The role of anisotropy and heterogeneity in Geothermal systems in meta-sedimentary rocks

Yves Vanbrabant

(Geological Survey of Belgium)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037

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Havelange demo-site presentation

What is anisotropy and heterogeinity?

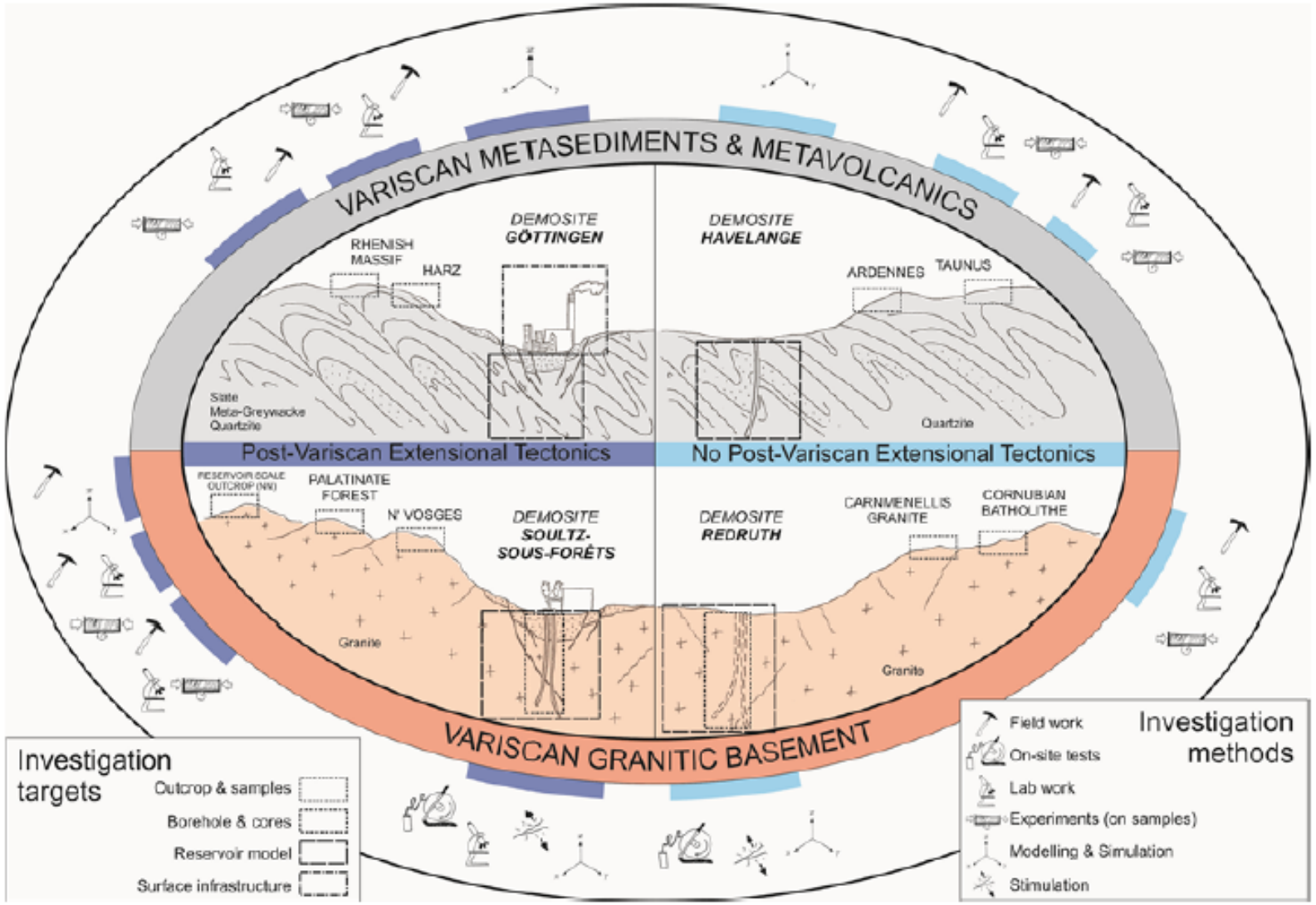
Anisotropy in Geology

Study case 1: thermal conductivity

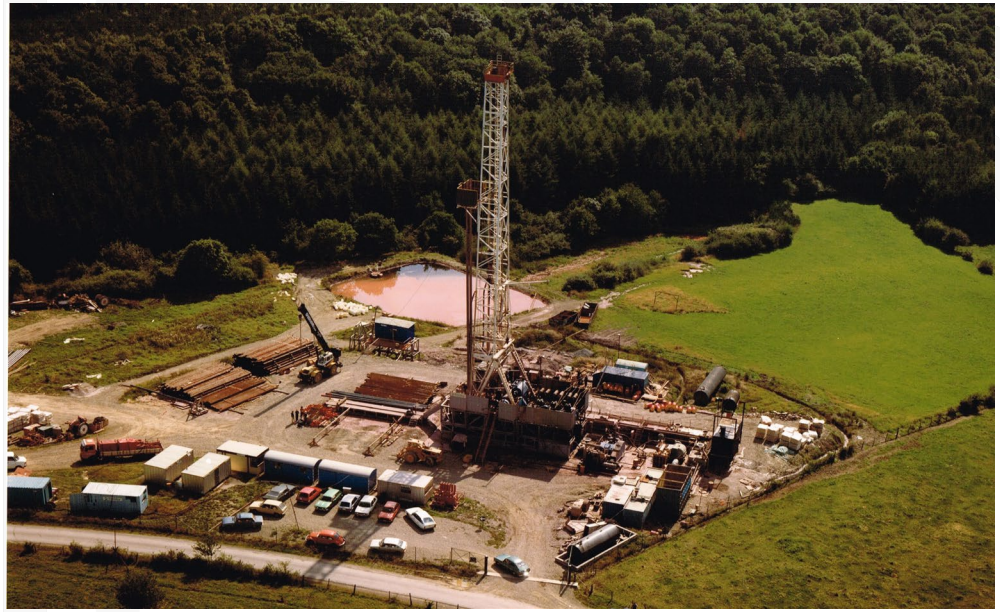
Study case 2: rock fracturation in metasedimentary formations

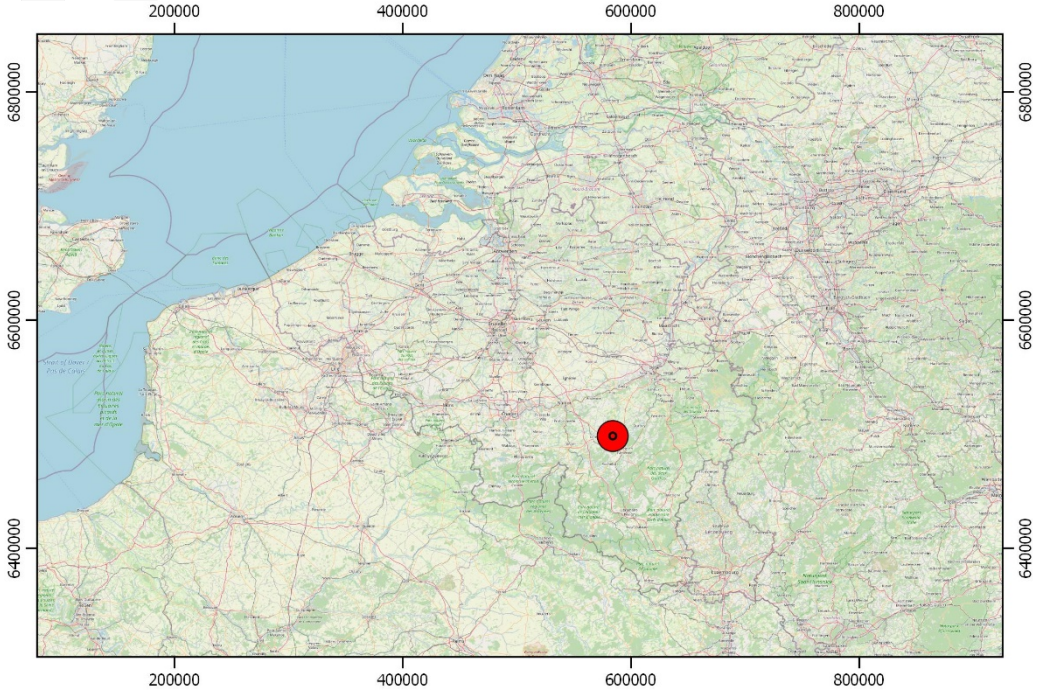
Take-away message

Havelange demo-site in the MEET project



Havelange borehole ID-card





Drilled from 1981->1984 near the village of Nettine (Belgium)

Reached a maximum depth of 5648 m (MD)

Aim: gas exploration well targeting hidden Upper Carboniferous coal measures under the main detachment level (Midi Thrust Fault)

Encountered stratigraphy from Upper- to Lower-Devonian formations

Located in the Dinant Synclinorium: a sub-unit of the Ardenne Allochthon part of the Rhenohercynian fold-and-thrust belt (Variscan Orogeny)

Located about 23 km South of the Variscan Front

Geothermal targets: Lower Devonian quartzite units observed ~4.3 -> 5.3 km

Recorded temperature (down hole): 126°C

Havelange available information

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Cuttings samples (one sample every 1 to 5 m) + cores at shallow depth (Famennian shales) and at great depth (quartzite)

Logs (paper-format) -> during the MEET project: GR, Dipmeter, Sonic, Caliper were digitized

