WHAT IS BENEATH OUR FEET?

How Earth Scientists Understand the Subsurface

Bruce Yardley

Earth Scientists investigate the rocks beneath our feet:

- **What types of information can they obtain?**
- **How deep can they predict what will be found?**
- **How reliable are their predictions?**

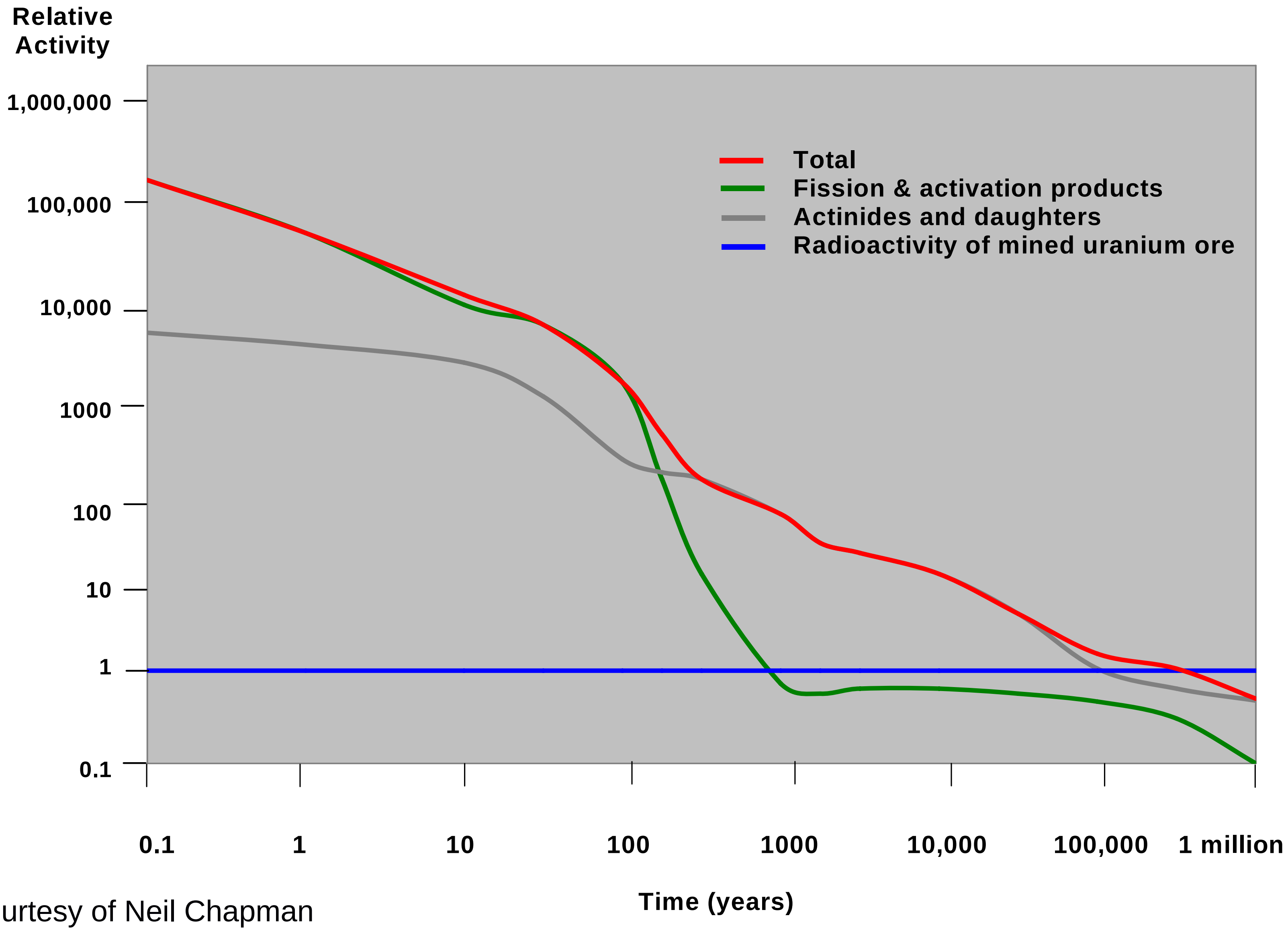
There is an enormous range of information that we might report, depending on the underlying reasons for a study, so we also need to consider what information is critical from the point of view of planning the disposal of radioactive waste.

If the objective is to determine the suitability of a site for waste disposal and to inform the design of a repository, then :

- **What will be the chemical environment around the repository?**
- **What is the permeability structure in the vicinity of the repository?**
- **Where is the water table?**
- **What has been the past history of geological activity?**

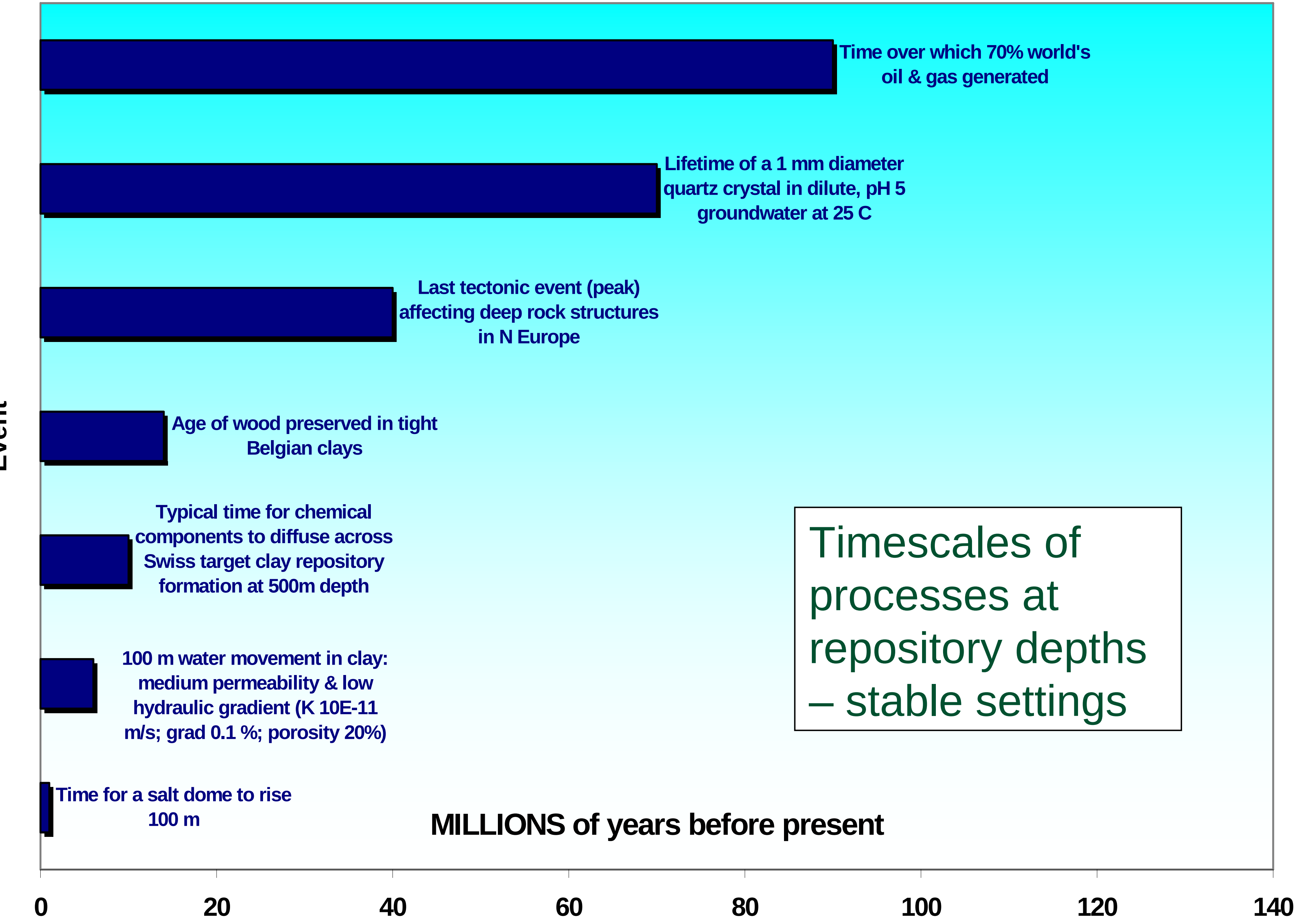
Classical geological concerns, such as the origins of the rocks, may be of lesser interest.

Containment: how long are we talking about…..?



Courtesy of Neil Chapman

Timescales of processes at repository depths – stable settings



Courtesy of Neil Chapman

So relevant information might include:

- **The distribution of materials with different mineralogy (capacity to retard migrating nuclides)**
- **The distribution of rocks with different permeability**
- **The distribution of fractures and their impact on fluid flow**
- **Evidence of changes over the past million years (geologically recent past!)**

