Durham University

CeREES
Centre for Research into Earth Energy Systems

Cosmic Ray Muon Tomography; A Monitoring Tool for Carbon Storage?

Jon Gluyas[1], Vitaly Kudryavtsev[2], Neil Spooner[2], Max Coleman[3], Sean Paling[4] & Sam Telfer[2]

[1]Department of Earth Sciences, Centre, Durham University,
[2]Department of Physics and Astronomy, University of Sheffield,
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
[4]Science & Technology Facilities Council, Rutherford Appleton Lab, Didcot

Geological Society/AAPG, London, November 2011

CCS European Commitment

- Anticipates <1% leakage / 1000 years – monitoring required

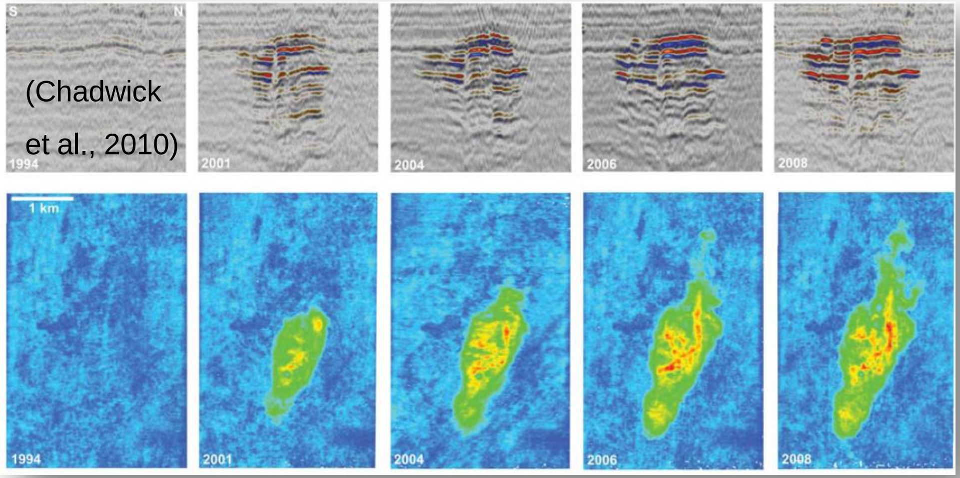
Monitoring

Marine

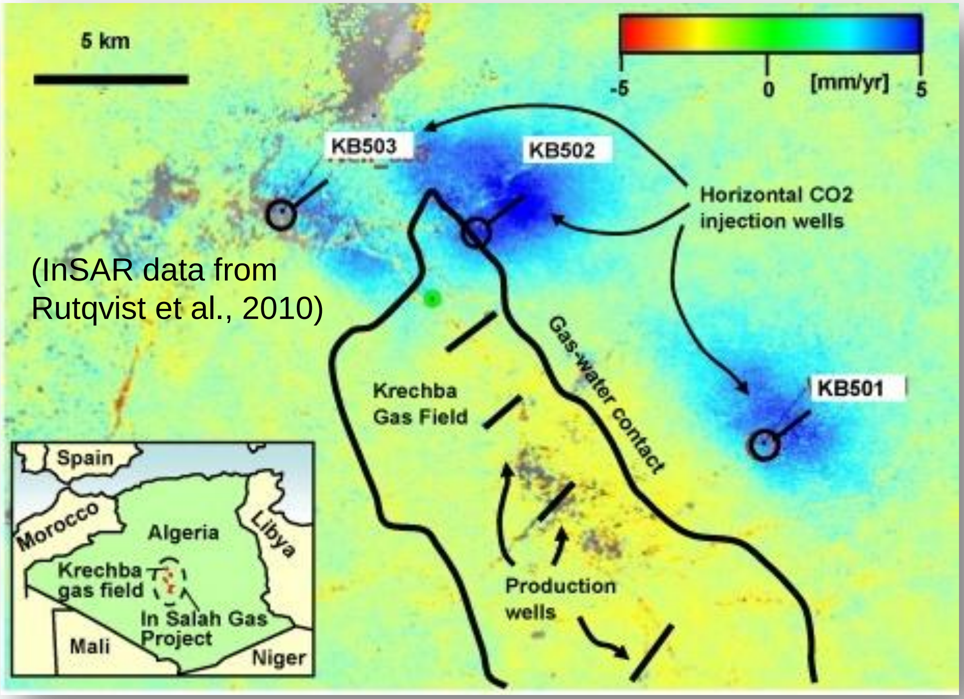
- **4d seismic**
- Electro-magnetic surveys

