

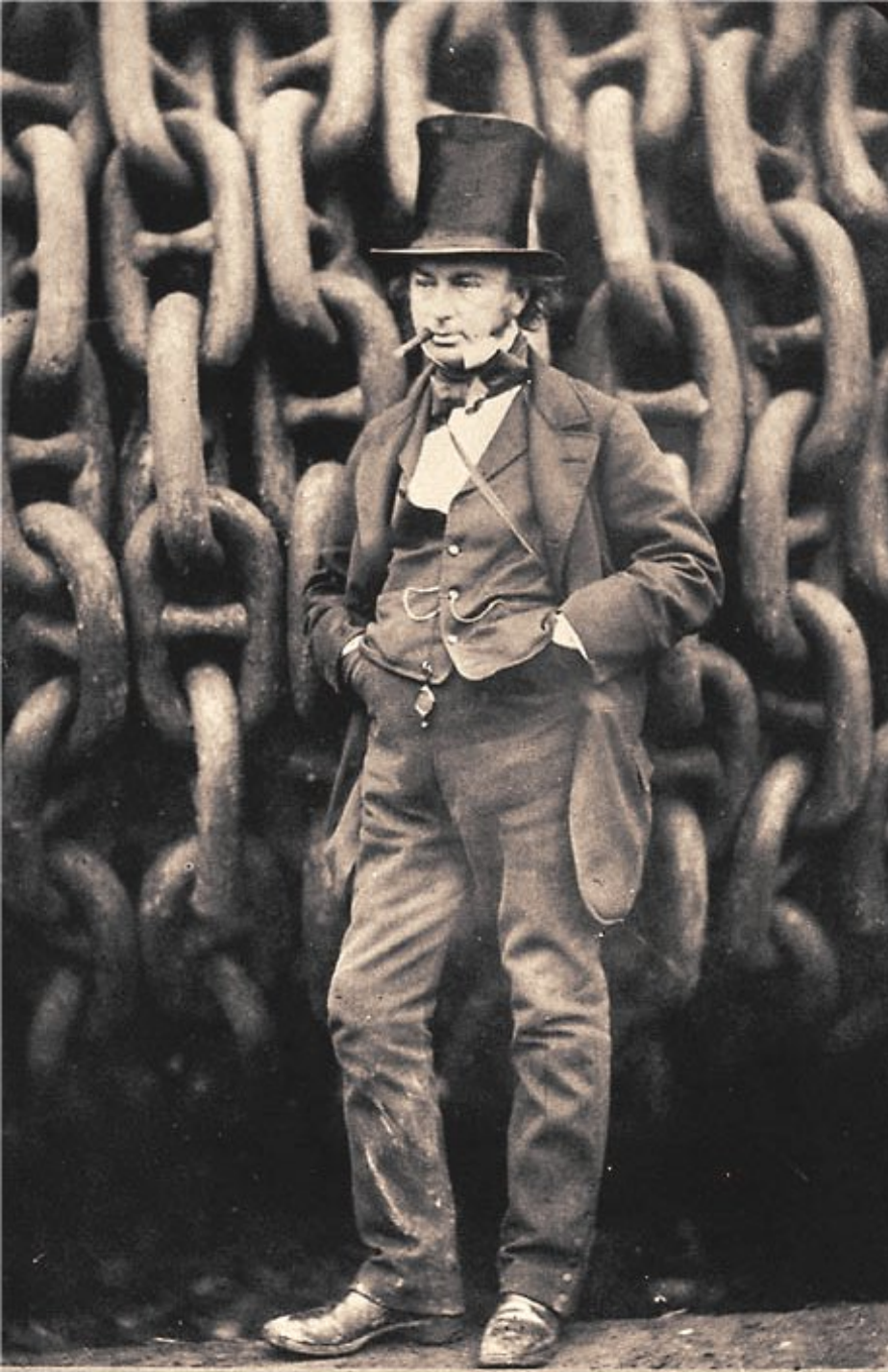
# Managing Nuclear Power on a Dynamic Earth

A scenic view of a lake at sunset or sunrise. The sky is filled with dark, heavy clouds, with a bright glow on the horizon where the sun is setting or rising. In the foreground, there is a small boat docked on the left side of the lake. The water is calm, reflecting the light from the sky. In the distance, a nuclear power plant is visible, with several large cylindrical structures and tall chimneys. The overall atmosphere is serene and somewhat somber due to the dark clouds.

*Neil Chapman*

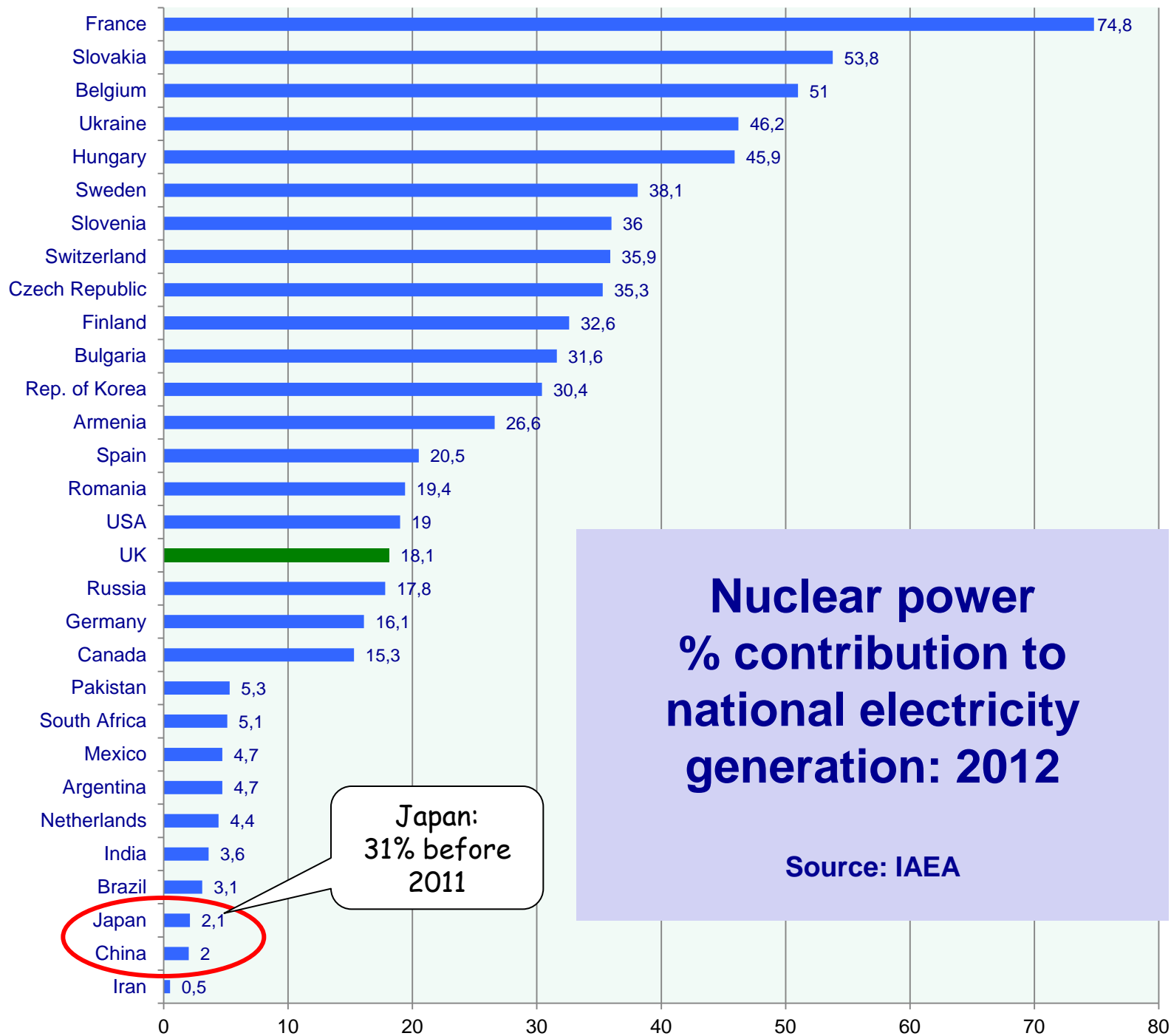
*MCM Switzerland*

*University of Sheffield, UK*



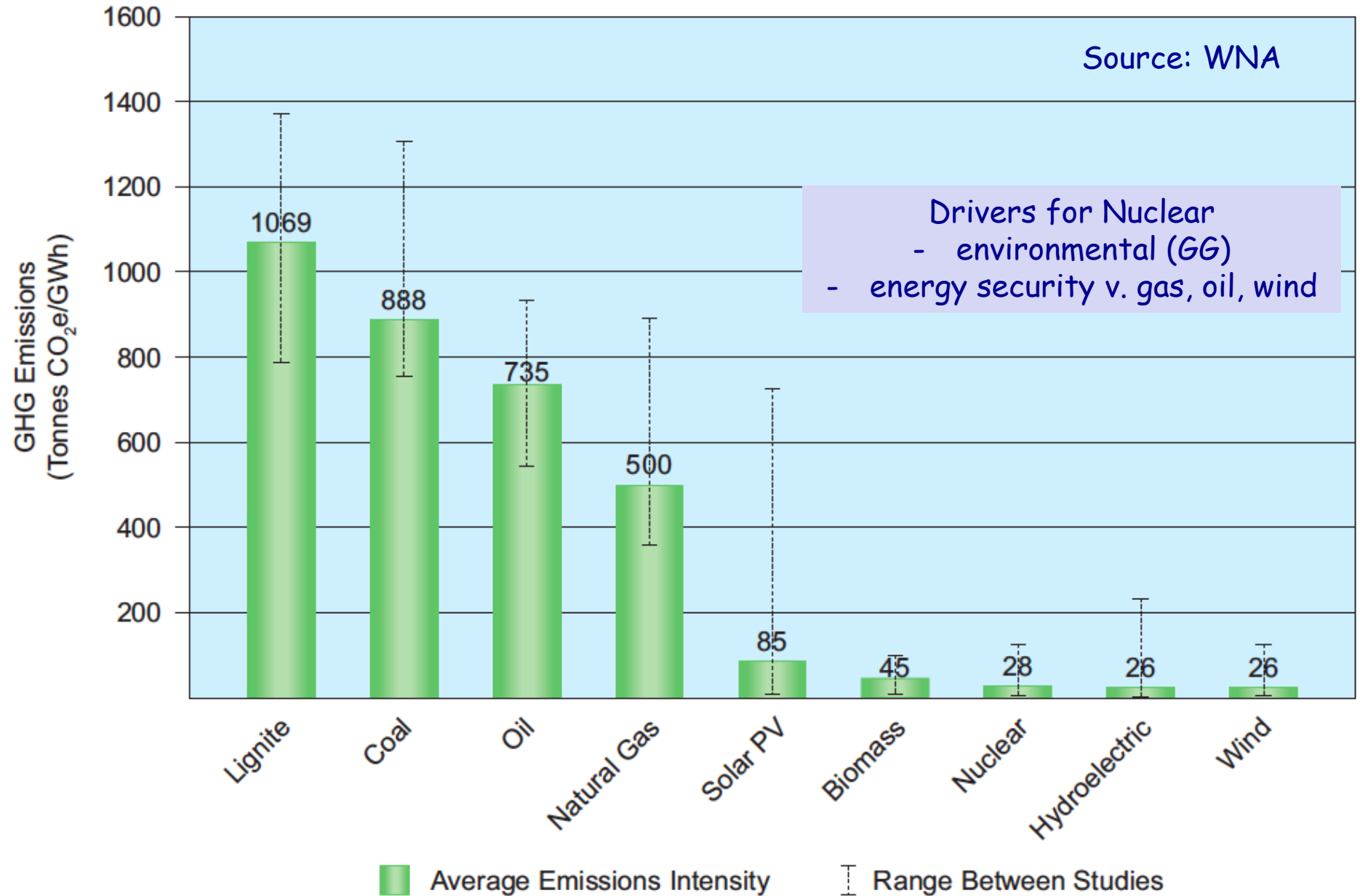
*.....I must observe that no man can be more sensible than I am of the great advantage it would be to me as a civil engineer to be better acquainted with geology.....*

