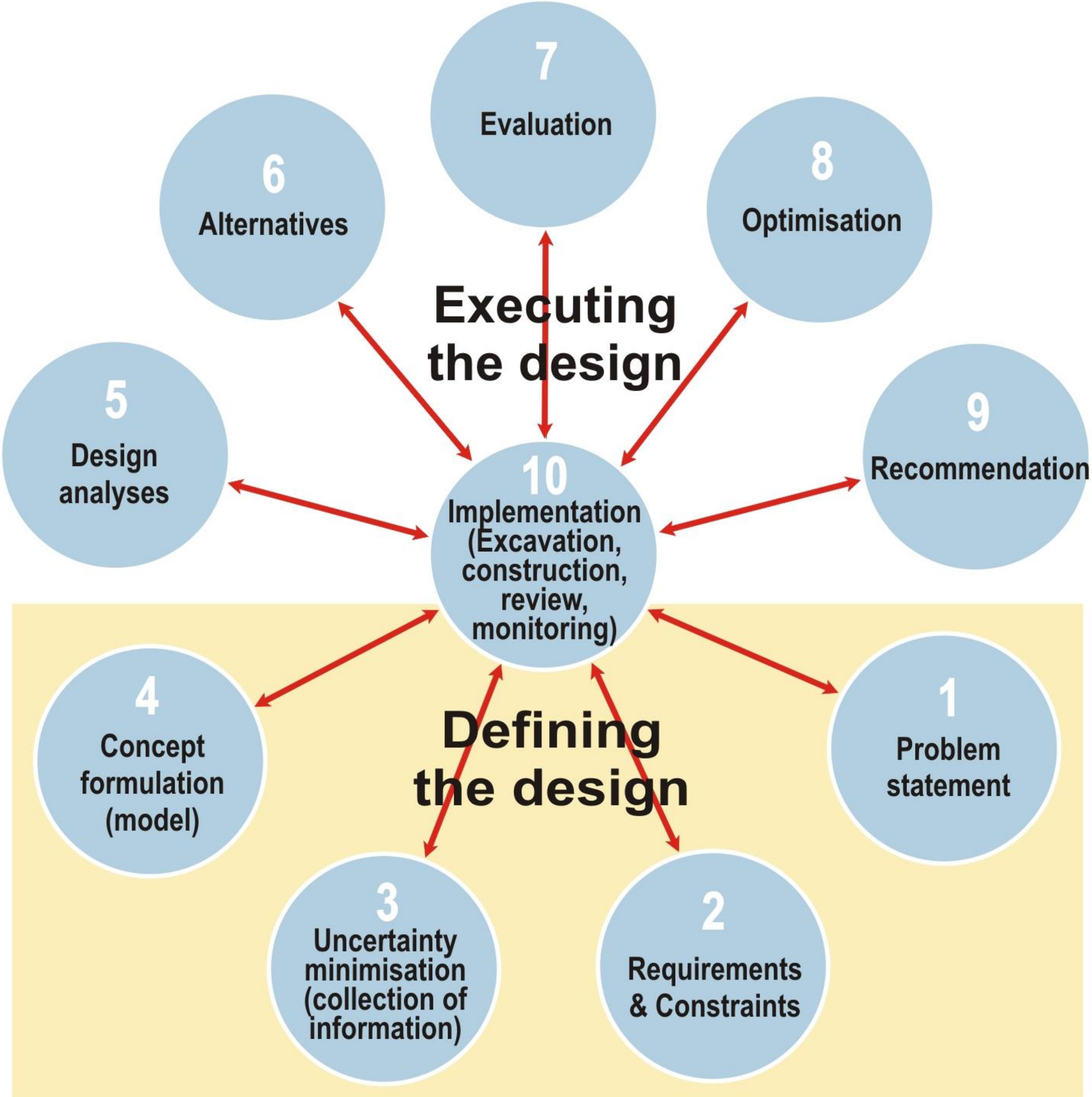
PREDICTION AND DESIGN IN ROCK ENGINEERING

Dick Stacey

Mining and tunnelling are progressing to deeper levels, with competent rock and tight confinement conditions

Can we predict the behaviour when developing in these “new” conditions?

Rock engineering design process


7
Evaluation
6
Alternatives
8
Optimisation
Executing
the design
5
Design
analyses
9
Recommendation
10
Implementation
(Excavation,
construction,
review,
monitoring)
4
Concept
formulation
(model)
Defining
the design
1
Problem
statement
3
Uncertainty
minimisation
(collection of
information)
2
Requirements
& Constraints

Step 3: Design inputs

Rock strength
Rock mass structure
In situ stresses
Groundwater
Etc

Rock strength and deformation properties

Conventionally determined by tests on core in the laboratory

Are the results correct?

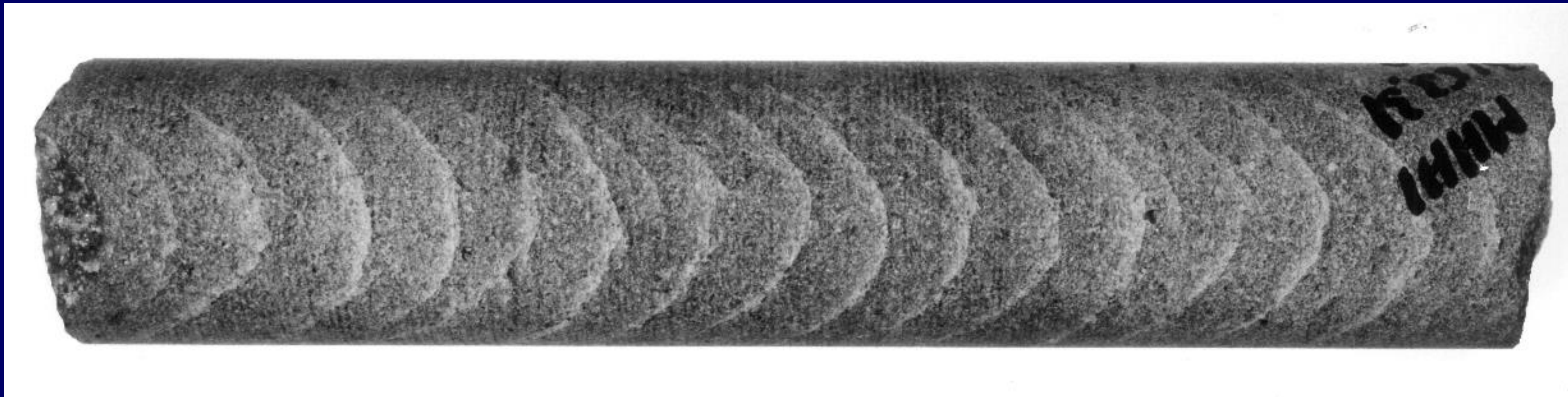
Specimen length to diameter ratio

Quality of specimen preparation: ends parallel and flat

etc

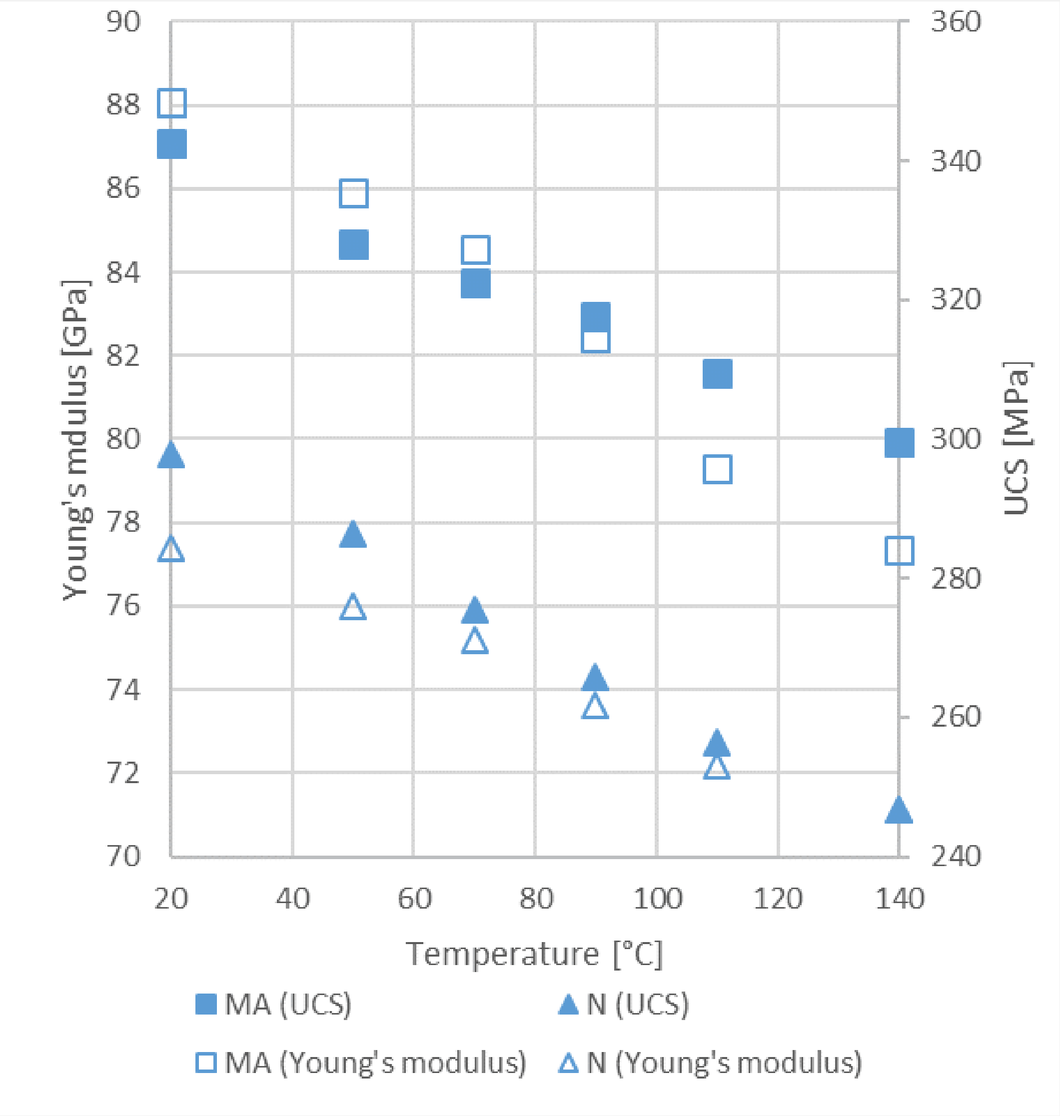
Specimens are retrieved by core drilling – what effects?

