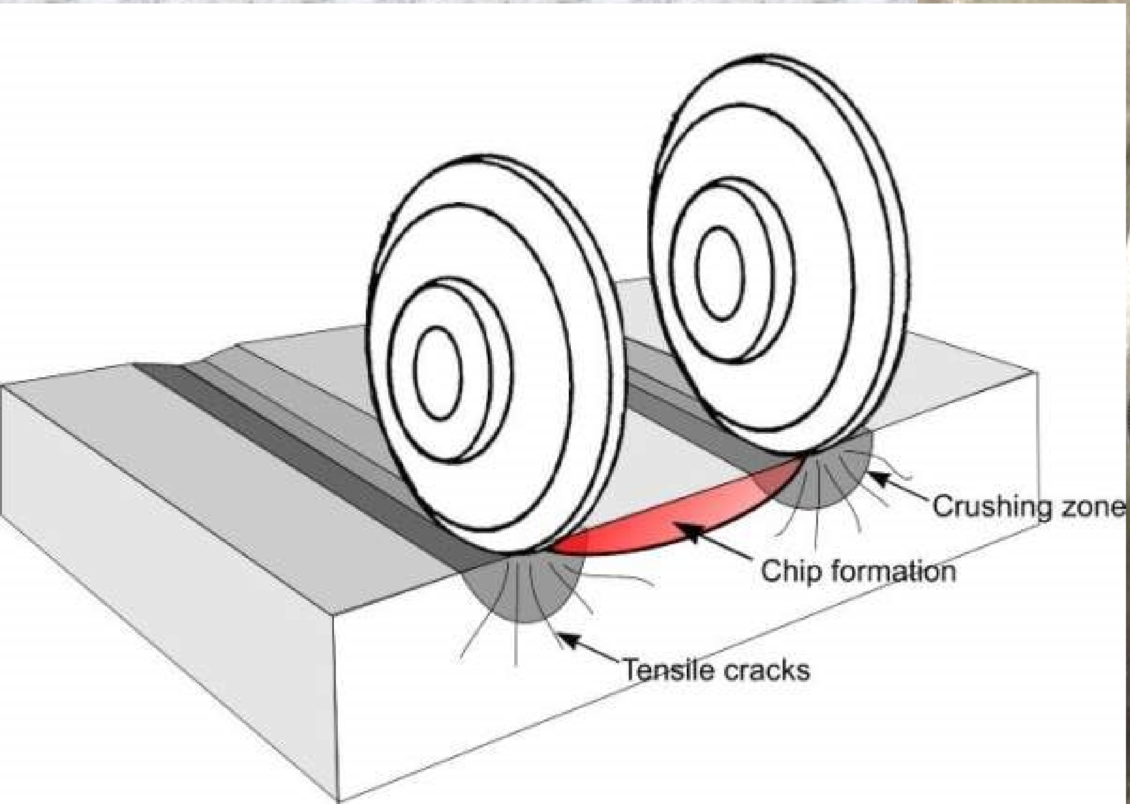
Recent experiences in tunnelling

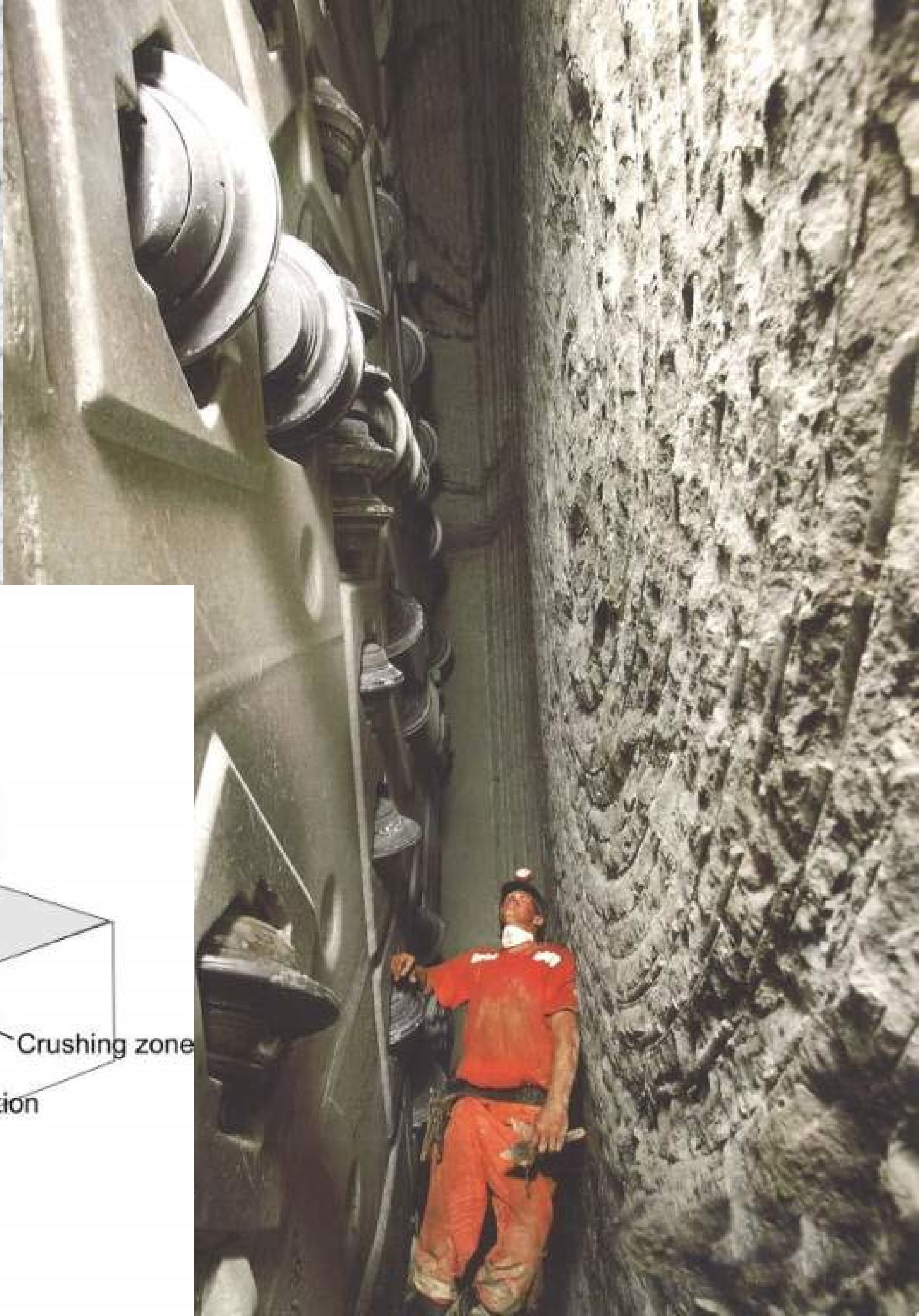
Evert Hoek

Athens, October 2009

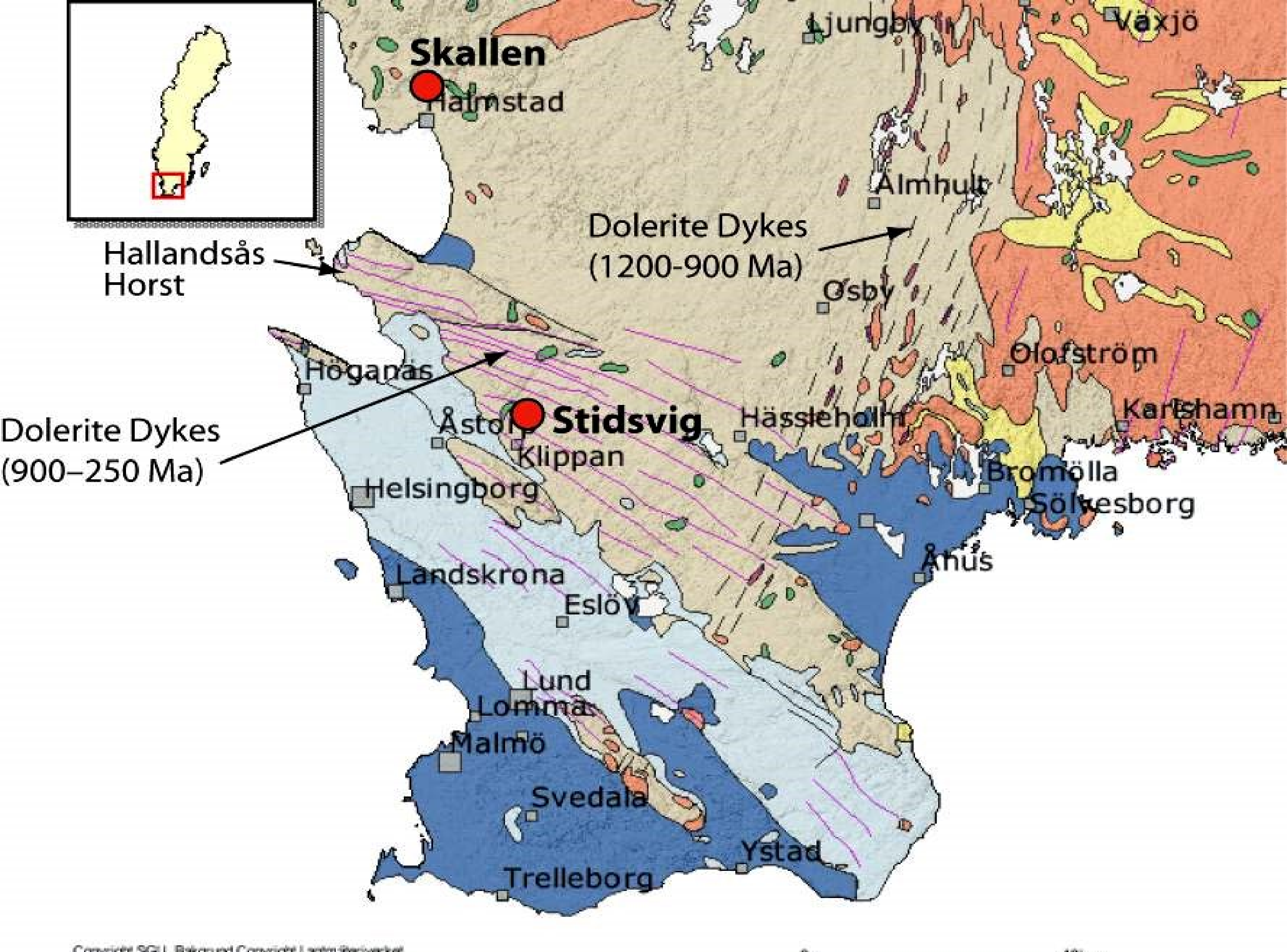

Hallandsås Tunnel,
Sweden

Hard rock TBM cutting by chip formation between parallel cutter tracks

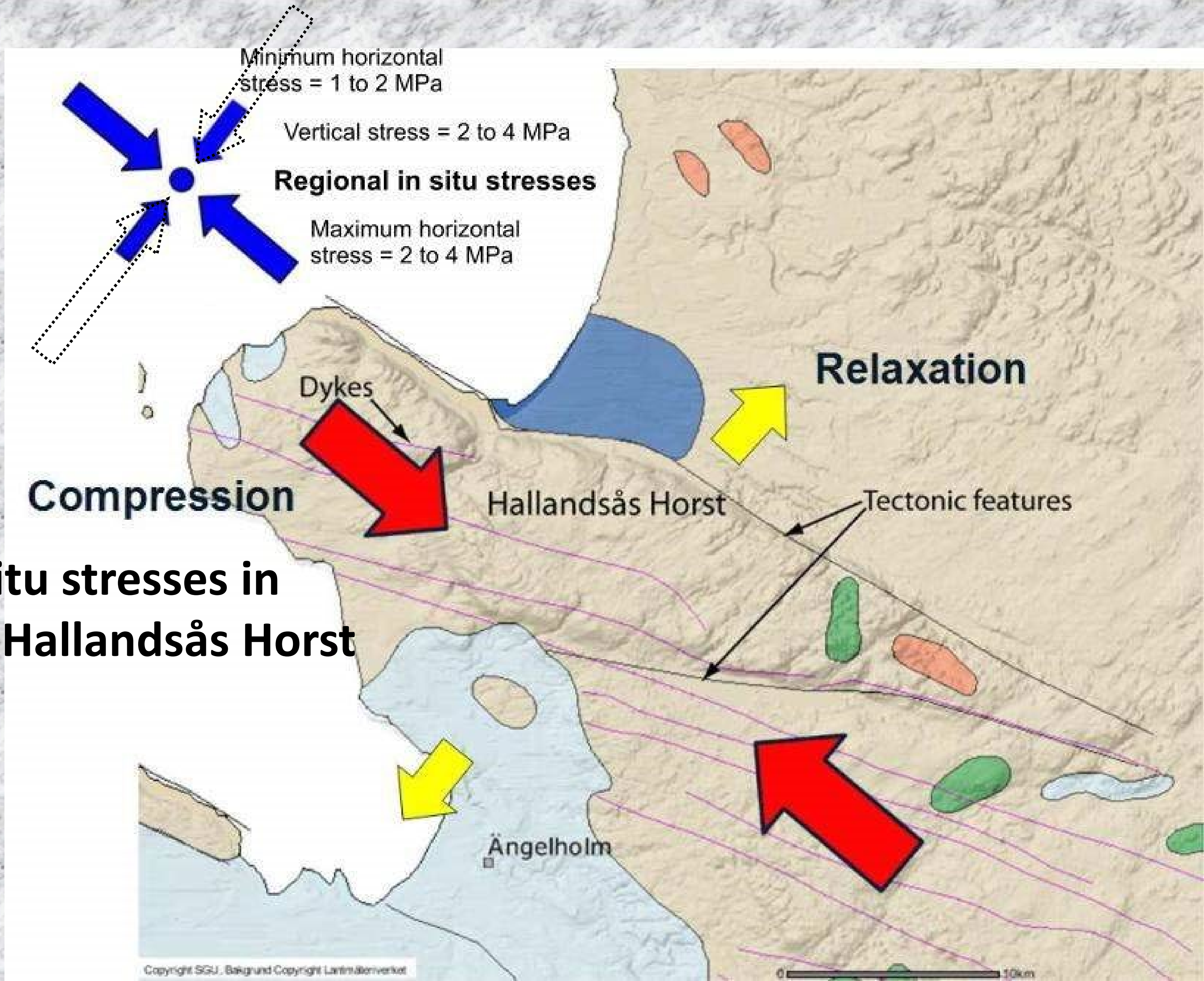


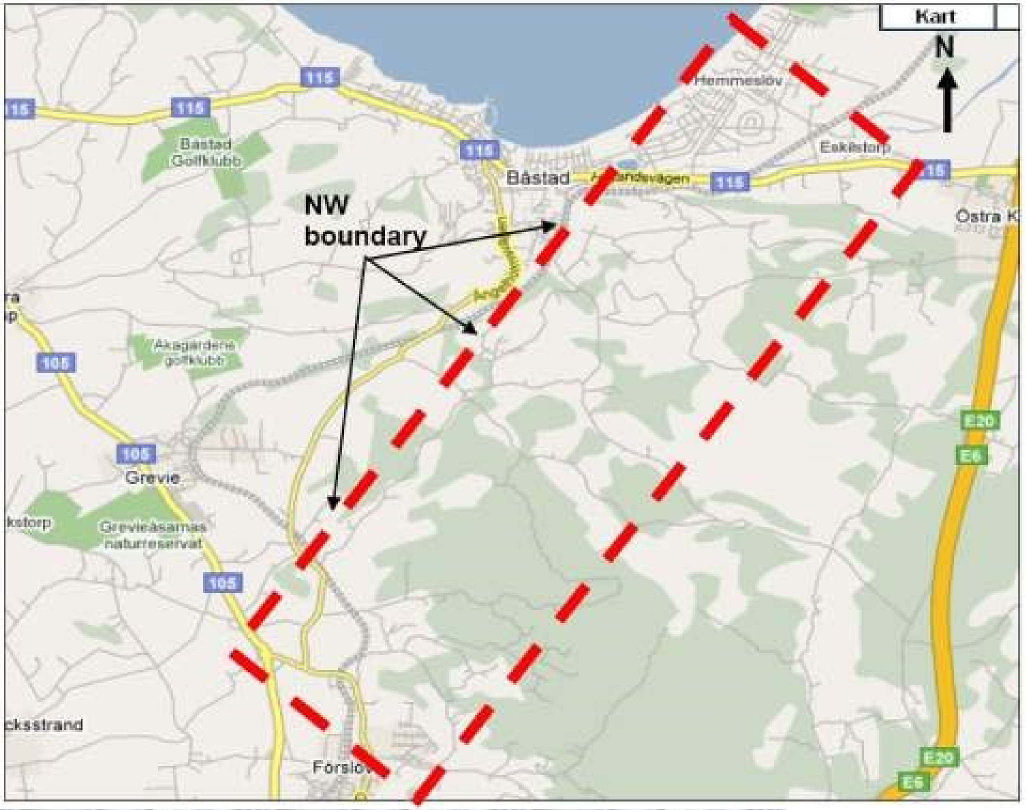


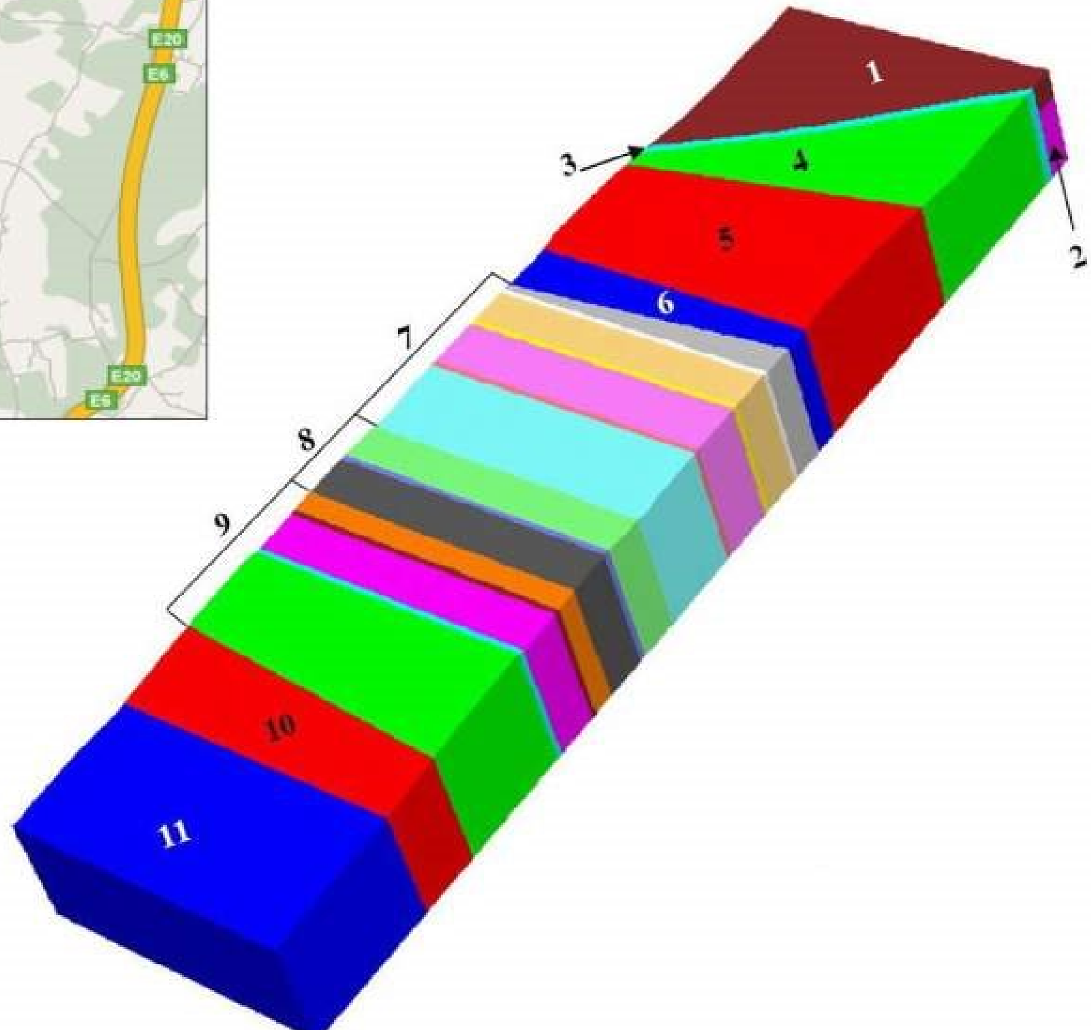
Comparison between chip formation for a normal hard rock TBM (on the left) and the Hallandsås TBM (on the right)


Skallen
Halmstad
Ljungby
Växjö
Älmhult
Dolerite Dykes
(1200-900 Ma)
Hallandsås
Horst
Osby
Olofström
Höganäs
Dolerite Dykes
(900–250 Ma)
Åstorp
Stidsvig
Klippan
Hässleholm
Karlshamn
Bromölla
Sölvesborg
Helsingborg