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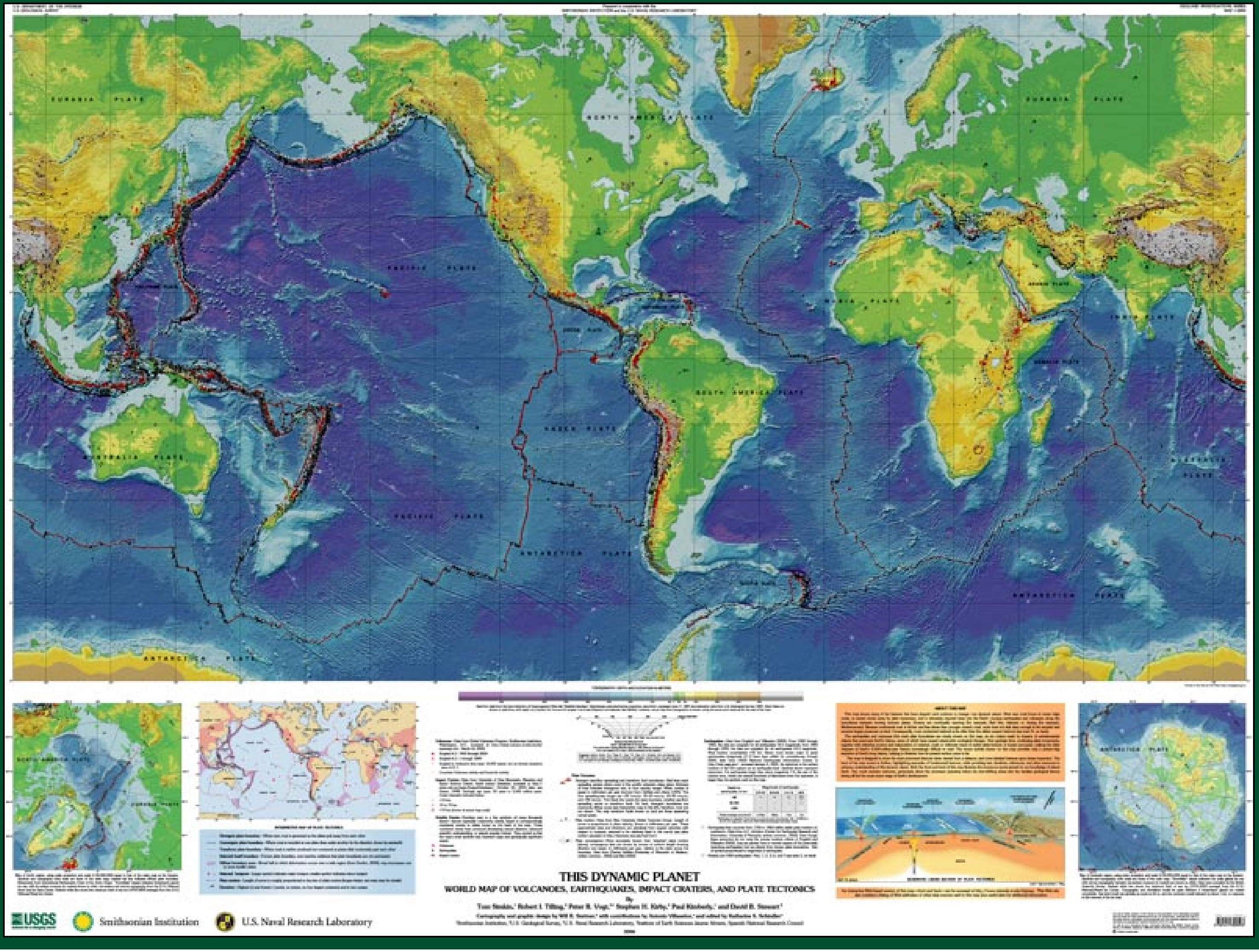
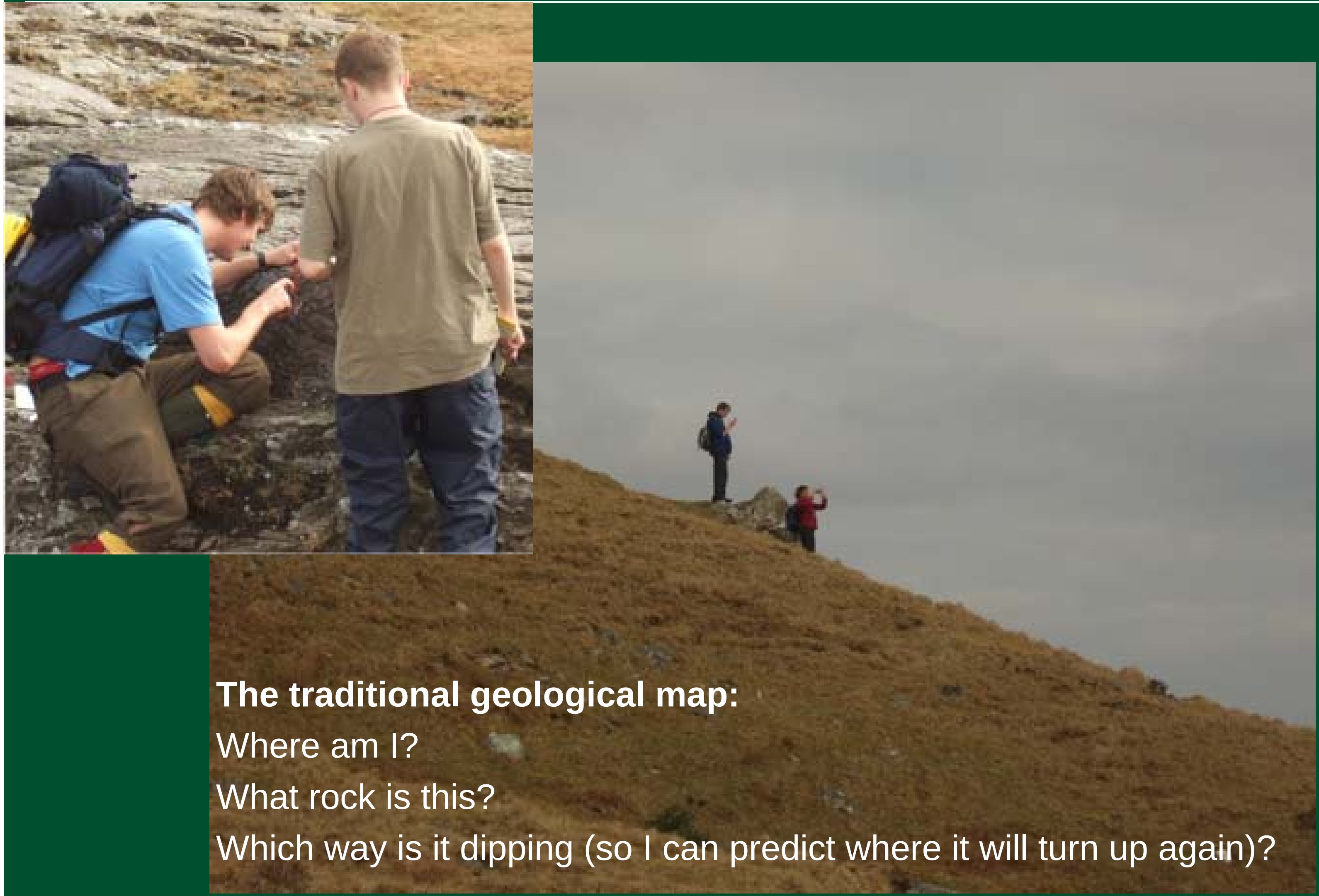


Tectonic movements are focussed in specific zones – northern Europe lies well outside these and has done since the formation of the Alps.

An Active Plate Margin: Uplift of the Central Southern Alps, N.Z., is at rates of c. 1cm/year, so that the rocks now at the summit of the highest mountains were below sea level less than half a million years ago.

Vertical movements around Torbay are rather more modest (by a factor of 500): raised beaches dating back over a similar period are within 10m of present sea level.

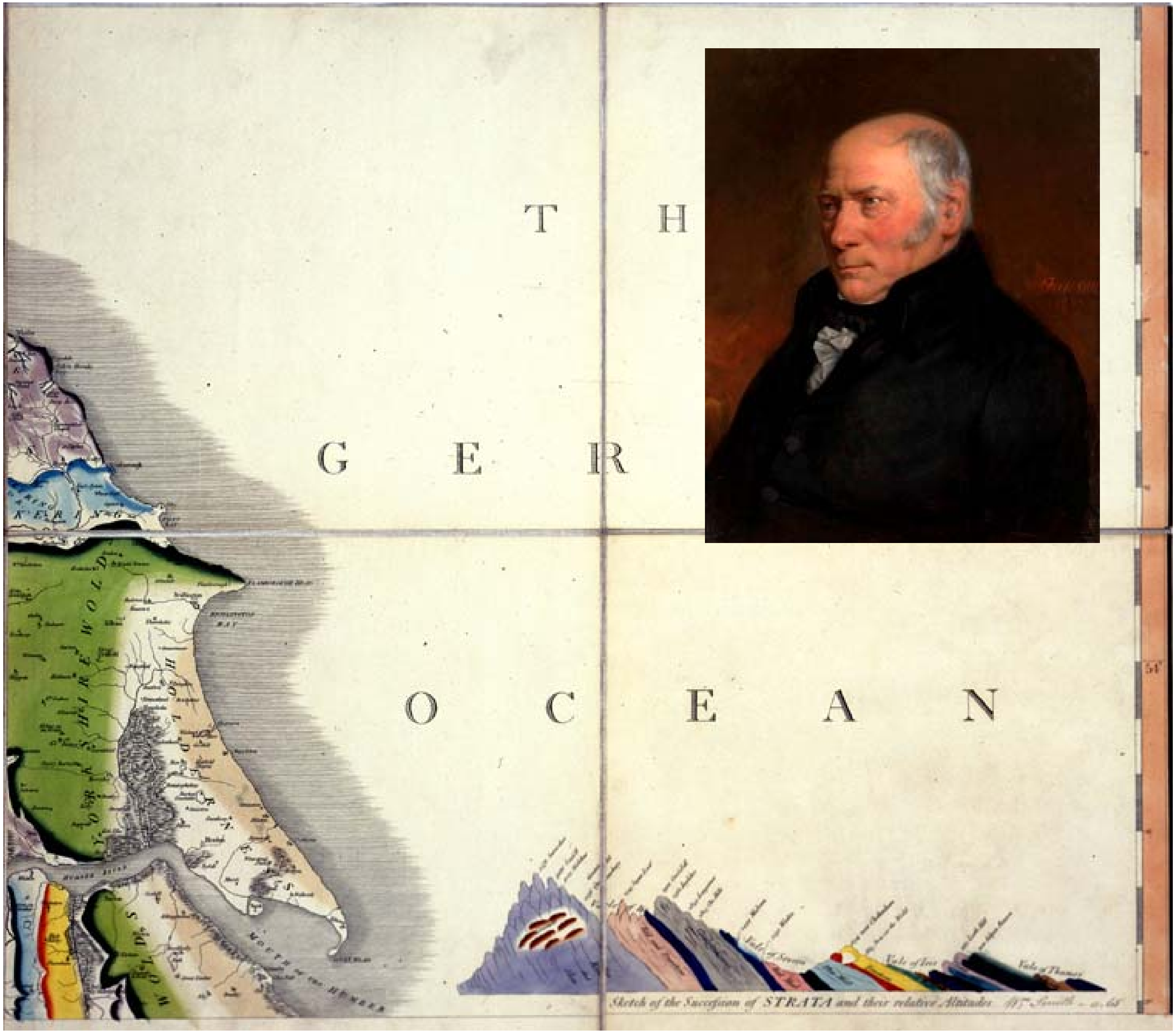


The traditional geological map:

Where am I?

What rock is this?

Which way is it dipping (so I can predict where it will turn up again)?



