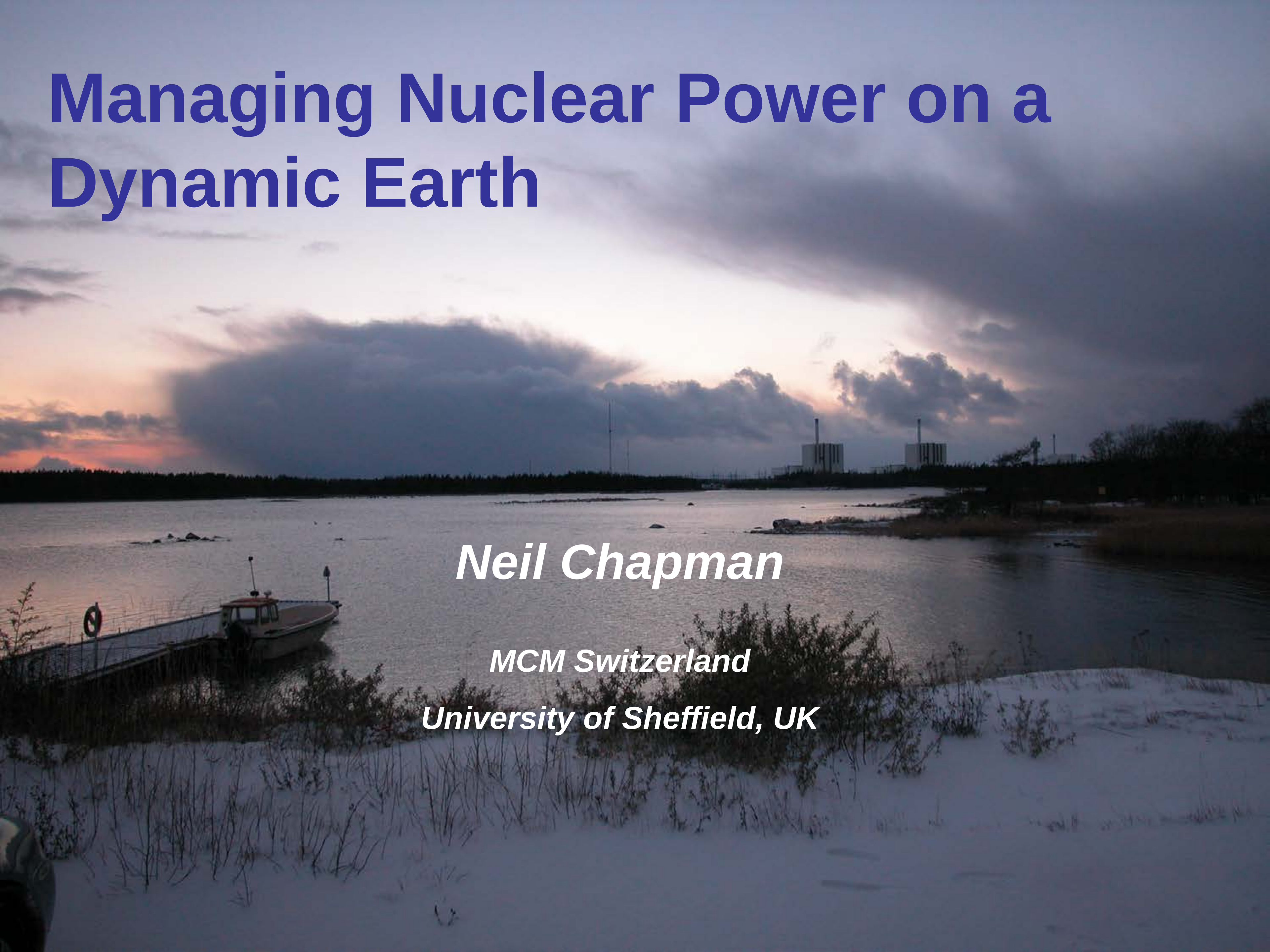
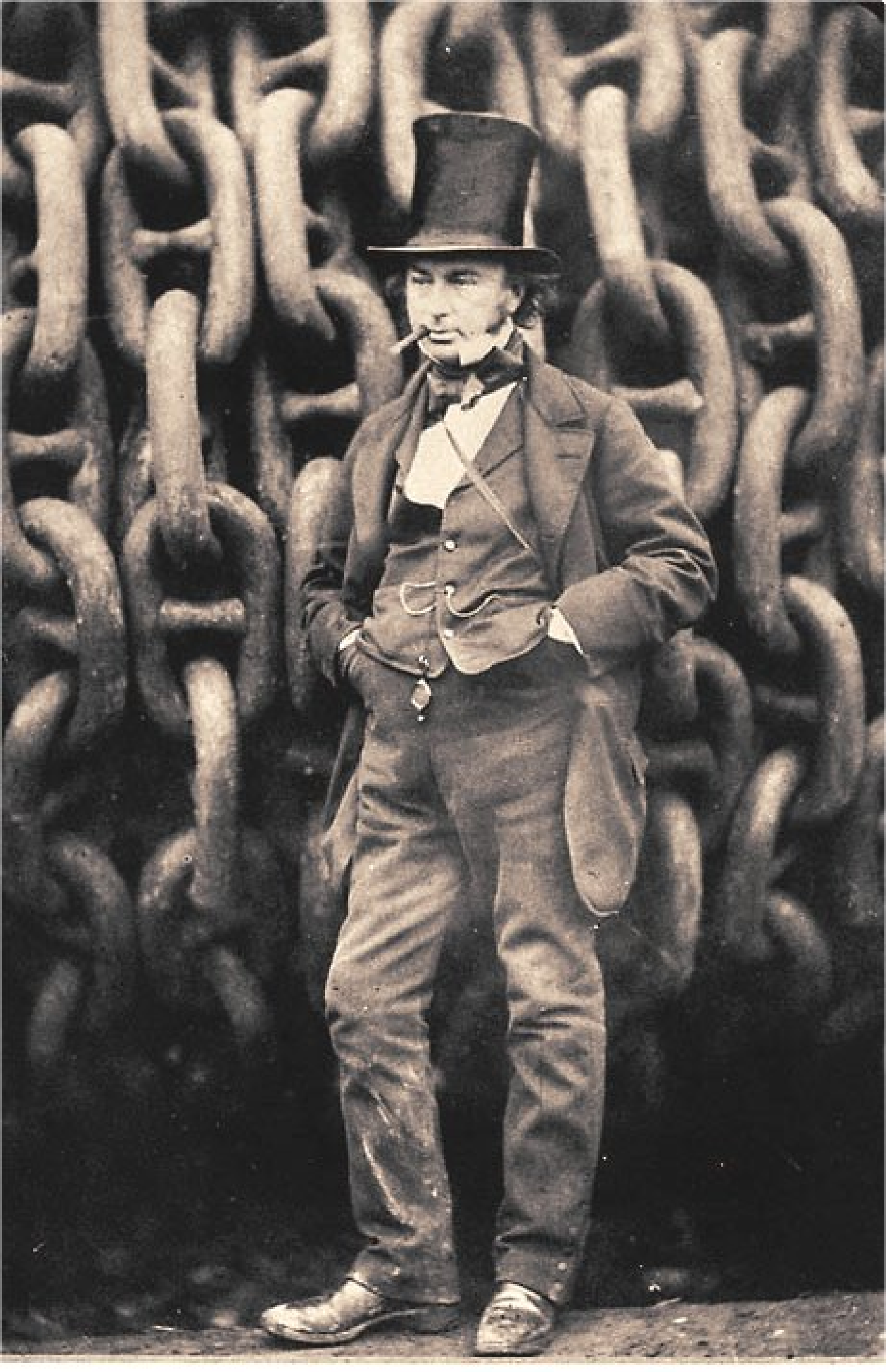


Managing Nuclear Power on a Dynamic Earth

Neil Chapman

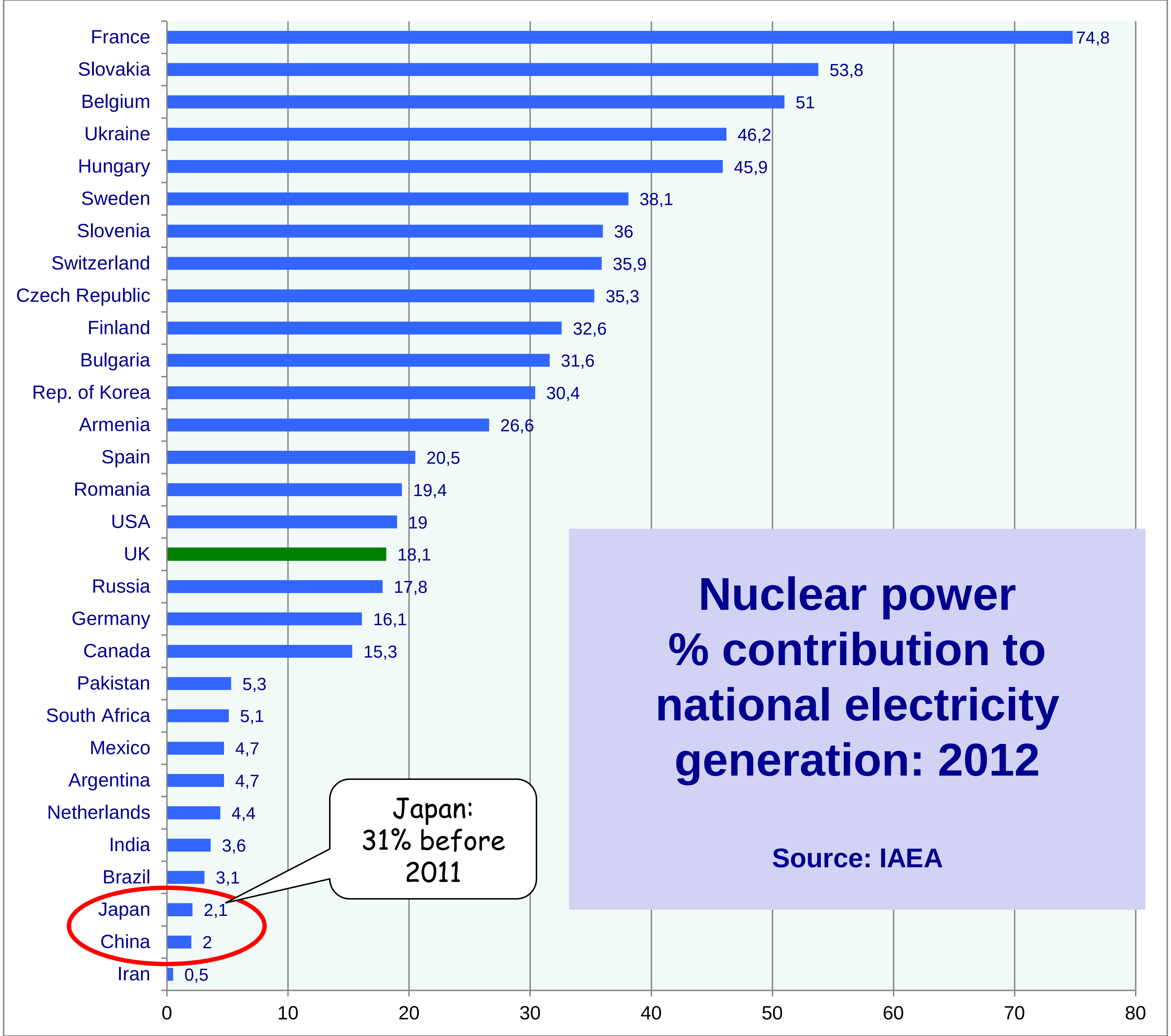
MCM Switzerland

University of Sheffield, UK



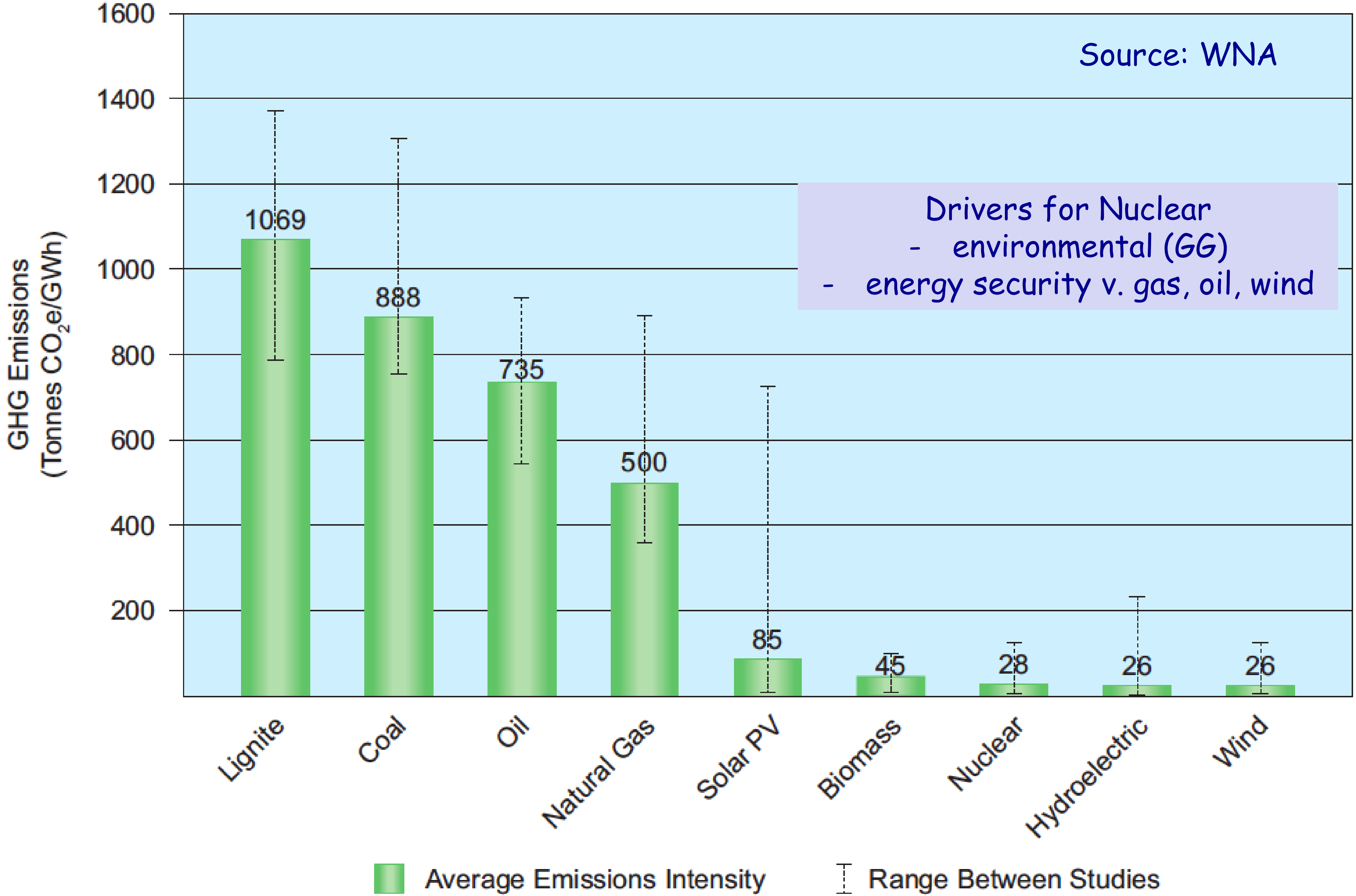
.....I must observe that no man can be more sensible than I am of the great advantage it would be to me as a civil engineer to be better acquainted with geology.....

I.K. Brunel, June 1842



Nuclear power
% contribution to
national electricity
generation: 2012
Source: IAEA
France 74,8
Slovakia 53,8
Belgium 51
Ukraine 46,2
Hungary 45,9
Sweden 38,1
Slovenia 36
Switzerland 35,9
Czech Republic 35,3
Finland 32,6
Bulgaria 31,6
Rep. of Korea 30,4
Armenia 26,6
Spain 20,5
Romania 19,4
USA 19
UK 18,1
Russia 17,8
Germany 16,1
Canada 15,3
Pakistan 5,3
South Africa 5,1
Mexico 4,7
Argentina 4,7
Netherlands 4,4
India 3,6
Brazil 3,1
Japan 2,1
China 2
Iran 0,5
Japan:
31% before
2011
0
10
20
30
40
50
60
70
80

Greenhouse gas emissions



Drivers for Nuclear
- environmental (GG)
- energy security v. gas, oil, wind

Do we understand the external, natural hazards?

Can we evaluate the risks to people?

Can we design safe and resilient systems?

Simulation of 14 m inundation

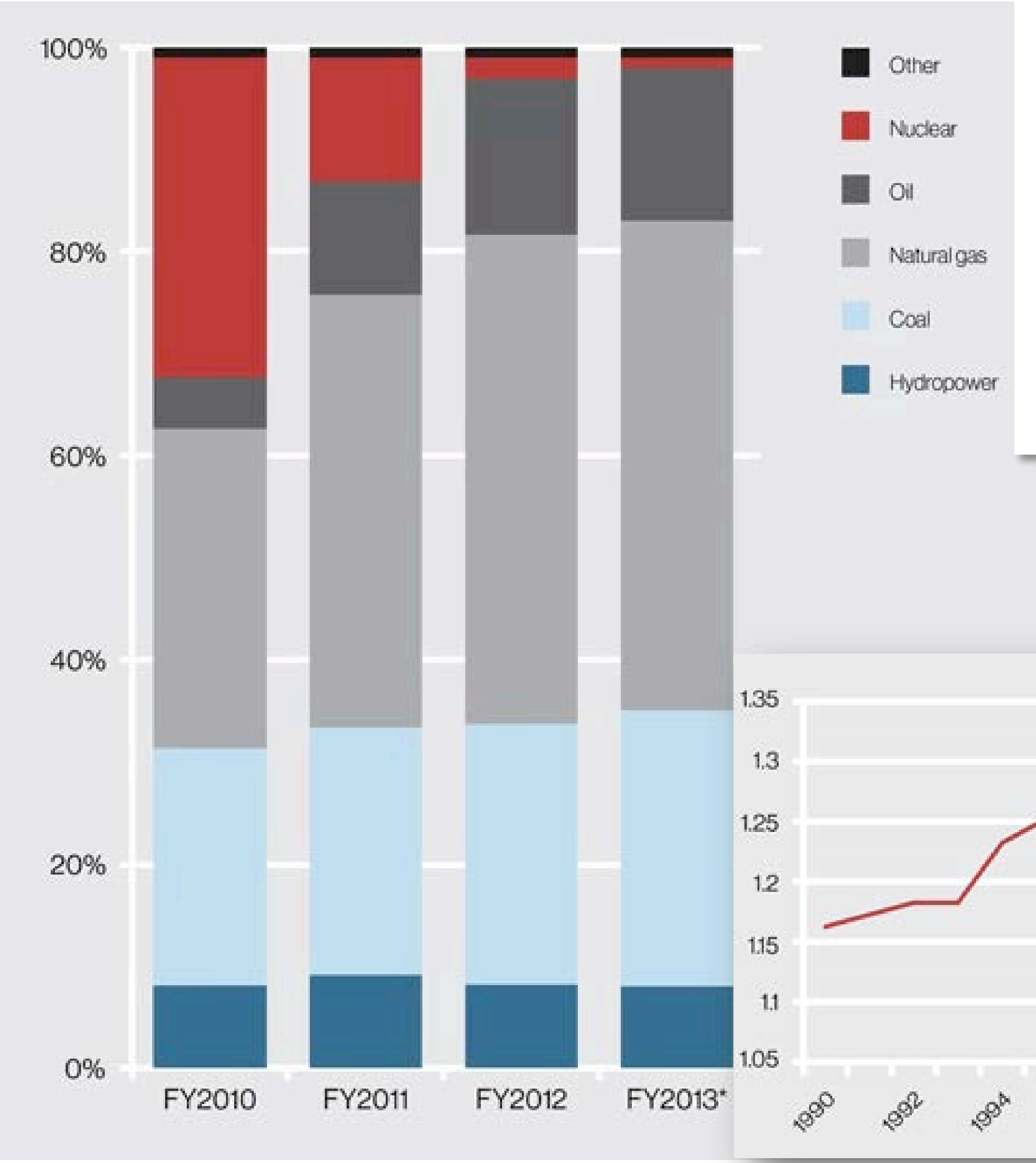
Lacassin, R and Lavelle, S; Earth Science Reviews, 2016

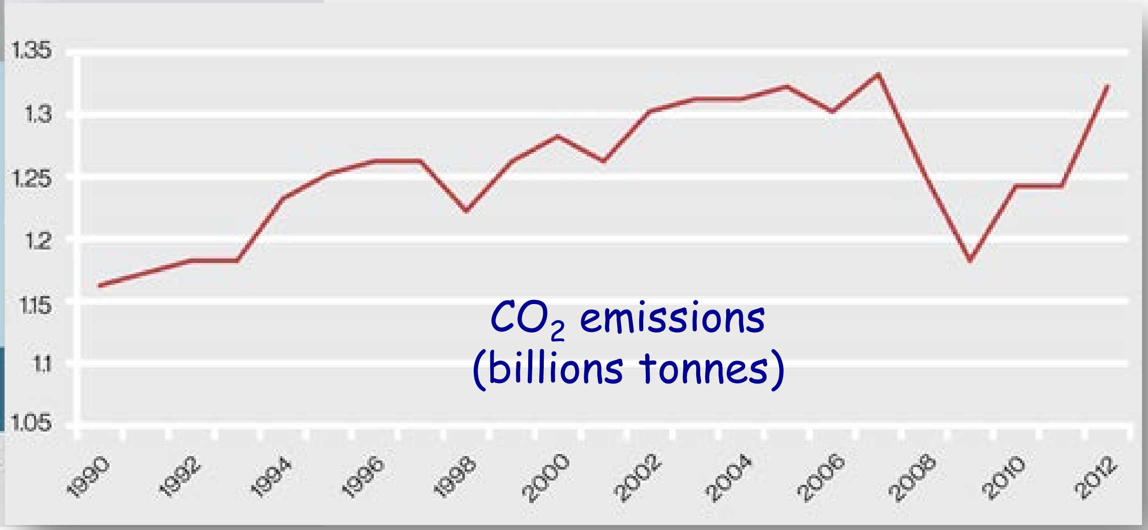
11 NPPs were operating in the region and shut down automatically when the earthquake struck, but….