Åhus
Landskrona
Eslöv
Lund
Lomma
Malmö
Svedala
Ystad
Trelleborg
0
43km

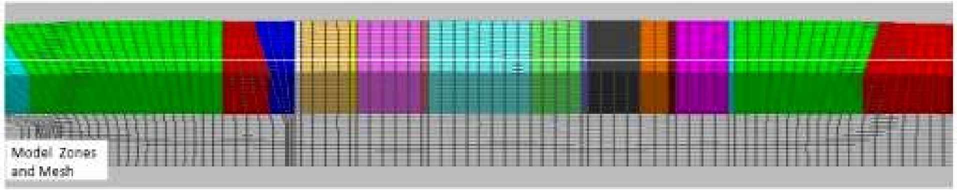
In situ stresses in the Hallandsås Horst



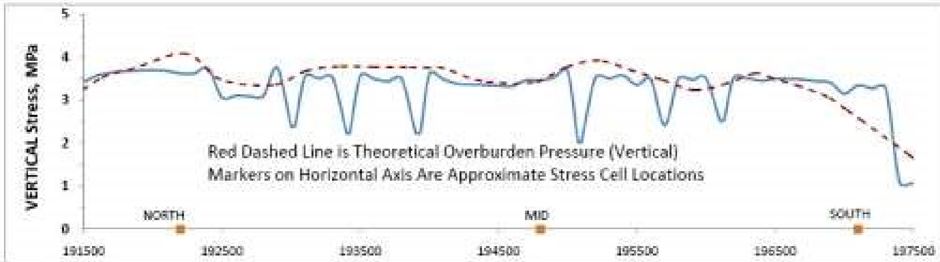




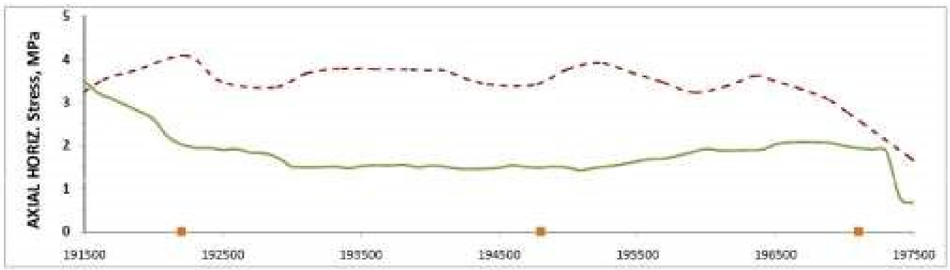
SINTEF FLAC3D stress model to show stress variations due to different rock mass stiffness



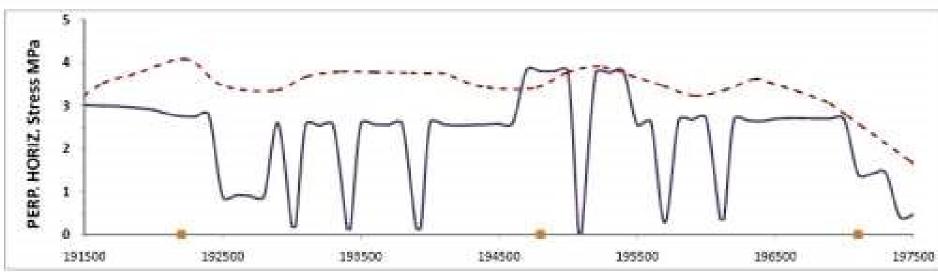
FLAC3D model



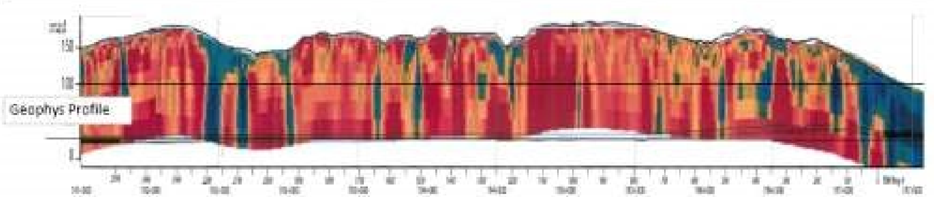
Vertical stress compared to calculated overburden stress



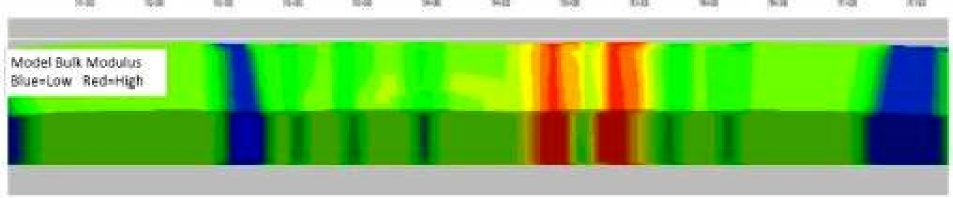
Horizontal stress along tunnel axis compared to calculated overburden stress



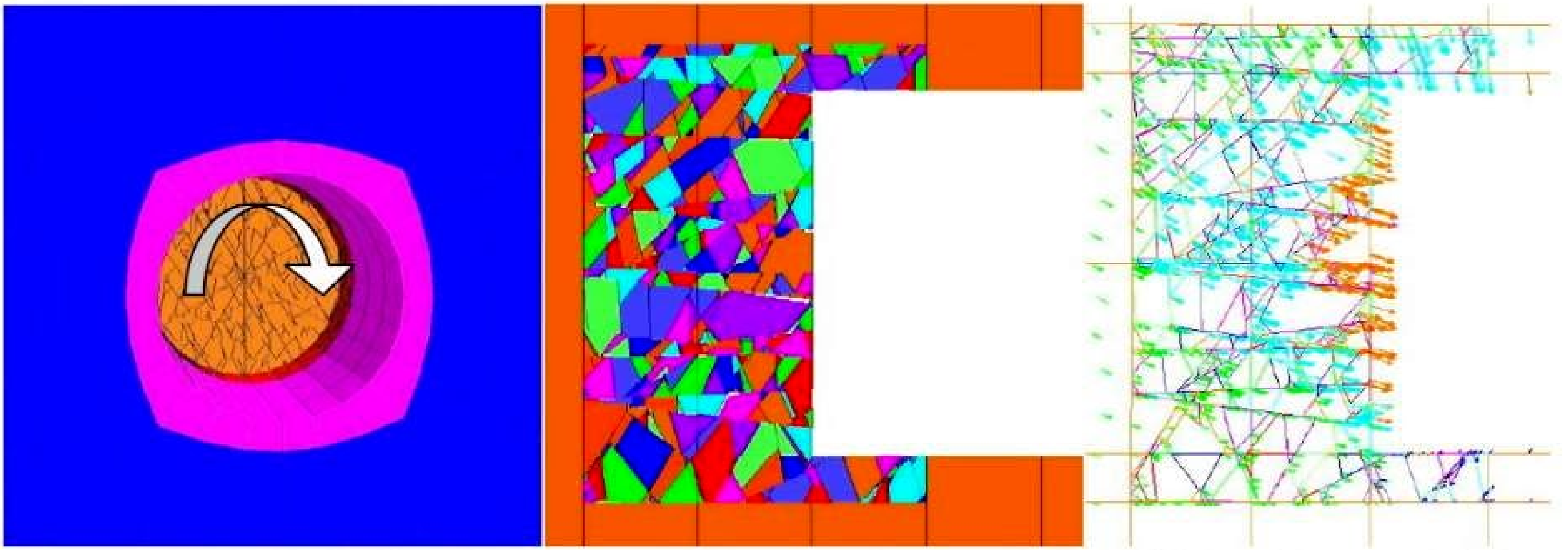
Horizontal stress normal to the tunnel axis compared to calculated overburden stress



