Prof. Pierre Londe.
(1922- 2002)

MECHANICS IN ROCK ENGINEERING

(DEDICATED TO PIERRE LONDE)

Croix d'Officier de la Légion d'Honneur

A presentation to The French Committee for Rock Mechanics

by

Charles Fairhurst.*

December 5, 2013

**Professor Emeritus, University of Minnesota, USA.*
Senior Consultant, Itasca Consulting Group, Inc.

Ch. Fairhurst PL Kutter E. Hoek


un tourist

Prof. Leopold Müller.
(1908-1988)

….les discontinuités et l'anisotropie sont les propriétés les plus caractéristiques des massifs rocheux, et les propriétés des roches fracturées dépendent bien plus des propriétés des interfaces entre les blocs rocheux que de la roche elle-même. «

President L. Müller, ISRM Congress, Lisbon, 1966

Unlike classical fracture mechanics, new fracture systems are introduced as the scale of the problem increases –

"We are at the age of multi scale computation, with a growing need to understand not only phenomena on each of many scales but also the interaction not between phenomena at very different scales."
A.J.Chorin (Intro. to 'Scaling' by G.I. Barenblatt (2003)

Heterogeneity should now be added

Background to this presentation.

FIRST Global Grand Challenges Summit,

*LONDON, March 12-13, 2013 **

Sponsors

Chinese Academy of Engineering

Royal Academy of Engineering (UK)

US. National Academy of Engineering

Second Global Grand Challenges Summit.

BEIJNG. 2015.

Will We LOOK A LITTLE DEEPER ?

in Beijing, 2015

* See full televised program at http://raeng.tv/group.aspx?tag=GGCS2013&item=92

Global

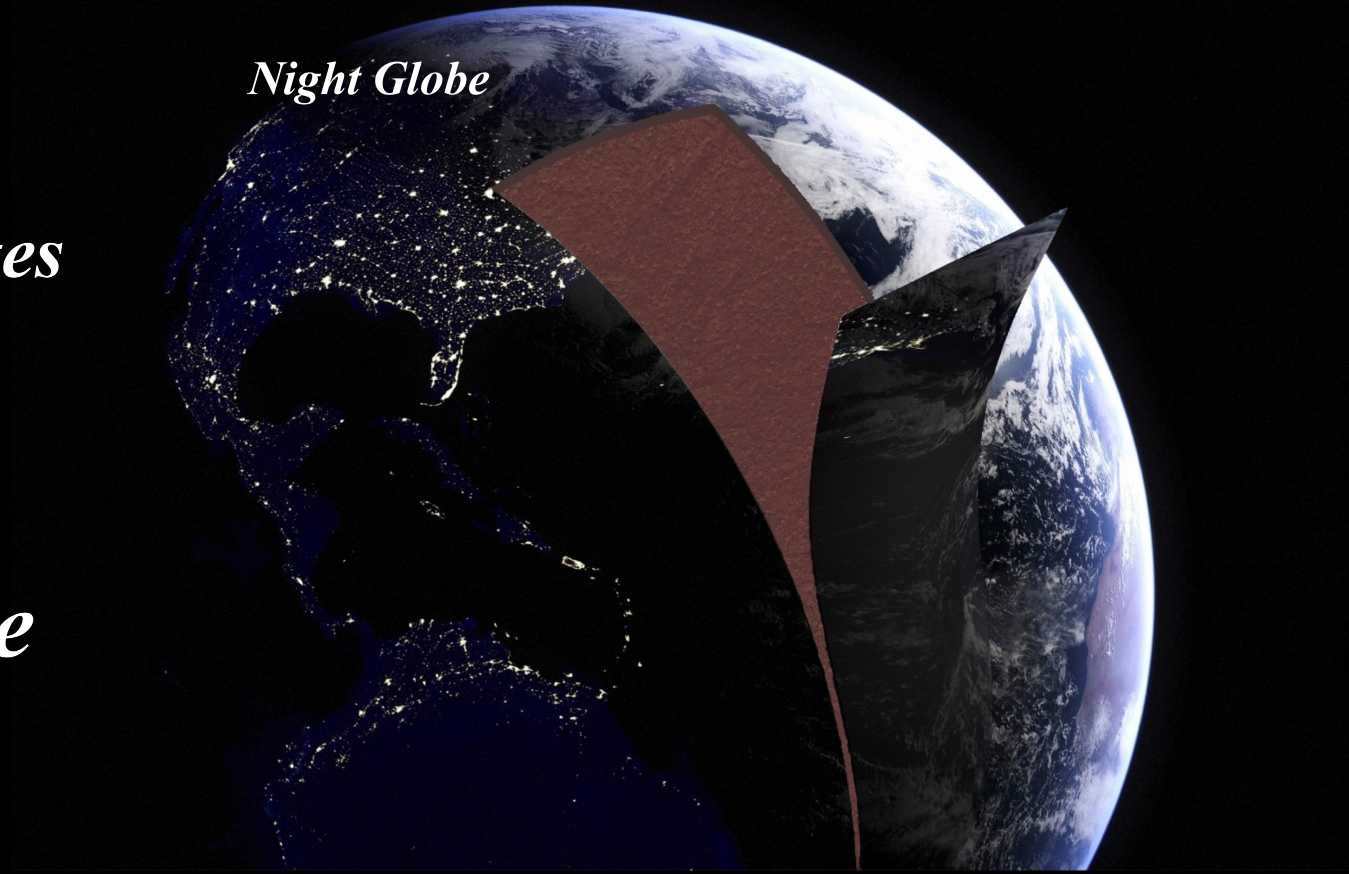
Grand Challenges

of

Inner Space

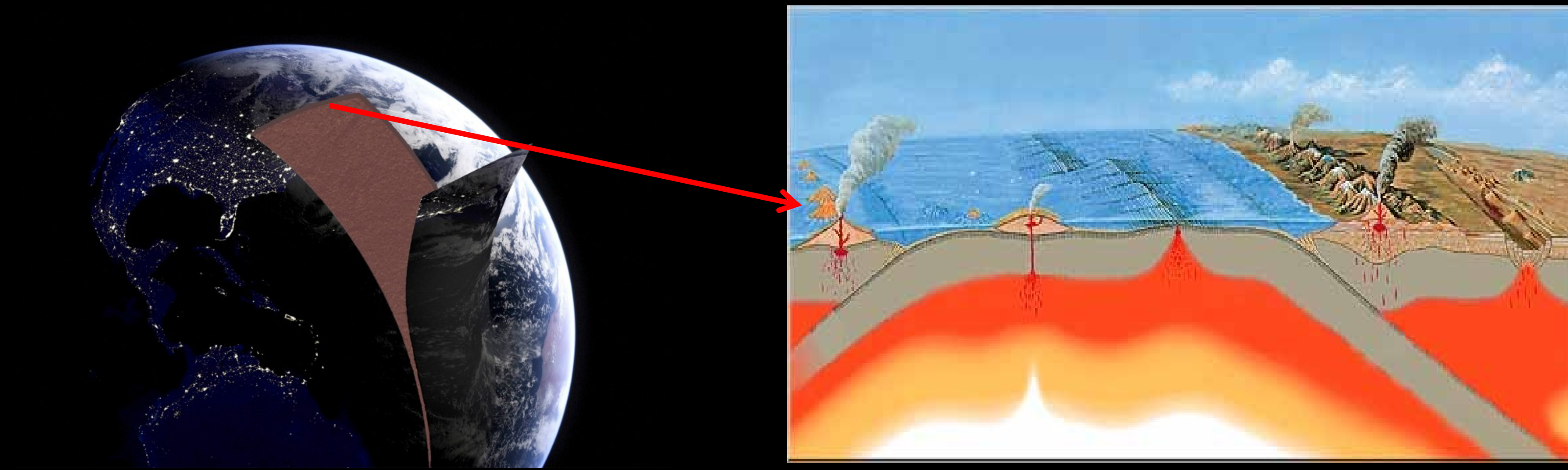
need
t o be

Illuminated.



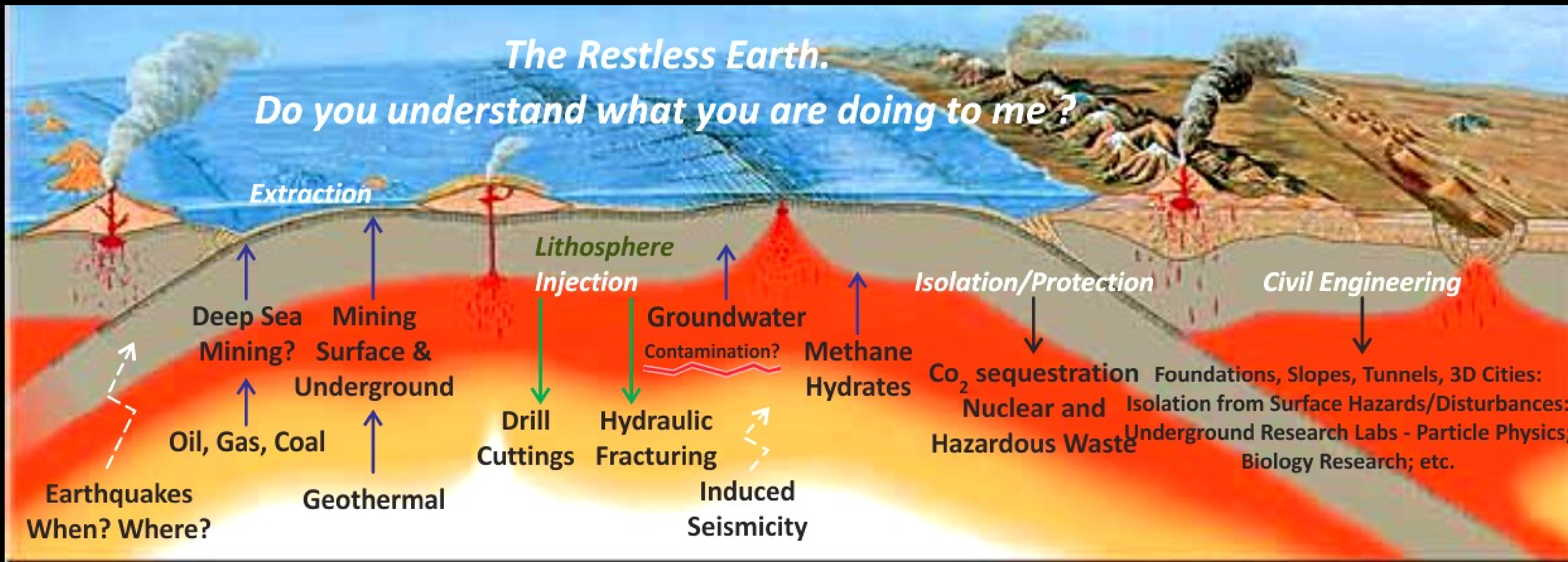
The subsurface is not Inert

The Restless Earth.



En abolissant les minerais de l'usage de l' humanité, on supprimerait toutes les méthodes de soutien, de protection de la santé, et de maintien de la vie.
Sans minerais, l'humanité retournerait à une existence bestiale et miserable avec pour toute subsistance les glans, fruits et baies de la forêt.   Agricola, De re Metallica, (1556)

Earth Resources Engineering is Critical to 21st Century Societal Well-Being



Earth Resources Engineering

"Engineering applied to the discovery, development and environmentally responsible use *of subsurface earth resources."*

Earth Resource activities are all relatively shallow in the lithosphere [Earth's crust; ~ (40 km-300 km thick.]

Deepest borehole is 12 km. Deepest mine is 4 km.

Rock temperature increases approx. 25°C/km depth

Vertical rock pressure σ_v increases ~ 27MPa/km.

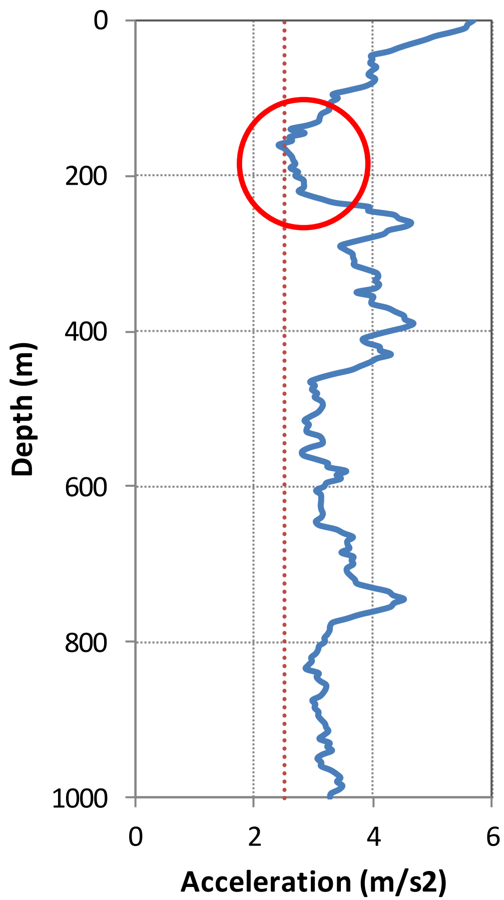
Horizontal pressure σ_h ~ (0.5- 3) σ_v

Earthquakes vary from ~ 20 km to 700 km in focal depth.

