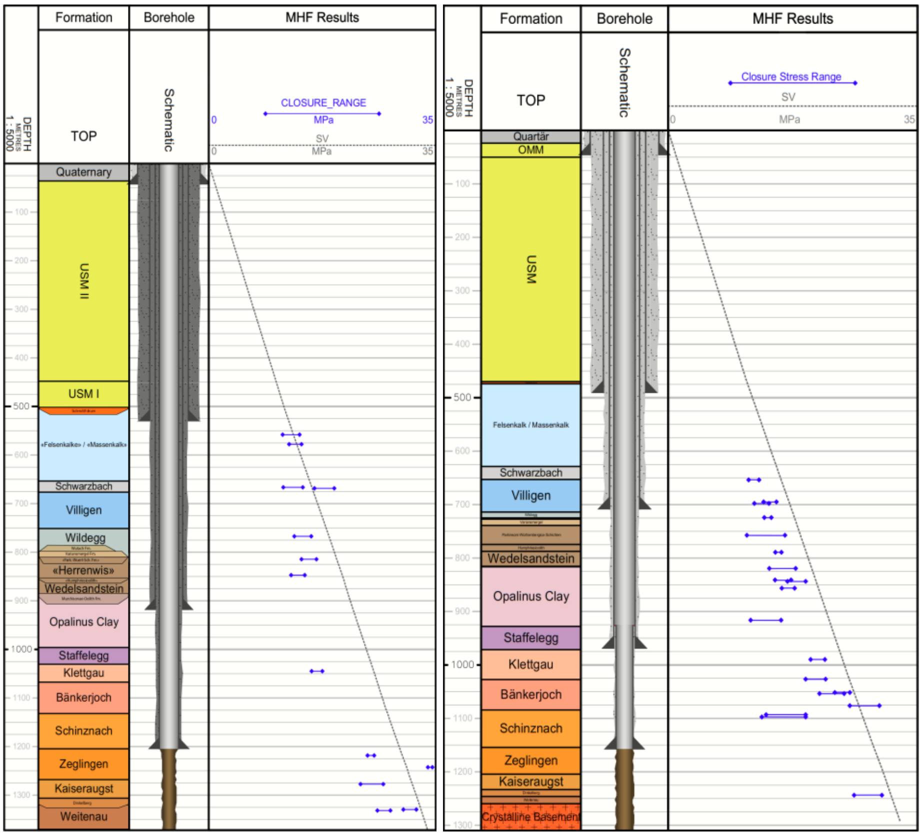

Figure 2 Range of closure stress from MHF tests for two of the boreholes of the siting campaign (after Desroches et al., 2023). The black line corresponds to the integration of rock density.

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Calibration of geomechanical models – Examples from the site selection process for a nuclear waste repository in northern Switzerland

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Abstract for poster/presentation

Estimating the contemporary stress state in the Earth's crust is both an academic and an applied objective. The latter concerns the classical utilisation of the subsurface for the extraction of water, building materials, minerals, or energy resources. The extraction of thermal energy, intermediate storage of energy and final disposal of carbon dioxide or radioactive waste are increasingly coming into focus. The geomechanical stability of the host rock is particularly relevant for the barrier integrity of a geological repository for nuclear waste. A key question in this context is if induced stress changes due to pore pressure diffusion and the thermal front of the heat-generating radioactive waste can lead to rock failure in the barriers. Therefore, a detailed knowledge of the stress state helps in designing, building, and the operation phase.

Various techniques have been established to measure or derive individual stress tensor components. The database of the World Stress Map (WSM) project was initiated in the mid-80s to compile systematically the orientation of the maximum horizontal stress (S_{Hmax}) and the stress regime (Heidbach et al., 2018), while only local databases exist for stress magnitudes (e.g., Morawietz et al., 2020). Thus, it must be assumed that little to no stress magnitude data is available for any area of interest. Since the stress state is strongly controlled by the heterogeneity of the rock density and stiffness as well as by discontinuities (faults), interpolation methods are ruled out for estimation of the stress state, even if several data are available. The most appropriate way to describe the stress field is by means of geomechanical models that use the Finite Element Method for a numerical solution. These models require detailed knowledge of the underground structures and rock properties as well as horizontal stress magnitude data as calibration points. To achieve a best-fit to these data lateral displacements can be determined automatically provided that the problem is a linear system (Reiter & Heidbach, 2014).

As part of the site selection process for the final disposal of radioactive waste, three candidate areas in Switzerland were explored (Fig. 1). The comprehensive exploration programme also included the creation of local geomechanical-numerical models. The structural models were set-up based on current 3-D seismic surveys. The models have a lateral side length between 11.2 and 14.8 km and the meshes consist of 1.9 to 2.7 million finite elements representing 17 or 18 lithologies and 6 or 7 faults. A total of nine boreholes provides detailed information on the rock parameters. Furthermore, 139 successful Micro-Hydraulic Fracture (MHF) and (dry) Sleeve Re-opening (SR) tests resulted in 123 estimates of the magnitudes of the minimum

horizontal stress S_{hmin} and 65 estimates of the S_{Hmax} magnitude. Furthermore, Formation Micro Imager (FMI) and Ultrasonic Borehole Imager (UBI) logs were analysed to derive the S_{Hmax} orientation. These tests and logs were carried out in all relevant stratigraphic units, in some cases several times.

This unique dataset provides the possibility to determine a best-fit model with respect to the S_{hmin} and S_{Hmax} magnitudes data from the MHF and SR tests. Furthermore, and probably more important, the models also allow to determine the bandwidth of stress magnitudes to be expected in the rock volume beyond the boreholes. We will show that a best-fit can be achieved with our model workflow, but that the prediction of the stress state in the larger volume is controlled primarily by the variability of the rock stiffness. As the rock stiffness is a probability distribution the prediction of the horizontal stress magnitudes in the larger volume is also a probability distribution.

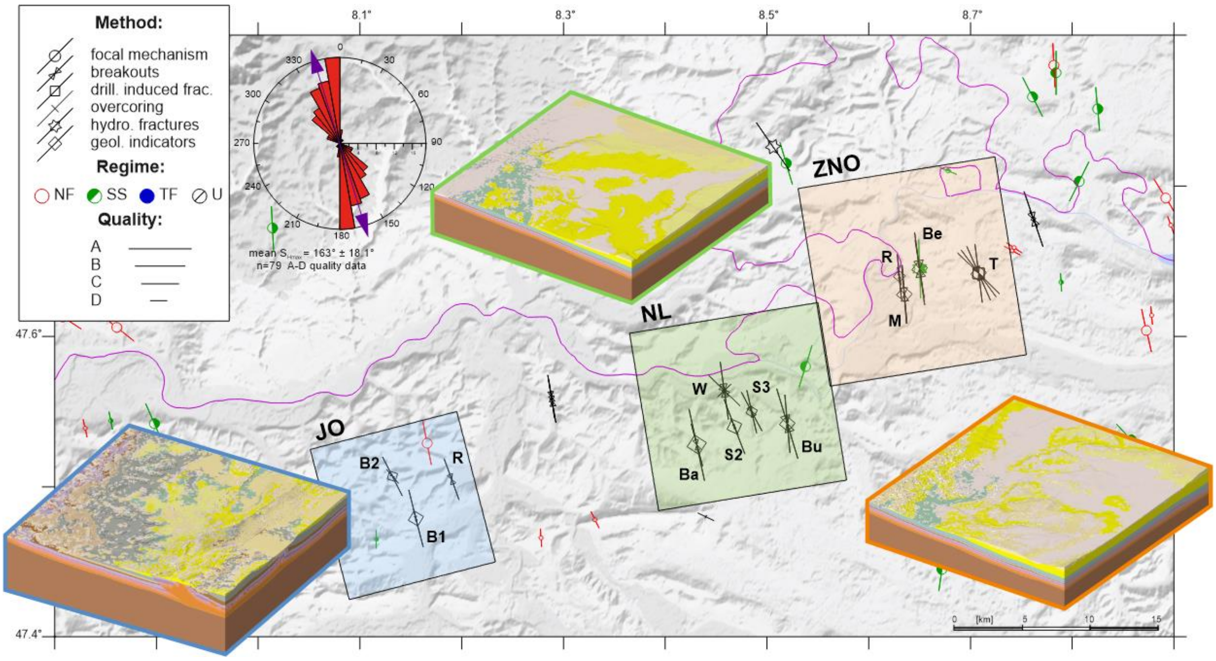

Figure 3 Map of the model areas in northern Switzerland with stress orientation data. Stress orientation map with 83 A–D quality data records of the revised World Stress Map database (Heidbach et al, 2018). Bars indicate orientation of maximum horizontal stress, S_{Hmax} symbols specify the type of stress indicators and colours mark to stress regime with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). Location of drilled and previously planned wells are Bözberg 1 and 2 (B1 and B2), Riniken (R), Bachs-1 (Ba), Weiach-3 (W), Stadel-2 (S2), Stadel-3 (S3), Bülach (Bu), Rheinau (R), Marthalen (M), Benken (Be) and Trüllikon (T). The model volumes of the geomechanical-numerical models Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) are shown on top of the map.