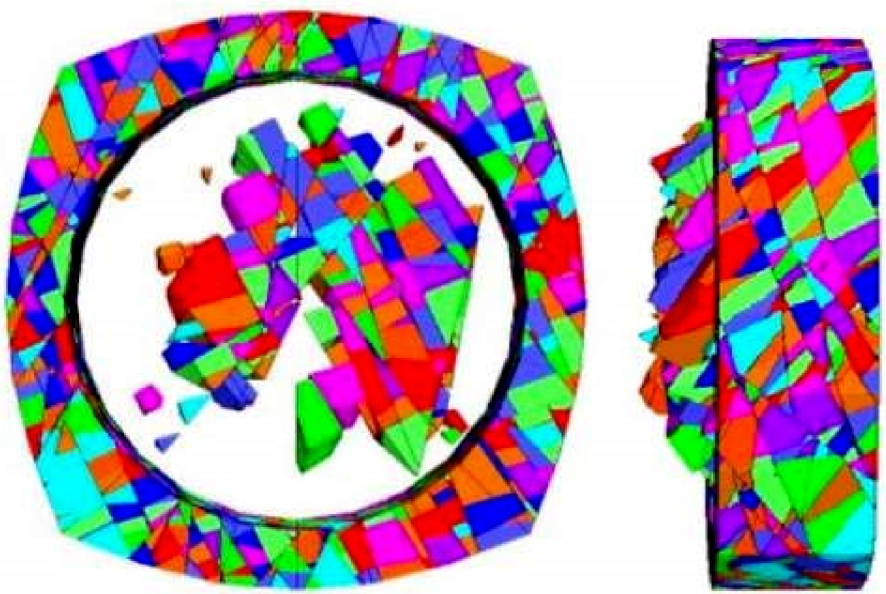
Magnetic survey along tunnel showing rock mass quality

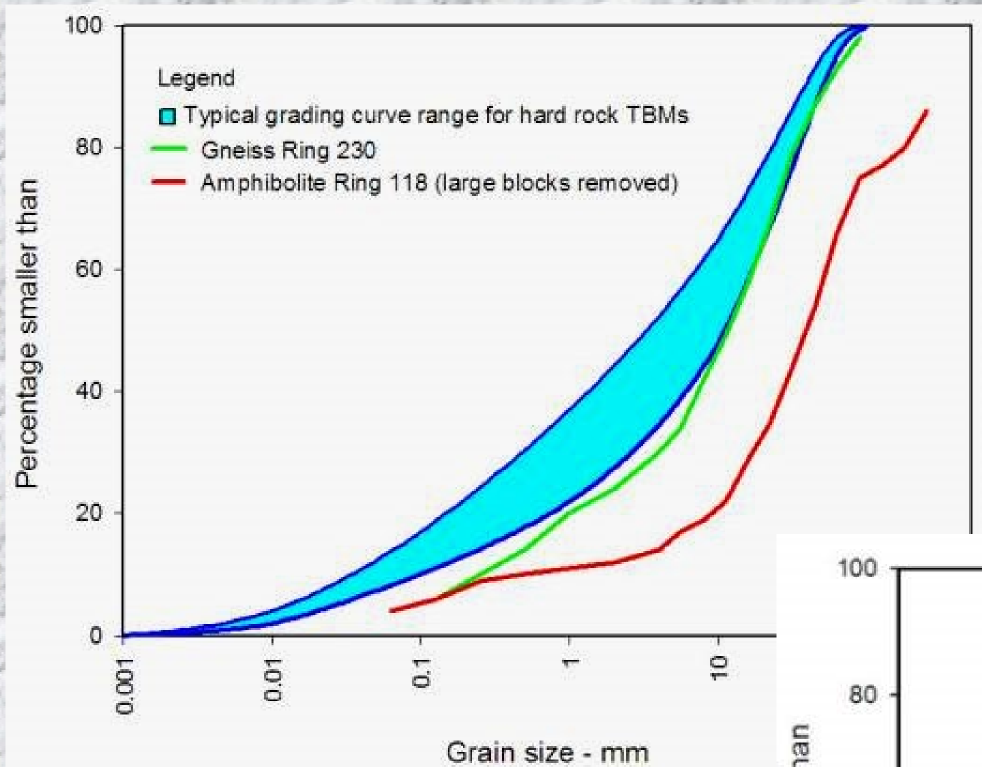


Modulus variation in FLAC3D model



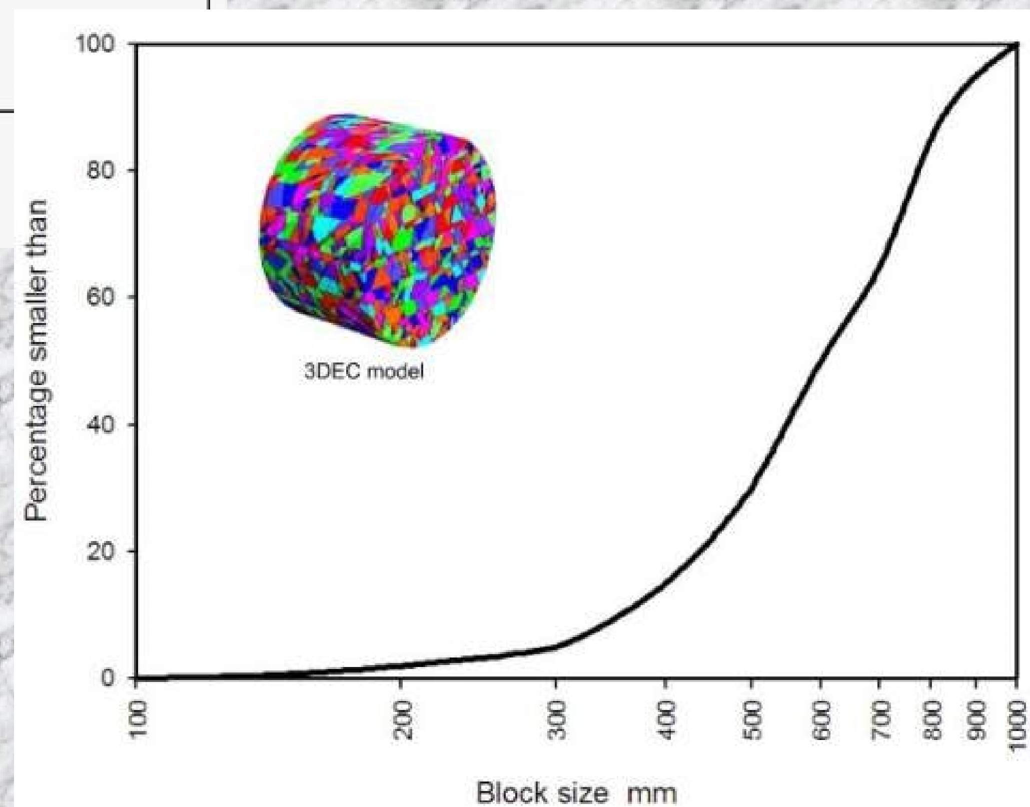
3DEC model of block instability due to low in situ stresses

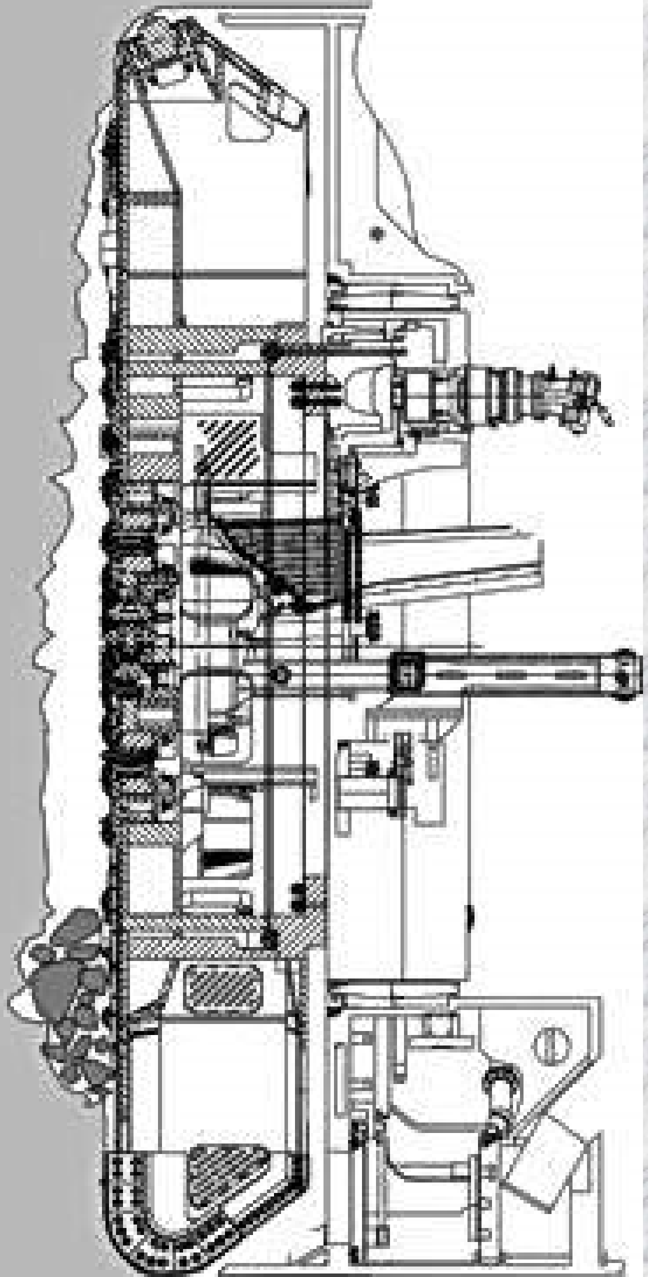




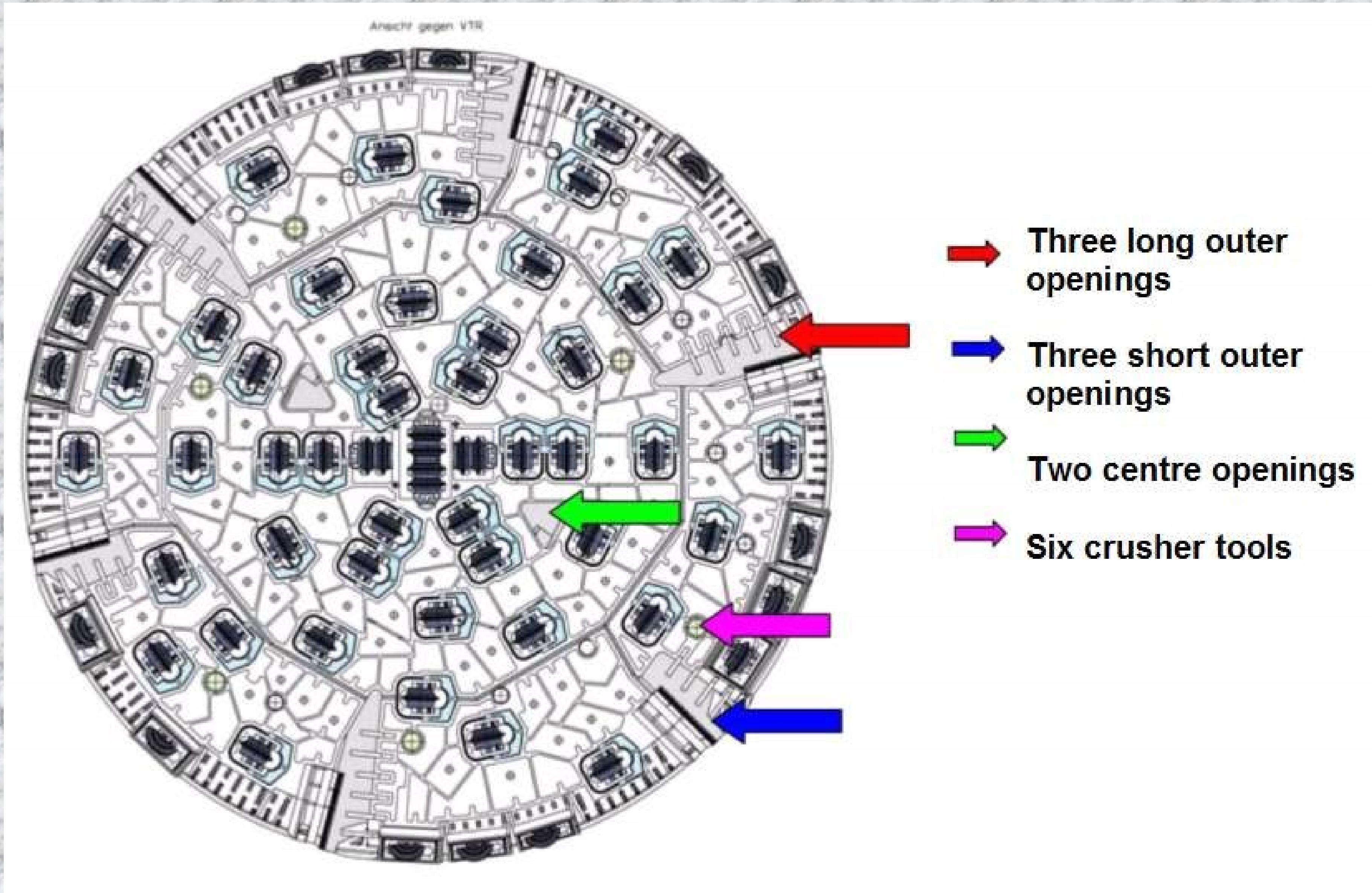
Muck pile grading curves

3DEC model grading curve





Schematic sketch of the zone in which most rock crushing takes place on the face. Herrenknecht drawing