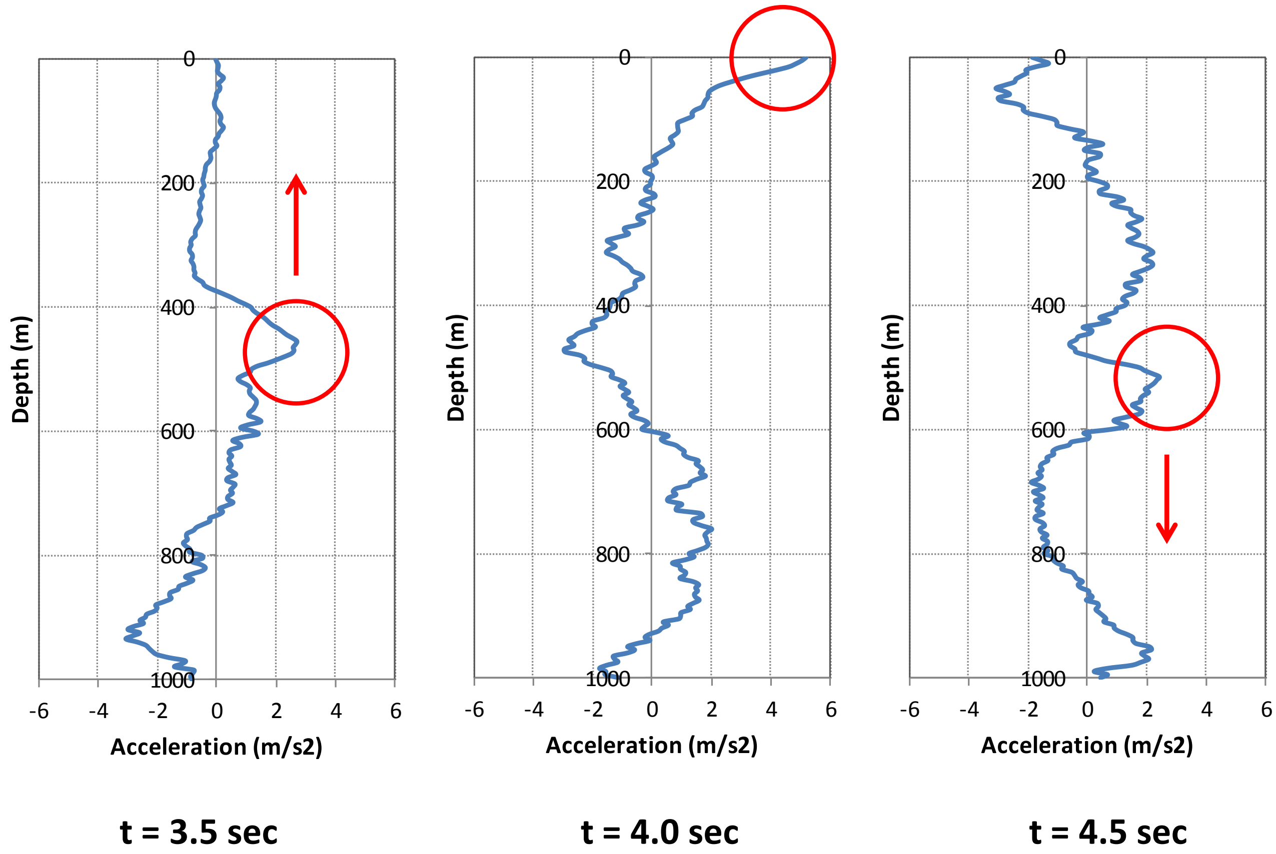
Engineering is limited to about top 10 km

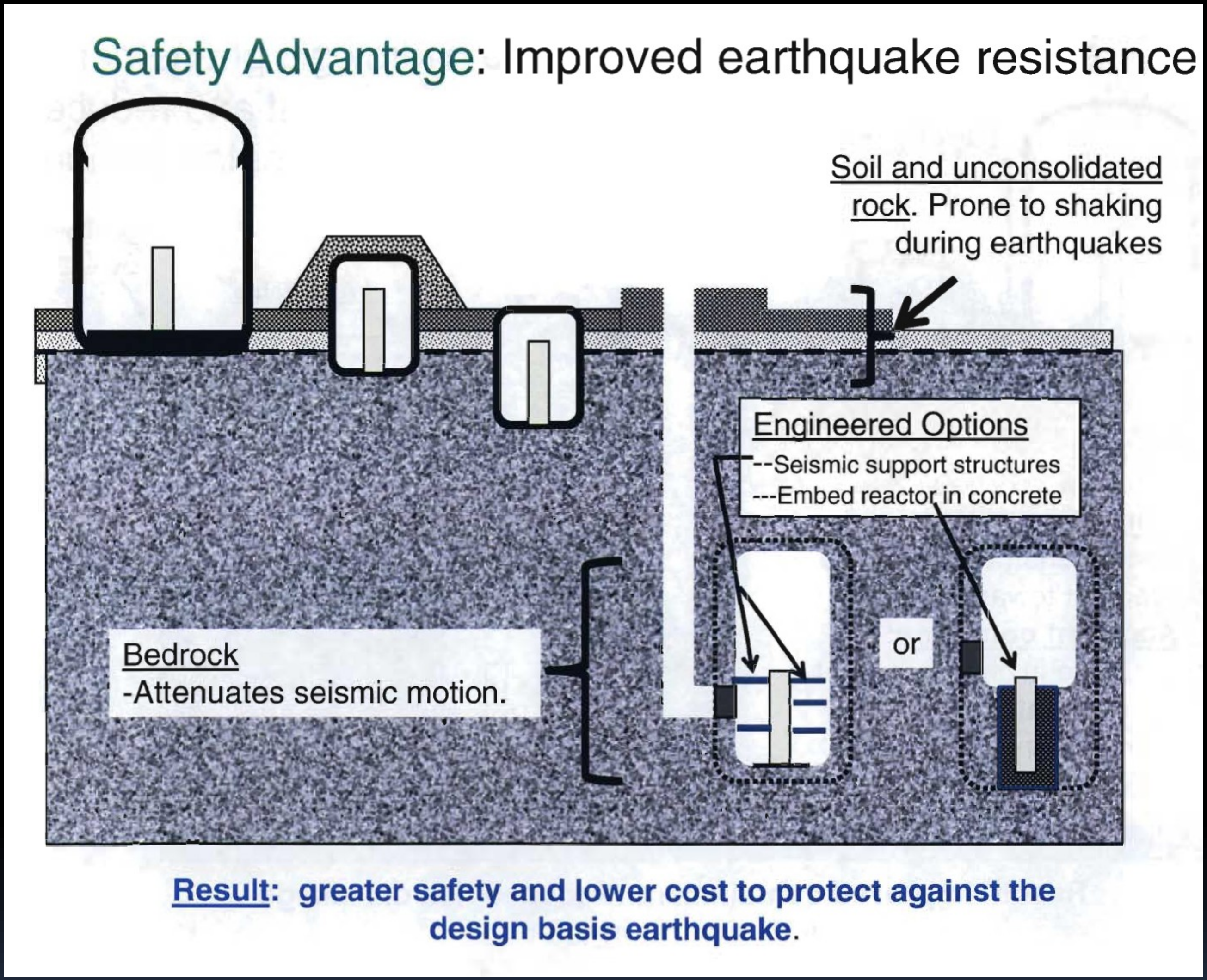
Maximum Acceleration

- Site Properties: Shear wave velocity = 1 km/s
- Ground motion: Dominant frequency ≈ 1.5 Hz (λ ≈ 667 m)
- Maximum absolute acceleration at a given location for the entire seismic event. It has to be greater than or equal to Peak Ground Acceleration (PGA) shown in dotted red.
- Local minima around 150-225 meters (λ/4).



Acceleration Profile





Underground Location of Nuclear Power Plants – Small Modular Nuclear Reactors

Myers, C.W. and J. M. Mahar, (2011) *Underground Siting of Small Modular Reactors: Rationale, Concepts, and Applications.* ASME Small Modular Reactor Symposium September 28-30, 2011 Washington, DC. \ http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-11-04777

Earthquakes.

Wenchuan Earthquake, 2008 M 7.9 (Richter)

Epicenter ~100 km W of Chengdu, Depth 10km

70,000 dead; 357,000 injured; 4.8 ~11 million homeless.

…………………………………………

Rockbursts

More than 69,000 mineworkers in South Africa lost their lives from 1900 to 1994, while a million had been injured.

The biggest contributors to fatalities and injury were rockfalls, rockbursts and seismicity. Leon Commission (South Africa) 1994.

Established 1845 SCIENTIFIC AMERICAN May 1975 Volume 232 Number 5

Earthquake Prediction

Recent technical advances have brought this long-sought goal within reach. With adequate funding several countries, including the U.S., could achieve reliable long-term and short-term forecasts in a decade

by Frank Press

The forecasting of catastrophe is an ancient and respected occupation. It is only in recent years, however, that earthquake prediction has parted company with soothsaying and astrology to become a scientifically rigorous pursuit. At present hundreds of geophysicists and geologists, mainly in the U.S., the U.S.S.R., Japan and China, are engaged in research with earthquake prediction as the direct goal. Most of these investigators believe that the goal is attainable. Some are more pessimistic. A few actually think that the side effects of prediction might be worse than the benefits and that the goal should be abandoned. Research on earthquake prediction therefore exemplifies many of the problems that face modern society: technology assessment, the design and organization of a massive mission-oriented project, the competition for funds and the political niceties of an undertaking involving admittance to previously inaccessible regions of another country.

I share the view of most of my colleagues that earthquake prediction is a highly desirable goal. Because of the large increase of population density in the earthquake-prone sections of the U.S., the potential loss from an earthquake as strong as the San Francisco shocks of 1906 could be as high as tens of thousands dead and hundreds of thousands injured, with property damage

“Earthquake Prediction is a Grand Challenge “ (1975)

Dr. Frank Press, President US National Academy of Sciences 1981-93

Science Advisor to US President Carter

Heterogeneity is Pervasive

To forget this fact leads to over-simplified rules that can be very misleading. Examples,

- *"The rock mass is critically stressed everywhere";*
- *Vertical stress is everywhere equal to the product of depth in meters and an average density of rock of 2,700 kg/m^3"*
- *Coefficient of friction on rock joints is 0.6. (Byerlee's law)*

- *Newtonian Mechanics is obeyed, of course ,*

  but

- *Forces and Deformations in rock mass have evolved over (long) Time*

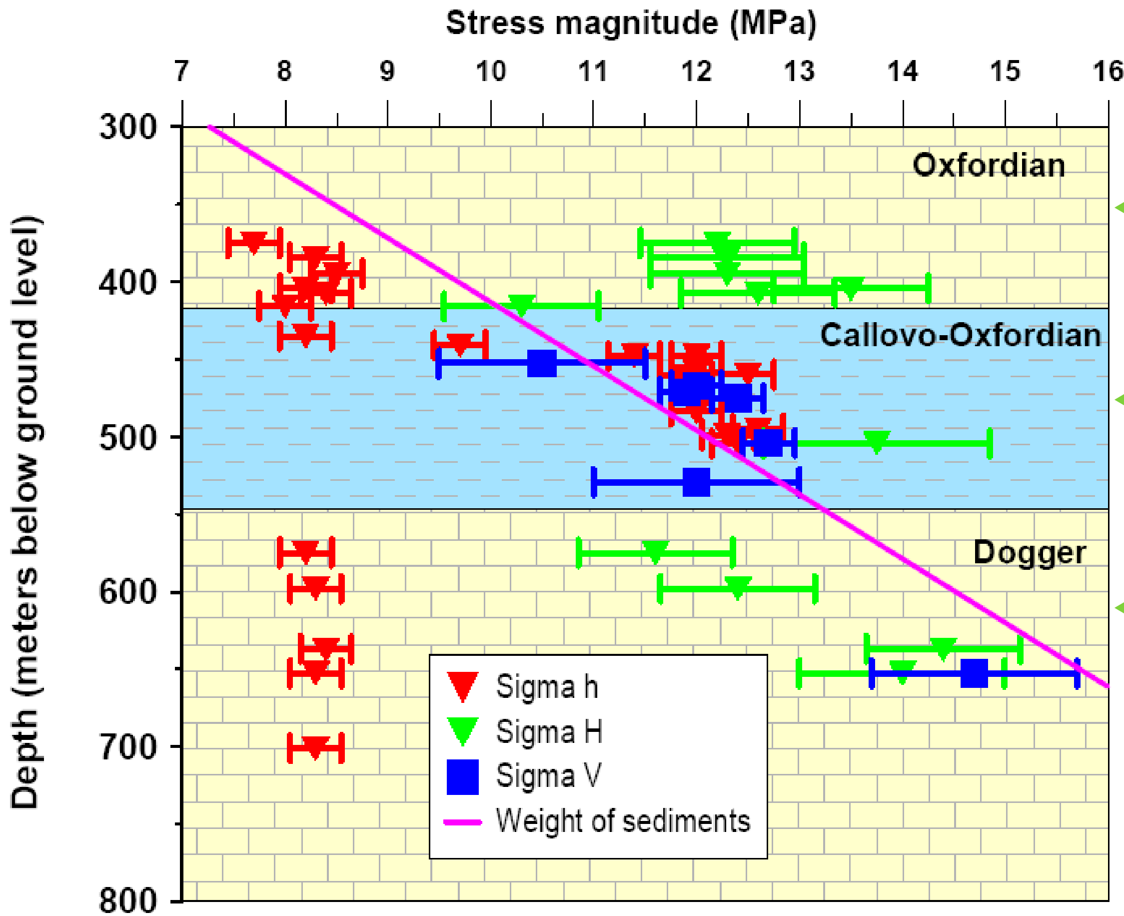


Figure 13 : Profile of magnitude of the in situ stress at the Bure Site

(Underground Research Laboratory, Bure. France)

Limestone

$\sigma_H > \sigma_V > \sigma_h$

indurated clay)