The William Smith map: the Wolds

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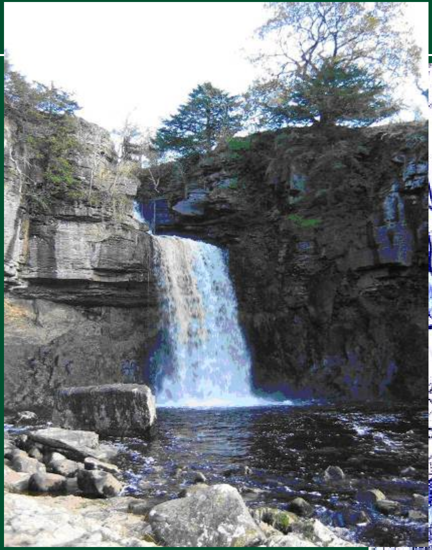
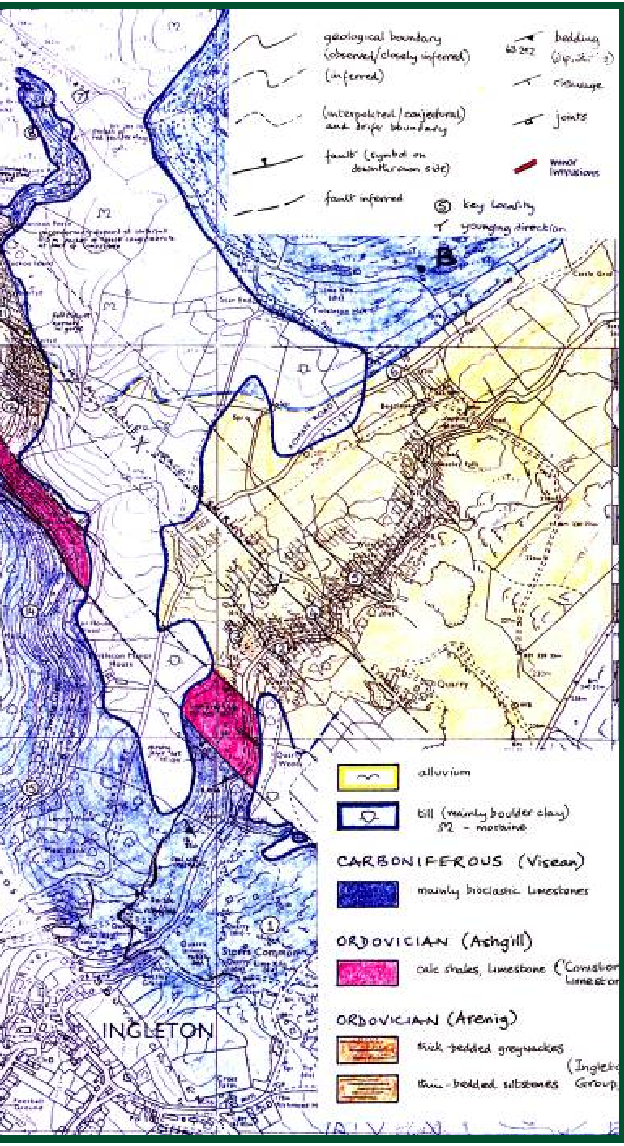
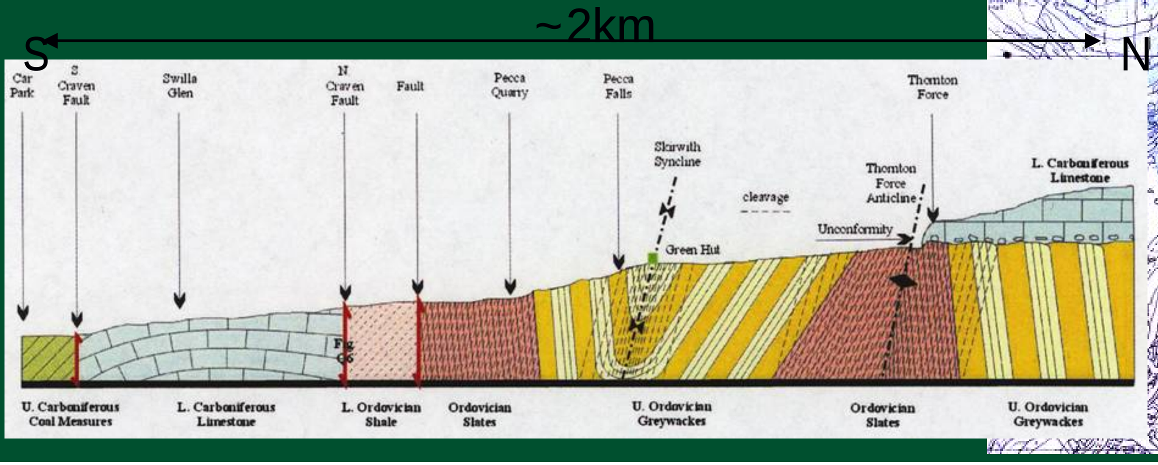
Example: detailed field map of Ingleton by Jack Soper, with a cross section showing the underground structure inferred from the measured dips.



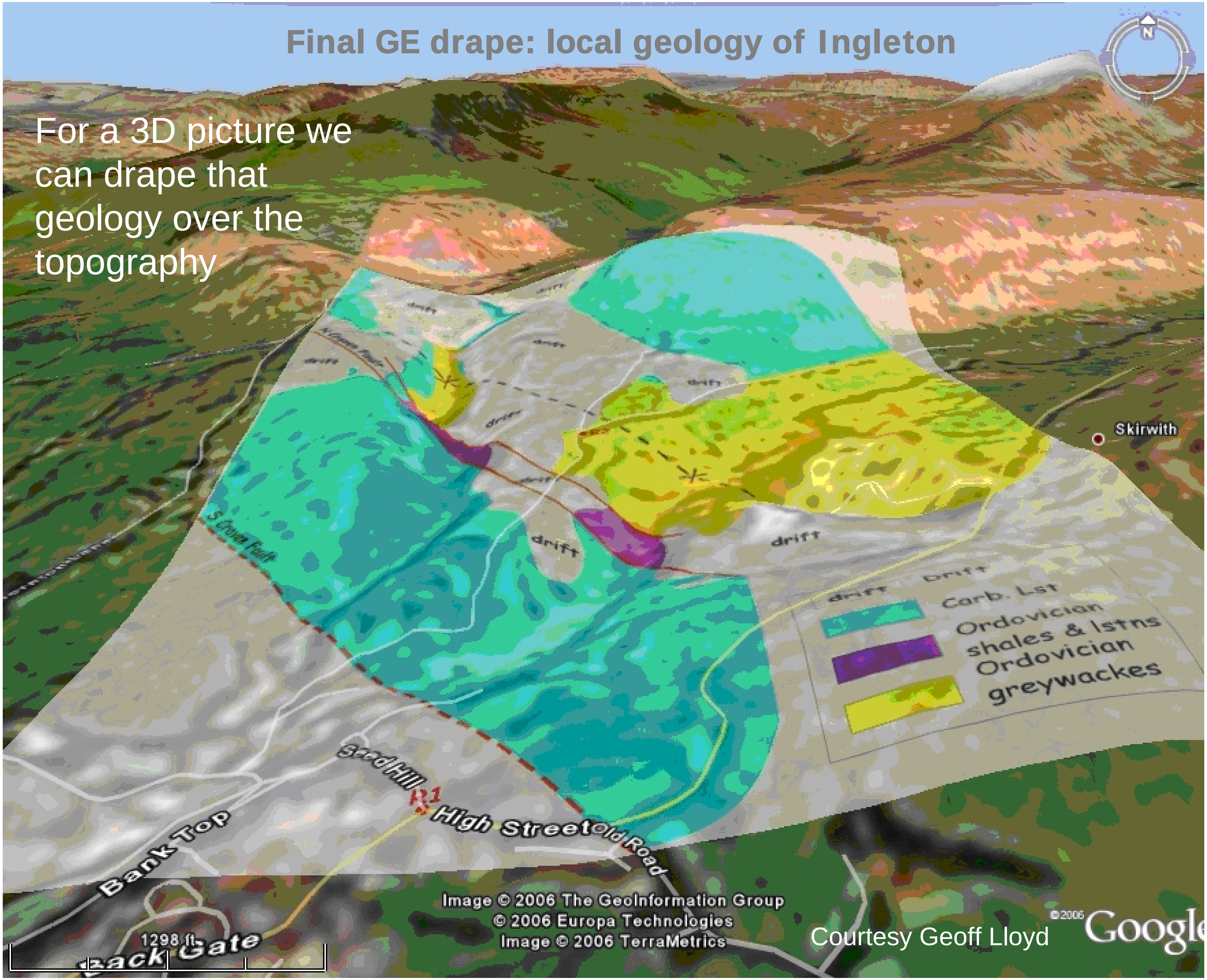
DRY ...