Rock may be under high stress – does this affect the integrity of the retrieved specimen?



But will we know whether much smaller core-drilling induced fractures occur in our specimen, which may affect the strength measured?

Core will be retrieved from probable high temperature, dry conditions. In the laboratory it will conventionally be tested with short term loading, and at room temperature. What effects?

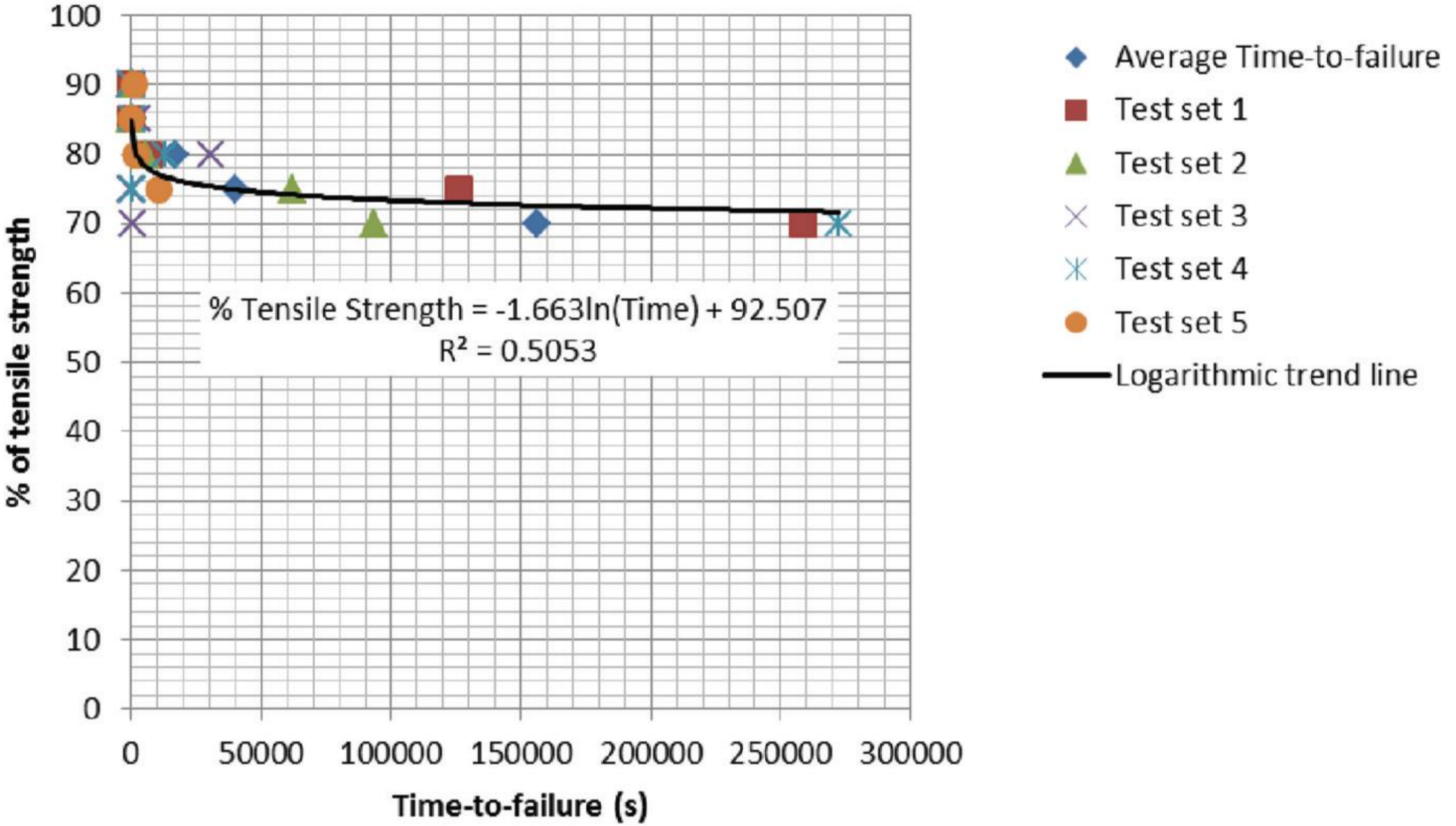


Young's mdulus [GPa]
UCS [MPa]
Temperature [°C]
90
88
86
84
82
80
78
76
74
72
70
360
340
320
300
280
260
240
20
40
60
80
100
120
140
MA (UCS)
N (UCS)
MA (Young's modulus)
N (Young's modulus)

What about moisture?

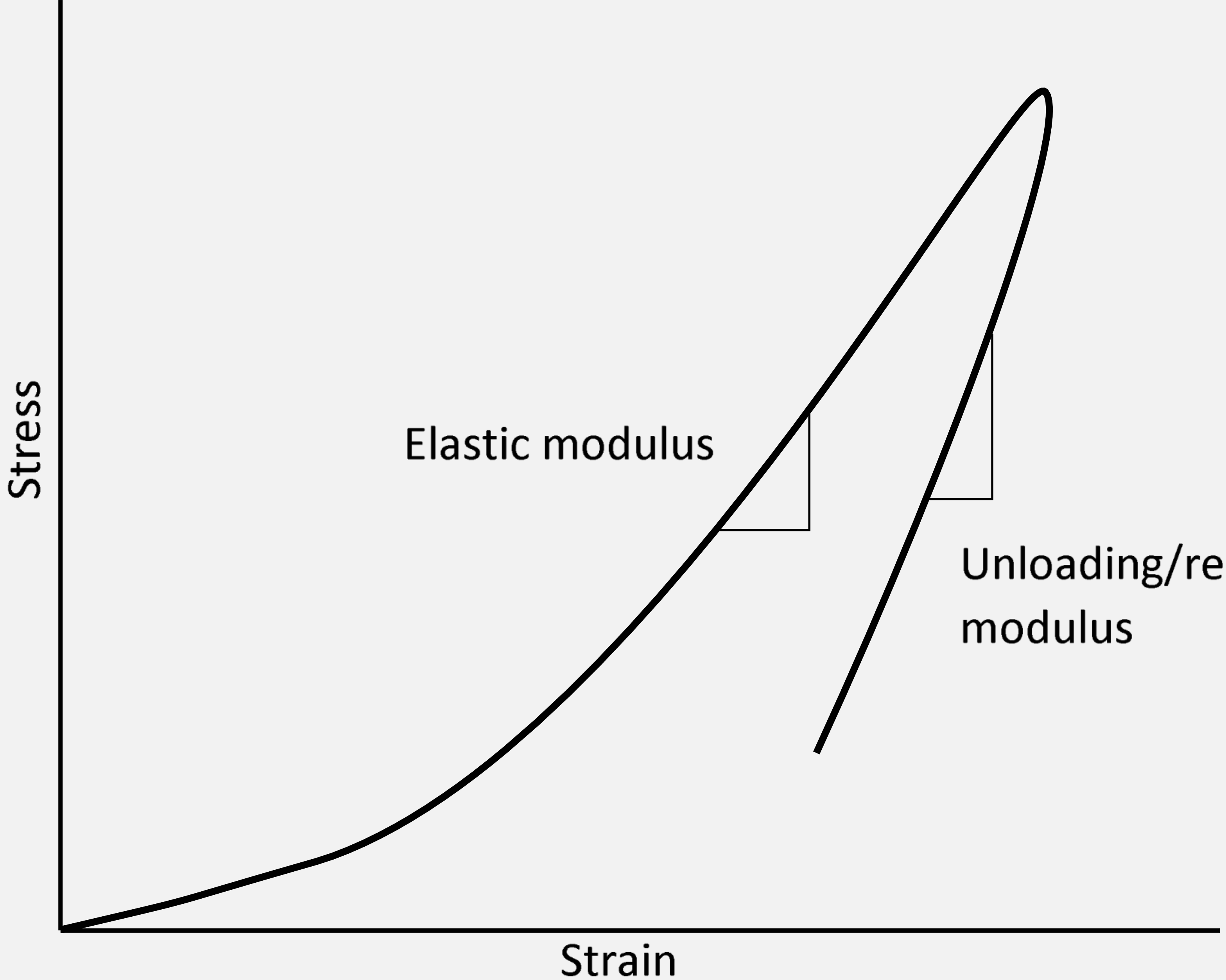
From published data, for porous rock types, saturated strength can be about 50% of the dry strength. For granite, the equivalent is about 70%. Will the rock be exposed to water/moisture in our underground project?