8 seismic lines were shot in 1978

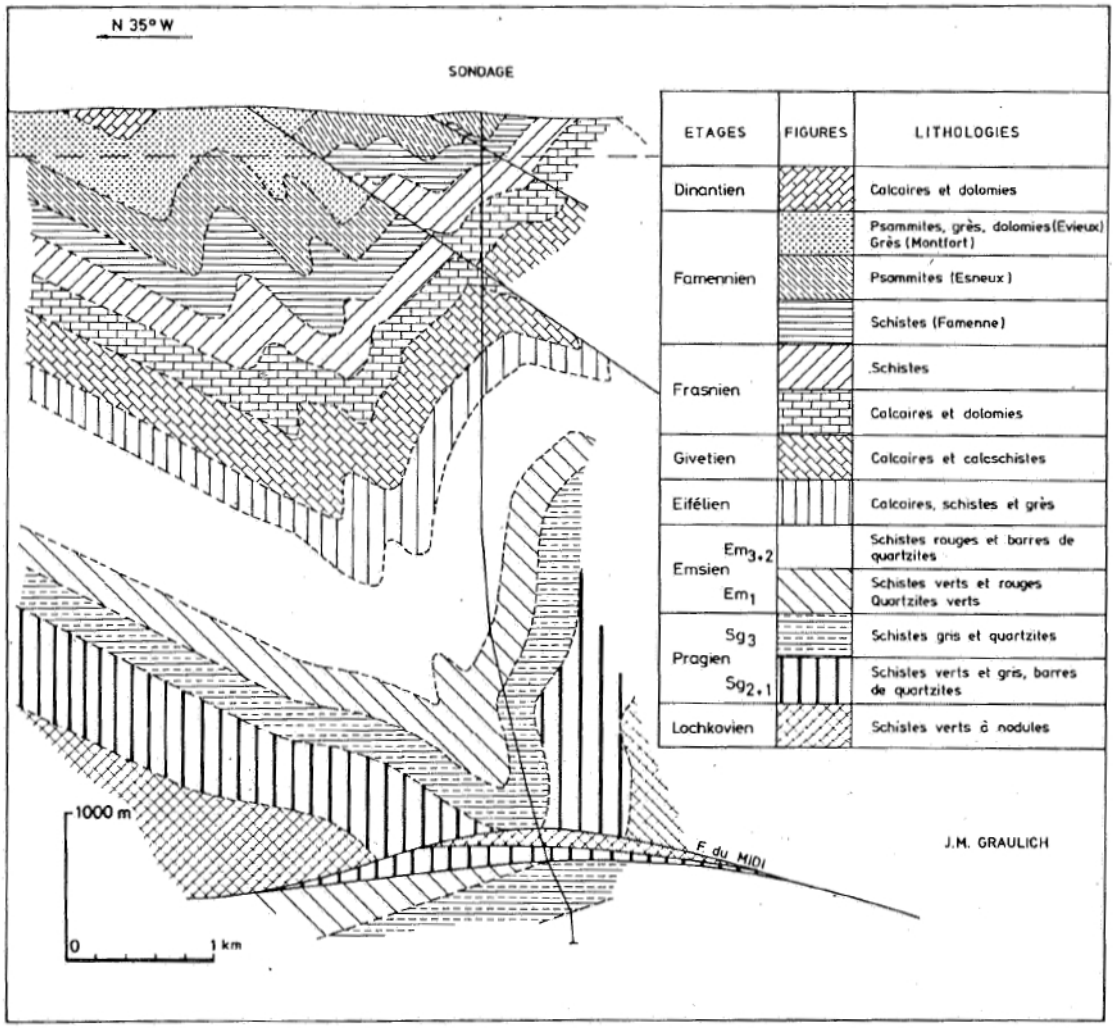
During the MEET project, additional information were collected:

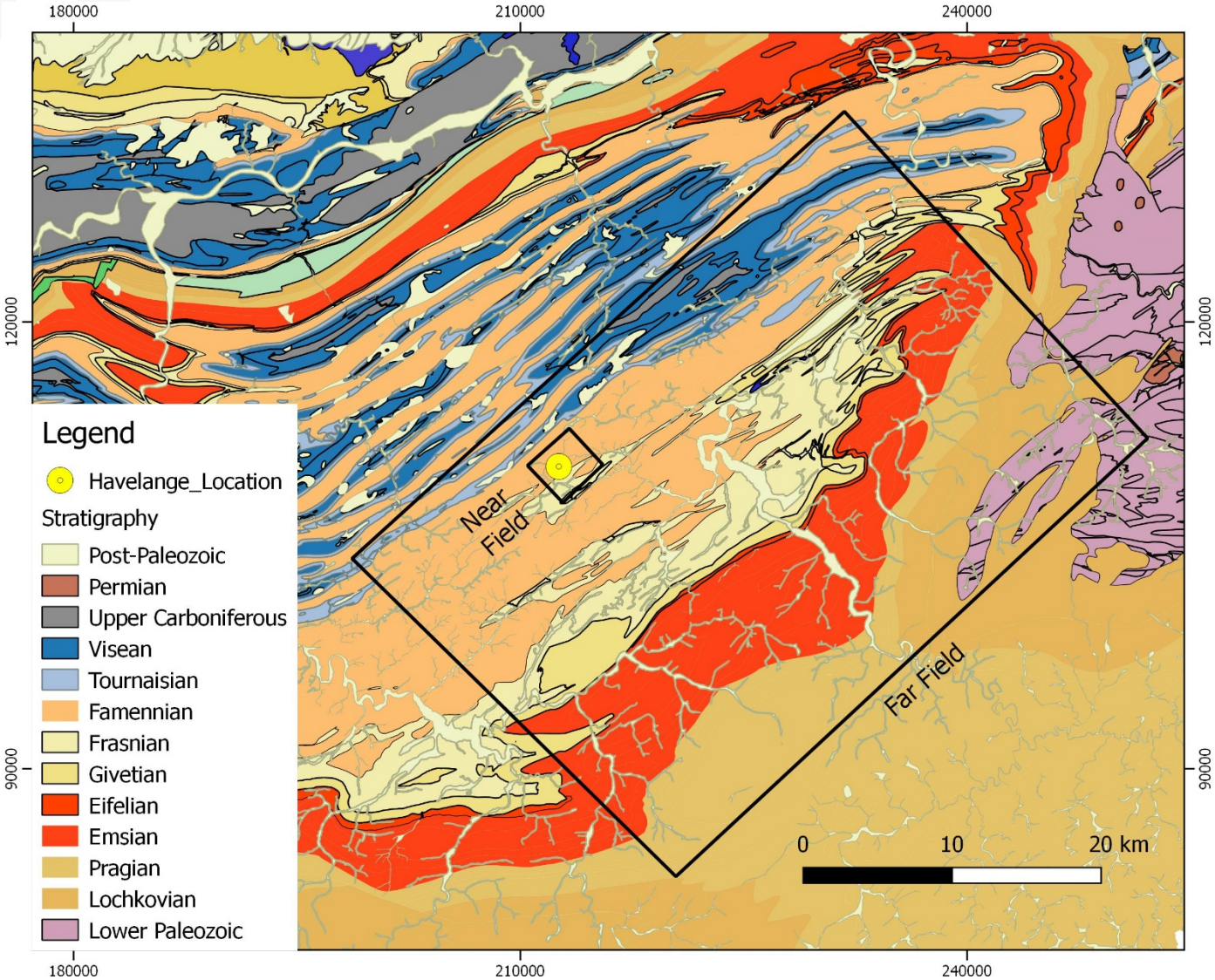
- Restudy of the mineralogical composition of cutting and core samples;
- Restudy of daily drilling report (mud lost analyses);

In the near-field: main activities were the acquisition of drone image during the drought period of Summer 2018 and sampling of spring water

In the far-field (analogue field): main activities were study of outcrops, collect rock samples for rock mechanical tests and sampling of spring water

Havelange analog field and field works





What is anisotropy?

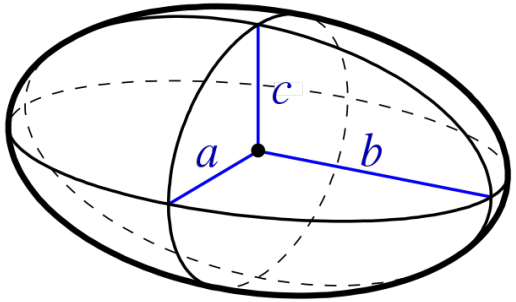
The definition of Wikipedia: Anisotropy is the property of a material which allows it to change or assume different properties in different directions

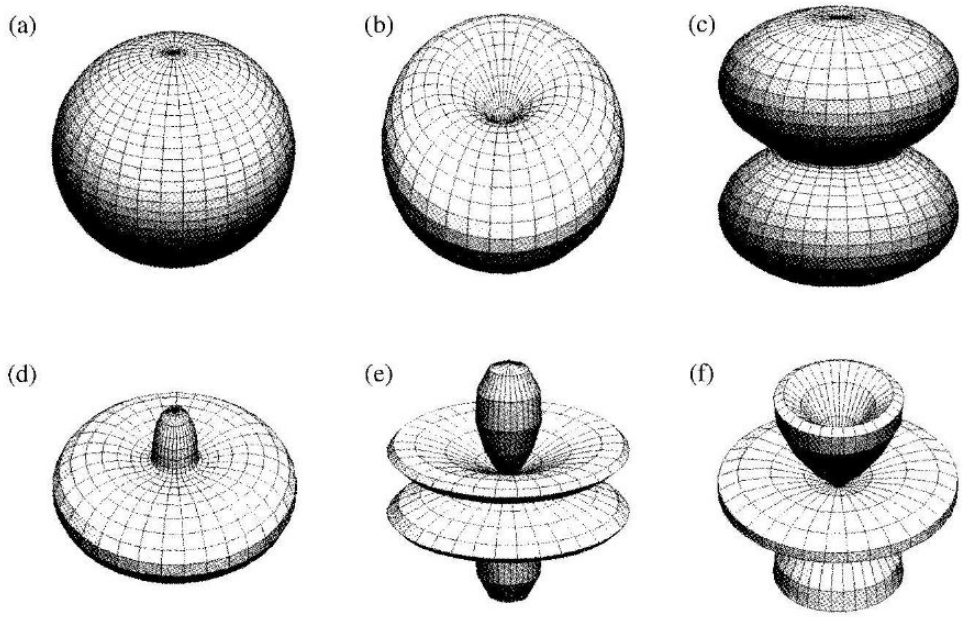
Anisotropy >< Isotropy

For the simple cases: anisotropy in 2D can be defined as a ratio: Param_in_max_direction/Param_in_min_direction (@90°) and for those cases the anisotropy is represented by an ellipse(2D)/ellipsoid (3D).

The isotropy is represented by a circle(2D)/sphere (3D).