Land

- 4d seismic
- **Insar**
- CO_2 seep detection



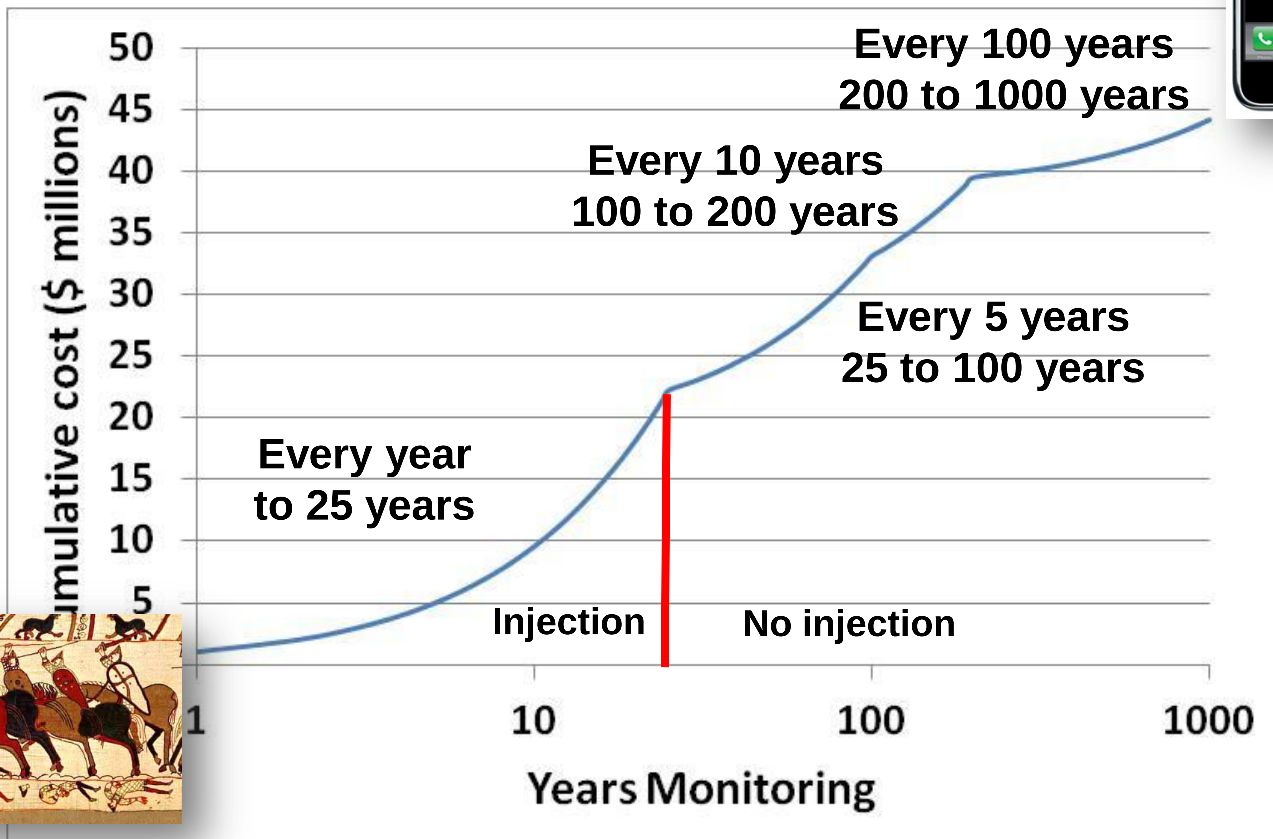
(Chadwick et al., 2010)



(InSAR data from Rutqvist et al., 2010)

Seismic Monitoring of Carbon Storage 1

- Assumptions
  - Money of today (no inflation)
  - $1 million for initial survey
  - Declining 1% per shoot
  - Stepped increase in survey spacing



Size of the Problem

- UK has >400 oil & gas fields
- ~100 might be used for CO_2 storage
- ~50 more large saline aquifers may also be used
- ~150 sites requiring 4d seismic
- ~25 years average injection period – requiring annual survey
- ~1000 year monitoring period @ £50 million / site
- £7.5 billion in today's money.......oops

Seismic Monitoring of Carbon Storage 2

- Expensive
- Episodic
  - What happens between surveys?
- Does not directly measure CO_2
  - Measures acoustic contrast *f* (density, velocity)
  - Positioning issues survey to survey (weather)

The Ideal Monitoring Methodology

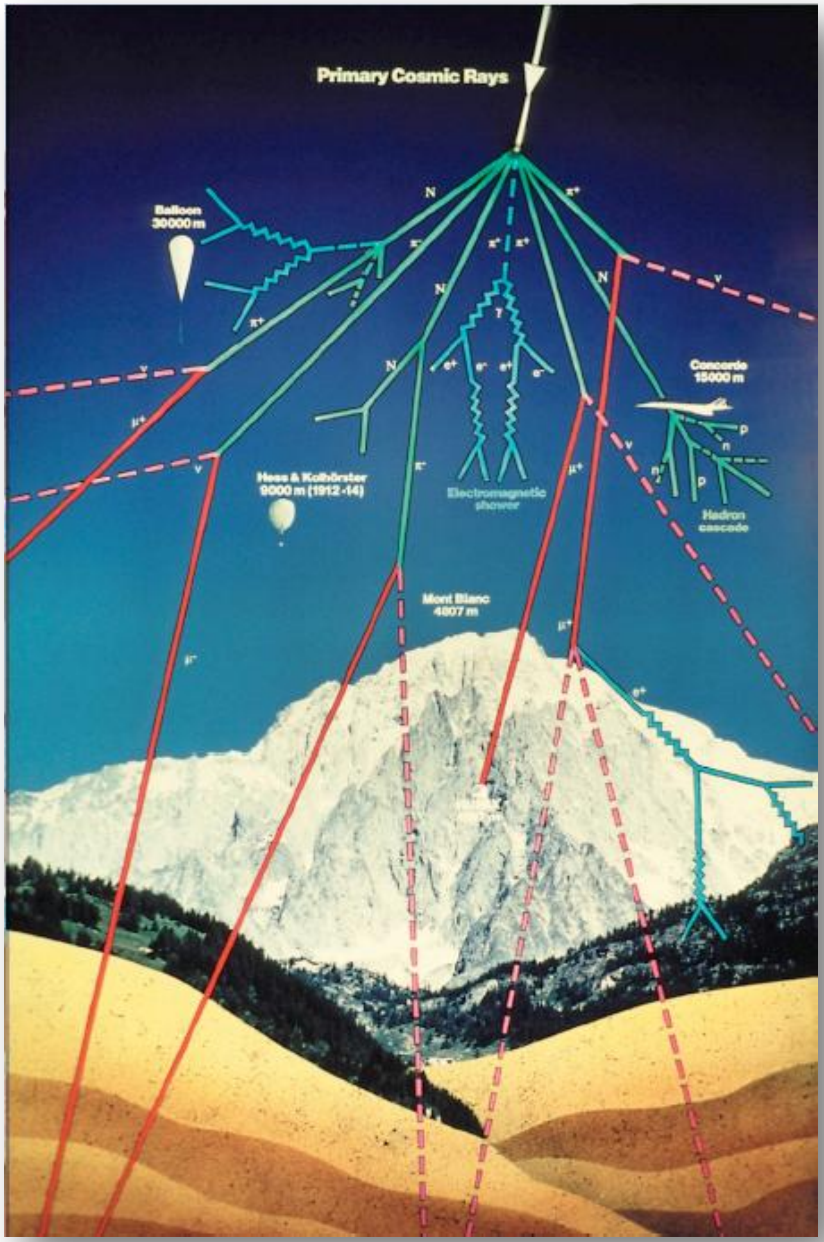
- Inexpensive
- Continuous (24/7)
- Passive
- Direct response to CO_2
- Lasts 1000+ years