I.K. Brunel, June 1842



# Greenhouse gas emissions

Source: WNA





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



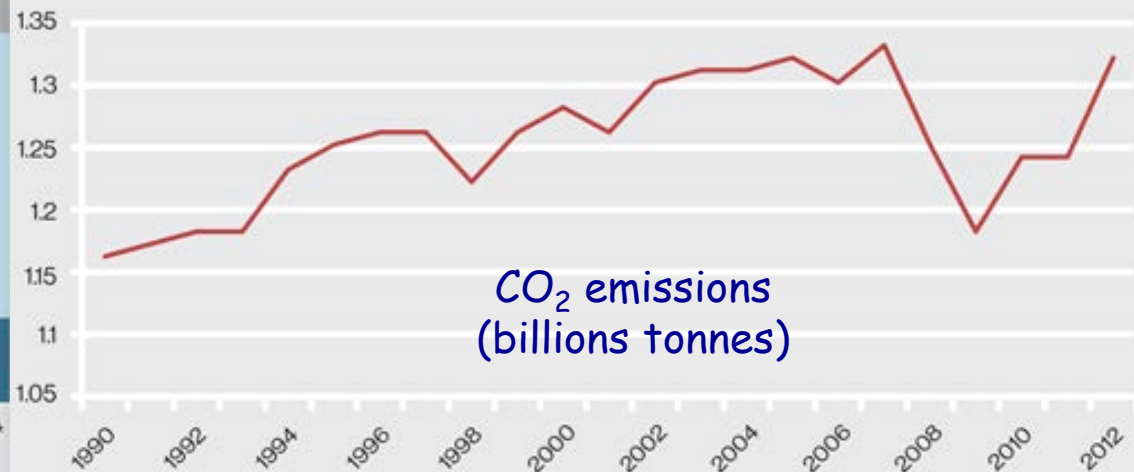
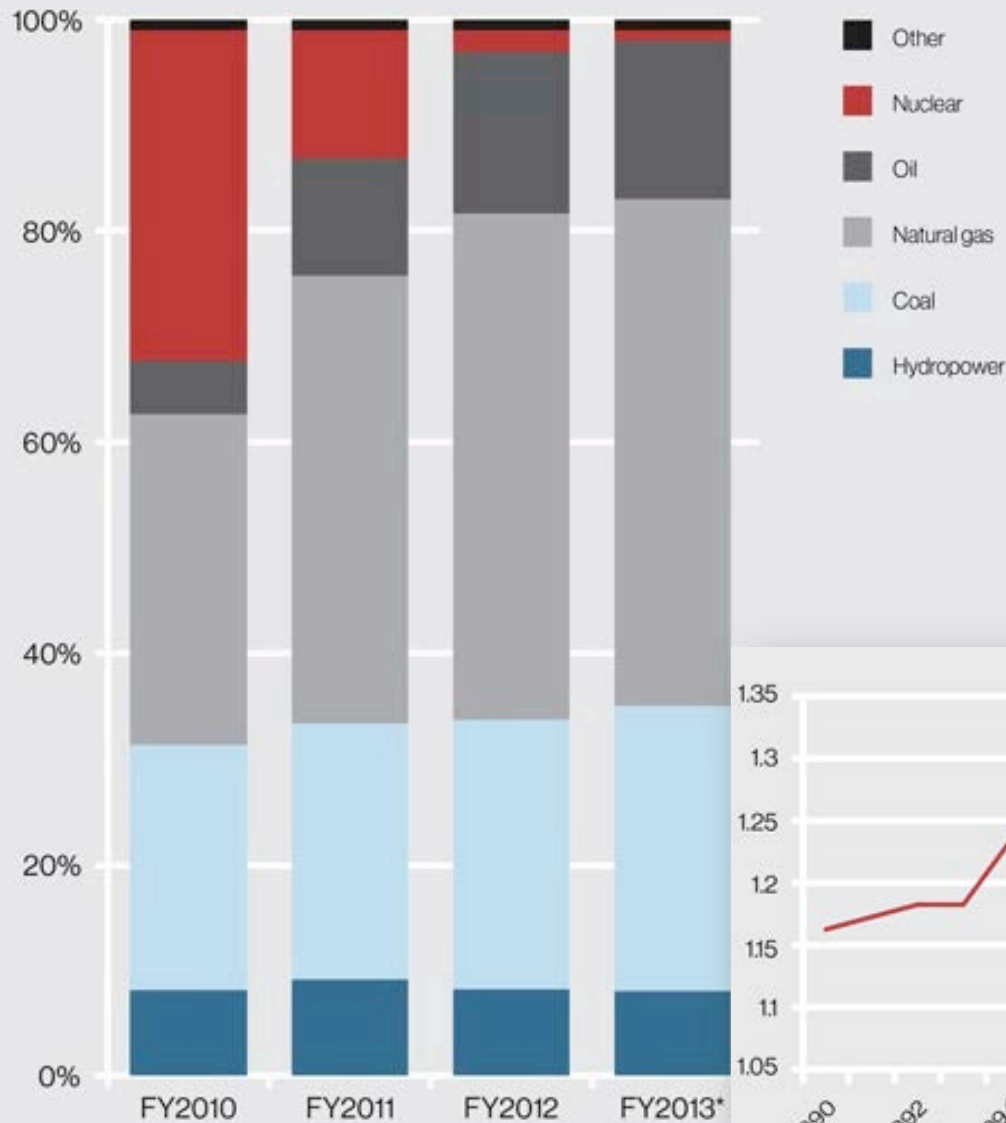
11 NPPs were operating in the region and shut down automatically when the earthquake struck, but....



## Japan's electricity supply, post-Fukushima

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

Source: MIT Technology Review



CO<sub>2</sub> emissions  
(billions tonnes)