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Session Four: Keynote talk & Group Discussion

KEYNOTE - Mark Zoback

Implications of Seismicity Triggered by Large-Scale Injection of Produced Water for Massive-Scale CO_2 Storage in Saline Aquifers

Mark D. Zoback
Professor of Geophysics, *Emeritus*
Stanford University

It has long been recognized that carbon capture and storage in geologic formations (CCS) needs to be a component of decarbonization strategies to limit global warming. Recent studies indicate the enormous scale at which CCS activities must be undertaken, in a very short period of time. The IEA estimates that about 1 GT CO_2/y needs to be stored in the subsurface by 2030 and about 6 GT CO_2/y by 2050. Meeting the 1 GT CO_2/y goal requires a 50-fold increase of the anthropogenic CO_2 currently being stored in the subsurface. The longer-term goal of 6 GT CO_2/y by 2050 would be equivalent to storing a volume of fluid roughly 50% more than all the oil produced, transported and consumed in 2020. In this talk I will challenge a number of assumptions currently associated with strategies to meet these goals with a focus on geomechanical issues affecting long-term storage efficacy. First, it is widely assumed that saline aquifers, will accommodate an almost limitless amount of CO_2. Of course, utilization of saline aquifers at a large scale will require significant data acquisition, analysis and modeling in formations about which there is very little currently known. More challenging will be avoiding the conditions responsible for the numerous cases of injection-induced seismicity that have occurred over the past 10 years in North America. These earthquakes resulted from very small pressure increases caused by disposal of water co-produced with oil and gas into saline aquifers. This concern is especially relevant for basal aquifers. A number of cases of moderate size earthquakes (with magnitudes up to 5.8) have occurred where injection-related pressure changes have induced slip on critically-stressed faults in underlaying basement. If CO_2 injection is associated with triggering earthquakes, it will be perceived by the public as a hazardous activity which should be stopped. Second, depleted oil and gas reservoirs are a viable option for long-term storage of CO_2, assuming that existing wells. In this case it is also important to understand both the mechanical changes of the reservoir rocks and stress changes that resulted from depletion. Such knowledge is required to predict how pressure associated with CO_2 injection will affect the reservoir over long time periods.

Session Five: Geomechanics & Fluid flow I

Murmurations of stress: fractures from flowrates.

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Previous studies (Heffer, 2012) have indicated that fluctuations in flowrates from or into wells over the detailed production history of a mature oilfield can be treated as approximate proxies for geomechanical strain changes. As well as being related to stress orientation and fault traces, interwell temporal correlations in detrended flowrate fluctuations were found to be statistically significant over long distances between wells, somewhat analogous to bird murmurations and symptomatic of a near-critical system. This led to a new tomographic-like methodology for the extraction of fracture characteristics from fieldwide correlations of flowrate "noise", with the following stages.

A statistical physics approach provides the probability distribution of rates of energy changes due to either dissipative Darcy fluid flow or fluctuations in rock strain energy. From this is derived a relationship between the covariance matrix of flowrate fluctuations across all pairs of wells in the field and a matrix of parameters involving components of effective permeability and non-local stiffness tensors. Estimates of stress interactions between nearest neighbour wells are found by requiring their consistency with the set of indirect far-field stiffness values. The stress interactions can then be best fit using the theoretical orientational distribution of the stress field around a given extensional fracture to extract estimates of fracture density and orientation at each well. These can be interpolated over a grid with a simple algorithm.

Applications of this technique to a synthetic model, oil and gas reservoirs and a geothermal field have produced encouraging results; some are briefly described below; others will be presented.

1) Synthetic 2D model (figure 1)

This model was created (Zhang et al., 2007) by VIPS Ltd. (now SLB) with their VISAGE™ model of coupled geomechanics and fluid flow. In that study time series of uncorrelated random pressures were assigned to a 5-spot pattern of injector and producer wells. The domain throughout contained 8 fracture sets at regular 22.5 degrees azimuthal spacing, the permeabilities of which were sensitive to their dilations and compactions as stress states changed; tractions at the boundaries of the model with a NNE-SSW trend in SHmax placed the system in a near critical stress state. Therefore the resultant flowrates at wells were a consequence of elastic and inelastic strain changes as well as the input pressures. In figure 1 the fracture strikes and intensities (lengths of lines) resulting from the application of the new methodology to the flowrate histories are overlaid on a map of the shear strains resulting directly from the VISAGE™ model. The fractures are interpreted at wells (black lines) and also interpolated (white lines). A radar plot of the interpreted fractures (inset) shows a peak close to the azimuth of SHmax, although a secondary peak occurred at a larger angle, possibly associated with the NE-SW direction between neighbouring wells. Interpolating the fracture strikes continuously produced a pattern (in red), emanating from a major shear zone in the model, that has some similarity to the stress trajectories around a sheared fracture (in green), although of course other shear zones will also be affecting the trajectories.

2) Gröningen gas field, onshore Netherlands (figure 2)

This depleted sandstone reservoir has undergone a large pressure drop (~300 bar), the compaction from which has caused significant subsidence and over 1500 small earthquakes of magnitudes up to ML3.6. Finely gridded modelling of the depletion with the geomechanical models ARAMIS & APOLLO by Geomex Software Solutions (p.c. Dr N. Koutsabeloulis) has provided estimates of the displacements across the field, from which maximum horizontal compressional strains were calculated, shown as black lines. The analysis of the production history yielded the fracture *normals* at wells plotted as red lines, with interpolated fracture normals shown as yellow lines. There is good agreement.

3) Valhall oil field, Norwegian North Sea (figure 3)

Many of the fracture strikes (black lines) interpreted from the production history of this chalk reservoir follow a quasi-circular pattern similar to that demonstrated by fast shear waves (blue lines) in the formation above the reservoir (Olofsson et al., 2003), indicative of local Shmax and deriving from the compaction of the depleting reservoir. Those interpreted fractures that are contrary to the nearby fast shear waves (red lines) may be affected by nearby faults.

Figure 1: synthetic model

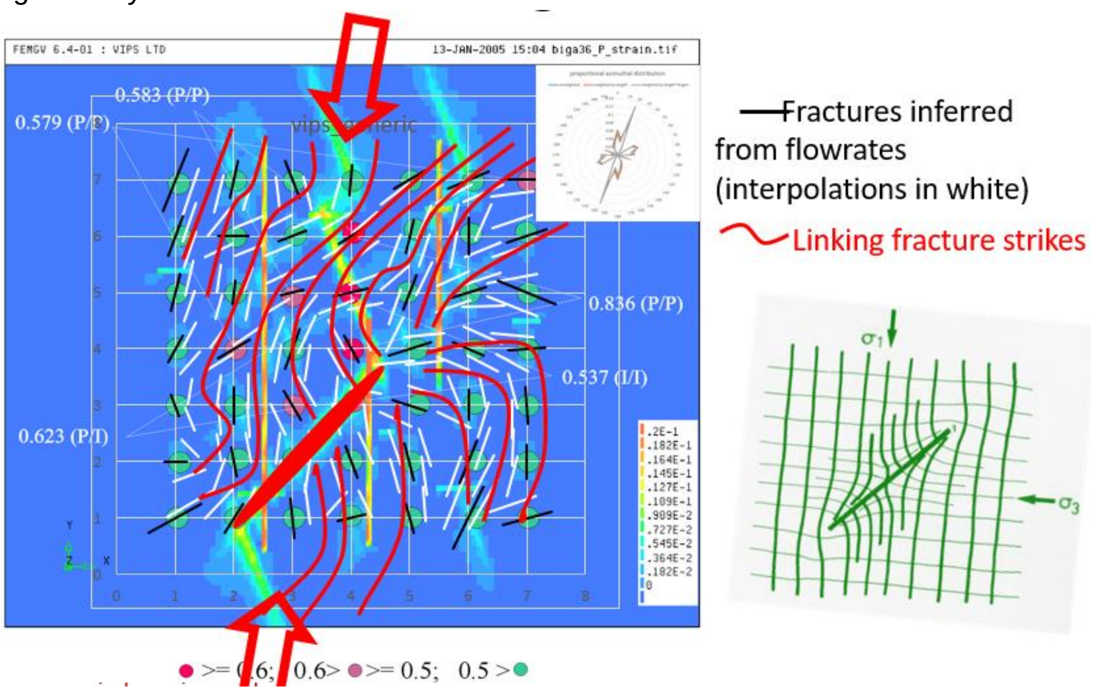


Figure 2: Gröningen field

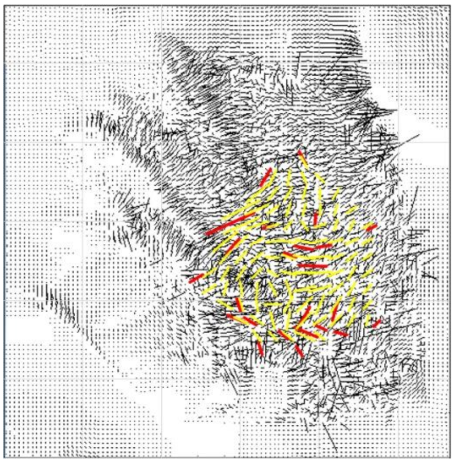
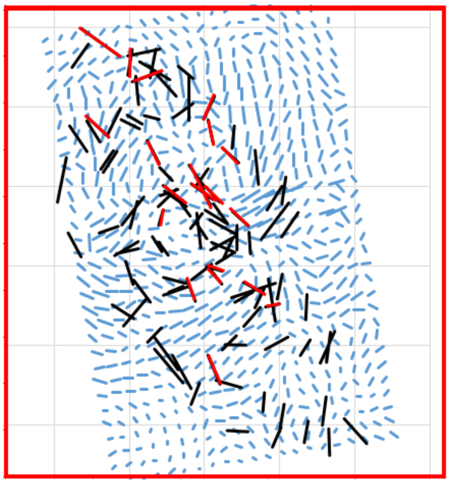