And what about time – loading in the laboratory is short term, always much less than the in situ loading time?



100
90
80
70
60
50
40
30
20
10
0
% of tensile strength
0
50000
100000
150000
200000
250000
300000
Time-to-failure (s)
% Tensile Strength = -1.663ln(Time) + 92.507
R² = 0.5053
Average Time-to-failure
Test set 1
Test set 2
Test set 3
Test set 4
Test set 5
Logarithmic trend line

Excavation causes unloading of the rock mass adjacent to the rock surface. Therefore, should we be using the loading modulus or the unloading modulus in our design?


Stress
Elastic modulus
Unloading/recovery modulus
Strain

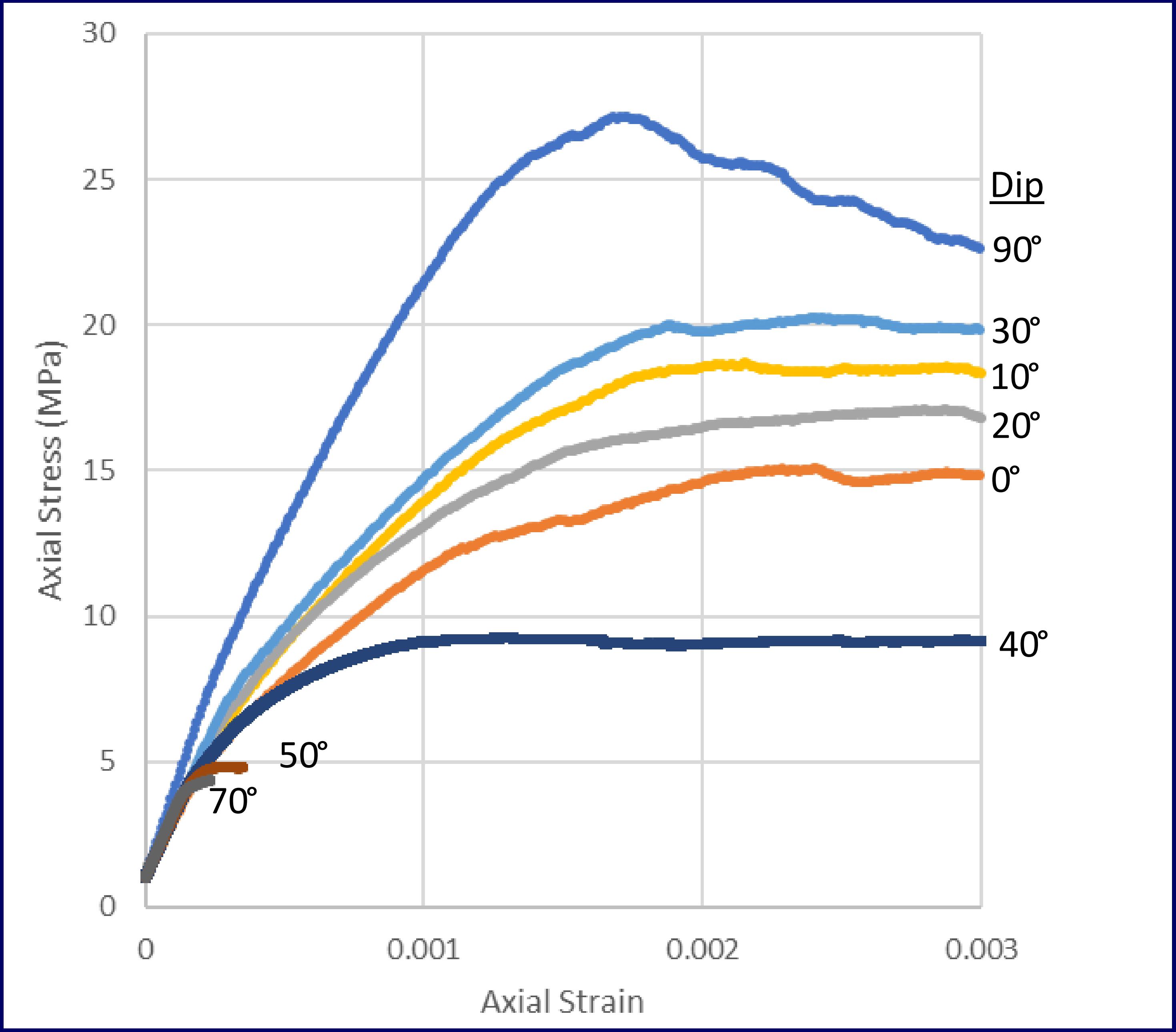
Depending on the rock mass structure (eg anisotropy) and induced fracturing, the unloading modulus could be much less than the loading modulus

And the rock and rock mass deformation properties?

Is it valid to use a single modulus value determined from rock mass classification? Rock mass moduli are sometimes measured, but has anyone heard of Poisson's ratio for a rock mass being measured?

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & \frac{-\nu_{zx}}{E_z} & 0 & 0 & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & \frac{-\nu_{zy}}{E_z} & 0 & 0 & 0 \\ \frac{-\nu_{xz}}{E_x} & \frac{-\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix}$$

Six moduli and three Poisson coefficients! The jointing in a rock mass will always mean that the modulus (and Poisson's ratio) are likely to be different in different directions. The next slide shows the stress-strain curves for different loading directions in an anisotropic rock mass (from a synthetic rock mass analysis)



30
25
20
15
10
5
0
0
0.001
0.002
0.003
Axial Stress (MPa)
Axial Strain
Dip
90°
30°
10°
20°
0°
40°
50°
70°

Rock and rock mass failure criteria.

Mohr-Coulomb and Hoek-Brown have served us well. But they are 2D, ignore σ_2 and are shear failure based. CWFS works well in brittle rocks, but is also 2D, shear based. Fine for design in known conditions with FOS, but are they suitable for *prediction?*

What about any of the "smear" criteria, such as energy, octahedral shear strength etc? Will they be any good for prediction?

"Smear" criteria are not related to mechanisms

THREE DIMENSIONS!

All excavations are 3D. Fracture and failure will develop as a result of the 3D stress field

Would you predict fracture and failure in the following examples?

Massive sandstone
Depth about 150m
Rock strength about 40 MPa
Consequence about $100million

Would you expect failure?

And the next example -

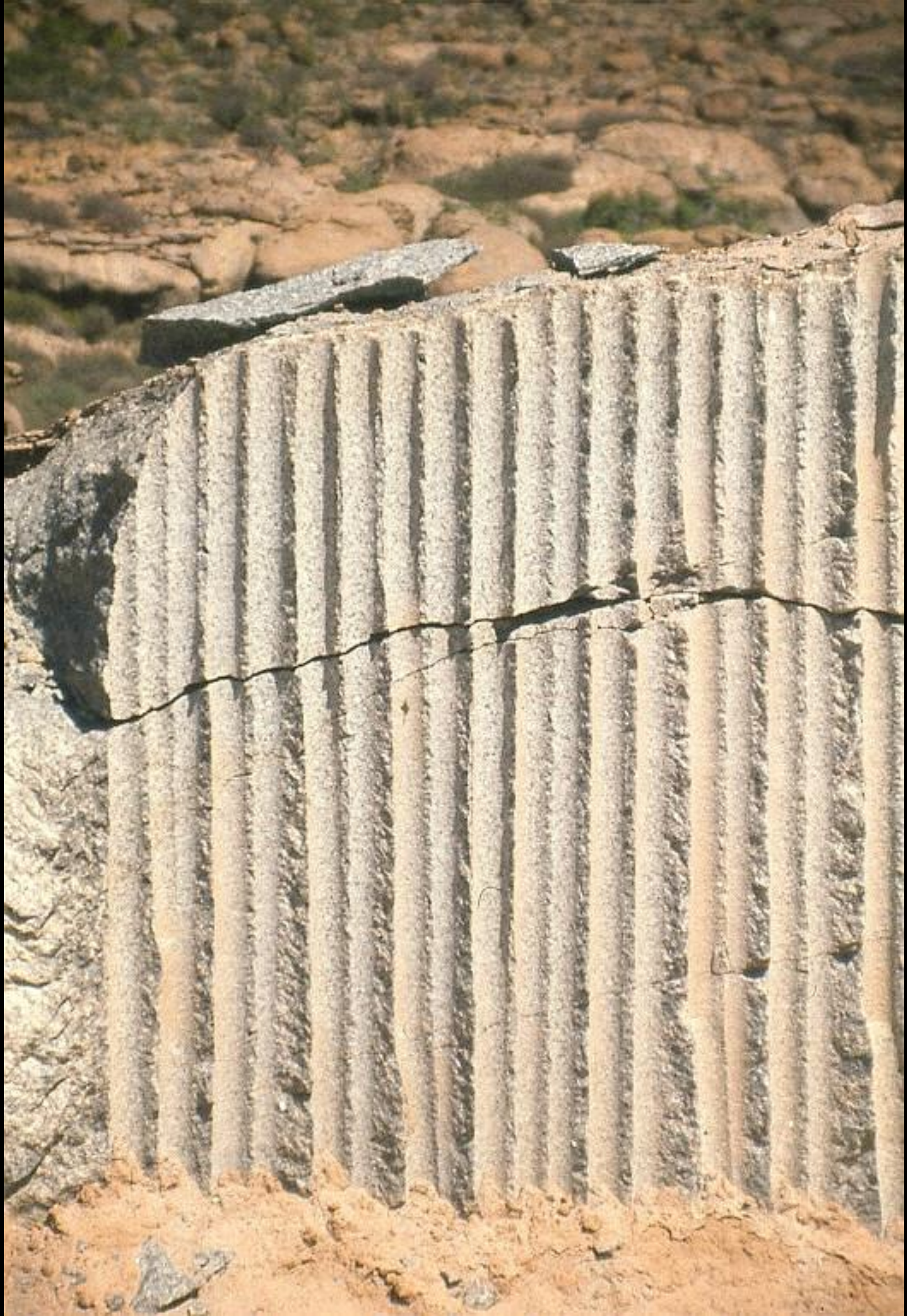
This is what happened about two months after boring