New Herrenknecht cutter head design to deal with operating in a predominantly crushing rather than a cutting mode

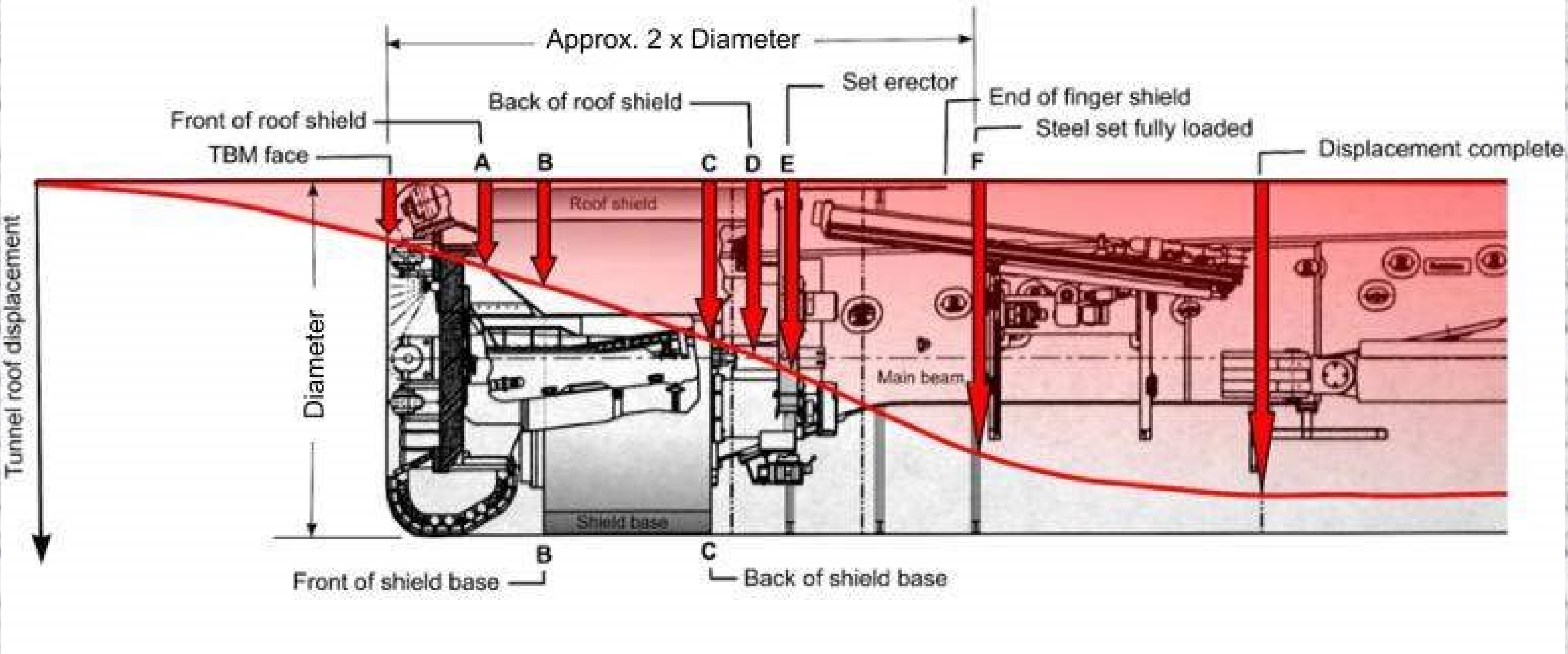

Los Olmos
Tunnel, Peru

- **The Olmos tunnel is a 5.3 m diameter, 13.9 km long water transfer tunnel through the Andes mountains in Peru at depths of more than 2000 m below surface.**

- **It is being driven by a Robbins open face hard rock TBM by the Brazilian contractor Odebrecht through quartz porphyry, andesite and tuff with UCS ranging from 60 to 225 MPa.**

- **Launched in March 2007 the TBM had progressed 5 km by August 2008 at an average advance rate of 22 m per day. Rockbursting has been a constant problem but has been controlled by the installation of steel sets and lagging as illustrated in he following video and slides.**

Video of rockbursting in the Olmos tunnel in Peru



Typical displacement profile for an advancing open face hard rock TBM. Note that the first point at which the steel sets can be fully loaded is behind the finger shield, approximately 2 diameters behind the face. About 80% of the deformation has already taken place at this distance. For a self-stabilizing tunnel (for which open face TBMs are suitable) this means that the load on the steel sets is usually very small.

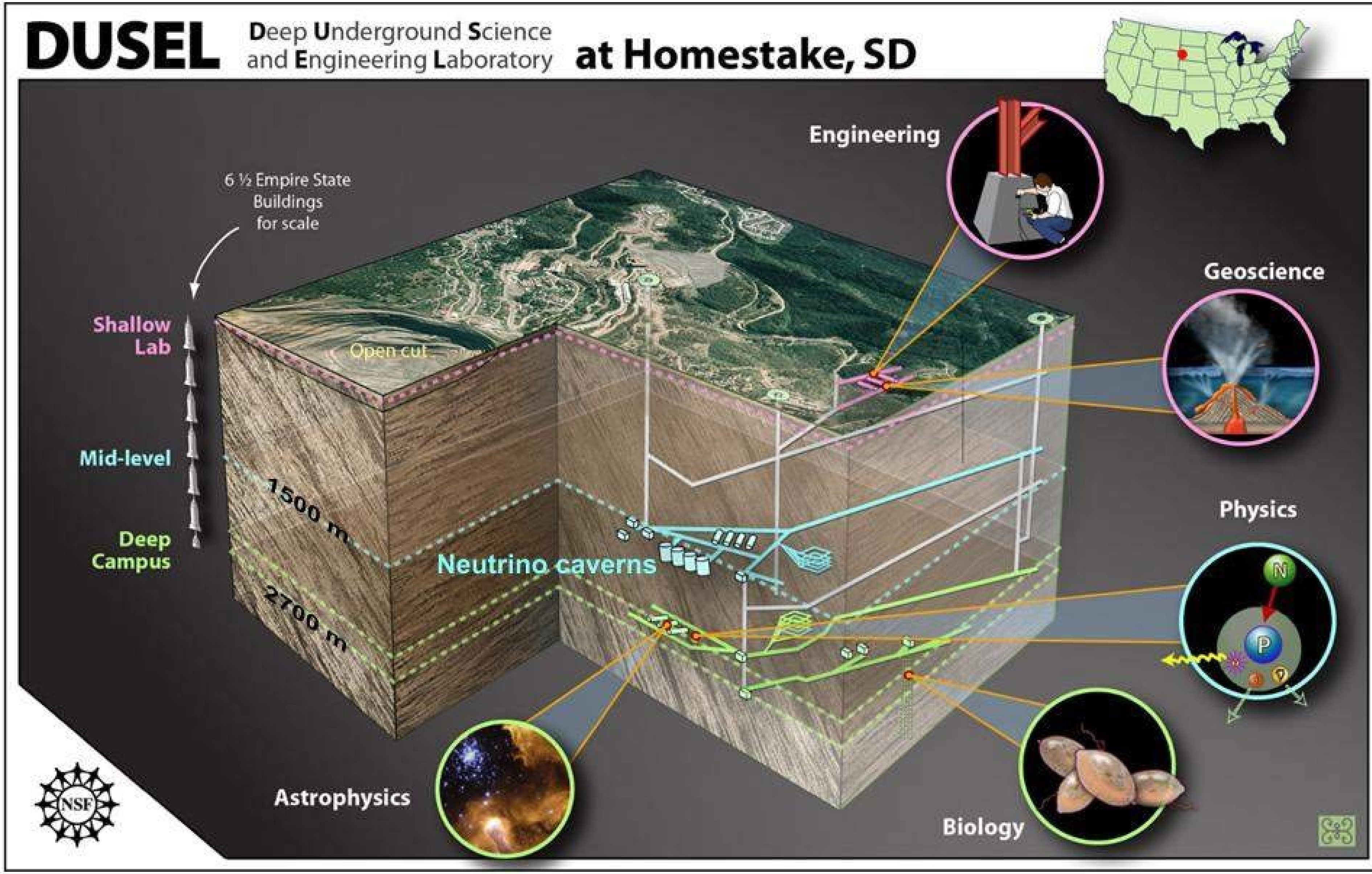
Original Olmos support system – wire mesh under steel sets installed inside finger shield

Wire mesh under steel sets installed inside finger shield – Acheloos tunnel, Greece

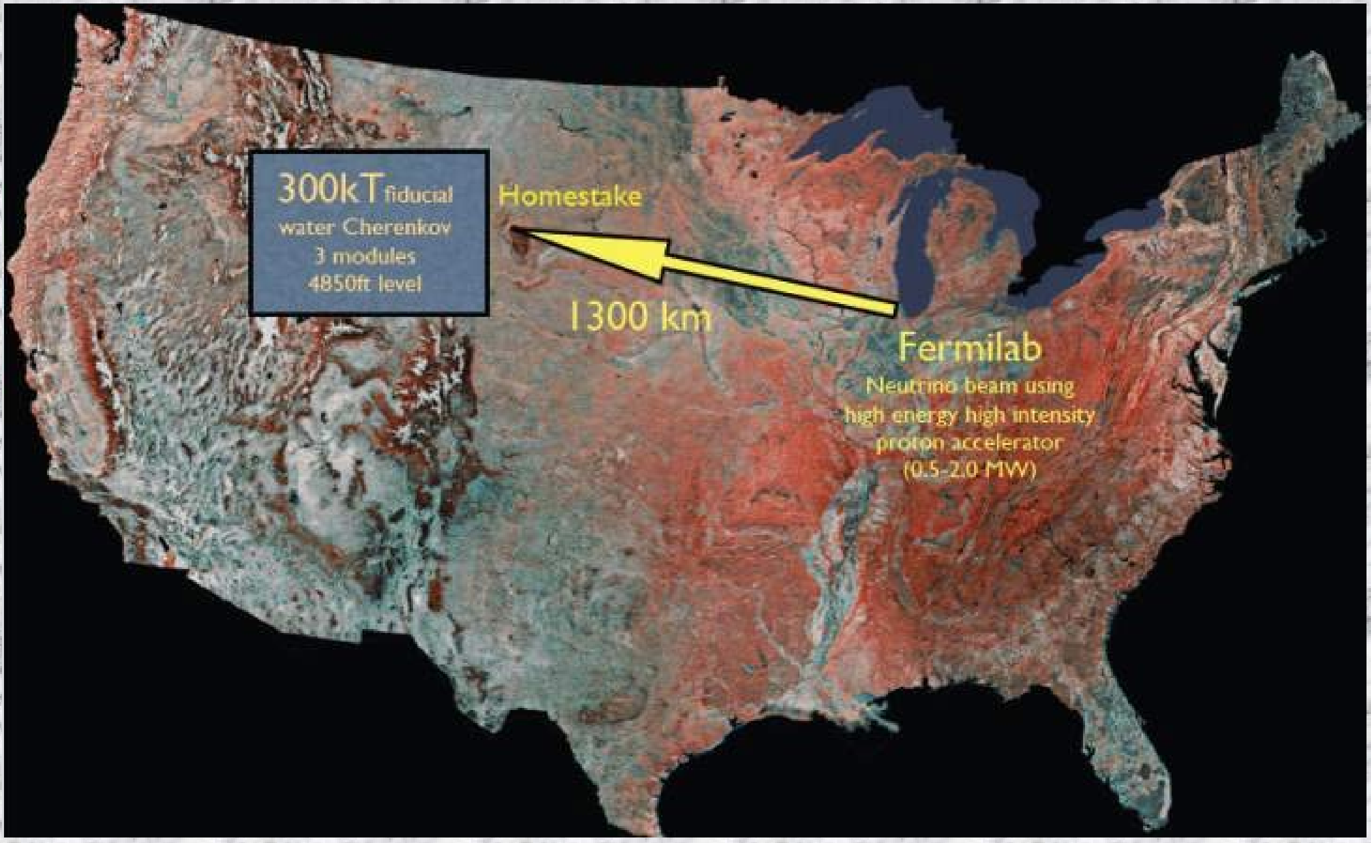
Surface model of McNally support system adopted for use in the Olmos tunnel

Detail of McNally system showing "magazine" for rebar packages above TBM shield

Deep Underground Science and Engineering Laboratory (DUSEL) project
Homestake Mine, South Dakota, USA