Figure 3: Valhall field



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Targeting critically stressed fractures to enhance production in the Lama Fm., Anoa Field, Natuna Sea, Indonesia

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Anoa is the eastern most field of the Natuna A block located in West Natuna basin offshore Indonesia. Two wells WL-5x (2012) and Anoa West-1 (2015) were deepened from the producing Gabus Fm. reservoirs to test the Lama Formation. The pre-drill key risk of both wells was reservoir deliverability due to the predicted low primary porosities and permeabilities. WL-5x flowed gas from what turned out to be a highly fractured deep Lama sand unit, while the AW-1 well failed to flow any significant volume of gas to surface from any Lama sand unit. An extended well test was subsequently conducted on WL-5x between August 2017 and November 2018 which produced gas at an initial sustained rate of 25 mmscf/d. Water started to encroach by November 2017 and the gas production started to decline rapidly and then stopped in June 2018.

These wells had been drilled without a detailed study of the structural geology, geomechanics and stress regime of the field, so a geomechanical model was then built internally to try and understand this behaviour, drawing heavily on the methodology of Zoback, 2007, and Hennings, et al, 2012.

The tectonic history, paleostress and present day in-situ stress of the region, field and individual wells were interpreted. Seismic data was holistically integrated with well data. Each well was put into context with regards to its regional structural setting, local structural setting and current stress regime. The interpretation identified three major strike slip faults influencing the area, with the Anoa field likely located on the termination splay of one of them, still active at present day. This results in a complex and varied stress field at Anoa, and it also provided the opportunity to chase open and conductive fracture systems in the Lama play.

Individual sand units in a single well showed differing stress states and orientations, a phenomenon also noted by Hennings and Zoback on the Suban field onshore Sumatra. This enabled recommendations to be made as to which sands to target for perforation, and why, and so this geomechanical model was subsequently tested with interesting results.

The project took an exploration approach to a producing asset, with a view to opening a play. It integrated a variety of stress data from plate to seismic to log scale to achieve this. Pore pressure data was sparse, while image log data for stress orientation was excellent. Elastic rock properties estimated from sonic and density logs provided by service companies had to be carefully analysed to try and understand the enigmatic magnitude of Shmax. Although the methodologies used have been well described in the literature, perhaps this is a case study that can support the value of geomechanical modelling and stress analysis toward decision making on naturally fractured fields.

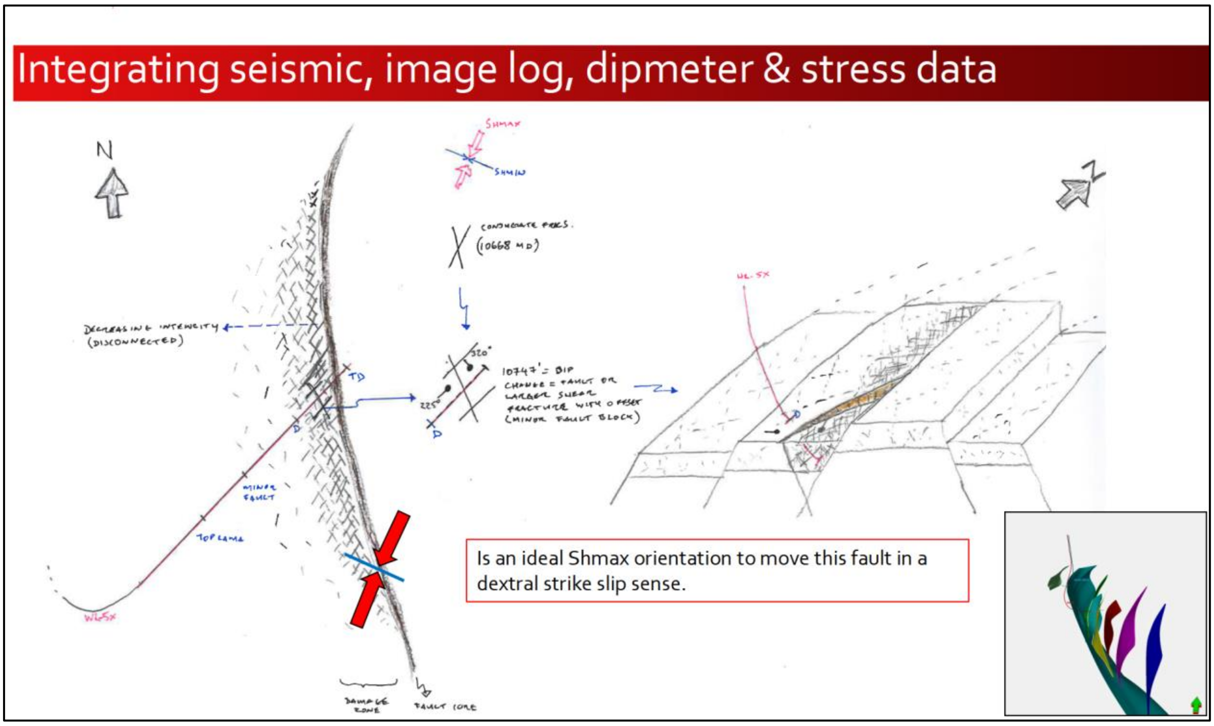

Figure 2: Sketch of the deepening of WL-5x into the Lama Fm., and how stress data informs the interpretation.

KEYNOTE - Adriana Paluszny

Numerical Simulation of Fault Slip During Hydrogen Storage in a Depleted Gas Reservoir

Adriana Paluszny, James Burtonshaw, Robert W. Zimmerman

Hydrogen is projected to become a significant component of global energy consumption by 2050, with estimates ranging from 16,000 to 48,000 TWh annually. To meet this demand, hydrogen storage technologies aim to utilise surplus renewable energy by storing hydrogen in subsurface porous media, including depleted reservoirs offshore and onshore. This study focuses on numerically modeling the geomechanical behavior of a depleted gas field, where gaseous hydrogen is cyclically injected into a North Sea-type reservoir over a three-year period.

The reservoir model consists of four layers representing the overburden, caprock, reservoir, and underburden, with a large-scale fault simulated within the reservoir, and in a second model, within the underburden. Parametric simulations investigate the influence of mechanical properties, including Young's modulus, Poisson's ratio, Biot coefficient, and intrinsic permeability, on fault slip and induced seismicity during storage cycles.

An in-house three-dimensional, hydro-mechanical finite-element code is employed, explicitly representing the fault as a mesh discontinuity and utilising an Augmented Lagrangian approach for fault contact modeling. Results indicate predominantly stick-slip behavior of the fault during operational cycles, with minor slip (<4 mm) occurring at transition points between injection, storage, and withdrawal phases. The study highlights the significant control of Young's modulus on fault slip within the underburden, while Poisson's ratio strongly influences the magnitude of induced seismicity. For seismic hazard mitigation, underburden rocks with low Young’s modulus (<15 GPa), high Poisson’s ratio (>0.25), low Biot coefficient, and low intrinsic permeability (<1×10^-19 m^2) are identified as favorable for hydrogen storage applications. These findings provide valuable insights for the design and operation of subsurface hydrogen storage facilities, contributing to the sustainable integration of hydrogen-derived energy into future energy systems.

Session Six: Seismicity and Seismic Hazards

KEYNOTE - Mike Kendall

Assessing stress from seismicity, focal mechanisms and anisotropy - implications for geomechanics

Quantifying Shallow Tectonic Stresses and their Influence on Active Faulting at the Hikurangi Subduction Margin, New Zealand

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Quantifying tectonic stress magnitudes is crucial in subduction zones for understanding crustal deformation processes, fault geomechanics, and variable slip behaviours on plate interfaces. The Hikurangi Subduction Margin (HSM), New Zealand is characterized by along-strike and down-dip slip variations at the plate interface, which may, in part, link to tectonic stress variations within the overriding plate. This research constrains orientations and magnitudes of the in-situ stress tensor along the HSM in order to understand variations in tectonic regime within the shallow (<3km) HSM forearc crust, slip and dilation tendencies on HSM active faulting, and the relationship of the stress field to larger scale subduction interface dynamics.

Our results reveal a 065°/245° SHmax orientation for the central HSM which rotates to dominantly 112°/292° to 140°/320° in the southern HSM. This rotation correlates spatially with along-strike variations in subduction interface slip behaviour, characterized by creep and/or shallow episodic slip events in the central HSM and interseismic locking of the plate interface in the south. Borehole SHmax orientations suggest contemporary stress field may result, in part, from along-strike variation in deformation imposed by clockwise rotation of the subduction forearc. In the southern HSM, borehole-derived SHmax orientations are inconsistent with focal mechanism-derived SHmax orientations within the subducting plate, implying a potential mechanical decoupling between the shallow hanging wall and subducting slab of the HSM.