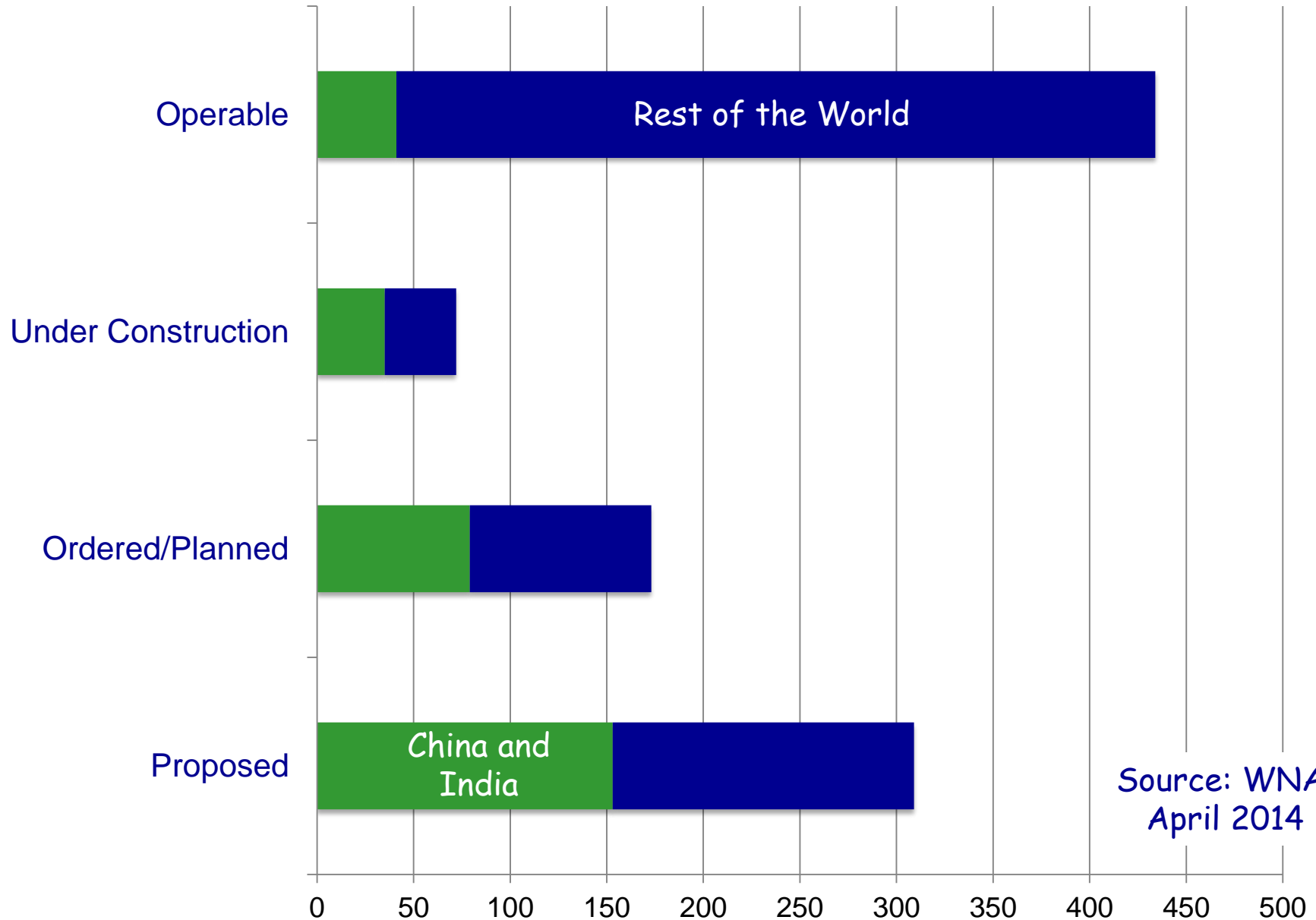
# Nuclear Power

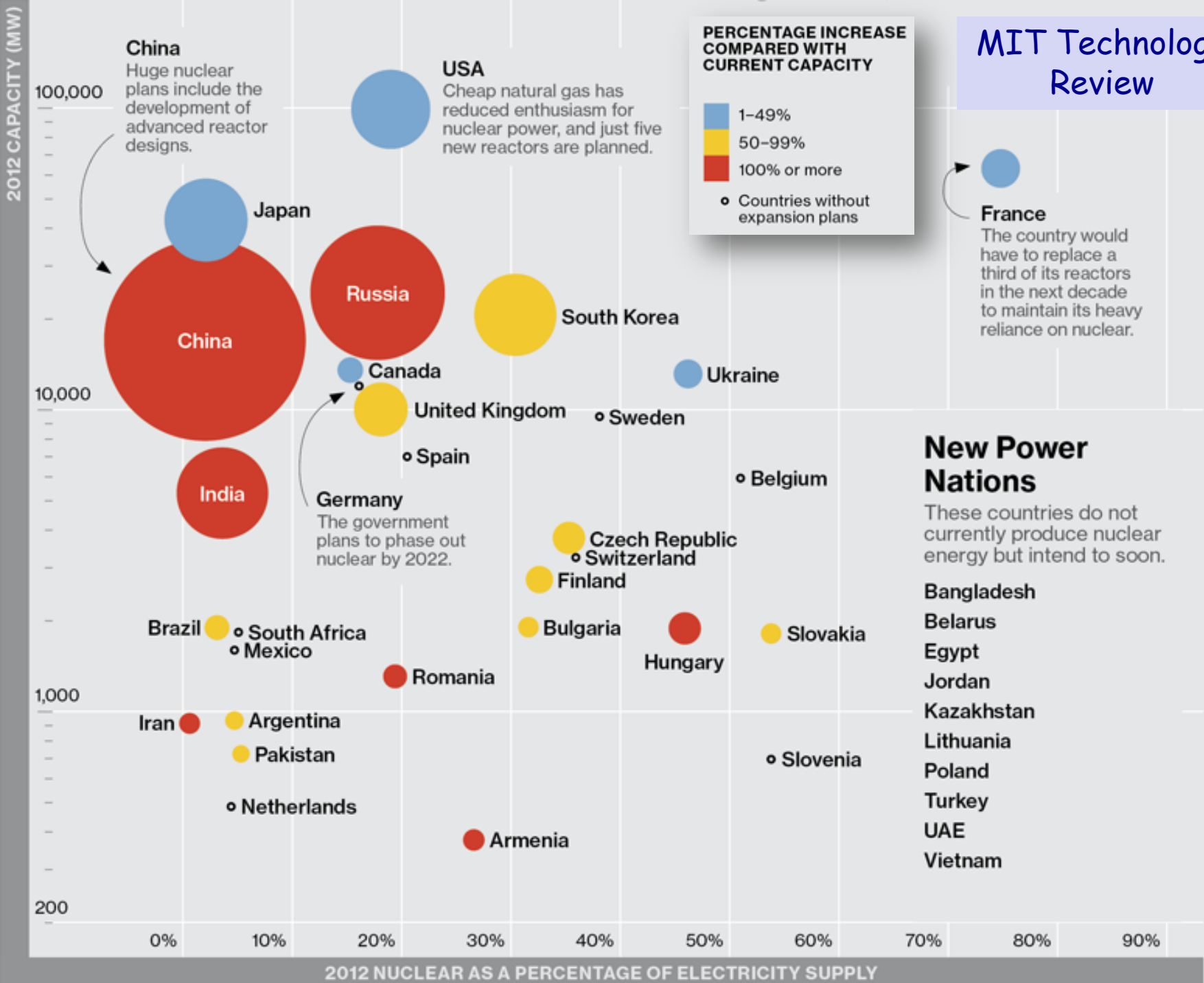
How much do we use it and  
where.....?