Japan's electricity supply, post-Fukushima

- became 2nd largest fossil fuel importer
- 30 billion $ increase in annual costs
- 1 billion $ to restart each reactor

Source: MIT Technology Review



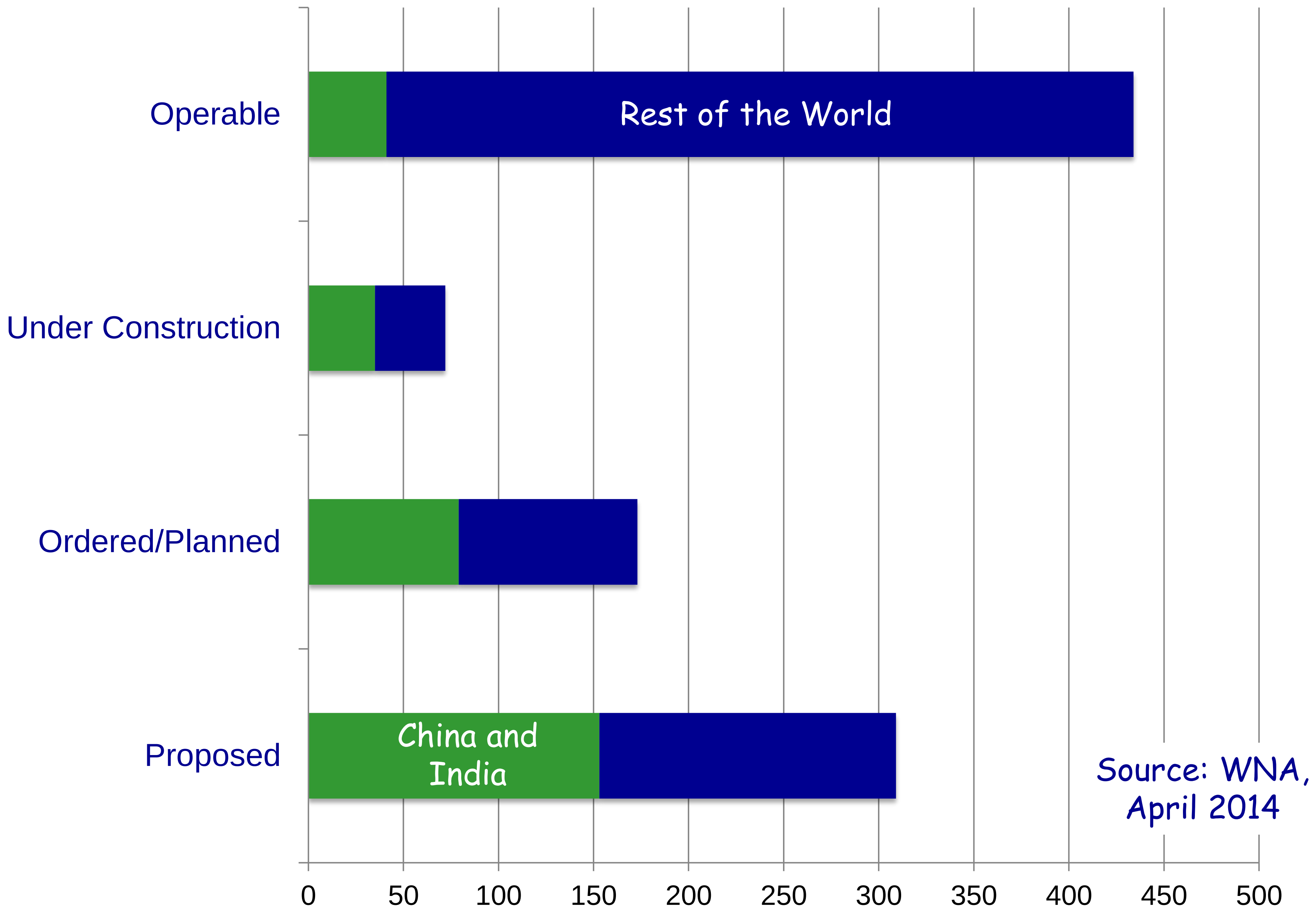


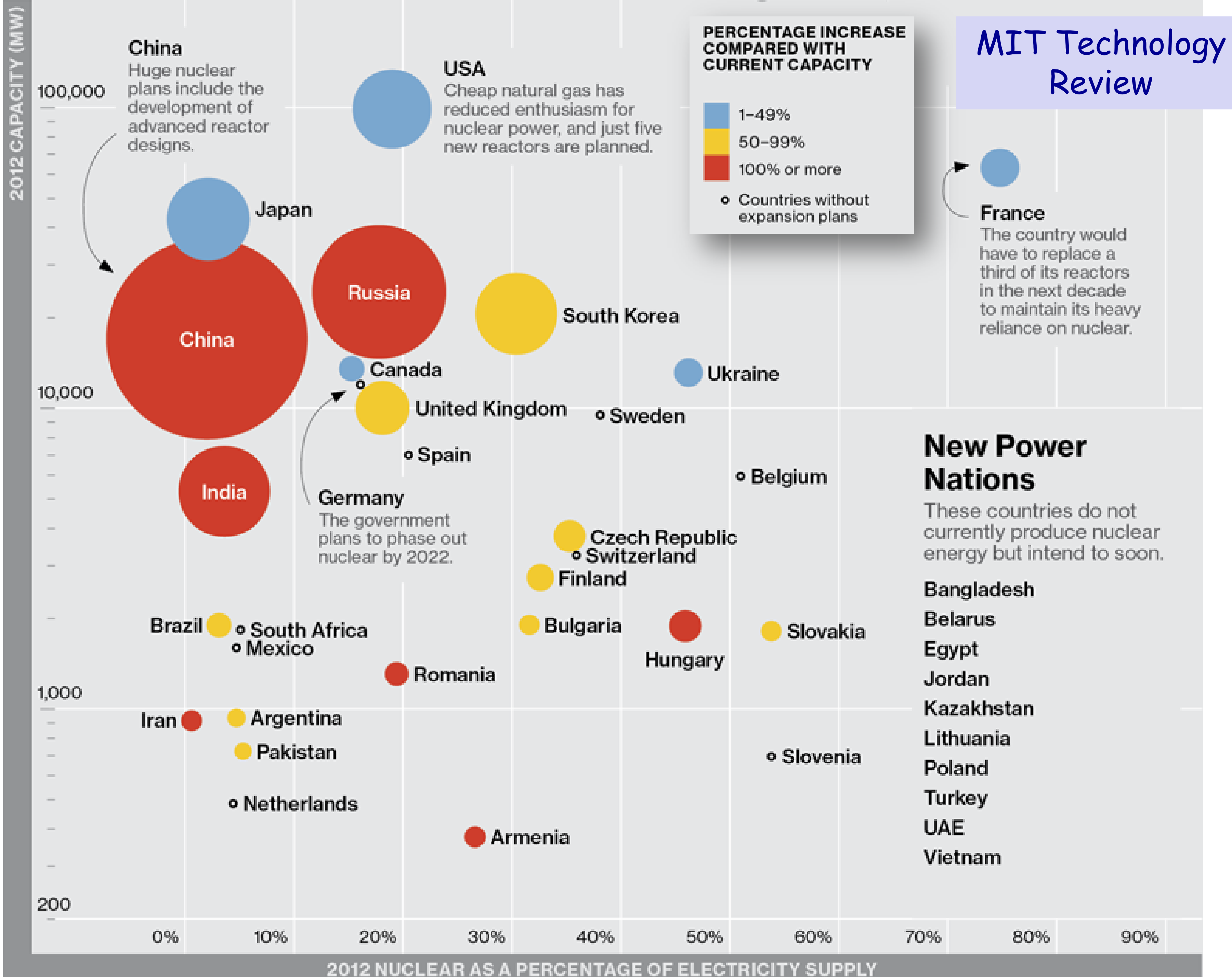
Nuclear Power

How much do we use it and where…..?

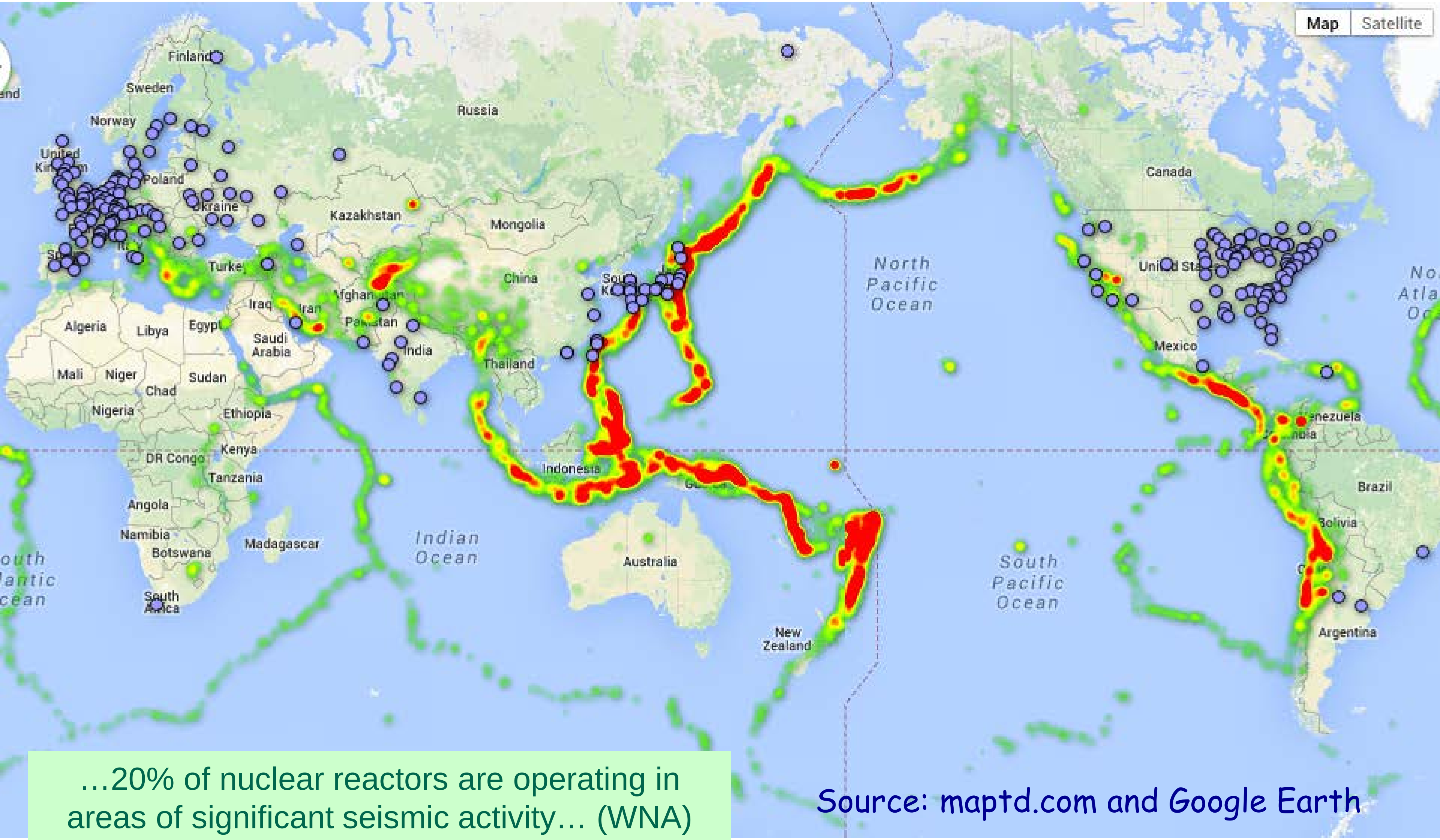
nuclear power plants
nuclear reprocessing plants
nuclear waste stores
nuclear waste disposal facilities

Nuclear Power Plants Worldwide by 2030




MIT Technology Review
PERCENTAGE INCREASE COMPARED WITH CURRENT CAPACITY
1–49%
50–99%
100% or more
Countries without expansion plans
2012 CAPACITY (MW)
100,000
10,000
1,000
200
2012 NUCLEAR AS A PERCENTAGE OF ELECTRICITY SUPPLY
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
China
Huge nuclear plans include the development of advanced reactor designs.
USA
Cheap natural gas has reduced enthusiasm for nuclear power, and just five new reactors are planned.
France
The country would have to replace a third of its reactors in the next decade to maintain its heavy reliance on nuclear.
Germany
The government plans to phase out nuclear by 2022.
Japan
Russia
China
South Korea
Canada
Ukraine
United Kingdom
Sweden
Spain
India
Belgium
Czech Republic
Switzerland
Finland
Brazil
South Africa
Mexico
Bulgaria
Hungary
Slovakia
Romania
Iran
Argentina
Pakistan
Slovenia
Netherlands
Armenia
New Power Nations
These countries do not currently produce nuclear energy but intend to soon.
Bangladesh
Belarus
Egypt
Jordan
Kazakhstan
Lithuania
Poland
Turkey
UAE
Vietnam

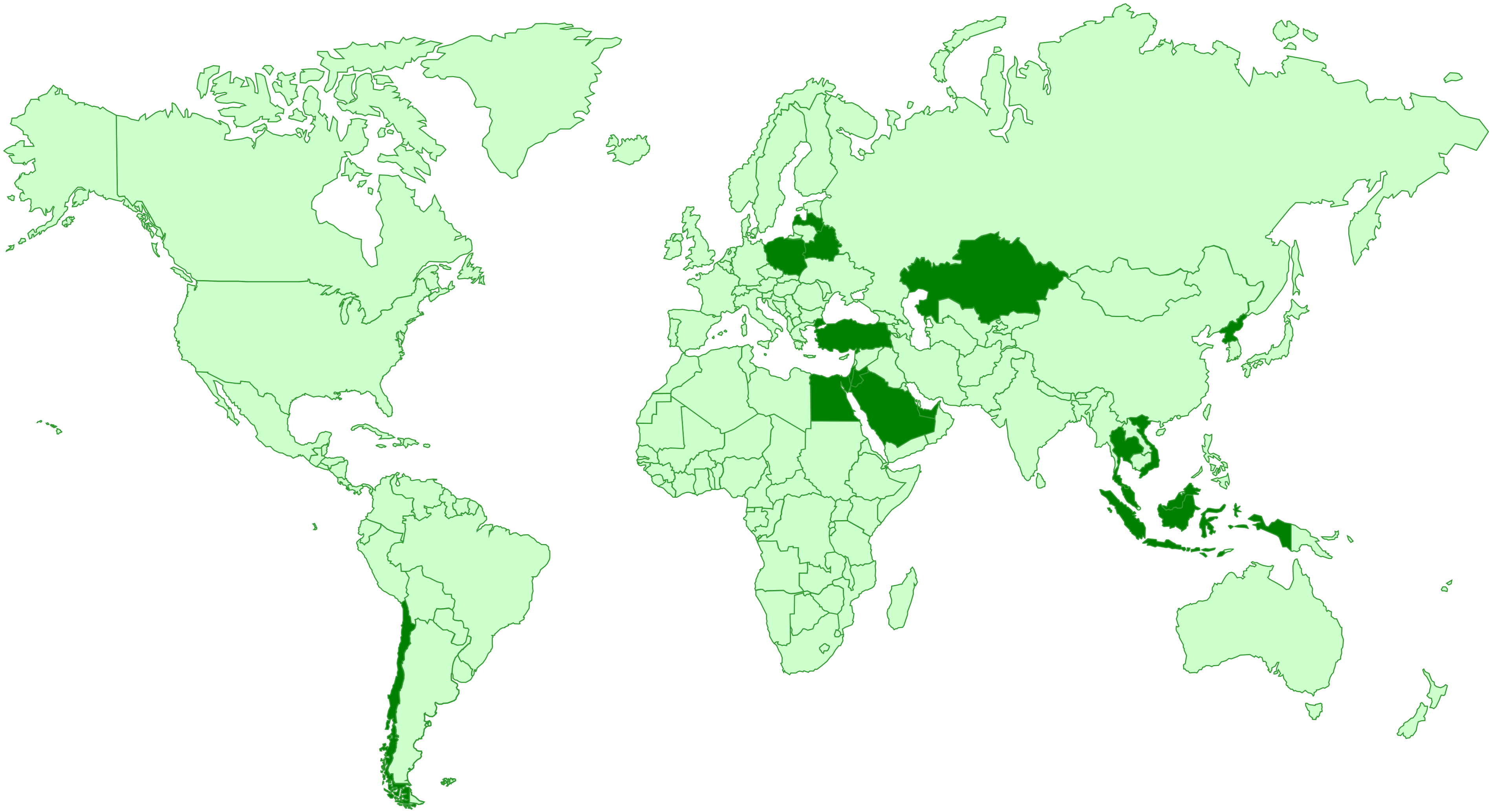
Nuclear Power Plants



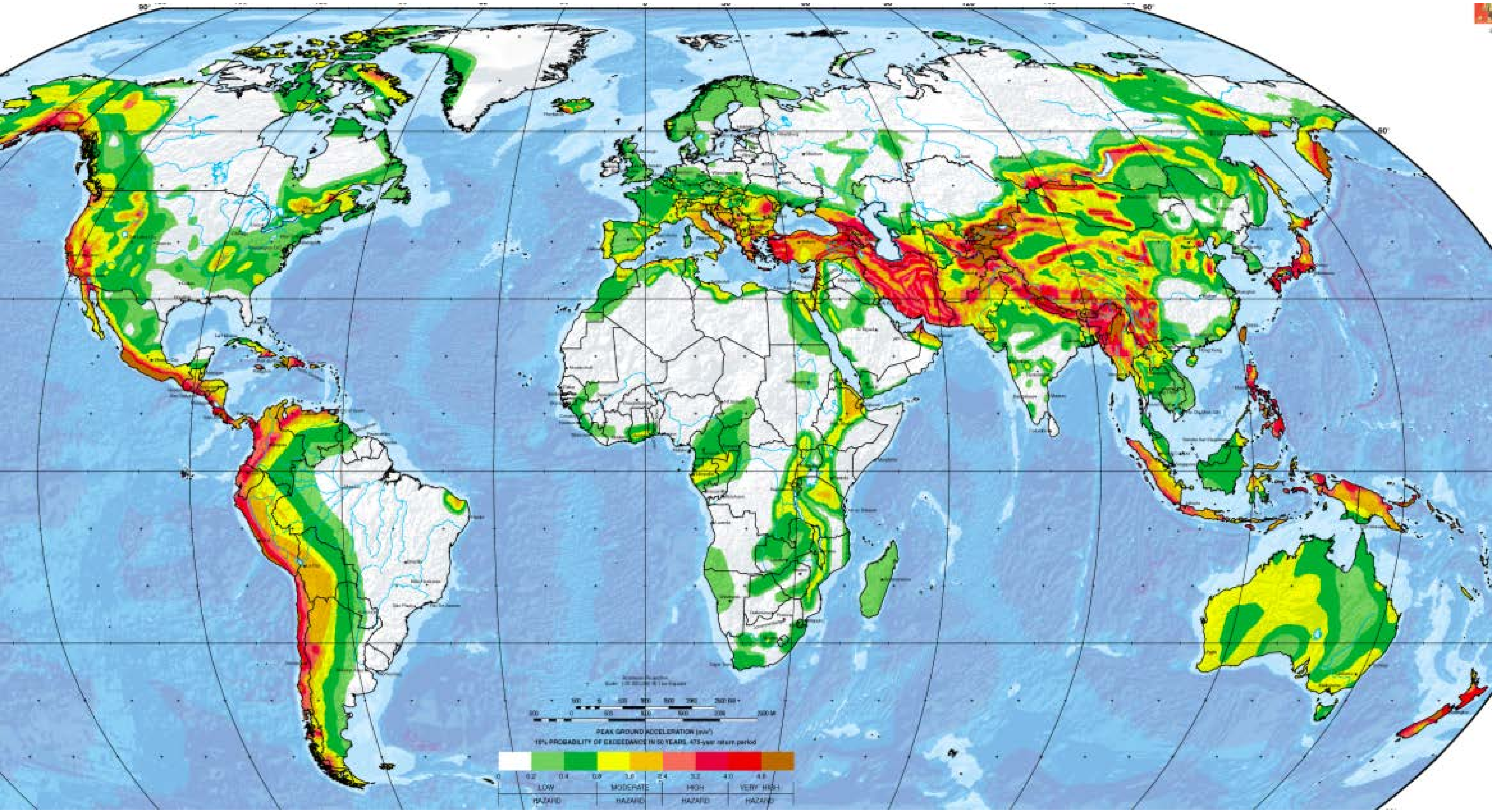
…20% of nuclear reactors are operating in areas of significant seismic activity… (WNA)

Source: maptd.com and Google Earth

Countries with no operable NPPs today, that are building, planning or proposing them in the next c.15 years



Global Seismic Hazard



Source: Global Seismic Hazard Assessment Programme (GSHAP)

Geological Hazards to Nuclear Facilities …….and Timescales

……..setting aside flooding, landslides, subsidence, etc

- seismic
- volcanic
- tsunami

- NPPs, nuclear fuel cycle facilities are operational for:
  - around 100 years
- geological disposal facilities for radioactive wastes:
  - also operational for around 100 years
  - but safety is evaluated for thousands of years…. to 1 million years

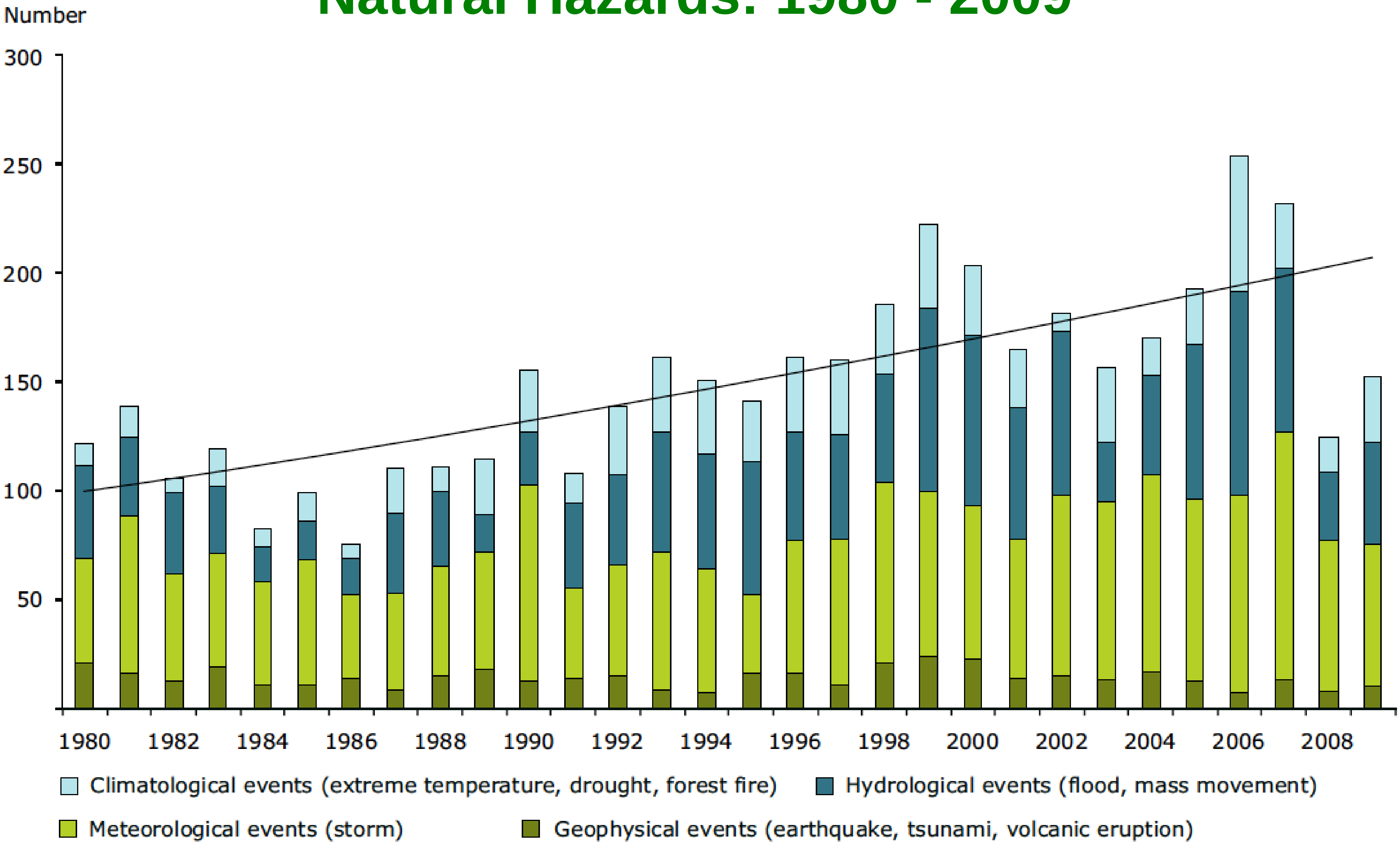
Hazards and Risks

- Hazards
  - earthquakes
  - volcanic eruptions
- Hazard potential
  - e.g. a feature, such as an active fault near a facility, has a specific hazard potential
- Risk
  - the probability that a hazardous event will happen, multiplied by its human consequences