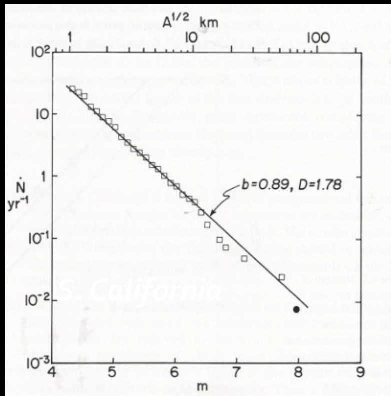
$\sigma_H = \sigma_V = \sigma_h$

Limestone

$\sigma_V > \sigma_H > \sigma_h$

In-situ stress state depends on long –term constitutive behaviour of rock

Heterogeneity in Horizontal Stress



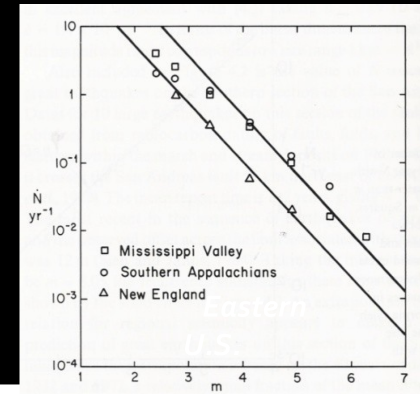
Protecting the Public

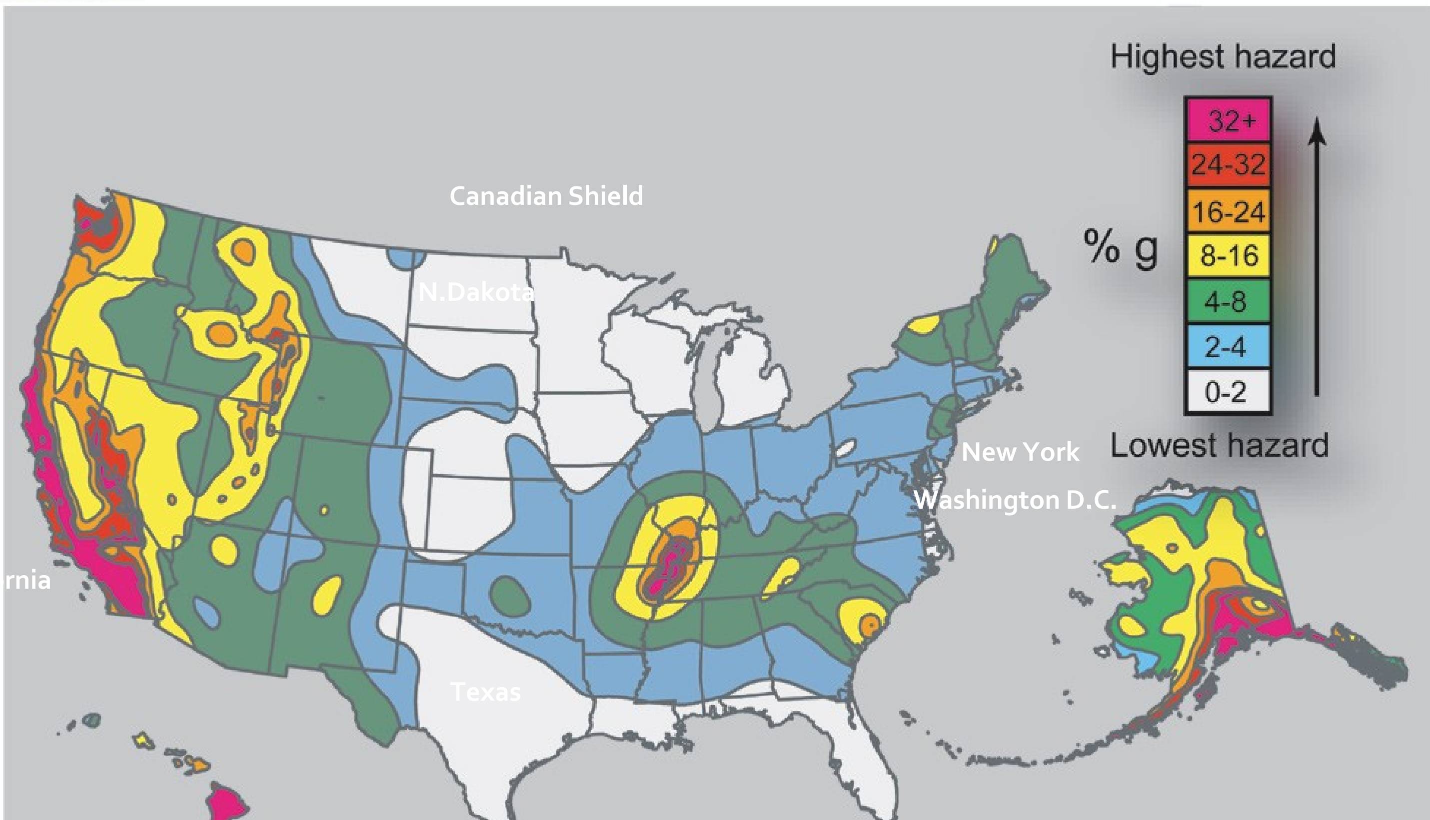
Hyraulic fracturing - trigger seismic events?

- contaminate groundwater?

Seismic Hazard Varies Widely Across US

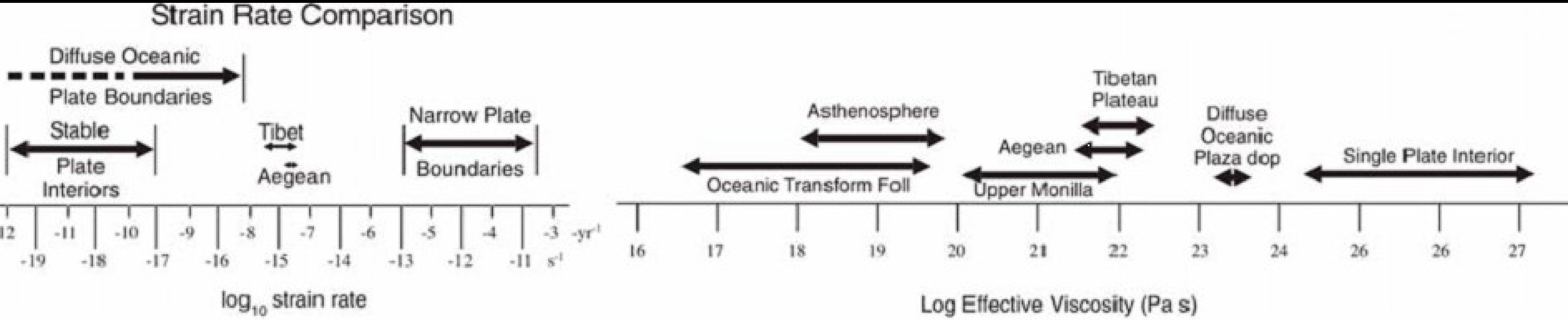
Three orders of magnitude higher hazard in S. California than in Eastern US

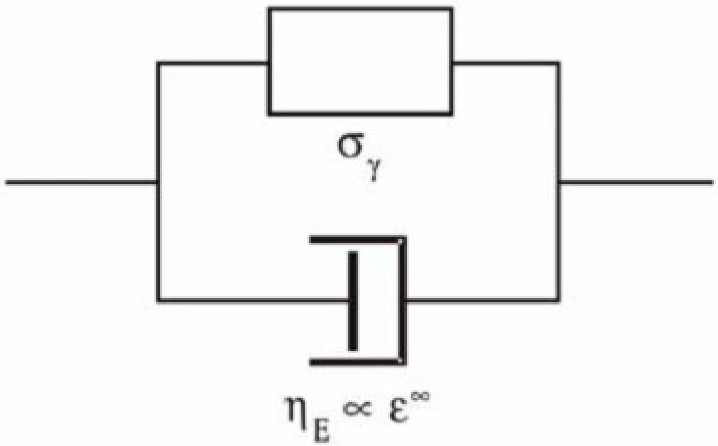




How can Potential for Induced Seismicity be Uniform across US ?

Heterogeneity on a Continental Scale





Tectonic Plates - Strain Rate varies over 8 orders of magnitude
Viscosity varies over 10 orders of magnitude

Gordon, R.G., (2000) Diffuse oceanic plate boundaries : Strain rates, vertically averaged rheology, and comparisons with narrow plate boundaries and stable plate interiors, in History and dynamics of global plate motions, edited by M. Richards, R.G. Gordon, and R.D.van der Hilst, pp. 143-159, American Geophysical Union, Washington, D.C., 2000.

***Rock** Engineering Problems are - 'data limited'.*[1]

- *and involve substantial uncertainty. "One seldom knows enough about a rock mass to model it unambiguously".*[1]
- *Modeling results must be treated as one input to the design decision – which requires the judgment of the engineer. "The most powerful computer in the world isn't nearly as **intuitive** as the one with which we are born."* [2]

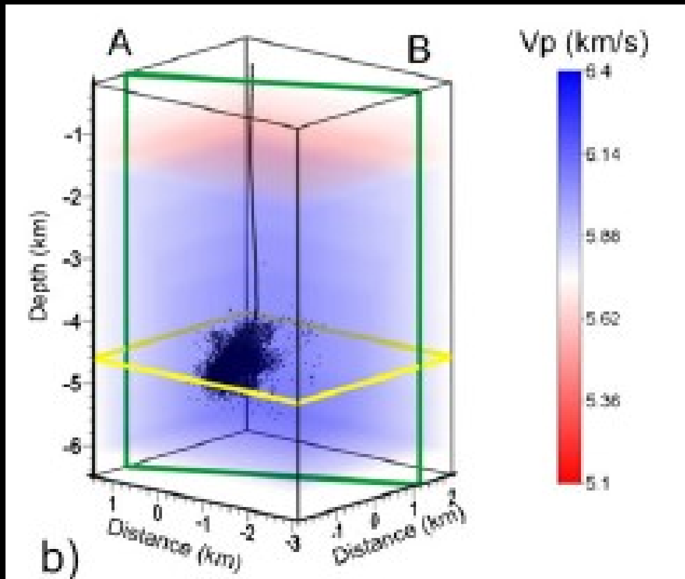
[1] *Starfield, A. M., and P. A. Cundall. "Towards a Methodology for Rock Mechanics Modelling," Int. J. Rock Mech., Min. Sci. & Geomech. Abstr.,* ***25****(3), 99-106 (1988).*

[2] *US President Obama (Brain Initiative speech 04/02/2013*
http://video.pbs.org/video/2364989692/
[

Scale

- *Increase in scale of a problem introduces new fracture systems.*
- *" We are at the age of multi scale computation, with a growing need to understand not only phenomena on each of many scales but also the interaction between phenomena at very different scales."* Chorin [3]

- [3] *Alexandre Chorin, Univ. Professor, Univ. of California, Foreword to* ***Scaling,*** *by G.I. Barenblatt, Cambridge Univ. Press (2003)*

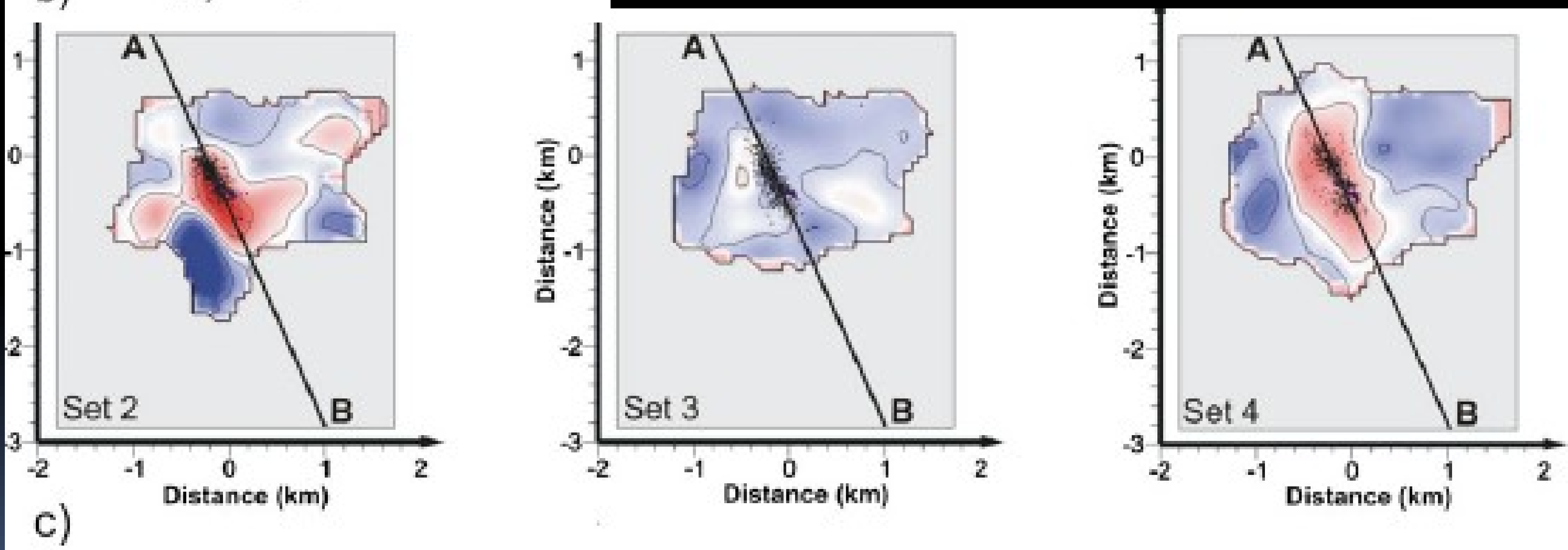


Vp 6.4 km/s = 1.00

ASEISMIC DEFORMATION (Soultz)

20% drop in P-wave velocity in region ~ 500m outside micro-seismic cloud. { Calo et al (2011)]

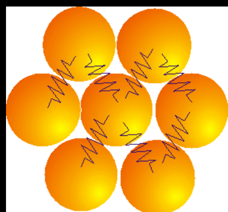
Vp 5.1km/s = 0.80



Calo, M; Dorbath, C; Cornet, F. H; & Cuenot, N. (2011). Large scale aseismic motion identified through 4D P-wave tomography; Geophys. J. Int. , 186, 1295-1314.