Massive sandstone
5m diameter TBM drive
Depth 150m: vertical stress about 4 MPa
UCS about 25MPa

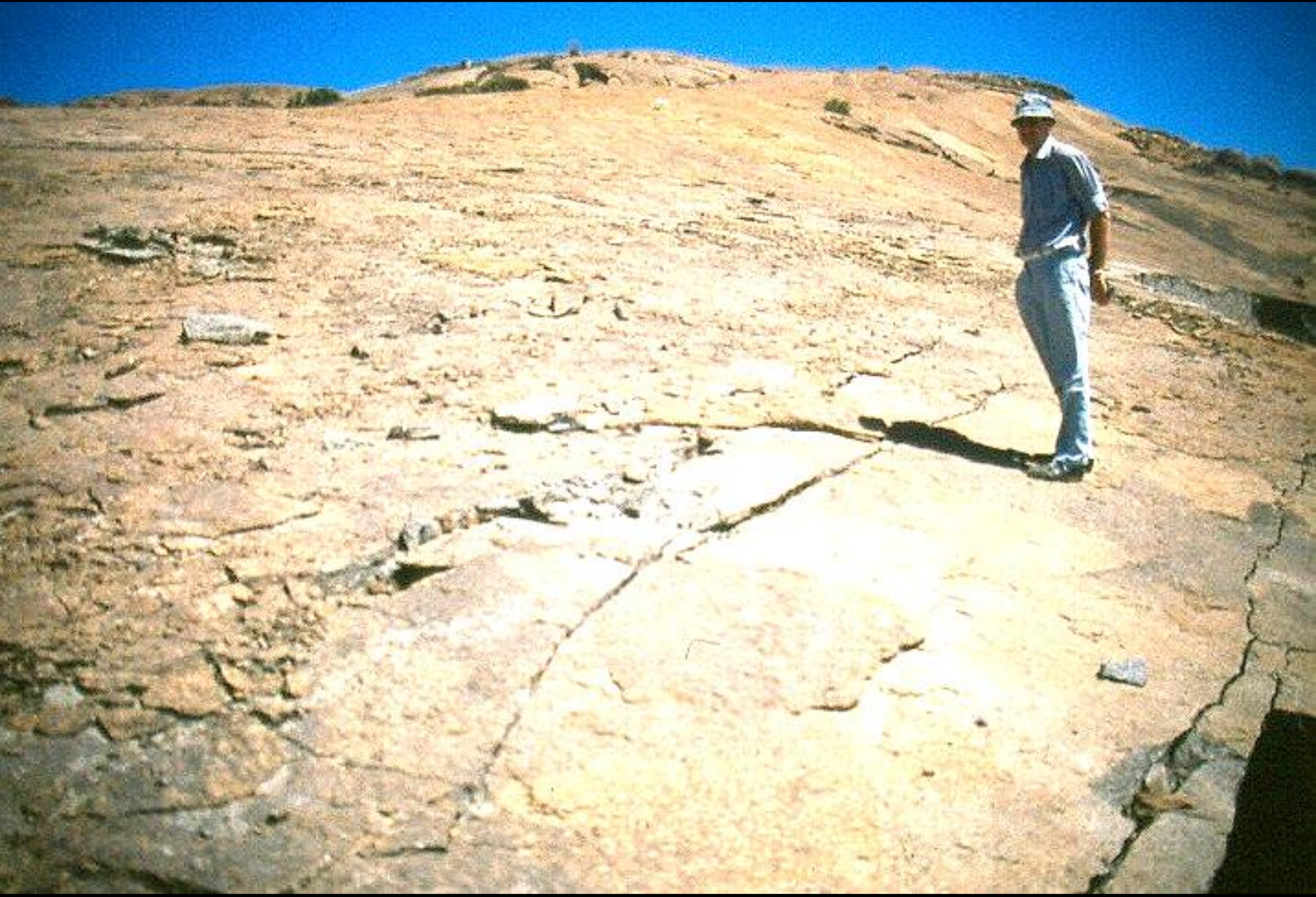
Would you expect failure?

Massive granite (dimension stone)
UCS say 250MPa
Depth about 3m

Would you expect fracture and failure?



Dynamic event – drill thrown about 3m into the air

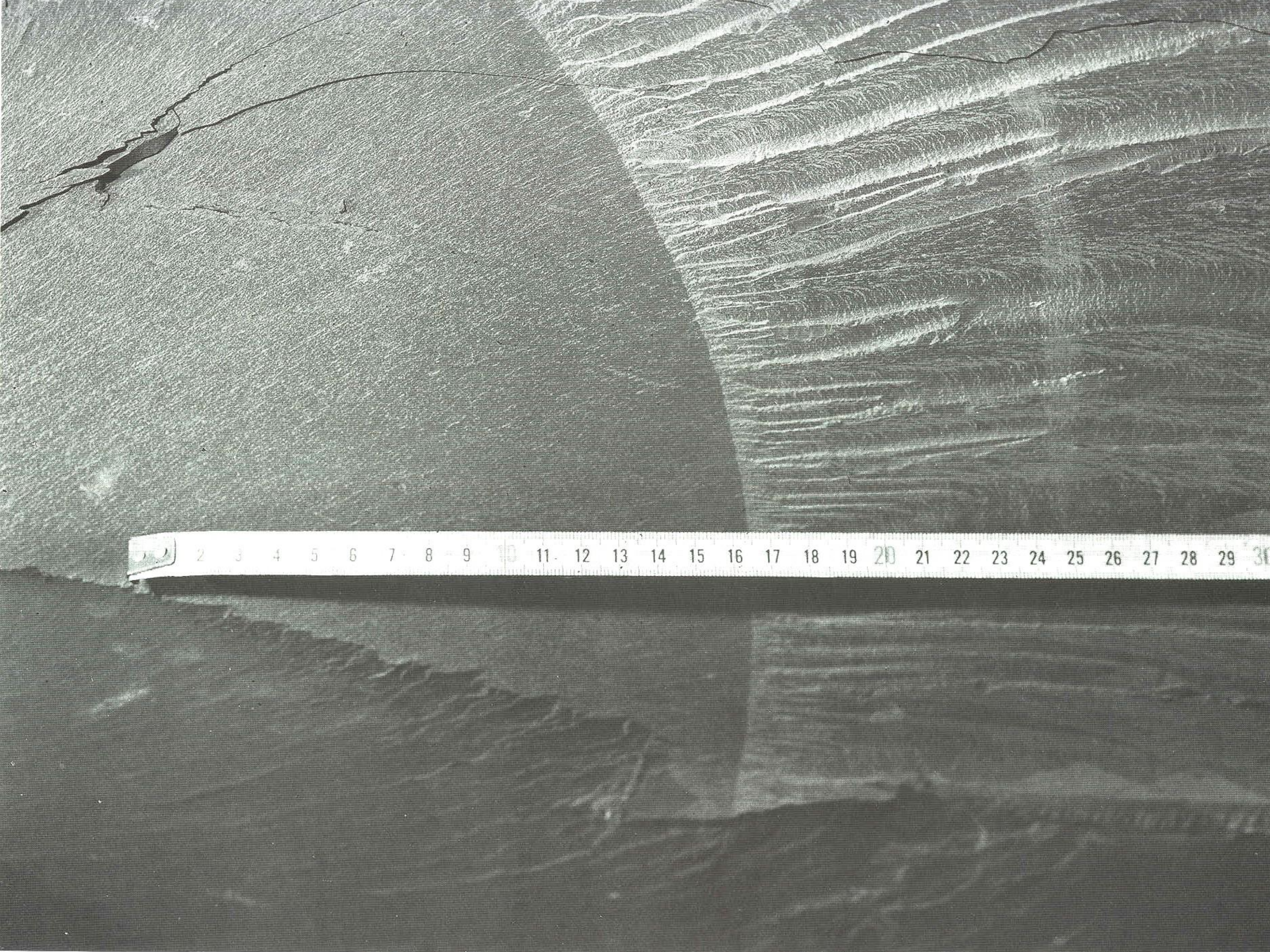


Dynamic failure in a coal mine

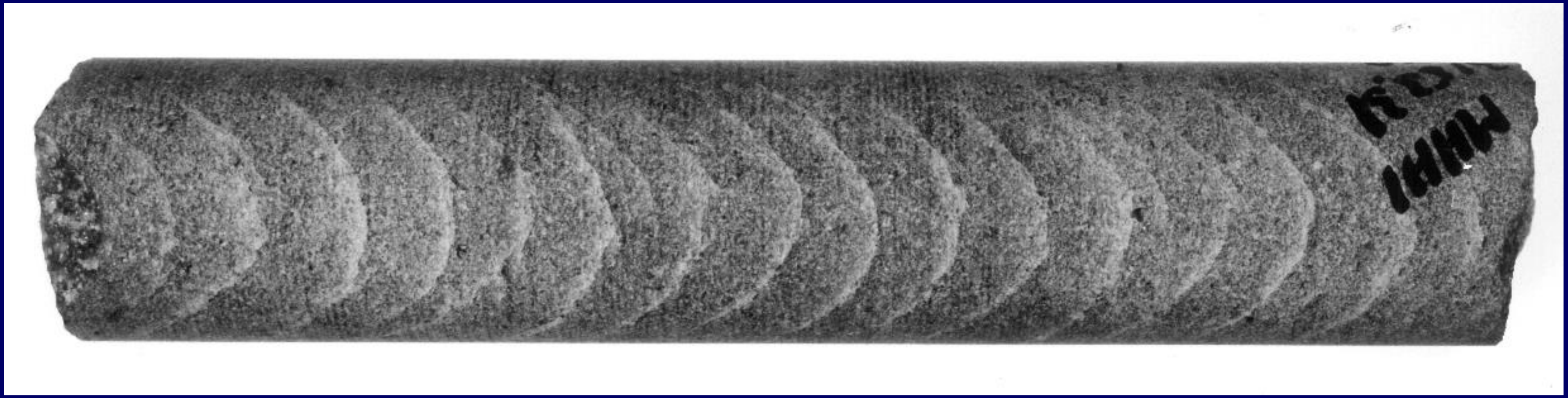
Depth about 22m

Span about 5m

UCS about 65MPa



Fracturing ahead of a bored face



The core is still intact. Therefore fractures are extension, with no shear along them. Implications for bored tunnels and raises?