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

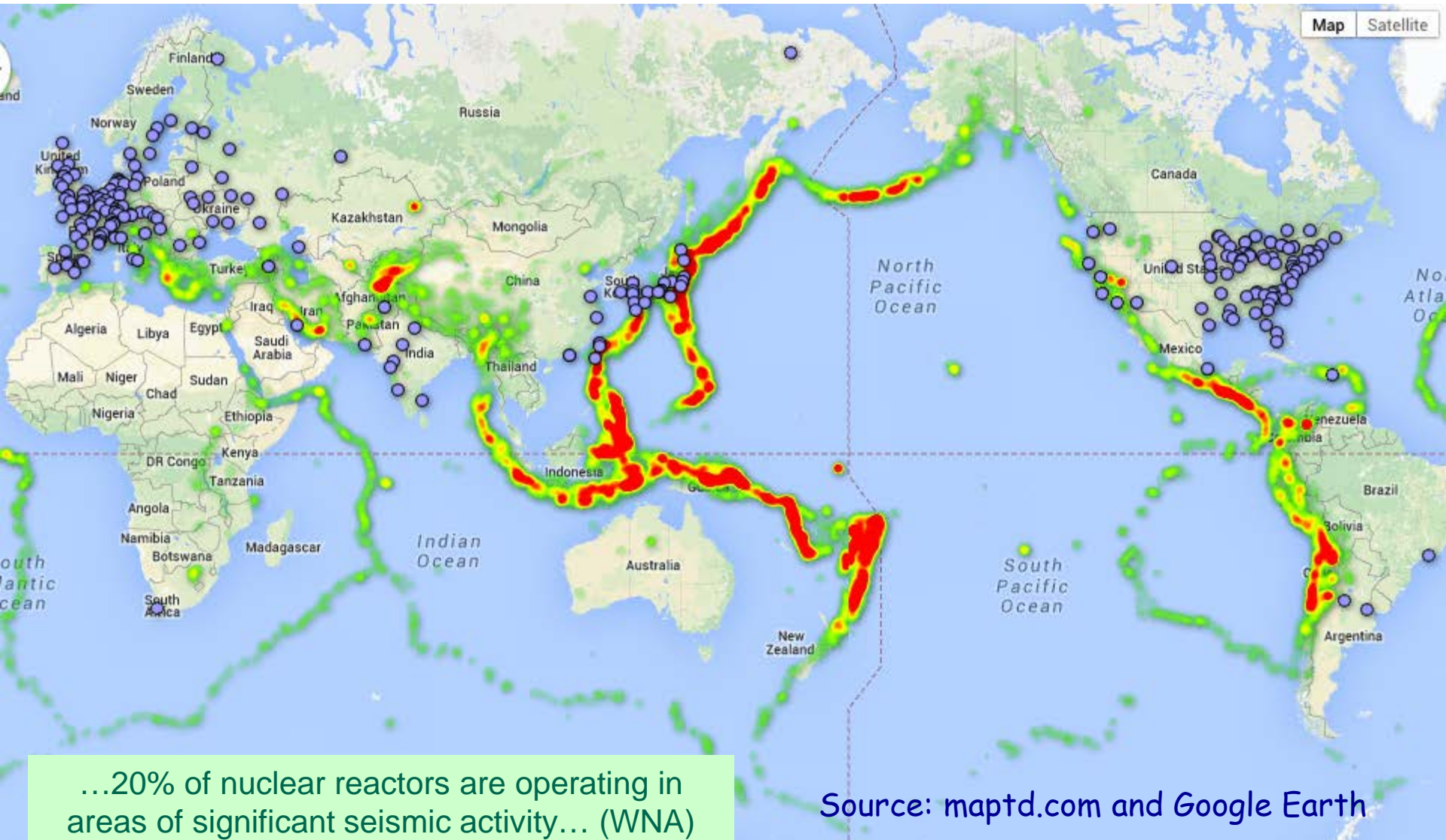


# Nuclear Power Plants Worldwide by 2030

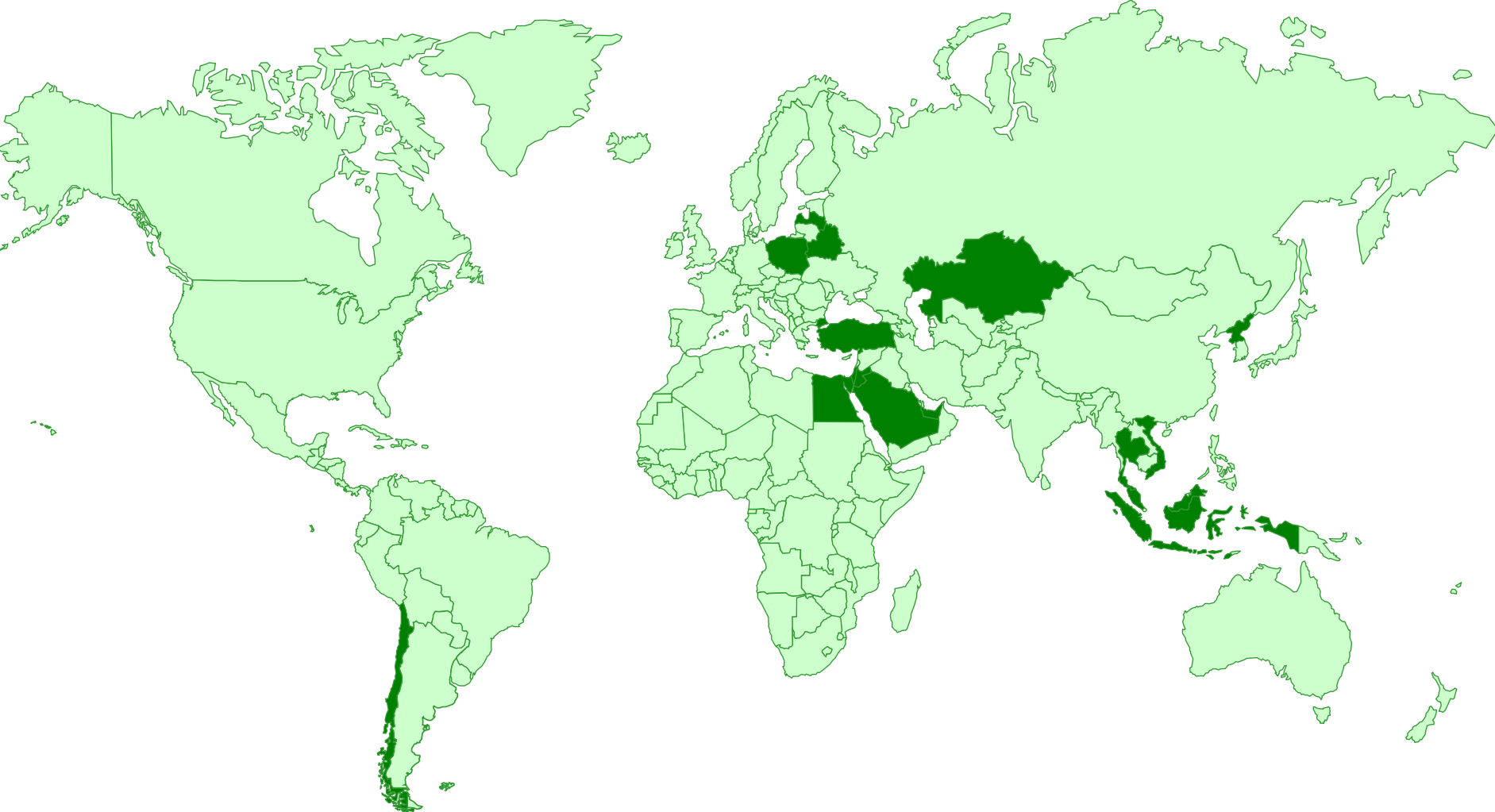




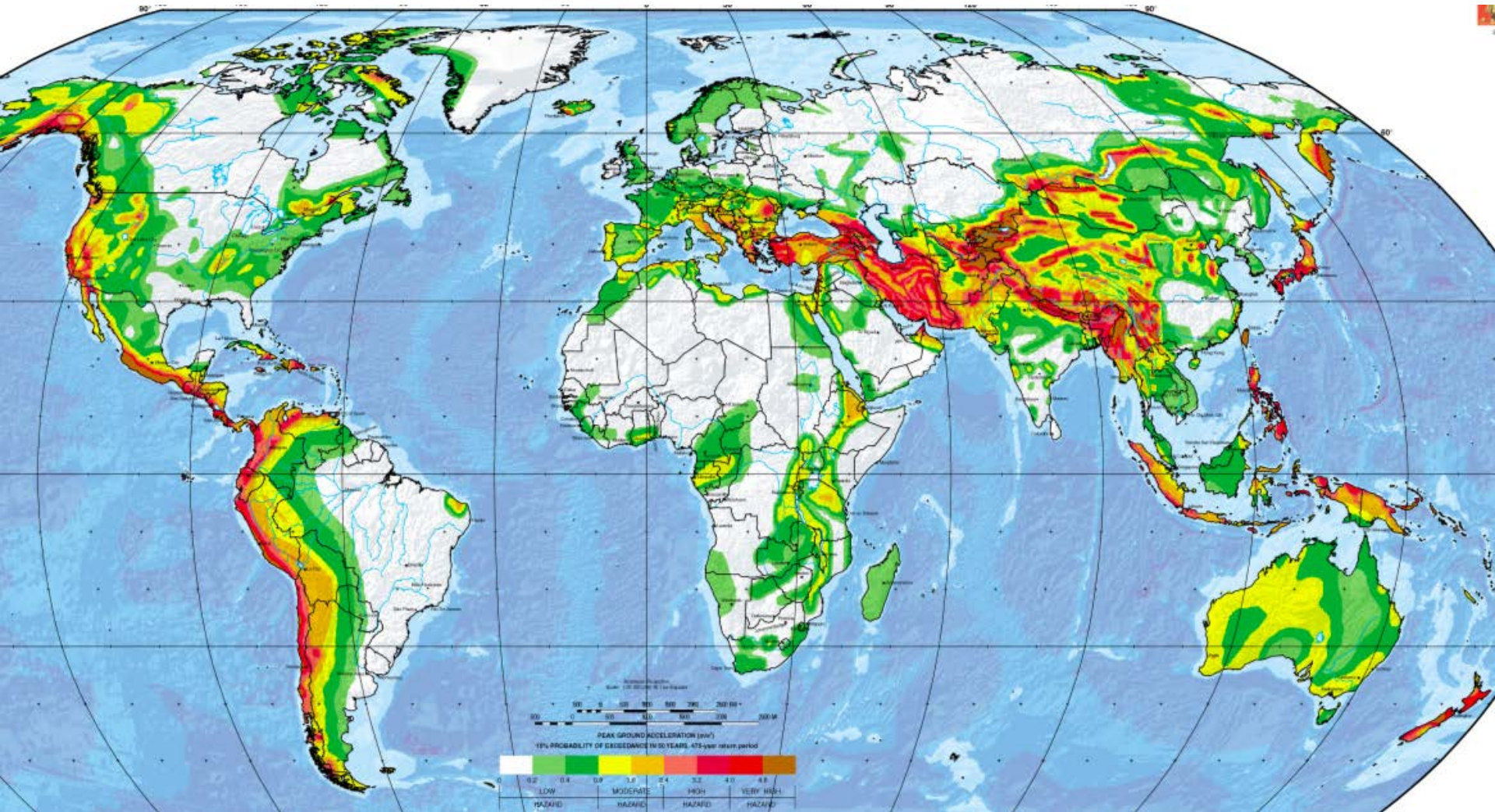
# Nuclear Power Plants



**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



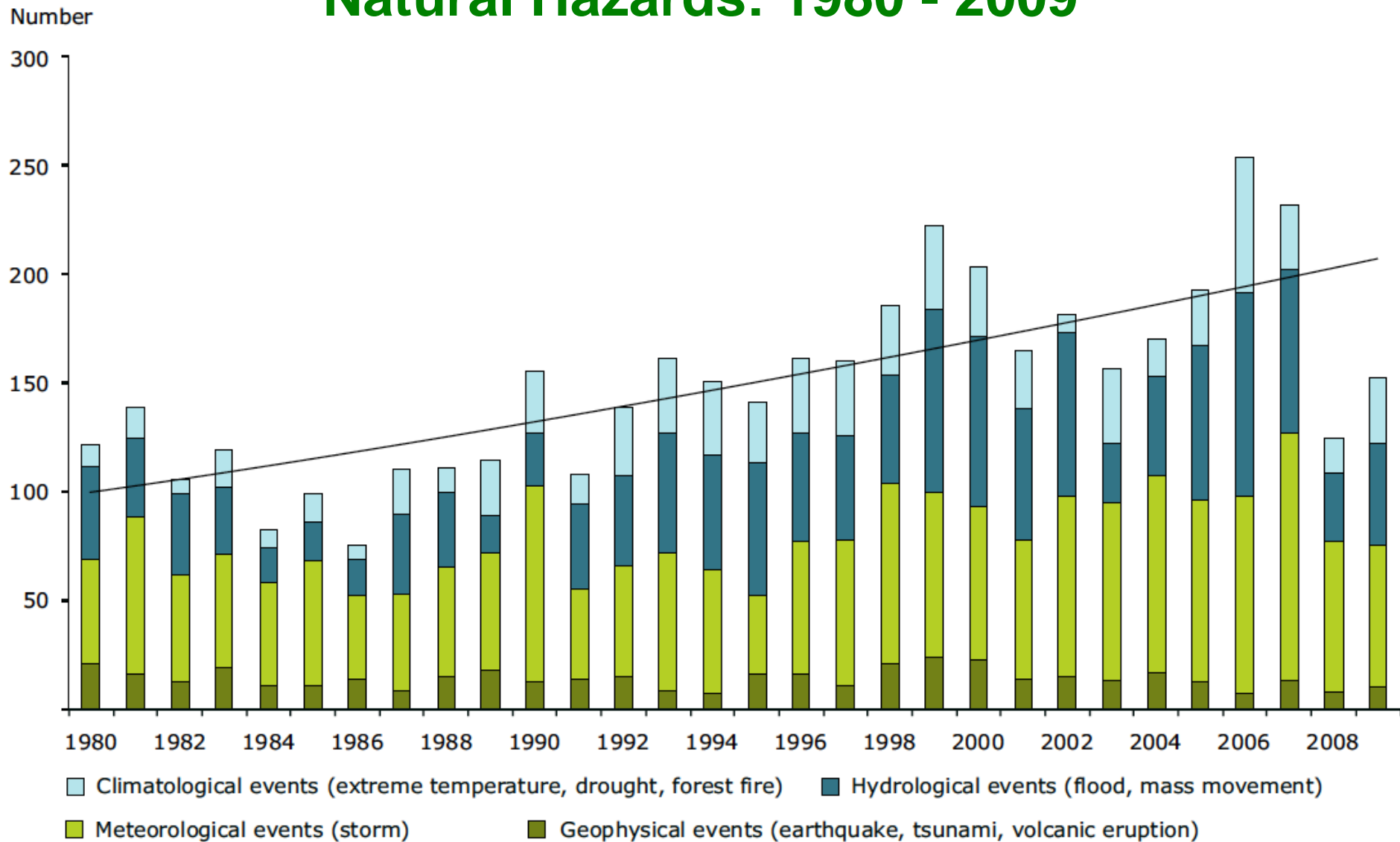
## Risk

- 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

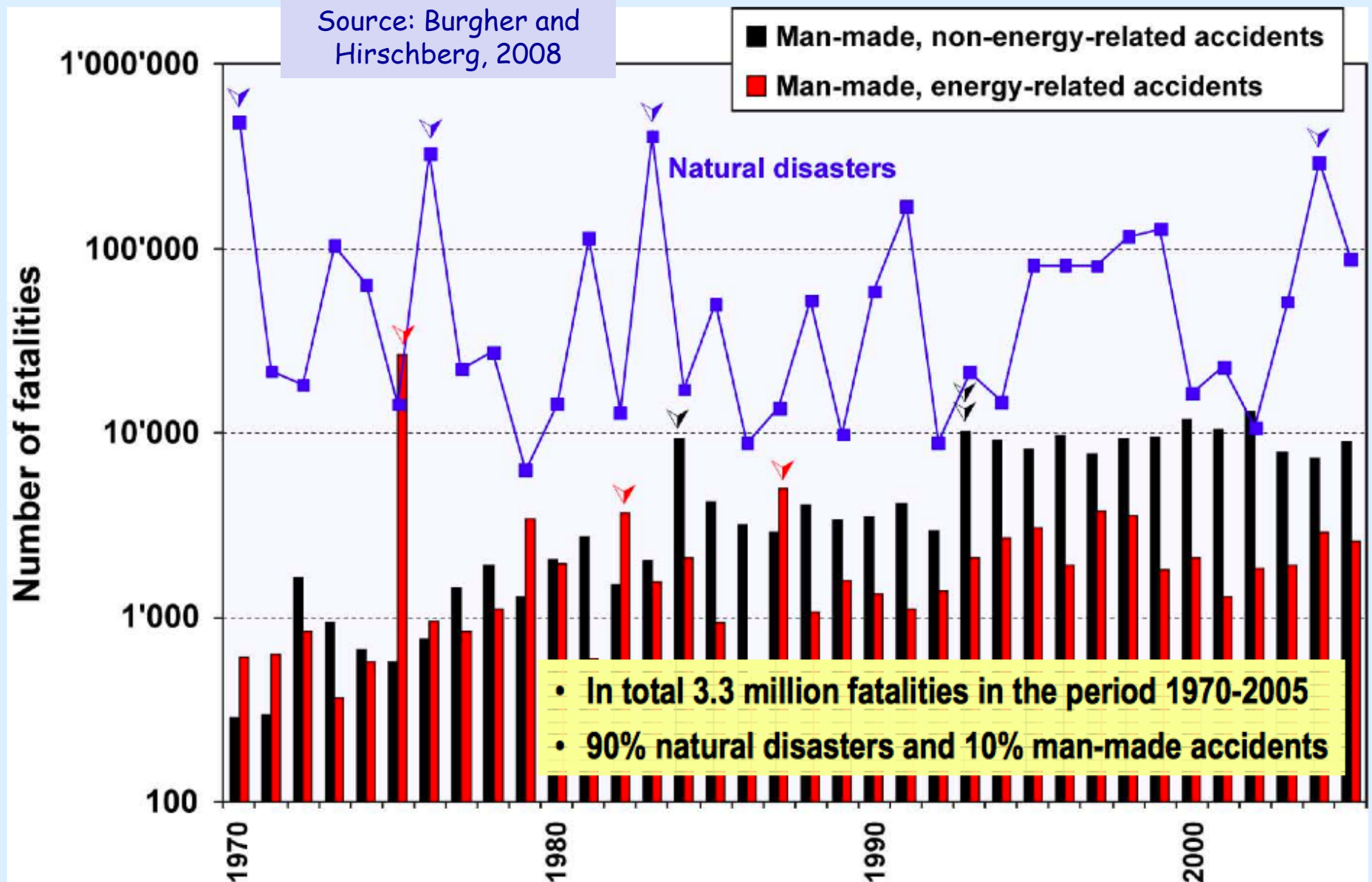
# Disasters in European Economic Area due to Natural Hazards: 1980 - 2009