Newton (ca 1687)

Molecular Model of Body Structure



Computer (1970 -)

Discontinuum

'Rock'
(a variety of materials)

Very Complex Structure

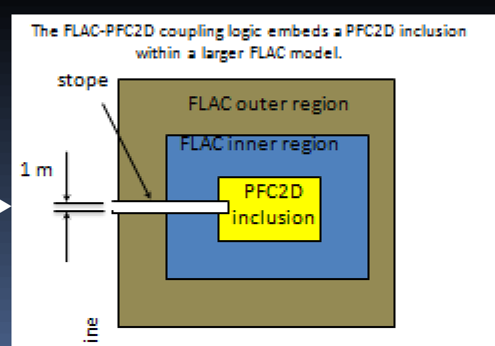
Empiricism

Modelling of Data -Limited Systems
(Starfield and Cundall ,1988)

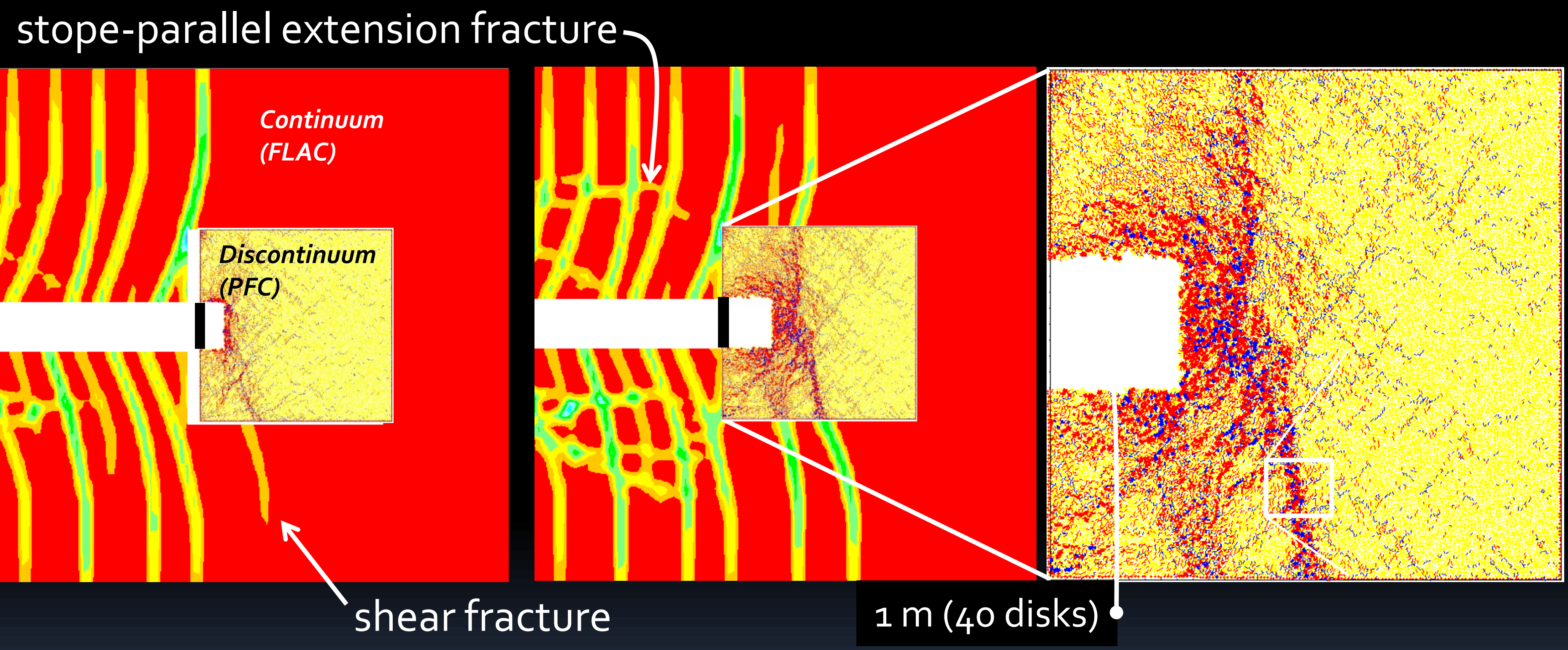
Infinitesimal Calculus

Continuum Hypothesis

Continuum Mechanics



Continuum-Discontinuum Model

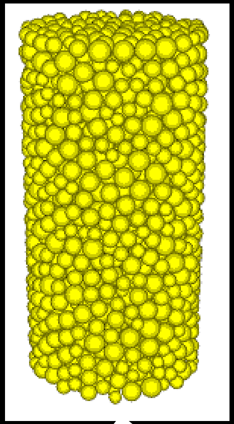


Numerical Modelling of 'Slot' Advance in South African Gold Mine.

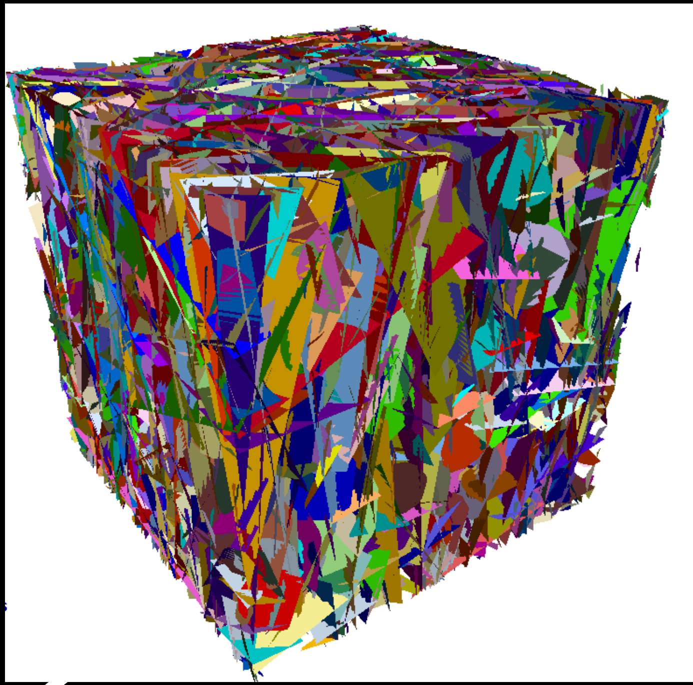
(Combined Continuum- Discontinuum)

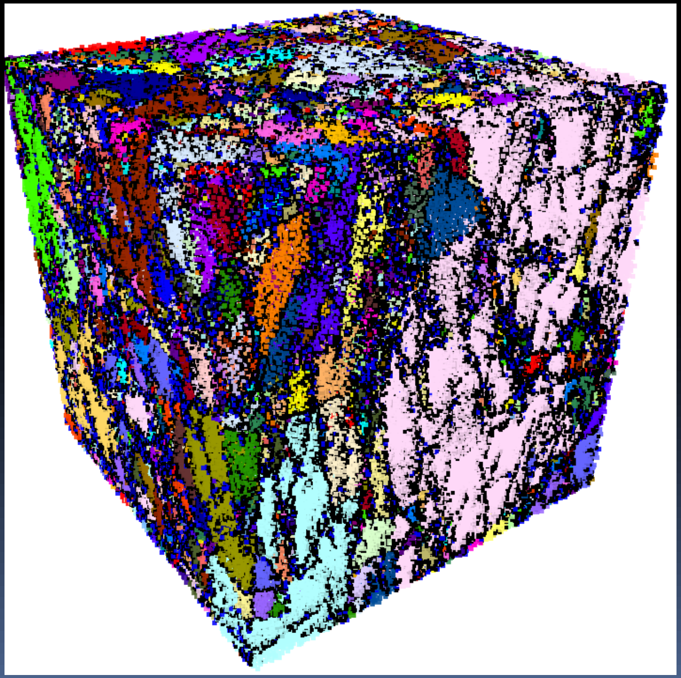
Synthetic Rock Mass

Intact rock representation (including brittle fracture)



Fracture representation – 3D DFN

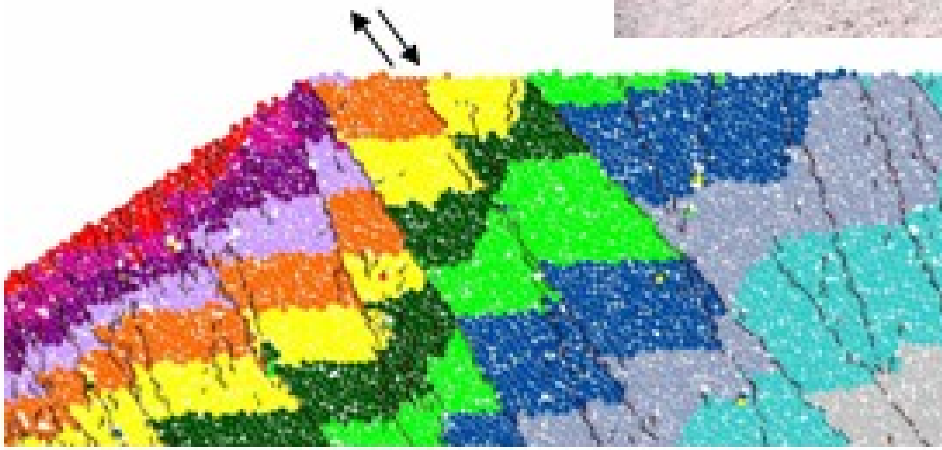




Bonded-particle assembly intersected with fractures (Smooth Joint Model – SRM)

Bench C2
West Wall Slope at Chuquicamata

note offsets



Reversed plot from
PFC model

Toppling Failure at Chuquicamata Open Pit Mine, Chile.

Underground

Nuclear Tests

in

French

Polynesia

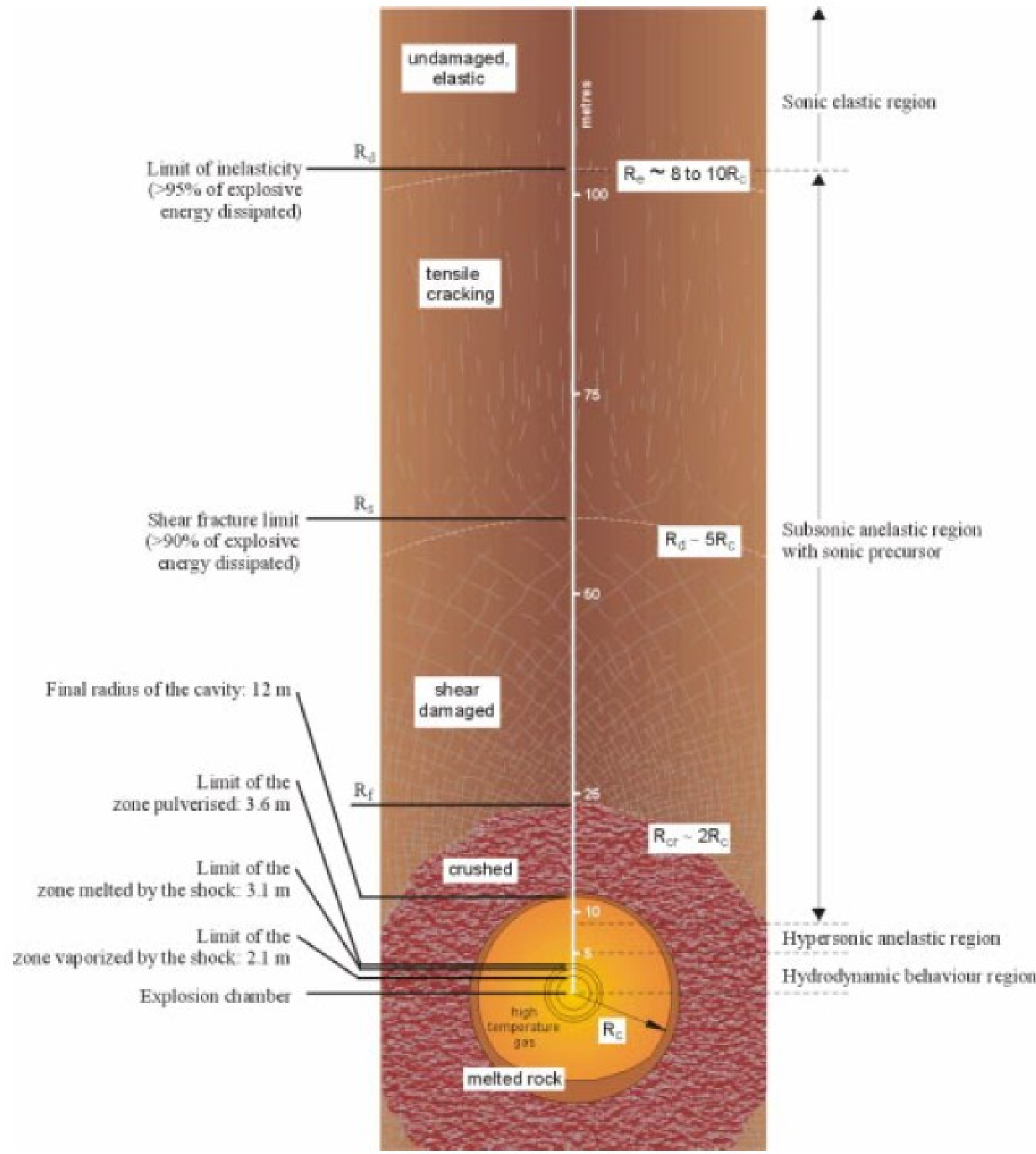


Figure 1.10 Presumed rock damage zones around a 1-kt nuclear explosion cavity in basalts at Mururoa and Fangataufa (The damage zones are expressed as multiples of the final cavity radius R_c, which increases in proportion to $Y^{1/3}$, where Y is the explosion yield in kt) [modified after Bouchez and Lecomte (1996); see also Fig. 3.7]