Cosmic Ray Muon Tomography

Inexpensive	Probably much less expensive than seismic
Continuous (24/7)	Yes
Passive	Yes
Direct response to CO_2	Yes (to density)
Lasts 1000+ years	No...but

Cosmic Ray Muons

- Charged, very penetrating particles created by cosmic radiation striking the atmosphere
- Loss through ionisation when travelling through matter
- Can be deflected when travelling through high atomic number materials
- Last ~ 2μsec
- Penetrate ~ 2km+ rock



Muon Detection

Energy loss depends on length travelled and the density of the material muons travelled through

By detecting muon intensity, the density change of hidden terrain can be detected, hence hidden terrain can be visualised

Muons can be deflected when travelling high atomic number materials

Deflected muons can provide an image of hidden radioactive materials such as dirty bombs, which have high atomic numbers

Present (possible) Uses

- Imaging a magma chamber in a volcano ✓
- Imaging hidden chambers in pyramids
- Detecting nuclear contraband ✓

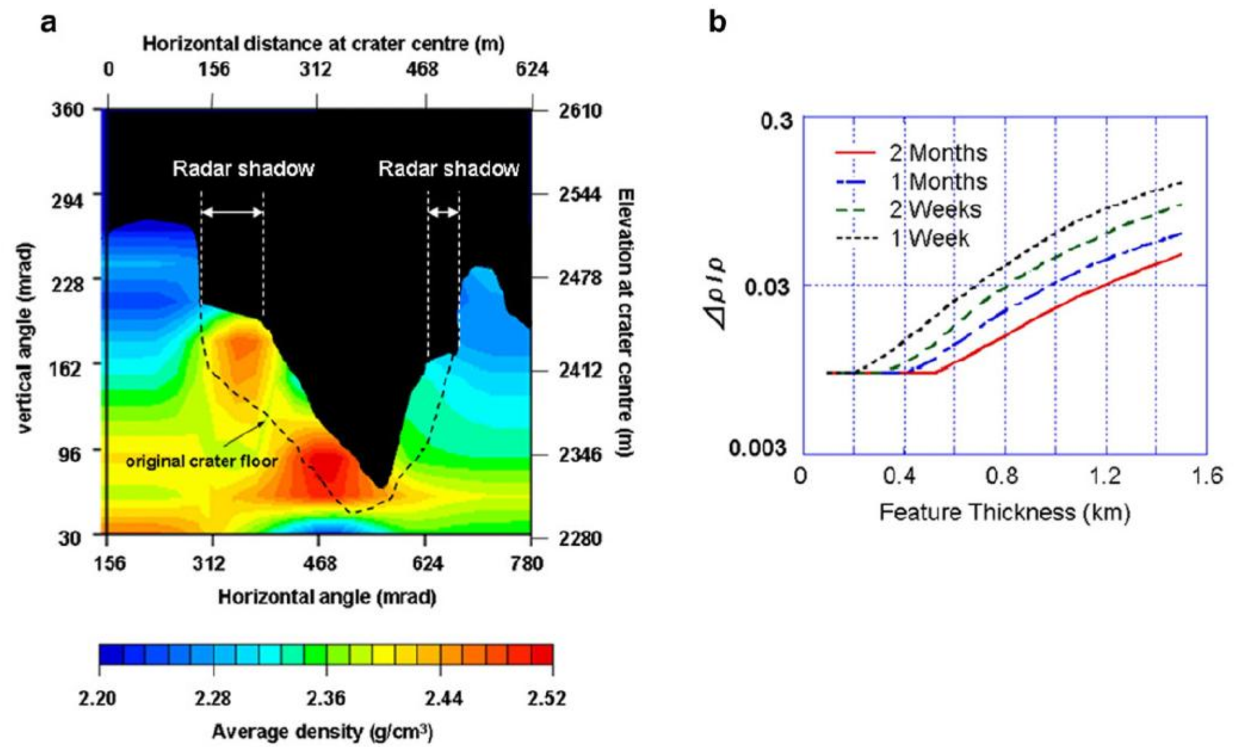
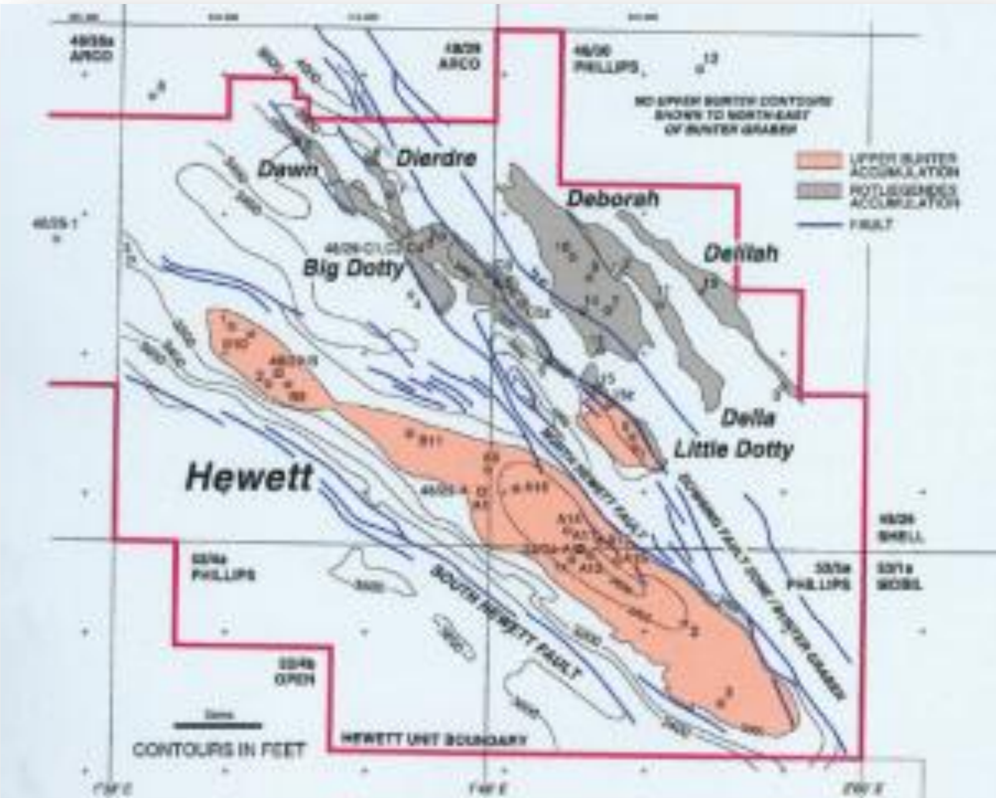
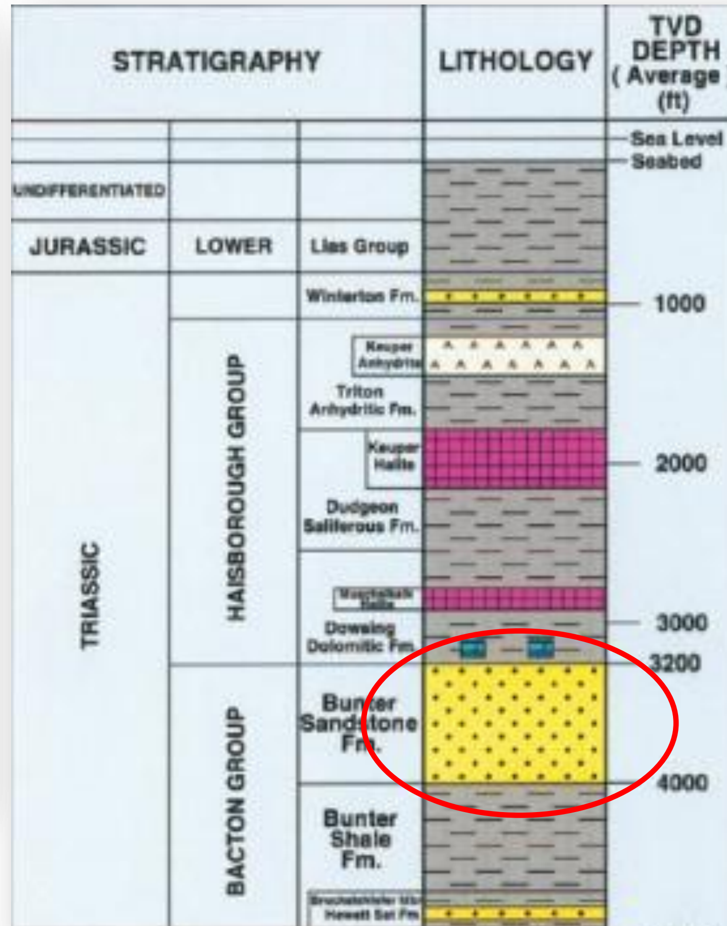


Fig. 7. (a) Reconstructed average density distribution for each muon path line and (b) the number of muons required to resolve, to one standard deviation, the presence of a feature of given thickness and differential density with respect to surrounding material with the present experimental setup. The average density distribution is plotted projected on the cross sectional plane. The distribution of the average density was reconstructed by applying the range-energy relationship for cosmic-ray muons through rock to the path length (L) calculated from the surface shape of the mountain for each arriving angle.