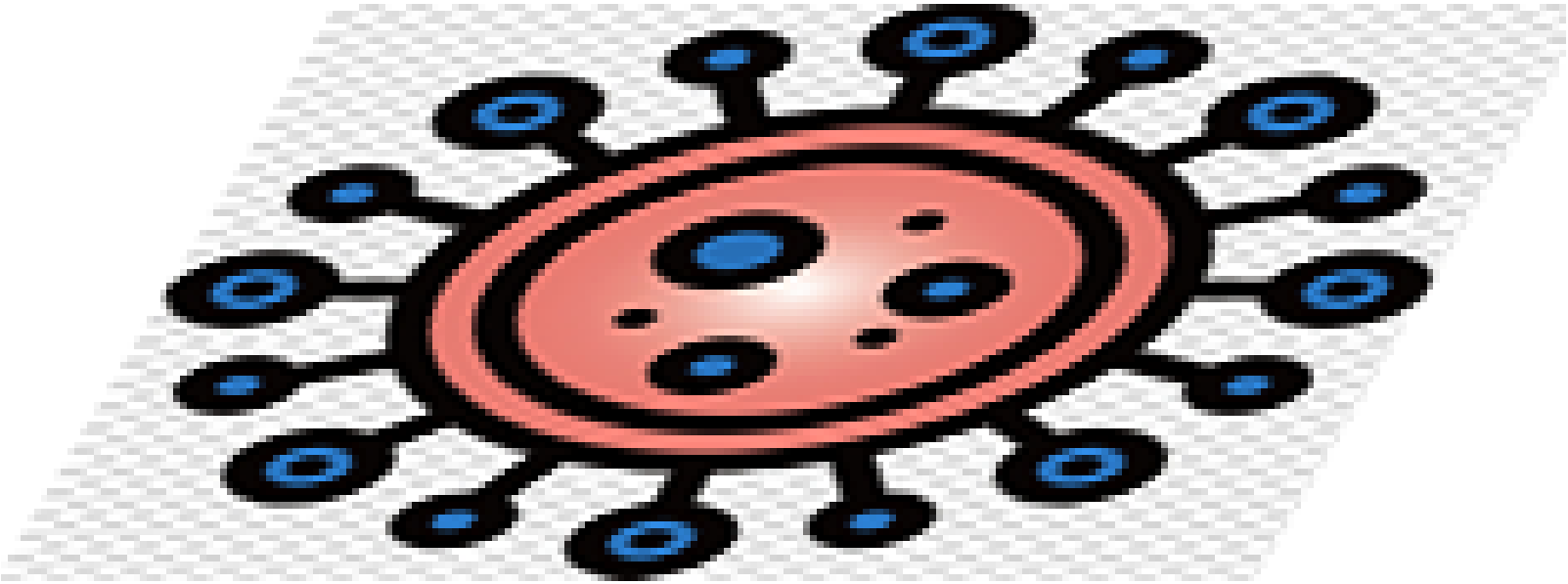
In other cases the anisotropy representation is more complex.



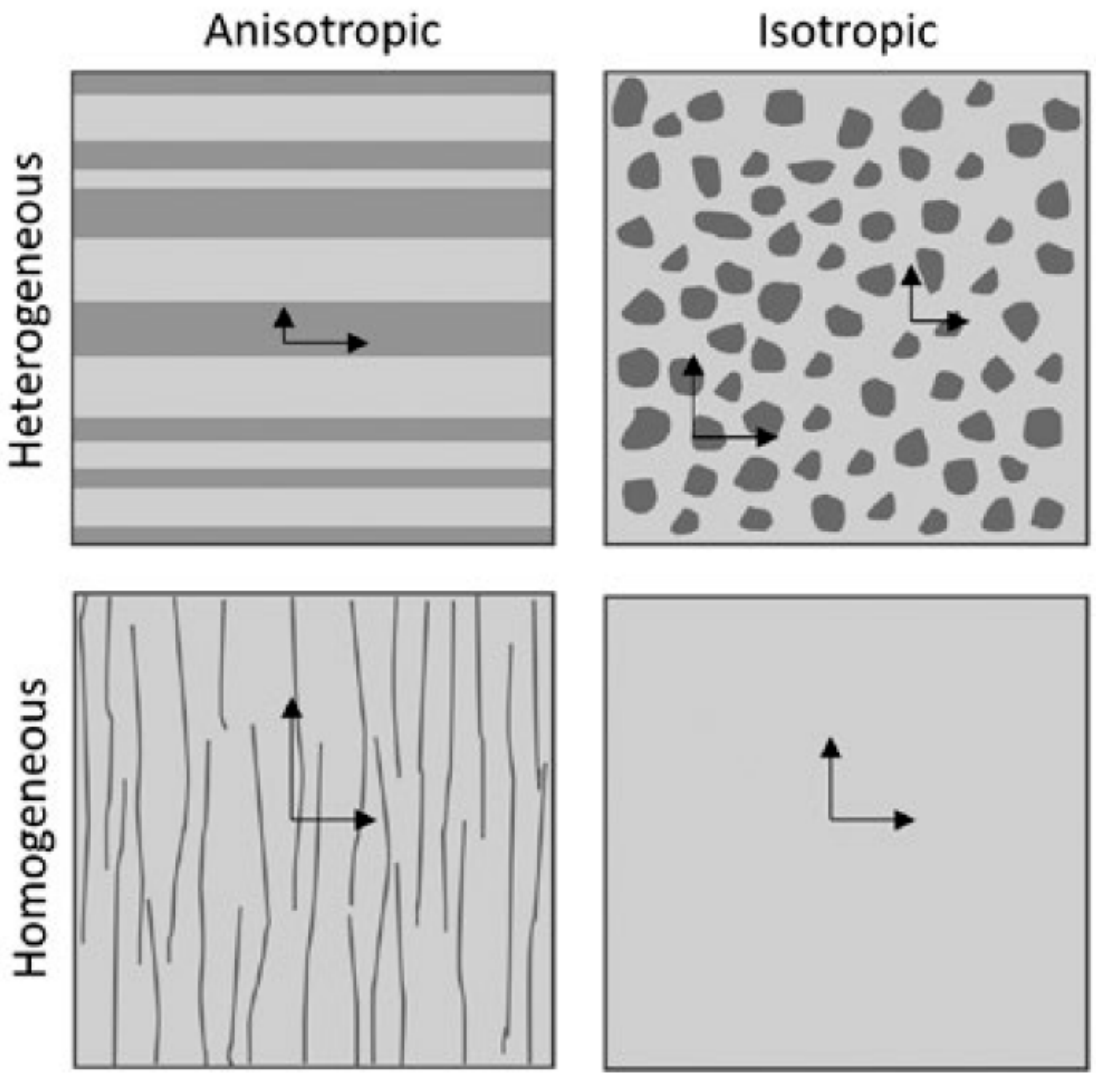


Skomski (2008)

Or even has a weird shape …



Anisotropy vs heterogenity?



Lynn (2018)

Anisotropy in Geology

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Anisotropy in Geology is present in numerous geological settings, at **different scales** regarding several properties.

Some examples of anisotropy in rocks: mineral plasticity, elasticity, fabric, sonic, electrical conductivity, thermal conductivity & expansion, magnetism, permeability …

Anisotropy is also strongly link to a scale: from a single crystal (plasticity, electrical conductivity), to hand-specimen or an outcrop for a field geologist or even at the scale of geological sequences or formations

The origin of anisotropy in a rock happens at different moment in the Geological cycle: intrinsic or primary anisotropy during sedimentary rock deposit and diagenesis to secondary anisotropy developing during tectonic processes (e.g. cleavage development related to stress)

Is it important to take in account anisotropy during modelling?

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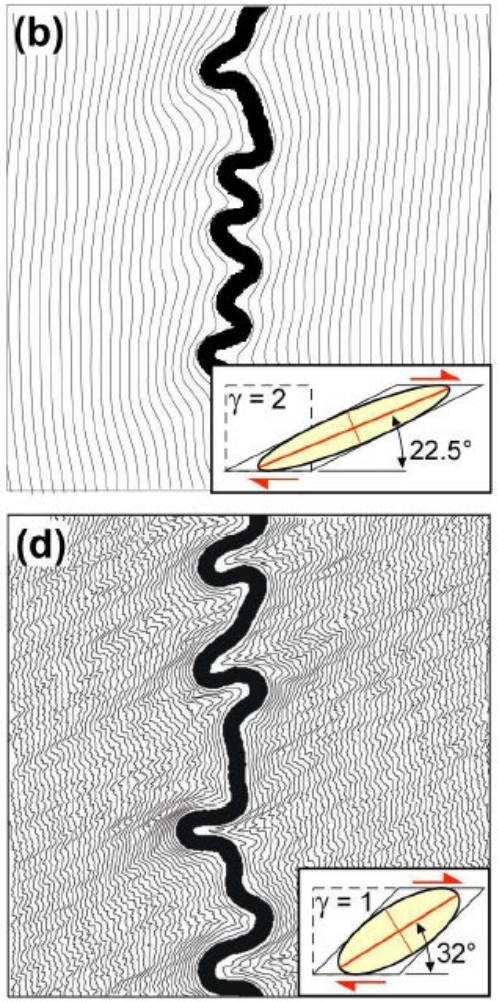
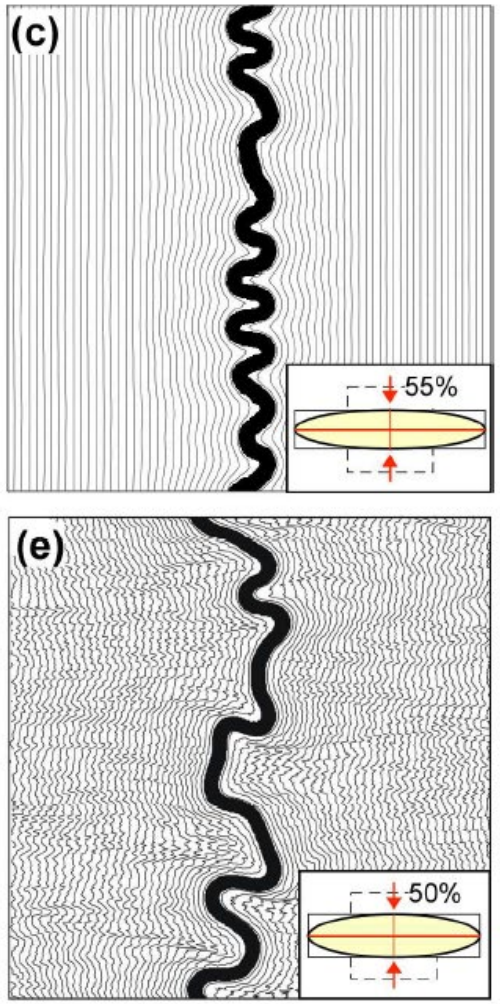
Crenulation cleavage