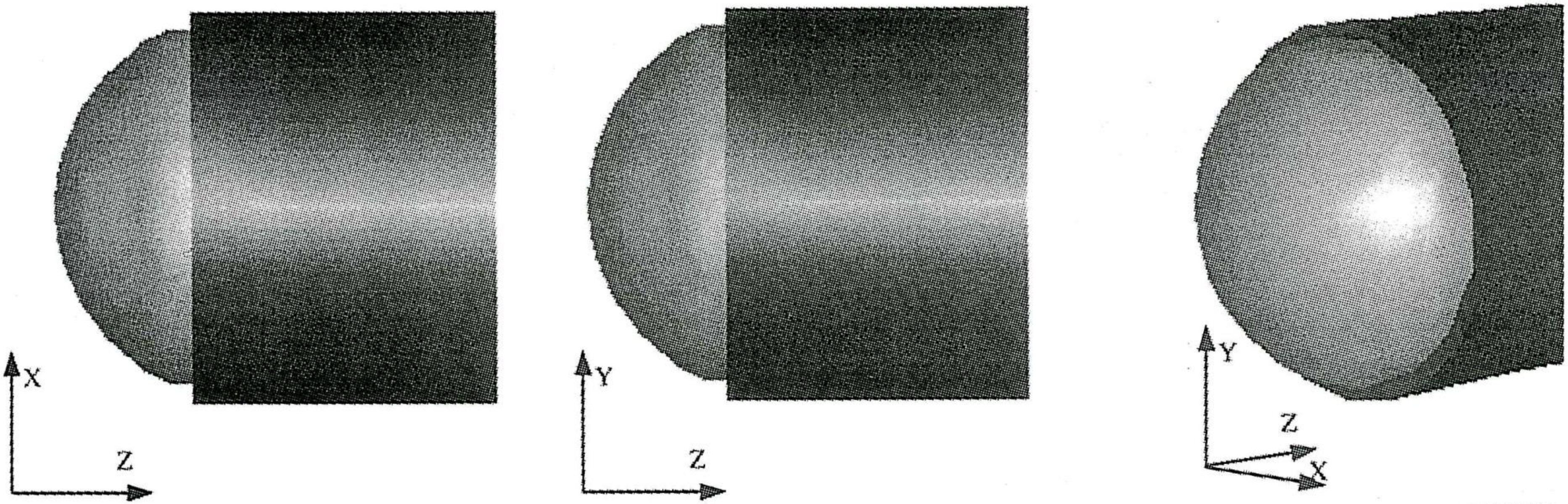


Figure 1: The 200 microstrain isosurface, σ_x = 70MPa, σ_y = 70MPa, σ_z = 35MPa.

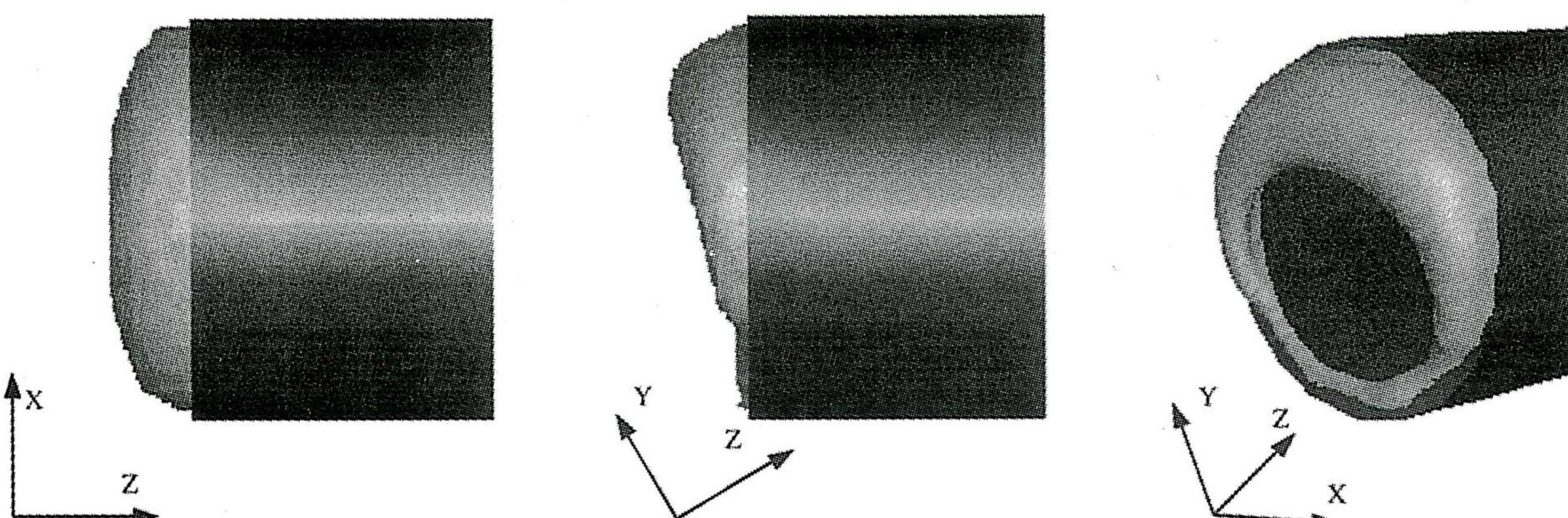
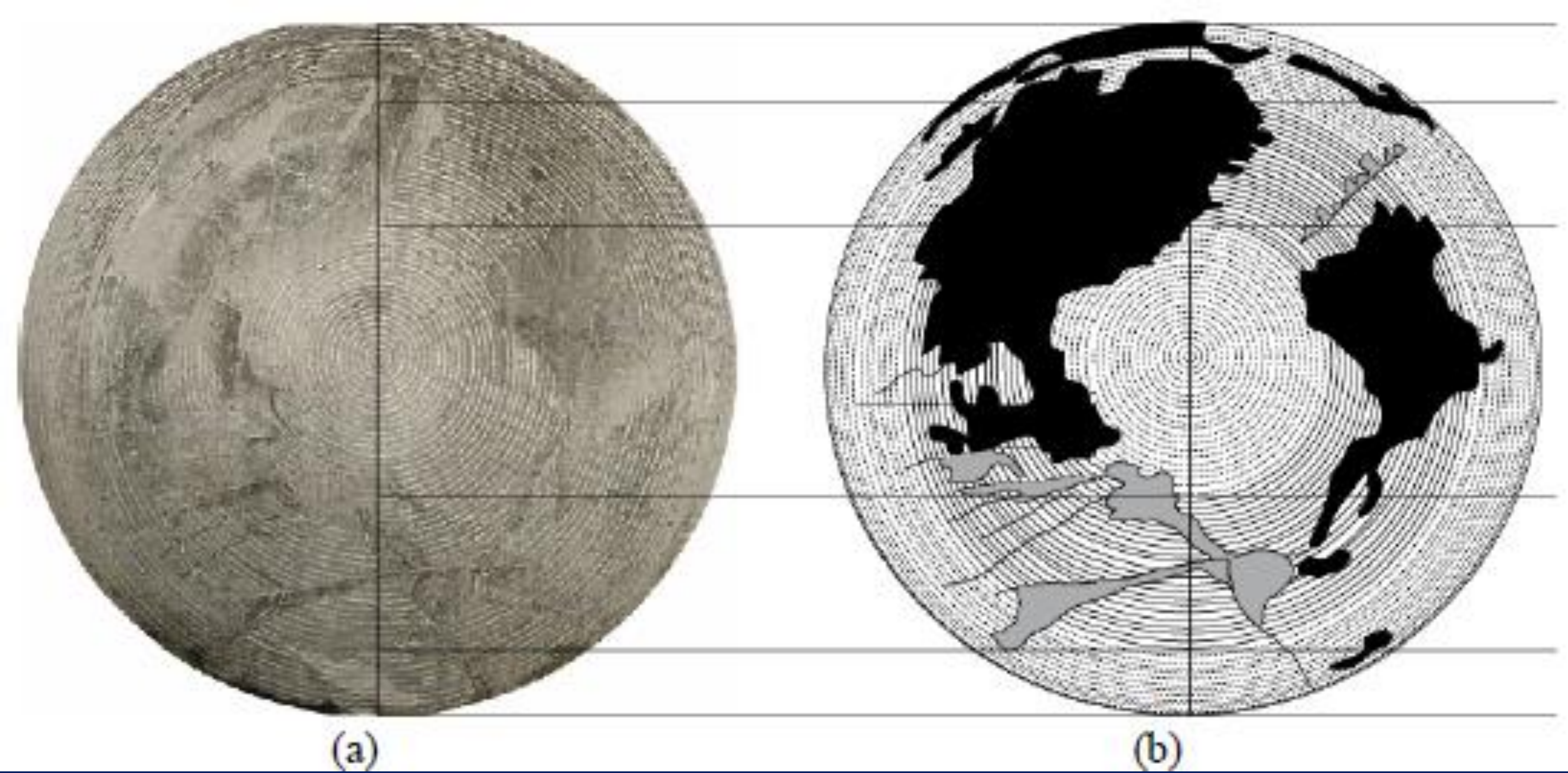
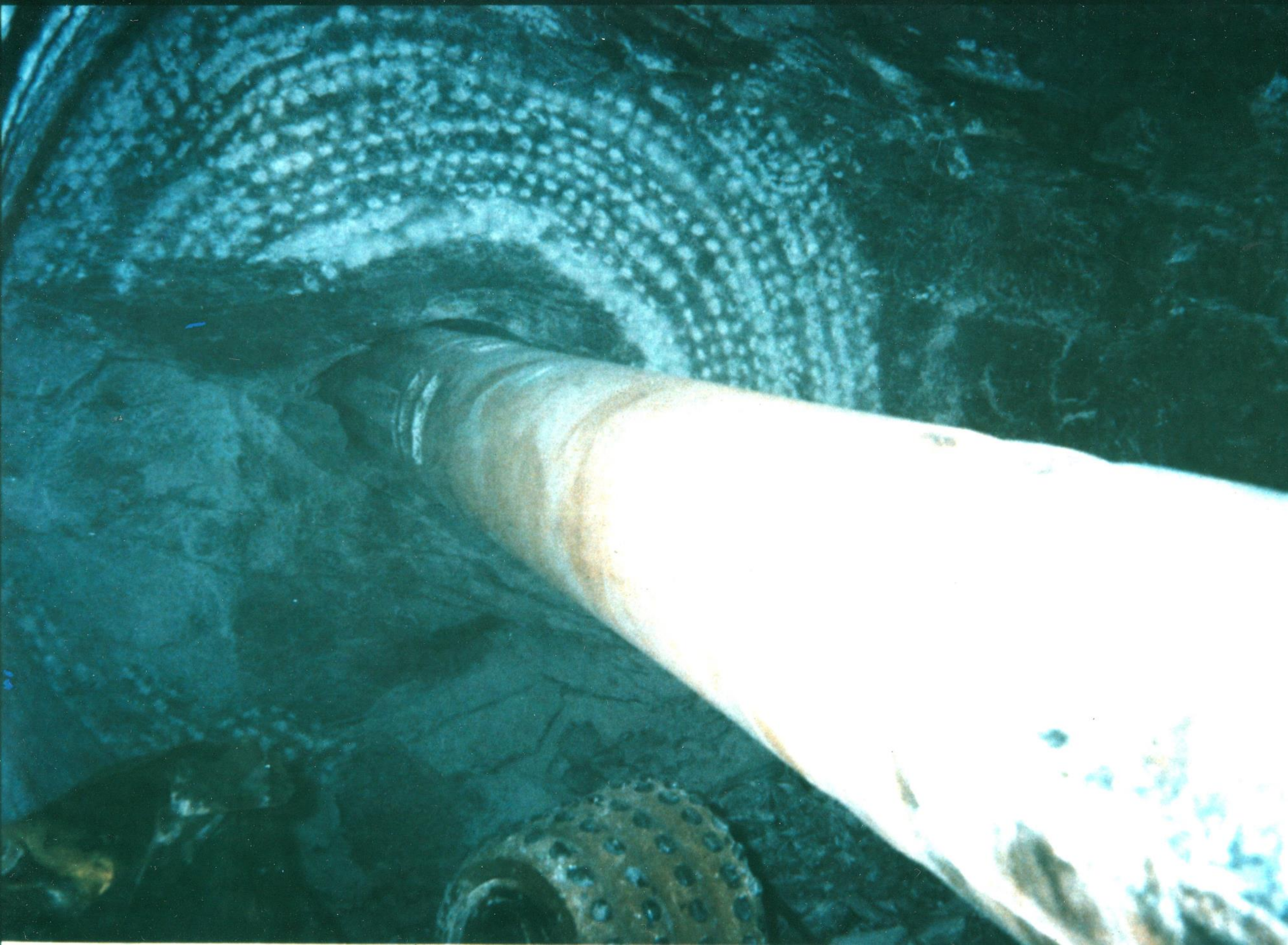