Final GE drape: local geology of Ingleton

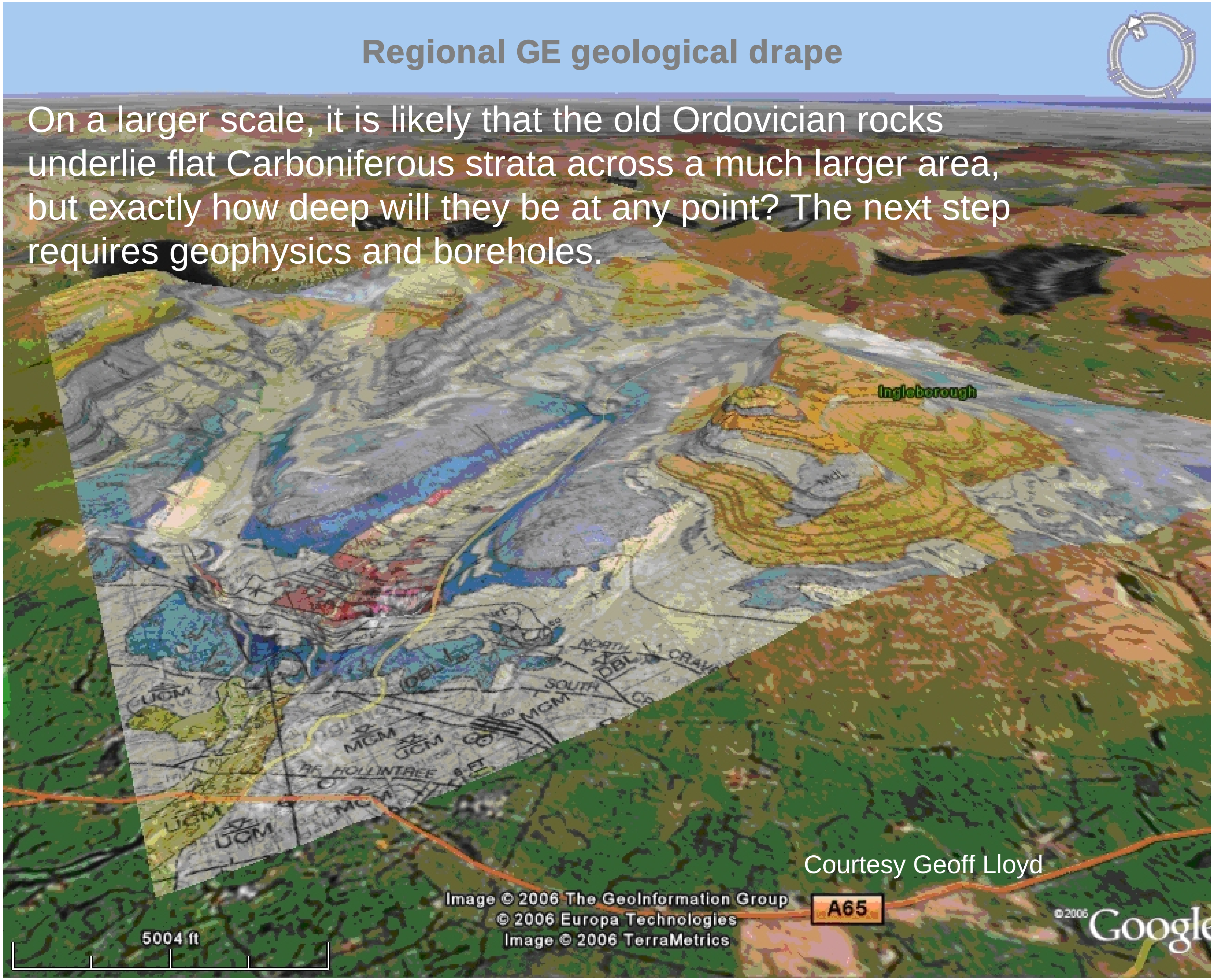
For a 3D picture we can drape that geology over the topography



Courtesy Geoff Lloyd

Regional GE geological drape

On a larger scale, it is likely that the old Ordovician rocks underlie flat Carboniferous strata across a much larger area, but exactly how deep will they be at any point? The next step requires geophysics and boreholes.



Courtesy Geoff Lloyd

Image © 2006 The GeoInformation Group
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Image © 2006 TerraMetrics

What are we observing?

Chemical Environments: Metal precipitation

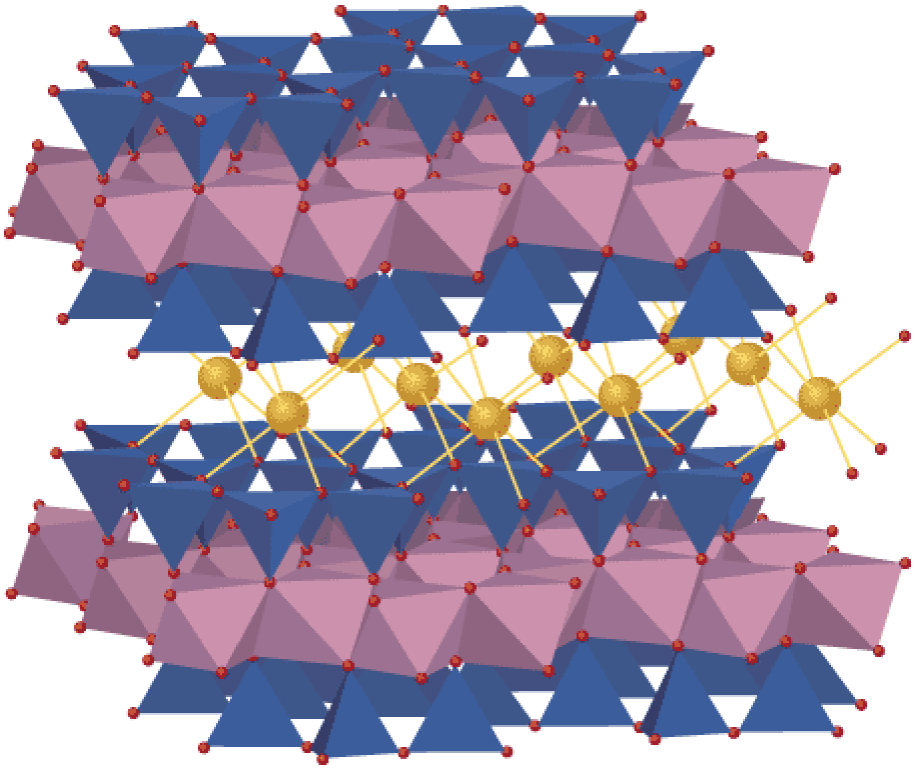
Limestone neutralises acid solutions and so retards the passage of some metals. The lead and fluorspar mines of the Pennine Ore Fields are largely hosted in limestone.

Navan

What are we observing?

Chemical Environments:

Clay minerals exchange cations with pore waters. Geological formations characteristically contain different amounts of clay and/or contain different clay minerals.



The molecular structure of smectite clays consists of 2 silicon-centered tetrahedral layers (blue) and one aluminum octahedral layer (purple) form crystalline sheets.

What are we observing?

Chemical Environments: Scale and cement

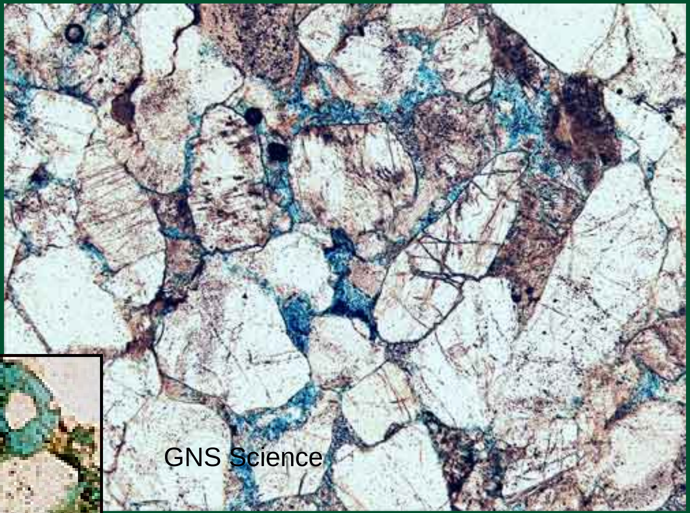
Sometimes fluids precipitate minerals as they move or mix in the subsurface. The formation of baryte scale in producing oilfields is an important example, and can seriously reduce production. Carbonates also precipitate in some situations, and occasionally the effects are even seen at the surface.

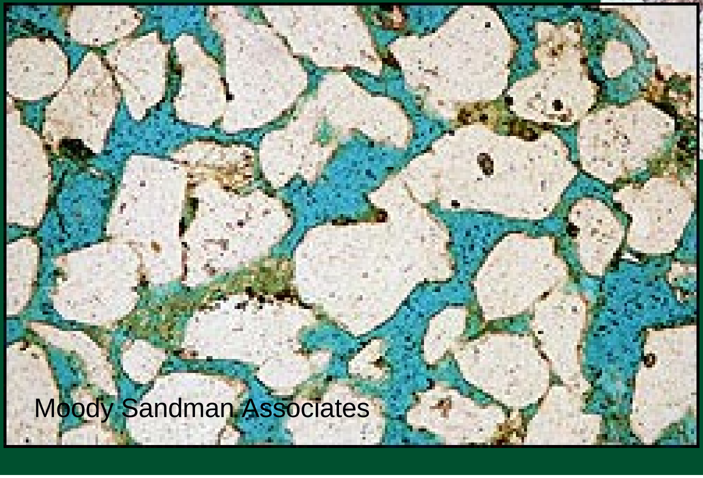
Oman: alkaline springs precipitate calcite scum as they reach the atmosphere; river gravels become firmly cemented together

What are we observing?

Permeability distribution:

Different rock types often have different characteristic porosity and permeability


GNS Science


Moody Sandman Associates

What are we observing?

Permeability distribution:

As rocks compact and cement, fracture permeability may become more important than porosity. Depending on their history, sediments may have porosity- or fracture-dominated permeability. And note that the cracks in the conglomerate on the right are now completely sealed leaving it with very little bulk permeability at all.

What are we observing?

Permeability distribution:

In some rocks, fluid moves through cracks rather than pores. Their distribution may be unrelated to the units mapped by a geologist


Saki Olsen

What are we observing?

Permeability distribution:

Fracture sets may show alteration features formed when they were conduits for flow at depth.

What are we observing?

Permeability distribution:

Even normally impermeable rocks such as granite can show evidence of fluid flow through fractures during specific episodes in the past

Altered zone associated with present-day flows at c. 2km depth from the Soultz geothermal borehole, Rhine graben

What are we observing?

Permeability distribution:

Mapped faults can act as conduits for flow, or as barriers

In Summary:

- Some structures which exert an important control on permeability crosscut rock types. If they do not constitute important faults, geologists may not map them.
- We have learnt to look at the rocks in detail for clues as to how they behave, and to distinguish past performance from present properties.
- Conventional geological maps and cross sections give a good picture of the spatial distribution of contrasting chemical environments

To get a more accurate picture of what is beneath the surface, what are the options?