Ran et al. (2018)



Simple shear



Pure shear

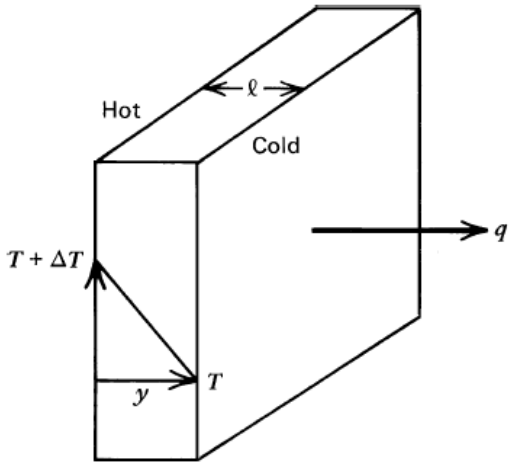
Isotropic rheologies
Folding seeds =
Variation of single layer thickness

« Anisotropic » rheologies taking into account mechnical anisotropy of the matrix.
Folding result from random variations in lattice orientation

Study case 1: thermal conductivity anisotropy

Reminder:

Heat transfer mechanisms: conduction, convection and radiation



(Turcotte & Schubert, 2002)

Let's consider a 1D-approach of Fourier's Law of Heat Conduction:

q is the heat flux

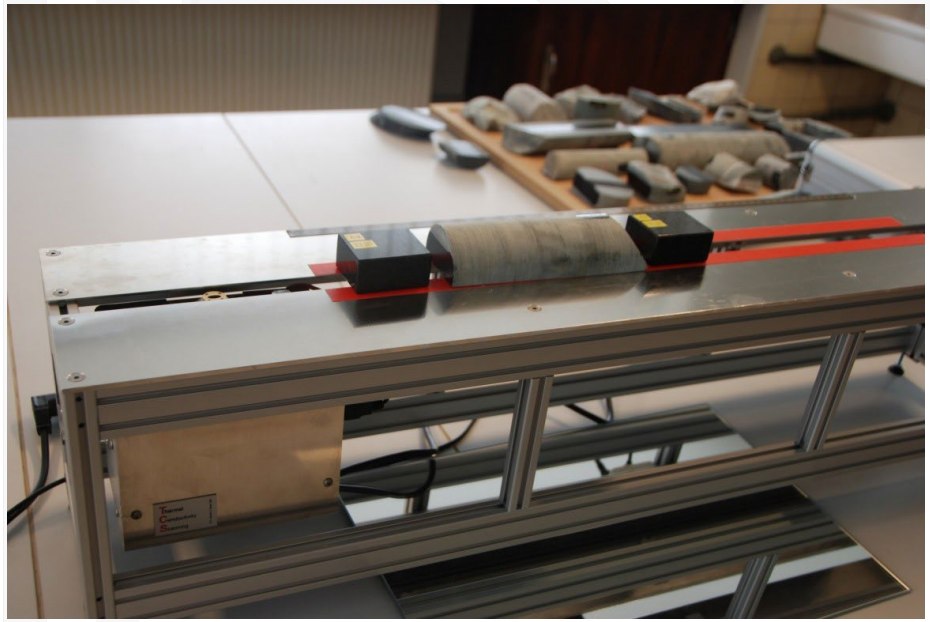
$$q = -k\,\frac{\Delta T}{l} \qquad [\mathrm{W/m^2}]$$

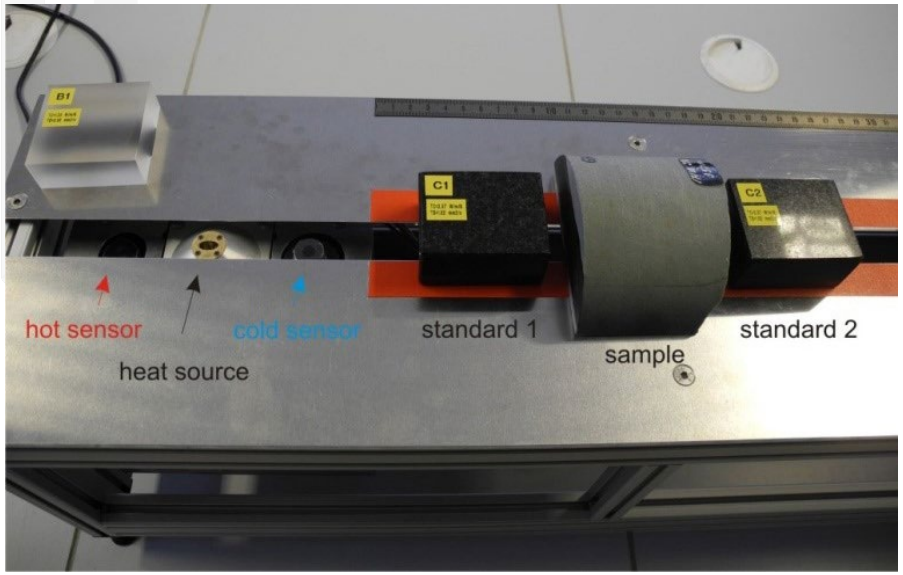
k is the coefficient of thermal conductivity $[Wm^{-1}K^{-1}]$

k for rocks ranges from ~1.2 (shale) to ~5 (dolomite, quartzite)

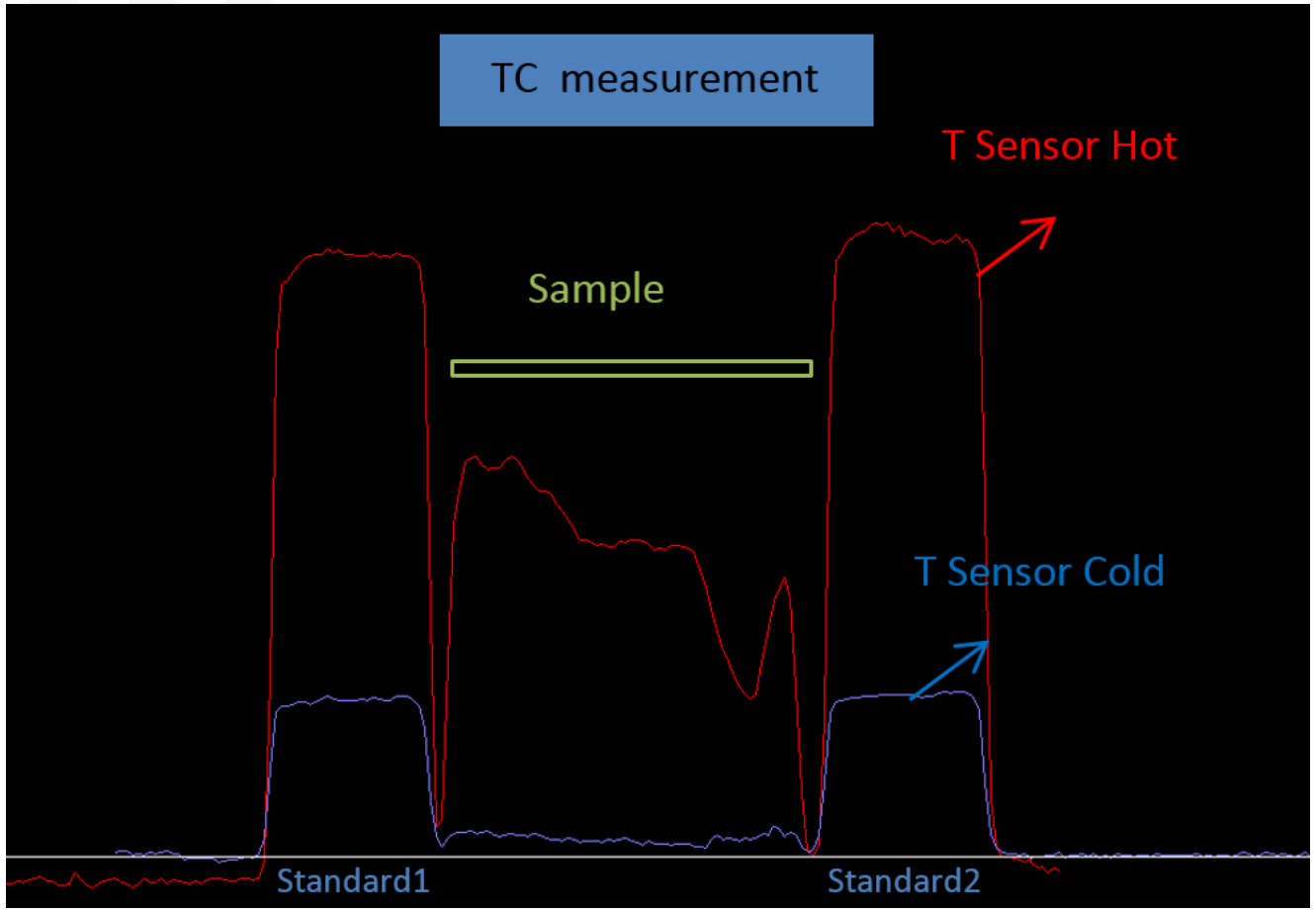
k values can be measured in lab or directly in borehole conditions

Thermal Conductivity Measurements @GSB





Thermal Conductivity Scanning – TCS



(Popov et al., 1999, 2012 ; Hartmann, 2005)

Thermal conductivity anisotropy

Regarding metasedimentary formations:

Laminated rocks conduct heat preferentially parallel to bedding planes

k values measurement are conducted on surface perpendicular to bedding according for at least 2 directions: parallel to the bedding (k_{par}) and perpendicular to the bedding (k_{perp}, usually = k_{min})

We can define the anisotropy as the ratio k_{par}/k_{perp}. According to Davis et al. (2007), anisotropy values range between 0.8 and 2.1.