Figure 2: The 200 microstrain isosurface, σ_x = 35MPa, σ_y = 35MPa, σ_z = 70MPa.



(Kaiser, date unknown)

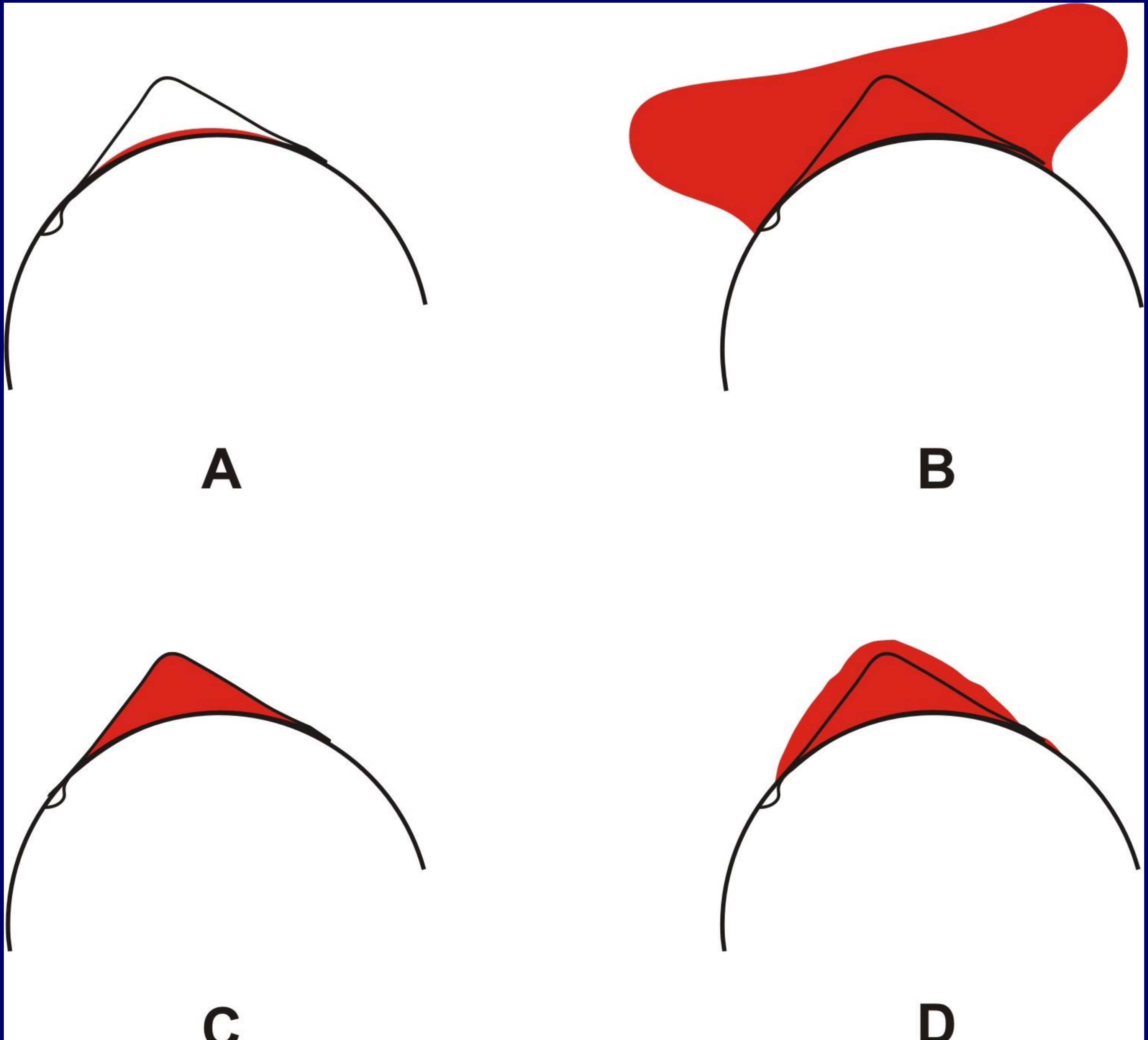
And raise boring?