Constrained In situ stress magnitudes within the shallow (<3 km) overriding plate of the HSM reveal σ3:Sv ratios of 0.6–1 at depths above 650–700 mTVD and 0.92–1 <700 mTVD along the entire HSM. Additionally, at depths below 650–700 m TVD, SHmax:Sv ratios of 0.95–1.81 are reported for the central HSM and 0.95–2.3 for the southern HSM. These stress ratios suggest a dominant contractional to strike-slip (σ1=SHmax) faulting regime across the central and southern HSM. However, as the central HSM presents NNE-NE striking contractional faulting within a contemporary ENE-WSW σ1 (SHmax) we infer that the stress state here has evolved with time from a contractional to a strike-slip state, changing contractional direction from HSM margin perpendicular (NW-SE) to oblique (ENE-WSW). This temporal change in stress state may be explained by forearc rotation, likely combined with the development of upper plate overpressures. In the southern HSM, contemporary WNW-ESE/NW-SE σ1 (SHmax) and NNE-NE striking contractional faults indicate that stress state has remained perpendicular to the HSM margin over time.

Deciphering the modern stress field facies in Costa Rica and vicinity from earthquake focal mechanisms and GNSS support

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A database with 2.493 earthquake focal mechanisms is compiled and analyzed, for modeling by formal inversion, the modern tectonic stress field of Costa Rica, southern Nicaragua and northern Panamá (Fig.1). The general orientation of the maximum horizontal stress SH Max is found to be sub-parallel to the N 32° E convergence direction of the Cocos plate with the Caribbean plate along the Middle America Trench, although a counterclockwise rotation of +- 60° is detected below 30 km depth (Fig.2).

Three orders of stress are identified, the first imposed by the absolute motion of the Cocos plate, the second, with high magnitude boundary forces, generated by the interaction of the former with the Caribbean and Nazca plates and the third order is due to the density contrasts caused by trench-parallel active volcanic, igneous, and sedimentary mountain ranges, which in combination with regional faults and their intersecting arrays, act together as deflectors of the local tectonic stress.

Observed and modeled GNSS data of the NNE oriented horizontal velocity field show a very good correlation with the direction of the interpolated SH Max in the upper layer (Figs.3 and 4). All these features and properties, together with abundant local and regional permutations of the stress ellipsoid axes, explain the relative overlapping and instability of the tectonic regimes and their neo tectonic complications.

Strictly applying the WSM categories of stress regimes together with the R' tectonic relationship, a detailed 2D-3D scenario was generated that presents realistic and more objective seismotectonic boundaries than classical proposals.

Relevant tensors are being used as input to fault reactivation potential determinations via 2D and 3D Slip-Dilation tendencies analysis and Coulomb Failure Stress with practical implications to seismic hazard, geotechnics, geothermal exploitation, and oil exploration.

This study is being complemented by the analysis of fault-slip indicators from several hundred outcrops for the entire lithologic column, monogenetic Quaternary volcanic cones and dykes along with oil wells breakouts to construct and decipher the complete stress scenario.

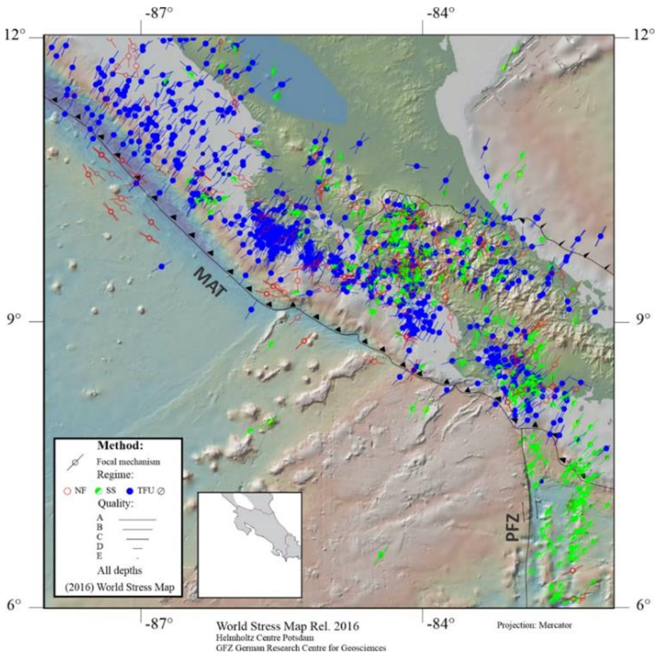

Fig. 1. Total stress field map of Costa Rica and surroundings from the database of 2493 focal mechanisms, all depths and magnitudes, presented in this investigation,

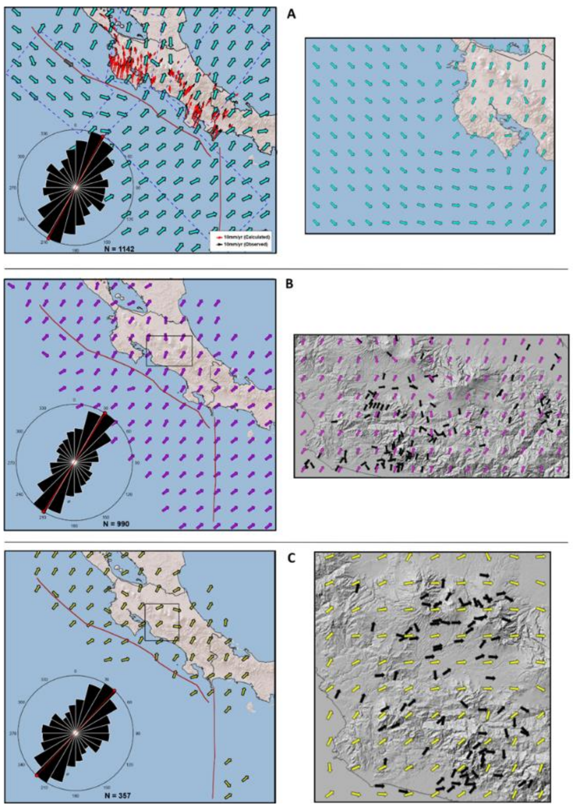

Fig.2. A. Superposition of the SH Max interpolated trajectories derived from 1142 FM at the upper crust layer with the calculated and observed GPS data of the horizontal velocity field calculated by Carvajal et al. (2020). The right panel is a detailed local interpolation to show the variability and transitions of the SH Max. B and C are the equivalent for the intermediate and deeper layers. Each directional rose corresponds to the azimuths of the crude data with the mean value denoted by a line and dot. Red lines are the MAT and PFZ.

Landslides, earthquakes and far field stress on a passive margin: Australia's North West Shelf

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The Exmouth Plateau, off the coast of NW Australia, hosts a large landslide province comprising 14-16 discrete, mappable mass transport deposits (MTDs), all of which are post mid-Miocene in age. Ranging in area from ~7,500km^2 to ~11,000 km^2, slides range in volume from ~450 km^3 to ~700km^3. Currently mapped in a somewhat piecemeal fashion, these events are named for the 3D volume in which they were first identified (e.g the Gorgon slide), resulting in a number of different names for these MTDs, sometimes for the same event.

We have mapped ~14 discrete, mappable MTDs across 8 3D seismic surveys, with an astonishing degree of clarity, and with seamless transition between surveys. This has vastly increased the known area/range of the mass transport province. We are currently incorporating additional results from an adjacent 3D volume, in which four smaller MTDs have been mapped. Seismic facies and architectural elements show a range of mechanisms including basal shear, slide blocks several kilometres long and areas of chaotic mass flow.

Spatial links between faults and headscarps, and reactivation and inversion of older faults indicate that seismicity and fault reactivation are one triggering mechanism for the MTDs. The current right-lateral strike-slip state of stress (as determined by focal mechanisms of onshore and offshore earthquakes), with SHmax of ~110° is responsible for a surprising number of relatively high magnitude intraplate earthquakes in this region and affect much of NW Australia. Most recently, the July 2019 Mww 6.6 event off the coast of Broome, Western Australia, yielded an almost pure strike-slip focal mechanism, mimicking the results of ~40 other events for which focal mechanisms were able to be calculated.

Interestingly the 110° orientation for SHmax does not reflect the plate boundary configuration in the region, as might be expected in a region with an active plate collision (Australia-Banda Arc, in the region of Timor island). Instead it may be controlled by tectonic activity along the Ninety East Ridge, a >5000 km-long volcanic ridge in the Indian Ocean, that is thought to the site of incipient breakup of the Indian and Australian tectonic plates. Stress orientations and focal mechanism solutions for the Wharton Basin (northern Ninety East Ridge) compare favourably to those on the NWS. The Wharton Basin was the site of the largest strike-slip earthquakes ever recorded in 2012 (Mw 8.6). If the cause of the 110° azimuth of far-field stress is related to the Ninety East Ridge, it raises questions as to mechanisms of stress transmission in oceanic crust, given that the ridge lies ~3500km to the NE of our study area.

Session Seven: Geomechanics & Fluid flow II

Recurrent reservoir triggered earthquakes in Koyna, western India: insights from scientific drilling and borehole investigations

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Triggered seismicity in the Koyna region, starting soon after the impoundment of Shivajisagar water reservoir in 1962, has continued to this day. The activity, confined to 20 km x 30 km area and 10 km depth, is modulated by the annual loading and unloading cycle of the Shivajisagar and nearby Warna reservoirs. The 1967 M6.3 Koyna earthquake caused a NNE-trending surface rupture zone near Donichawadi, along which the seismic activity in the past few decades is aligned.