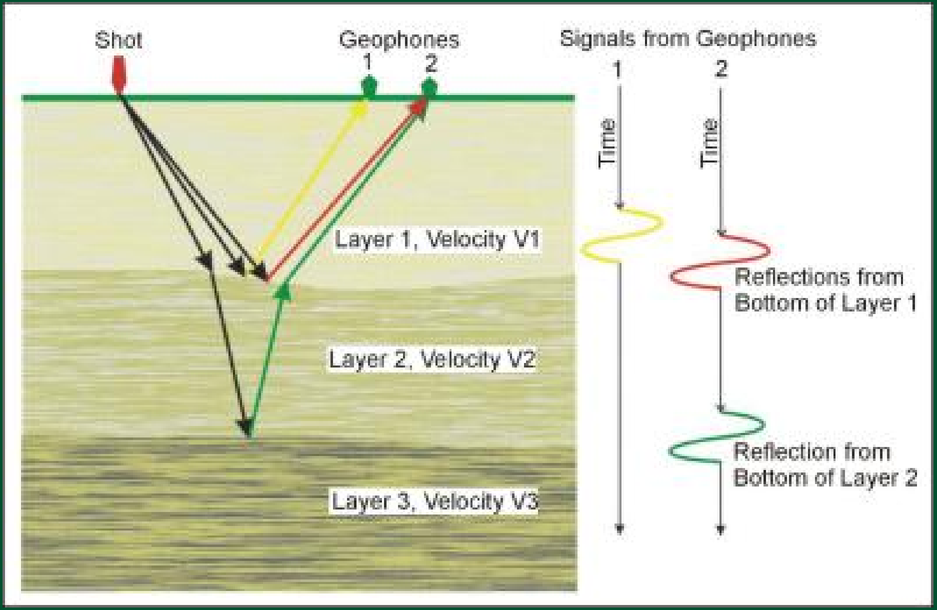
Detailed Geophysical Surveys

Drilling

Downhole and Cross-Hole Geophysics

Geophysical Methods:

Seismic Reflection



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Geophysical Methods:

Seismic Reflection

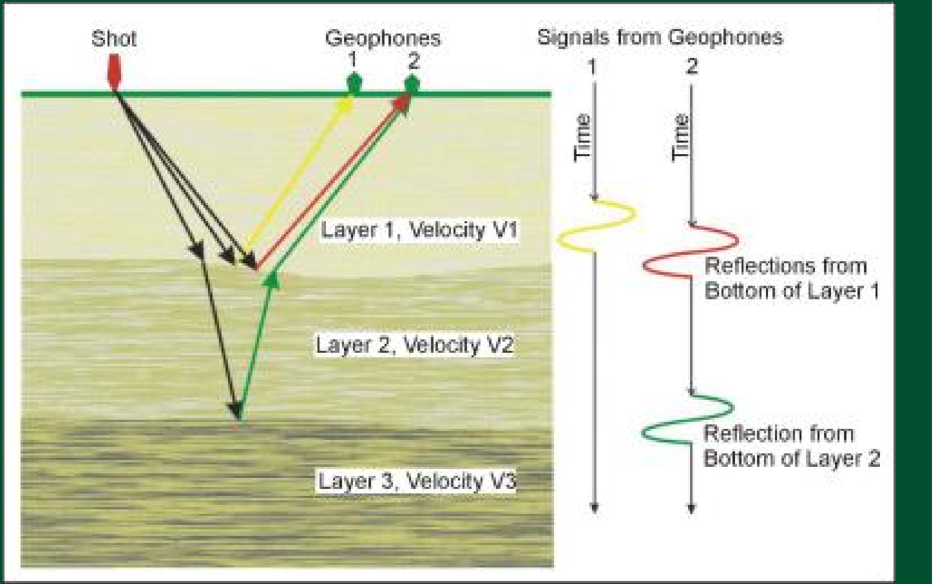
Most widely used method for identifying layering in rocks

Sensitive to changes in velocity and density, which are related to porosity

Absolute depth estimates depend on estimating seismic velocities (check by drilling)

Can investigate regional volumes or be used for detailed site investigation with 3D surveys

Seismic anisotropy detects fracture networks



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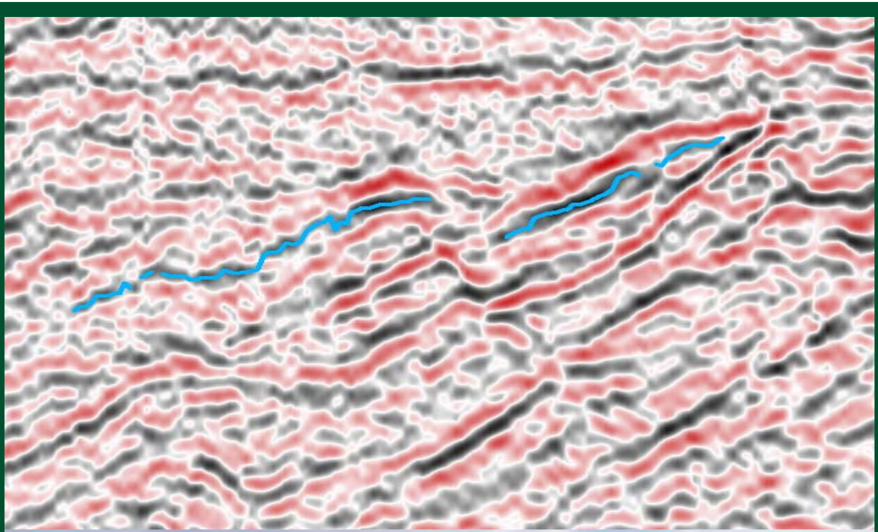
Geophysical Methods:

Seismic Reflection



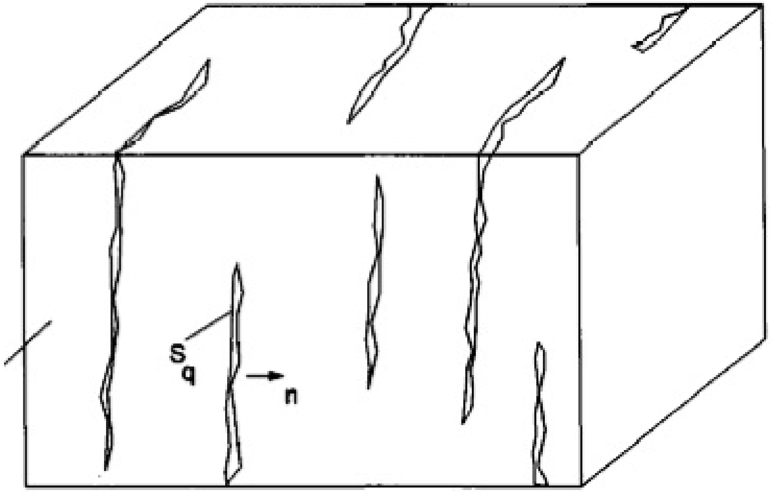
A reflection survey across an area of faulted and folded strata illustrates structures similar to those seen in surface outcrops

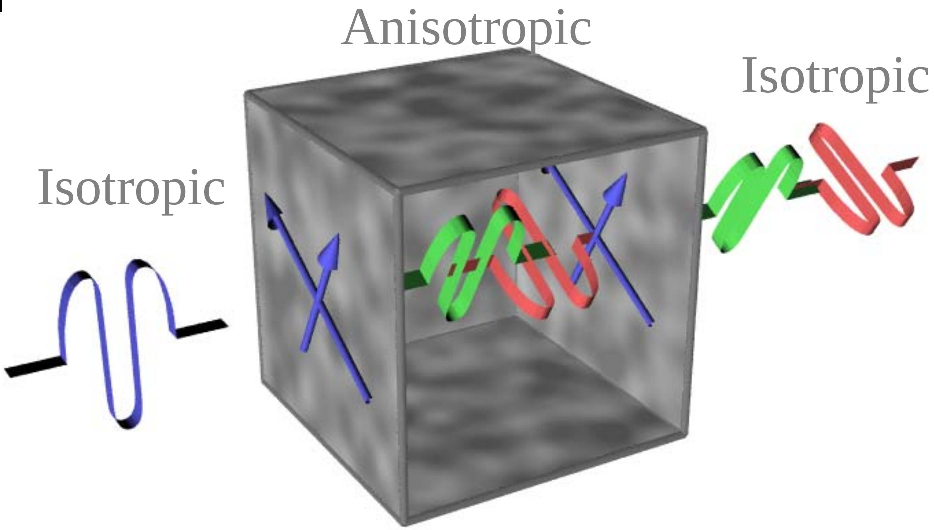
Courtesy of RDR Ltd./Rob Knipe

Detecting sub-seismic scale cracks and fractures

A region with aligned cracks behaves like a homogeneous but anisotropic medium.

Can detect such effects with techniques like shear-wave splitting analysis (birefringence).