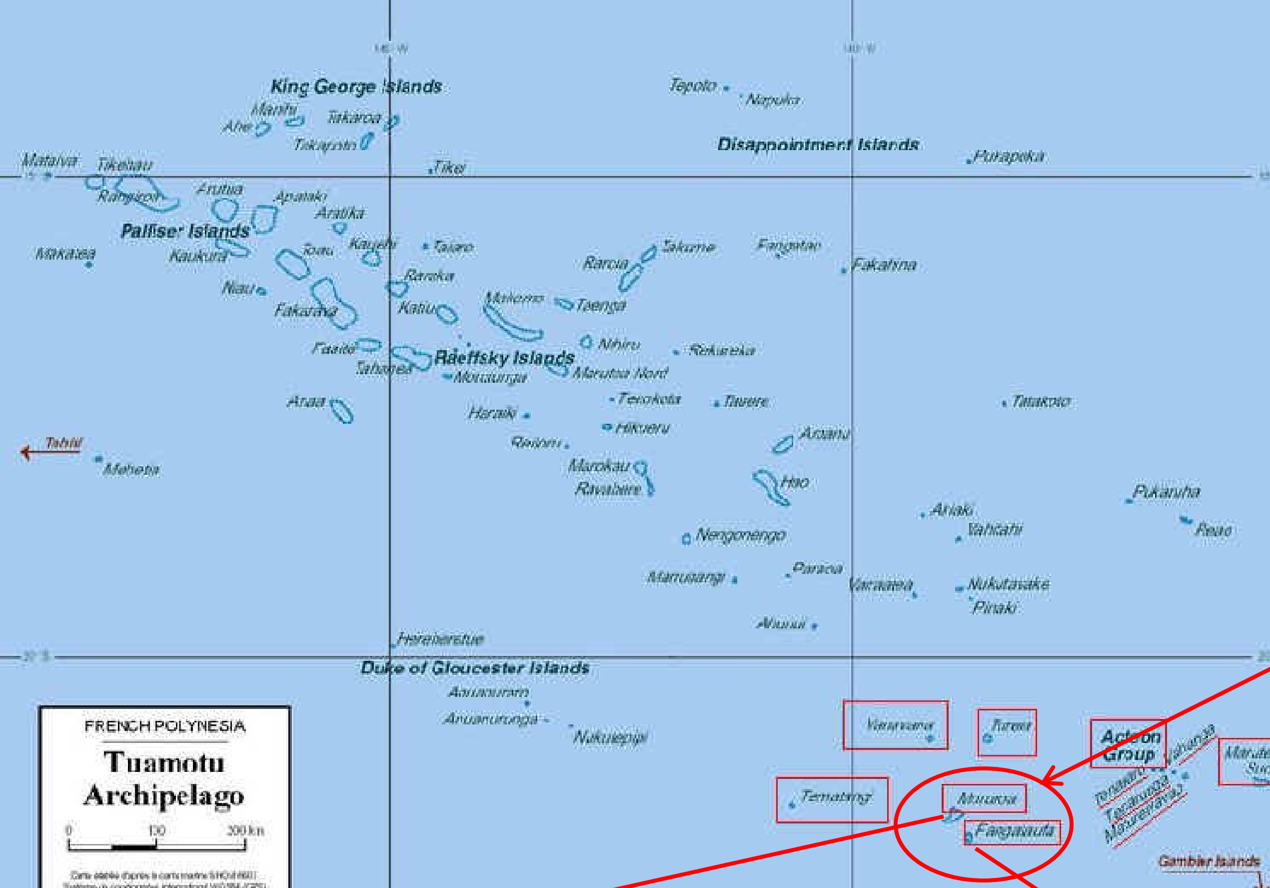
Underground Nuclear Testing in French Polynesia\. (1999)

Report of the International Geomechanical Commission.

Charles Fairhurst, Chairman

This report is published in three volumes: Volume I, *General Results*; Volume II, *Technical Analyses*; and Volume III, *Les Essais Nucléaires Souterrains en Polynésie Française: Stabilité et Hydrogéologie* (French language extracts from Volumes I and II). These volumes may be obtained from:

La Documentation Française
29, quai Voltaire
75344 Paris
Cedex 07
France

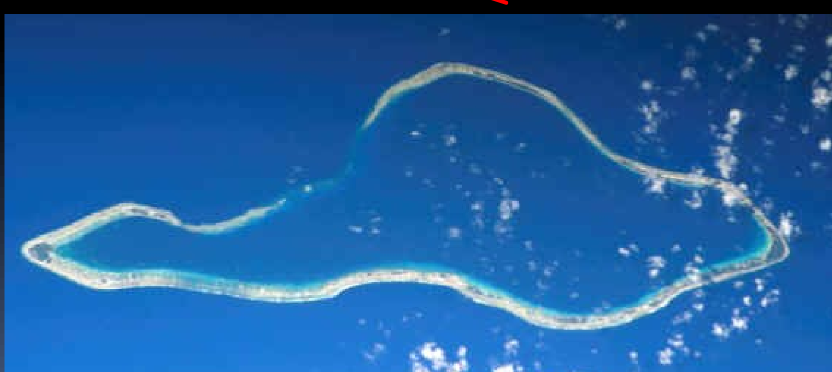


Mururoa and Fangataufa

Atolls.