Scientific drilling of a 3 km deep borehole KFD1 passing through 1247 m thick Deccan Traps and continuing 1767 m in the granitic basement in one of the active seismic clusters, provided an unprecedented opportunity to determine the physical and mechanical properties of subsurface rock formations, delineate fault damage zones, and estimate stress and temperature regime in the Koyna seismic zone at depth. Various geophysical logs were acquired in the borehole and hydraulic fracturing tests for determining stress regime were carried out at eight depths in the crystalline basement. Salient findings are as follows: (i) Several major zones of anomalous physical and mechanical properties are delineated by geophysical data below 2100 m depth. These zones are also characterised by stress-induced shear wave velocity anisotropy. (ii) The majority of the anomalous zones are associated with breakout rotations, which are strongly suggestive of fault damage zones. (iii) The stress-depth profiles determined from hydrofrac tests indicate a strike-slip to normal faulting regime. (iv) Consistent strike azimuths of steeply dipping fractures with S_{Hmax} orientation indicate possibilities for both strike-slip and normal faulting. (v) In the critically stressed Koyna region, earthquakes may be triggered in the favourably oriented faults/fractures with a small modification in stress regime.

Informing Geothermal Prospectivity using Structural Permeability Patterns in Averaged Stress Fields

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Geothermal fields often require structurally-enhanced permeability to achieve flow rates high enough for sustainable energy production. Fractures, which form the basis of structural permeability, are more common near large faults and often follow regional fault orientations. Flow in a fracture also depends on aperture, which has a varied response to the stress field via "dilation tendency".

We developed a geoprocessing workflow to carry out the objective estimation of the relative magnitude of structurally-enhanced permeability at geothermal evaluation sites. We used the geometry and various properties of Getech's 1:1M Structures layer to estimate basin-scale geothermal prospectivity by scoring how structurally-enhanced permeability is likely to dilate with stress orientations from World Stress Map data.

We assume that 1:1M scale mapped faults represent rock damage and therefore structurally-enhanced permeability. Faults from the structures layer are scored using their structural significance (plate-bounding, basin-bounding or intra-basin), sense of movement (using the fault permeability database of Scibek, 2023), and the length of a fault is used to estimate a damage zone width using length-displacement-damage zone scaling relationships (Lathrop et al., 2022). Separately, faults are segmented and average S_{Hmax} is estimated at each segment centroid from World Stress Map Data using the same procedure as smoothed World Stress Map grids. Directional distance (L or R of fault) from fault damage zone (calculated above) is used with a distance-temperature decay from published models (Guillou-Frottier et al., 2024). Combining fault property, dilation, and distance scores gives a coordinate-fault pair score (between 0 and 1) which is then summed at each coordinate to allow for the effect of intersecting or closely spaced faults.

We carried out tool validation throughout the North Island of New Zealand, where stress data are abundant and the structures are well mapped, and found areas with high scores agree well with the locations of geothermal plants in the Taupo Volcanic Zone, despite a higher density of faults in the axial ranges to the SE. We therefore show the inclusion of dilation tendency during initial geothermal screening and pre-feasibility studies can substantially alter results, and that elevated structurally-enhanced permeability may be effectively estimated from basin-scale structures and stress orientation estimates.

These tools can be used as part of a wider workflow to assess geothermal potential and prospectivity in appropriate geological settings.

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Rupture Directivity of Fluid-Induced Seismic Events

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The hazards associated with induced seismicity have been hard to predict, especially when new technologies have been deployed, or when extant technologies have been deployed or up-scaled in new settings. The failure to adequately manage induced seismicity hazards has had major economic and environmental implications in many countries, where regulators have been forced to shut down industry operations. Recent examples include the Groningen gas field in the Netherlands, hydraulic fracturing of the Bowland shale in the UK, the CASTOR offshore UGS site in Spain, and the Pohang and Basel deep geothermal projects in South Korea and Switzerland respectively, with the latter one being seismically active several years after the injection well was shut-in.

To better understand the complex rupture processes of induced earthquakes, we first compile the seismic waveforms of multiple seismic events induced by different fluid injection operations, as hydraulic fracturing (HF) in shale gas wells and enhanced geothermal systems, wastewater disposal (WWD), and gas storage. We then implement the Empirical Green's Function (EGF) method to measure for each analysed induced earthquake their rupture time and directivity, which complement other key source mechanism parameters of the same events already calculated, as moment magnitudes and focal mechanisms.

The EGF method allows the measurement of the Source Time Function (STF) of a seismic event at each seismic station that recorded it, by deconvolving its seismic signal with the one from another seismic event of smaller magnitude but with very similar hypocentral location. This deconvolution between seismic waveforms from Target and EGF events allows a numerical removal of all factors that affect the recorded seismic waveform (like the earth structure, the near surface, and the instrument response) except for the event's source itself, obtaining a STF for each target event at every seismic station (see example in Figure 3).

We then measure for each target event the rupture time at each station from the obtained STF, and invert the rupture times with respect to each station's azimuth. We use the coefficient of determination (R^2) of the inverted rupture time variation with azimuth to determine whether an induced earthquake had a predominant unilateral or bilateral rupture (Figure 4). In most cases, we observed a consistent self-similar scaling of the earthquake's magnitude and mean rupture time, and a predominant unilateral rupture for higher magnitude events (Figure 5). In each case, we also examine whether the rupture directivity is driven by the local stress conditions, or by the fluid injection that induced them. Finally, we discuss the possibility of implementing the same methods to monitor the recently awarded CCS licenses in the UK Continental Shelf.

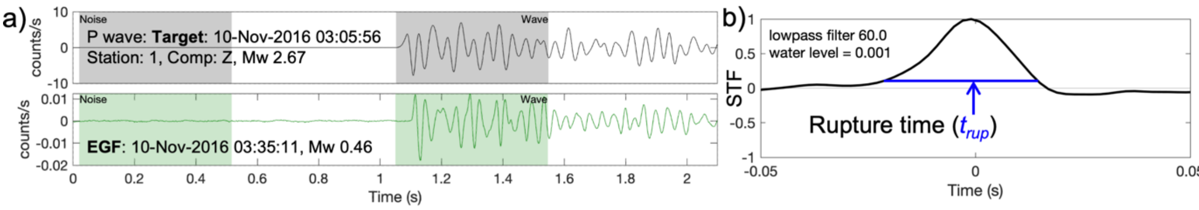

Figure 3. a) Seismic waveforms recorded at the same monitoring station, of two seismic events induced during a hydraulic fracturing stimulation in western Canada (dataset described in Eaton, et al. 2018) with hypocentres located less than 200 metres apart, of magnitudes 2.67 (Target event) and 0.46 (EGF event). The rupture time shown in b) for the Target event at this station, can be measured from the Source Time Function (STF) obtained from the deconvolution of the two waveforms shown in a).

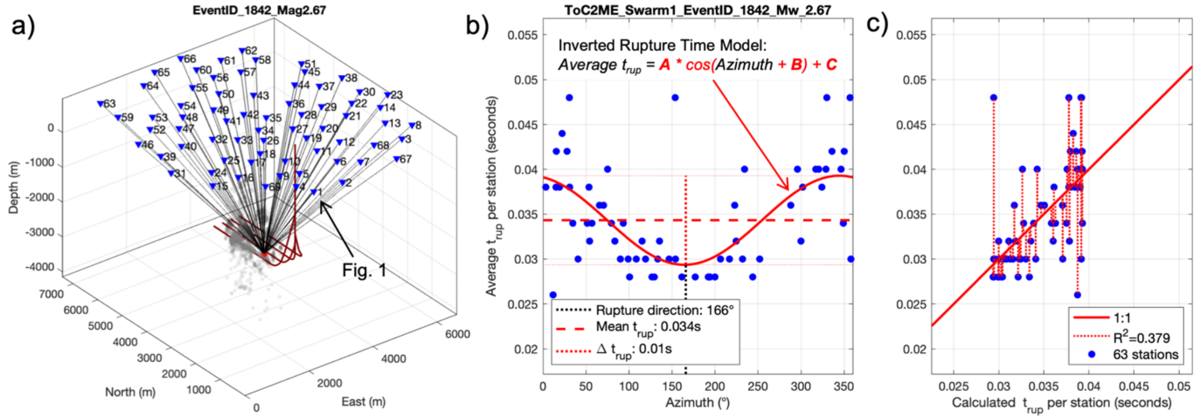

Figure 4. a) Isometric view of the seismicity induced by a multi-stage hydraulic fracturing stimulation in western Canada (dataset described in Eaton, et al. 2018) and the near-surface monitoring stations, including the station shown in Figure 3. The rupture times measured at every station are inverted with respect to the azimuth relative to the location of the Target event (shown in b), with a rupture direction of 166° (which corresponds to the azimuth with the lowest rupture time), a mean rupture time of 0.034 seconds, and a coefficient of determination (R^2) from this linear inversion of 0.379 (shown in c).