Source: European Environment Agency, 2010



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



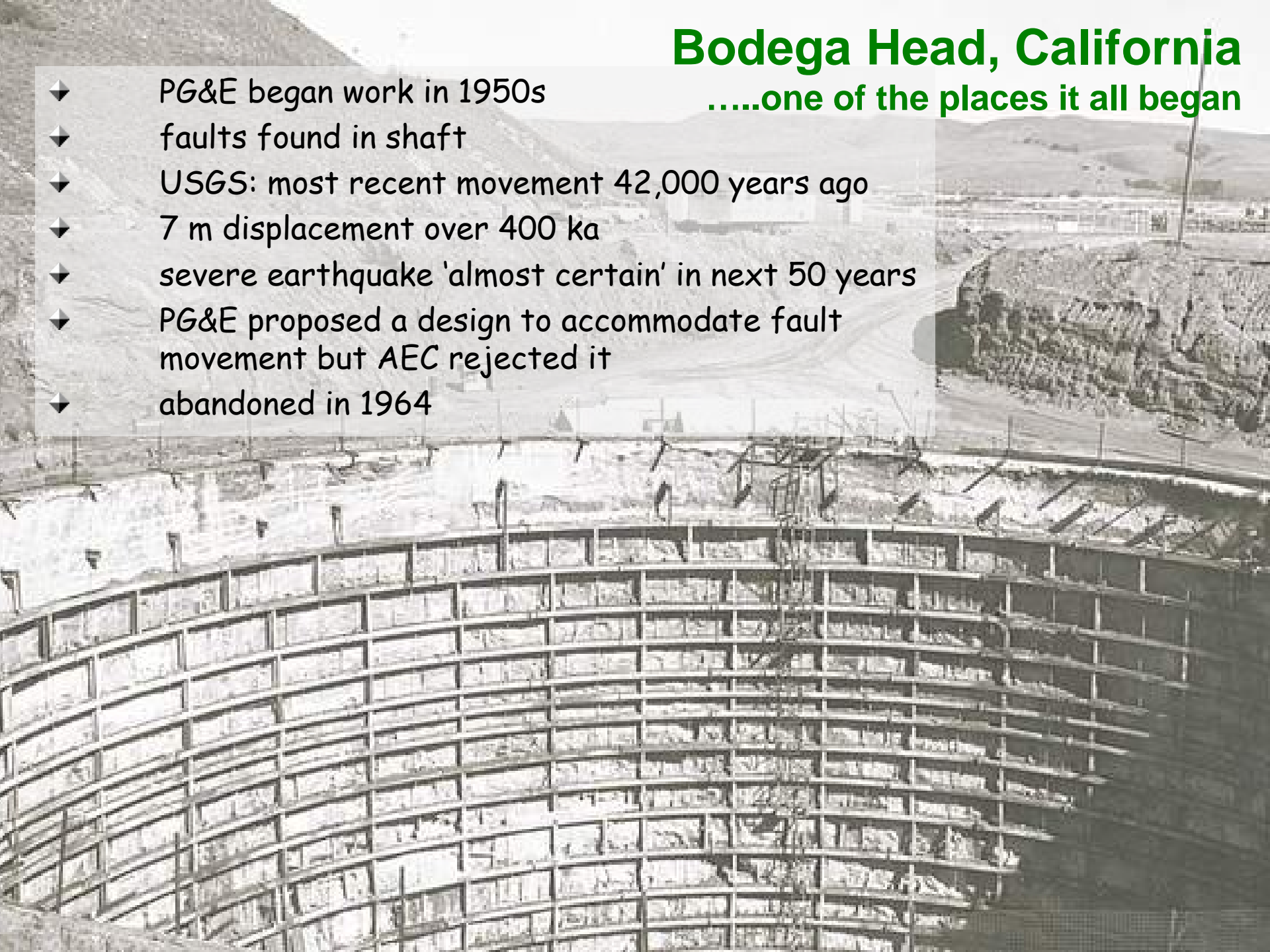
# Fukushima health impacts: United Nations UNSCEAR report, 2014

- ◆ ...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

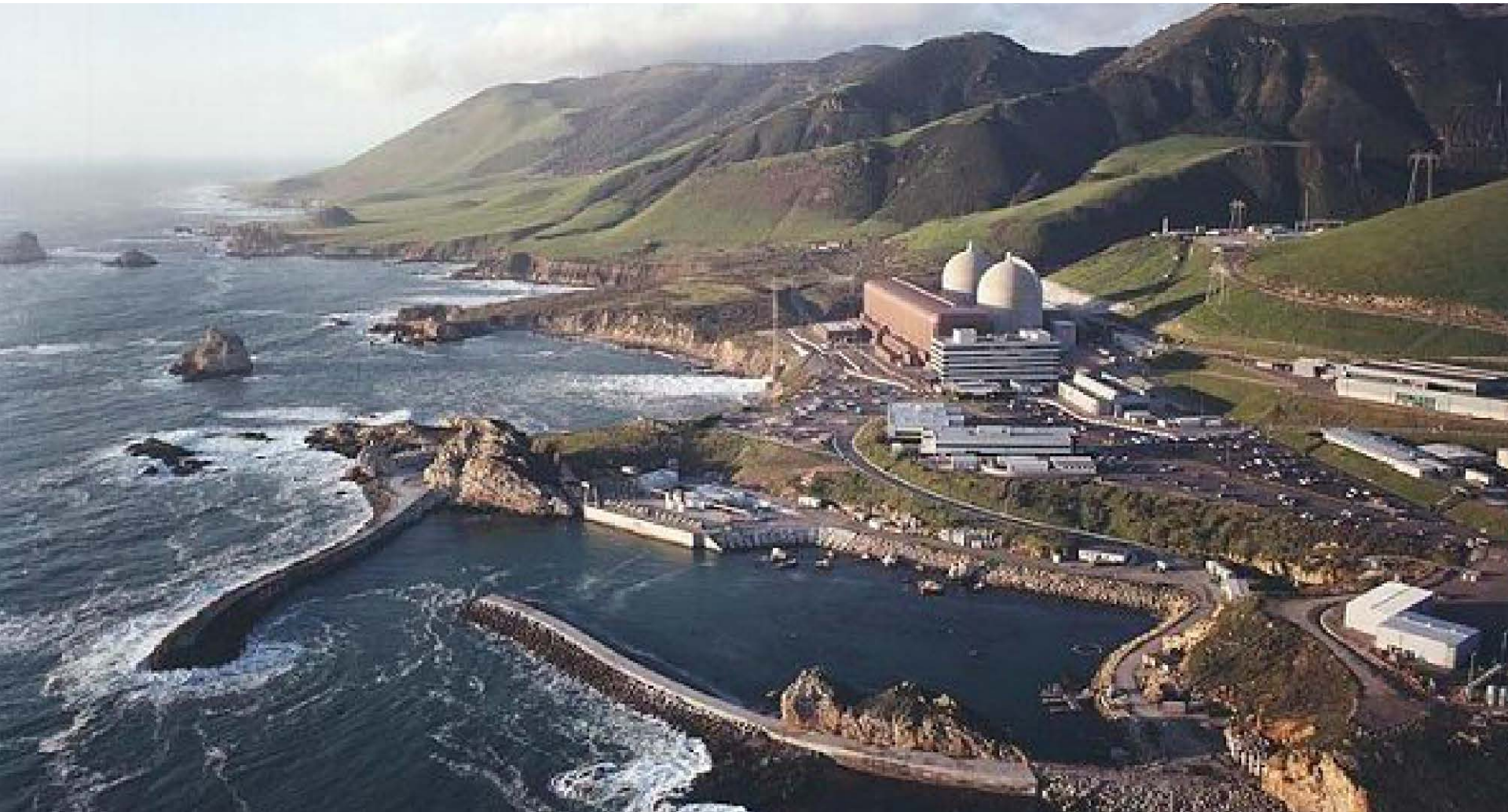
# Bodega Head, California

.....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



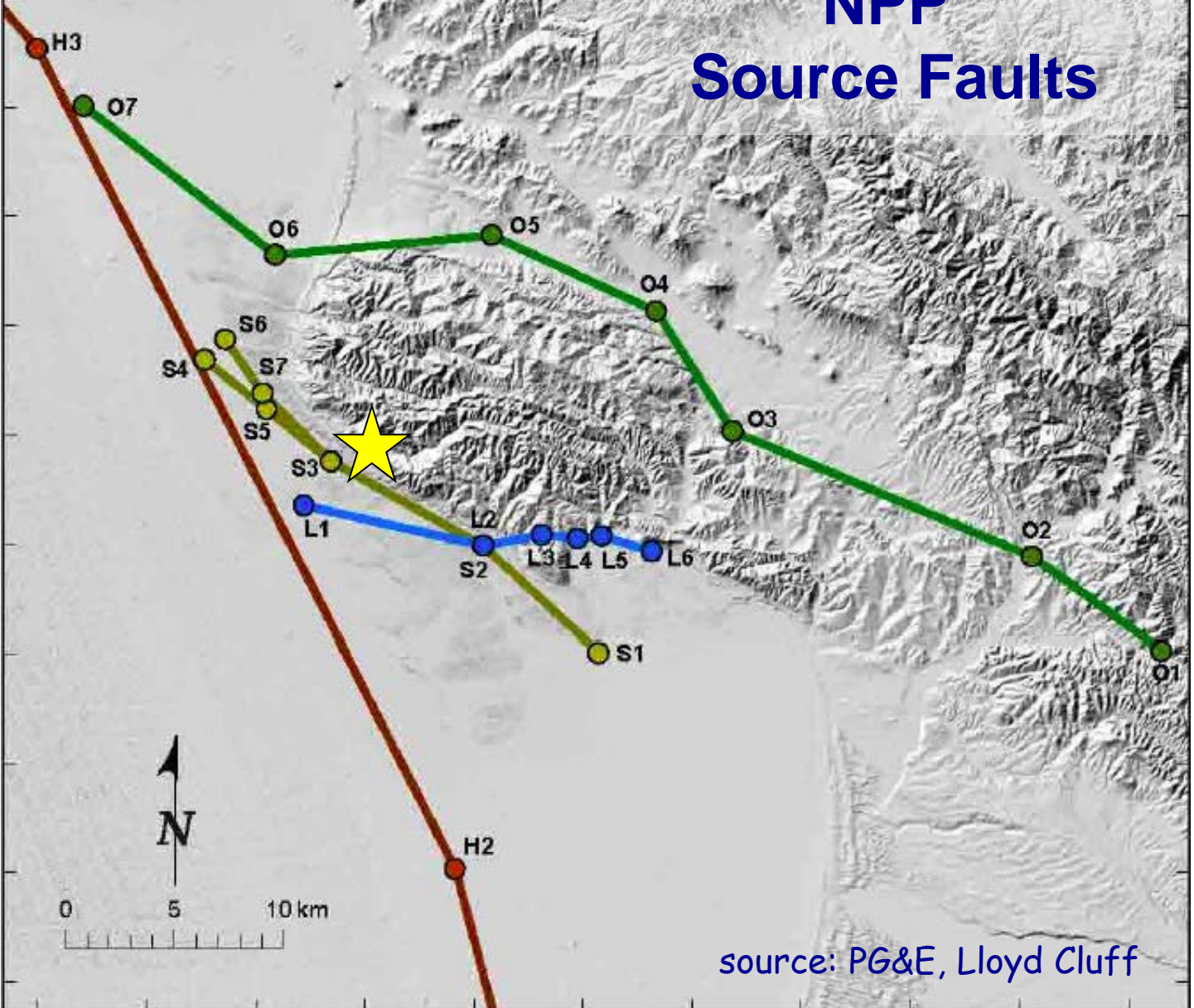
The Diablo Canyon NPP, California, USA, looking north along the coast. The Hosgri fault zone lies about 5 km offshore