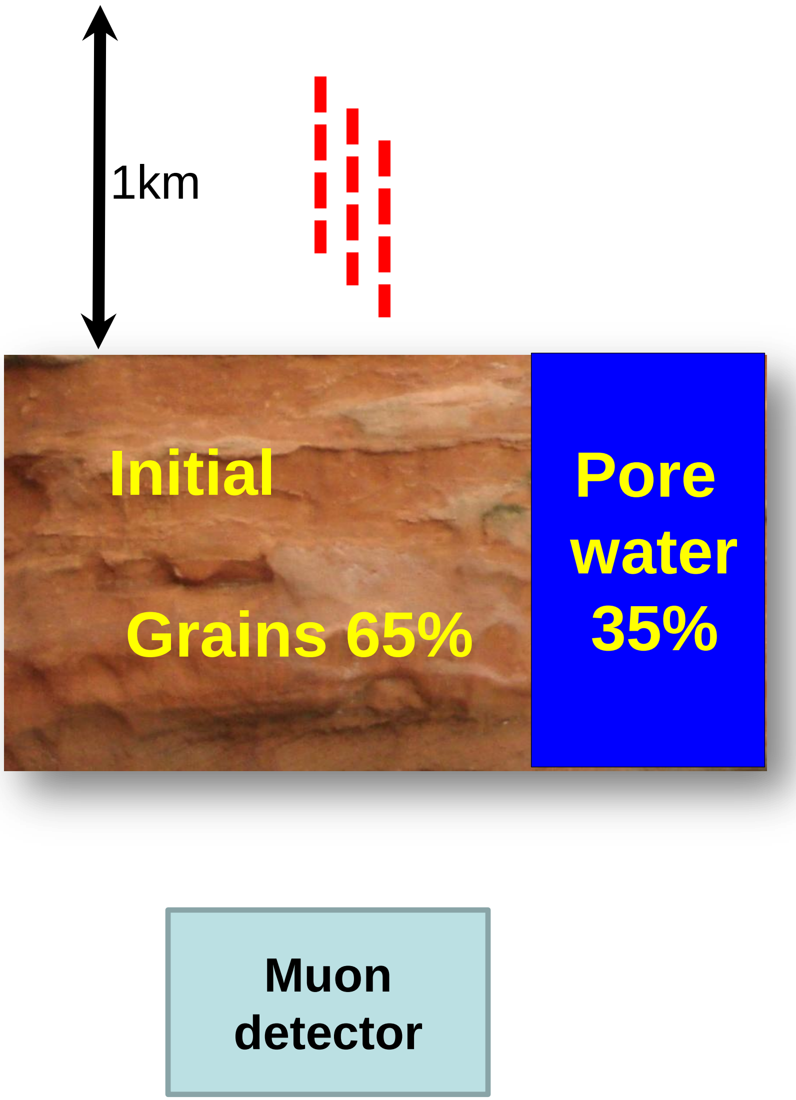
Detecting CO_2

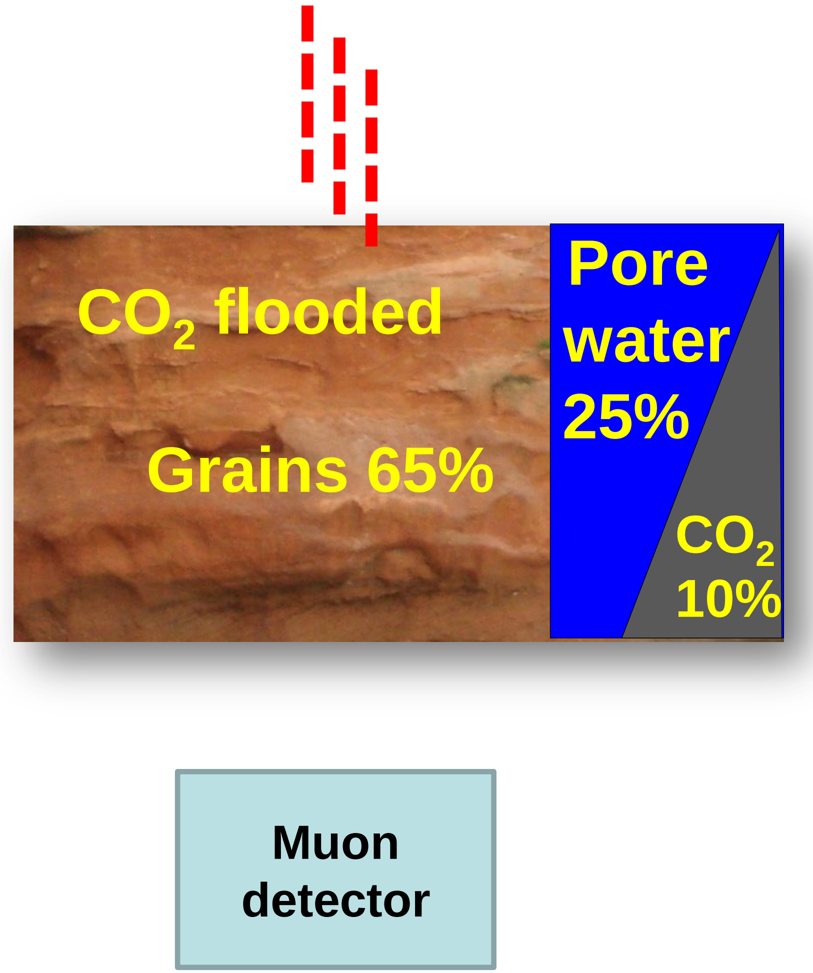
- Hewett Field a possible storage site for CO_2