French Polynesia,

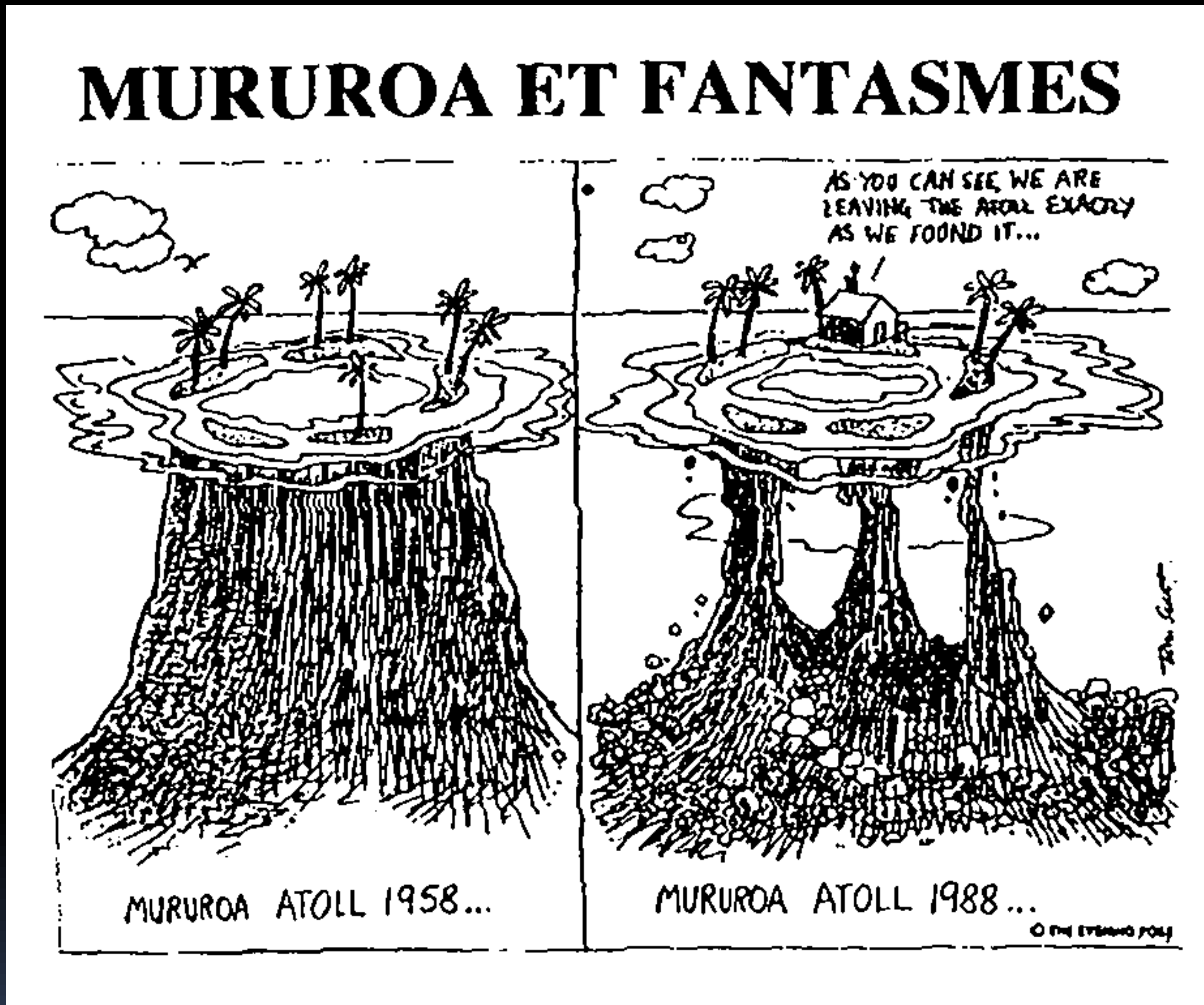
South Pacific Ocean



Mururoa *Fangataufa*

Aerial Views

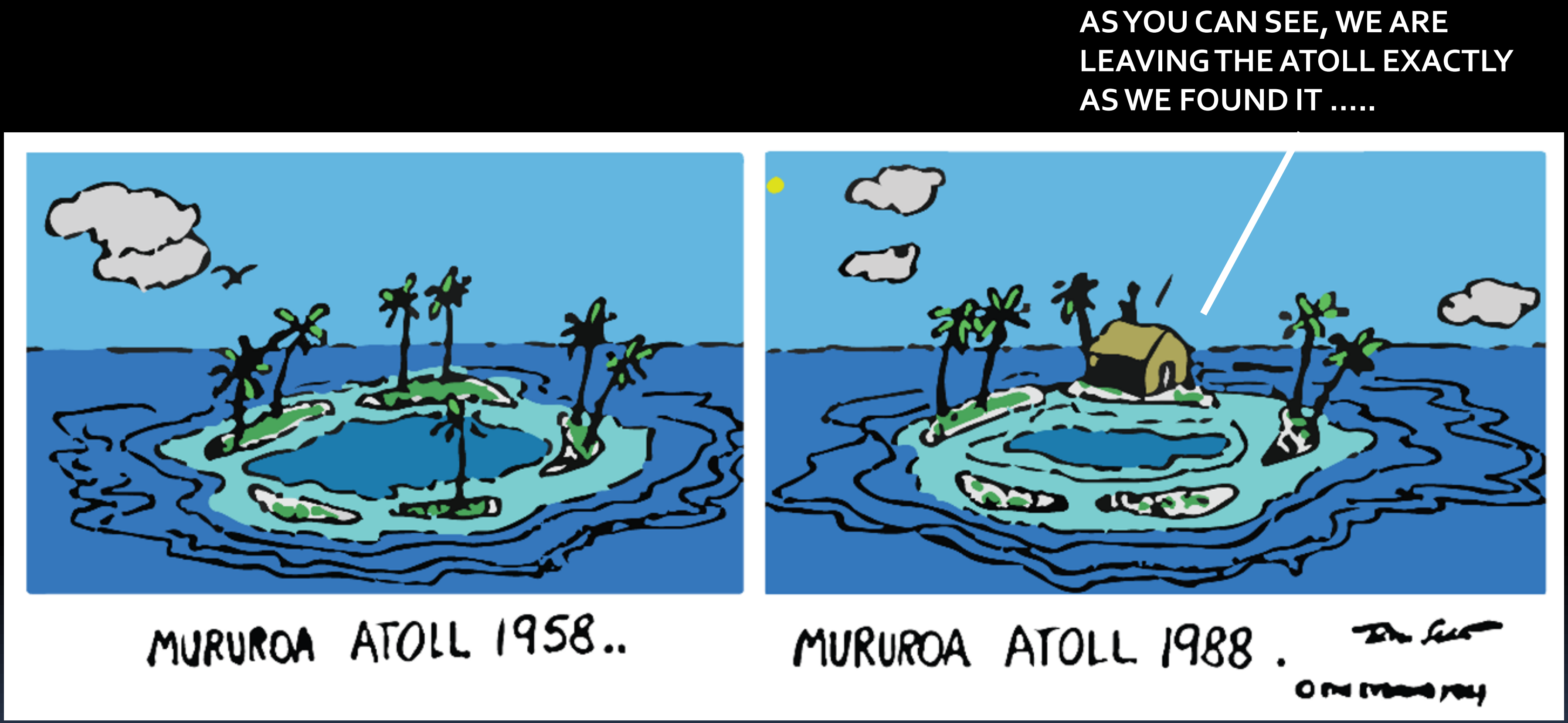
Mururoa Atoll - Polynésie française



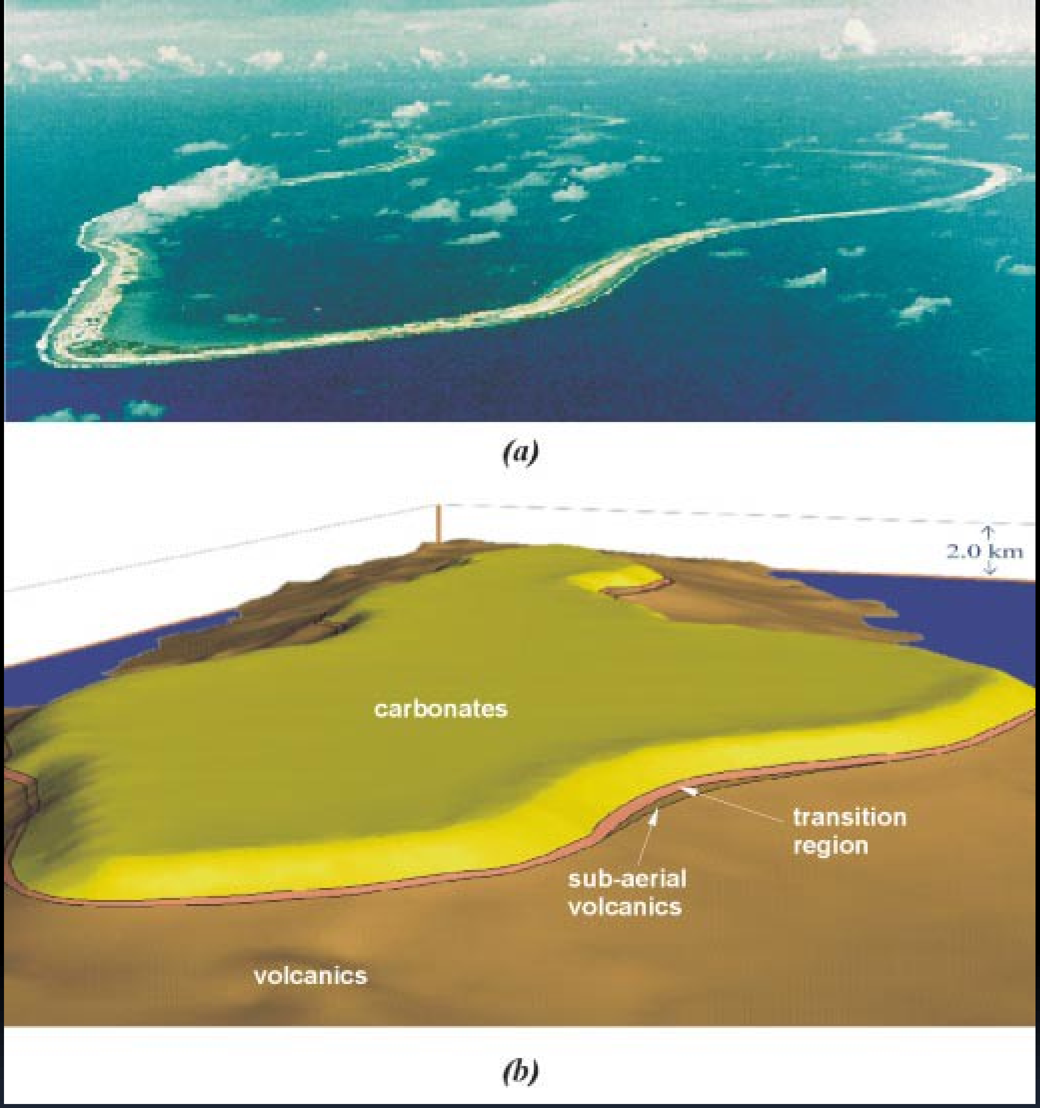
Cartoon published in the Auckland Evening Post (ca 1988)

A Genuine Public Concern -

*"**what** **i**s happening that we cannot see? ? "*



Cartoon. Auckland Post (modified)



L'Atoll de Mururoa

(a) vue aérienne

(b) (vue bathymétrique (depuis le même point d'observation) jusqu'à une profondeur de 2,0 km

Le massif volcanique est surmonté par les carbonates; la perspective est orientée dans la direction sudouest (S 65° E, altitude 21° audessus de l'horizon) avec la zone d'essais 1

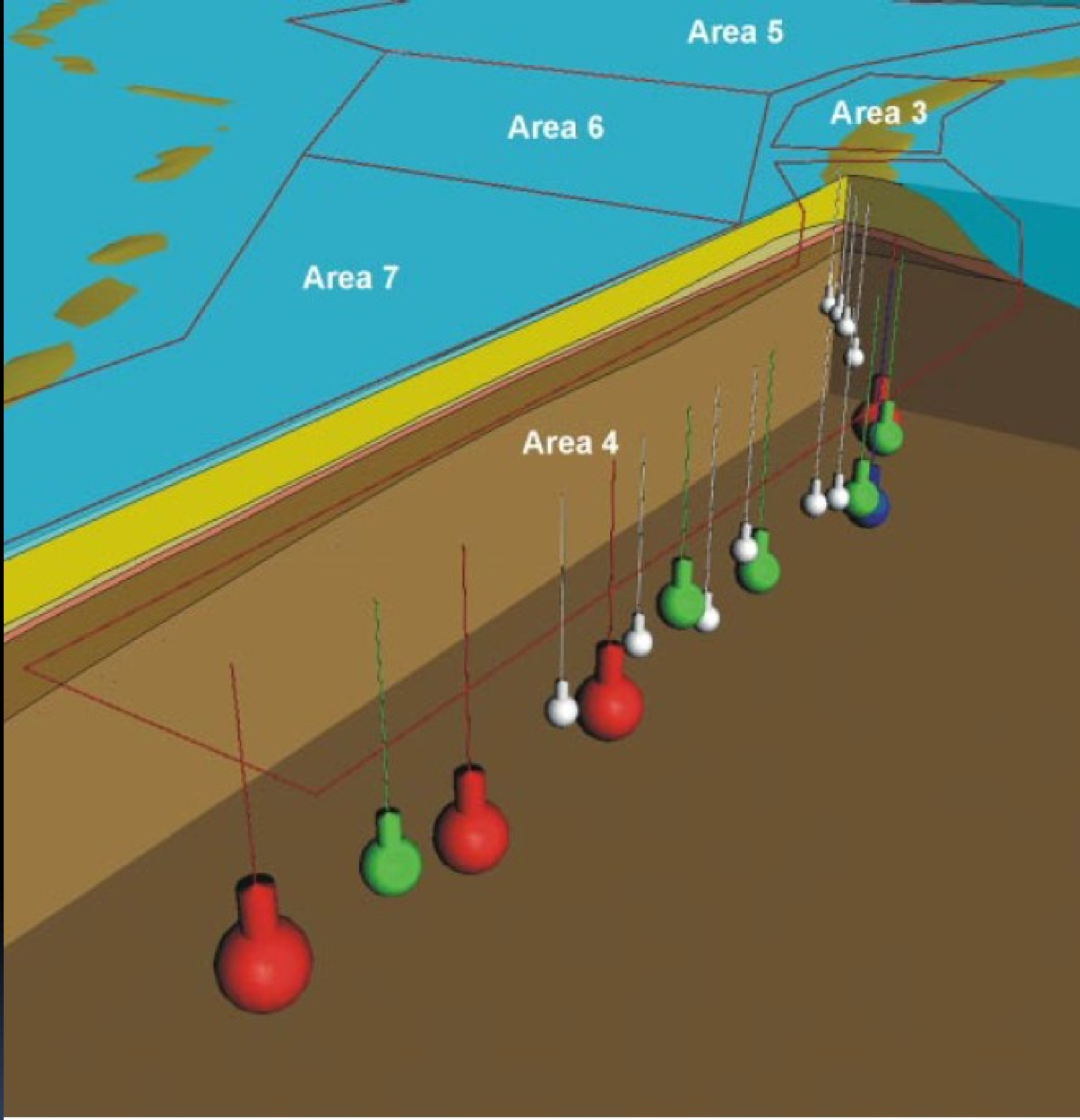
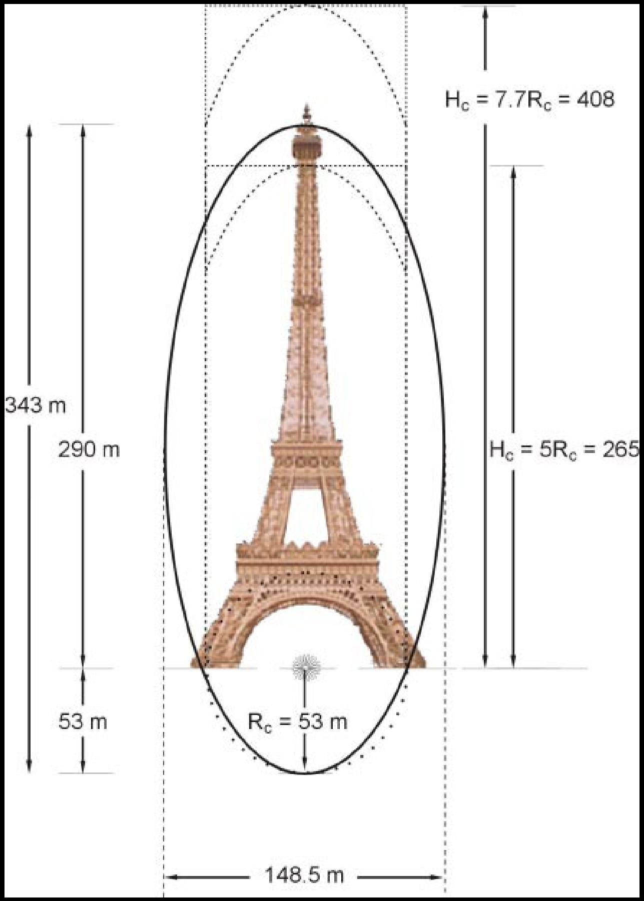


Figure 1.20 Schematic illustration of regions of enhanced permeability (R_p = 2.5R_c, H_c = 5 R_c) associated with underground tests in test area 4 on Mururoa; colours indicate low (white) ($<$ 5 kt), intermediate (green) ($<$ 20 kt), high (blue) ($<$ 80 kt) and large (red) ($<$150 kt) explosions



Comparative dimensions of cylindrical (flat or arched roof) and spheroidal* (chimney/cavity produced by a 150kt yield (Y) nuclear explosion at a depth of 1100 m at the PTC.

Cavity radius R_c = 10 Y cylindrical chimney height Hc = 5 R_c (first case) and 1100 $(Y/h)^{1/3}$ = 7.7 R_c (second case).
The Eiffel Tower is 318.7 m high, including the TV tower, and 127.5 m wide at the base)
** i.e. ellipsoid of rotation with K = 1.4*
The spheroidal cavity/chimney is of the same volume as the 7.7 R_c flat roof cylindrical cavity/chimney.

Figure 1.22 Aerial view of western part of test area 4 on Mururoa taken in July 1996 (i.e. 16 years after rim testing ceased) from the ocean side, looking toward the lagoon (note that several test sites and settlements in the western end of test area 4 are underwater; see also Fig. 1.23)

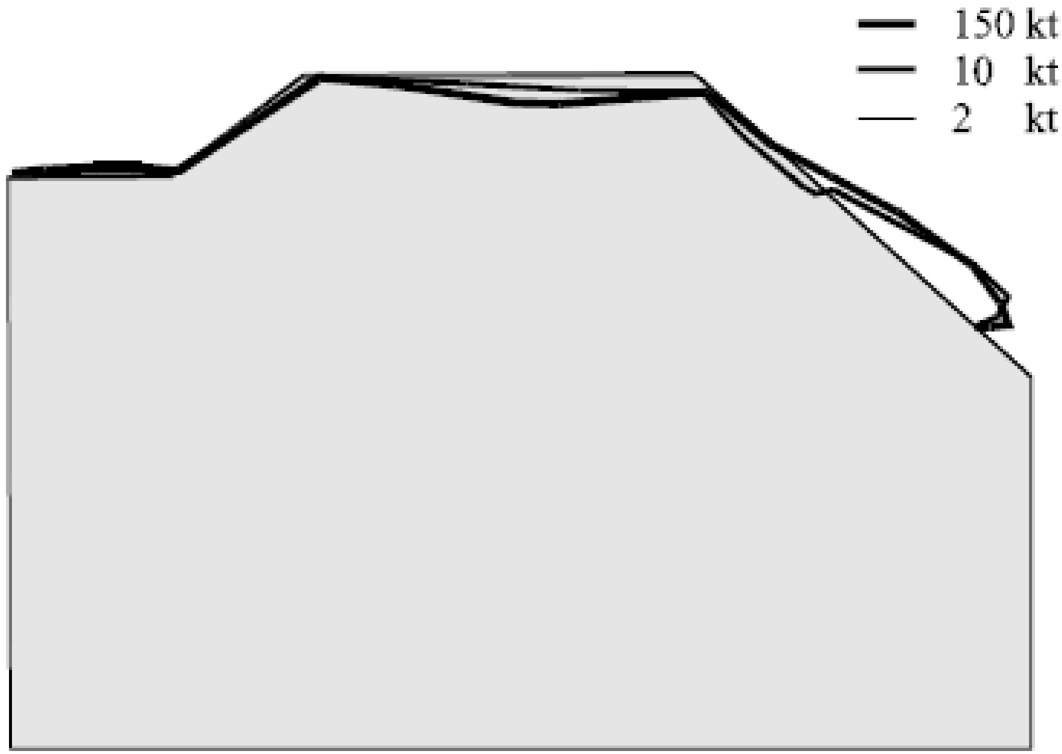


Figure 4.10 Exaggerated (50x) deformation of the model (maximum displacements = 1.32 m)