# 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

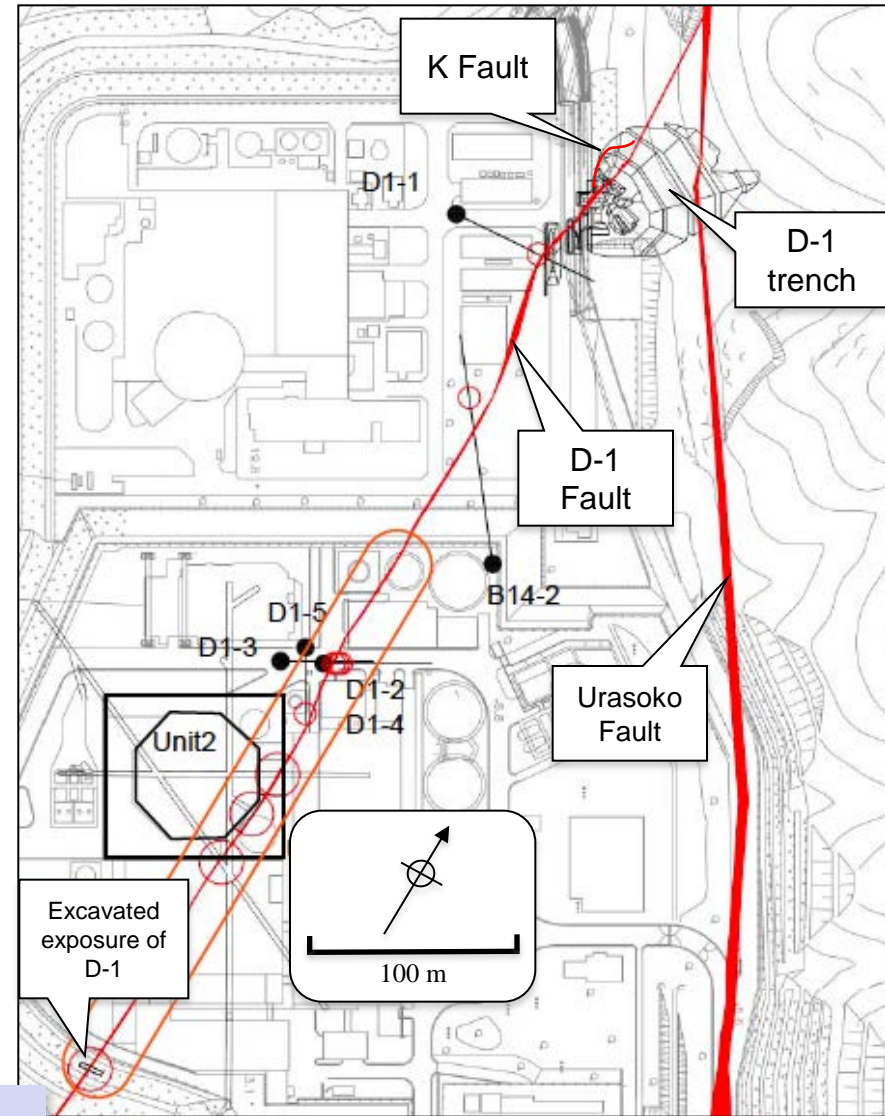
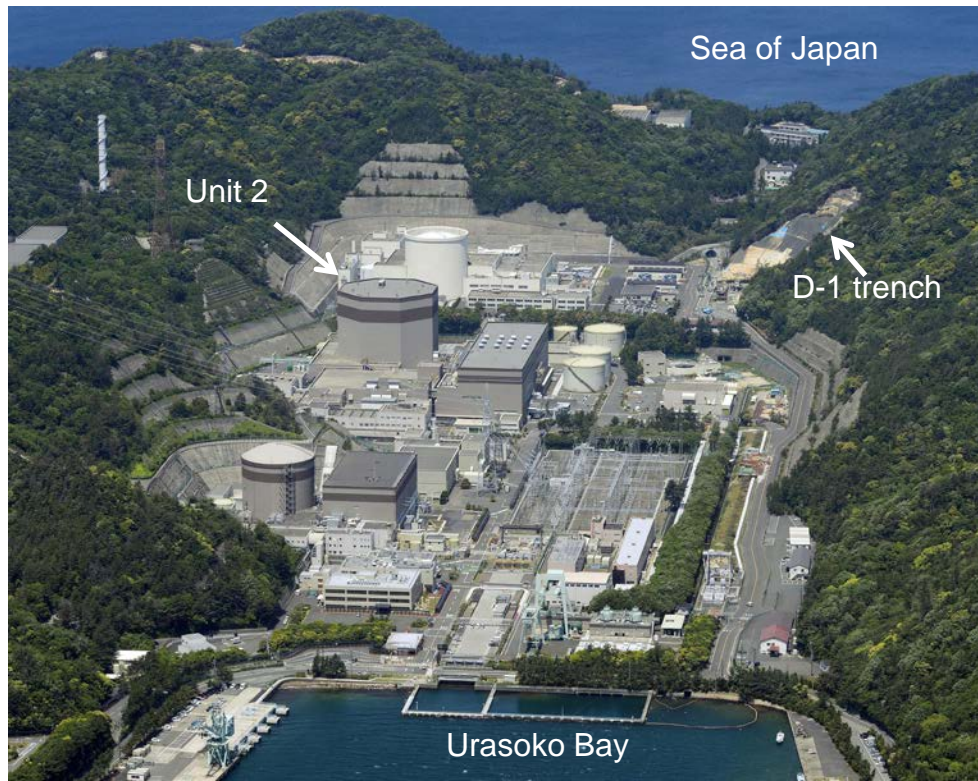
# The process that developed at Diablo Canyon

- 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







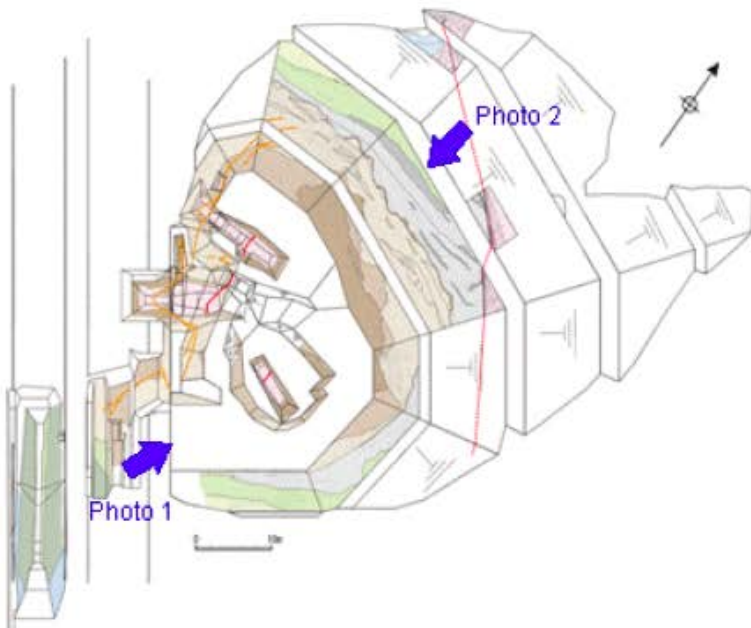
## Tsuruga NPP, Japan

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

# Trench at Tsuruga NPP, Japan

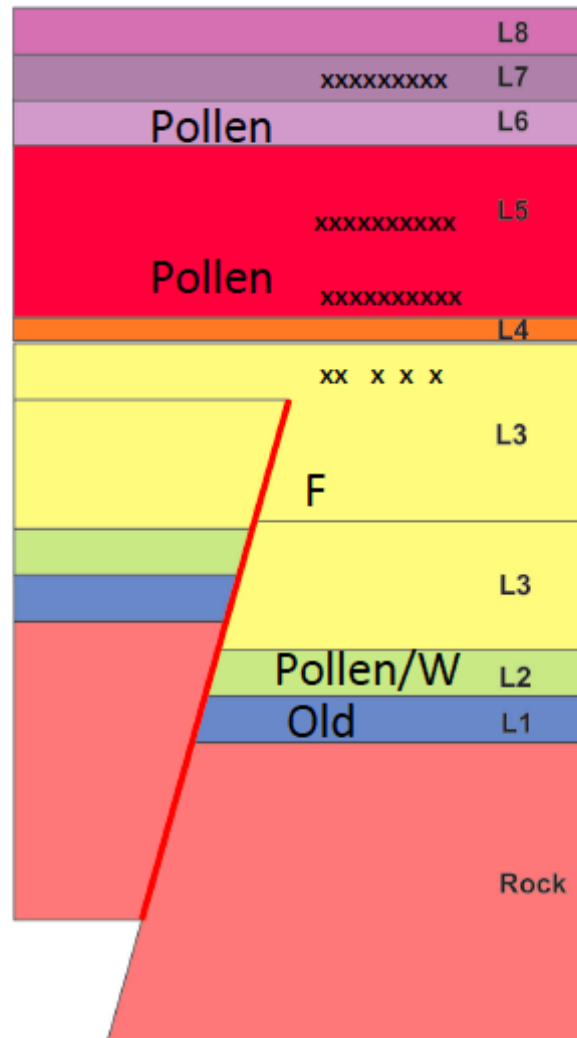


Photo 1



# 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



← DKP – 58 ka  
MIS 5a-c  
MIS 5c  
← K-Tz – 95 ka  
MIS 5e  
← Mihama – 127 ka

MIS 6 (130–200 ka)

MIS 7? – 200-220 ka

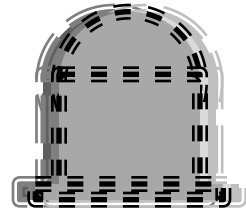
- ◆ pollen analyses
- ◆ volcanic ash (tephra)
- ◆ isotopic evidence



# What tools have we got?

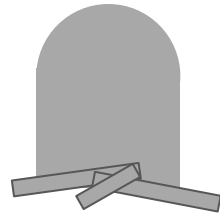
## ➔ Probabilistic Seismic Hazard Analysis

- 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

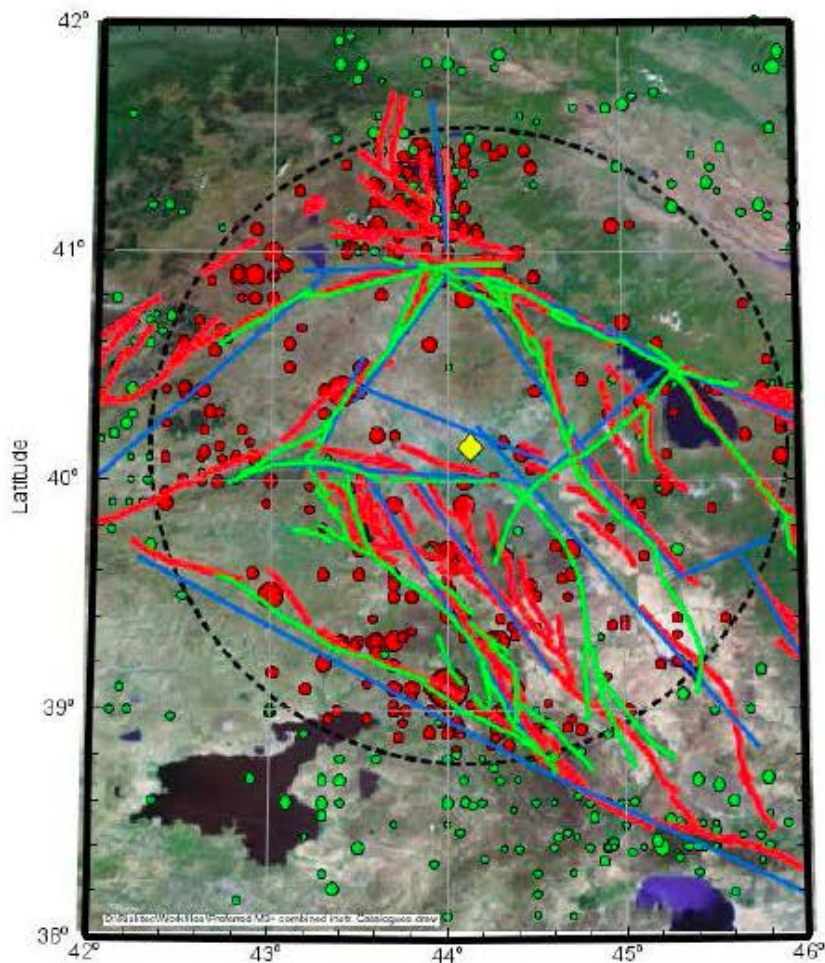
- would any of these cause damage and consequent radiological hazard - if so, what is the RISK?
- how can risks be mitigated?