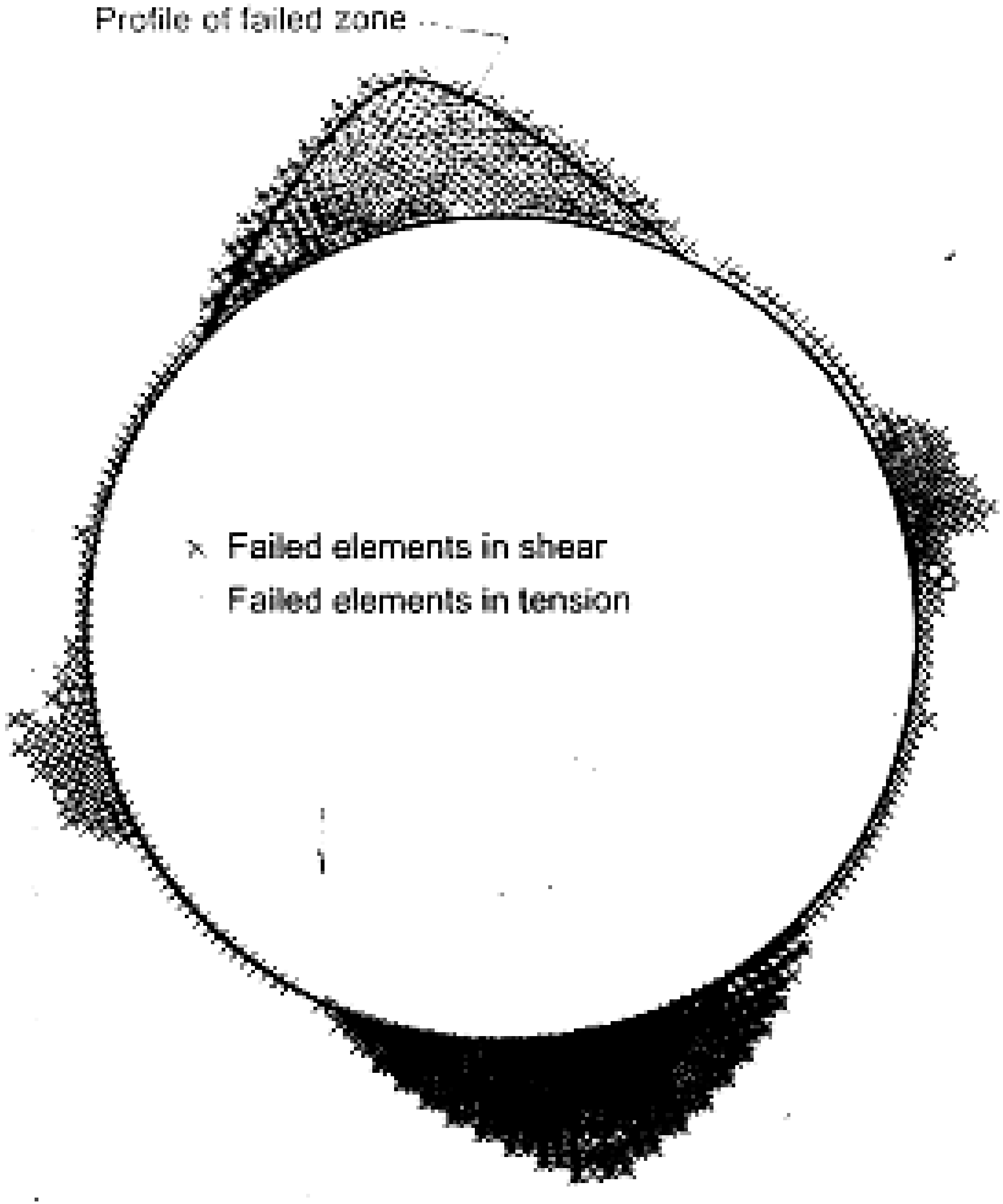


A relevant case: a 6.2m diameter raise-bored shaft

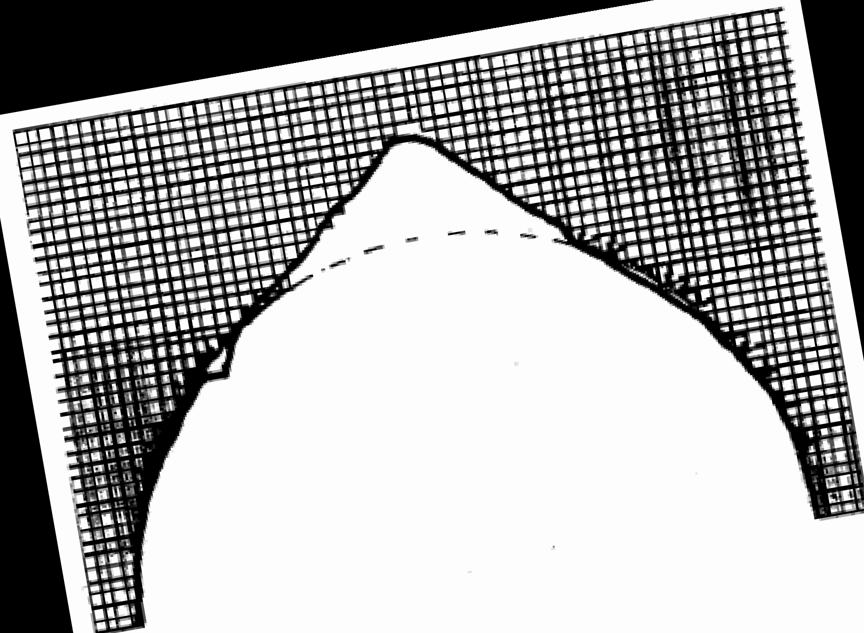
"… the bit body lost penetration. The bit body was lowered and found to be completely compacted. Large boulders fell from the cutting face and became trapped between the cutter wings and the stabiliser wings." (Hern and Engelsman)

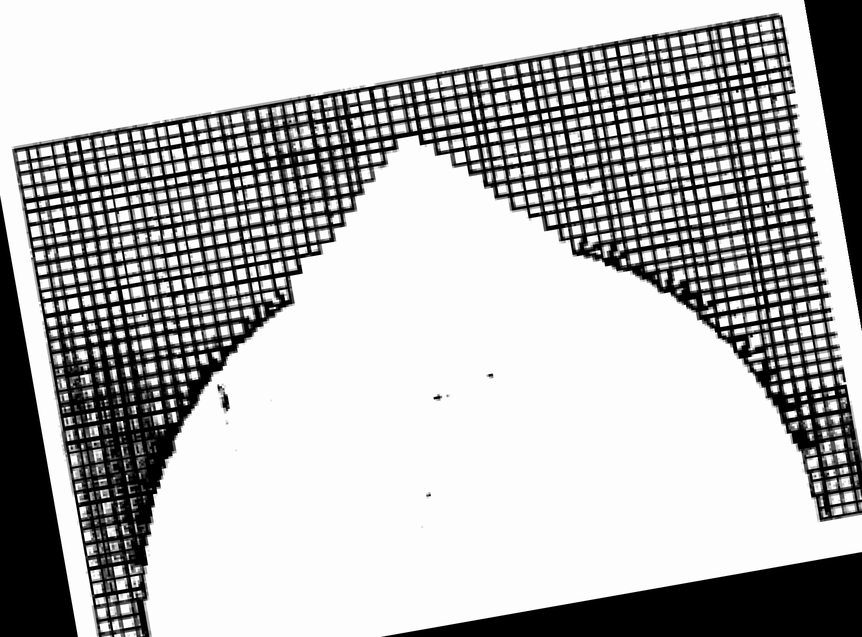
Breakouts and dog ears


A
B
C
D



Profile of failed zone
× Failed elements in shear
· Failed elements in tension





We must use the appropriate fracture and failure criteria for successful *prediction*.
Relevant criteria are likely to be different at different stages of failure

And the reason for my preoccupation with extension fracturing -

Libanon mine 2000m depth

- 3m diameter TBM, two horizontal grippers
- Sedimentary rock structure, strike parallel to tunnel axis
- Dipping bedding planes
- Sidewall breakouts occurred leading to gripping problems
- Rock engineering input? None!
- Design process definitely not followed
- Result: failed application, TBM removed