Surface settlement occurs by Equivoluminal (Isochoric) Shear - not by Compaction

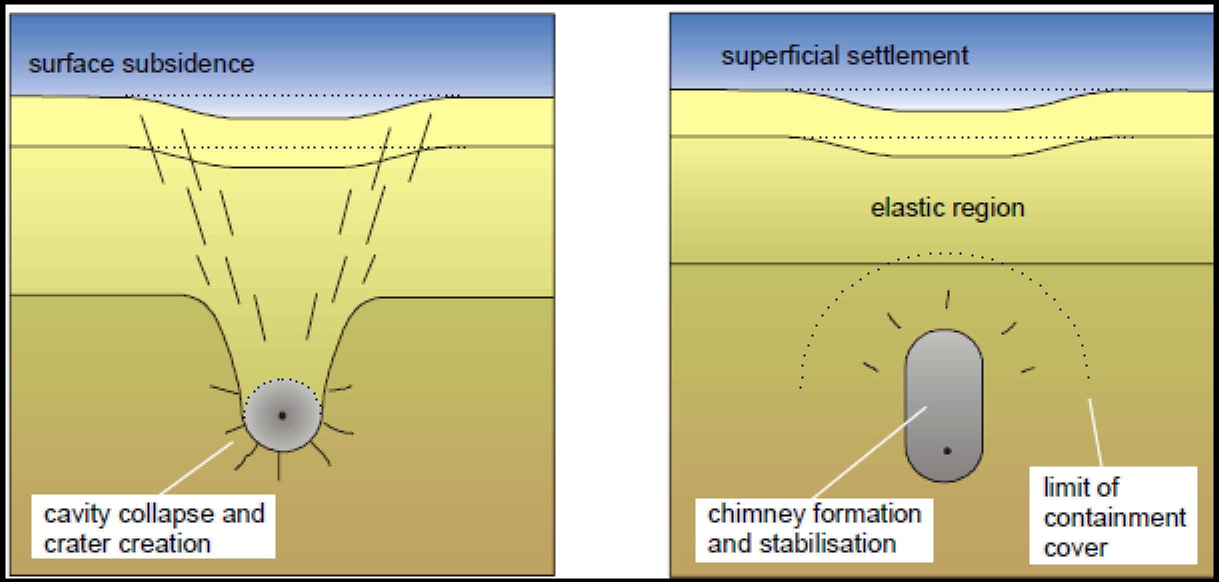


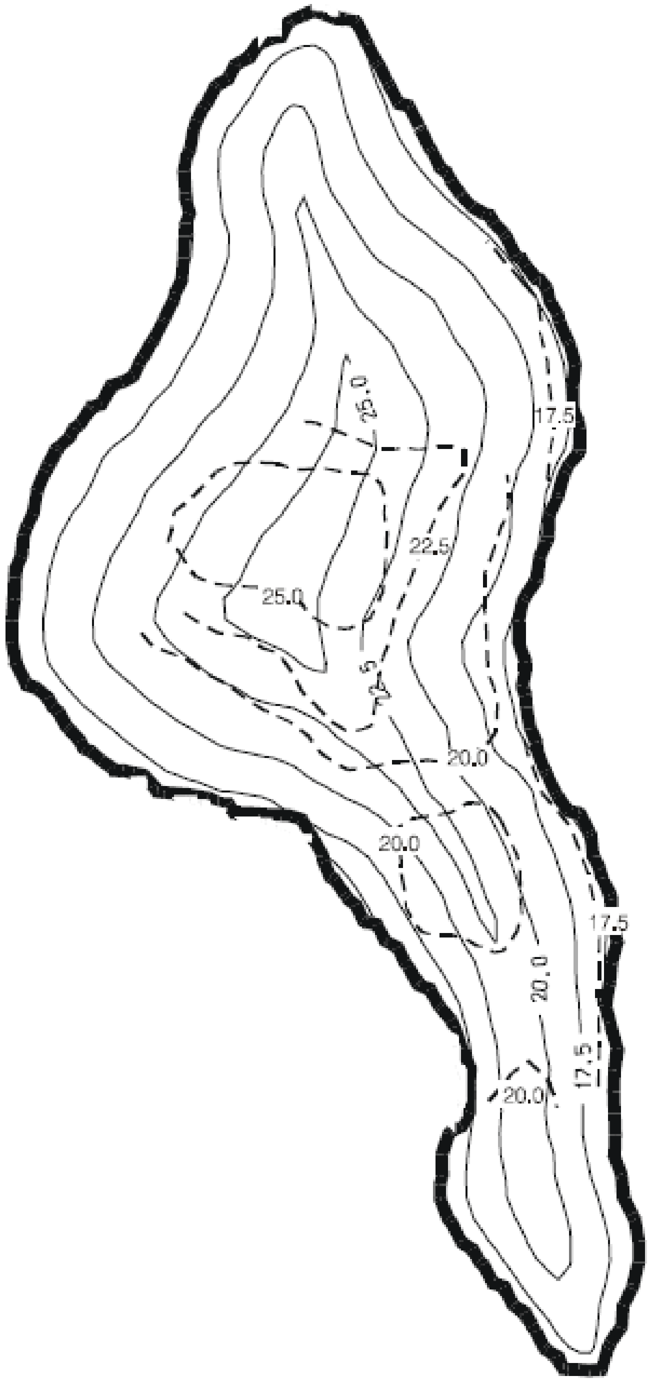
FIG. 2.24 Comparaison entre la subsidence qui survient sur le Nevada Test Site (NTS) et les affaissements produits par les essais au CEP (d'après Bouchez et Lecomte, 1996,

Analysis Confirms Existence of barrier of Intact Rock between Surface and top of Collapse Cavity at Atolls .

This contrasts with tests at Nevada Test Site (NTS) where Collapse Cavity reaches Surface

Fig. 6.12 Comparison of predicted isotherms calculated with the 3D model at a distance of about 50 m above the volcanics-carbonates interface in Mururoa (solid lines) with isotherm contours, provided by DIRCEN/CEA in the karstic layer near the base of the carbonates (dashed lines)

[Perrochet and Tacher 1997 (a)]



Conclusions

Urgent to draw international attention to Earth Resource Engineering (ERE)

Need to attract young scientists and engineers to ERE

Need for interdisciplinary R&D to begin to address major problems

Advances in other fields could benefit ERE.

Need informed rational balance between environmental protection and providing essential services.

One Initiative.

CEFoR

Director –E . Detournay.

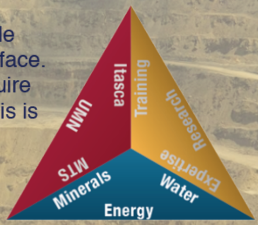
For details – see
www.cefor.umn.com

Also
Elements of Crustal Geomechanics
by
Francois Henri Cornet

Cambridge University Press
Available ' Late 2014'

CEFoR: Center for Engineered Fracturing of Rock

Future development of world society is critically tied to the effective and sustainable development of the water, energy and mineral resources within the Earth's subsurface. Responsible and efficient harvesting of these resources to meet this need will require dramatic improvement in techniques for the fracture and fragmentation of rock. This is a Grand Challenge of Engineering. It can be met, but will require fundamental developments in fracture processes and innovative imaging/control subsurface technologies that are environmentally sound, economically robust, and benefiting society. CEFoR is conceived to accomplish this goal.



CEFoR is an interdisciplinary partnership of academic and technological experts on fracture and fragmentation of rock in the subsurface. An industrial consortium, CEFoR has a dual objective of developing

- 21st century subsurface modification technologies, and
- an elite workforce with the skills to harvest the Earth's subsurface resources responsibly and efficiently.

CEFoR brings together the unique assets of scholarship, innovation and excellence in earth resource engineering that are hallmarks of research and development at the University of Minnesota, Itasca Consulting Group, and MTS Systems Corporation - all strategically located in the Minneapolis/St Paul metropolitan area, a Midwest hub of leading high-technology industries.

- The affiliated academic units from the College of Science and Engineering at the University of Minnesota are comprised of world leaders in research disciplines related to rock fragmentation, hydraulic fracturing, subsurface imaging, and computational mechanics.
- Itasca Consulting Group provides the Center with over 30 years of expertise in software development and multi-physics numerical modeling applied to subsurface engineering in complex environments.
- MTS Systems corporation, a world leader in the development and manufacturing of problem-specific testing equipment, provides the Center with critical capabilities toward bringing technical innovations and products to mining, energy and exploration industries.

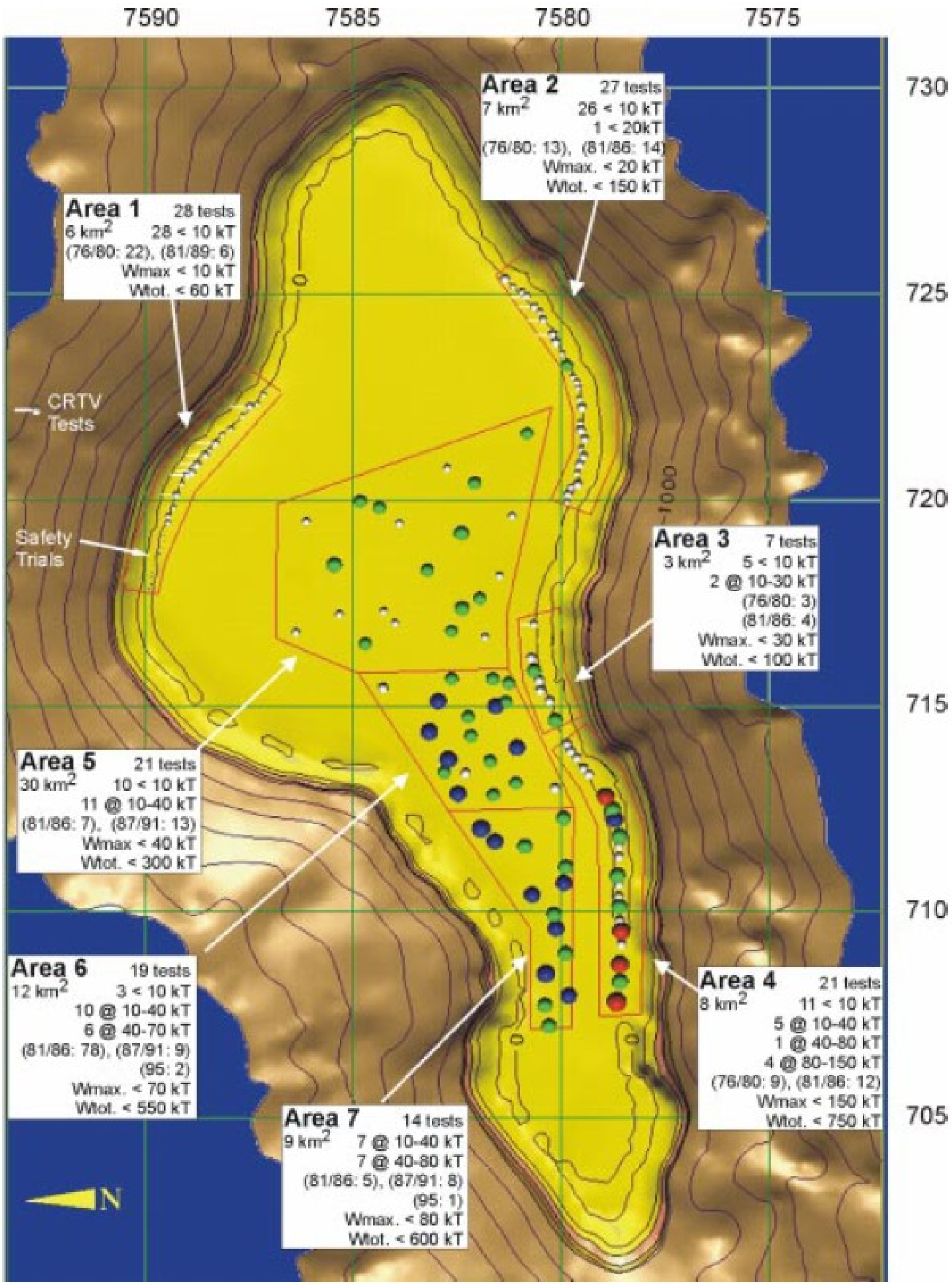
ITASCA Consulting Group, Inc. | College of Science & Engineering | MTS

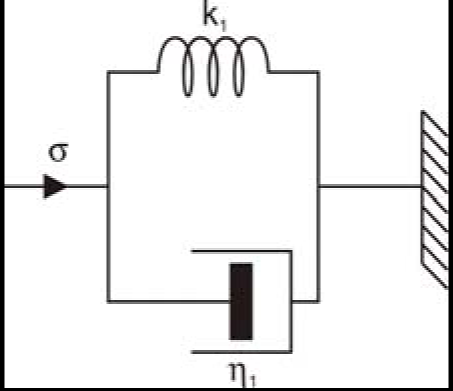
The multi-disciplinary activities within CEFoR are enriched by diverse research interactions fostered over decades of national and international collaboration. This extended network connects the Center to global expertise in key related areas including mathematics, physics, system control, earth science, environmental economics, and public policy.

For more information about the Center, visit www.cefor.umn.edu

UNIVERSITY OF MINNESOTA
Driven to Discover℠

Back –up Slides


7590
7585
7580
7575
730
725
720
715
710
705
Area 1 28 tests
6 km2 28 < 10 kT
(76/80: 22), (81/89: 6)
Wmax < 10 kT
Wtot. < 60 kT
Area 2 27 tests
7 km2 26 < 10 kT
1 < 20kT
(76/80: 13), (81/86: 14)
Wmax. < 20 kT
Wtot. < 150 kT
CRTV Tests
Safety Trials
1000
Area 3 7 tests
3 km2 5 < 10 kT
2 @ 10-30 kT
(76/80: 3)
(81/86: 4)
Wmax. < 30 kT
Wtot. < 100 kT
Area 5 21 tests
30 km2 10 < 10 kT
11 @ 10-40 kT
(81/86: 7), (87/91: 13)
Wmax < 40 kT
Wtot. < 300 kT
Area 6 19 tests
12 km2 3 < 10 kT
10 @ 10-40 kT
6 @ 40-70 kT
(81/86: 78), (87/91: 9)
(95: 2)
Wmax. < 70 kT
Wtot. < 550 kT
Area 4 21 tests
8 km2 11 < 10 kT
5 @ 10-40 kT
1 @ 40-80 kT
4 @ 80-150 kT
(76/80: 9), (81/86: 12)
Wmax < 150 kT
Wtot. < 750 kT
Area 7 14 tests
9 km2 7 @ 10-40 kT
7 @ 40-80 kT
(81/86: 5), (87/91: 8)
(95: 1)
Wmax. < 80 kT
Wtot. < 600 kT
N

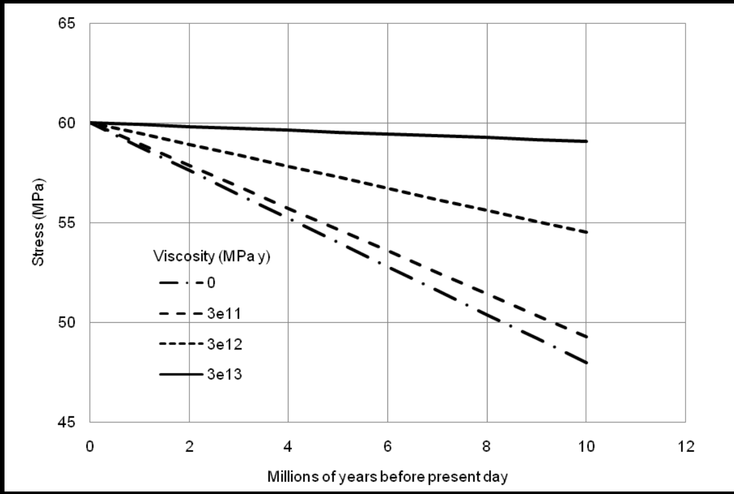


$\sigma = \eta_1 d\varepsilon/dt + k_1 \varepsilon$

or

$\sigma = d\varepsilon/dt\,(\eta_1 + k_1 t)$

Kelvin Rheological Model used by Gordon (2000)