The Reservoir Interval



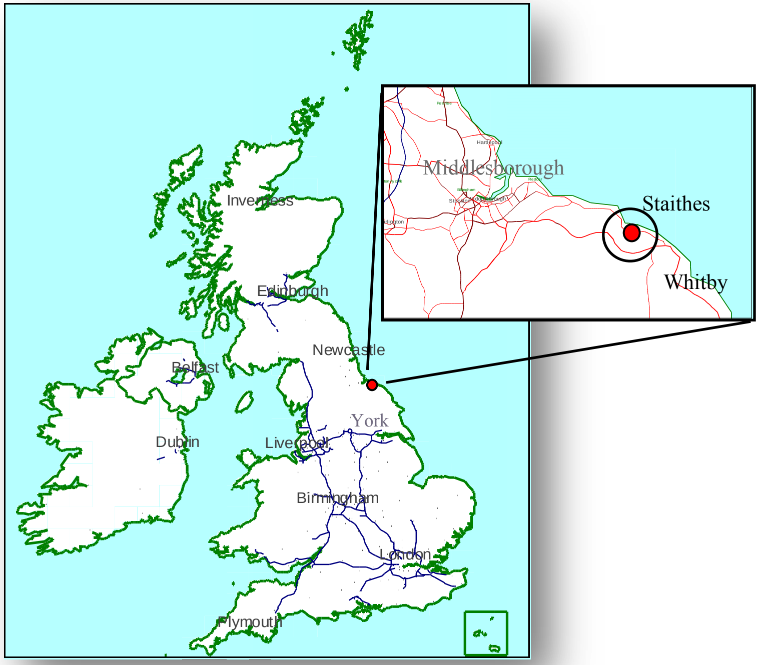


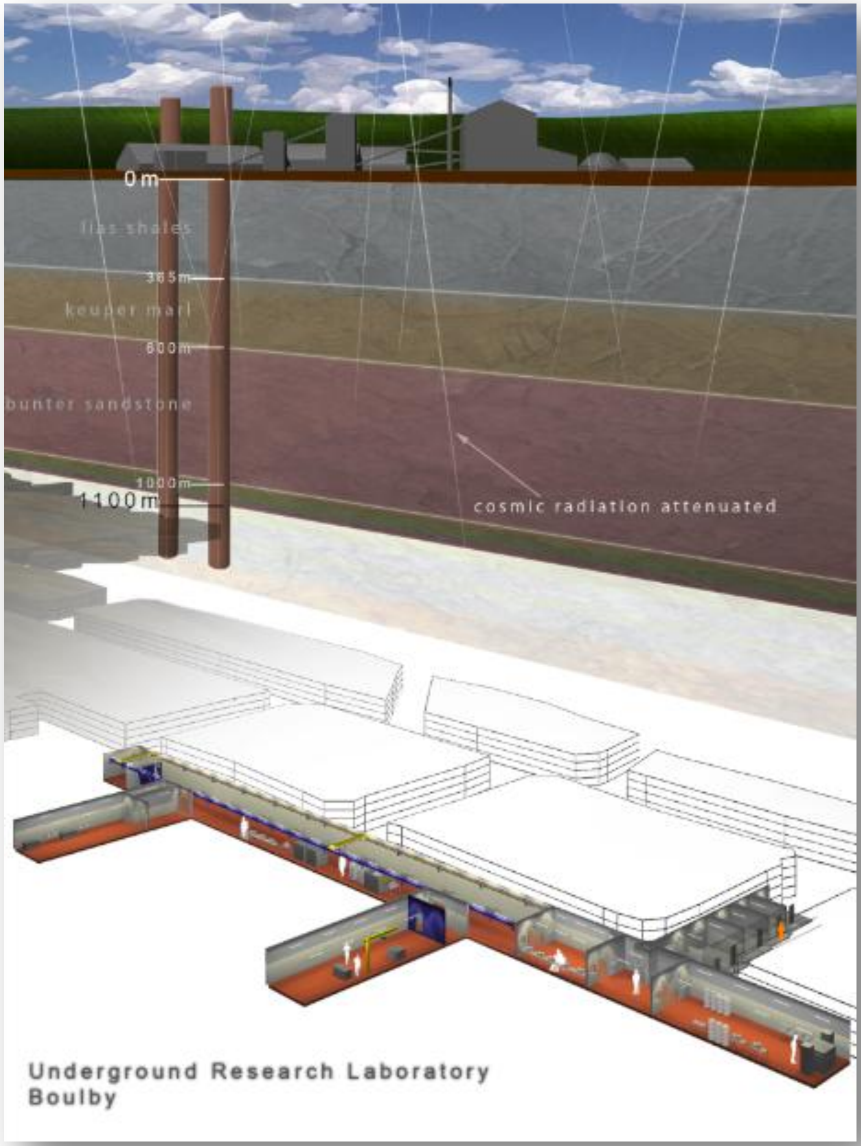
Can we detect muons?

Can we detect change in muon flux?