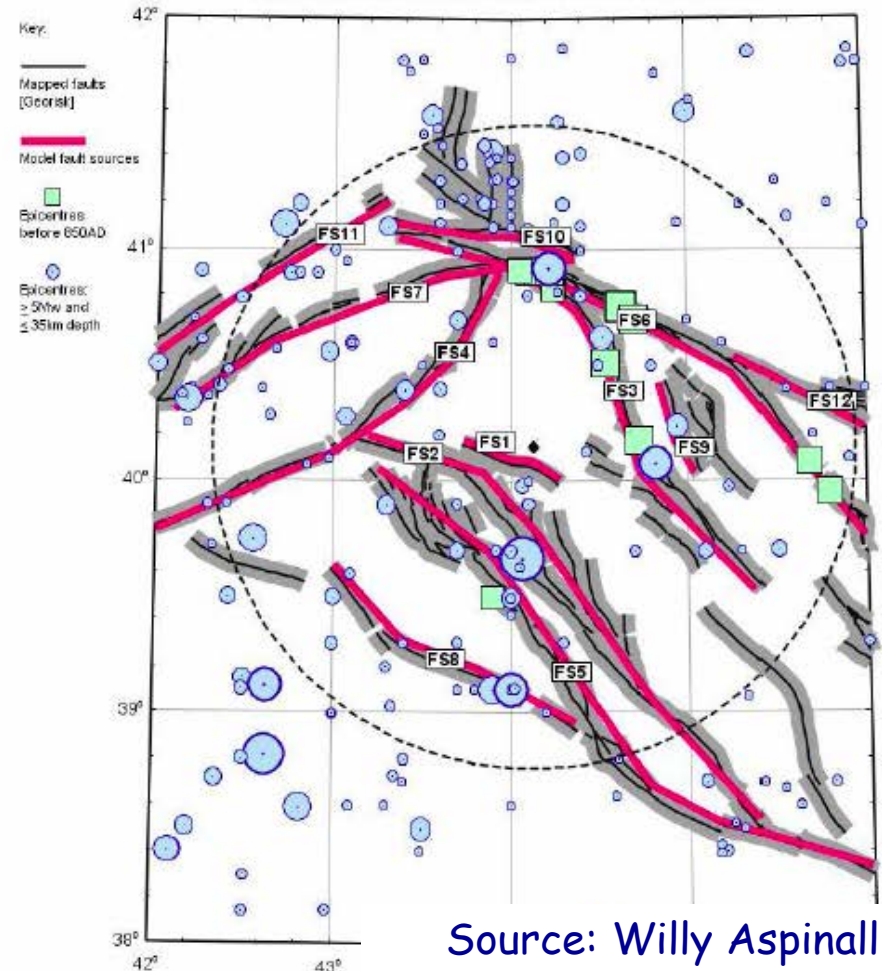
# PSHA applied in Armenia (Metsamor NPP)

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

Combined Armenian instrumental catalogues  
- preferred solutions magnitude M3+, with fault models -

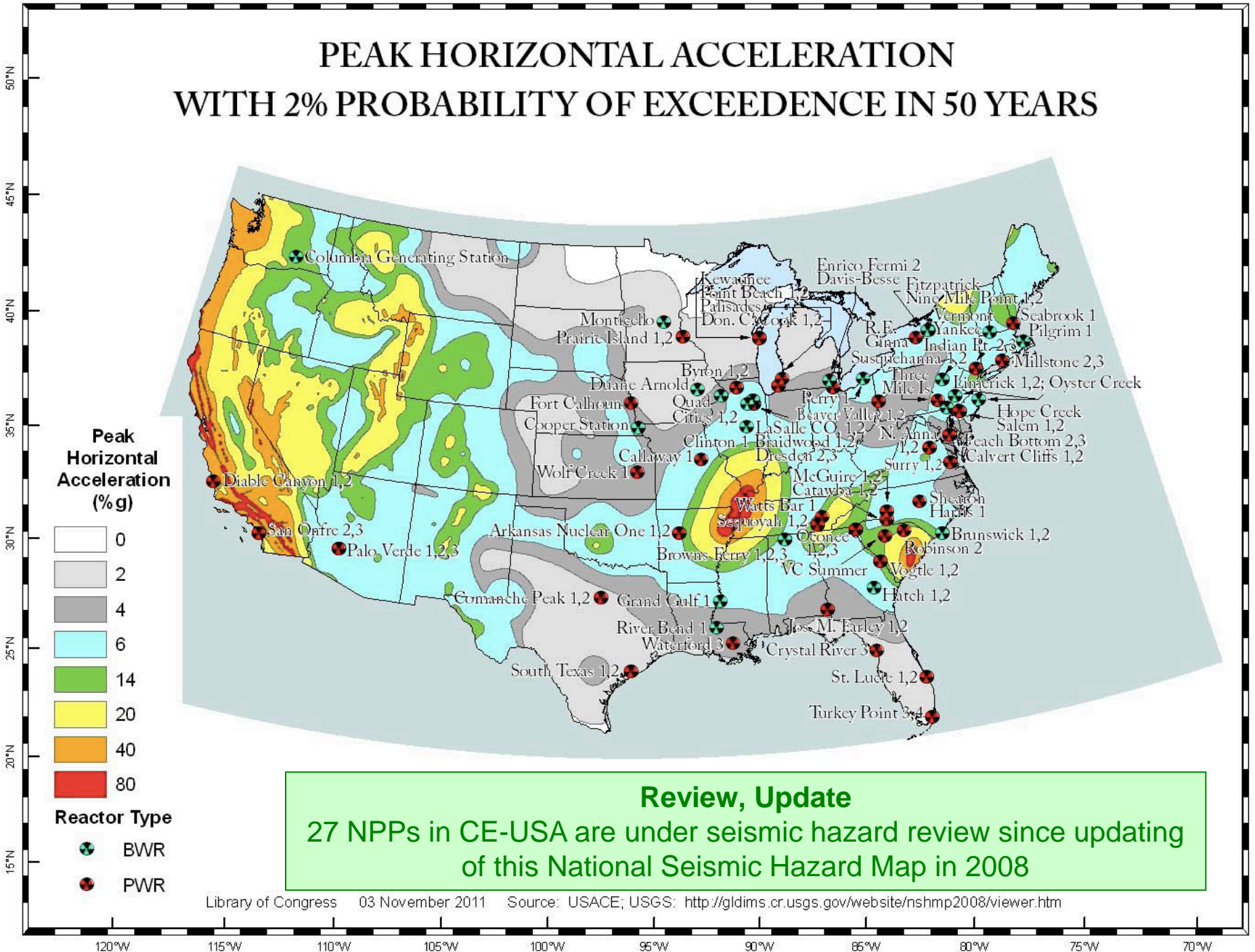


Shallow Set 1 epicentres - 5Mw and greater since 850AD  
showing Georisk faults with  $\pm 8\text{km}$  association bands, and modeled fault sources



Source: Willy Aspinall

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



# 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

In the country that gave the world the word tsunami, the nuclear establishment largely dismissed the potentially destructive force of this disaster. The word did not even appear in government guidelines until 2006, decades after nuclear plants were built along the coast. At Fukushima Daiichi, the plant's designers were struggling to make a name for a phenomenon dotting the Japanese coastline.

The lack of attention may help explain how, on an area of coast surrounded by clashing tectonic plates, conditions can produce a tsunami that is 10 times as large as the nearly 14-meter, or 46-foot, tsunami that overwhelped the Fukushima plant on March 11. The plant was designed to guard against tsunamis, such as the one that grew three times as tall as the bluff on which the plant had been built.

Japanese officials have had to determine how they could not have predicted the tsunami. A 9.0 earthquake — by far the largest recorded in Japan. Even so, seismologists and tsunami experts had not readily available data on the coast with a magnitude as low as 8.0. The garden variety around the Pacific Rim — could have made a tsunami large enough to top the bluff at Fukushima.

After an advisory group issued non-binding recommendations in 2002, Tokyo Electric Power, the plant owner and Japan's biggest utility, raised its maximum projected tsunami at Fukushima Daiichi to between 5.4 and 5.7 meters — considerably higher than the 4-meter-high bluff. Yet the company appeared to respond only by raising the level of an electric pump near the coast by 20 centimeters, or 8 inches, regulators said.

"We can only work on precedent, and there was no precedent," said Tsuneo Futami, a former Tokyo Electric nuclear engineer who was the director of Fukushima Daiichi in the late 1990s. "When I headed the plant, the thought

tsunami set off the nuclear crisis by flooding the backup generators needed to power the reactor cooling system.

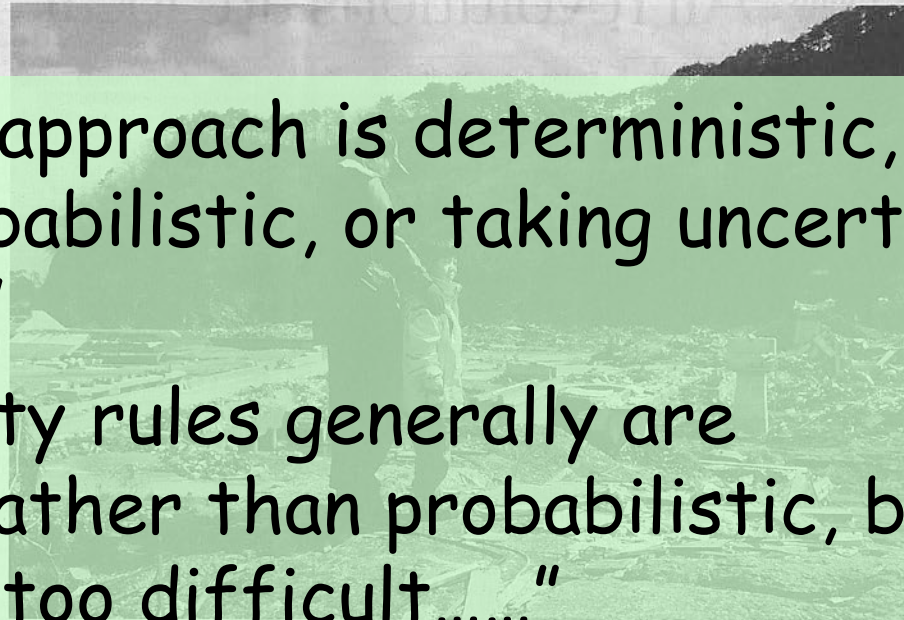
Japan is known for its technical expertise. For decades, though, Japanese officialdom and even parts of its engineering establishment clung to older methods of risk assessment, failing to make use of advances in seismology and tsunami science. At Fukushima Daiichi, the plant's designers were struggling to make a name for a phenomenon dotting the Japanese coastline.

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

a natural seawall, said Masaru Kobayashi, an expert on quake resistance at the Nuclear and Industrial Safety Agency, Japan's nuclear regulator.

Offshore breakwaters 5.5 meters tall were built as part of the company's anti-tsunami strategy, said Jun Oshima, a spokesman for Tokyo Electric. But regulators said the breakwaters — mainly intended to shelter boats — offered some resistance against typhoons, but not tsunamis.

Over the decades, preparedness against tsunamis never became a priority for Japanese power companies or nuclear regulators. They may have been billed as such, but the fact that

official records dating from 1600 showed that the strongest earthquakes off the coast of present-day Fukushima Prefecture had registered between magnitude 7.0 and 8.0, Mr. Kobayashi said.