Design for UK nuclear facilities is based on natural events with a probability of occurrence of more than 1 in 10,000 years (10^{-4}/year)

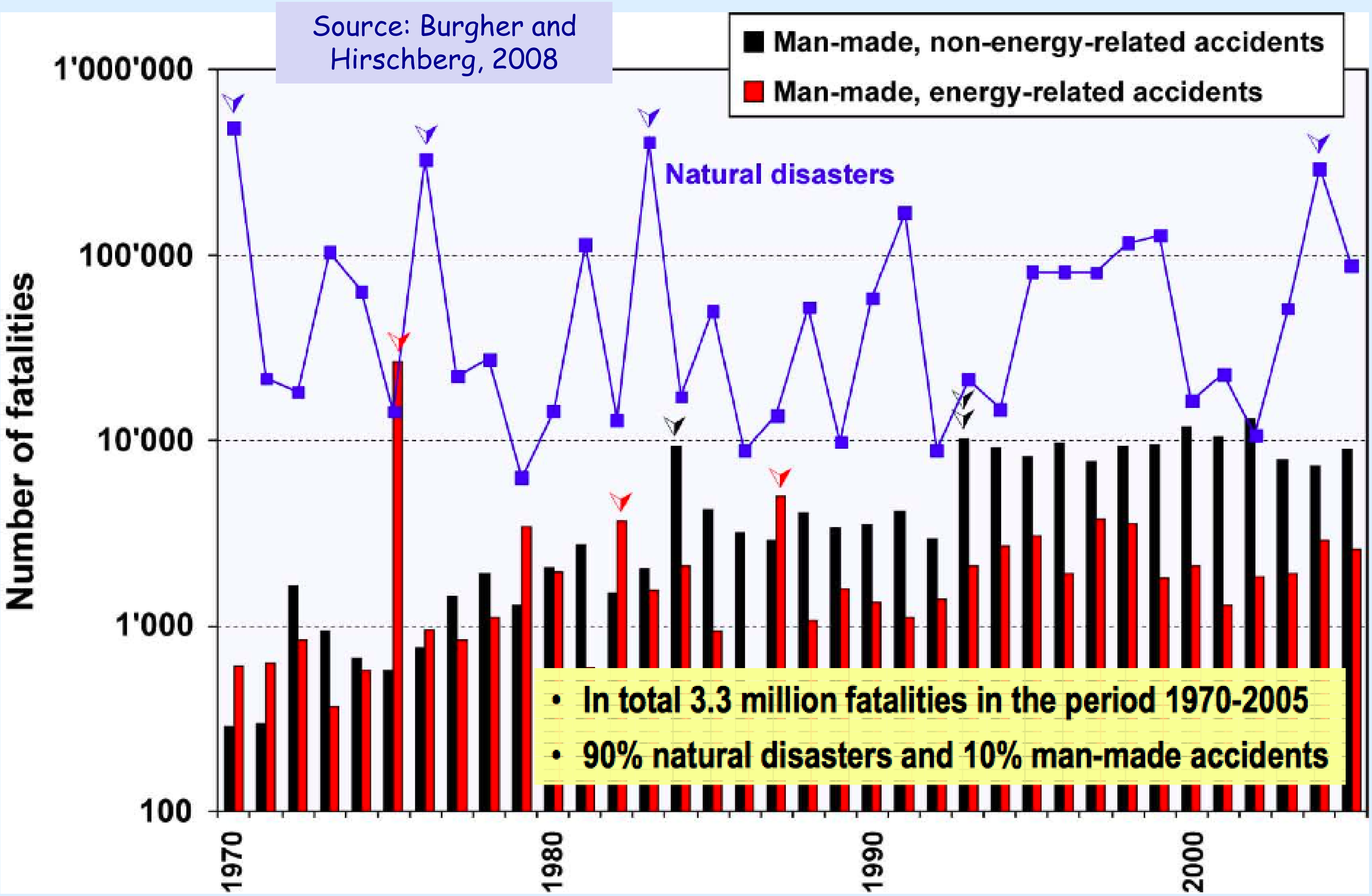
probability that you will be struck by lightning : 10^{-7} / year

Disasters in European Economic Area due to Natural Hazards: 1980 - 2009



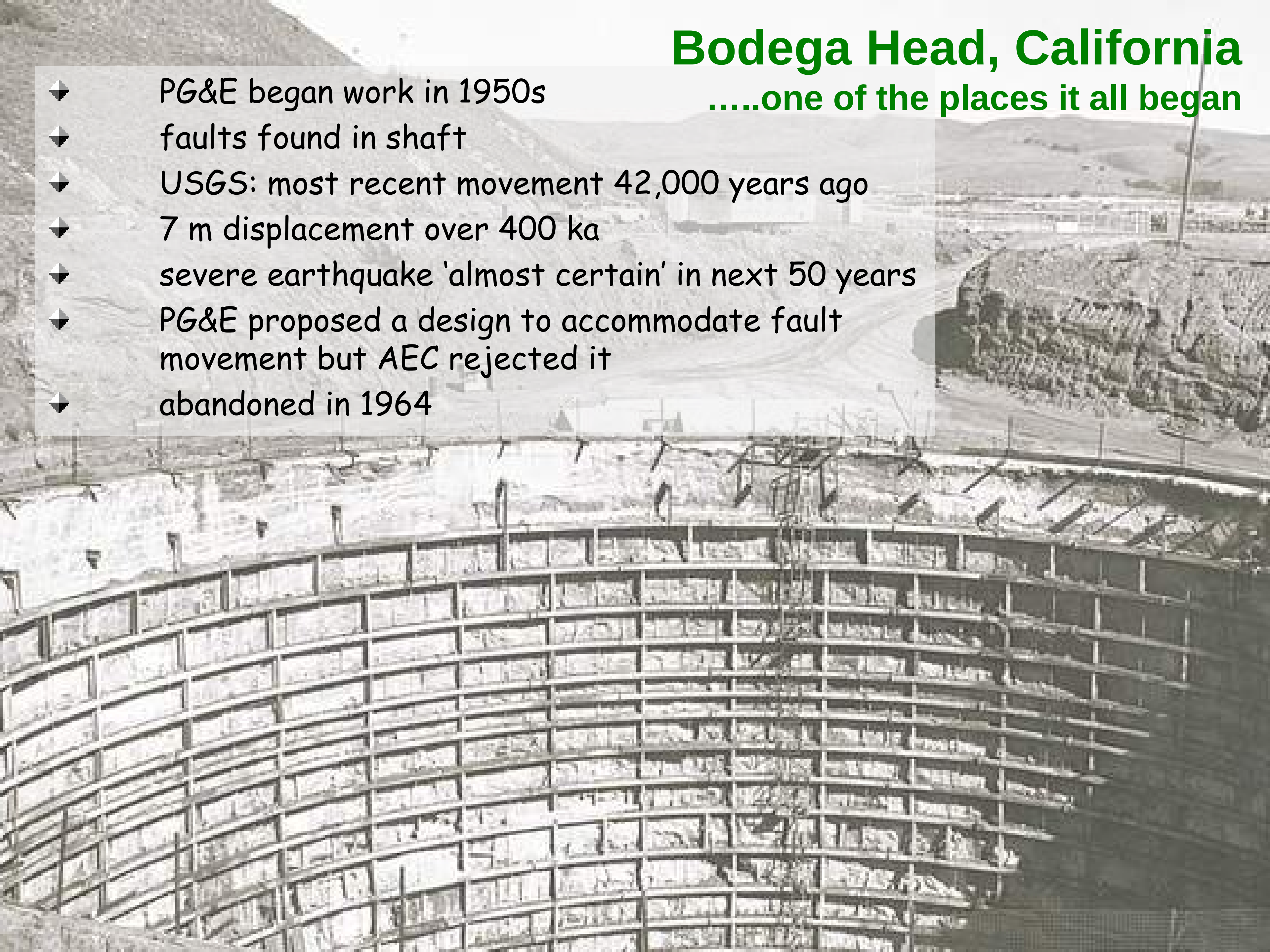
Source: European Environment Agency, 2010

Fatalities from severe accidents and natural disasters worldwide, 1970 - 2005

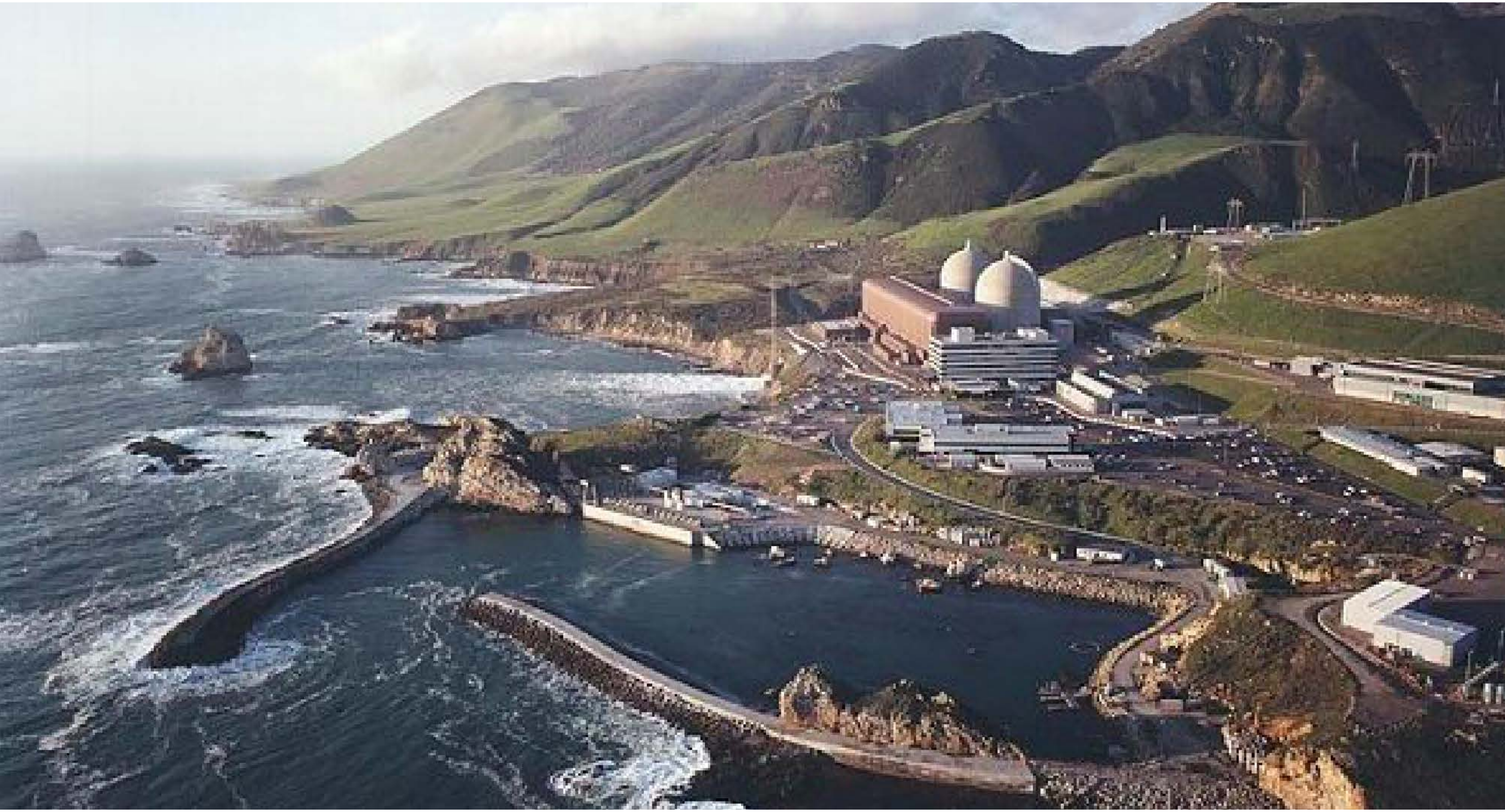


Fukushima health impacts: United Nations UNSCEAR report, 2014

- ….doses to the general public…… during the first year and estimated for their lifetimes, are generally low or very low.
- No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants.
- ……most important health effect is on mental and social well-being, related to enormous impact of earthquake, tsunami and nuclear accident, and fear and stigma related to perceived risk of exposure to ionizing radiation
- Increased ..detection of thyroid …cancers …observed during first round of screening… are to be expected in view of high detection efficiency [modern high-efficiency ultrasonography]
- …similar screening protocols in areas not affected by the accident imply that the apparent increased rates of detection among children in Fukushima Prefecture are unrelated to radiation exposure


Bodega Head, California
…..one of the places it all began
PG&E began work in 1950s
faults found in shaft
USGS: most recent movement 42,000 years ago
7 m displacement over 400 ka
severe earthquake 'almost certain' in next 50 years
PG&E proposed a design to accommodate fault movement but AEC rejected it
abandoned in 1964

Diablo Canyon NPP; California

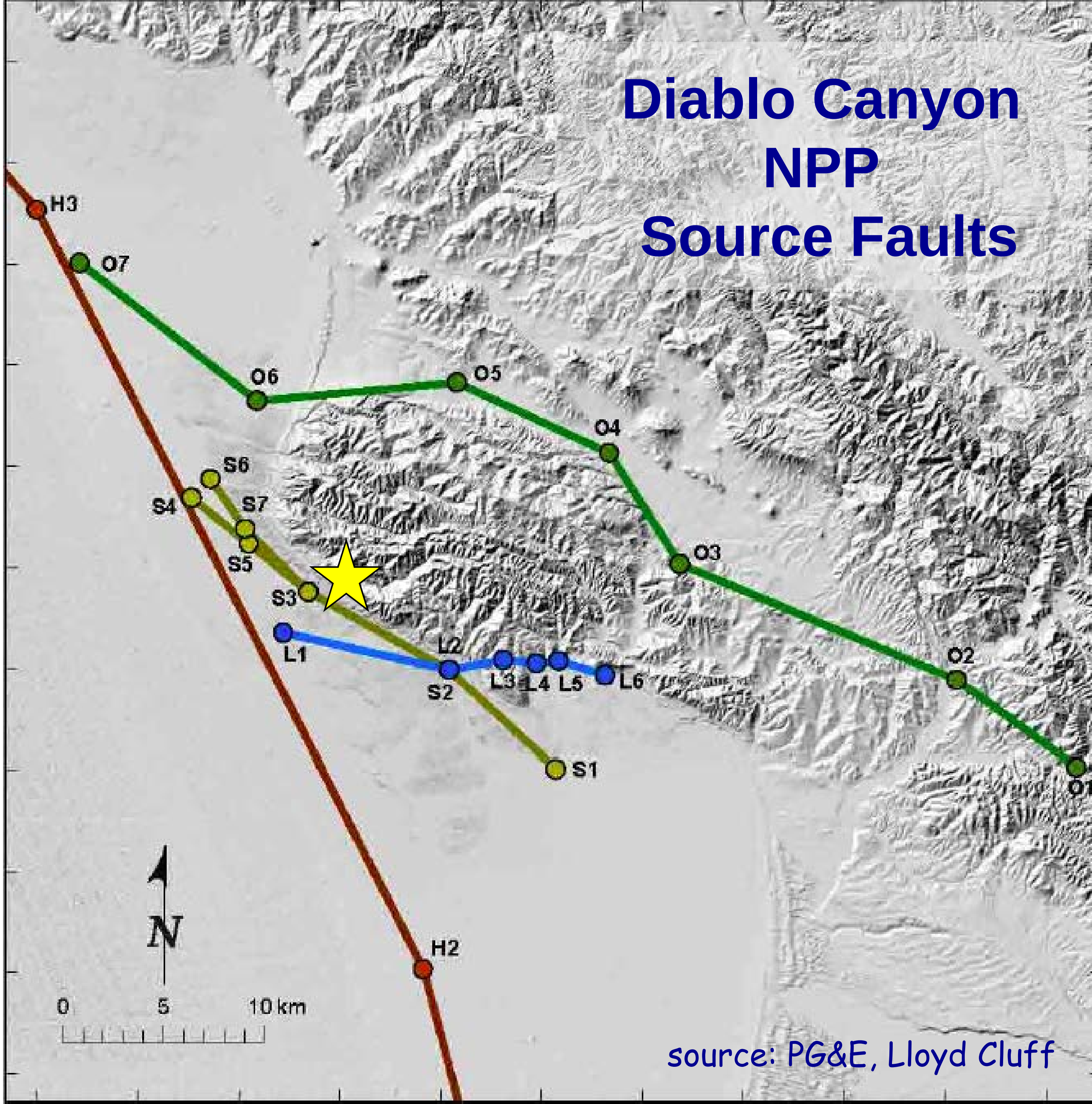


The Diablo Canyon NPP, California, USA, looking north along the coast. The Hosgri fault zone lies about 5 km offshore

Diablo Canyon

- PG&E began work in 1969
- seismic hazard became a major issue
- start-up delayed until 1984
- initiated major programme of interaction between regulators (NRC) and the operators
- Long Term Seismic Hazard programme
- foundation for modern seismic hazard analysis
- including probabilistic seismic hazard analysis (PSHA), now a foundation of regulations in several countries

Diablo Canyon NPP Source Faults

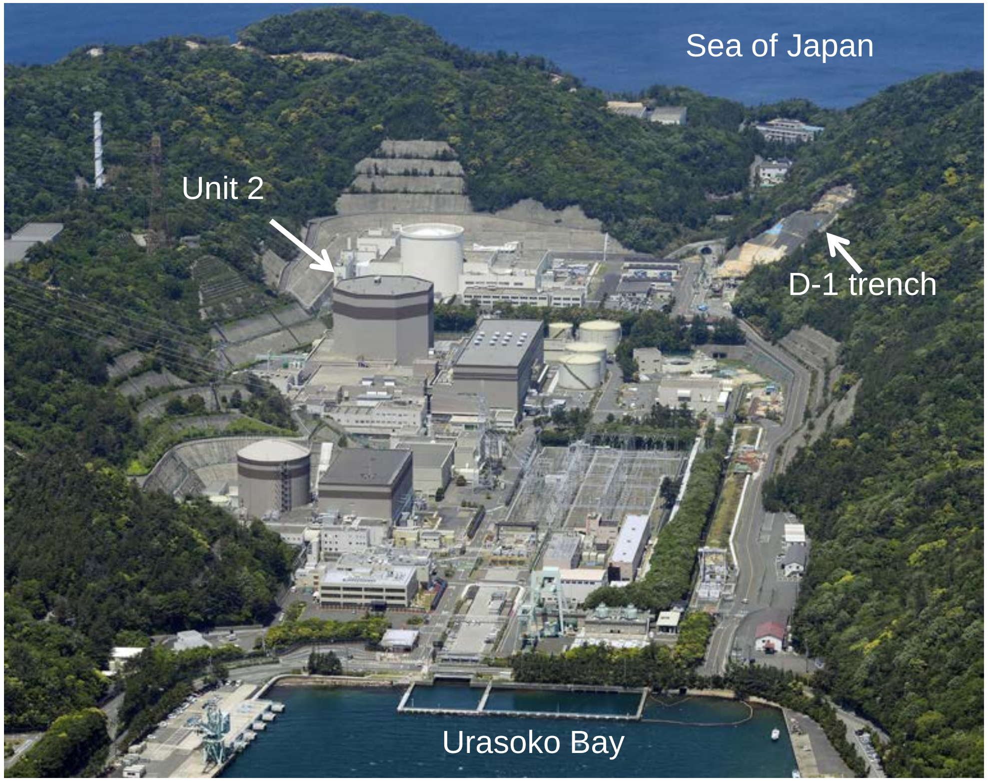


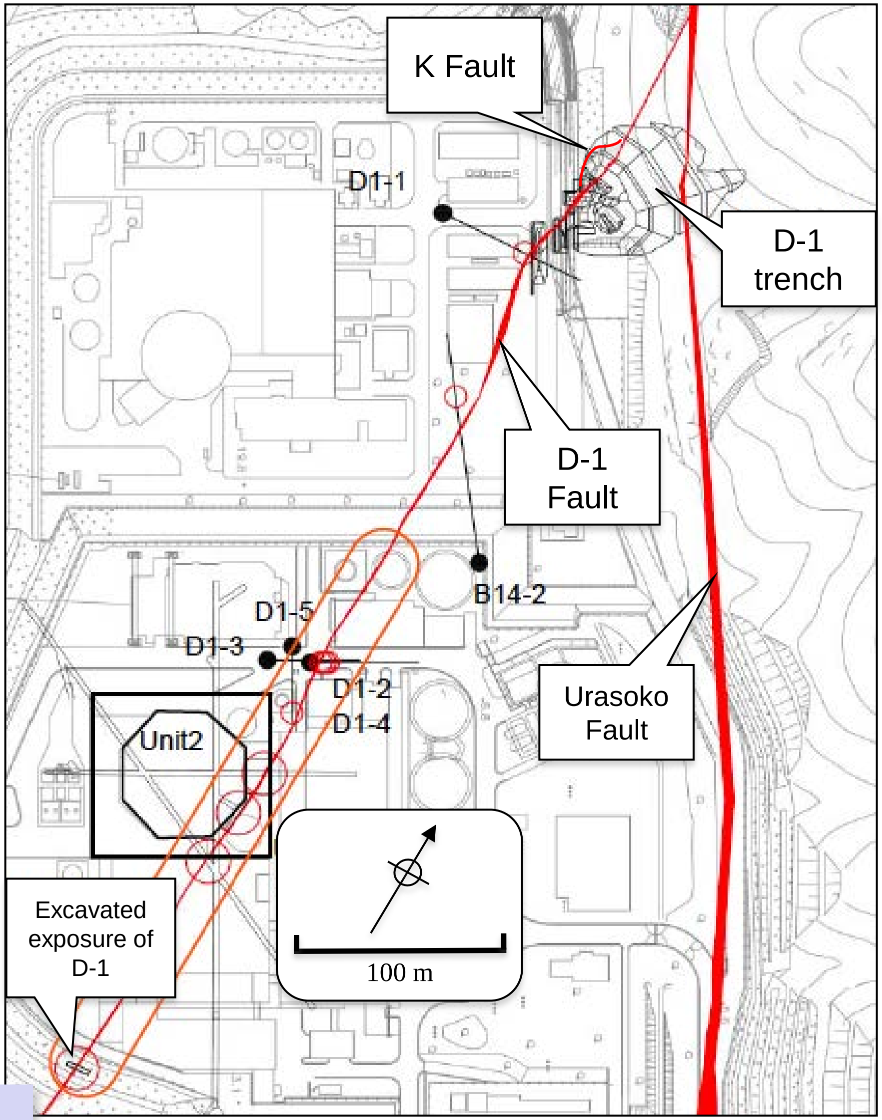
source: PG&E, Lloyd Cluff

The process that developed at Diablo Canyon

- Evaluate the performance of critical facilities during earthquakes
- Understand hazards and risks
- Characterise sources of seismic hazard
  - Magnitudes
  - Fault geometry and style-of-faulting
  - Earthquake Source - rates of activity (slip-rates, mm/year)
  - Distance to the NPP
- Characterise the Ground Motion
  - Median and standard deviation for a given earthquake
  - Site effects
- Hazard Calculation
  - Probabilistic and deterministic