For a given angle we can derive an apparent thermal conductivy (k_{app})

(Davis et al., 2007)

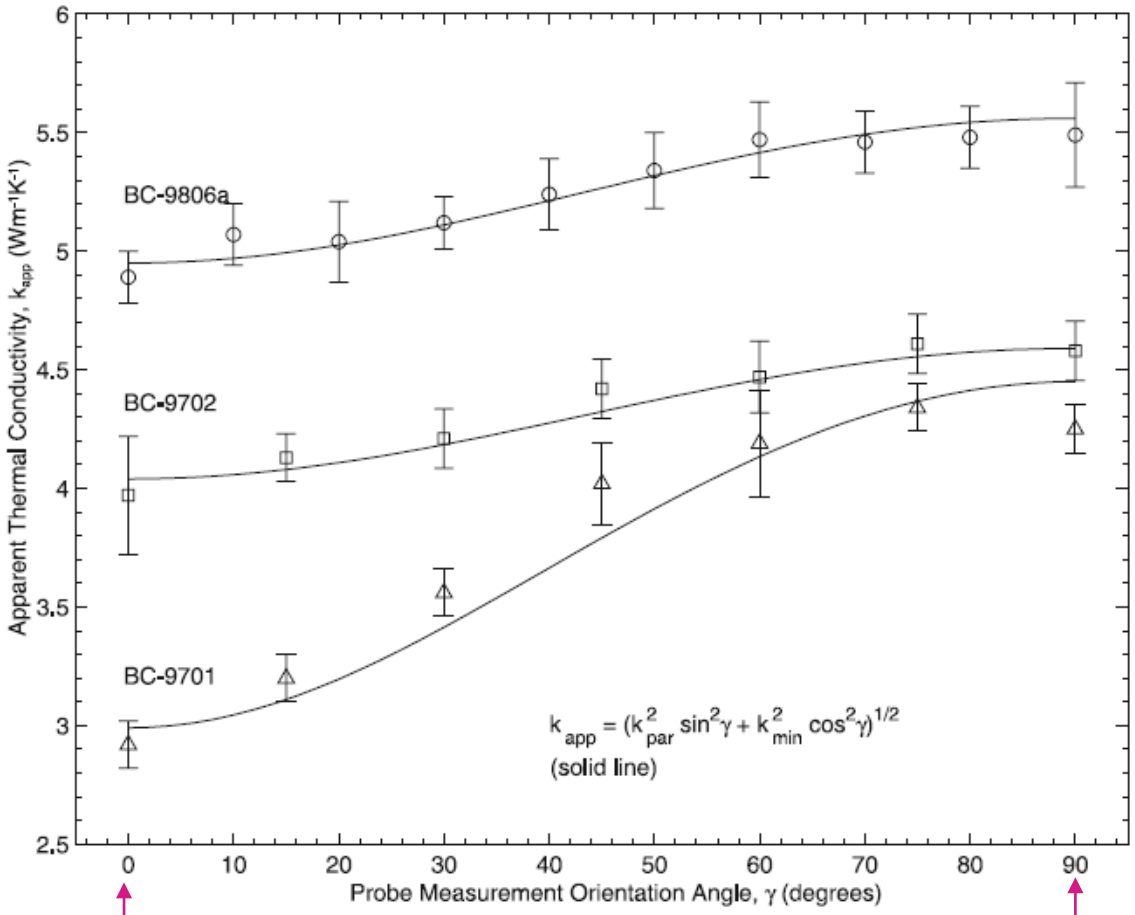


Figure 2. Apparent thermal conductivity as a function of probe orientation for samples BC-9701, BC-9702 and BC-9806a. BC-9806a has been offset by a value of 1 $Wm^{-1}K^{-1}$ to differentiate it from the other samples. Bars indicate the standard deviation of six or more measurements during one sample determination.

Measurement ⊥ to S0

Measurement // to S0

Exercise 1 – Impact of anistropy of q

$$q = -k\,\frac{\Delta T}{l} \qquad [\mathrm{W/m^2}]$$

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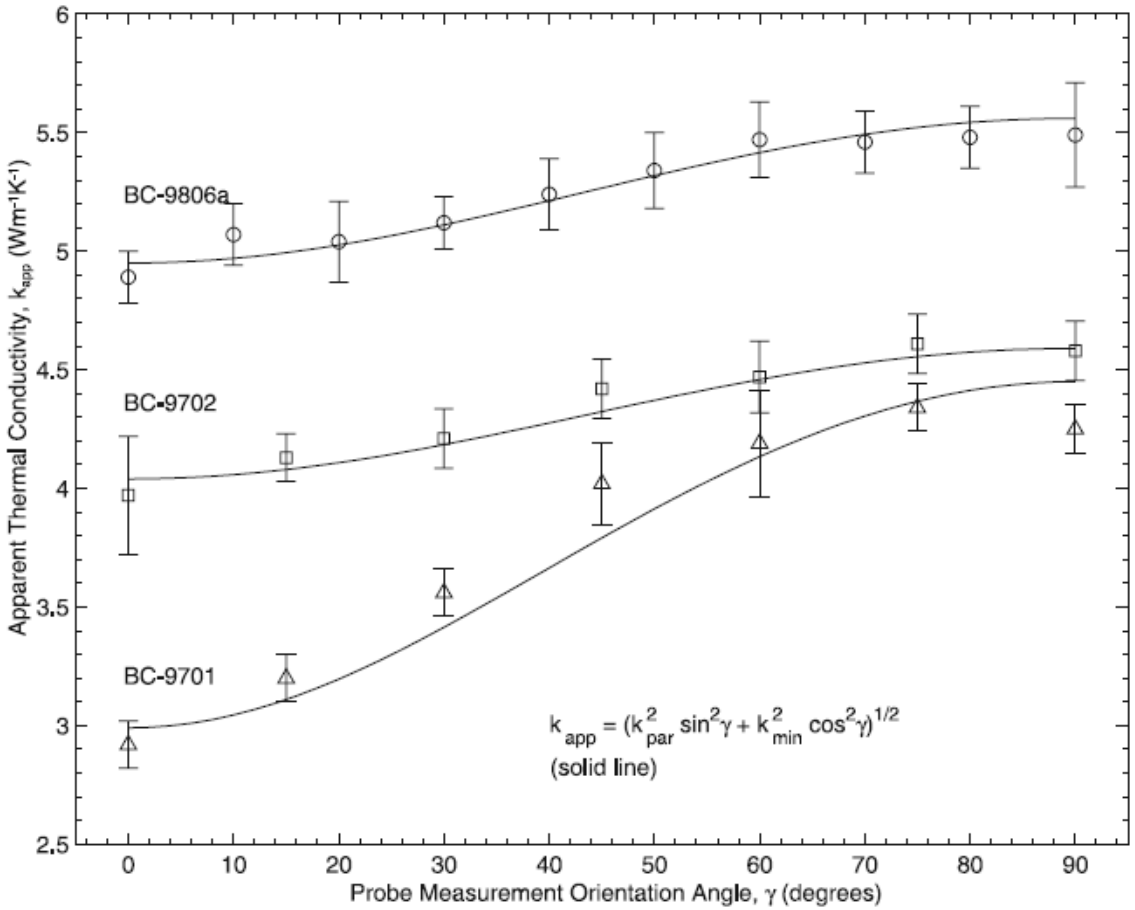
If we consider the Fourier's Law in 1D applied on the measurements conducted by Davis on sample BC-9701.

What is the computed k_{app} if the probe measurement orientation angle 40°?

What is the impact on q-value if the heat flux (Y) occurs perpendicular to the rock fabric with respect to the flux occuring // to this fabric?

Hints: you can consider for instance a difference of 3° between the hot and cold faces of the slab and its thickness is 100 m



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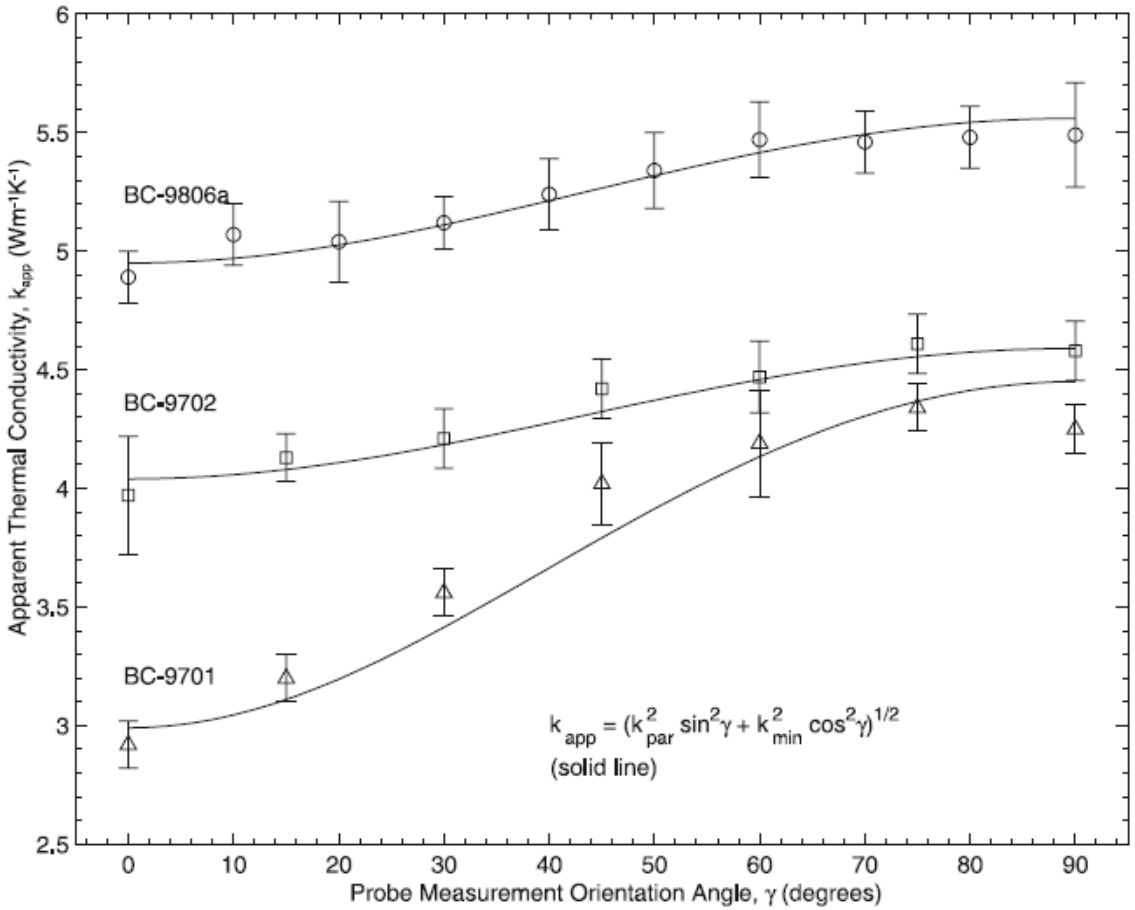