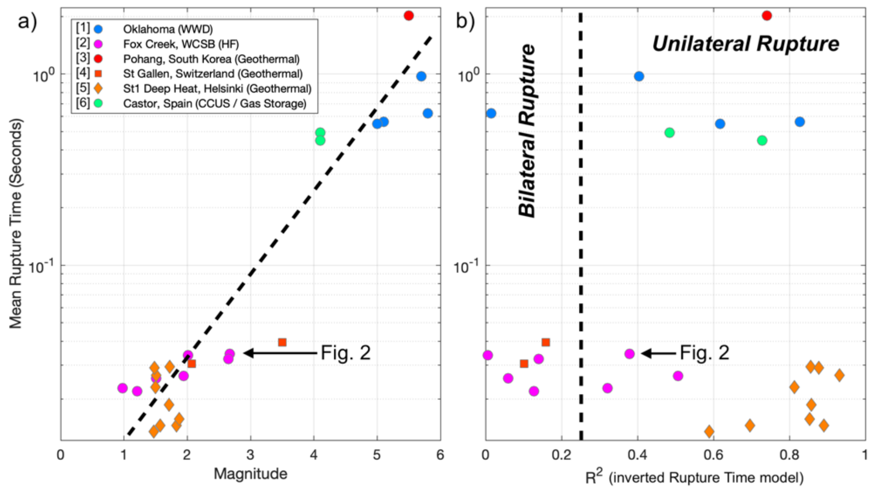

Figure 5. a) Mean rupture times of multiple seismic events induced by different fluid injection operations, including the example shown in Figure 4. The dashed line suggests a self-similar behaviour between mean rupture times and magnitudes. The obtained coefficient of determination (R^2) of the inverted source time model for the same events are used to determine in each case either a unilateral or bilateral rupture. Data sources: [1] Lui and Huang 2019; [2] Eaton, et al. 2018; [3] Cho, et al. 2023; [4] Diehl, et al. 2017; [5] Holmgren, et al. 2023; [6] Cesca et al, 2021.

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KEYNOTE – Mark Tingay

Mud Volcanoes: What They Tell Us About Stress and Pore Pressure

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Mud volcanoes are fascinating and unusual geological features that form from the release of highly overpressured fluids and the remobilization of subsurface sediments. Mud volcanoes are thus a natural laboratory for studying stresses and extreme pore pressures, and the geomechanical behavior of sediments at near zero effective stresses. This talk will review mud volcanoes in sedimentary basins around the world, exploring their significance, and particularly how they are controlled by tectonic stresses and subsurface pore pressures. I will examine how mud volcanoes and similar fluid escape features can be used to constrain the contemporary state of stress and how stress and pore pressure are coupled. This study will also explore our current understanding of mud volcano eruption triggering and associated geomechanical processes. Through understanding the relationships between stress, pore pressure and mud volcanism, we can better mitigate against these poorly understood and underappreciated geohazards.

Prediction of the recent crustal stress state of Germany – The SpannEnD project

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A reliable prediction of the recent crustal stress state is important for the usage of the subsurface such as geothermal reservoirs, stability aspects of boreholes or the site selection process of deep geological repositories for high-level nuclear waste. To achieve a continuous prediction of the recent crustal stress state 3-D geomechanical-numerical modelling is used. For the calibration of such models, data of the orientation of the maximum horizontal stress (S_{Hmax}) and in particular horizontal stress magnitude data are essential. However, stress data are sparse and incomplete in general and often not available in areas covered by smaller models. Here we show a large-scale model of Germany and neighbouring areas using the stress data from the World Stress Map project and a recent extension of this dataset with quality-ranked stress magnitude data. The model aims at understanding the large-scale stress pattern and to provide initial conditions for smaller scale models with higher resolution.

The model workflow is shown in Figure 1. First, a geological model is set up which is then discretized, and individual material properties are assigned to each model unit. Further steps are the definition of an initial gravity driven stress state and the calibration with given stress magnitudes. We assume linear elasticity and the partial differential equations of the equilibrium of forces are numerically solved using the Finite Element Method.

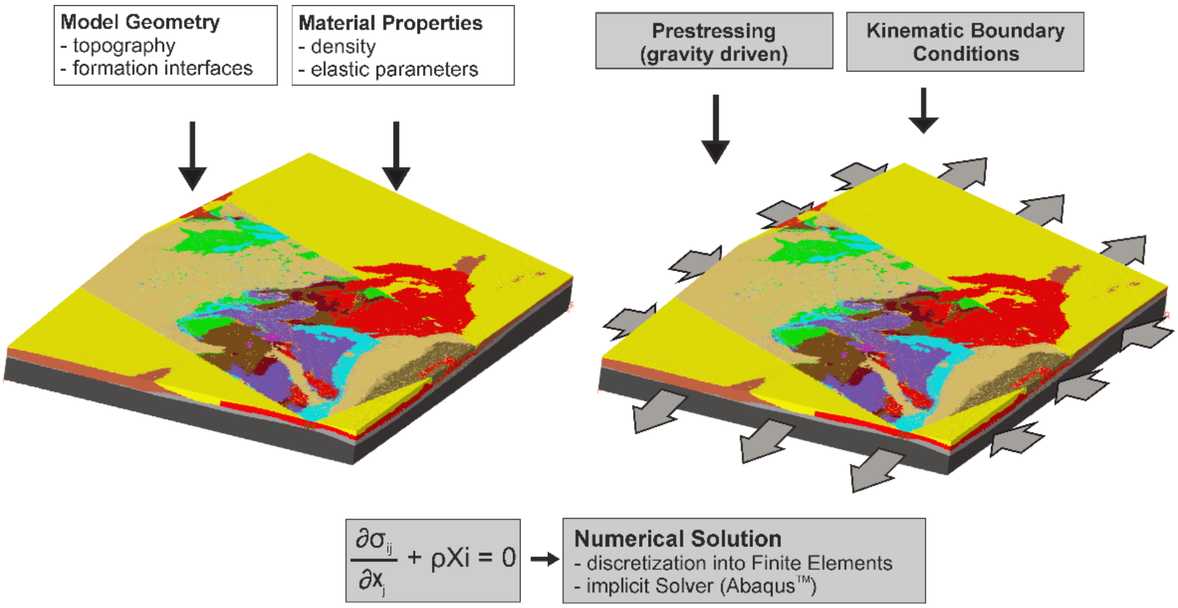

Figure 6: Workflow of the geomechanical-numerical modelling approach used (σ_{ij} stress tensor, x_j Cartesian coordinates, ρ density, and X_i body forces). The central part of the model, which covers the area of Germany, is indicated by a higher stratigraphic resolution.

Our model geometry is a combination of several geological models and additional 2D seismic sections. The final geometry has 50 different geological units which are discretized with about 10 million hexahedron elements resulting in a lateral resolution of about 4x4 km^2 and a vertical resolution of up to only 45 m in the upper five kilometres. Each geological unit is assigned to individual values of density, Young's modulus and Poisson's ratio. The orientation of the model boundaries is chosen in such a way that they are parallel or perpendicular to the prevailing S_{Hmax} orientation. The amount of applied displacements at the model boundaries is chosen in a way to achieve a best-fit of the modelled stress state in comparison to horizontal stress magnitude data.

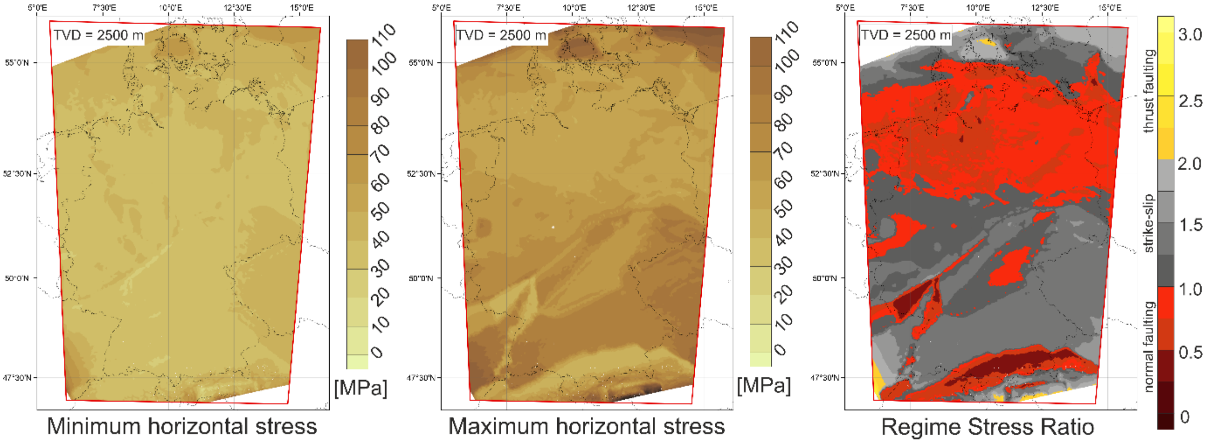

Figure 7: Depth slices showing minimum and maximum horizontal stresses and regime stress ratio at 2500 m true vertical depth predicted by the model.

The model results provide the complete stress tensor for the entire model volume. As an example, Figure 2 shows the minimum and maximum horizontal stresses for the area of Germany at a true vertical depth of 2500 m. In addition, the tectonic stress regime (normal faulting, strike-slip, thrust faulting is shown in terms of the regime stress ratio at the same depth. One application of the results is the estimation of slip tendency on a compilation of faults in Germany (Fig. 3). High values in the Upper Rhine Graben are consistent with the higher seismicity rate in this region.