Tsuruga NPP, Japan





Tsuruga NPP, Japan

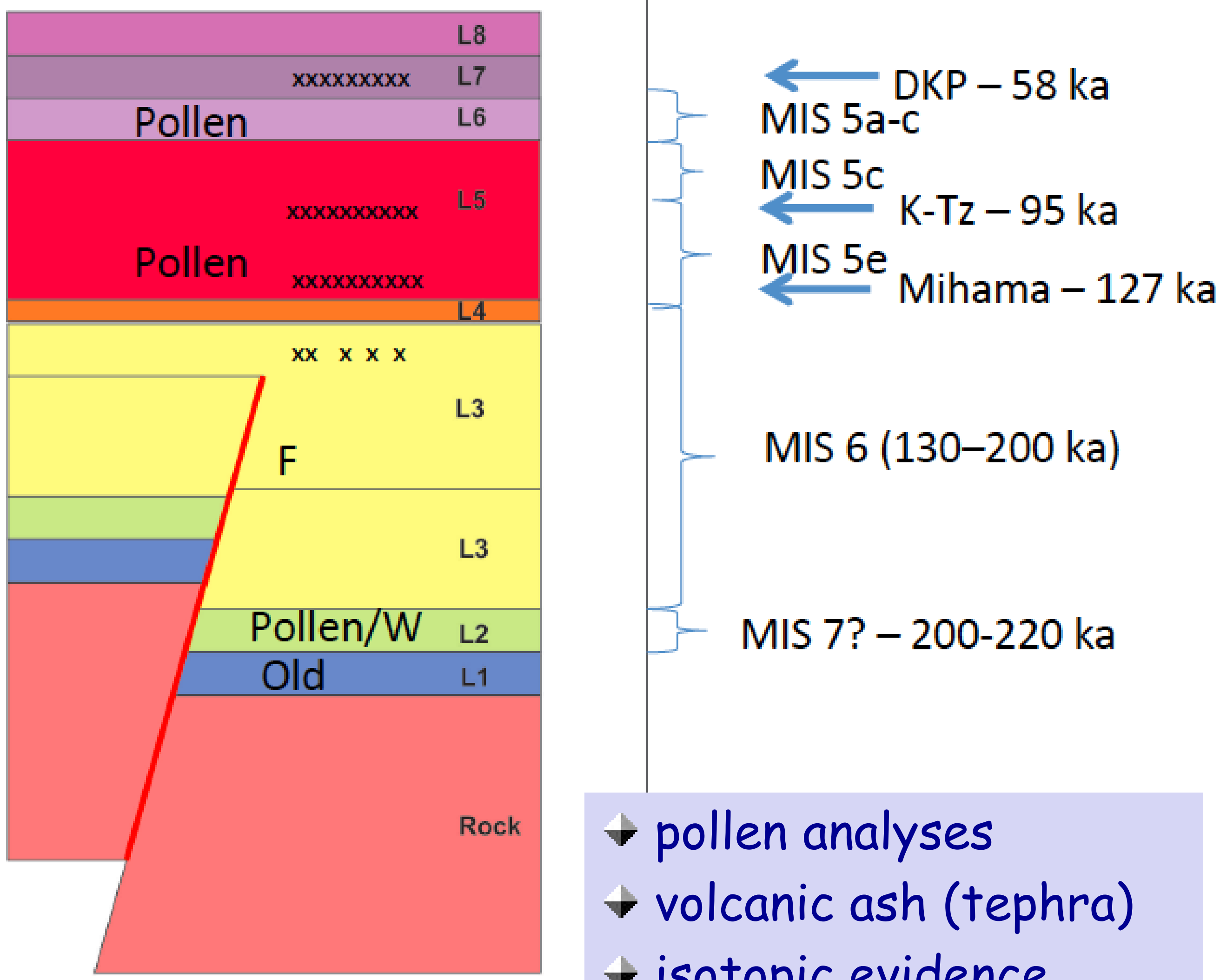
- what is an 'Active Fault'?
- NRA: movement in last 120,000 years

Trench at Tsuruga NPP, Japan

Photo 1

Palaeoseismology: dating fault movements using overlying Quaternary sediments

LAST OBSERVED MOVEMENT IS AFTER DEPOSITION OF MOST OF LAYER 3 AND BEFORE DEPOSITION OF LAYER 5



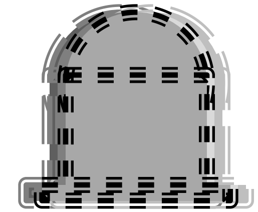
- pollen analyses
- volcanic ash (tephra)
- isotopic evidence

Source: K. Berryman, GNS and JAPC

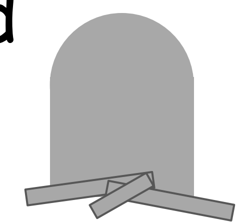
Source: Koji Okumura

What tools have we got?

- Probabilistic Seismic Hazard Analysis
  - looks at likelihood of ground motion (shaking) of various magnitudes and sets design basis for tolerable ground acceleration of NPP (e.g. foundation)



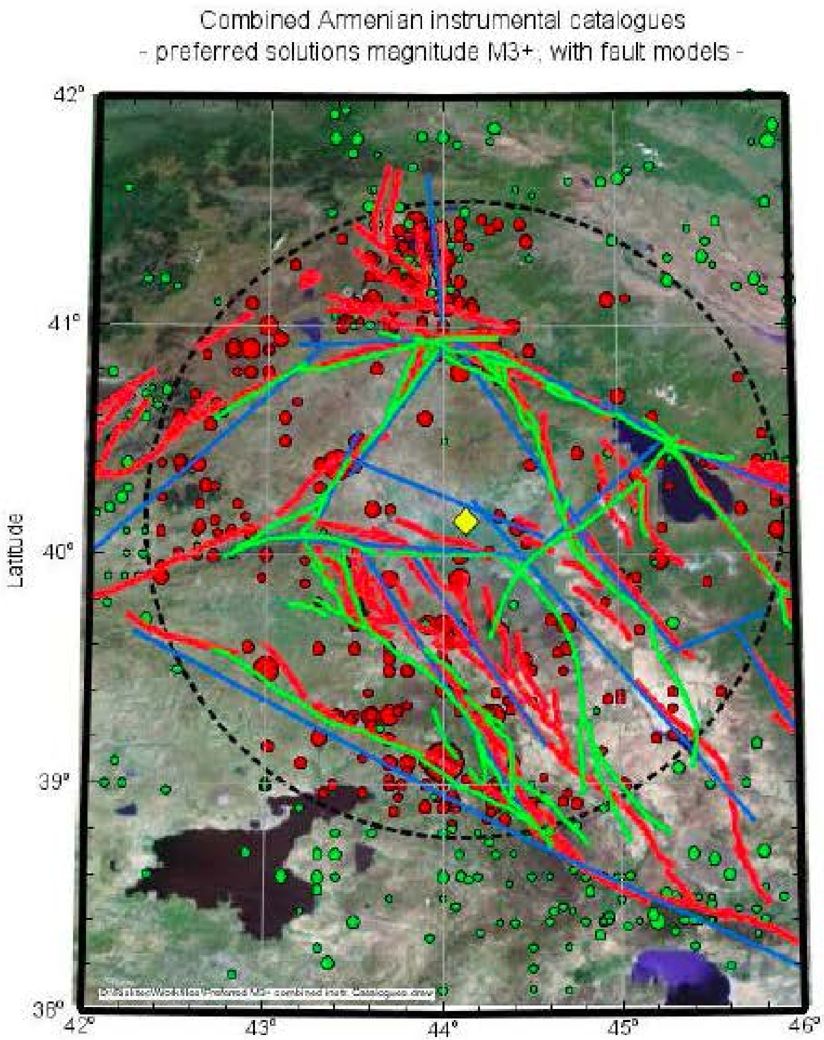
- Probabilistic Fault Displacement Hazard Analysis
  - looks at likelihood of a nearby earthquake and probability that it will cause sympathetic movement on fractures beneath and around NPP

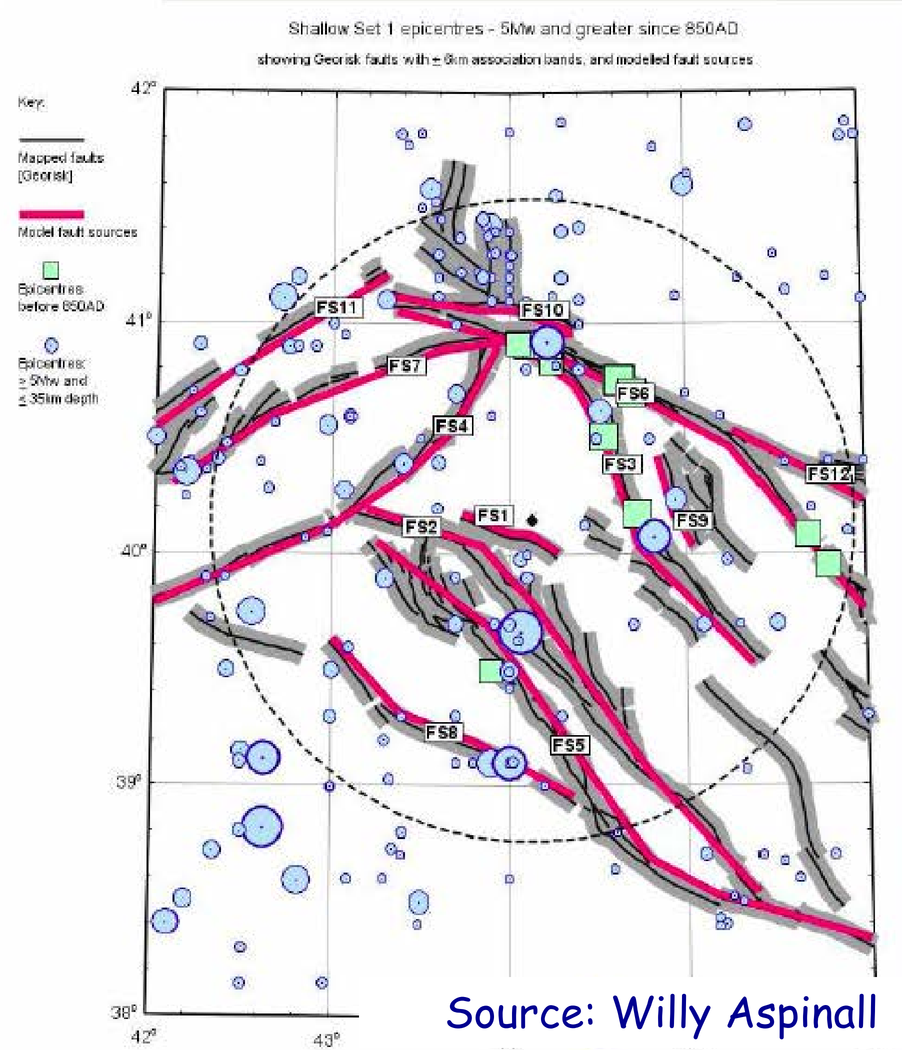


- Fragility assessment
  - would any of these cause damage and consequent radiological hazard - if so, what is the RISK?
  - how can risks be mitigated?

PSHA applied in Armenia (Metsamor NPP)

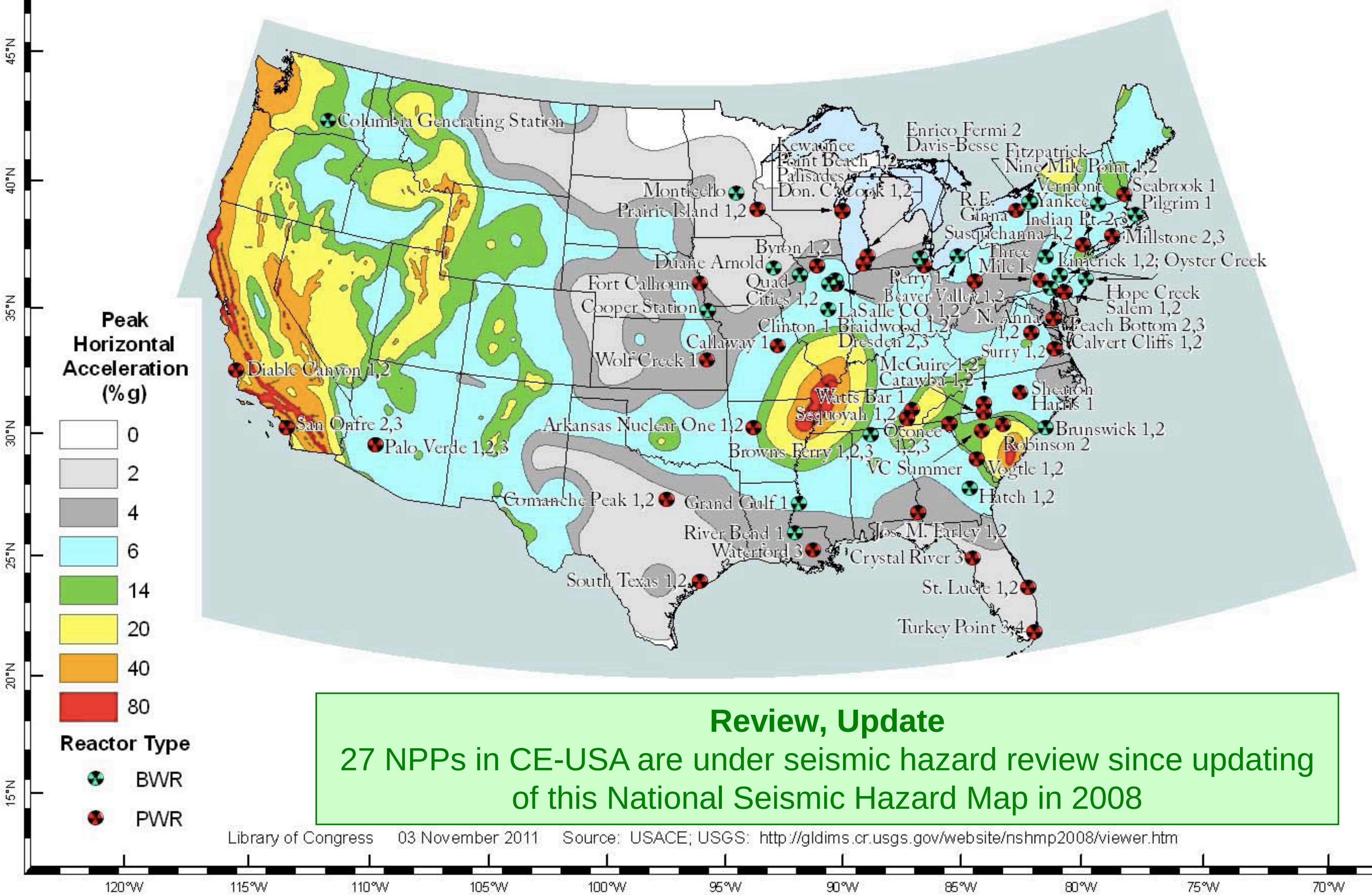
Identified active faults from Armenian specialists overlaying instrumental epicentres (left), and PSHA model fault sources (right panel – red lines)





Source: Willy Aspinall

PEAK HORIZONTAL ACCELERATION
WITH 2% PROBABILITY OF EXCEEDENCE IN 50 YEARS



Review, Update

27 NPPs in CE-USA are under seismic hazard review since updating of this National Seismic Hazard Map in 2008

Library of Congress 03 November 2011 Source: USACE; USGS: http://gldims.cr.usgs.gov/website/nshmp2008/viewer.htm

Probabilistic Methods are Essential

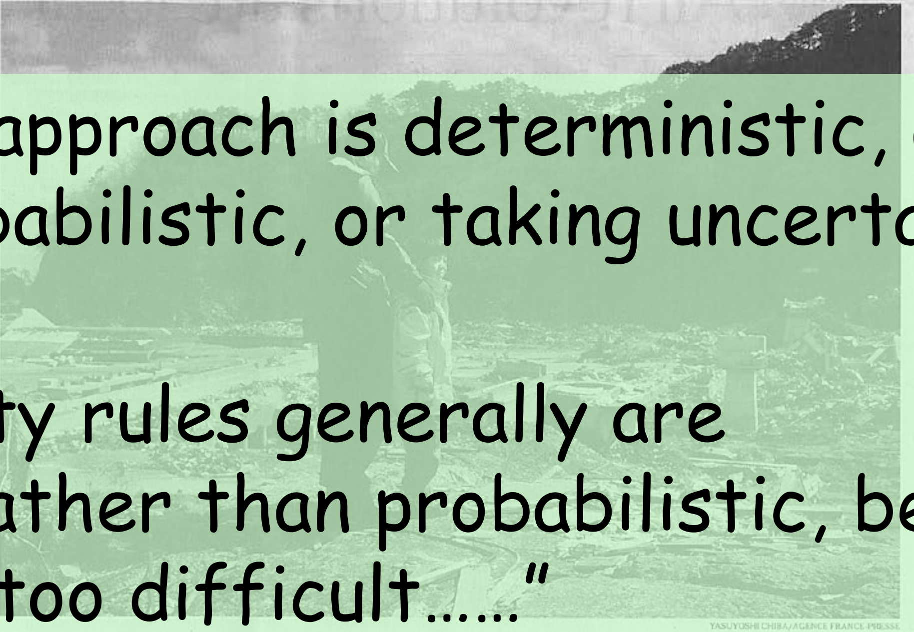
THE GLOBAL EDITION OF THE NEW YORK TIMES — MONDAY, MARCH 28, 2011 | 7

DISASTER IN JAPAN WORLD NEWS

Old methods left nuclear authorities unprepared for tsunami

TOKYO

BY NORIMITSU ONISHI AND JAMES GLANZ



A father and son in Tanohata, Japan, on Sunday. For decades, Japanese officials failed to make use of advances in risk assessment.

"The Japanese approach is deterministic, as opposed to probabilistic, or taking uncertainties into account….."