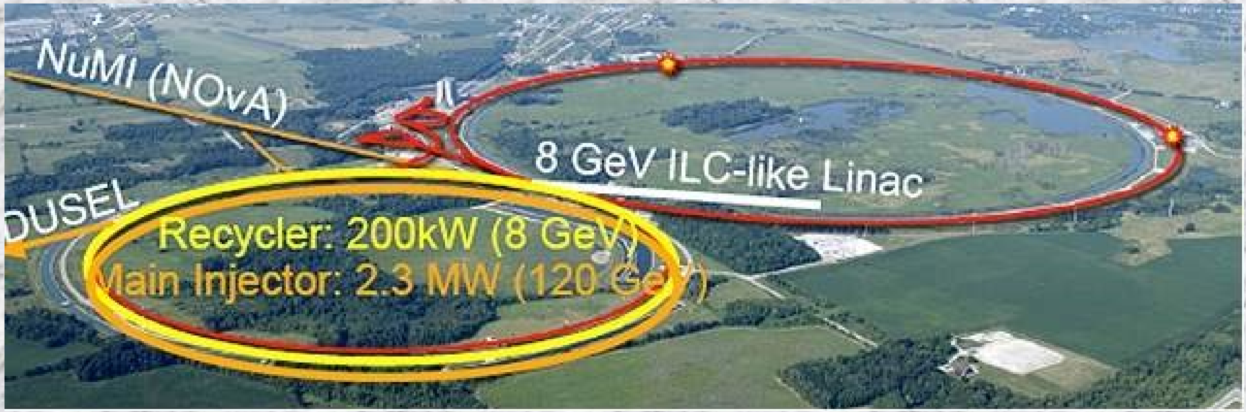


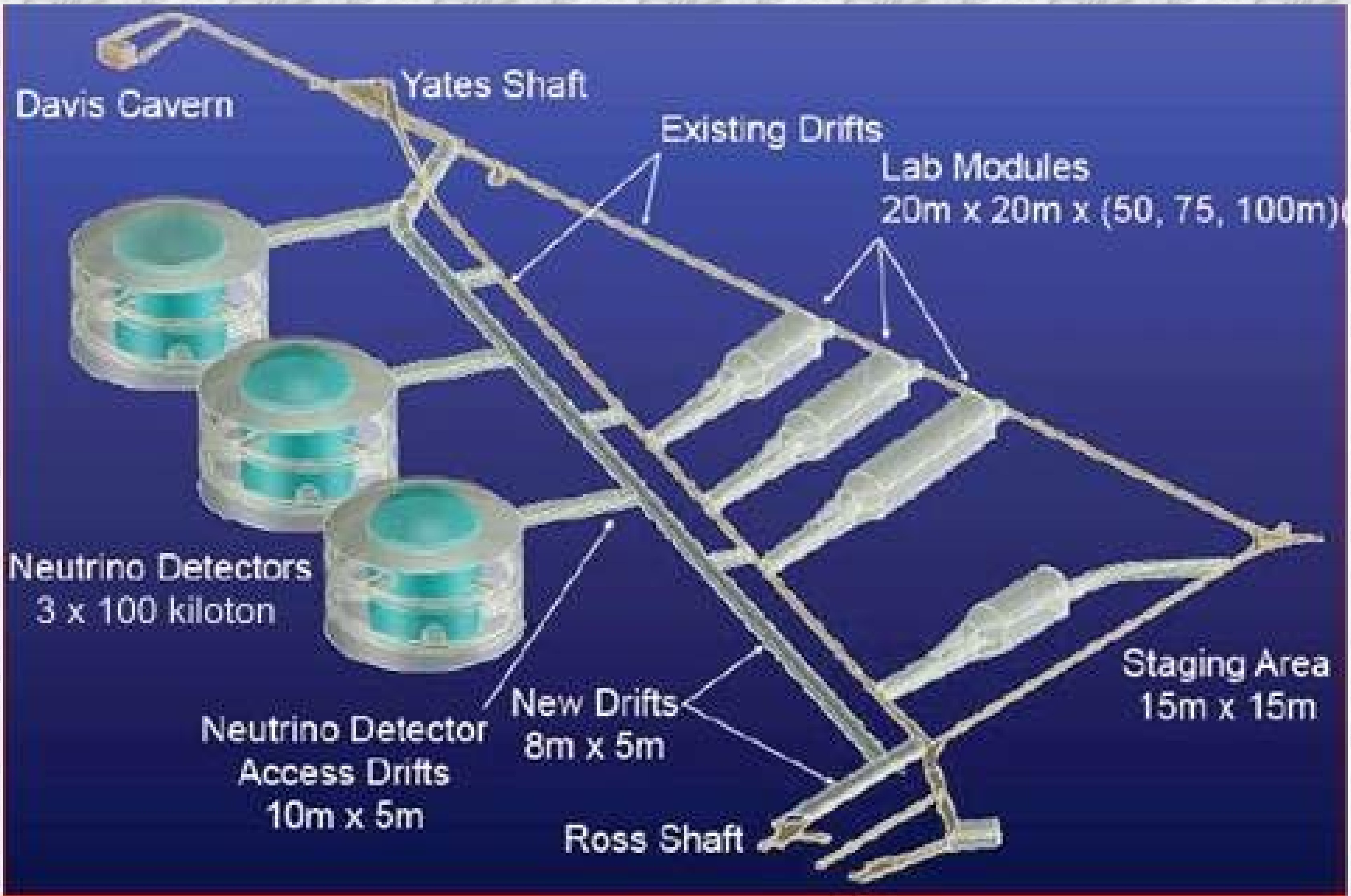
Conceptual model of the DUSEL complex



Location of DUSEL relative to the FERMI Laboratory near Chicago

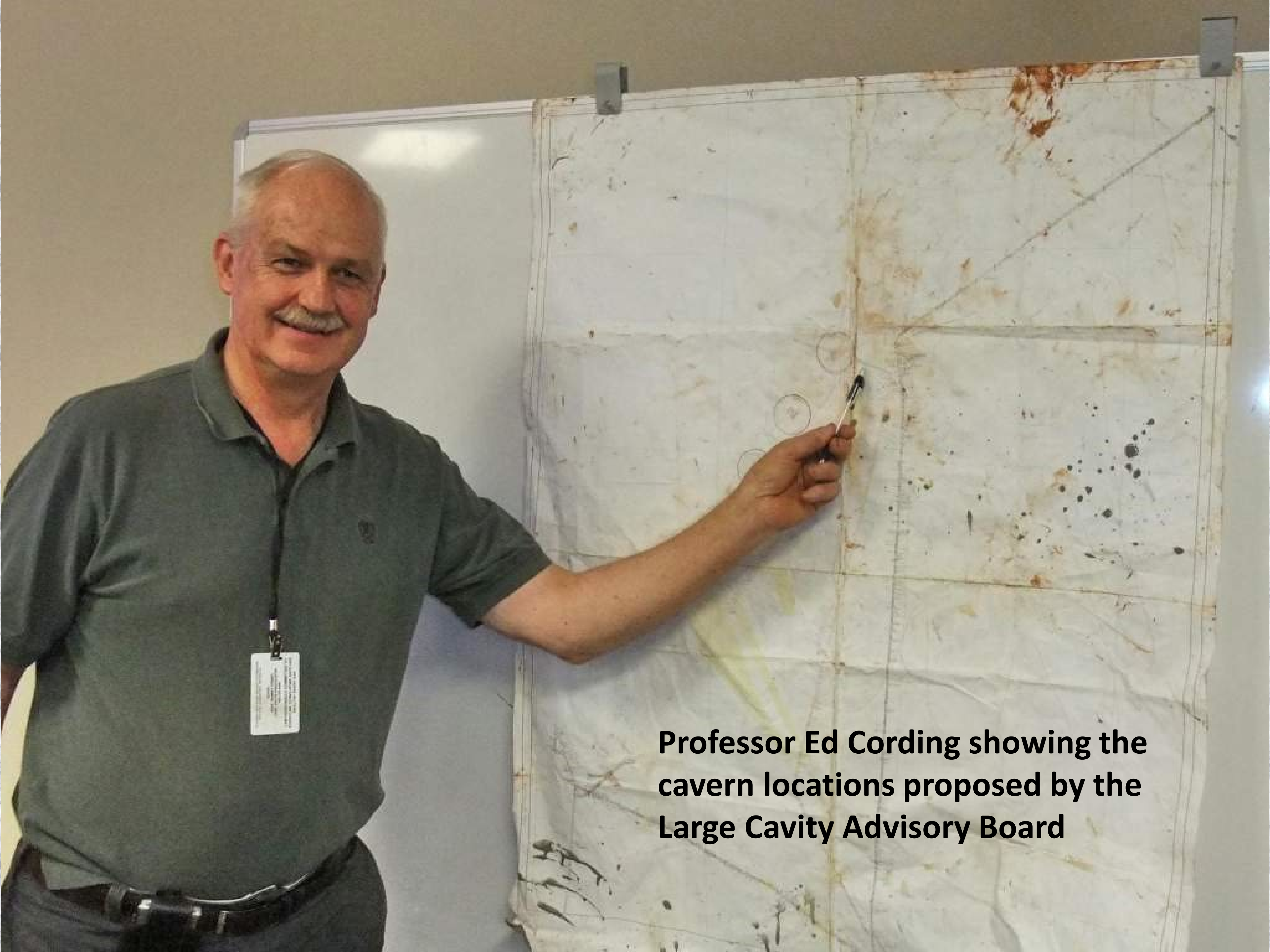
The addition of a new tunnel to the existing FERMI Lab layout will direct neutrinos to DUSEL





Conceptual layout of 3 neutrino detector caverns at DUSEL

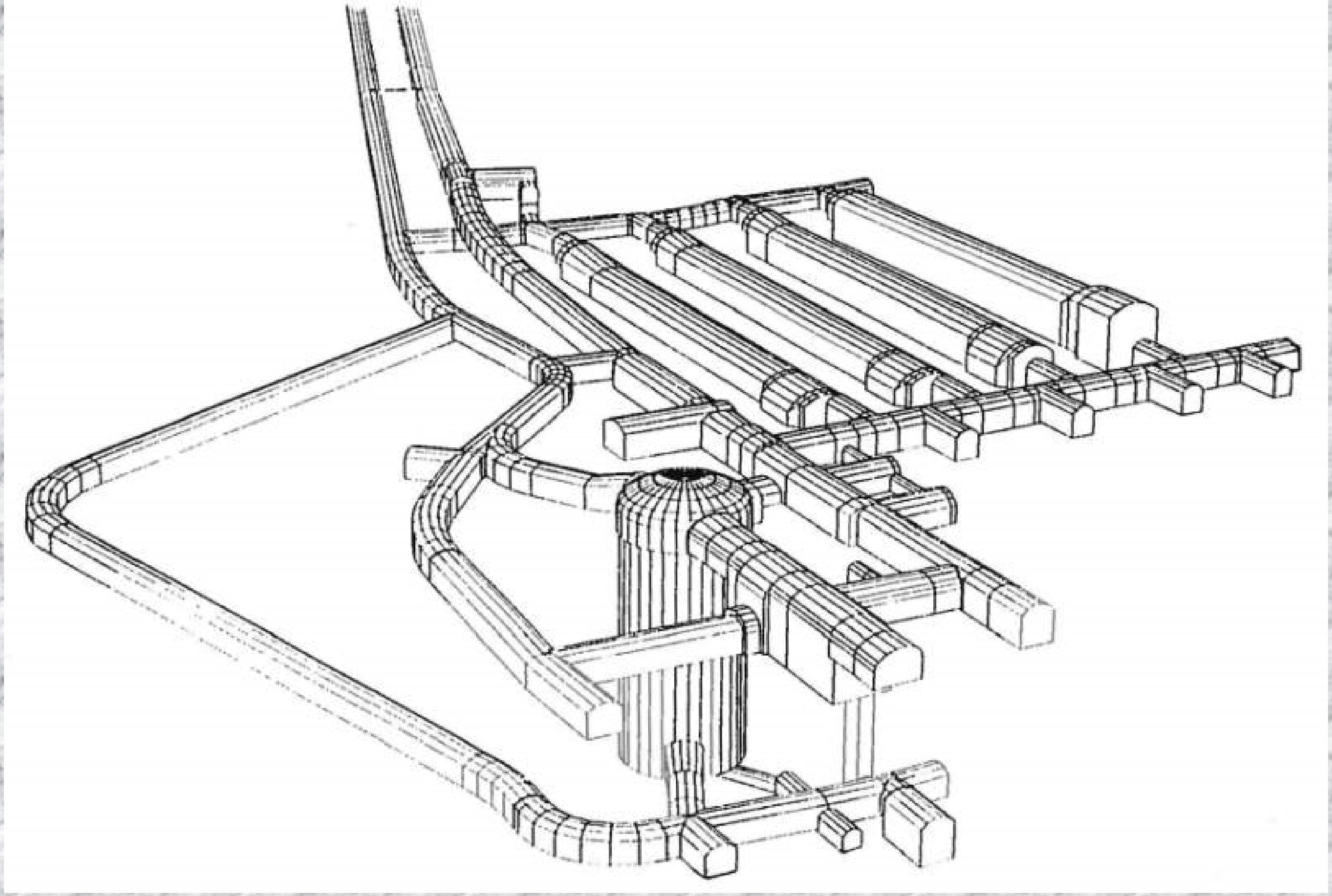
Large Cavity Advisory Board visit to recently dewatered
1500 m level in Homestake Mine, July 2009