For "stable interior plates", e.g. ***Canadian Shield*** *region of the North American plate, Gordon (2000) estimates the following values:*
Strain Rate $10^{-9.5}$ *to* 10^{-12} *per year*
Effective Viscosity 10^{25} *to* 10^{27} *Pa.s or* $3.(10^{11}$ *to* $10^{13})$ *MPa.yr*

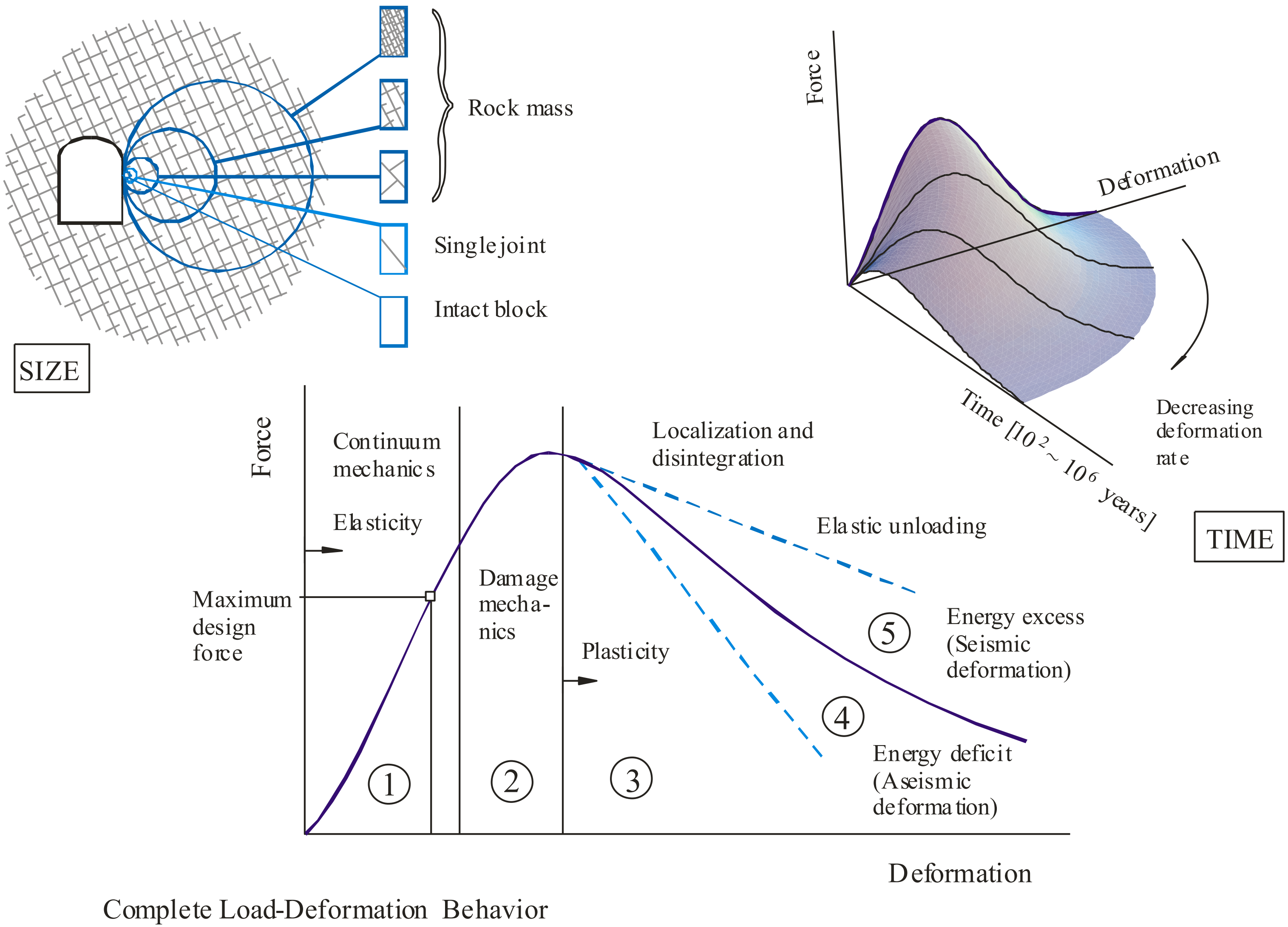
Lac du Bonnet batholith is ~ 2.6 billion years old uplifted to essentially its present position, ~ 2.1 billion years ago. [Near-surface thrust faulting formed ~ 2.3 billion years ago, while magma temperature was still elevated (Everitt and Brown,1992).]

Current westward movement of the North American Plate, including Lac du Bonnet batholith, started ~40 ~ 80 million years ago.

Rate of Stress Change
Canadian Shield
~1 MPa/10^6 years

Time-Dependent Deformation of Crystalline Rock over Geologic Time.

"We don't know the rock mass strength. That is why we need an International Society" Muller, 24 May 1962

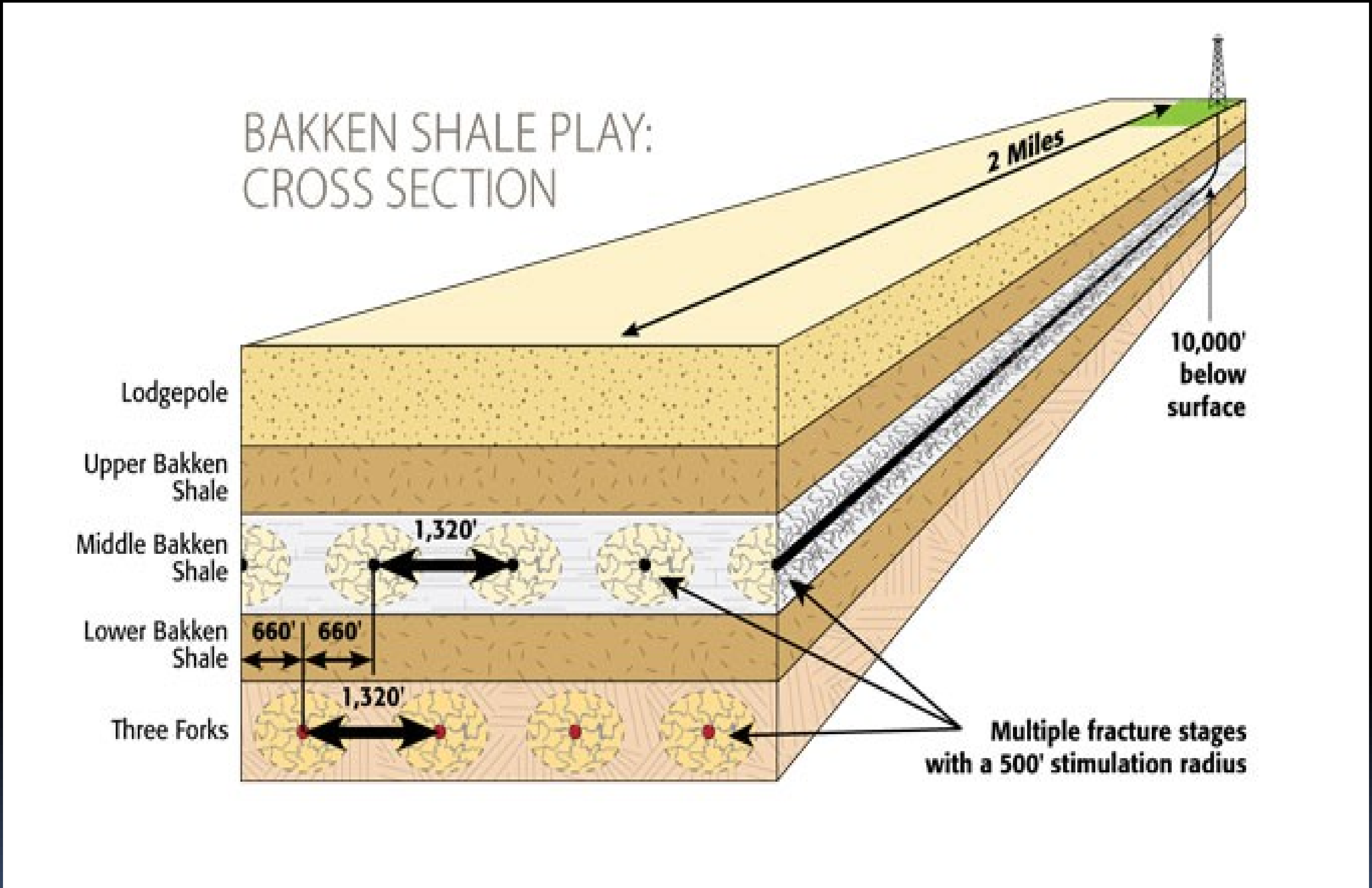


Babcock and Wilcox m-Power Modular Nuclear Reactor
- 180 MW

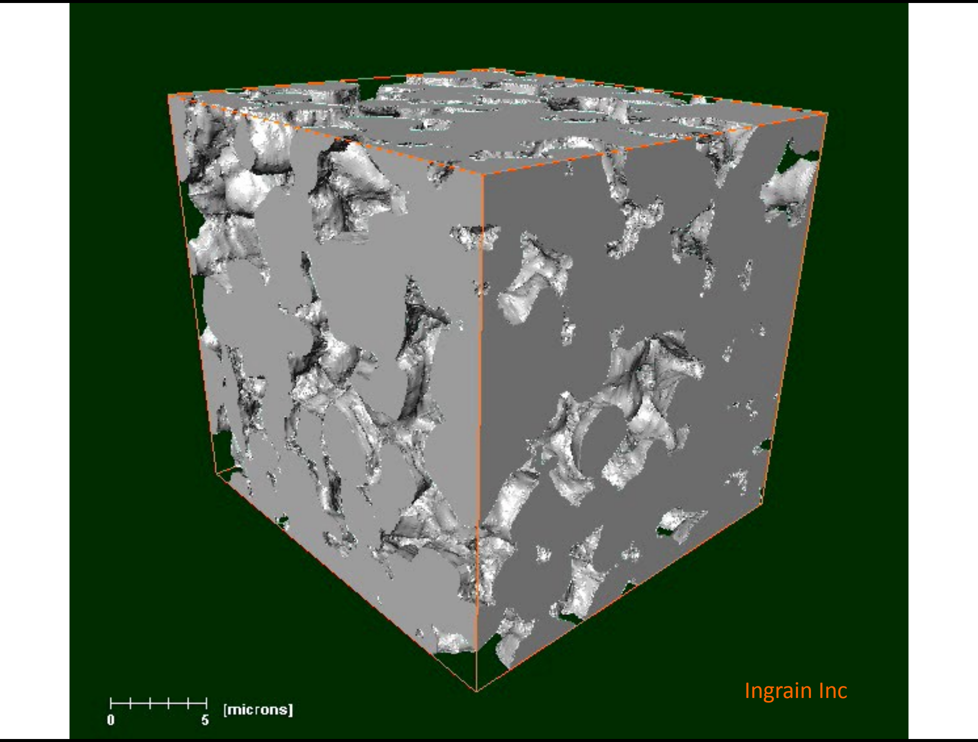
Height 10m. (33 ft); Diameter 4m (13ft).

- *In addition to being small enough to ship, the reactors are small enough to be installed underground, offering the advantage of earthquake protection;*
- *buried structures are less vulnerable than those above the surface. They may also be easier to defend from attack.*
- *the ability to air-cool the reactors further distinguishes them from big nuclear plants,*

For reference, -the world's largest power generating facility is the Three Gorges Dam in southern China. This hydropower facility has a capacity of 22,500 MW - equivalent to 125 of the 180 MW B&W modular reactors. Nuclear power plants operating today typically have a capacity in the range of 500 -1000 MW. This capacity could be achieved with 4 -8 of the 180 MW B&W modular reactors.



http://www.psgdover.com/en/oil-and-gas/oil-gas-market-overview/oil-gas-shale



Ingrain Inc
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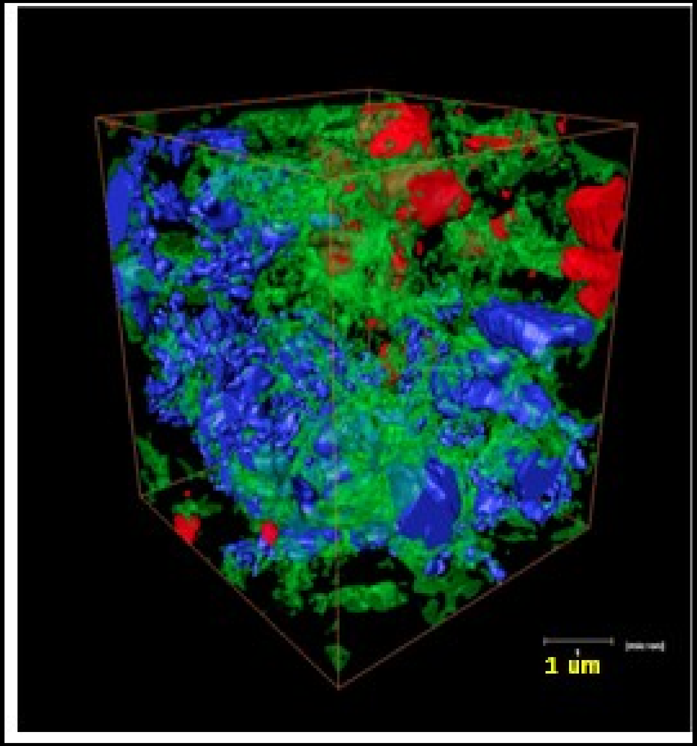
5
[microns]



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