"Japanese safety rules generally are deterministic rather than probabilistic, because probabilistic is too difficult……"

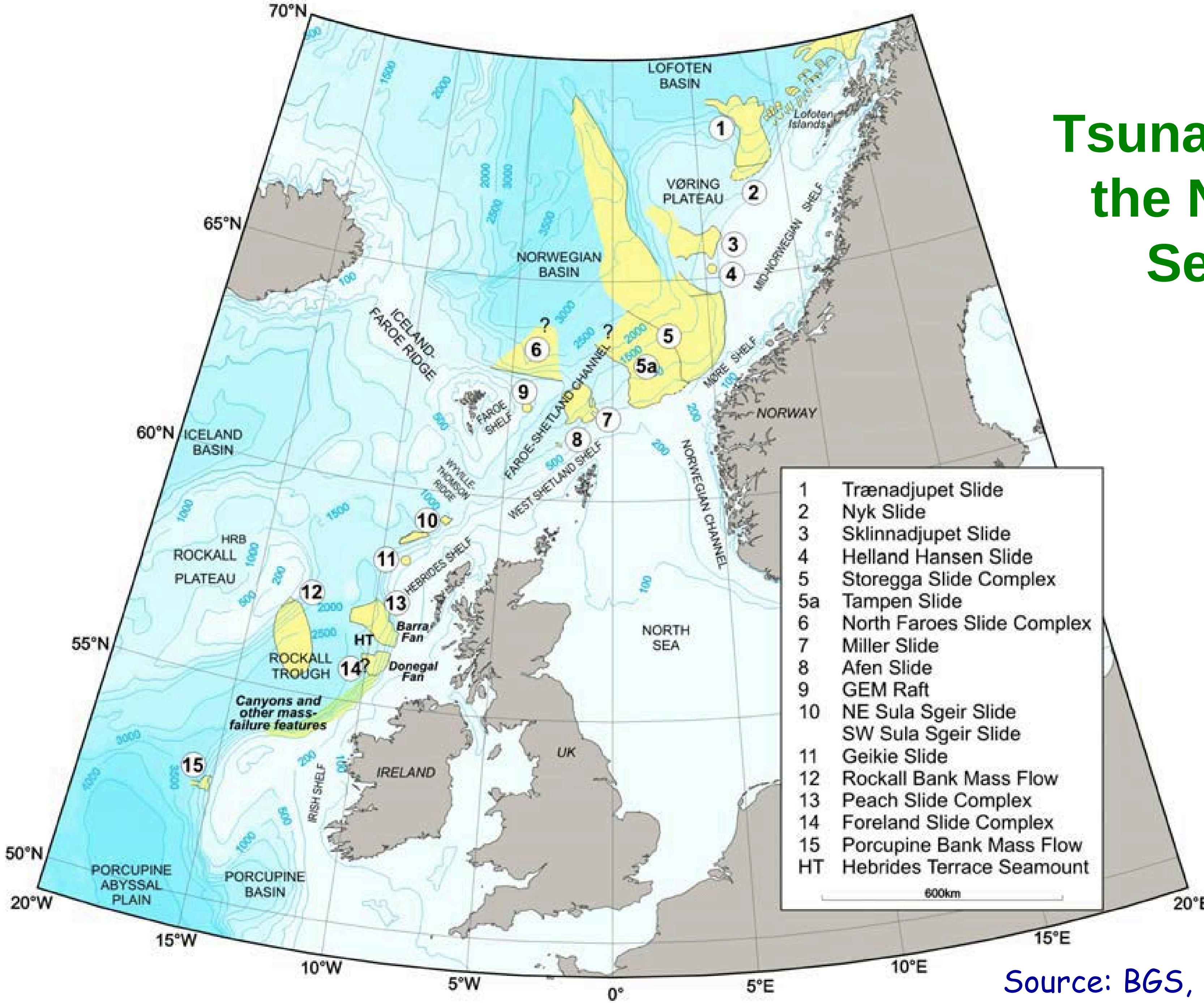
New York Times, March 2011

Lessons of Fukushima:

listen to Earth Scientists; use modern, probabilistic methods

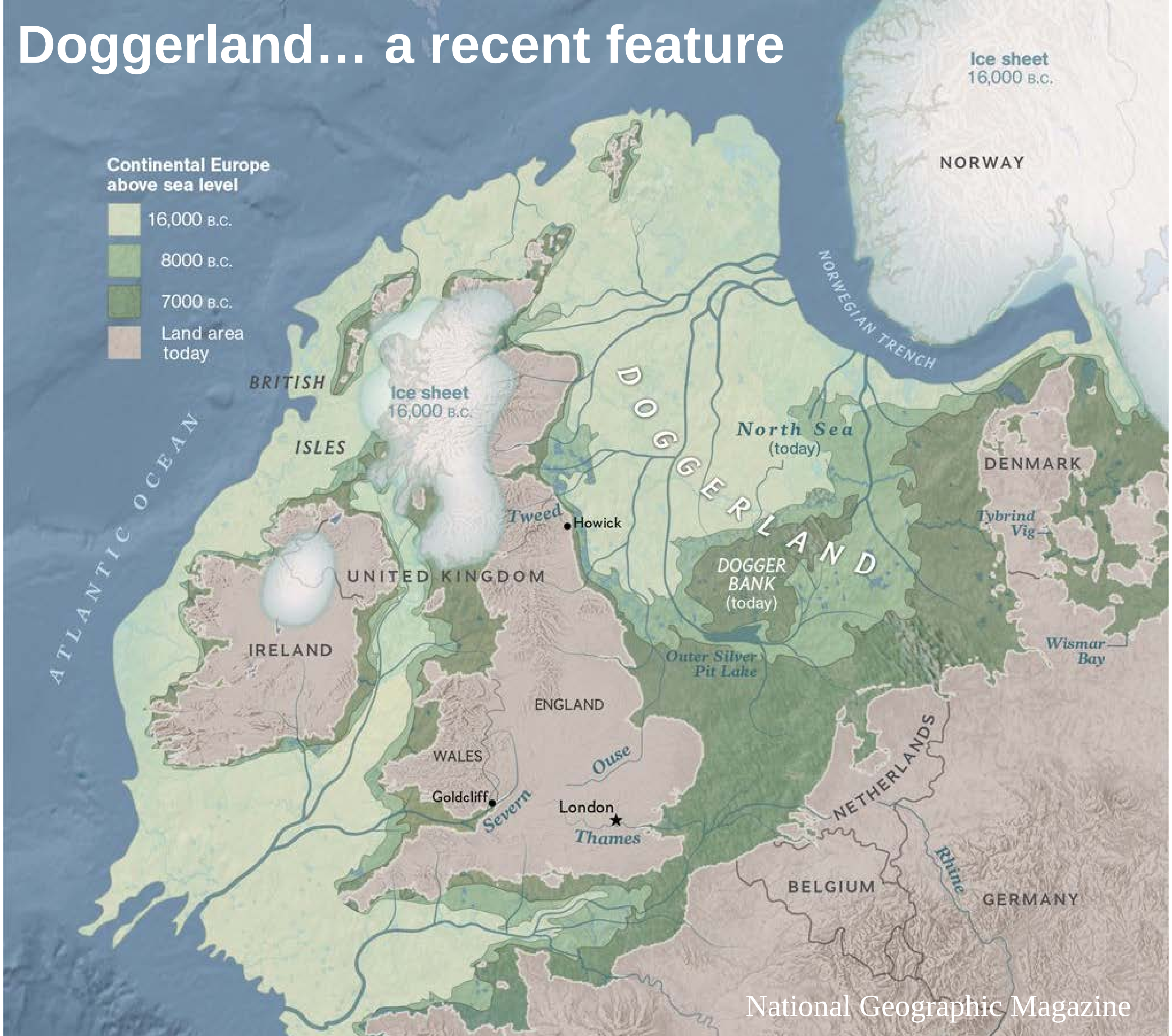
- Methods used (TEPCO & NISA) to assess tsunami risk were weak compared to latest international advice:
  - Insufficient attention to evidence of large tsunamis every thousand years ….'ignoring the tails of probability distributions'
  - Computer modelling inadequate
  - 2008 simulations suggesting tsunami risk seriously underestimated not followed up
  - Failure to review simulations
- Focus on seismic safety to exclusion of other risks
- Bureaucracy made nuclear officials unwilling to take advice from experts outside the field
- Failure to use local knowledge effectively
- *…..and many believed that such a severe accident was simply impossible*

Tsunamis in the North Sea?



Source: BGS, DEFRA

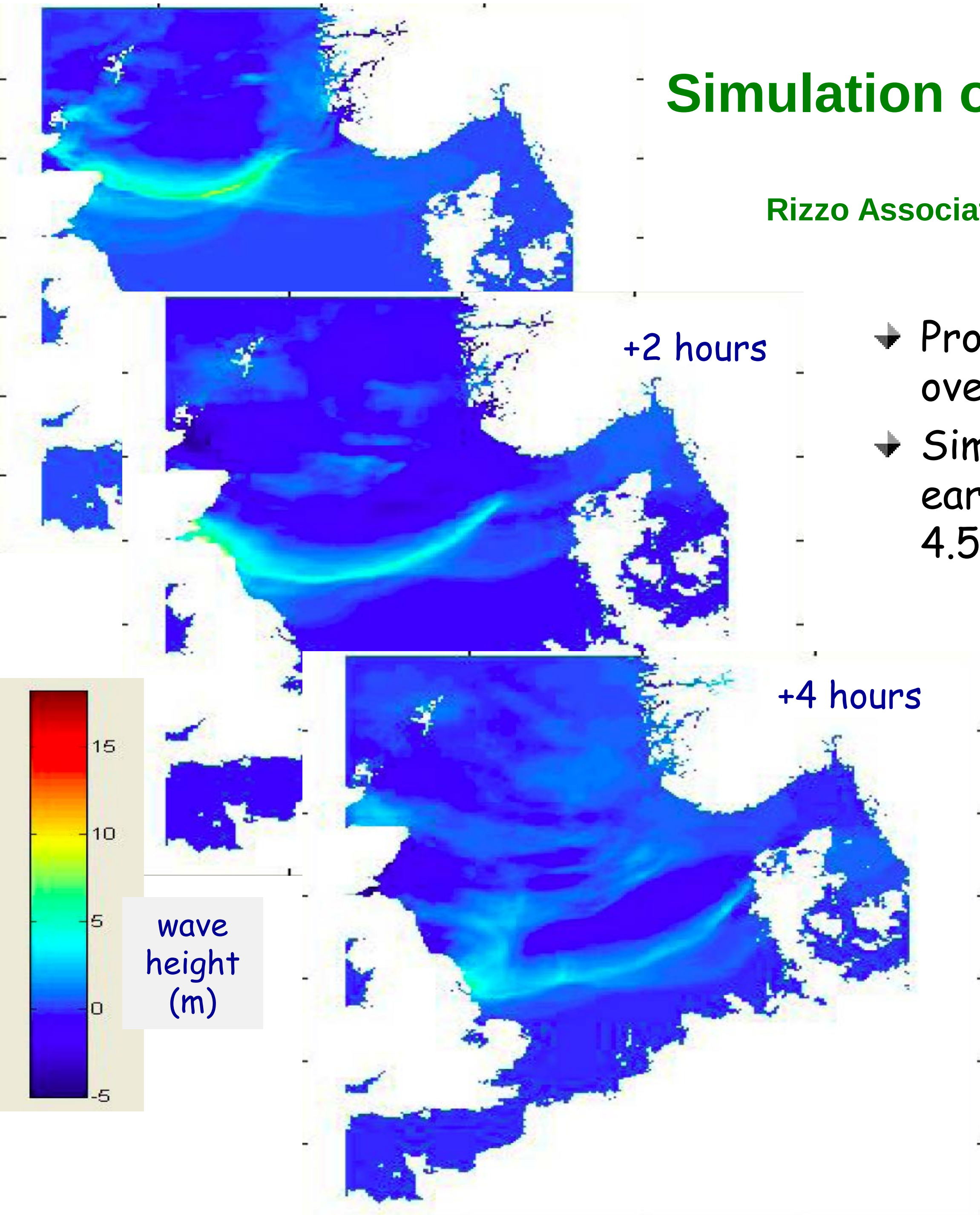
Doggerland… a recent feature



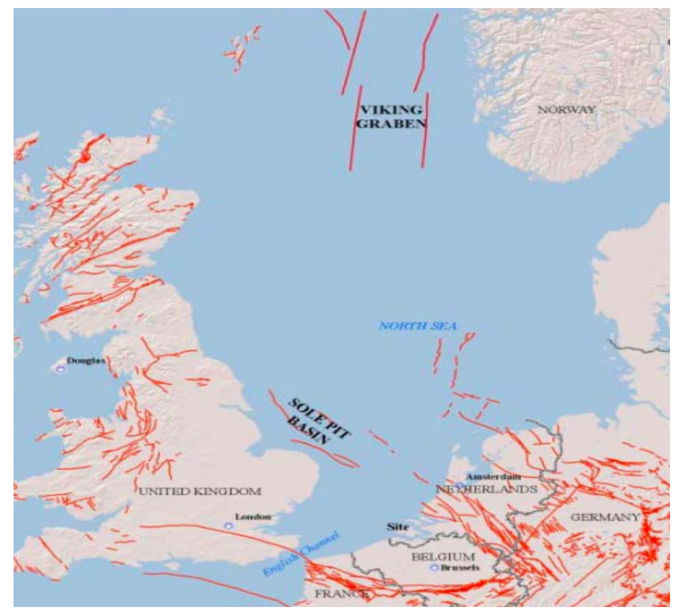
National Geographic Magazine

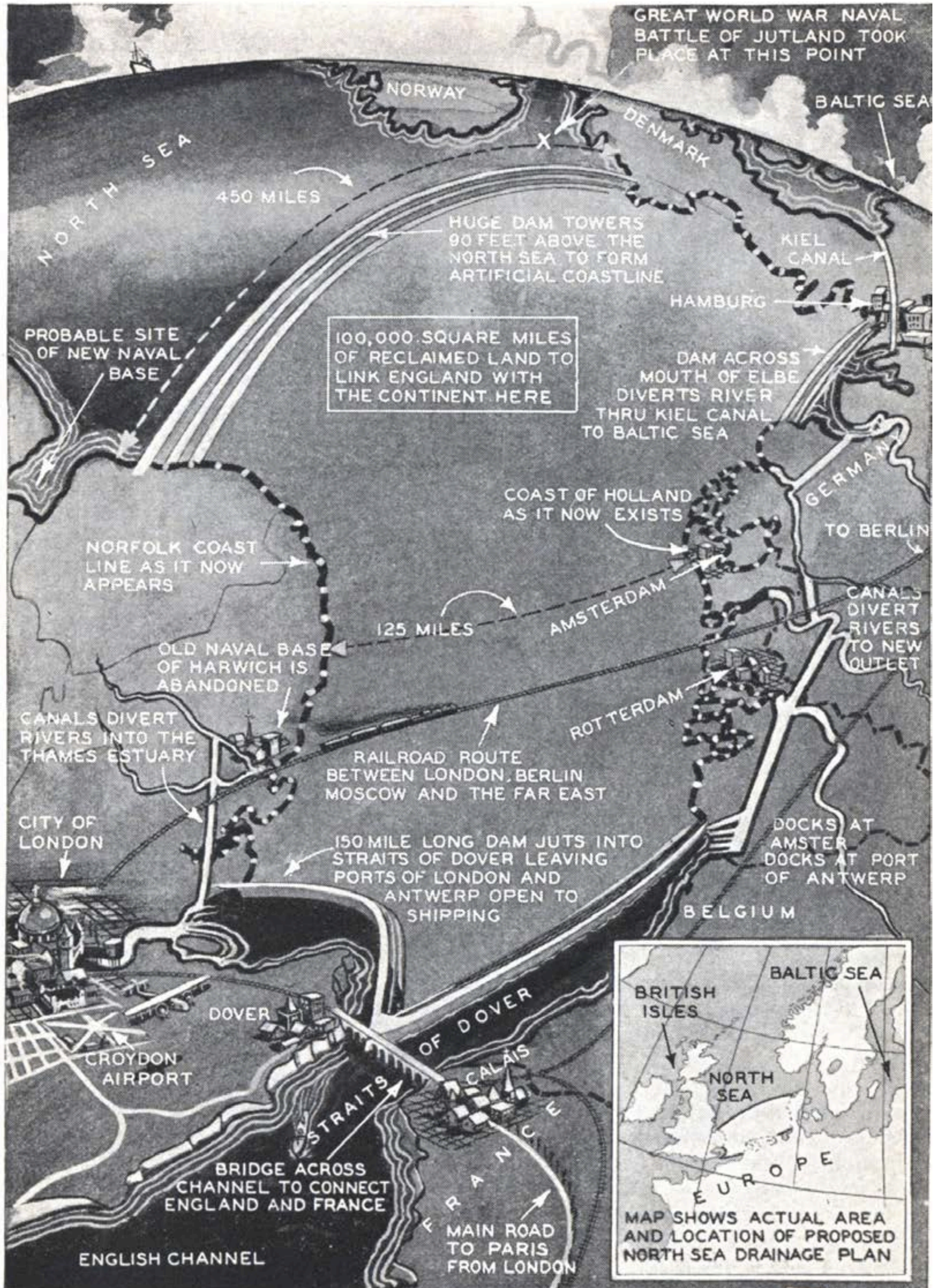
Simulation of 6 m landslide tsunami

Rizzo Associates: ISOPE meeting, Rhodes, 2012



- Probable maximum tsunami: 8.8 m, overtops dykes by 1.2 m
- Simulations of North Sea earthquake tsunami show PMT of 4.5 m: no overtopping





Wilder solutions… drain the North Sea

Modern Mechanix Magazine, September 1930

International Standards: the IAEA

IAEA Safety Standards
for protecting people and the environment

Seismic Hazards
in Site Evaluation
for Nuclear Installations

Specific Safety Guide
No. SSG-9

IAEA
International Atomic Energy Agency

IAEA Safety Standards
for protecting people and the environment

Volcanic Hazards in
Site Evaluation for
Nuclear Installations

Specific Safety Guide
No. SSG-21

IAEA
International Atomic Energy Agency

IAEA Safety Standards
for protecting people and the environment

Site Evaluation for
Nuclear Installations

Safety Requirements
No. NS-R-3 (Rev. 1)

IAEA
International Atomic Energy Agency

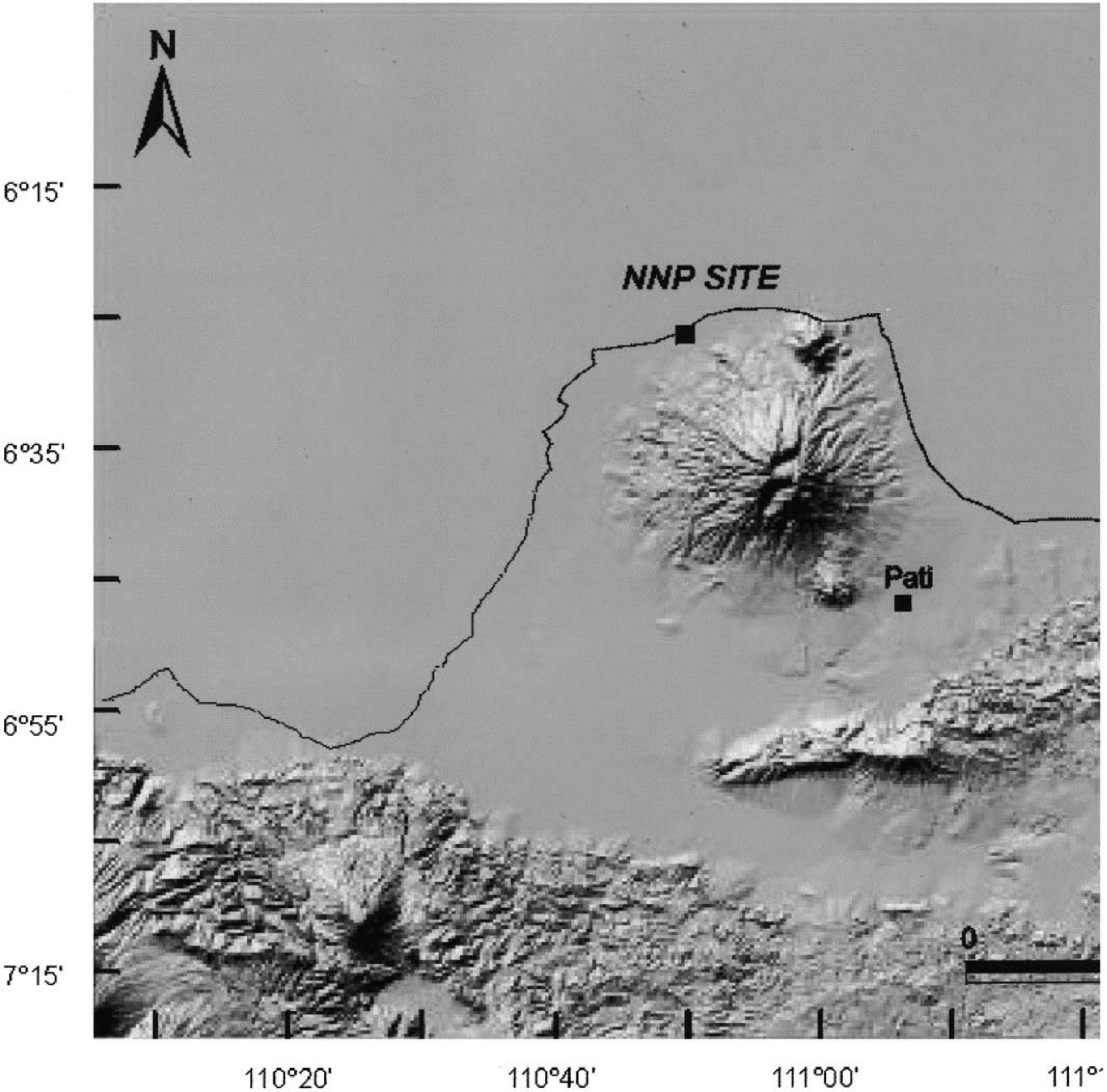
Where are we today?