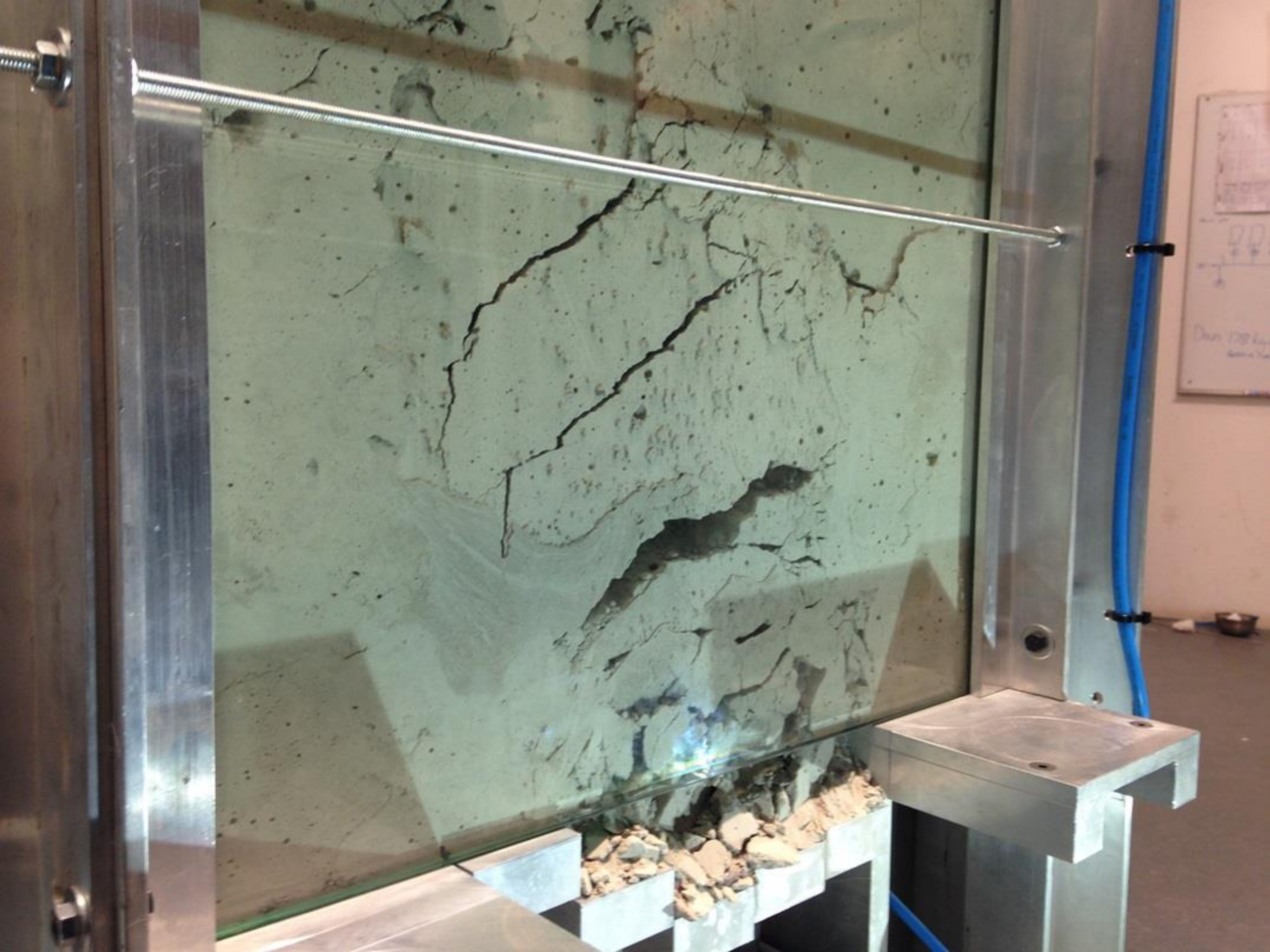
After the event investigation:

- 3D stress analyses
- No prediction of fracturing by stress-based criteria or Griffith criterion
- Minimum principal stress orientations and locations corresponded with observed fracturing
- in hind-sight, provided an extension strain criterion for prediction of fracture initiation

A subsequent deep level tunnel – different mining company, different gold mine:

3m dia, grippers at 45 degrees – no gripping problems, but

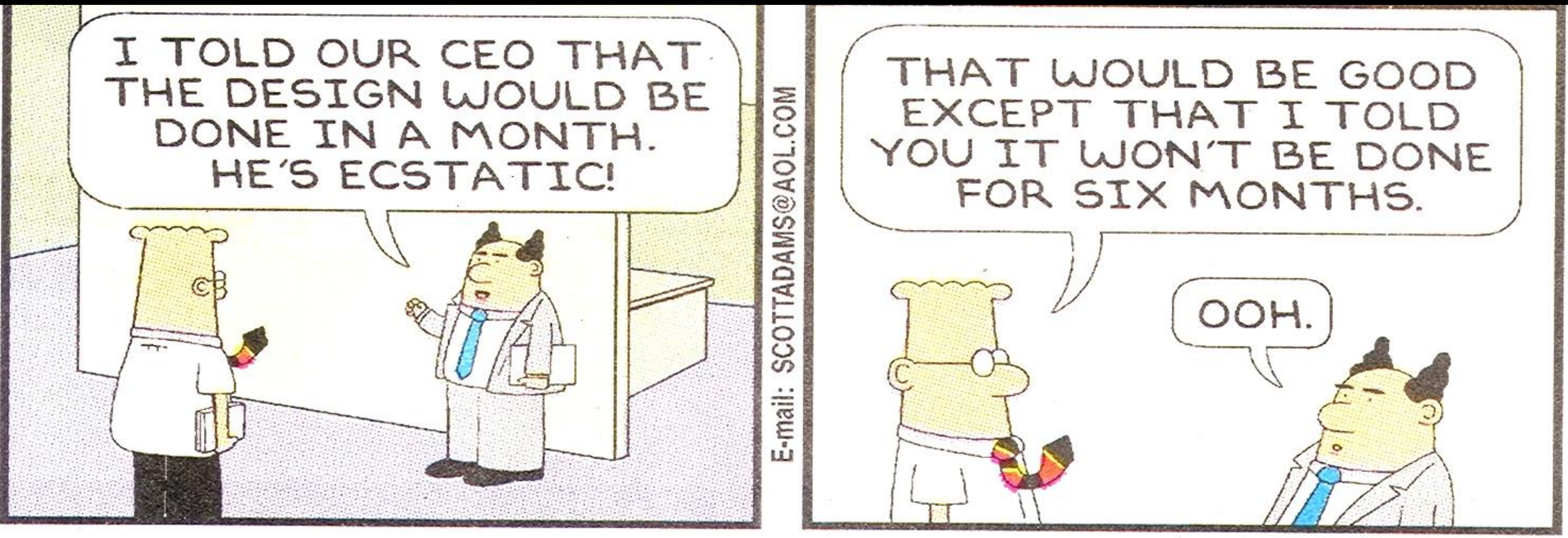
"… the tunnel face tended to come away in relatively large chunks, and these large rocks, which measured about 0,6m by 0,4m by 0,3m, caused the head to jam and continually damaged the front transfer chute." (Taylor et al). Rocks popped off the face, and, for safety, the TBM had to be retracted when cutters were changed.



Finally, my current hobby horse – QVP
a Quantified Value-created Process for decision making in mining

Key to responsibilities:
for information and decisions

Executives and Managers
Managers, Technical and Financial Staff
Managers and Technical Staff
Technical and Financial Staff


I TOLD OUR CEO THAT THE DESIGN WOULD BE DONE IN A MONTH. HE'S ECSTATIC!
E-mail: SCOTTADAMS@AOL.COM
THAT WOULD BE GOOD EXCEPT THAT I TOLD YOU IT WON'T BE DONE FOR SIX MONTHS.
OOH.

SO, I GUESS YOU'LL HAVE TO TELL HIM.
IT'S TOO LATE.
HE ALREADY ISSUED A PRESS RELEASE.
YOU'LL HAVE TO FINISH THE DESIGN IN A MONTH.
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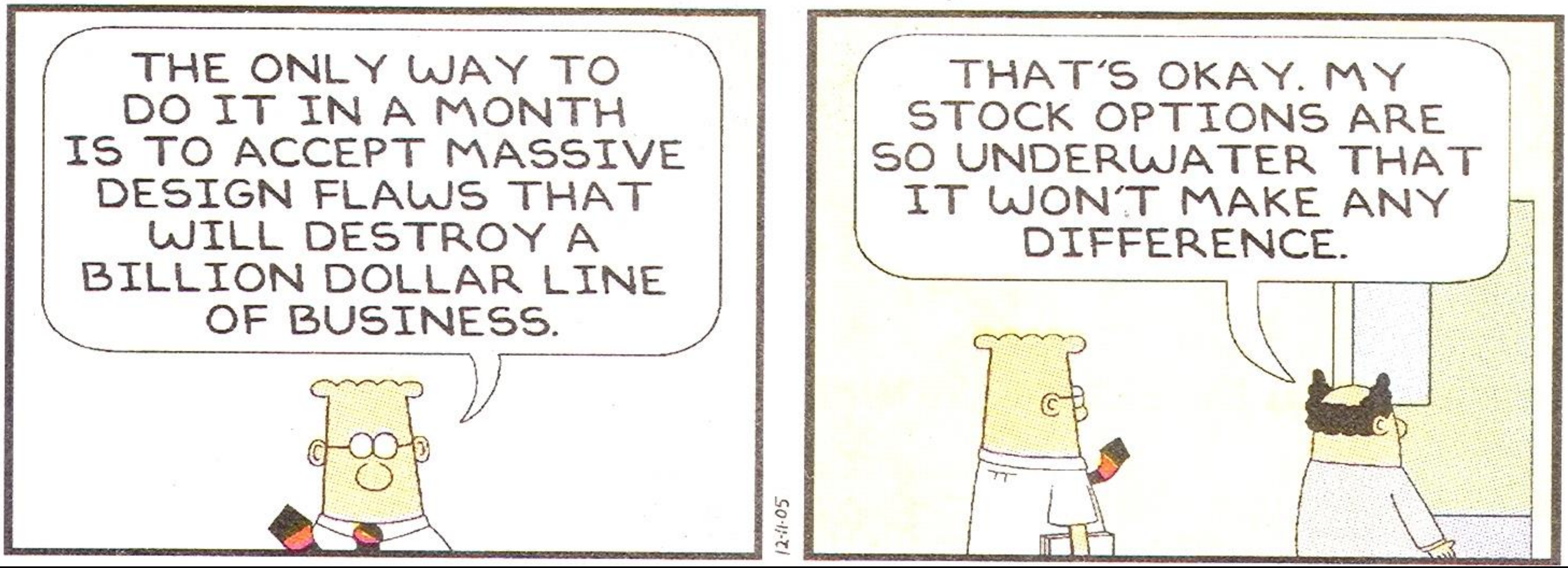
THE ONLY WAY TO DO IT IN A MONTH IS TO ACCEPT MASSIVE DESIGN FLAWS THAT WILL DESTROY A BILLION DOLLAR LINE OF BUSINESS.
12-1-05
THAT'S OKAY. MY STOCK OPTIONS ARE SO UNDERWATER THAT IT WON'T MAKE ANY DIFFERENCE.