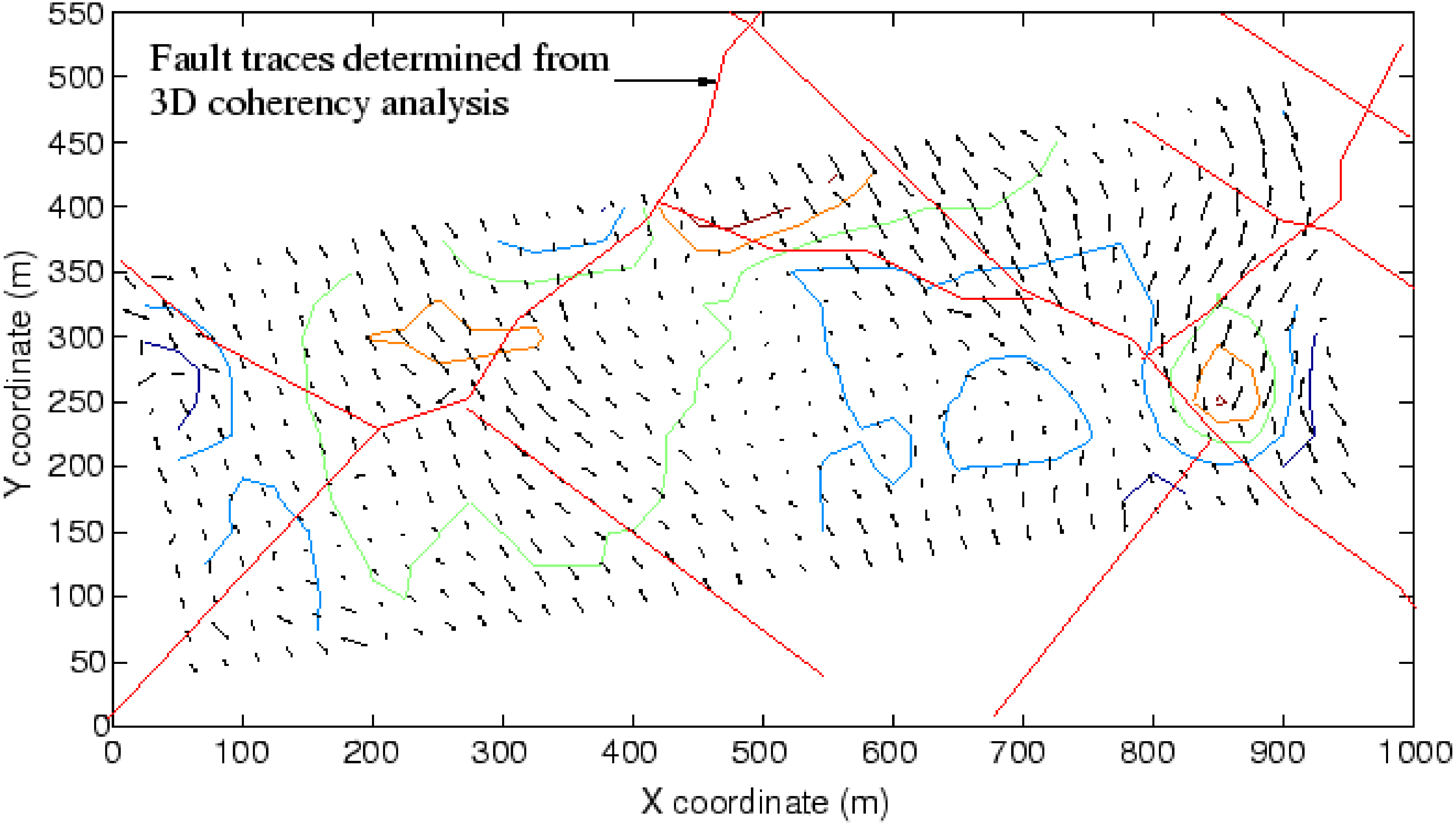




Yields the orientation of fracture anisotropy and the intensity of fracturing

Courtesy Prof Mike Kendall, Bristol

Detailed map of an area in which faults were mapped by a 3D seismic survey, showing fracture anisotropy

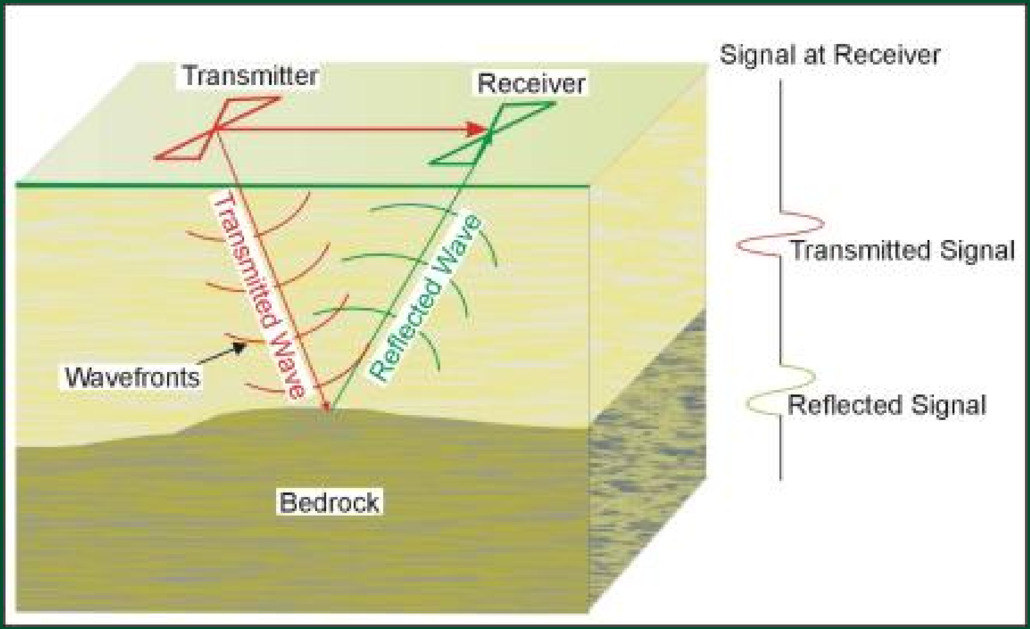


Courtesy Prof Mike Kendall, Bristol

(Hall and Kendall, 2003)

Geophysical Methods:

Ground Penetrating Radar



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Geophysical Methods:

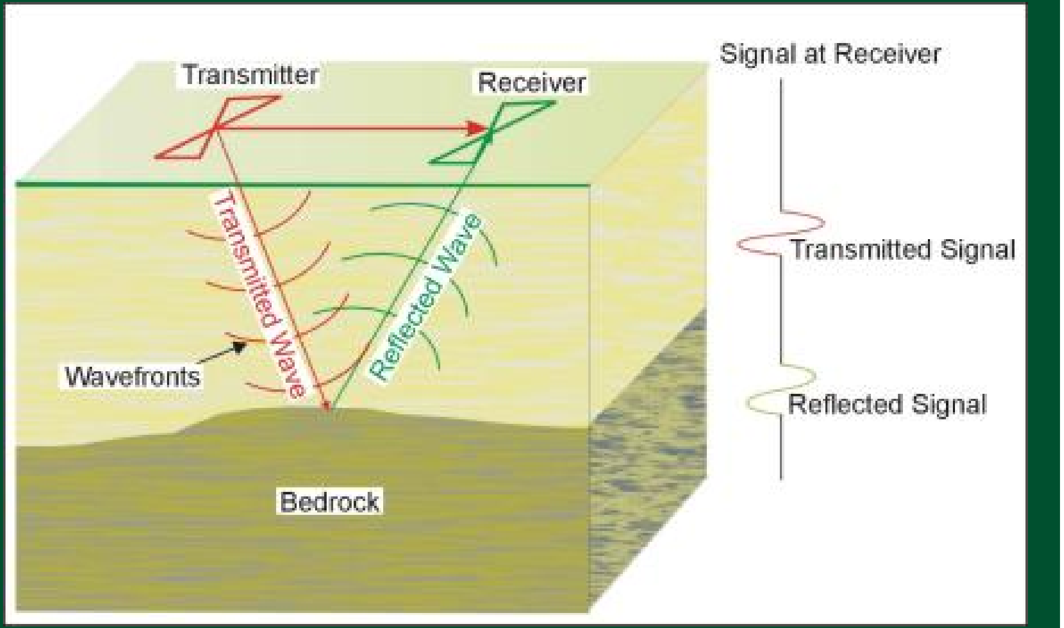
Ground Penetrating Radar

Very limited depth of penetration

Use at the surface is NOT RELEVANT

BUT can be used down boreholes

Will identify INDIVIDUAL fractures



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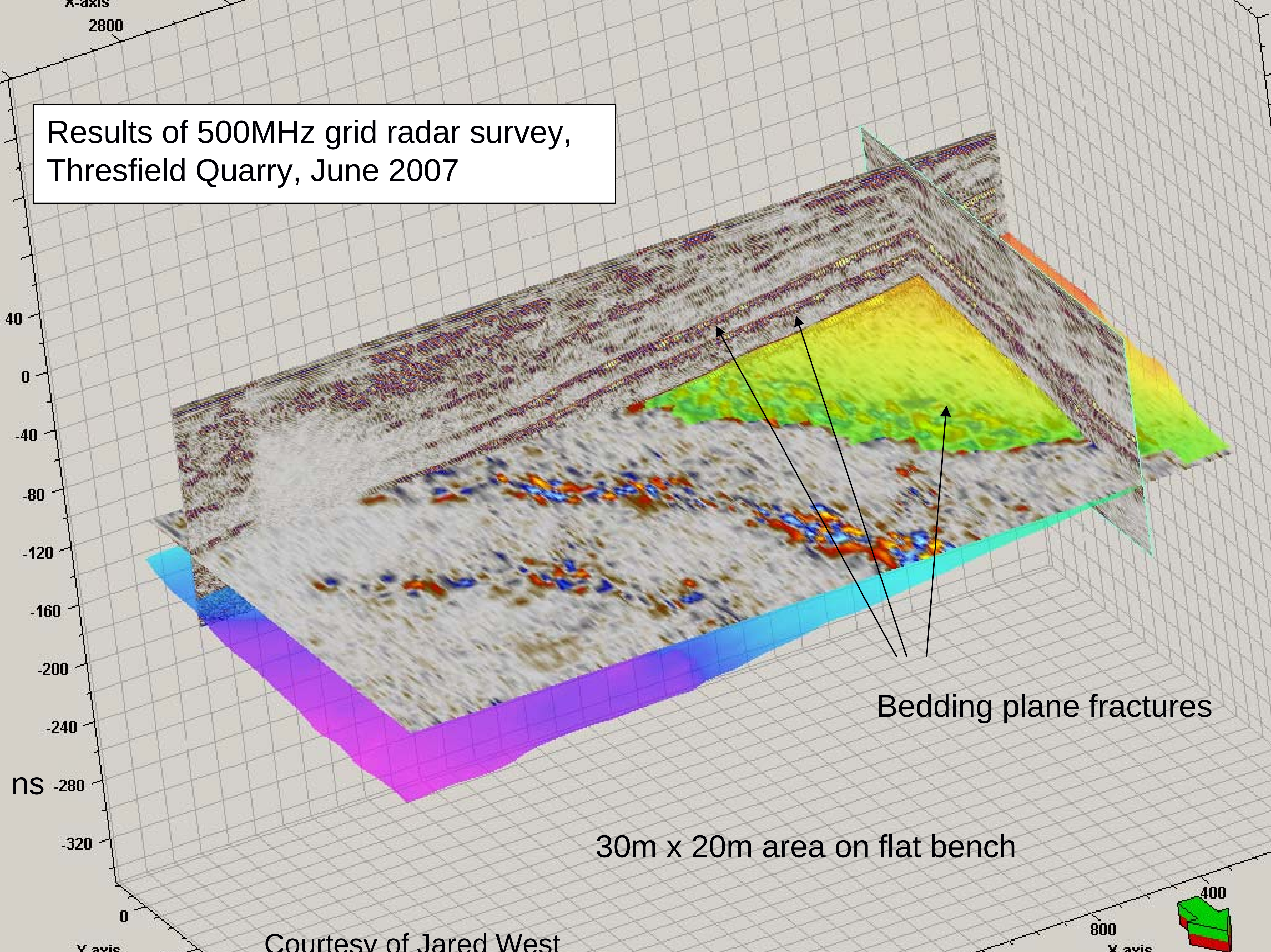
Results of 500MHz grid radar survey, Thresfield Quarry, June 2007