- we have advanced techniques for assessing both the hazards and the quantitative risks
- risks can be reduced and radiological hazards mitigated by sensible siting and design
- natural hazards are a central part of nuclear safety regulation
- IAEA has guidelines that can be adopted by any country with nuclear facilities
- *.... natural hazards are still only rarely included in our considerations of most of our other human activities*

Volcanic Hazard to Nuclear Facilities

- what could happen?
  - ash cloud modelling
  - probabilistic studies of ash deposition
  - lahars
  - pyroclastic flows
- will it happen – how likely?
  - probabilistic studies of volcanic event occurrence

Source: Chuck Connor

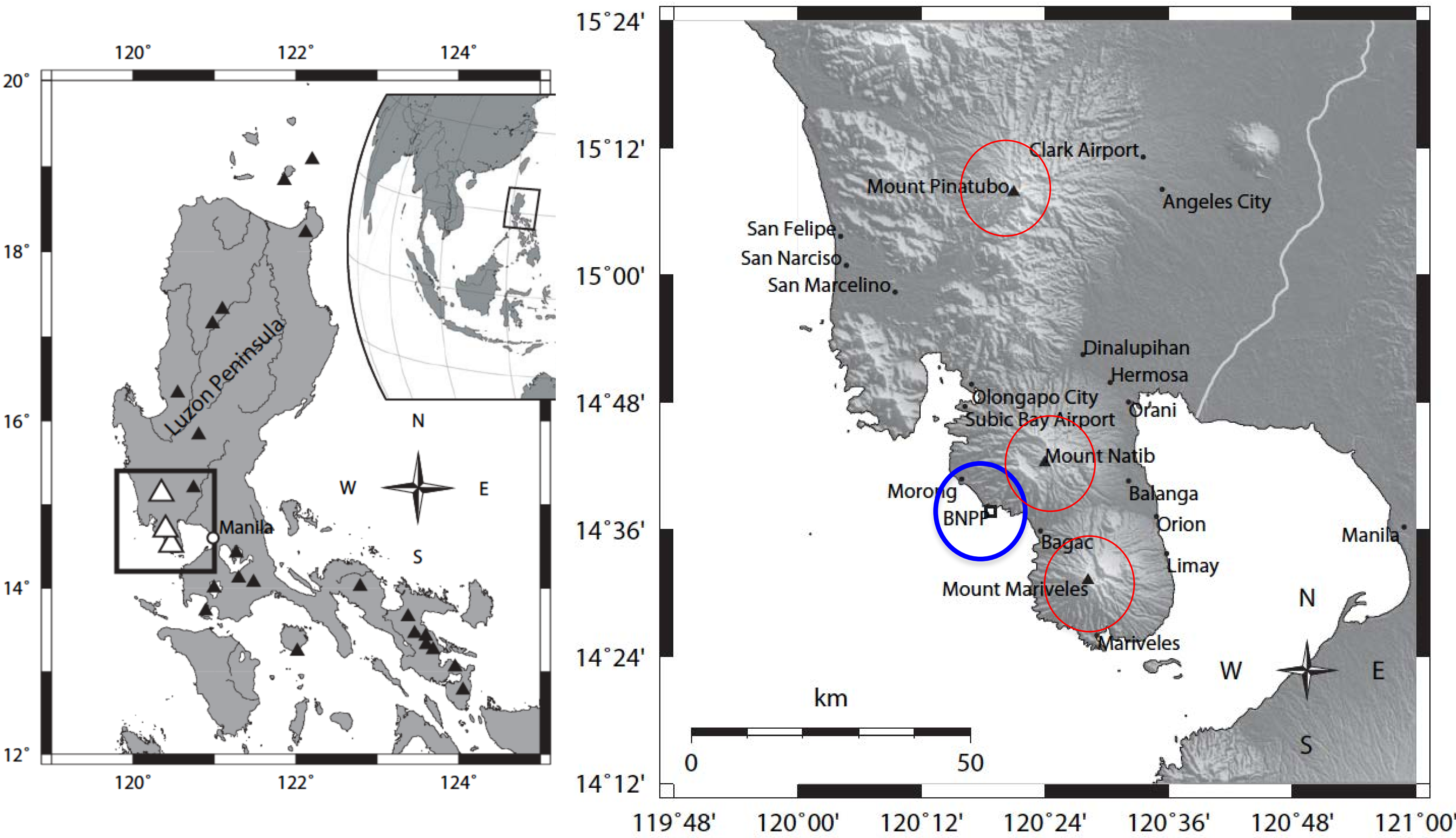


INDONESIA
Java: NPP near Muria volcano

Studied by McBirney, Connor et al

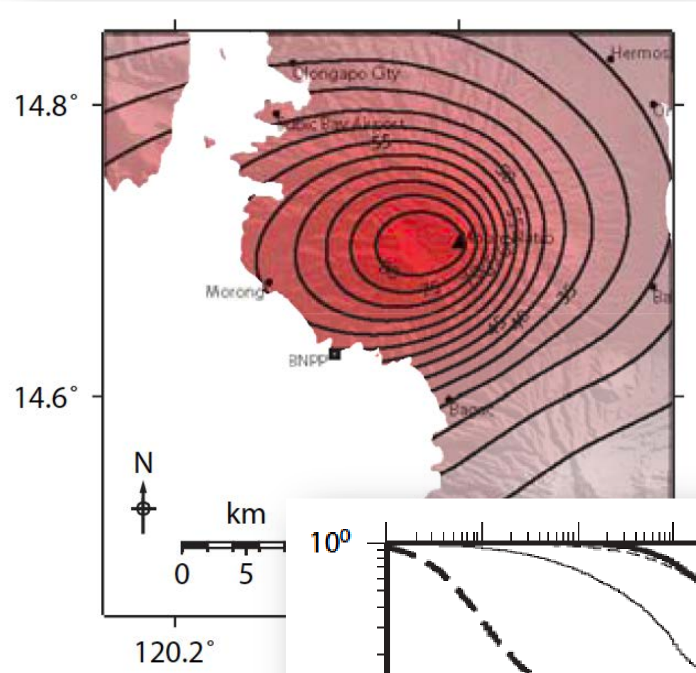
…..probabilities of major eruptive episodes impacting the site of 5×10^{-4} to 4×10^{-5} during the next 100 years

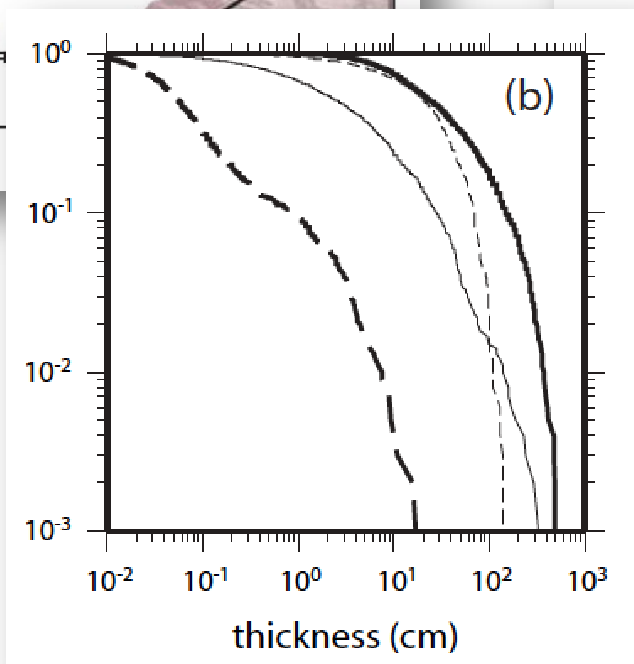
Bataan NPP, Philippines

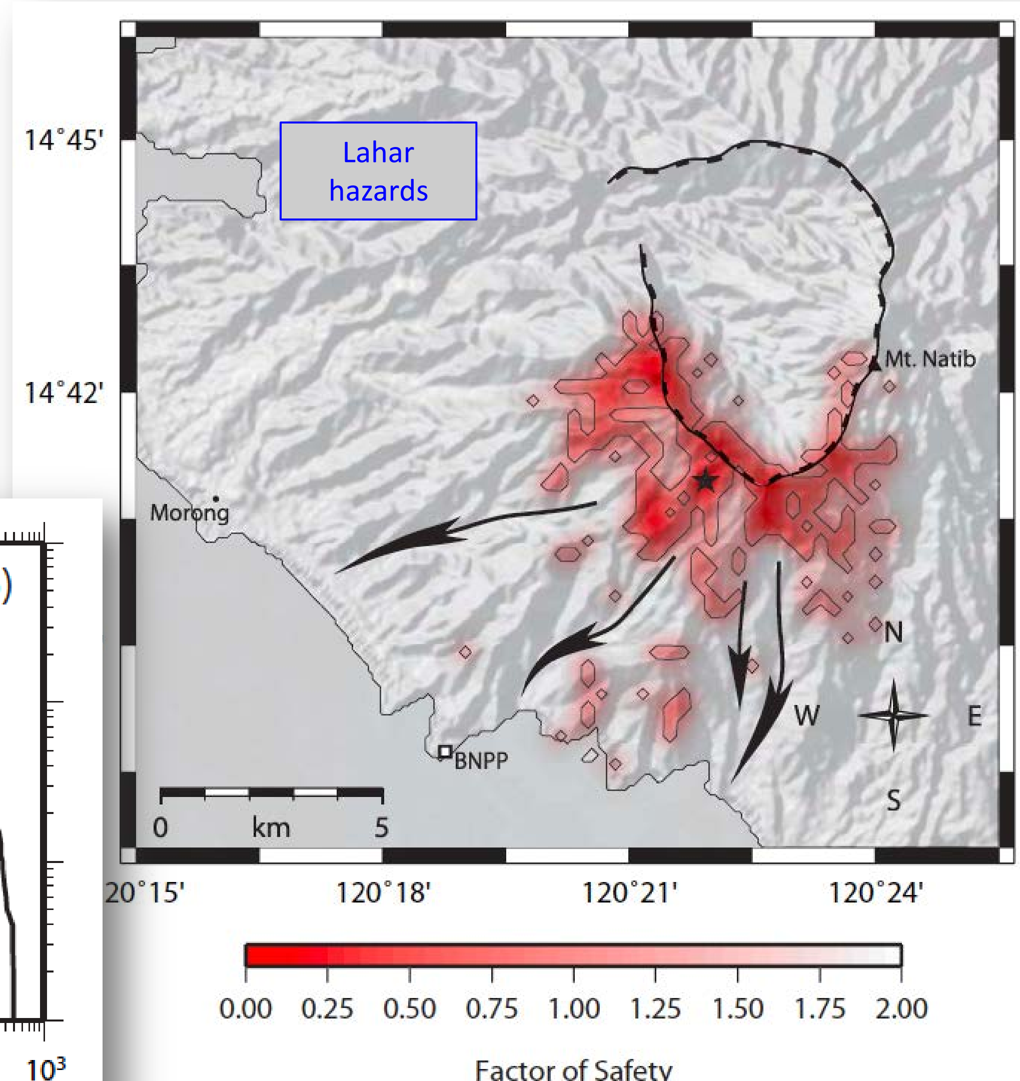


Source: Chuck Connor

Bataan Volcanic Hazards



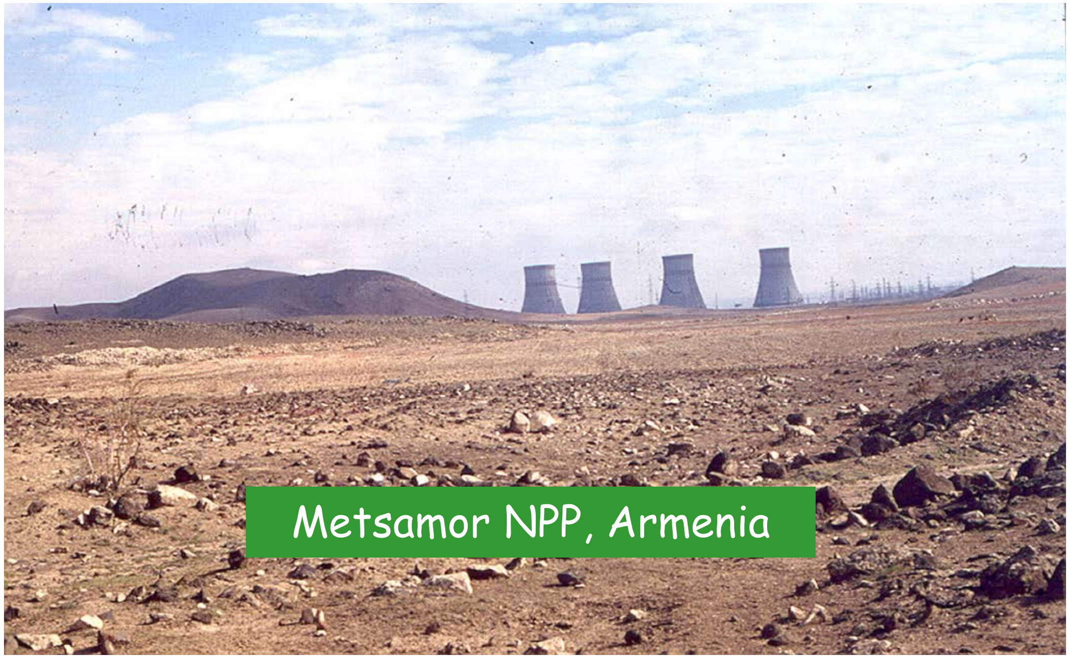




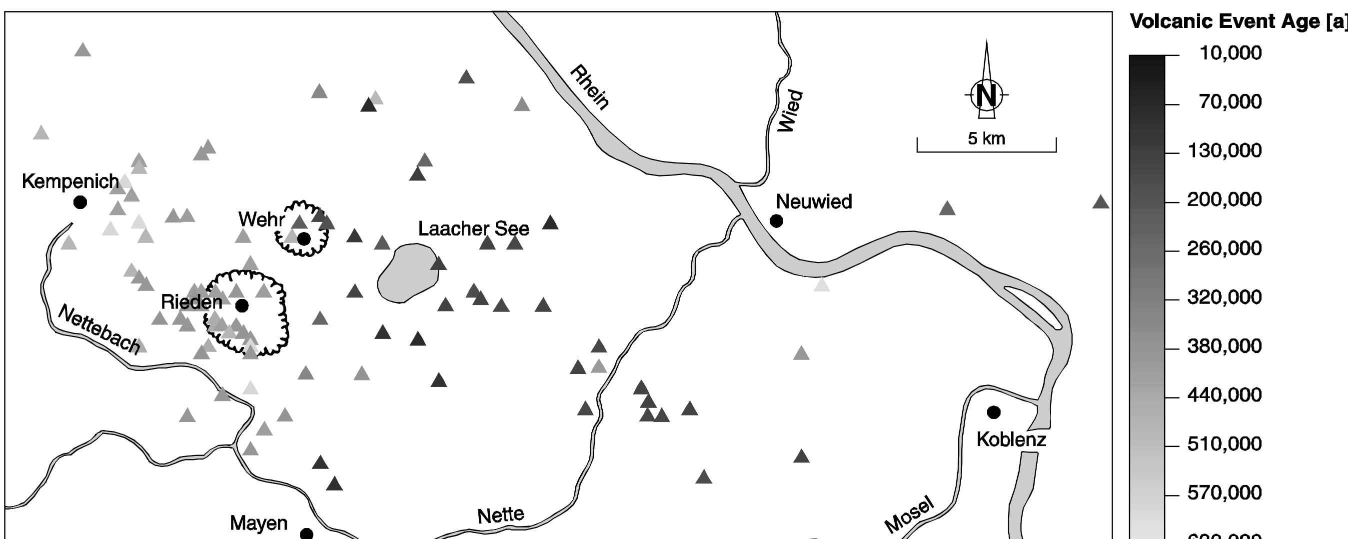
Probability of exceeding tephra thickness

Source: Chuck Connor

Some NPPs assessed probabilistically for volcanic hazard



Mülheim-Kärlich
Nuclear Power Plant,
Germany



Sources: Chuck Connor, Olivier Jaquet

The much longer term: geological repositories for long-lived radioactive wastes

contain and isolate for 10,000 to 1 million years

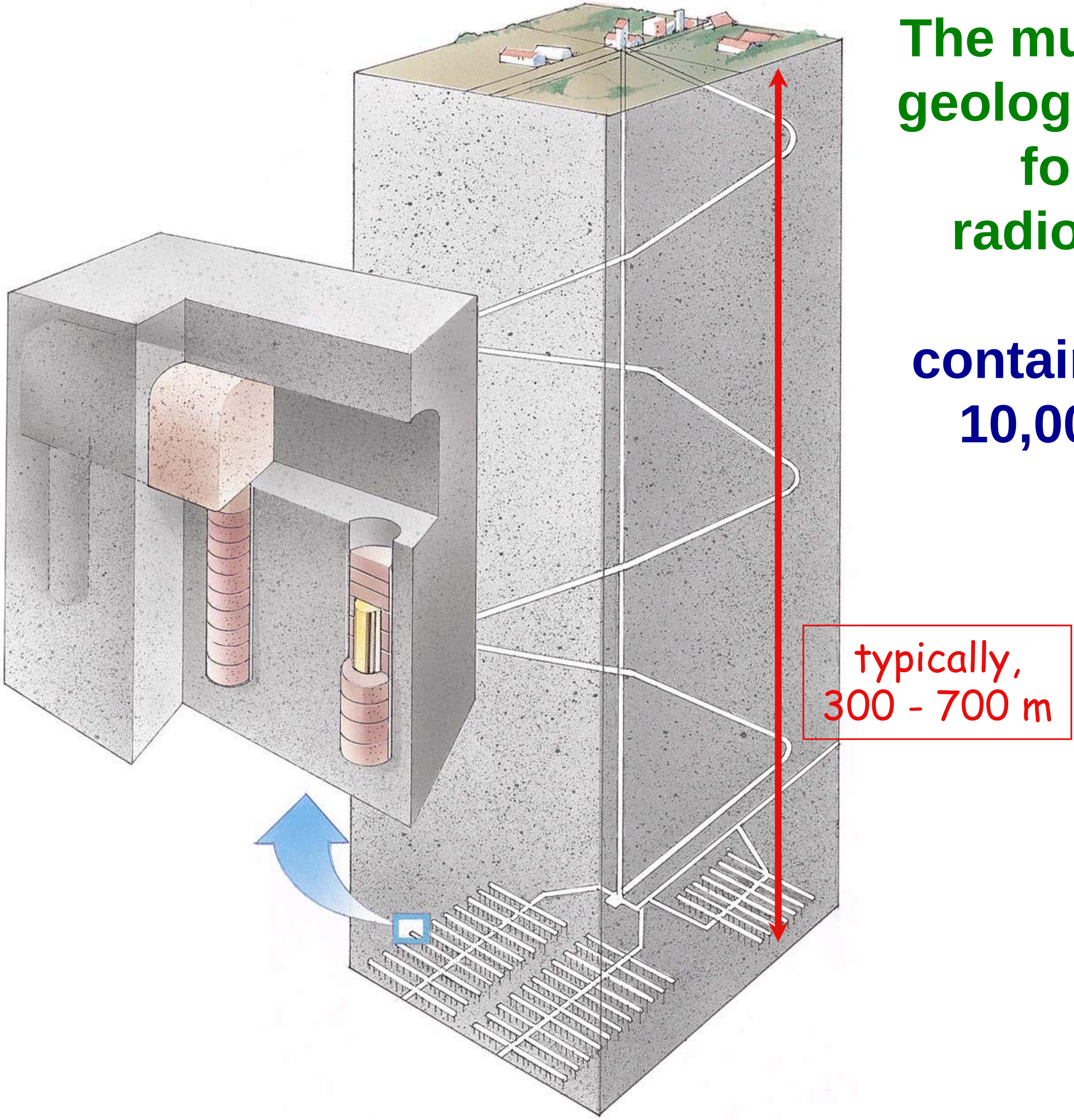


Image: SKB, Sweden

Finland: ONKALO and the Spent Fuel Repository

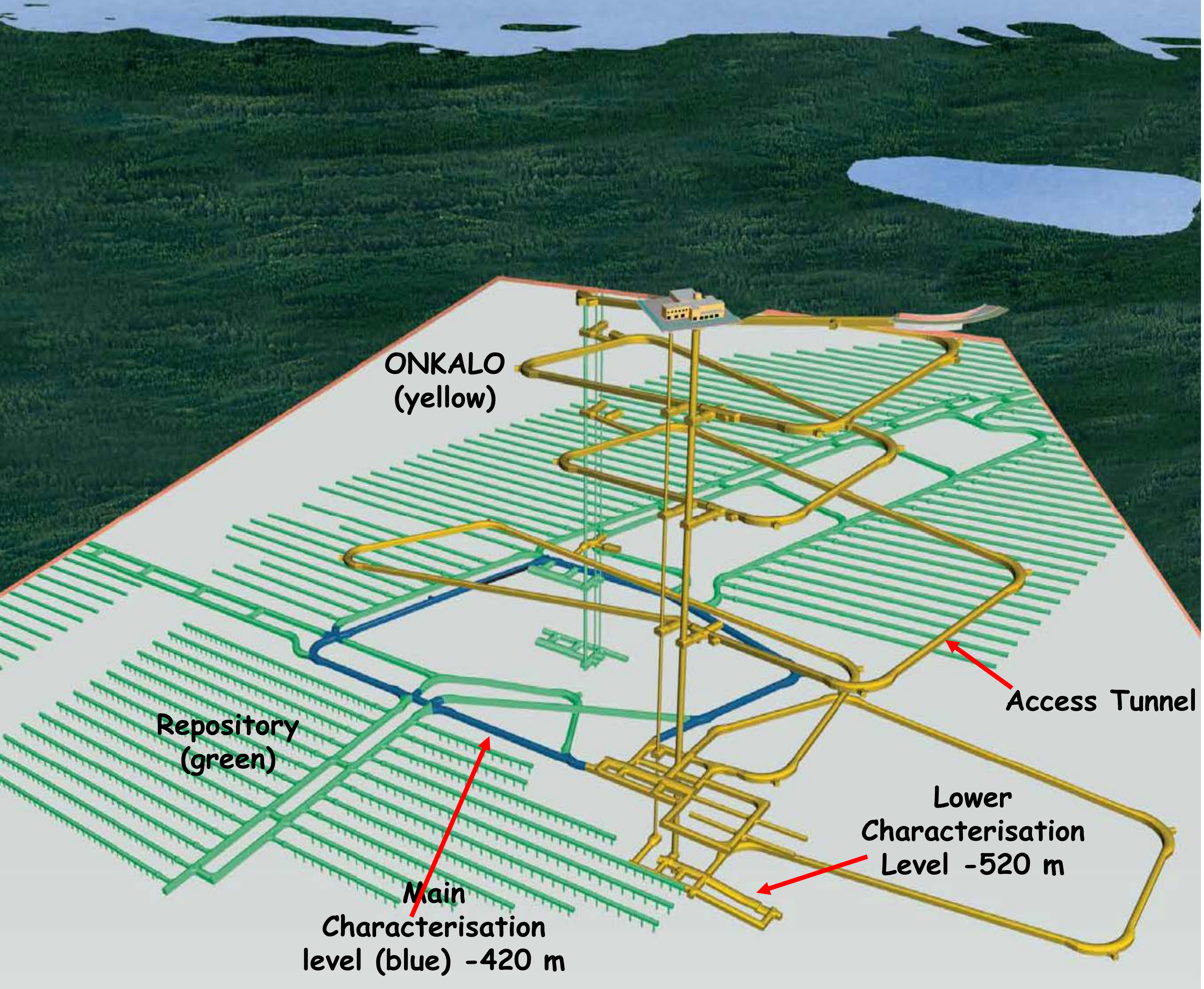
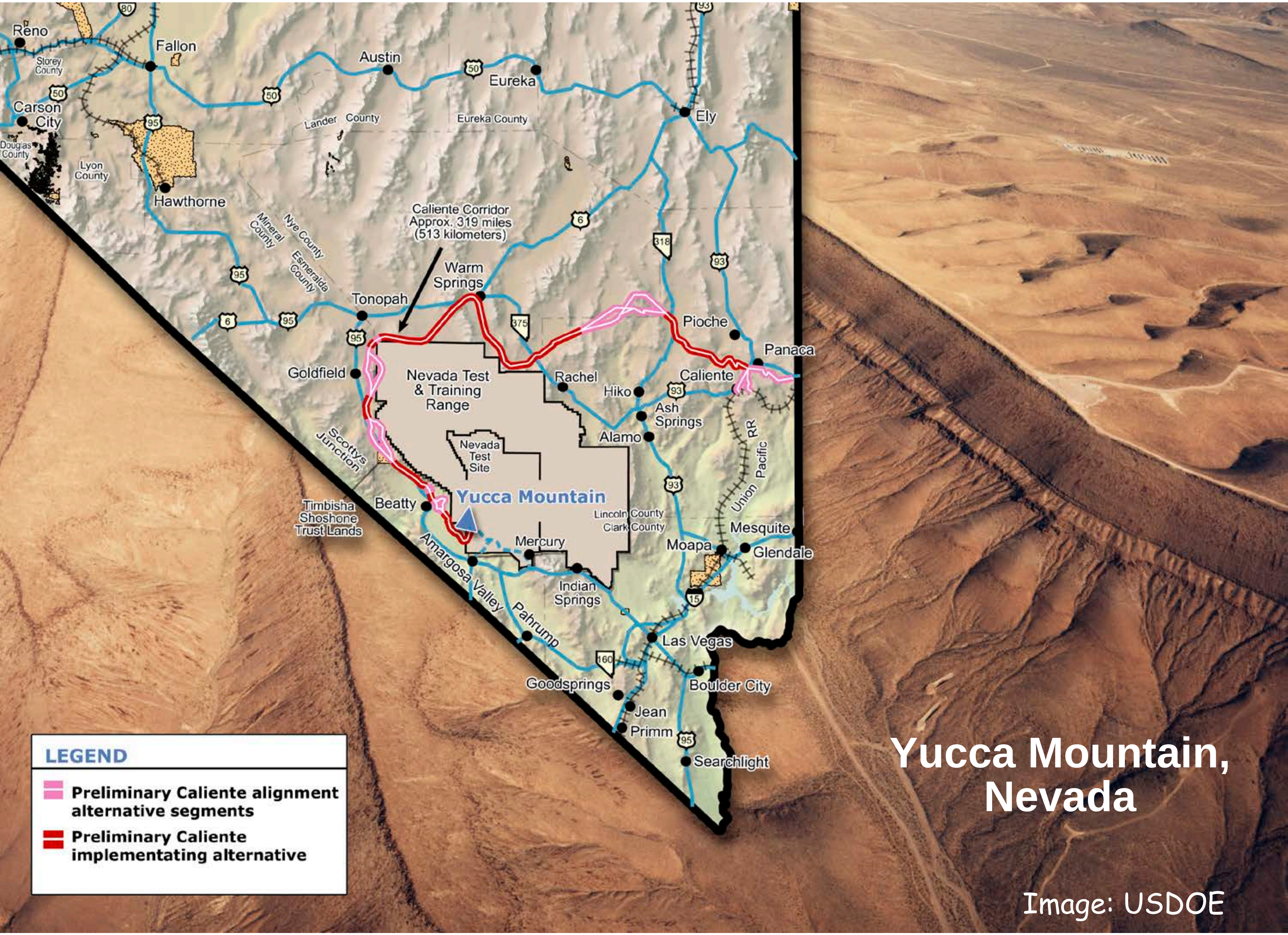