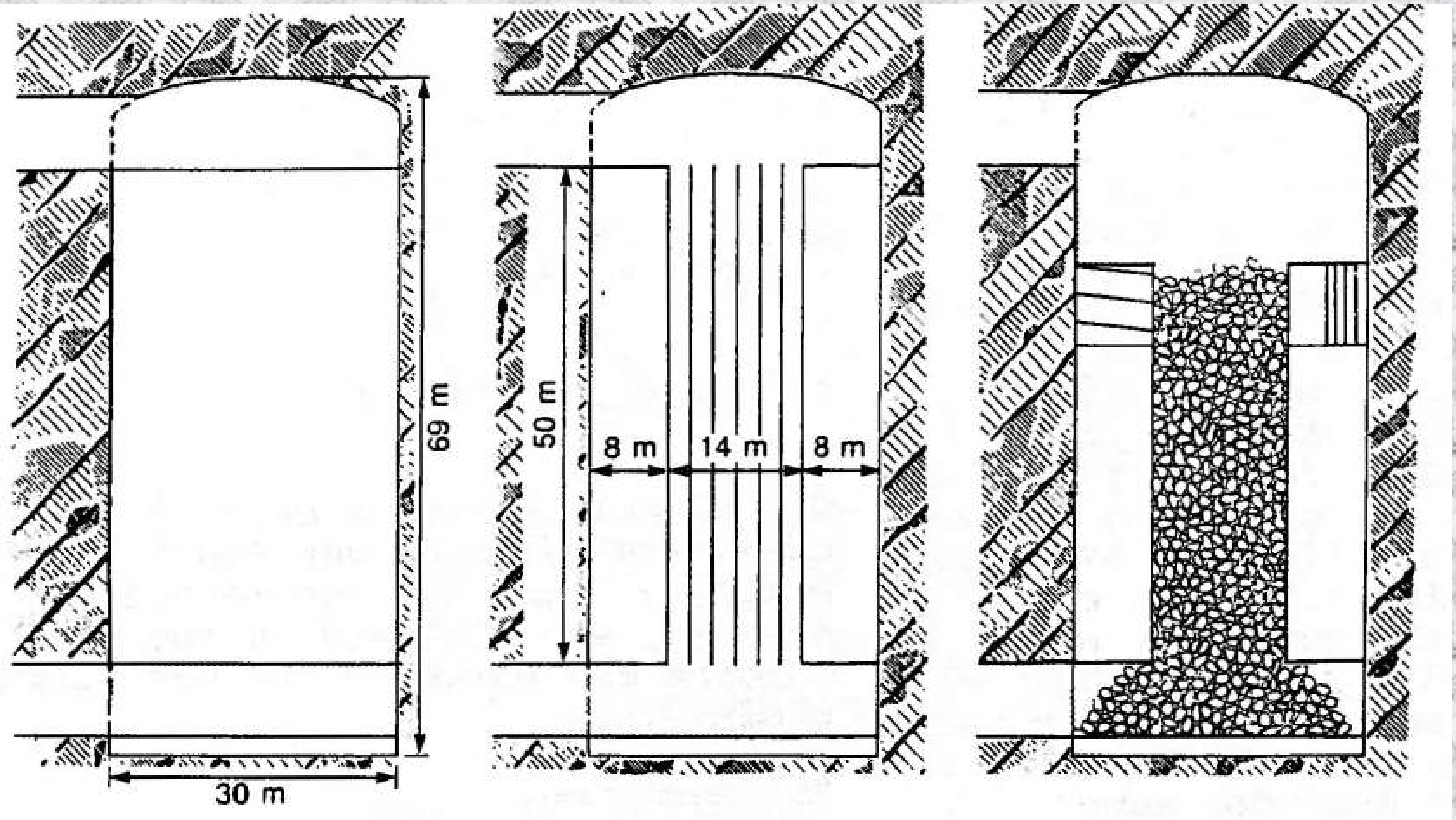
Professor Ed Cording showing the cavern locations proposed by the Large Cavity Advisory Board

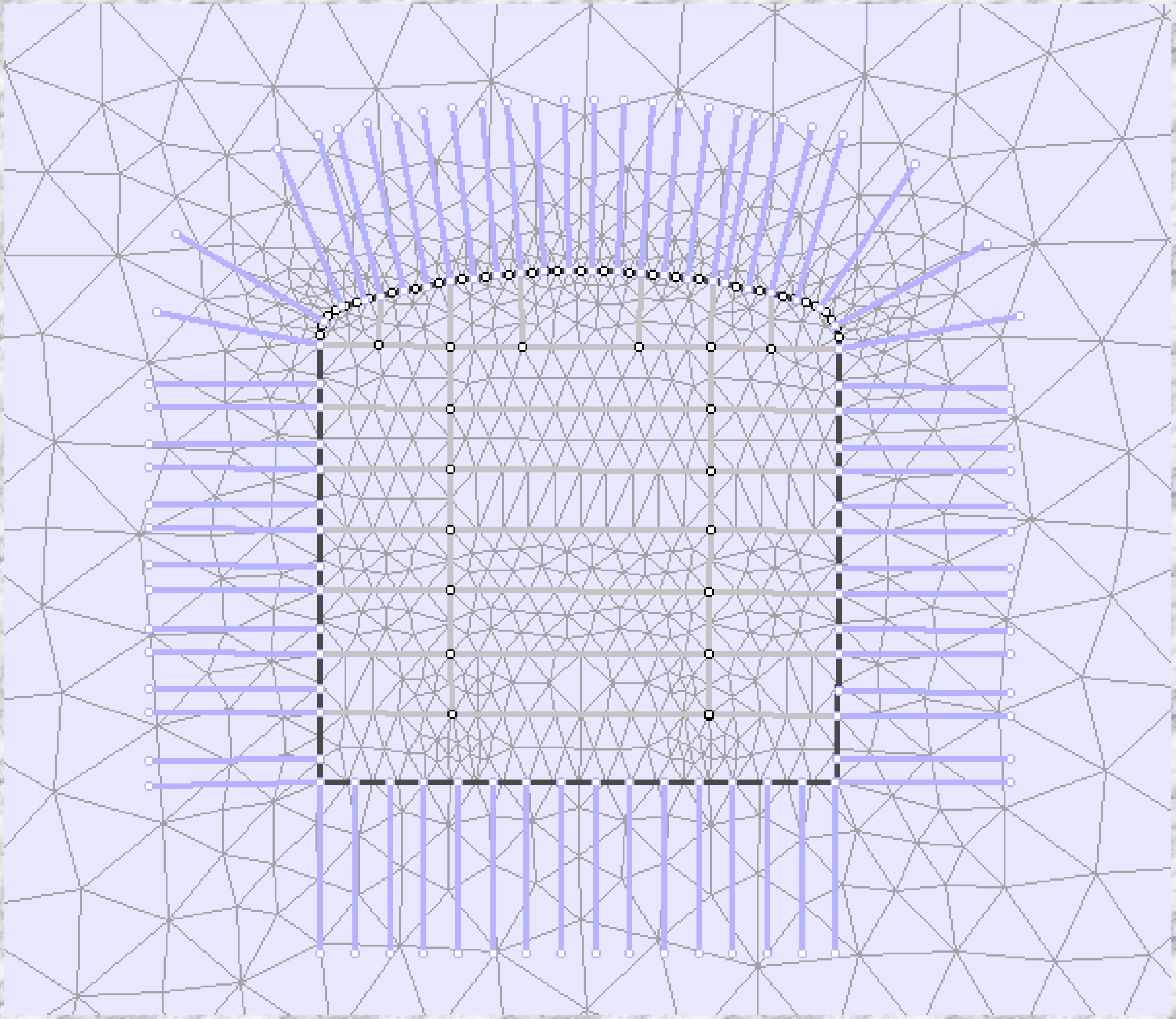
SFR Facility Forsmark, Sweden
A possible model for cavern construction

Underground excavations, approximately 60 m below Baltic sea

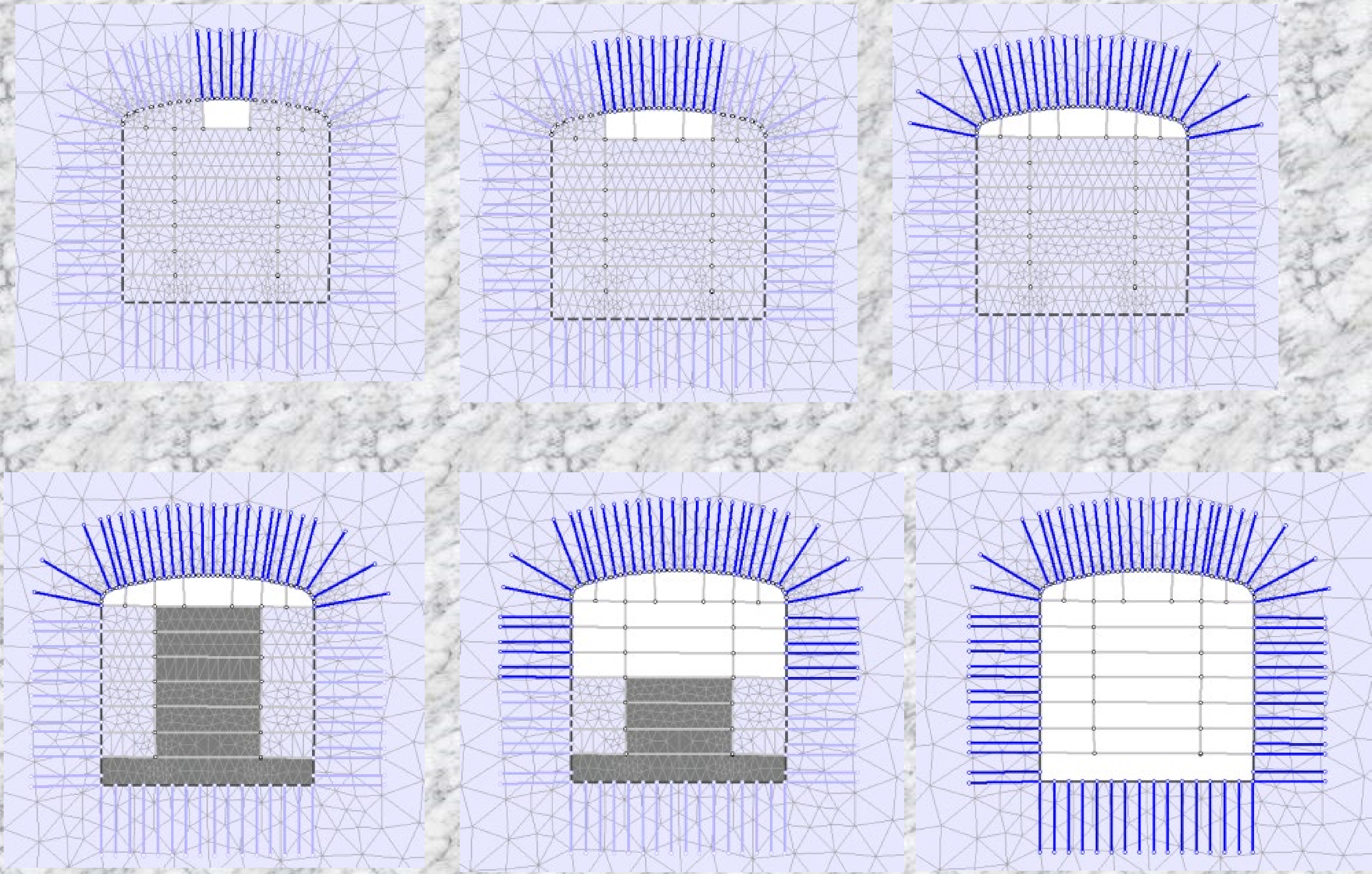


Excavation Sequence for the vertical cavern

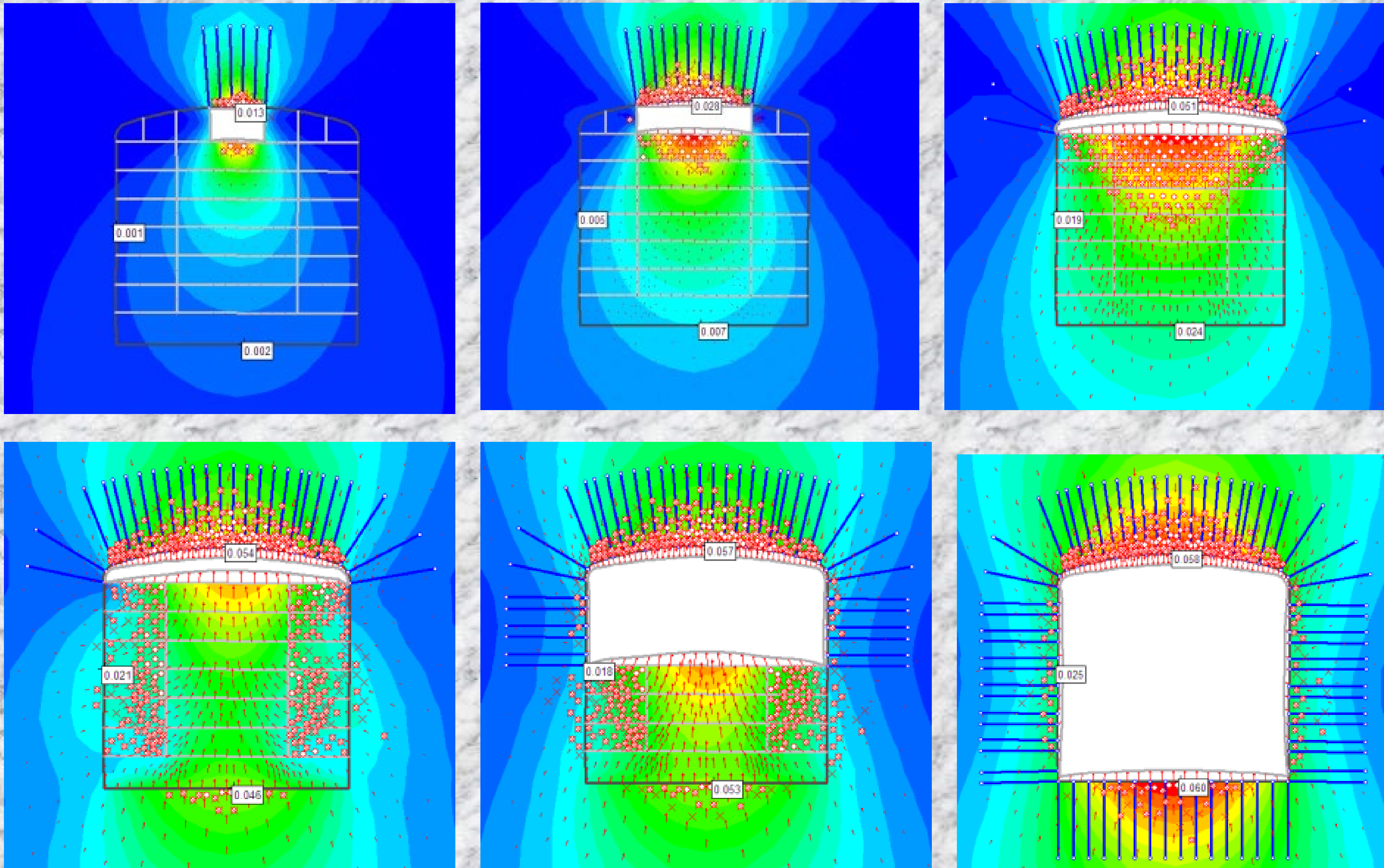




Two-dimensional finite element model of DUSEL cavern



Sequential excavation and support



Induced displacements

- **The DUSEL project design is being managed by the Lawrence Berkeley Laboratory with a budget of US$ 15 million**