Bedding plane fractures

30m x 20m area on flat bench

Courtesy of Jared West

Downhole Radar

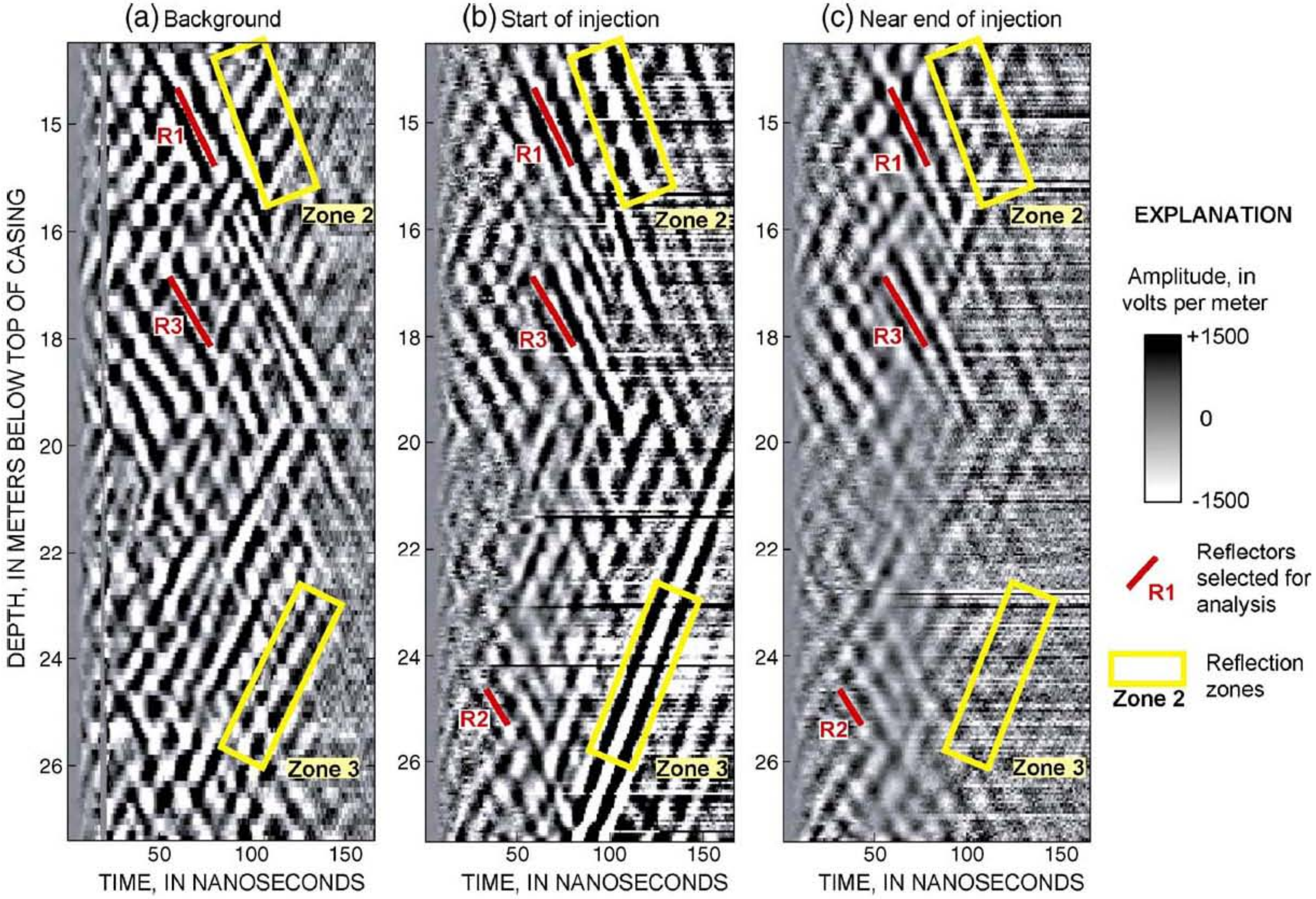
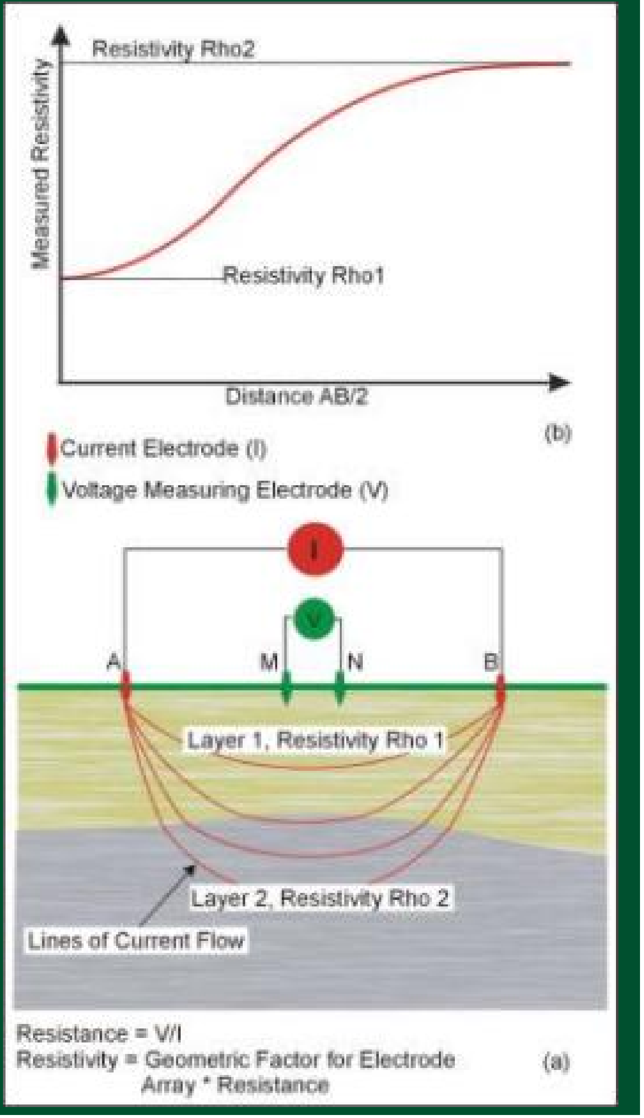


Fig. 9. Radar reflection data collected in borehole JBW-7817A. (a) Background data (August 2002). (b) One week after the start of the steam injection (September 2002). (c) Near the end of the steam injection (November 2002).

Geophysical Methods:
Resistivity



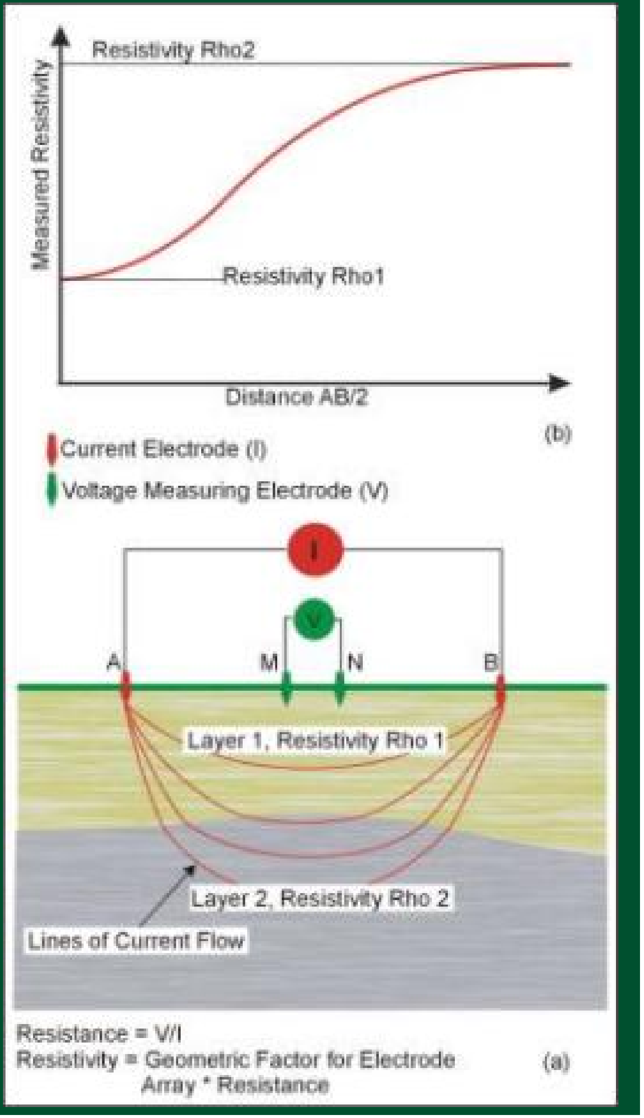
Geophysical Methods:

Resistivity

Sensitive to the presence of water in rock units or fractures

Surface-based measurements not relevant

BUT can be used between boreholes to demonstrate if water-filled fractures connect



Drilling:

- abundant detailed information
- accurate depths
- very localised
- disturbs the sub-surface
- expensive
- allows cross-hole measurements of properties

Yields:

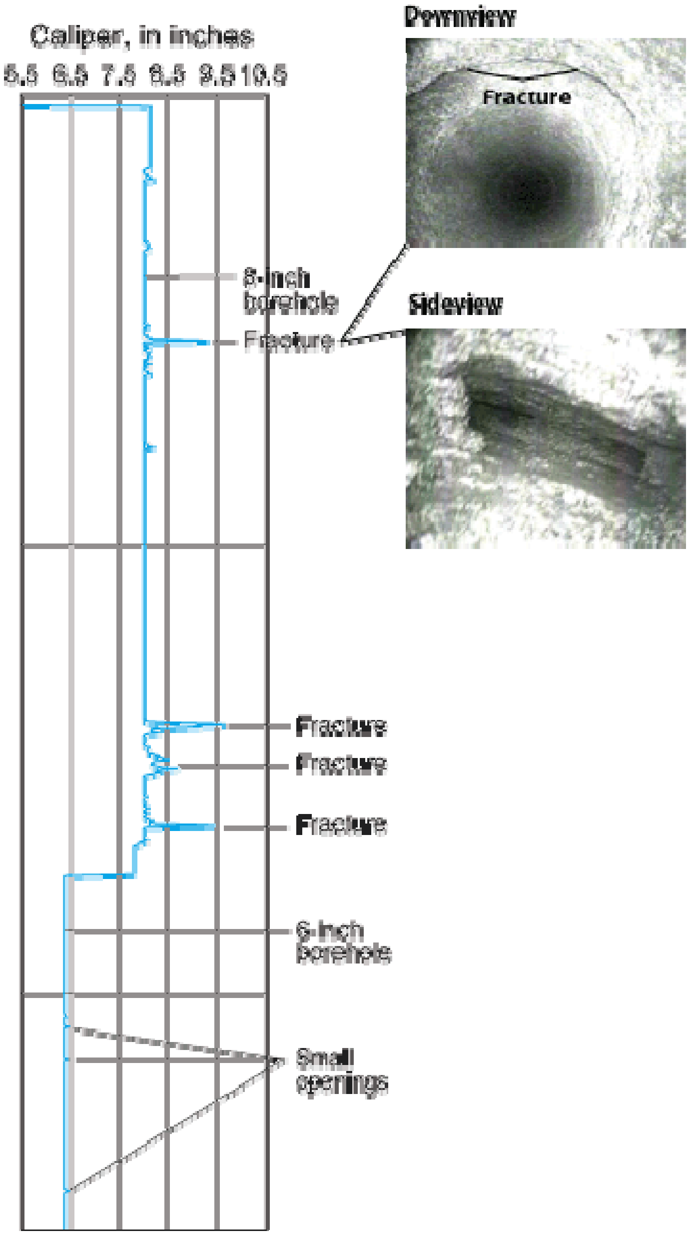
- Samples of rock (chippings or core)
- Samples of fluid
- Logs – records of rock properties down hole