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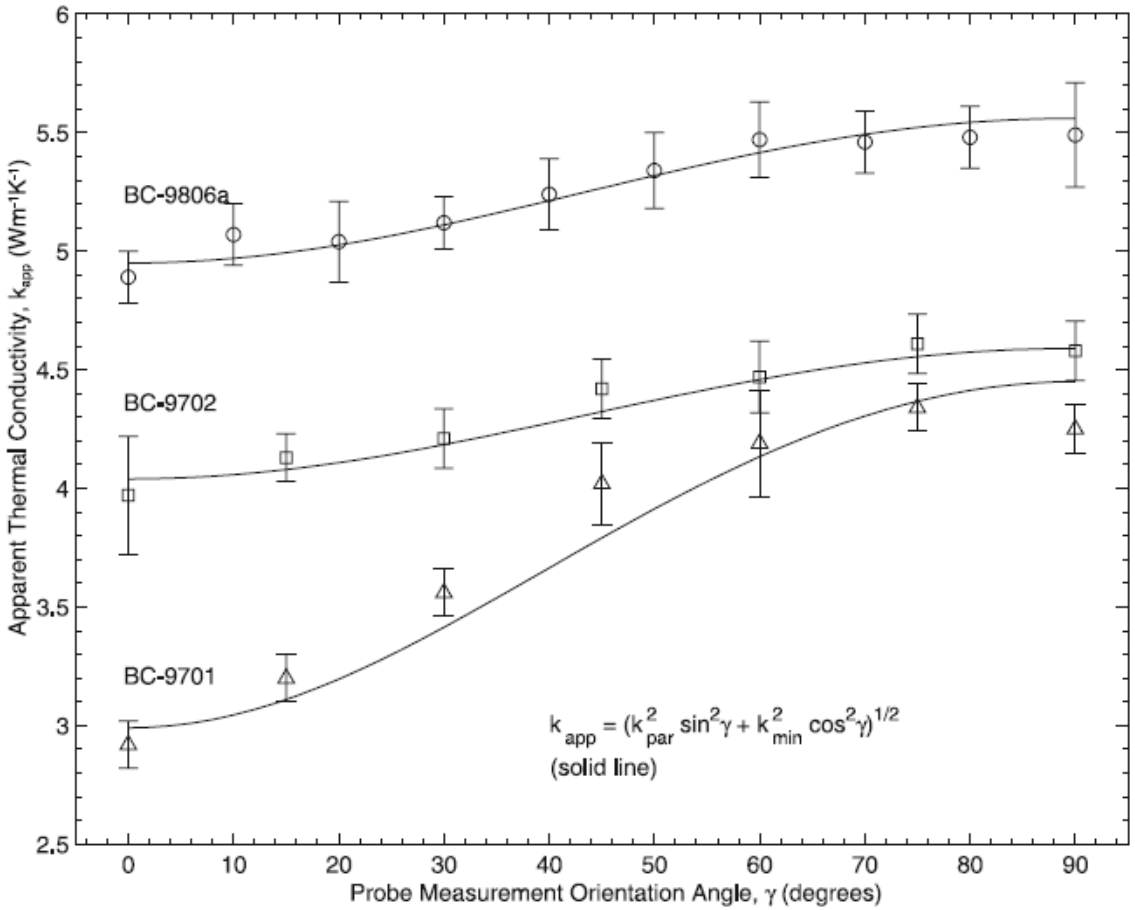
q// = 4.45 * 0.03 = 0.134 Wm-2
q ⊥ = 3.00 * 0.03 = 0.090 Wm-2
Reduction of ~33% of q



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Additional remarks/thoughts

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- The impact of thermal conductivity anisotropy is significant mainly for strongly laminated rocks (e.g. shale, slate). For non-fracturate granite: thermal conductivity -> isotropy
- For highly anisotropic materials it would be better to provide 2 k-values: one parallel to the bedding and one perpendicular
- The presented approach here is oversimplified (1D) and we have consider only the heat transfer of conduction, other factors or processes should be taken into account are: the convection -> permeability anisotropic, but also the heat generation

Study case 2: Rock fracturation in cases of heterogenous sequences

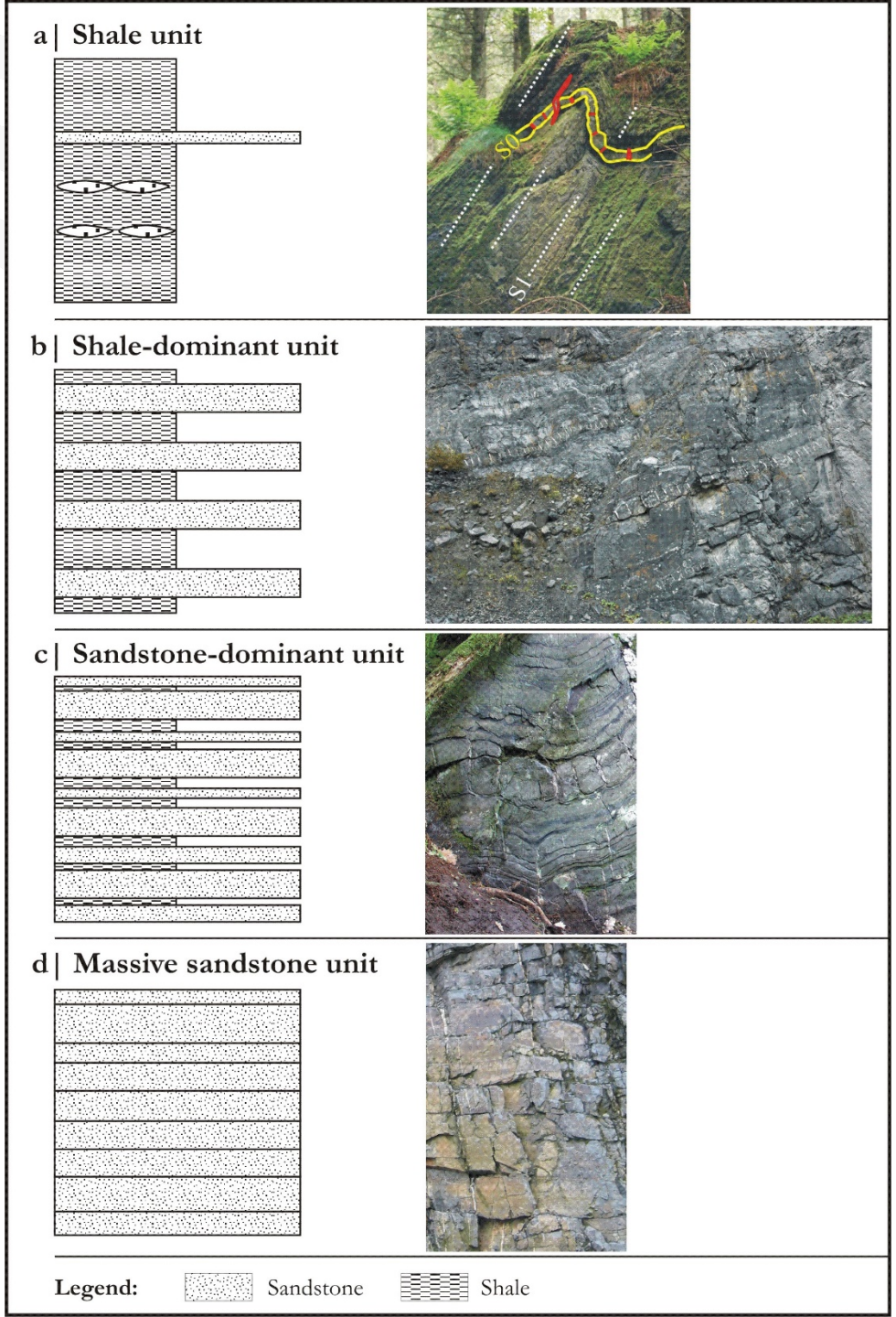
Presented cases come from the Belgian Ardenne

Lithologies: sandstone, quartzite and shale/slate layers

Rock sequences underwent first an extensional period during the metamorphism peak (basin in mature state) followed by a shortening period during the Variscan orogeny (330-300 Ma)

During the extensional period, rock formations underwent fracturation with the development of quartz veins.

Metamorphism grade: green-schist facies



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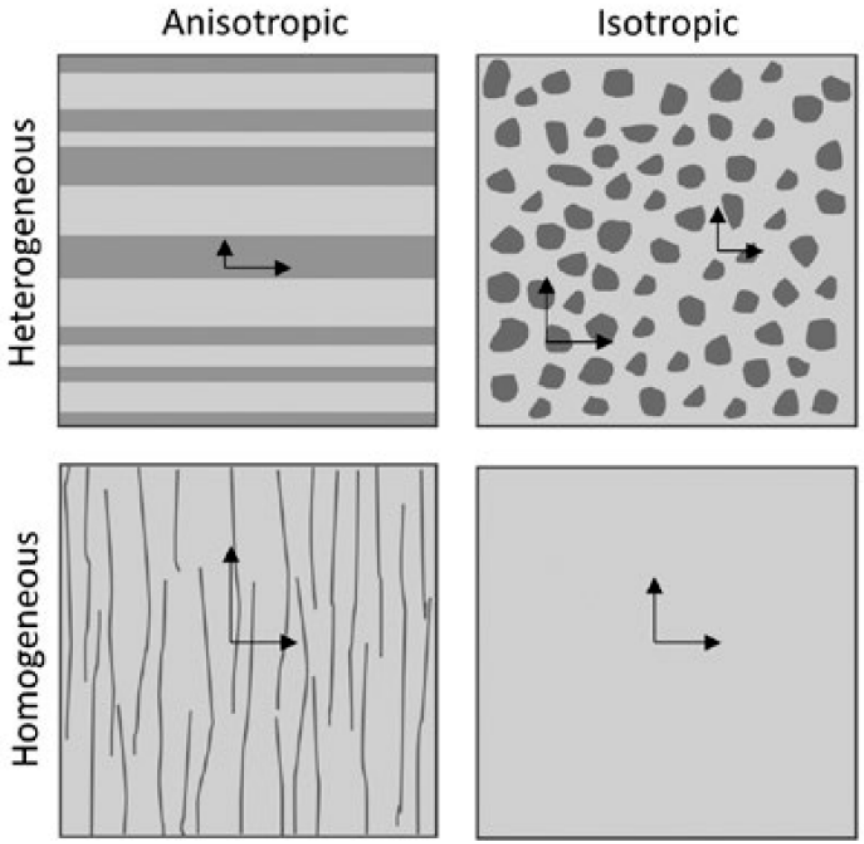
Fractures in a massive sandstone unit