Figure 8: Slip tendency (T_s) analysis of a representative fault set generic fault set using the model results.

Plio-Quaternary interaction between Adria and surrounding orogens: a Central-Northern Apennines perspective

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The evolution of the peri-Adriatic Apennine-Alpine-Dinaric-Hellenic orogenic system and Maghrebian
chain is associated with the convergence between the European and African plates and their interaction with the interposed Adria microplate. The present-day tectono-kinematic framework of the Adriatic and surrounding regions is analyzed with respect to structural setting of the Central-Northern Apennines, developed as a Pliocene lateral chain relative to the NW-SE Africa-Europe convergence. Within this context, the short-term kinematics of the Adria Plate, characterized by a firm NNE-directed kinematics relative to the stable Europe, seismicity and the crustal-lithospheric structure are taken into account to better understand the active interaction of Adria with the Pliocene-Quaternary evolution of the Central-Northern Apennine orogenic system and the building of the peri-Adriatic thrust belts, independently from the different geodynamic models that might trigger this kinematic framework.

In this study, the current central-northern portion of the Adria Plate is considered as dissected into four independent crustal/lithospheric blocks, characterized by distinctive kinematic patterns, structural and seismotectonic characteristics. By comparing and combining the present-day short-term kinematics, derived from geodetic measurements and the seismotectonic framework, considering the directions of P and T axes obtained from focal mechanisms solutions and stress data, with the tectonic setting across the Central-Northern Apennines and Adriatic foreland four main tectono-kinematic blocks are identified: i) The Adria foreland plate, Block 1); ii) The Pliocene-Quaternary Apennine orogenic wedge, Block 2; iii) The Quaternary extensional/transtensional domain, Block 3 and iv) The inner compressive domain, Block 4.

The characteristic counterclockwise roto-translational motion of the Adria Plate rules the active interaction among the identified kinematic blocks by triggering the following:

1) Deactivation, during Quaternary, of the Central-Southern Apennine thrust front and coupling of the orogenic wedge with the Apulian foreland domain.
2) Dragging and drifting towards NNE of the Northern Apennine orogenic wedge having an active thrust front from the Conero promontory, through the coastal area up to the Po Plain.
3) Differential velocities and kinematics between Blocks 2 and 3 triggering the seismogenic extensional deformation along the inner retro-Apennine domain.
4) Differential velocities within the foreland domain of Block 1 between the faster southern area (e.g. Gargano) and the slower northern sector (e.g. Po Plain), compensated by an active intra-plate deformation in the Central Adriatic (i.e. Mid-Adriatic Ridge), which is characterized by E-W-trending strike-slip and curved transpressional structures. The kinematic pattern of the Adria foreland domain is also triggering the active contractional deformation along the Southern Alps and Dinarides as well as the strike-slip transitional zone north to Istria.

The Morphology of Induced Tensile Fractures in Boreholes: Lessons learnt from Scientific Drilling

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Subsurface rock properties are strongly controlled by the presence of fractures, which can be pathways for fluid flow and effect the rock mass strength. Natural fractures are formed by tectonic deformation or other geological processes such as diagenesis. However, fractures can also be induced artificially while drilling a borehole, for instance as a result of stress concentrations or unbalanced fluid pressure. These induced fractures are routinely used to define the orientation of the (far-field) principal stresses and calibrate geomechanical models. Unfortunately, on borehole image logs the geometries of natural and induced fractures can be alike, impeding a reliable discrimination of these fracture types. Misinterpreting of natural fractures as induced fractures, or vice versa, is a common problem, leading to serious errors in the characterization of reservoirs as well as in the assessment of in-situ stresses (Barton & Zoback, 2000, *SPE IPCE*).

Here we present the results of NAGRA's scientific drilling campaign, which offers an unparalleled dataset for the discrimination and characterisation of induced fractures in boreholes. All wells drilled in the 'TBO' campaign 2019-2021 contain a continuous record of borehole image logs and whole cores. More than 5 km of whole core were examined and fully oriented by core goniometry. The direct correlation of the borehole wall and the core allowed to unambiguously discriminate natural fracture systems from induced fractures (Figure 1).

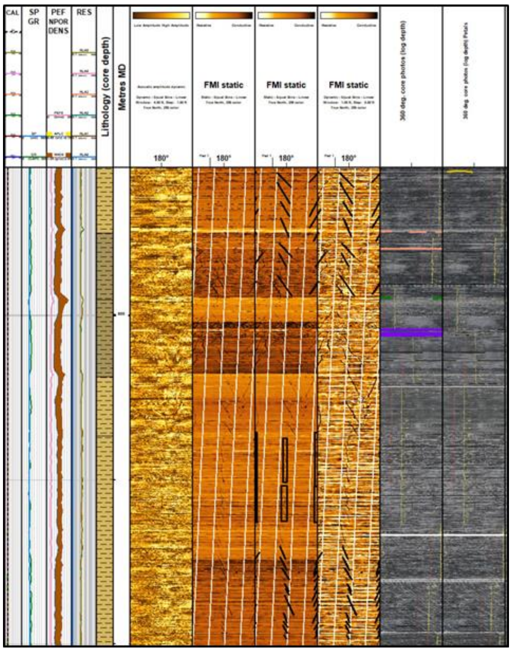

Figure 1. Unambiguous discrimination of induced and natural fractures by correlation of borehole image logs (BHI) and core data. The BHI shows numerous fractures at the borehole wall (black lines), whereas the core's circumference does not show any of these fractures. This proves that the fractures were induced during or after coring.

The systematic analysis of NAGRA's BHI and core data provided valuable insights into the morphology of induced tensile fractures at the borehole wall:

1) Atypical geometries of inclined fractures, which are not oriented co-axially with the (vertical) borehole, were identified. In vertical boreholes such fractures are commonly interpreted as the result of a non-Andersonian stress state, e.g. as a consequence of active faulting or stress perturbations caused by mechanical stratigraphy. The TBO wells of NAGRA revealed a stratigraphic control on the localisation of inclined induced fractures.

2) Several wells exhibited irregular fracture geometries that correlate with hydraulic fracturing and circulation losses. The integration with the drilling history showed that hydraulic fractures were generated during times of excessively high mud pressure. The observed hydraulic fractures typically show half-sinusoid geometries at the borehole wall (Figure 2), with fracture length of up to 20 m. Also, full sinusoids with short amplitudes, which are hard to discriminate from natural fractures without core data, were observed.

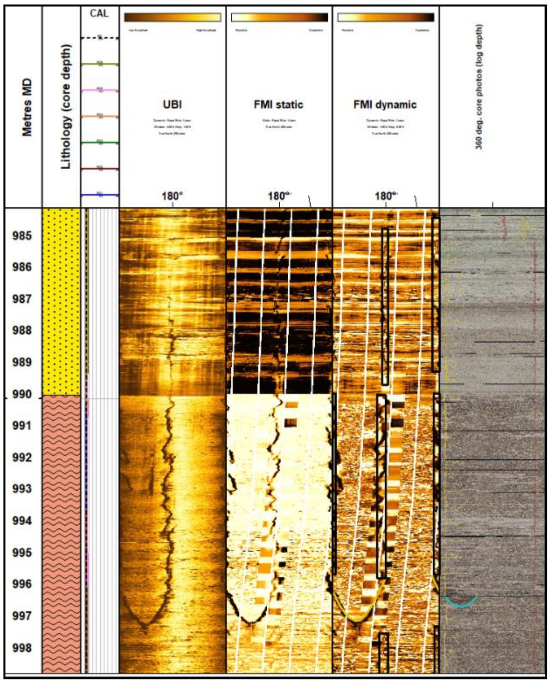

Figure 2. Hydraulic fracture associated with circulation losses. The fracture is sub-vertical and runs parallel to the borehole axis for about 15 m. At the bottom the BHI shows a half-sinusoid, indicating that the fracture tip bends away from the borehole.

The fracture morphologies obtained in this study were further used to design and calibrate 3D numerical forward models of drilling induced fractures. The numerical models illustrate that stepping DITFs geometries form when the wellbore is misaligned with the principal stress directions, as has been postulated in the literature. However, in a vertical wellbore, stepping fractures can also form in inclined mechanically layered sequences that are, at the large scale, under an Andersonian stress state.

The impact of tectonics on the geothermal resources distribution in the eastern Po Plain, northern Italy

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The subsoil of the morphologically flat southern Po Plain hosts the external sector of the Northern Apennines fault-and-thrust belt, whose persistent tectonic activity is well documented by both historical and instrumental seismicity. The buried accretionary wedge is partitioned in some major salients, one of which is the so-called Ferrara Arc. The latter basically corresponds to the investigated area. In the frame of the persisting regional shortening clearly confirmed by geodetic data, contractional deformation affecting this major tectonic feature is partitioned in several minor-order structures consisting of a system of low-to-medium angle reverse faults and associated folds. In these tectonic conditions, crustal scale volumes are characterized by differential vertical movements and particularly by localized uplift in correspondence of the hanging-walls blocks and especially of the hinge areas of these blind faults. On the other hand, the broader geodynamic setting is characterized by a regional-wide subsidence of the Adria foreland creating accommodation space in this wide intermountain region, which is continuously filled by the clastic deposits of the Po Plain. Accordingly, the competing role of the two tectonic processes affecting the subsoil together with sedimentation generated a complex geological setting in the subsoil with carbonate Mesozoic units locally at few hundred meters depth relatively close to pluri-kilometre thick Neogene clastic deposits. The consequent lithological lateral variability has a strong impact on the heat flow distribution across the region.