Logs:

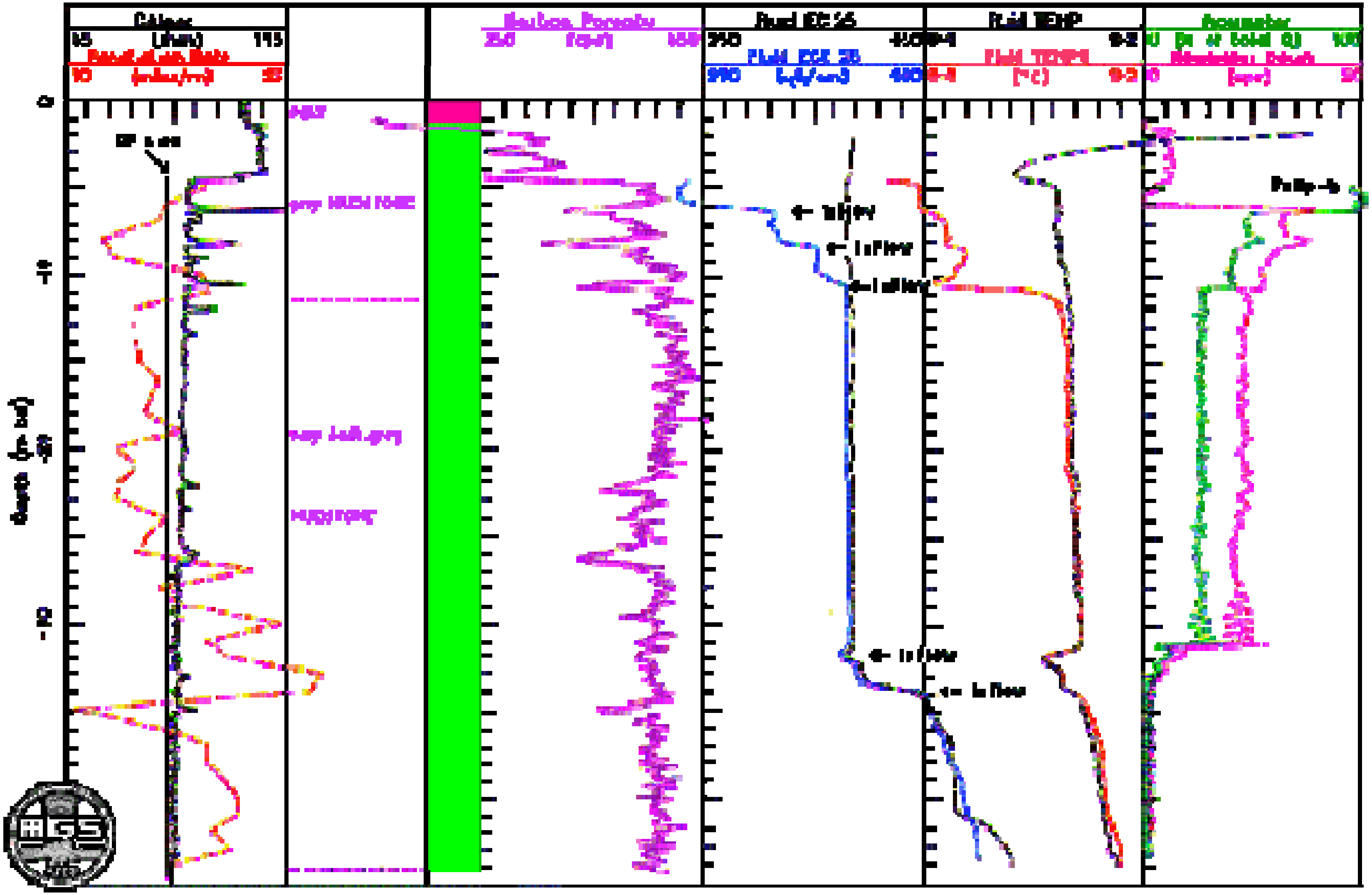
Logs can record features such as the occurrence of water flows, the presence of clay minerals and the clay mineralogy, as well as providing visual images of the borehole. It is also possible to record stresses and make a range of rock property determinations.

Example caliper log, recording borehole size and fracturing.

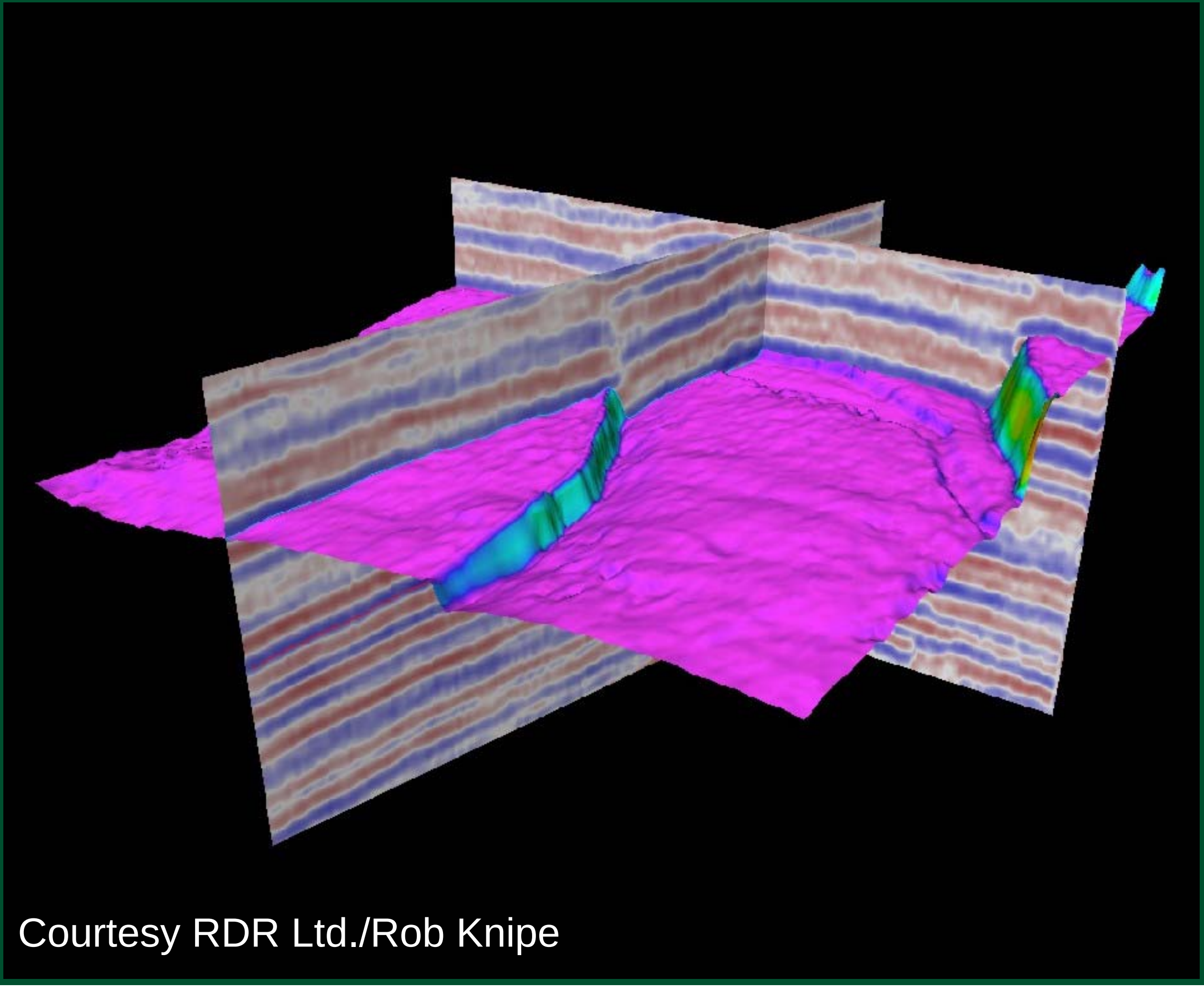
Spalling can indicate stress fields down the hole.



USGS image


Caliper
Neutron Porosity
Fluid EC 25
Fluid TEMP
(°C)
0
-10
-20
-30
Depth (m bsl)
grey MUDSTONE
grey-dark grey
MUDSTONE
← inflow
← inflow
← inflow
← inflow
← inflow
Pump-in
AGS

Integrated subsurface data: in place of maps



Courtesy RDR Ltd./Rob Knipe

Results from geophysical surveys and drilling are integrated into 3D models of the geology and structure of volumes of interest for mining or hydrocarbon extraction. This simple model shows how faults offset a bed, and the model can be viewed from all sides in the computer. Such models can be populated with rock properties, and their evolution through time can be monitored.

In Summary:

We already have outline knowledge of the geology and landscape evolution of the British Isles.

We also have a large body of geological understanding as to what is possible in the subsurface, based on the experience of the extractive industries in particular.

Steady developments to geophysical techniques of site investigation mean that as well as predicting geology and mineralogy at the depths of interest for a repository, we can also learn a lot about deep fluid behaviour prior to any excavation.