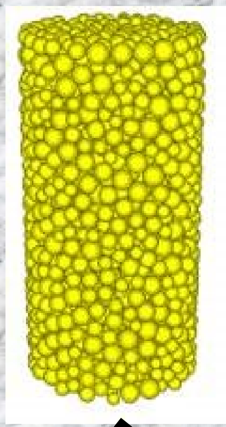
- **The South Dakota School of Mines is managing the site work at Homestake**

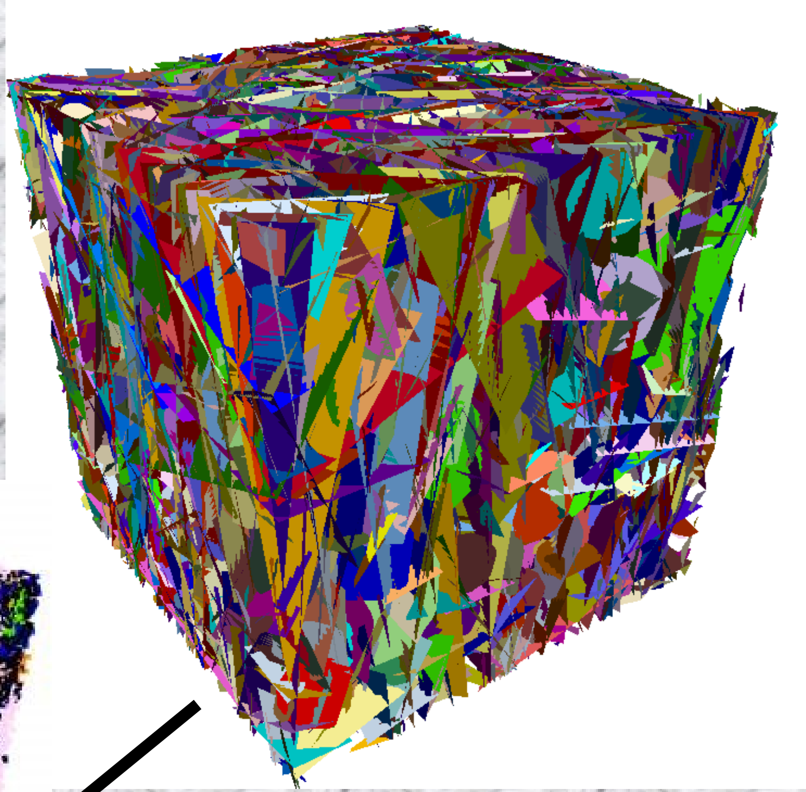
- **The detailed site investigations, in situ stress measurements, laboratory testing of rock samples and joints, creation of three dimensional geology models, numerical analyses of underground layouts, design of transportation and ventilation systems etc are being carried out by several companies contracted to do these tasks**

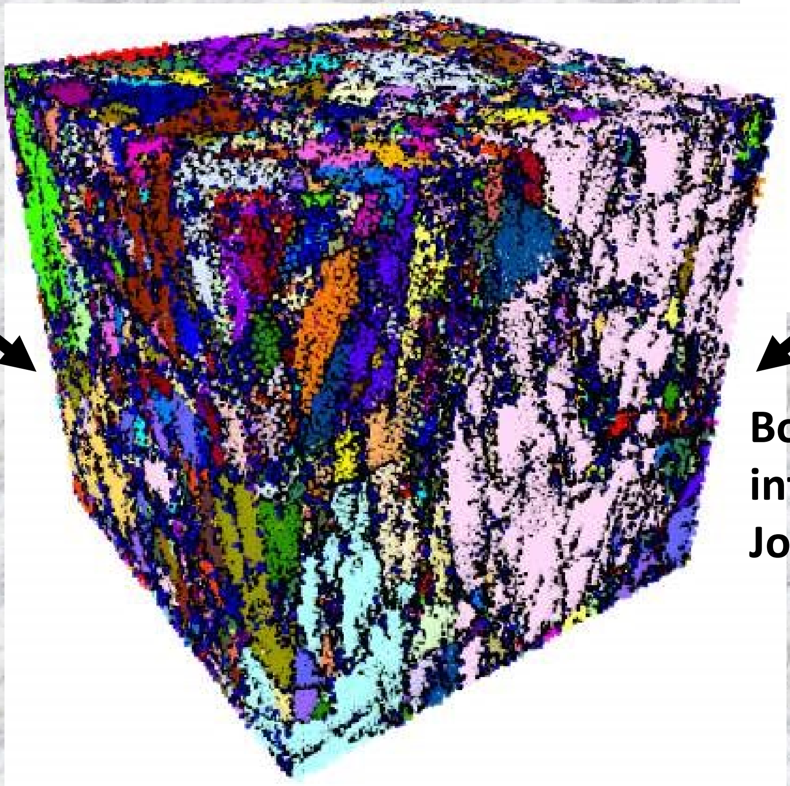
- **The final design will be completed in 3 years and it will then be presented to the US Congress for funding for the construction of the DUSEL complex**

Intact rock representation (including brittle fracture)

Fracture representation – 3D Discrete Fracture Network





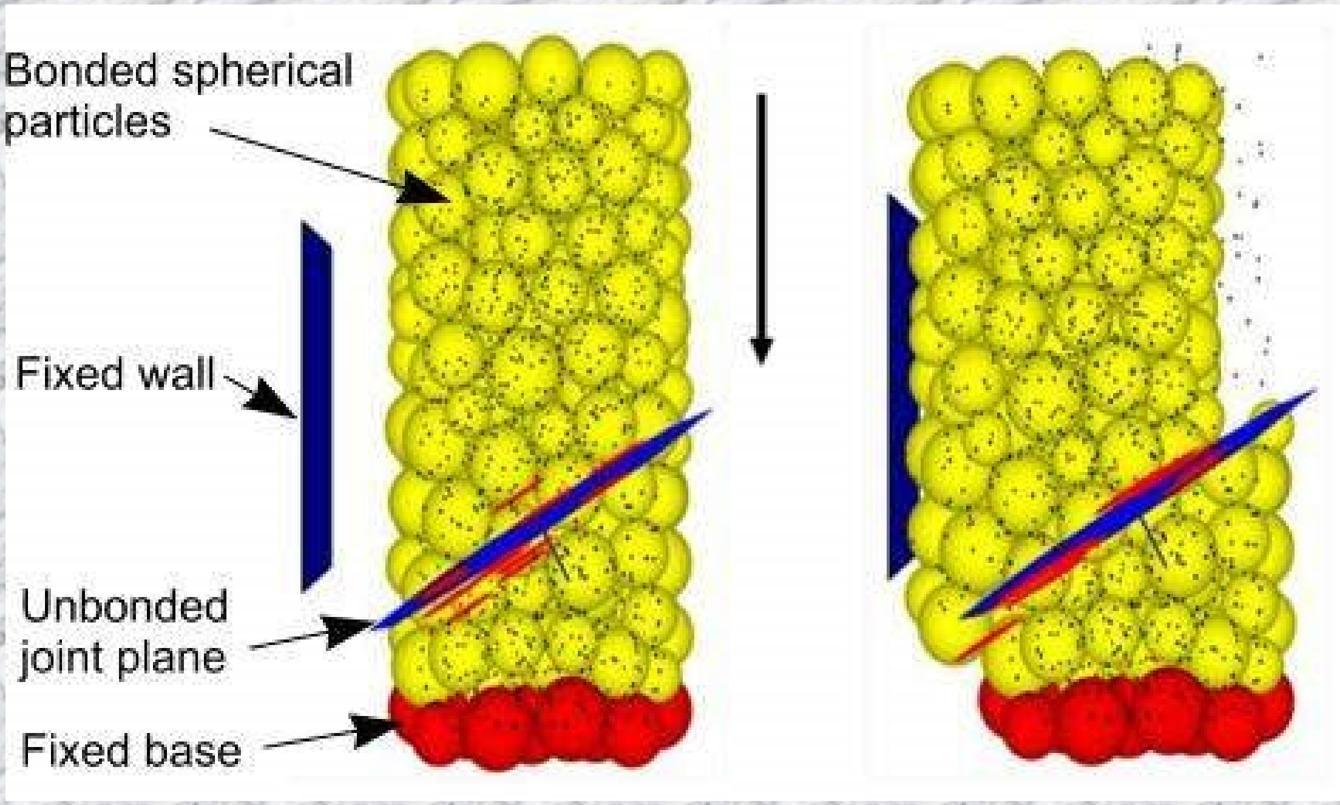


Bonded-particle assembly intersected with fractures (Smooth Joint Model – SRM)

Synthetic Rock Mass (after Cundall, 2008)

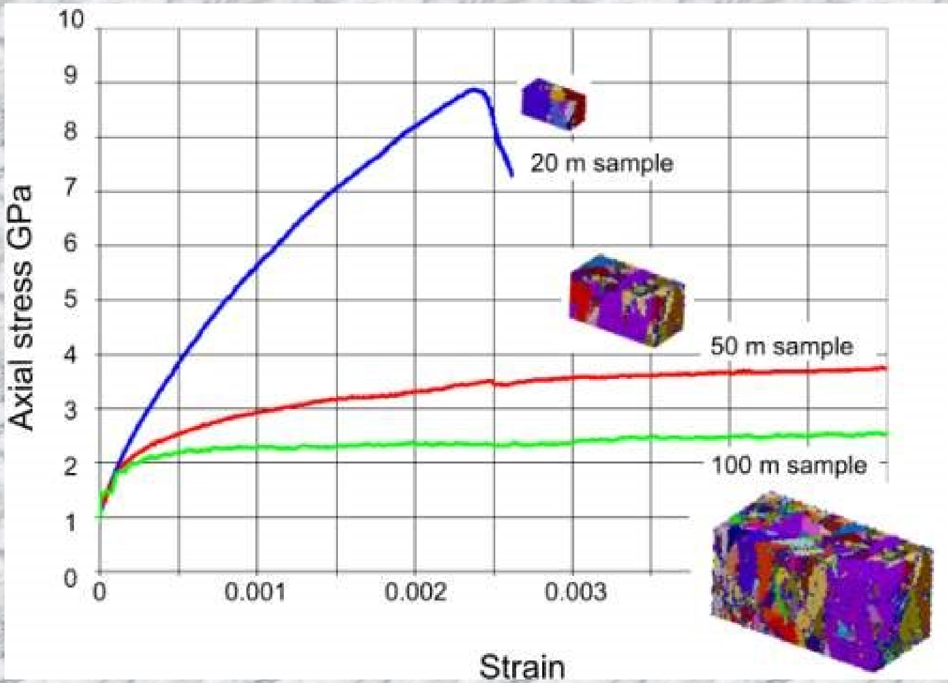
Potyondy and Cundall (2004), in discussing the challenge of modelling rock masses, point out that systems composed of many simple objects commonly exhibit behaviour that is much more complicated than that of the constituents. They list the following characteristics that need to be considered in developing a rock mass model:

- **Continuously non-linear stress–strain response, with ultimate yield, followed by softening or hardening.**
- **Behaviour that changes in character, according to stress state; for example, crack patterns quite different in tensile, unconfined- and confined-compressive regimes.**
- **Memory of previous stress or strain excursions, in both magnitude and direction.**
- **Dilatancy that depends on history, mean stress and initial state.**
- **Hysteresis at all levels of cyclic loading/unloading.**
- **Transition from brittle to ductile shear response as the mean stress is increased.**
- **Dependence of incremental stiffness on mean stress and history.**
- **Induced anisotropy of stiffness and strength with stress and strain path.**
- **Non-linear envelope of strength.**
- **Spontaneous appearance of microcracks and localized macrofractures.**
- **Spontaneous emission of acoustic energy.**