Deep Mine Muon Detection

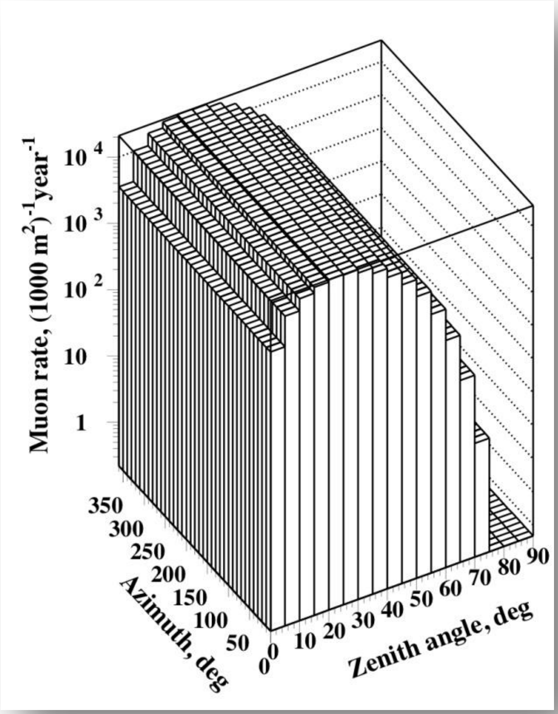
- Boulby Mine (Cleveland Potash Ltd)
- Deep dark matter lab @ >1km
- Overburden comparable to Southern North Sea
- Muons are detected!





Changes in Muon Flux - Modelling

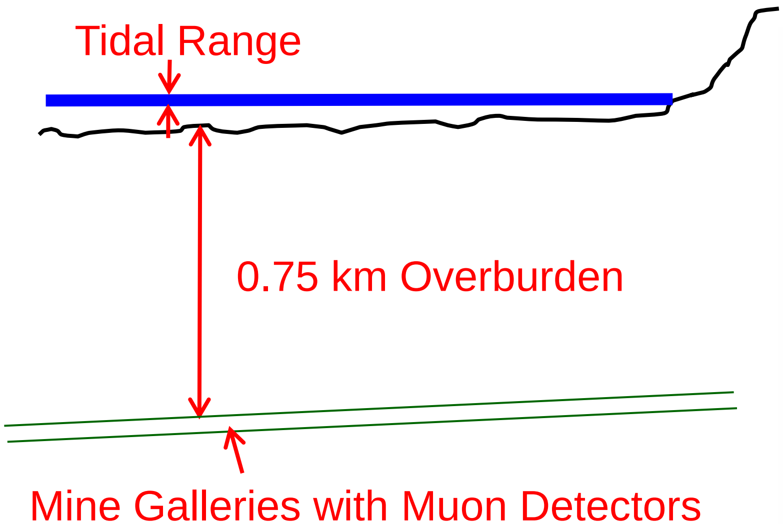
- 1D model
  - 1km overburden
  - 250m sandstone (ρ 2.70), 35% porosity, initially brine saturated (ρ 1.10) then with 10% CO_2 (ρ 0.75)
  - Initial results indicate that we could detect as little as 0.4% change in the mean reservoir density at ~1 km depth (≡ to 7% of pore volume).



Annual muon flux at the base of the sub-surface reservoir as a function of azimuth and zenith angles.

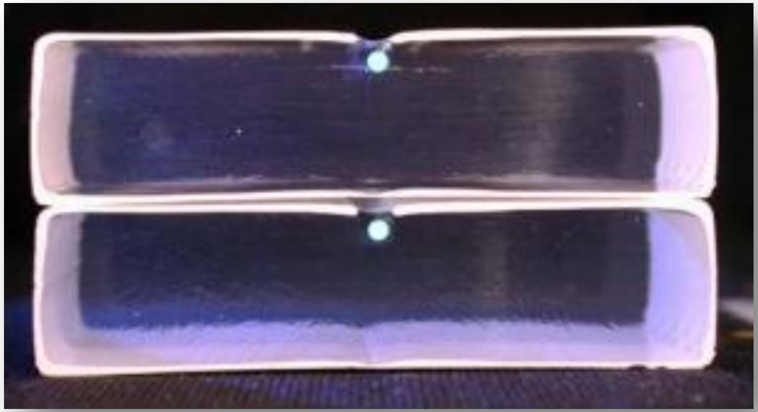
Changes in Muon Flux - Measurement

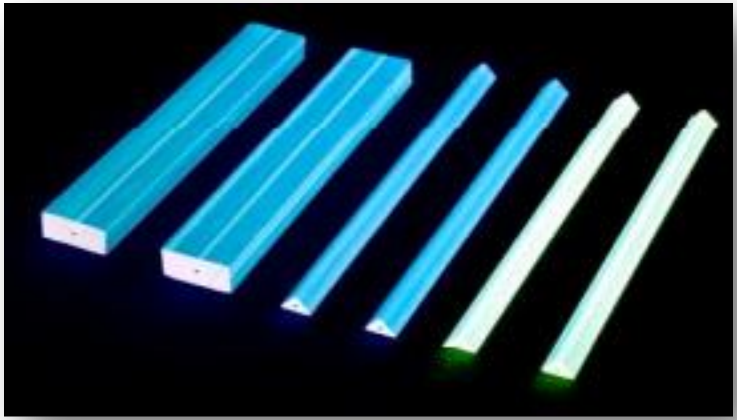
- Numerical modelling indicates:
  - Flux of about 35 muons/day/m^2 at 1km depth
- We can’t inject CO_2 into the sandstone layers overlying the mine!
- However, mine extends 7km offshore beneath the North Sea
- Can we detect diurnal or monthly tidal signals within muon flux?