The present research is devoted to contributing on the characterization of the low-to-medium enthalpy geothermal resources of this sector of the Po Plain. To achieve the goal, first, we analysed temperature data in selected deep boreholes to estimate the local thermophysical parameters of the underground. In order to discriminate the influence of the circulation fluids and then estimate the real temperature values of the surrounding rocks, we applied different methodological approaches. Secondly, different deep seismic reflection profiles for hydrocarbon exploration were analysed to evaluate the main lithological formation and tectonic assessment. Thirdly, we elaborated hydrochemical data obtained from borehole and temperature logs measurement to estimate the influence of the deep geothermal fluids on the shallow aquifer systems. Finally, the integrated analysis of all collected and elaborated data allowed to infer both the horizontal and vertical temperature distributions, which are clearly strongly affected by the geological, hydrogeological and tectonic evolution of the region. Based on the results it is possible to recognize the sectors of the eastern Po Plain with a highest geothermal potential.

For the calculation and mapping of the geothermal gradients and the heat flow, two reference levels were considered corresponding to the base of the marine Quaternary, Qm, and the top of the Scaglia, SC. Significant variations in the geothermal gradient have been attributed to the development of convective flows within the carbonate sedimentary succession. Following this approach, areas with greater geothermal potential have been identified due to the higher temperatures, like in correspondence of the Casaglia and Vignola wells, where at 1000 m-depths the geothermal fluid reaches ca. 90° C and 50°C, respectively. The exploitation of this geothermal resource could take place through an open circuit system that includes a withdrawal well and one or two for reinjection. Currently in the Casaglia area, the fluid contained in the geothermal reservoir is exploited with a flow rate of 400 m^3/h, providing a renewable thermal energy power of approximately 14 MWh_t.

Slip-dilation tendencies and CFS within an oil-gas prospective basin in Costa Rica

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The thrust and fold Limón basin is in the Costa Rica Caribbean back-arc with a tectono-sedimentary column displaying an very interesting oil and gas potential, which have been mapped and drilled in the past to trace the origin of surface findings and is expected to become reevaluated soon.

It also hosted the largest earthquake (Mw 7,6) in the planet during 1991, and from the associated aftershocks, recorded with top quality data due to the very good coverage of seismological stations, 62 focal mechanisms were calculated and then inverted to obtain reliable and representative local stress tensors at 5 regional deformed sub-areas covering nearly 12,000 km^2.

The determined dominant maximum horizontal stress is predominantly aligned NE-SW within the southern Limón basin and subparallel to the Cocos-Caribbean plates convergence. However, at the limit with the northern sector, in the Moín paleo-high which is acting as a deflecting barrier, it undergoes a 37° counterclockwise rotation, adopting a NNE-SSW orientation. This study unveils the previously unidentified coexistence and partial overlap of localized contraction and distension in the sub-basins, providing their comprehensive characterization and paving the way to foresee new practical implications. The tensors, some displaying significant instability due to extremely low or high values of the ellipsoid $R=\sigma2-\sigma3/\sigma1-\sigma3$, were also employed to model by means of the MOVE and FracPaQ programs, the slip ($\tau/\sigma n$) and dilation ($Td=\sigma1-\sigma n/\sigma1-\sigma3$) tendencies on 40 regional faults and all nodal planes. The results are crucial to understand the present day expected relative opening of fault-fracture systems, in a very partitioned scenario, and their capability to conduit fluids and to trigger fault reactivation and/or generate new ones. This scenario in turn is complemented by a finite fault model of the Limón earthquake from the USGS, which was used to implement the Coulomb static stress transfer (CFS) method and to detect its optimal structures, adding a significant input to the fault kinematic potential determinations.

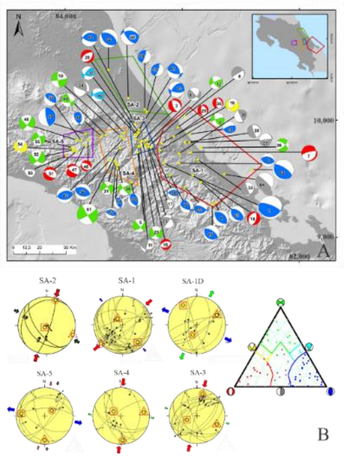
By integrating all the results, which also correlate very well with the interpretations of nearby breakouts, there is now a more realistic and coherent model that serves as a sound basis for further oil exploration and seismic-risk hazard studies.

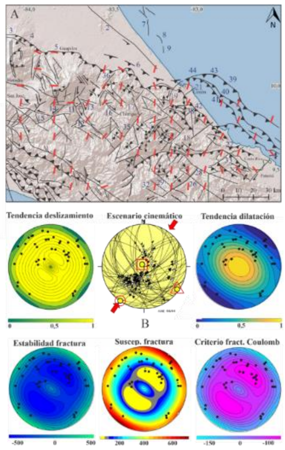
The poster and/or oral presentation includes, among other, figures depicting the

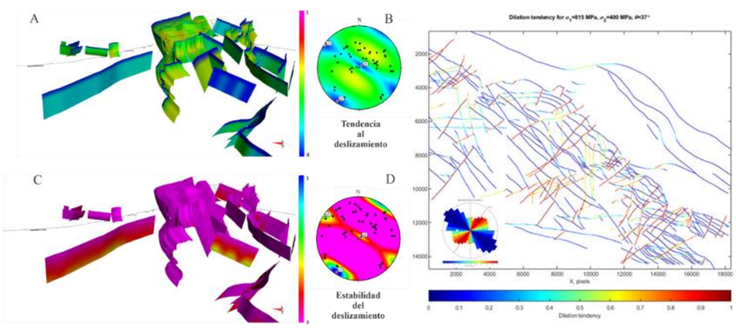
- Localities of the 62 focal mechanisms, their domains and calculated stress tensors.
- Statistics for the R, R’, friction angle, tectonic regime, and quality sensu WSM.
- Contouring of the R’ factor over the fault system map.
- Contouring of Ts at 10 Km depth, the mean of the aftershocks.
- CFS map and profiles with aftershocks epicenters, identifying reactivation prone faults.
- Stereograms for the Slip & dilation tendencies, fracture stability & susceptibility and Coulomb fracture criteria along with SH Max trajectories.
- 3D views for Ts and Slip stability along with their stereograms.
- Fault trace maps and rosettes showing the along strike variability of Ts and Td at different depths.
- Deformation couple synthetizing the structural findings.

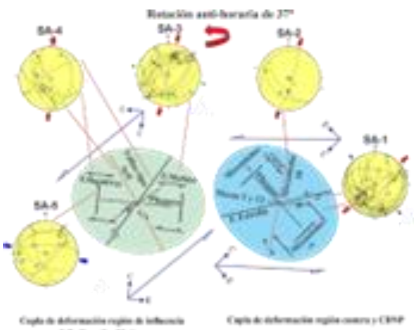
- 3D block with interpreted seismic profiles
- Results of Breakout interpretation and localities of tested drillings.

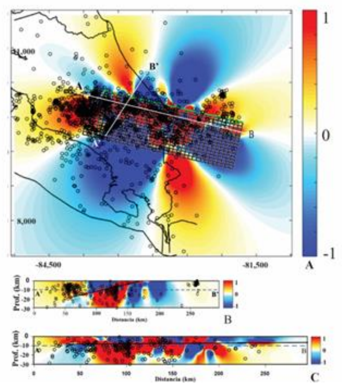
Some examples to be translated follow :

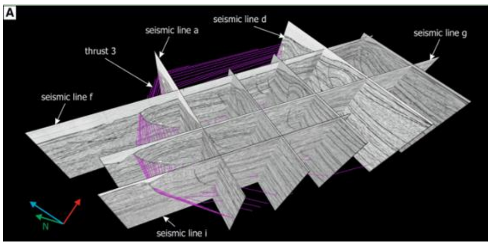












New seismologic inversion method for absolute crustal stress and deep pore-fluid pressure

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Lithospheric stress has a significant impact on the crustal deformation and tectonic structures. However, present-day absolute stress and pore-fluid pressure in deforming deep crust are poorly known because stress magnitude and fluid pressure cannot be measured directly below borehole depths. Here we build a seismologic inversion method to invert for the 3-D spatial distribution of absolute deviatoric stress and variation of strength with depth using focal mechanism solutions and coseismic stress changes produced by large earthquakes. We further analyze the deep pore-fluid pressures by assuming the pressure dependence of brittle crustal strength. We apply the method to the M9 Tohoku-oki earthquake and the M7.6 Chi-Chi earthquake and obtain a 1D crustal strength profile to 21 km depth of northern Japan and to 14 km depth of western Taiwan. We conclude that upper crust is weak in both northern Japan fore-arc crust and in western Taiwan and that effective stress and strength are regionally nearly homogeneous with depth in the deforming western Taiwan plate-boundary zone.

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