Fractures in a sandstone-dominant unit

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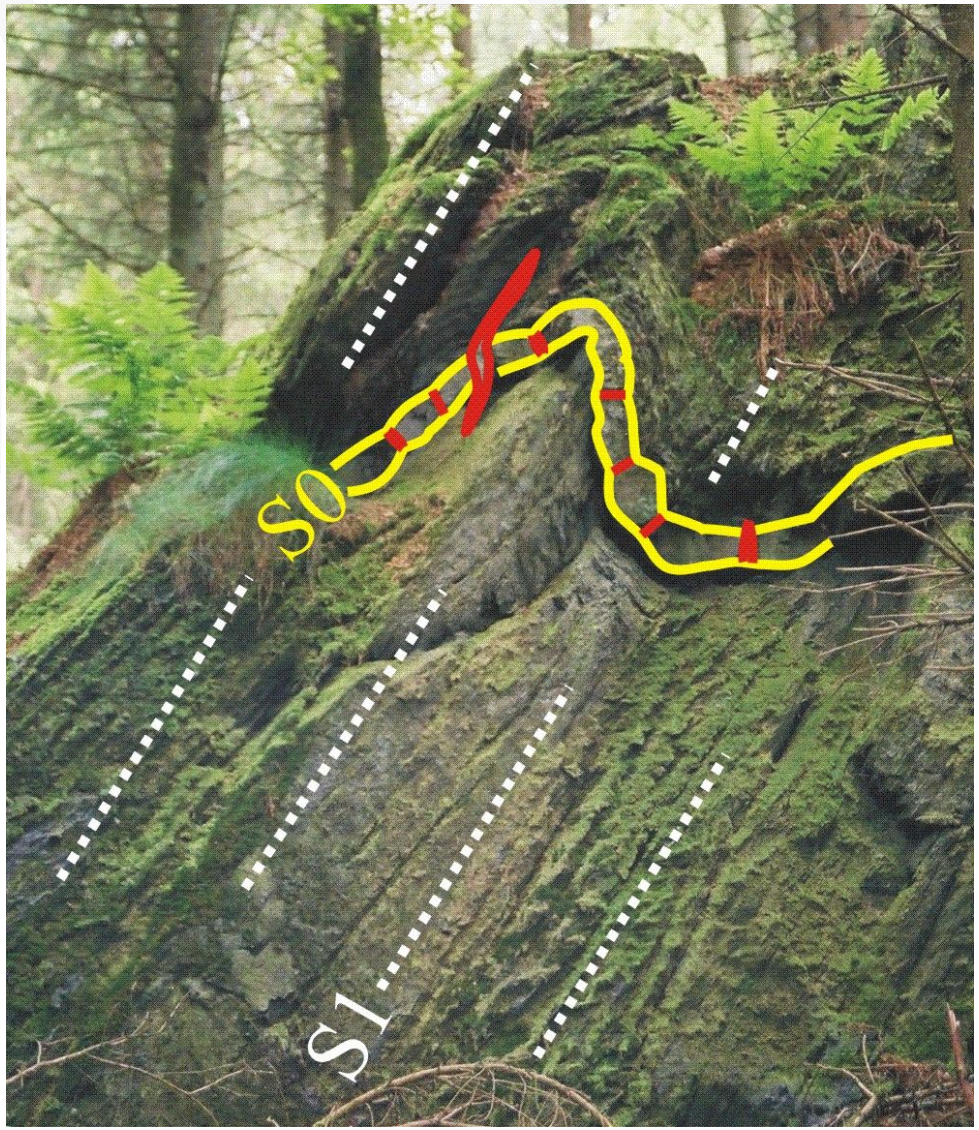
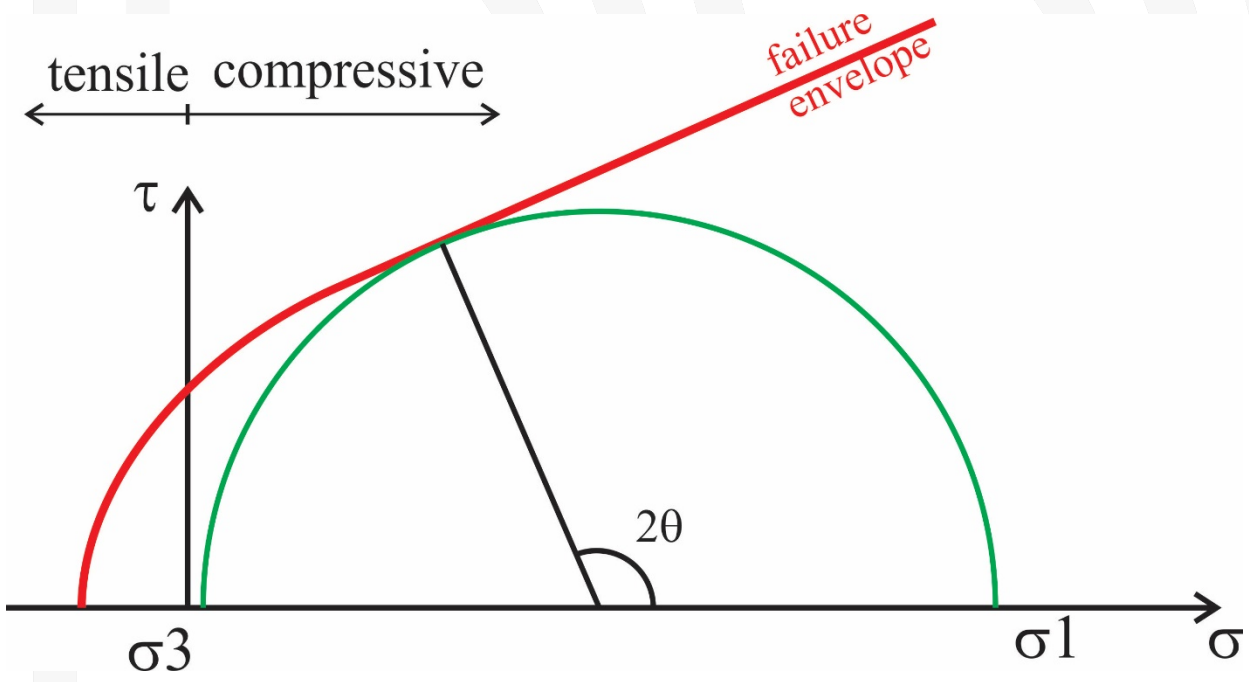
Fractures in a shale unit



Mohr's circle: Reminder



It's a convenient and geometrical approach to represent the stress state

It links the normal stress (σ) to the shear stress (τ)

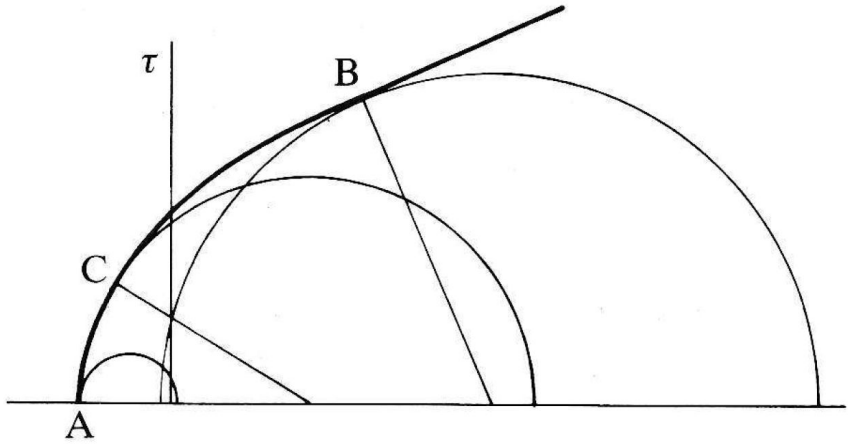
The failure envelope defines the differential stress ($\sigma1$-$\sigma3$) required for a failure to occur

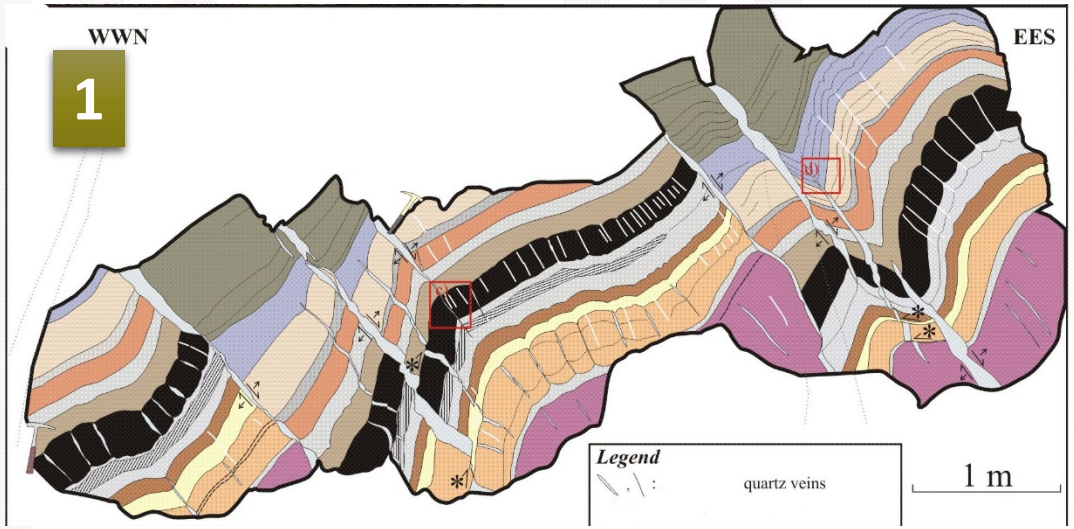
The newly-formed fracture develop at an angle θ with respect to $\sigma1$ orientation