Image:
Posiva



Reno
Fallon
Storey County
Carson City
Douglas County
Lyon County
Hawthorne
Austin
Eureka
Lander County
Eureka County
Ely
Mineral County
Nye County
Esmeralda County
Caliente Corridor
Approx. 319 miles
(513 kilometers)
Warm Springs
Tonopah
Goldfield
Nevada Test & Training Range
Nevada Test Site
Pioche
Panaca
Rachel
Caliente
Hiko
Ash Springs
Alamo
Scottys Junction
Union Pacific RR
Yucca Mountain
Beatty
Timbisha Shoshone Trust Lands
Lincoln County
Clark County
Mercury
Mesquite
Moapa
Glendale
Indian Springs
Amargosa Valley
Pahrump
Las Vegas
Goodsprings
Boulder City
Jean
Primm
Searchlight
LEGEND
Preliminary Caliente alignment alternative segments
Preliminary Caliente implementating alternative
Yucca Mountain, Nevada
Image: USDOE

Proposed Repository at Yucca Mountain

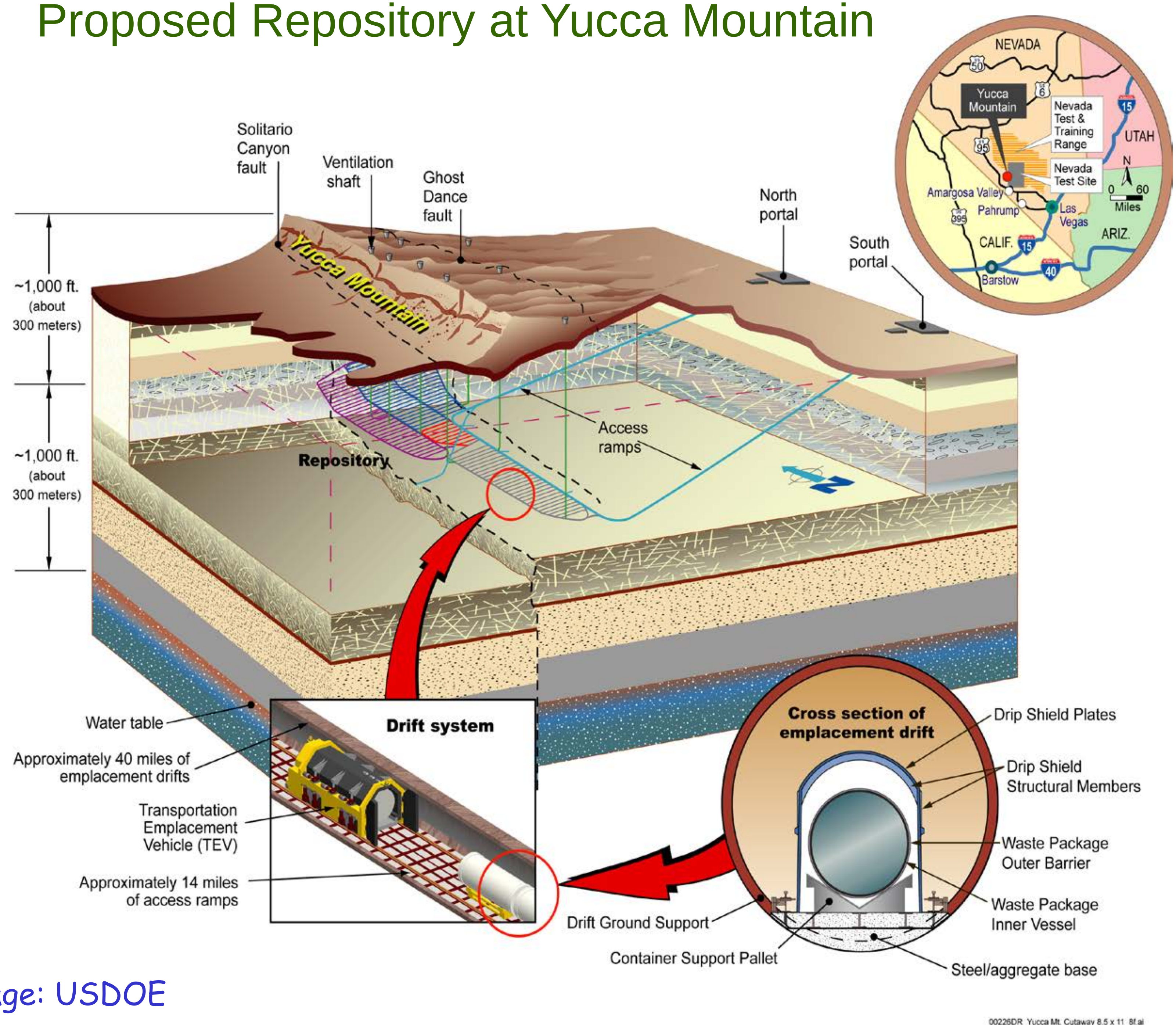
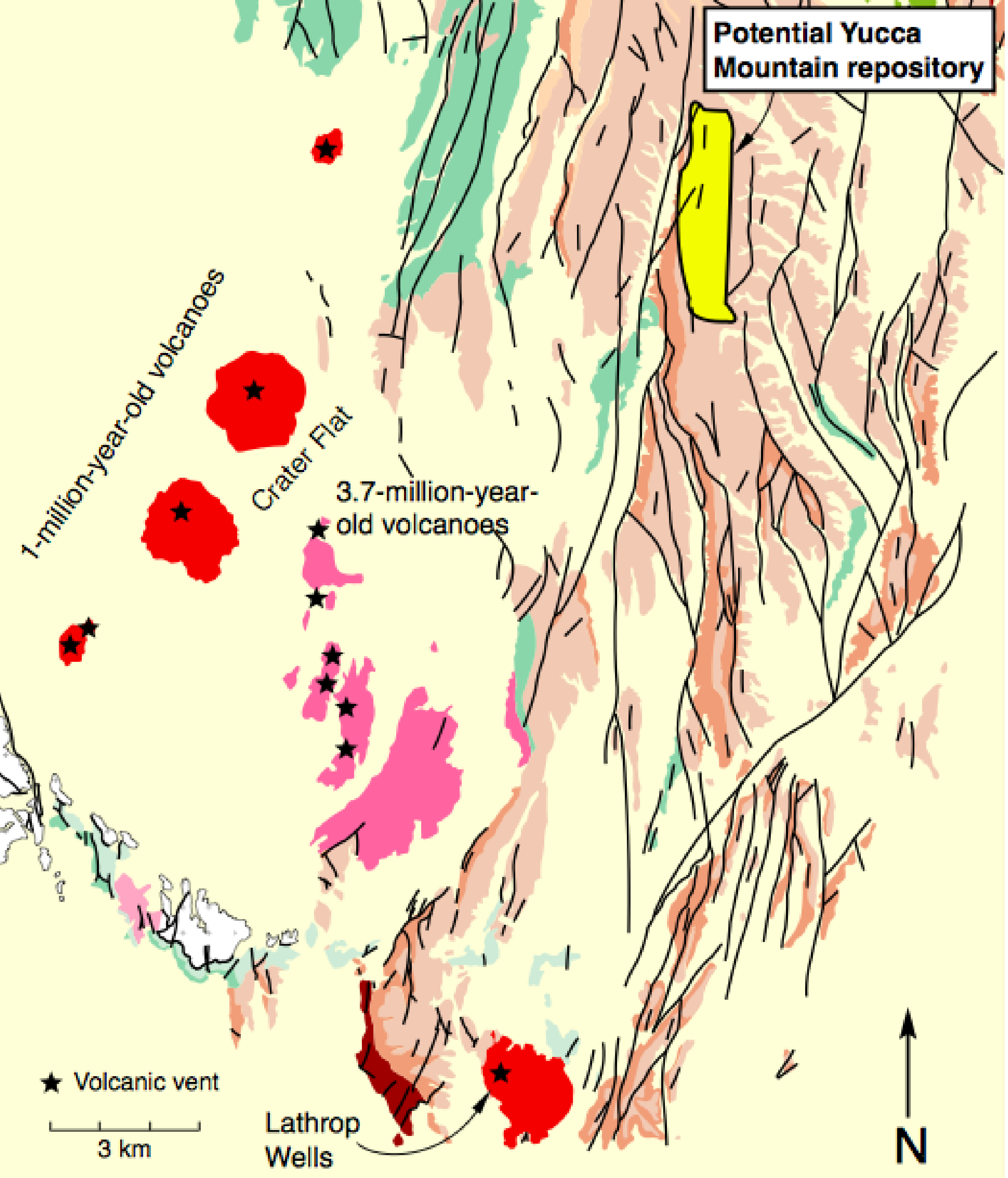


Image: USDOE



Volcanism around Yucca Mountain

Source: Los Alamos National laboratory

Volcanic Eruption through the Yucca Mountain repository?

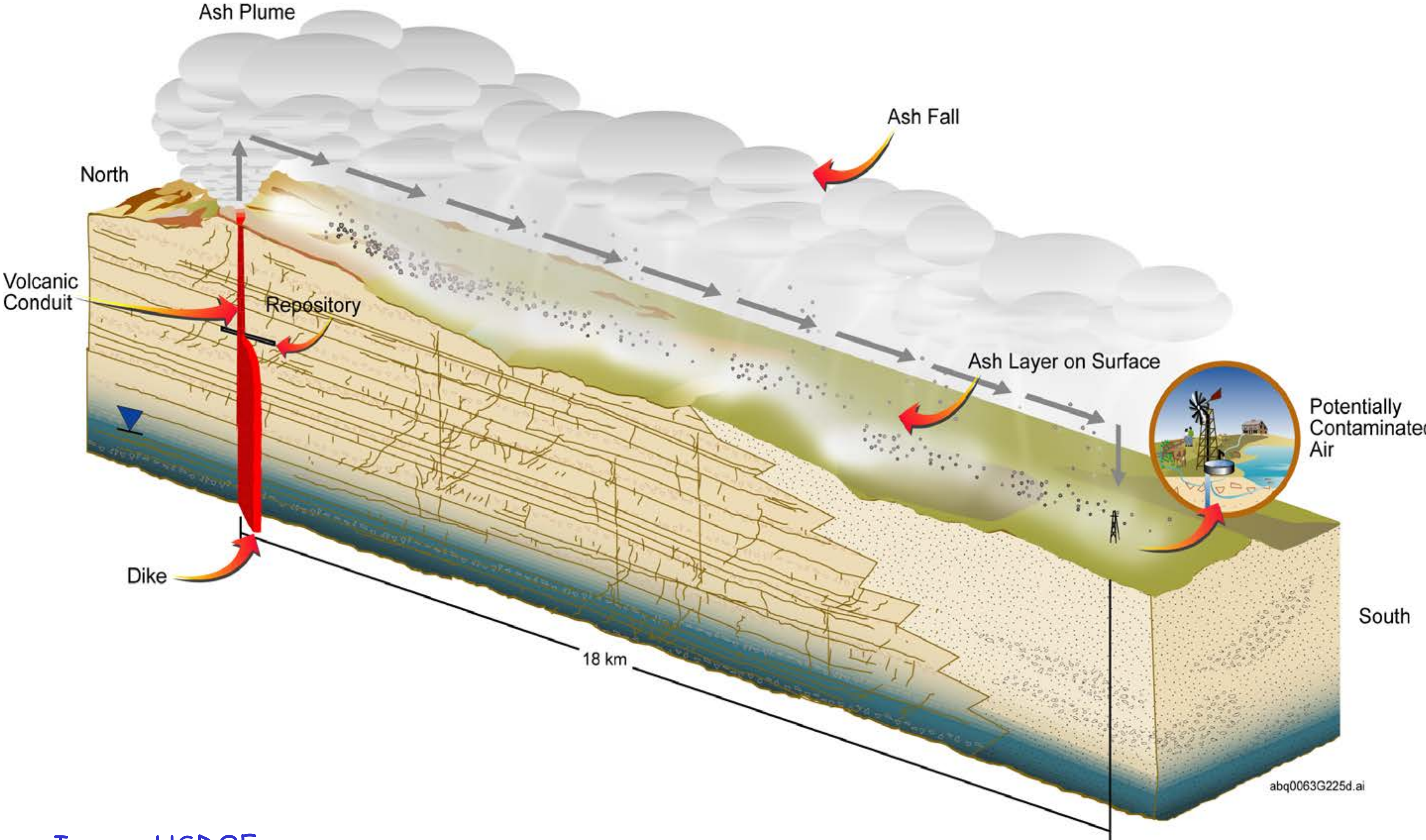
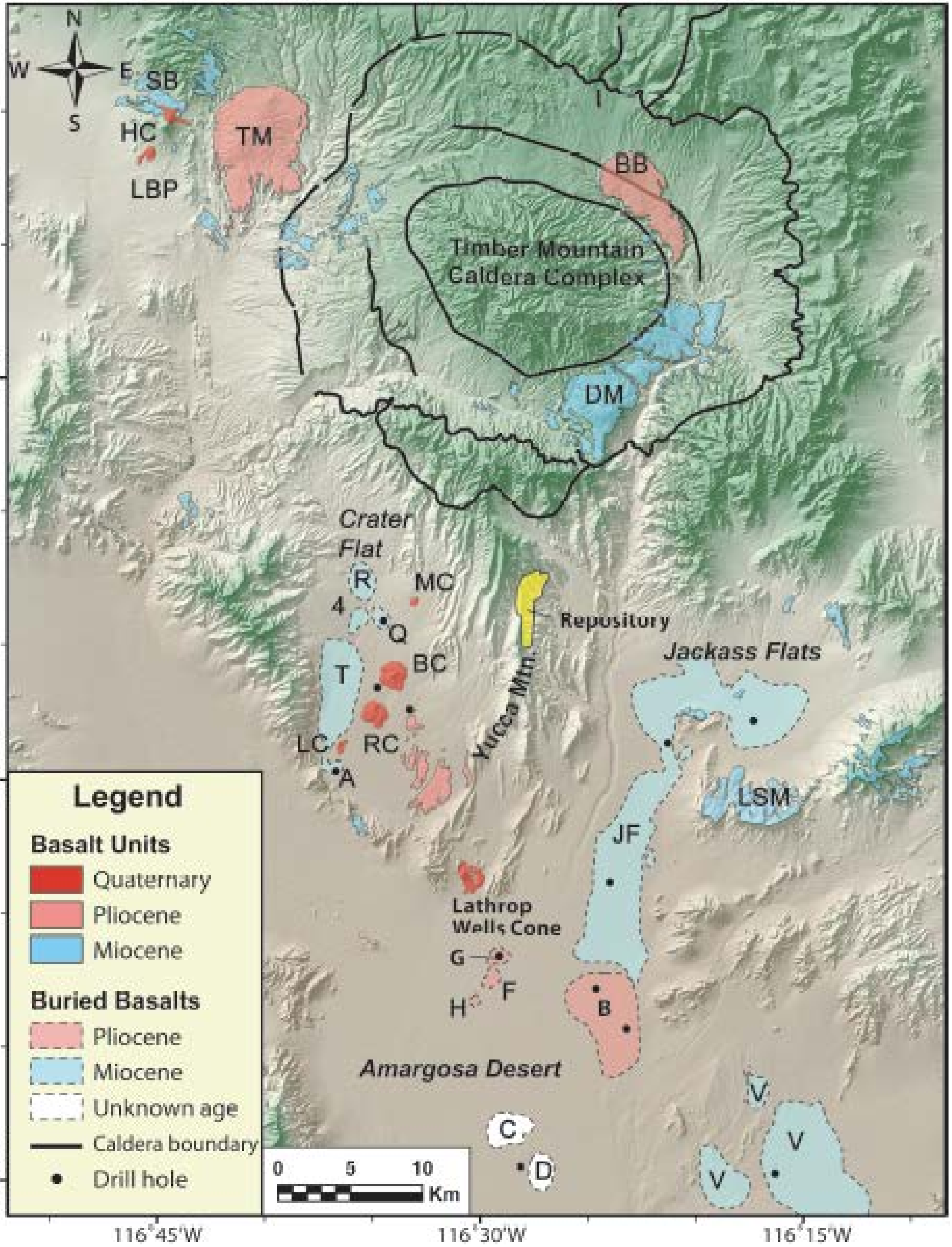


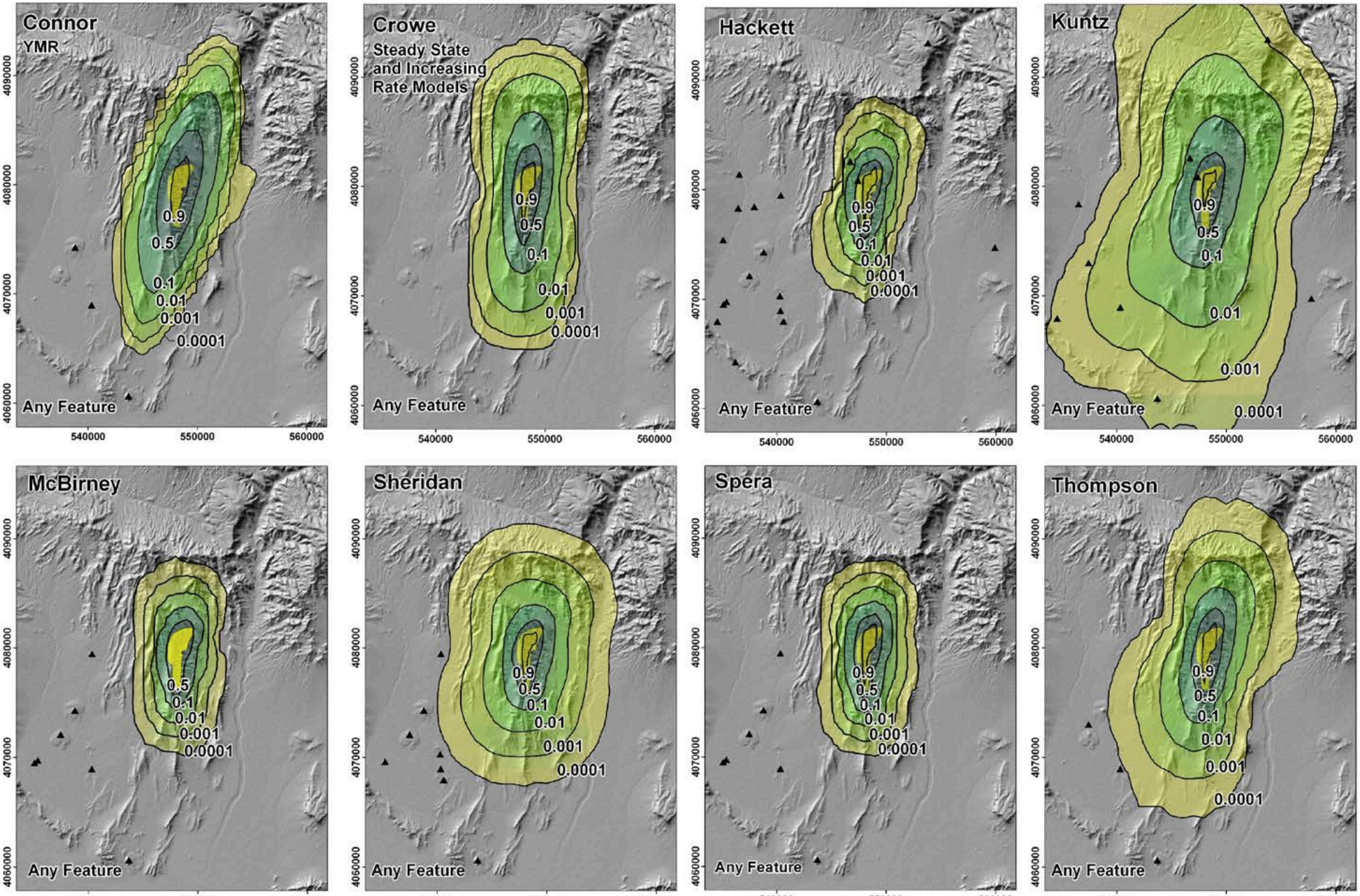
Image: USDOE



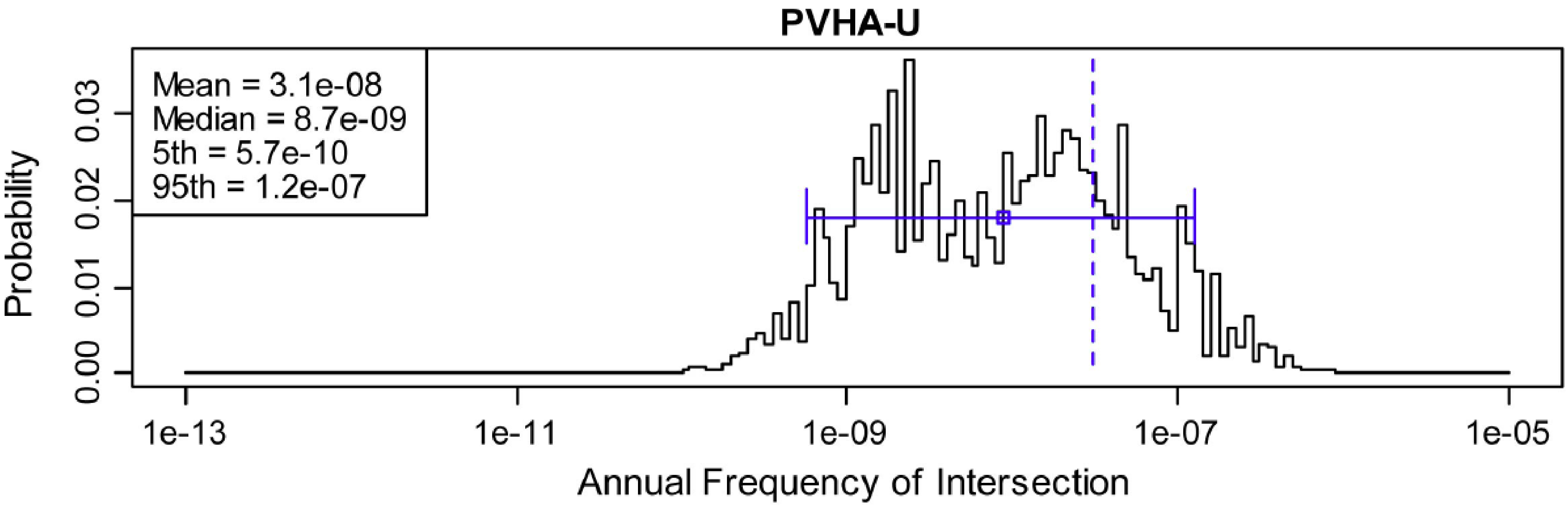
Comprehensive Probabilistic Volcanic Hazard Assessment

Figure from: Valentine and Perry: Volcanic risk assessment at Yucca Mountain, USA. In: Volcanic and Tectonic Hazard Assessment for Nuclear Facilities, Cambridge University Press.