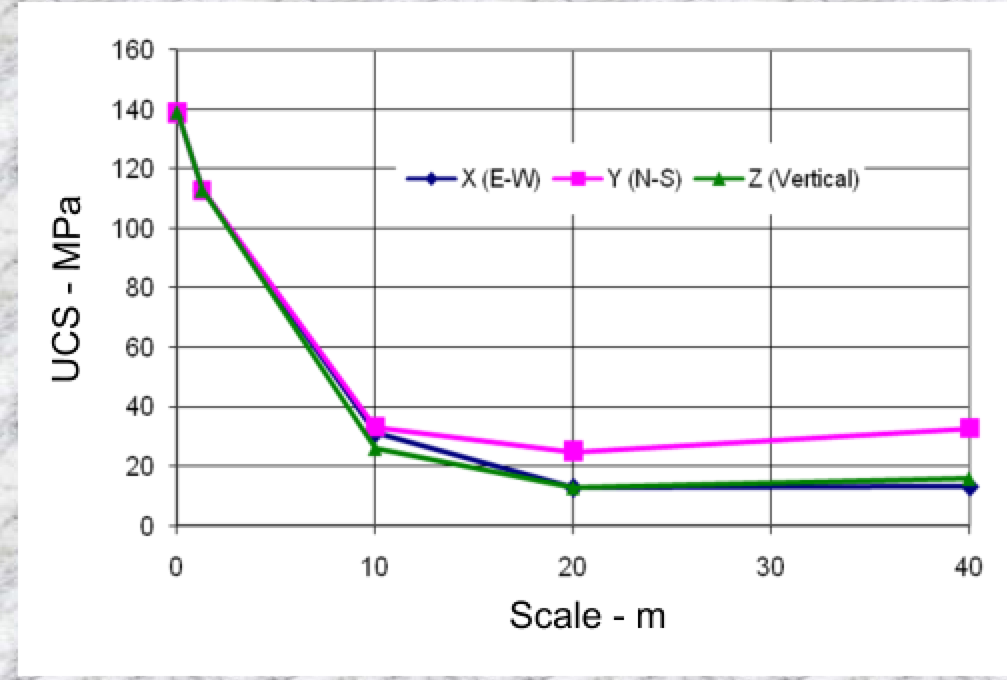


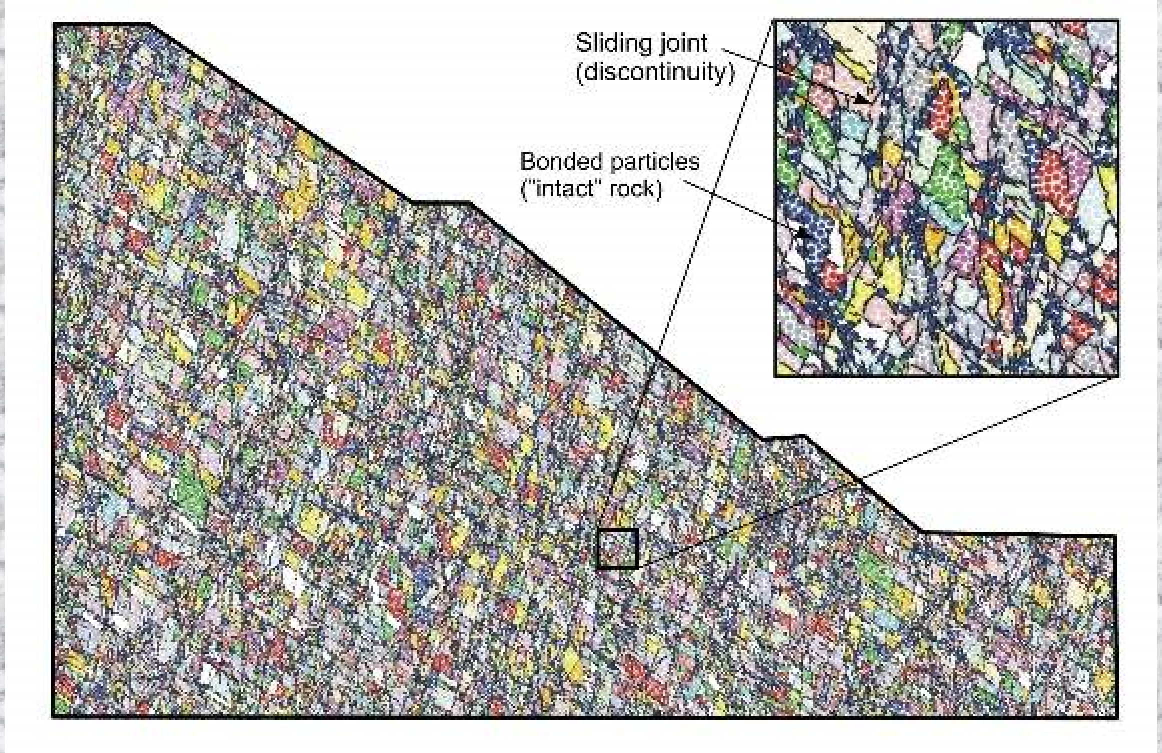
Bonded Particle Model and the Smooth Joint Model

Cundall, P. A, Pierce, M.E and Mas Ivars, D, Quantifying the size effect of rock mass strength, *Proceedings, 1st Southern Hemisphere International Rock Mechanics Symposium, Perth*, Y. Potvin et al., Eds., Australian Centre for Geomechanics, Nedlands, Western Australia, Vol. 2, 2008, 3-15.



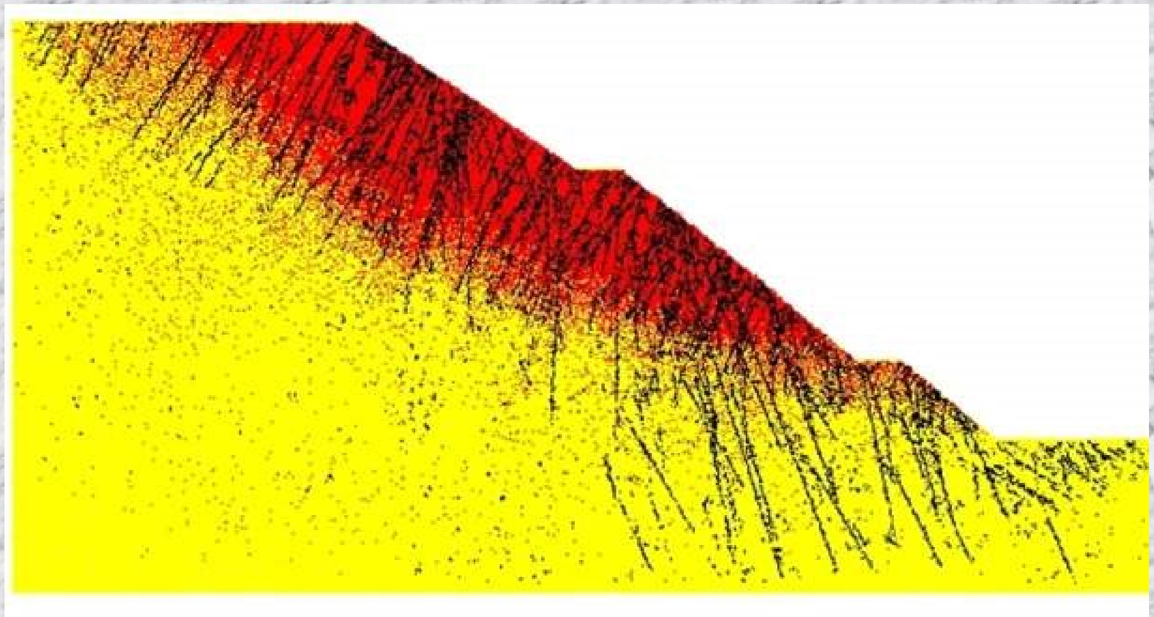
Influence of scale on the behaviour of a Synthetic Rock Mass model (After Cundall, 2008)

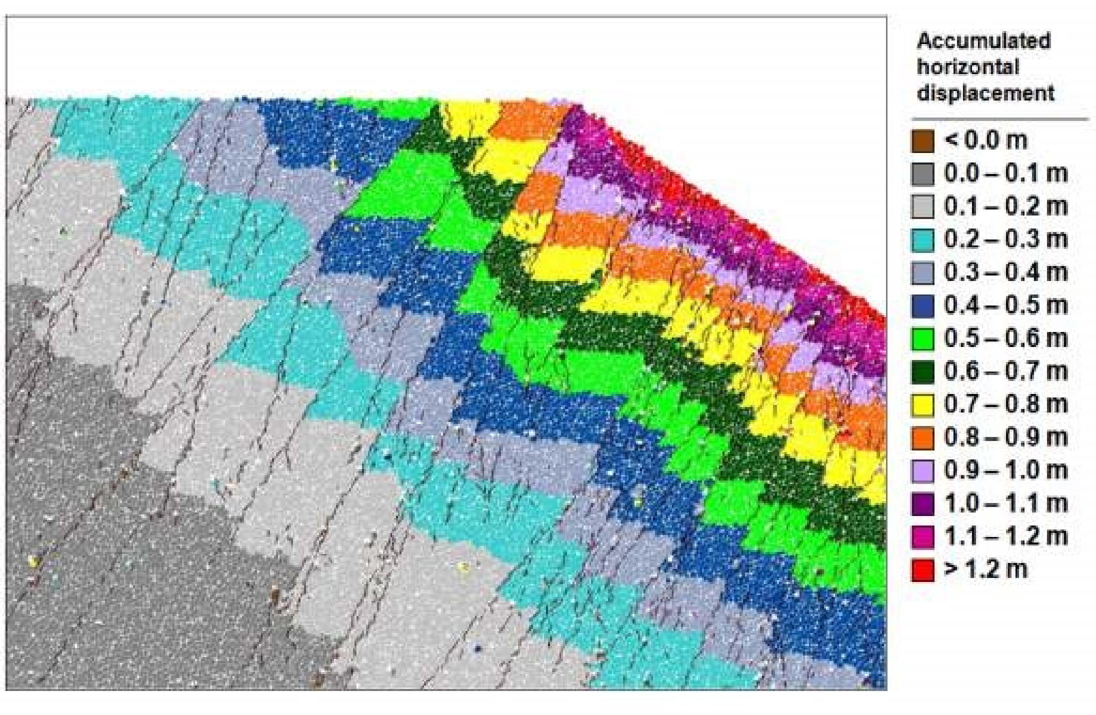




SRM model of the Chuquicamata West Wall

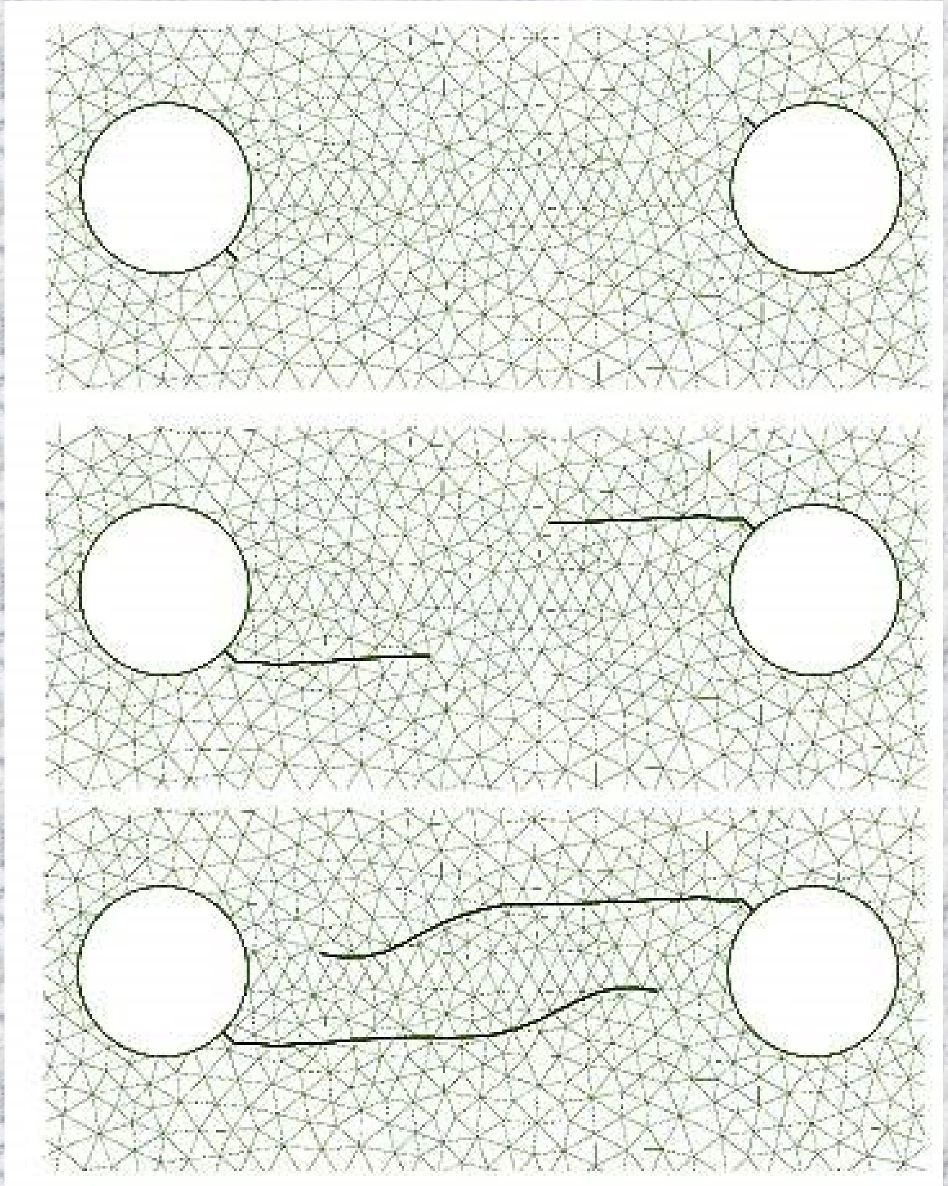
Mining induced horizontal displacements





Detail of mining induced horizontal displacements at slope crest

Toppling in the benches of the Chuquicamata West Wall



Interesting developments in fracture propagation modelling using the eXtended Finite Element Method have been directed by Professor Ted Belytschko of the Department of Mechanical Engineering at Northwestern University, Evanston, Illinois.
http://www.tam.northwestern.edu/X-FEM/

The discontinuities are completely independent of the finite element mesh: they can cross elements in any manner. This is particularly useful for a number of mechanical engineering problems as well as cracks, shear bands and joints in rock. In problems involving the evolution and motion of discontinuities, it avoids the need for remeshing.

Belytschko, T, Moës, N, Usui, S and Parimi, C, 2001, Arbitrary discontinuities in finite elements. *International Journal for Numerical Methods in Engineering*, Vol. 50, 2001, 993-1013.

CONCLUSIONS

Many interesting developments in numerical modelling are in progress and, over the next decade, promise to free us from the empiricism of classification based rock mass property estimates or, at least, a means of calibrating these classifications.

The most advanced method is the Synthetic Rock Mass but some interesting alternative methods are also under development. As with all numerical models it will be important to ensure that the most appropriate method is chosen for each particular application and that the user fully understands the input requirements and the limitations of the method chosen.

A WORD OF WARNING

The geotechnical literature abounds with papers describing the application of numerous jointed continuum models and discrete element models to rock mechanics problems. Many of these models are “immature” in that they do not incorporate all of the physics required to capture the behaviour of real rock masses, particularly the failure of the intact rock components. Many of these papers include impressive illustrations or refer to videos of rock block movements. The fact that these illustrations look impressive does not make them correct.