Instrumentation (for deployment)

- T2K (*scintillating*) bars
  - Strips of extruded poylstyrene (up to 3.8m) doped with small fractions of organic scintillators
  - Scintillators are excited by ionizing radiaction (eg muons) and de-excite by emitting light
  - *Wavelength shifting* fibre optic within bar

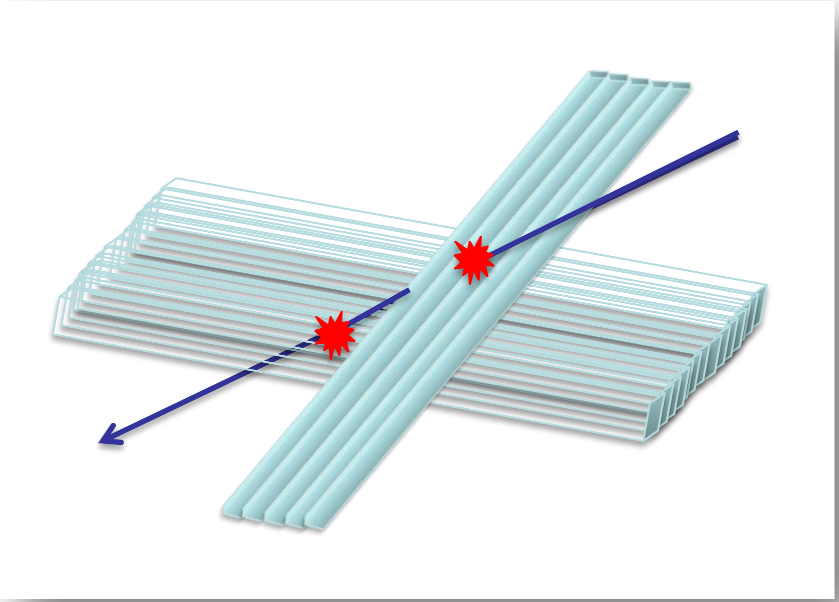


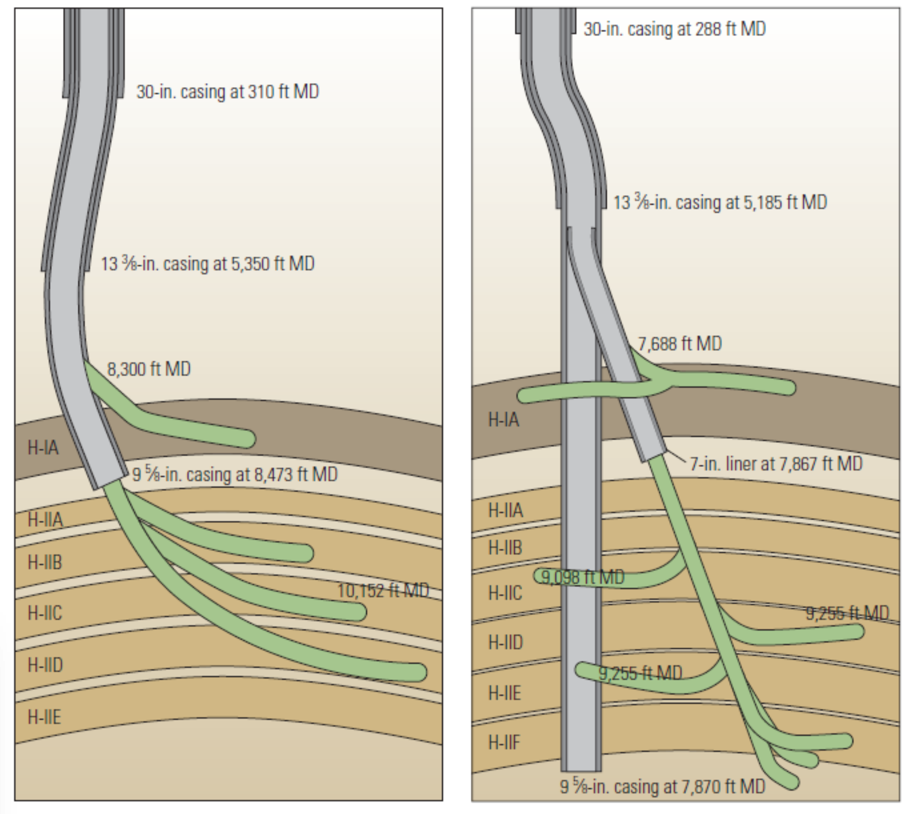


Next Steps

- Development of detectors & electronics to withstand hostile environment within wells
- Deploy, test & retrieve in vertical well (possibly Science Central well Newcastle – 1.85km)
- Continued numerical simulations based on real geology
- *Test deployment at injection location*

Deployment Possibilities





- Coil tubing drilling Zakum Field
- Fishbones AS (technology)

Commercial Interest & Potential Impact

- Estimated cost base for episodic (annual) 4d seismic on one site annually for 25 years
  - ~£22 million
- Estimated cost base for continuous muon tomography
  - CT wellbores ~£0.5 million/well x 10 per site = £15 million for 25 years + w/o costs thereafter

Conclusions

- Muon tomography may be a suitable technology for monitoring flux of carbon dioxide during geostorage
- Numerical simulations look promising – but much more work is required
- Detection and instrumentation programmes planned

A Final Thought

...it might just be possible that we could use cosmic rays generated in deep space supernova as a tool to combat climate change here on Earth...