Conditional probability of any event hitting the repository



Probability of disruption in 1 million years



10^{-8} per year
1 in 7000 chance in next 10,000 years

Seismic Scenario Model

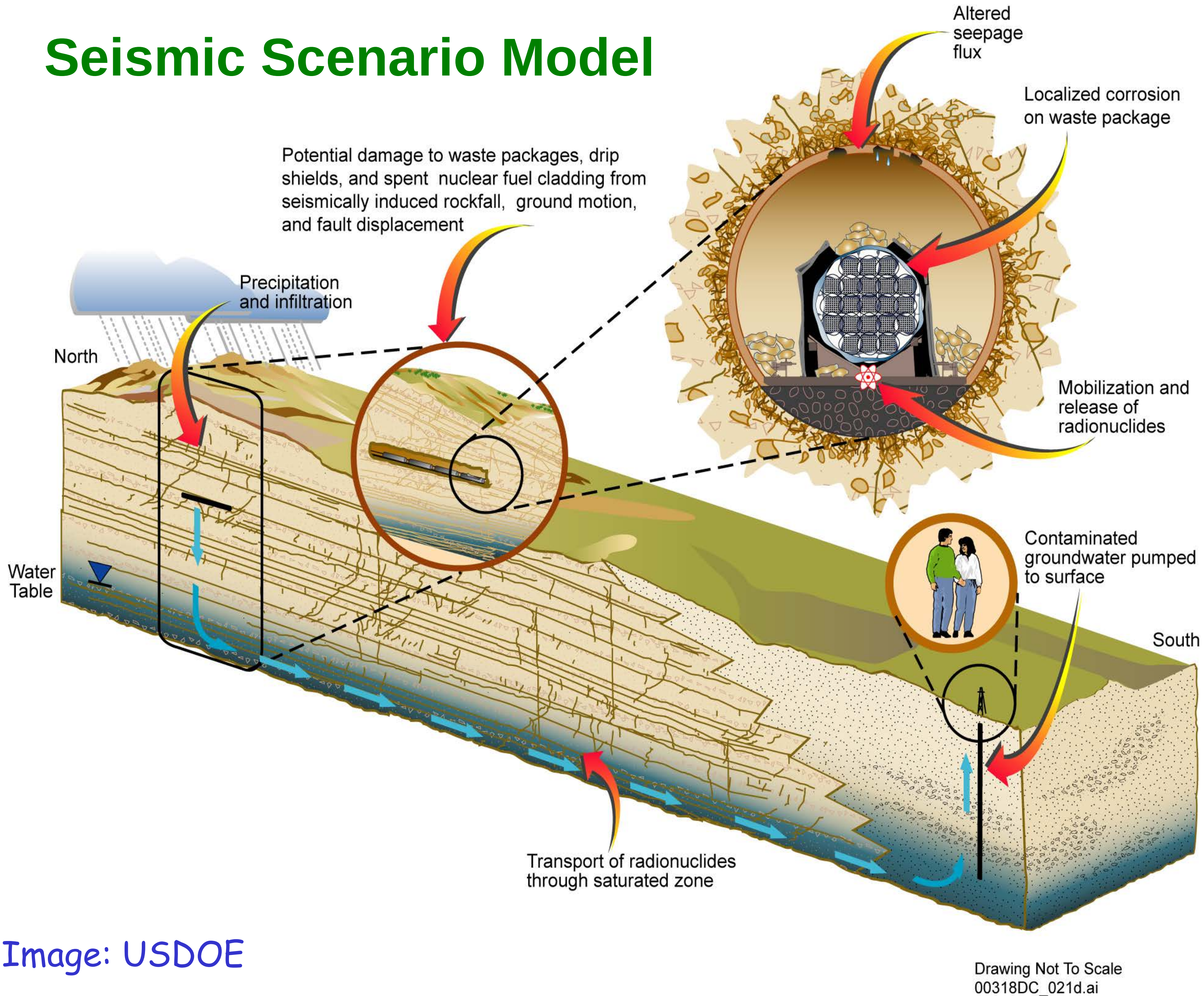


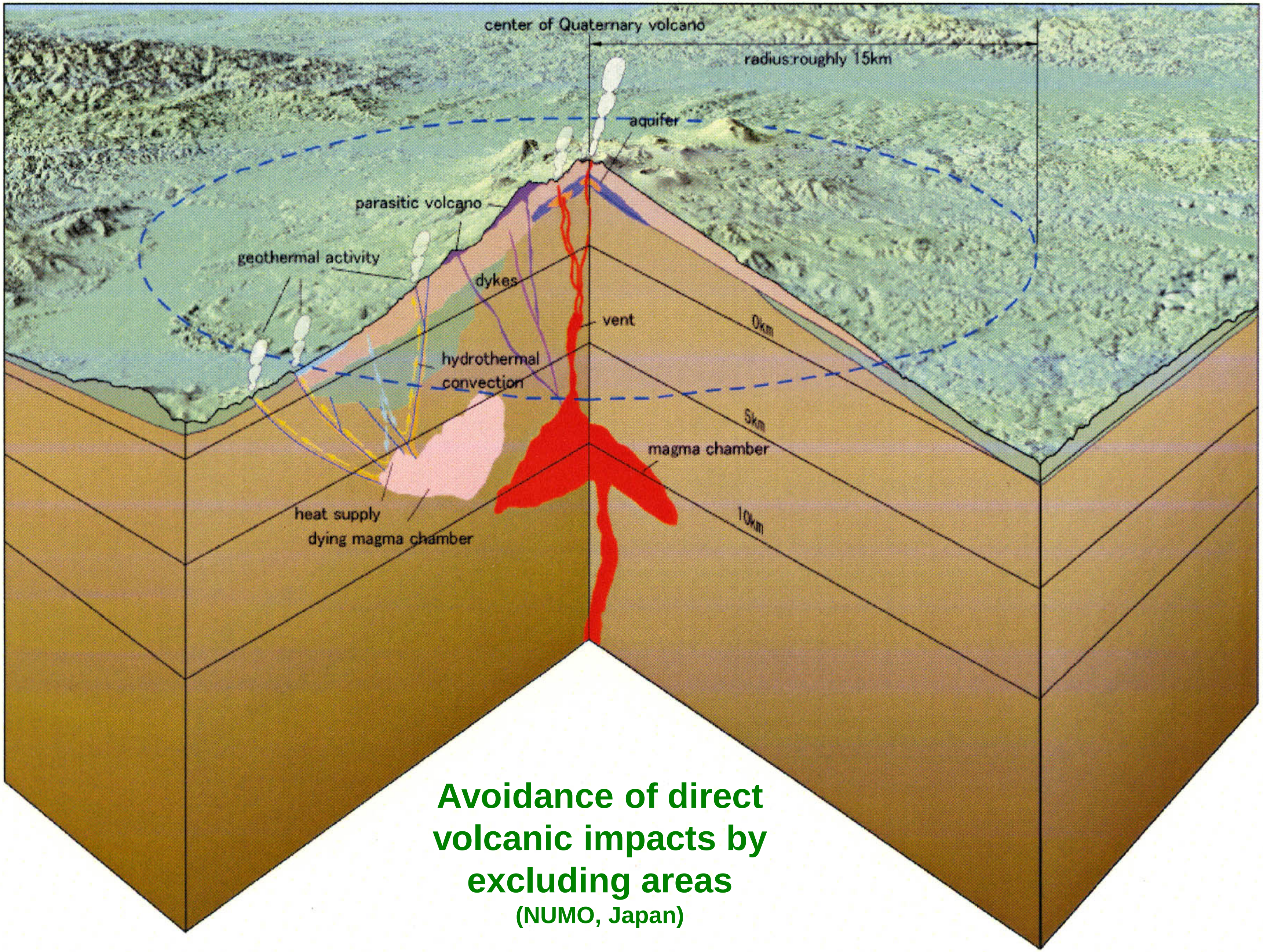
Image: USDOE

Yucca Mountain

Precariously balanced rocks

Exposed surfaces dated using cosmogenic isotopes

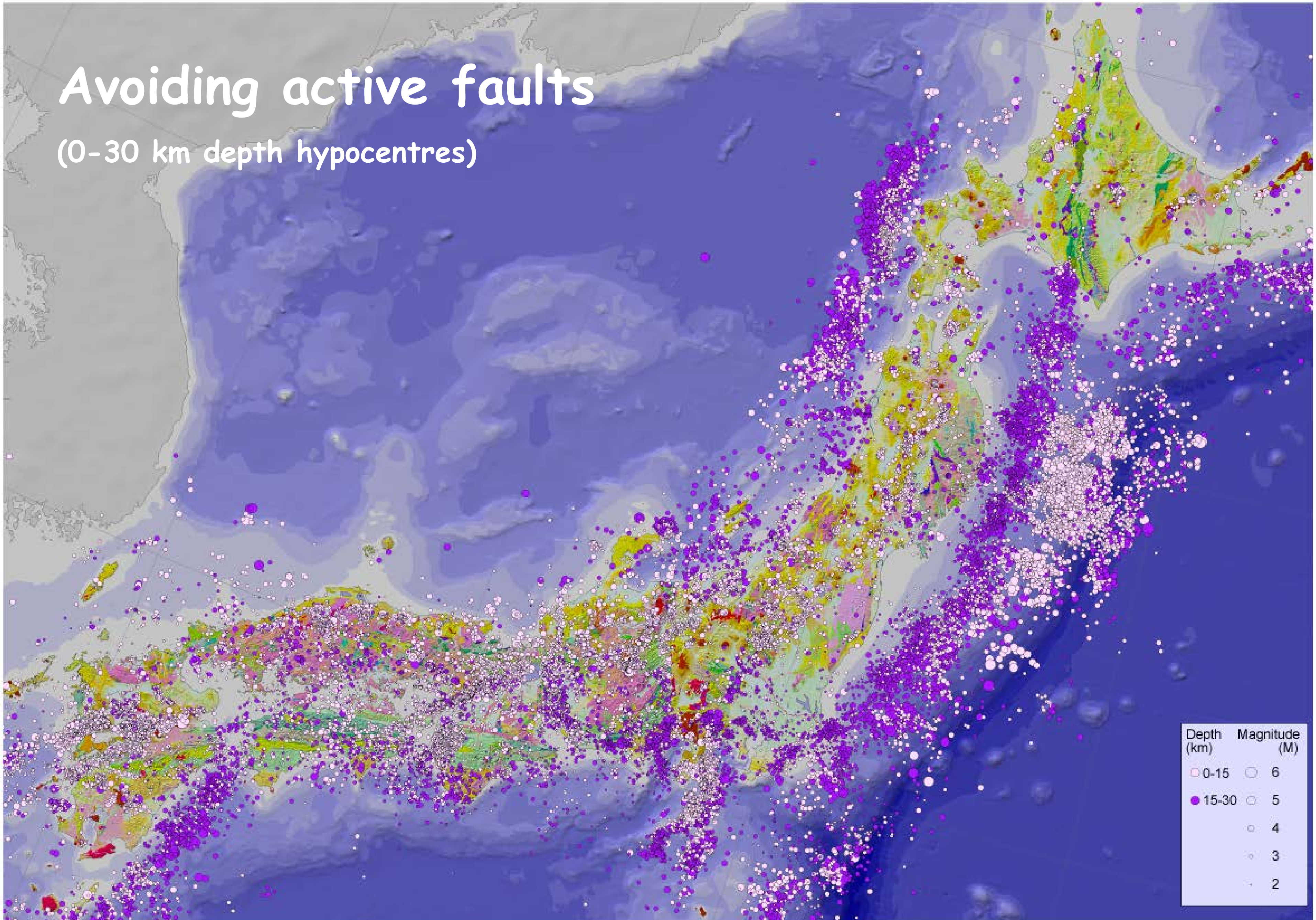
Modelling tests fragility to different degrees of ground shaking (related to earthquake magnitude)



Avoidance of direct volcanic impacts by excluding areas
(NUMO, Japan)

Avoiding active faults

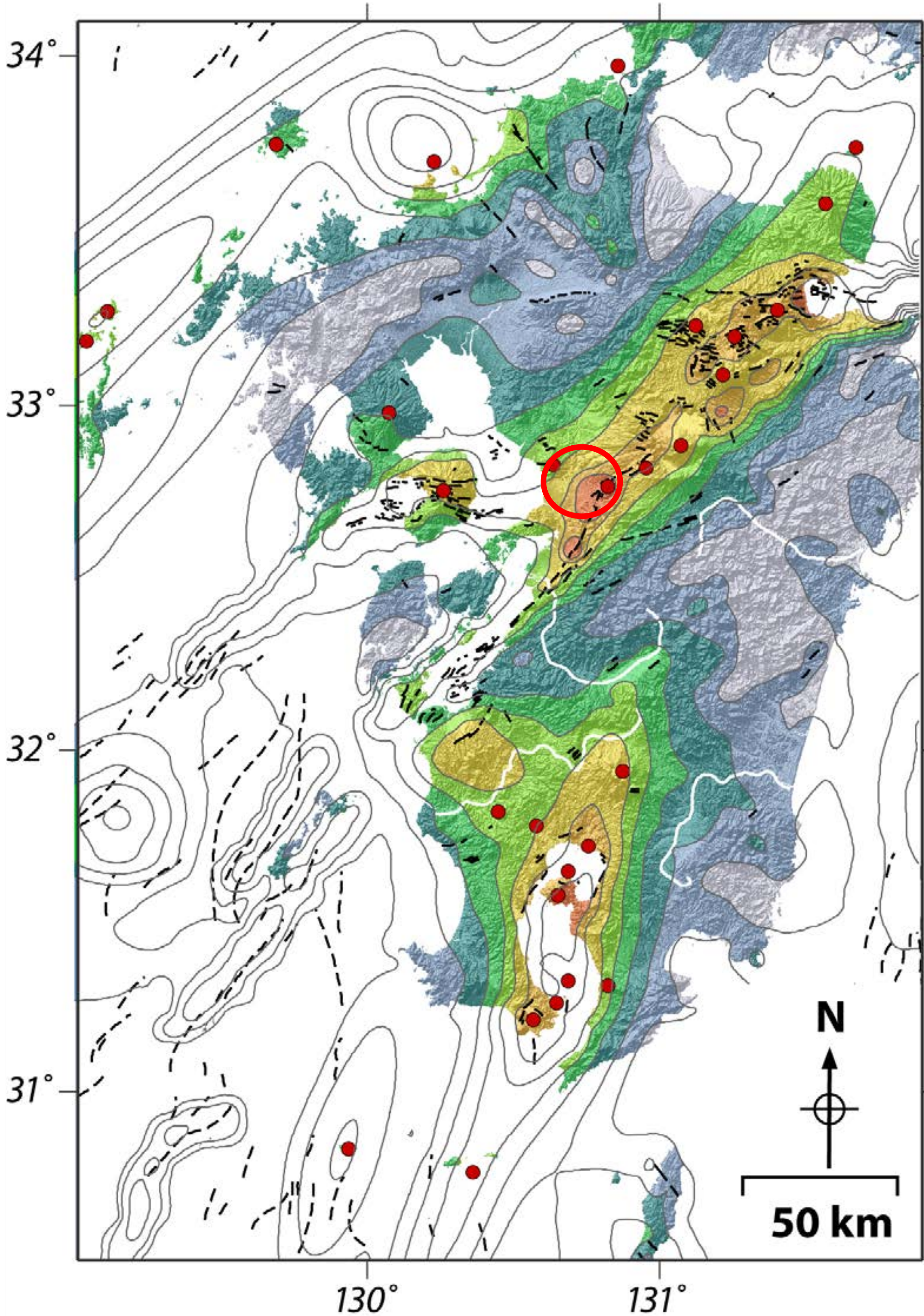
(0-30 km depth hypocentres)



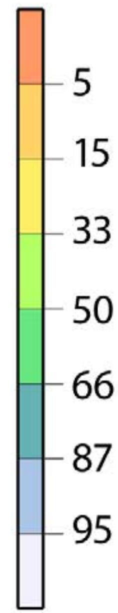
Neodani fault at Midori, October 1891, M8 event

6m vertical, 3m horizontal displacement

Photo: B Koto



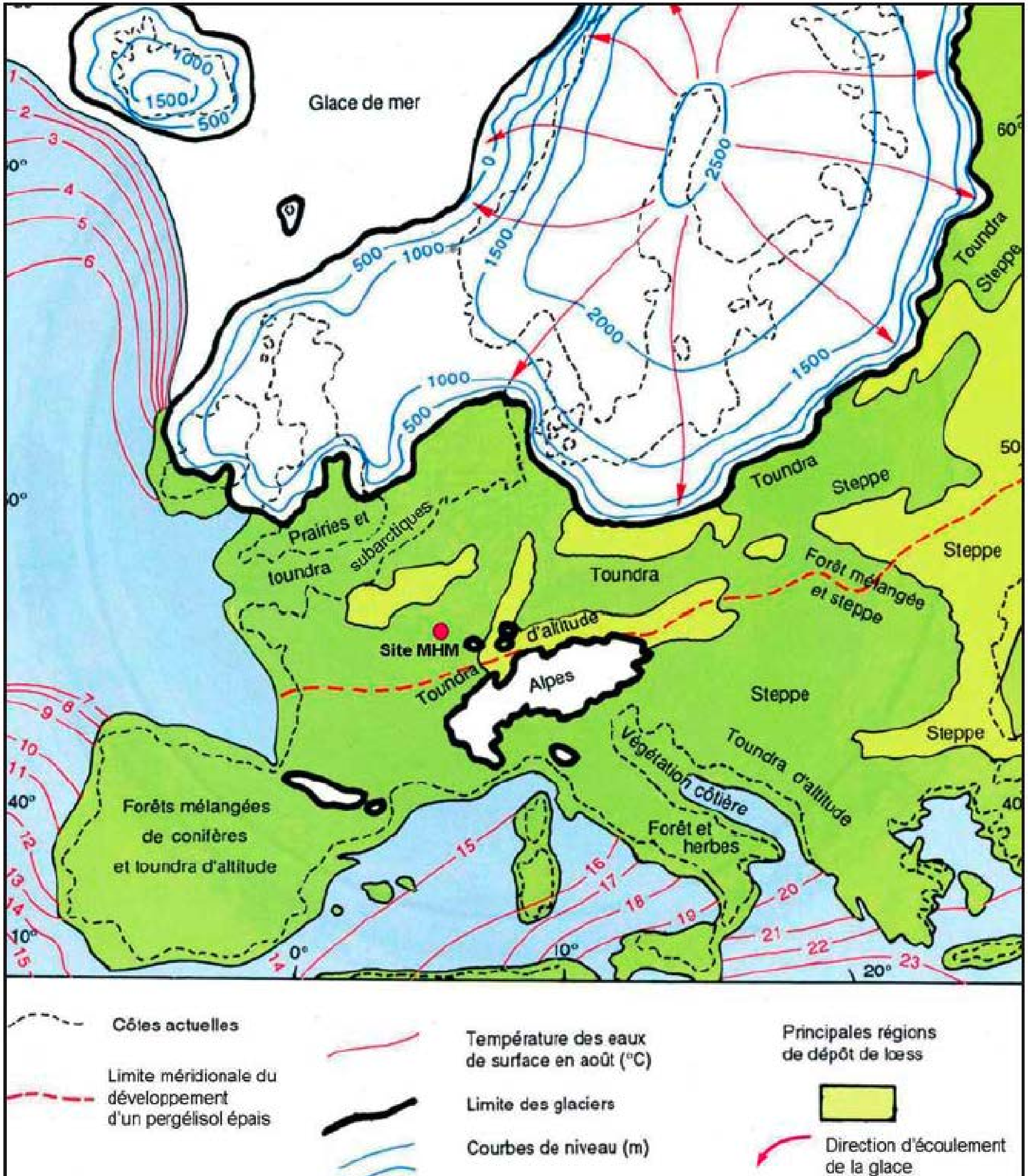
Relative Hazard from Volcano Spatial Density + Combined Tectonic Strain (gps, fault, seismic) (%)



Kyushu, Japan

Probabilistic Tectonic Hazard Map

April 2016 M_W 7



Europe 18,000 years ago

Thick ice sheets

Extensive permafrost

Sea level as low as -165 m

Followed by very rapid deglaciation

Likely to occur again (several times over next 1 Ma)

Image: ANDRA

Post-Glacial Faulting Sweden

….major earthquakes about 9000 years ago

Pärvie Fault: 150 km long

M_W 8

Source: Lagerbäck and Sundh, 2006

Copper and cast-iron containers for geological disposal of spent nuclear fuel: Sweden and Finland

- surrounded by clay buffer
- 450 m deep in granites/gneisses
- 5 - 10 cm shear?
- when will the next glaciation come
  - 50,000 years
  - 250,000 years?

What might we conclude?

- many technological facilities and much of Earth's population are exposed to natural hazards
  - *that exposure is growing with population and the need for energy*
- nuclear facilities are sited and built to rigorous international safety standards for natural hazards
  - more than 13,000 plant-years of safe operating experience
- how those standards are applied, updated and monitored is a matter of national cultures and practices
  - Fukushima taught us how badly things can go wrong if we don't use scientific knowledge appropriately
- even though the radiological health consequences are tiny, our sensitisation to all things nuclear means that the objective impacts have been huge
- ……..and we need to be humble in the face of nature

…some further reading