There are 2 main domains: tensile and compressive

Tensile stress conditions can occur in rocks due to high fluid pressure

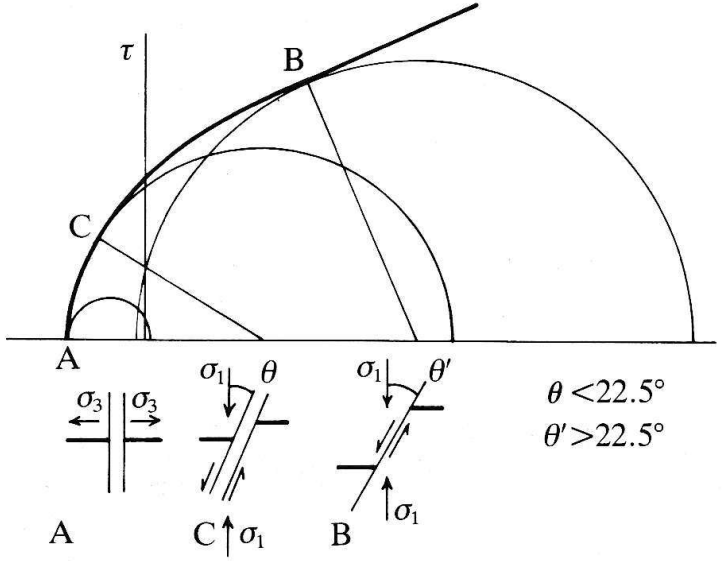
Exercise 2 – Classify the fractures according to their Morh's circle

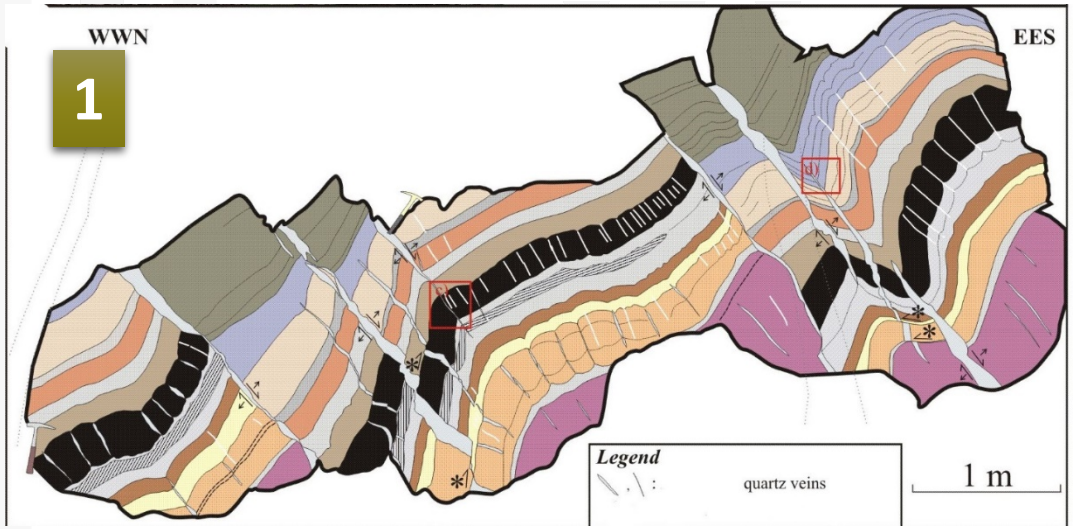




Circle-A	Circle-B	Circle-C

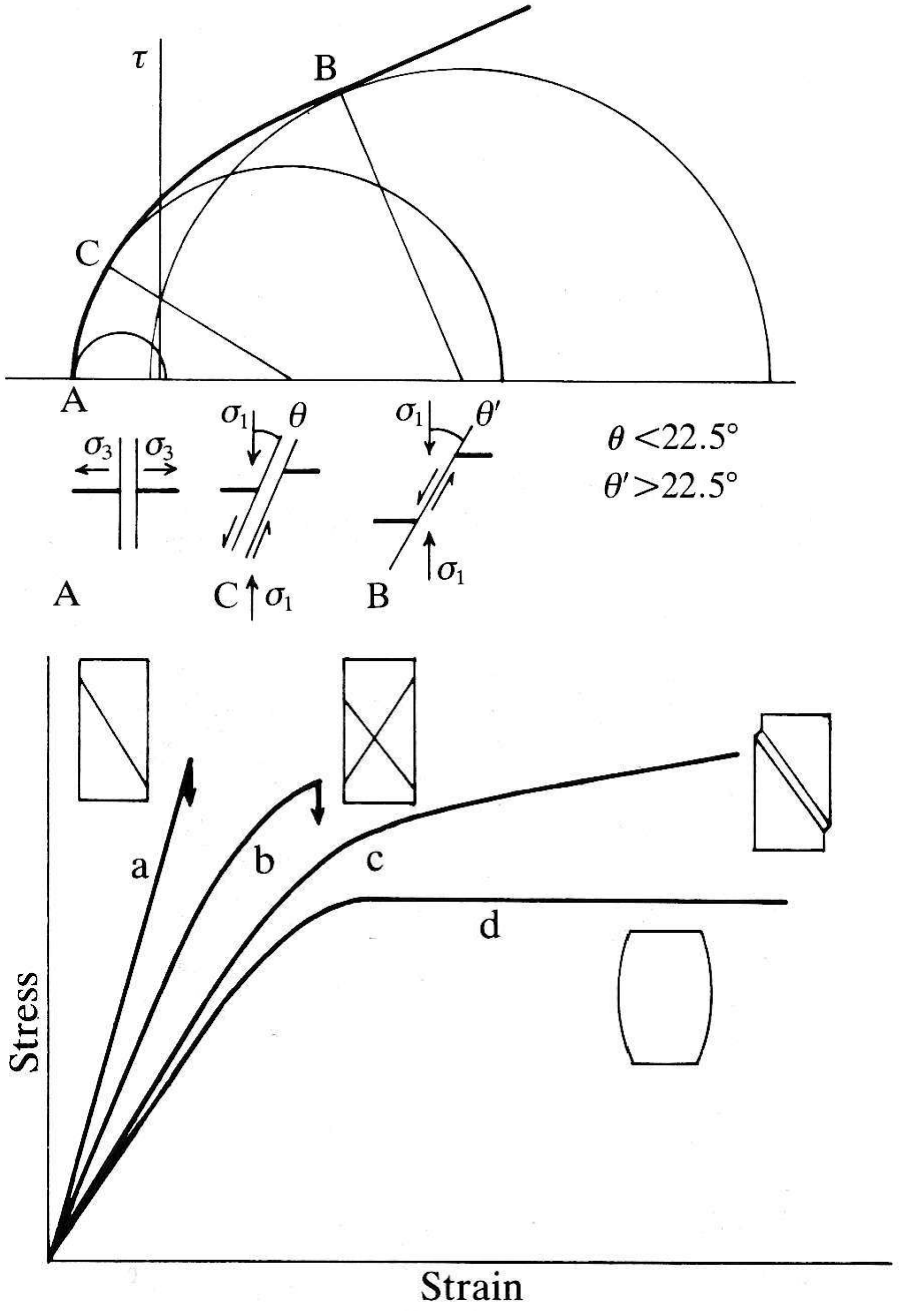
Exercise 2 – Classify the fractures according to their Morh's circle





Circle-A	Circle-B	Circle-C
2	3	1

Rheological contrast



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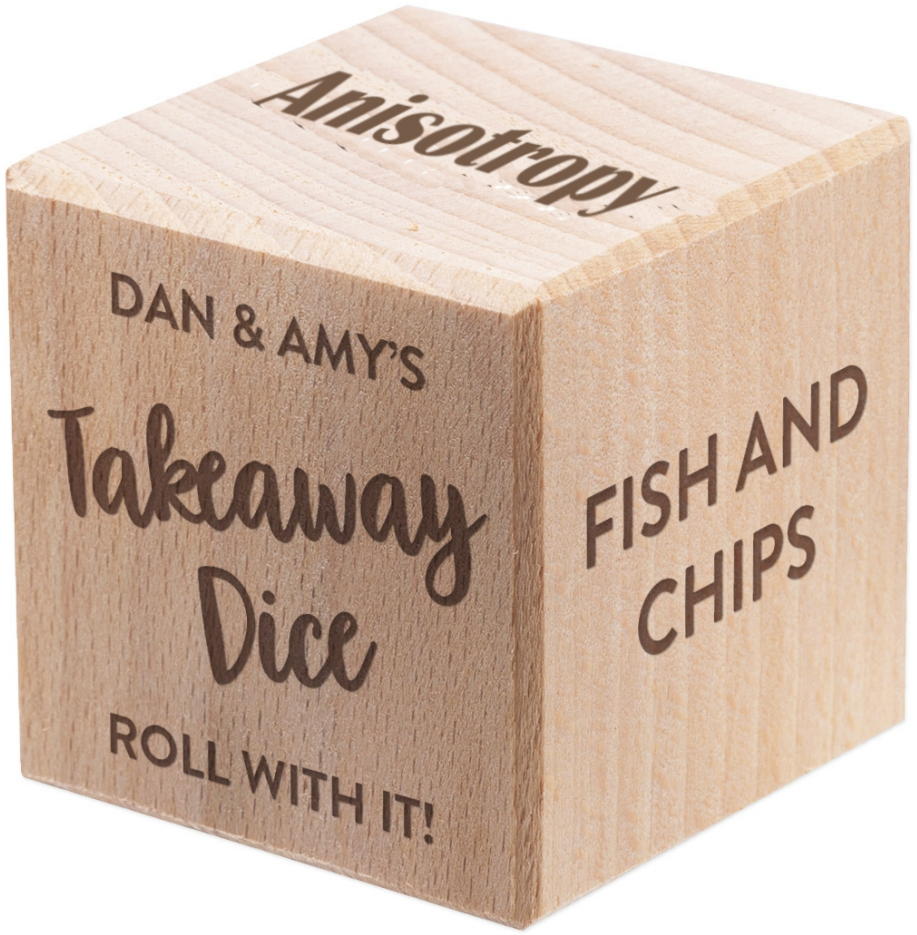
Interlayer of shale and sandstone layers from the Mardasson Quarry (Bastogne, Belgium)



'There seems to be one elephant left in the room that is still commonly overlooked or ignored in these numerical models: anisotropy." (Ran et al., 2018)

Thank you very much for your attention

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MEET
Multi-sites EGS Demonstration

Geological Survey of Belgium

This work was performed in the framework of the H2020 MEET EU project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037

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