Eventually, experts on the advisory committees started to push for tougher building codes, and by 1981, guidelines included references to earthquakes but not to tsunamis, according to the Nuclear and Industrial Safety Agency. That pressure grew exponentially after the devastating Kobe earthquake in 1995, said Kenji Sumita, who was deputy chairman of the government's Nuclear Safety Commission of Japan in the late 1990s.

though the U.S. Nuclear Regulatory Commission has come under severe criticism for not taking the adoption of those new techniques far enough, the agency did not change many of them in Japan. Eventually, experts on the advisory committees started to push for tougher building codes, and by 1981, guidelines included references to earthquakes but not to tsunamis, according to the Nuclear and Industrial Safety Agency. That pressure grew exponentially after the devastating Kobe earthquake in 1995, said Kenji Sumita, who was deputy chairman of the government's Nuclear Safety Commission of Japan in the late 1990s.

For whatever reasons — cultural, historical or simply financial — Japanese engineers who were working on nuclear plants continued to base their predictions of maximum earthquakes on records.

Those methods did not take into account serious uncertainties, like as-yet

"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....."

The Japanese approach, known in the field as "deterministic" — as opposed to "probabilistic," or taking unknowns into account — somehow stuck, said Noboru Nakao, a consultant who was a nuclear engineer at Hitachi for 40 years and was part of Japan's training center for operators of boiling-water reactors.

Japanese safety rules generally are deterministic because probabilistic methods are so difficult," he said, "and the consequences of not more risk

assessment of tsunamis advanced, it developed far better measurements of their size, vastly expanded statistics, and computer calculations that help predict what kinds of tsunamis are produced by quakes of various sizes. Two independent draft research papers by leading tsunami experts — Eric Geist of the U.S. Geological Survey and Costas E. Synolakis, a professor of civil engineering at the University of Southern California — indicate that earthquakes of a magnitude down to about 7.5 could create tsunamis large enough to go over the 4-meter bluff at Fukushima Daiichi plant.

Mr. Geist's underestimation of the tsunami risk a "cascade of stupid errors that led to the disaster" and said it had been virtually impossible for anyone in the field to overlook relevant data.

The first clear reference to tsunamis appeared in new standards for Japan's nuclear plants issued in 2006. "The 2006 guidelines referred to tsunamis as an accompanying phenomenon of earthquakes, and urged the power companies to think about that," said Mr. Aoyama, the structural engineering expert.

The risk had been drawing attention from the nuclear industry's advisory committees, but it was not until 2006 that the Nuclear and Industrial Safety Agency published recommended tsunami guidelines for nuclear operators.

The same group had recently discussed revisions to those standards, according to a member who spoke on the condition of anonymity, citing the sensitivity of the situation. At their last meeting, just over a week before the recent tsunami, researchers debated the use

New York Times, March 2011

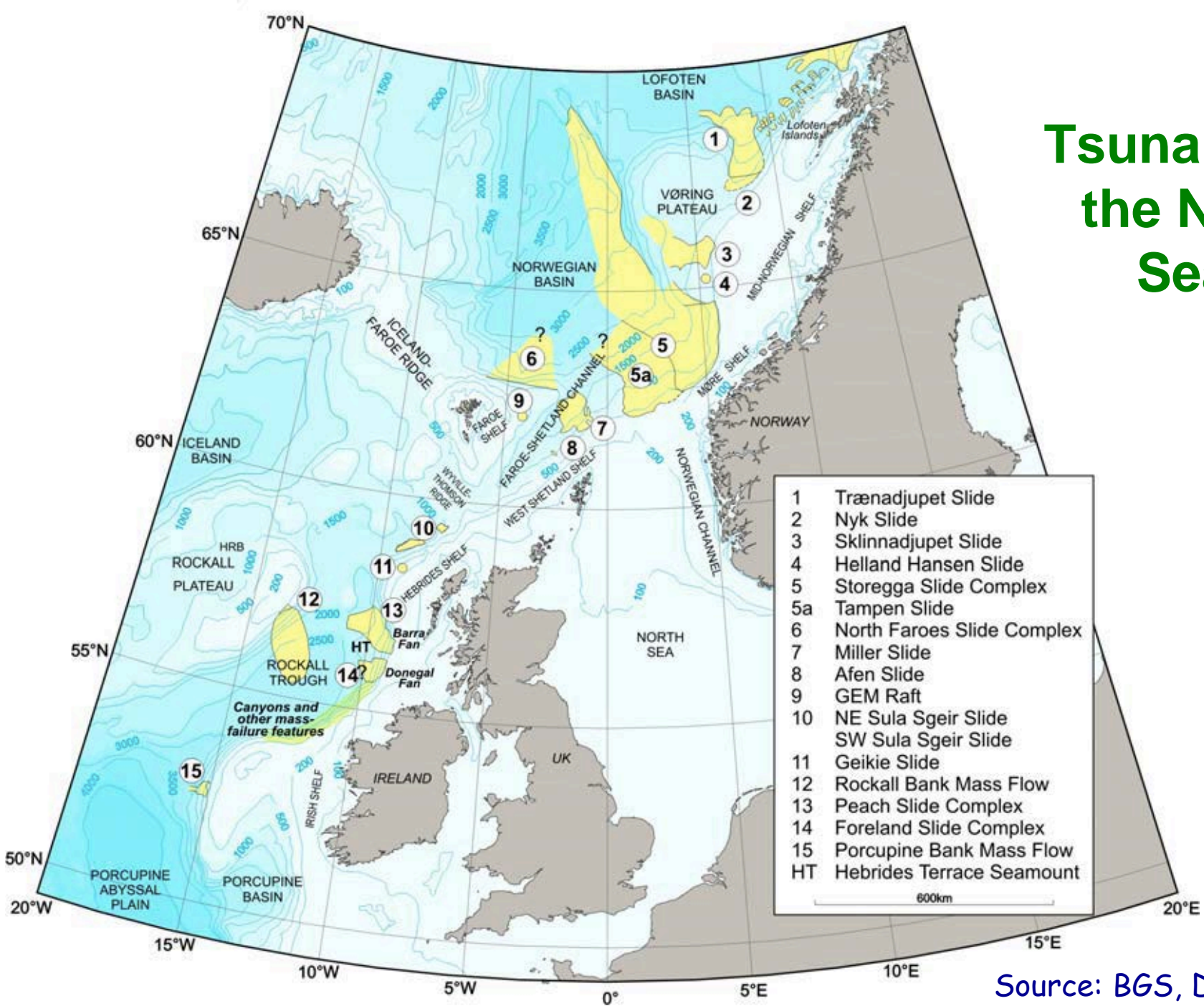


# Lessons of Fukushima:

## 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?



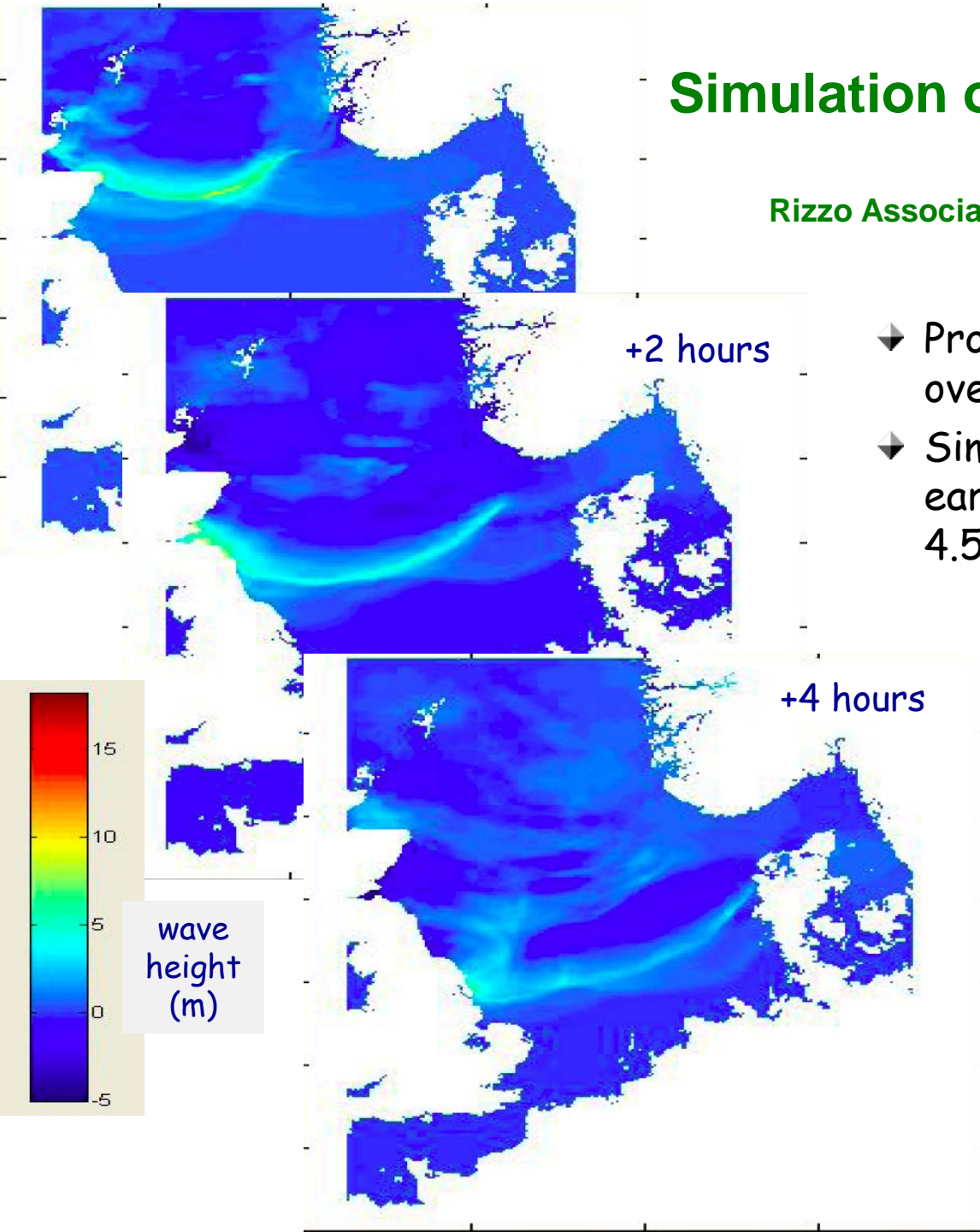
Source: BGS, DEFRA

# Doggerland... a recent feature

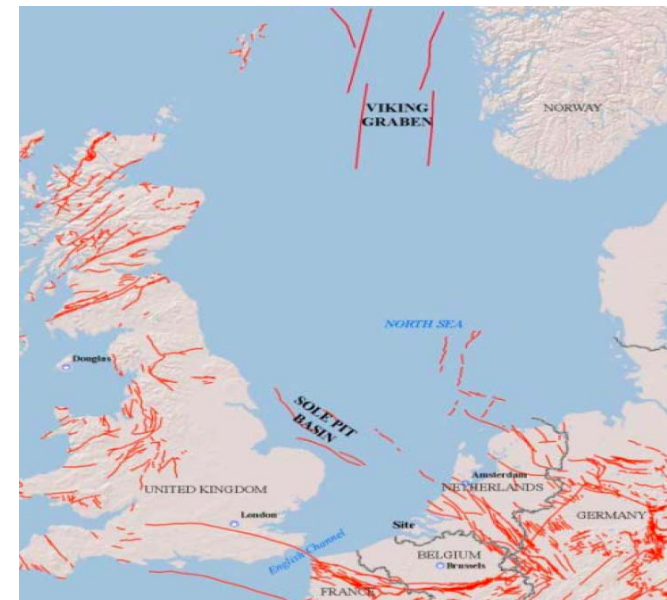


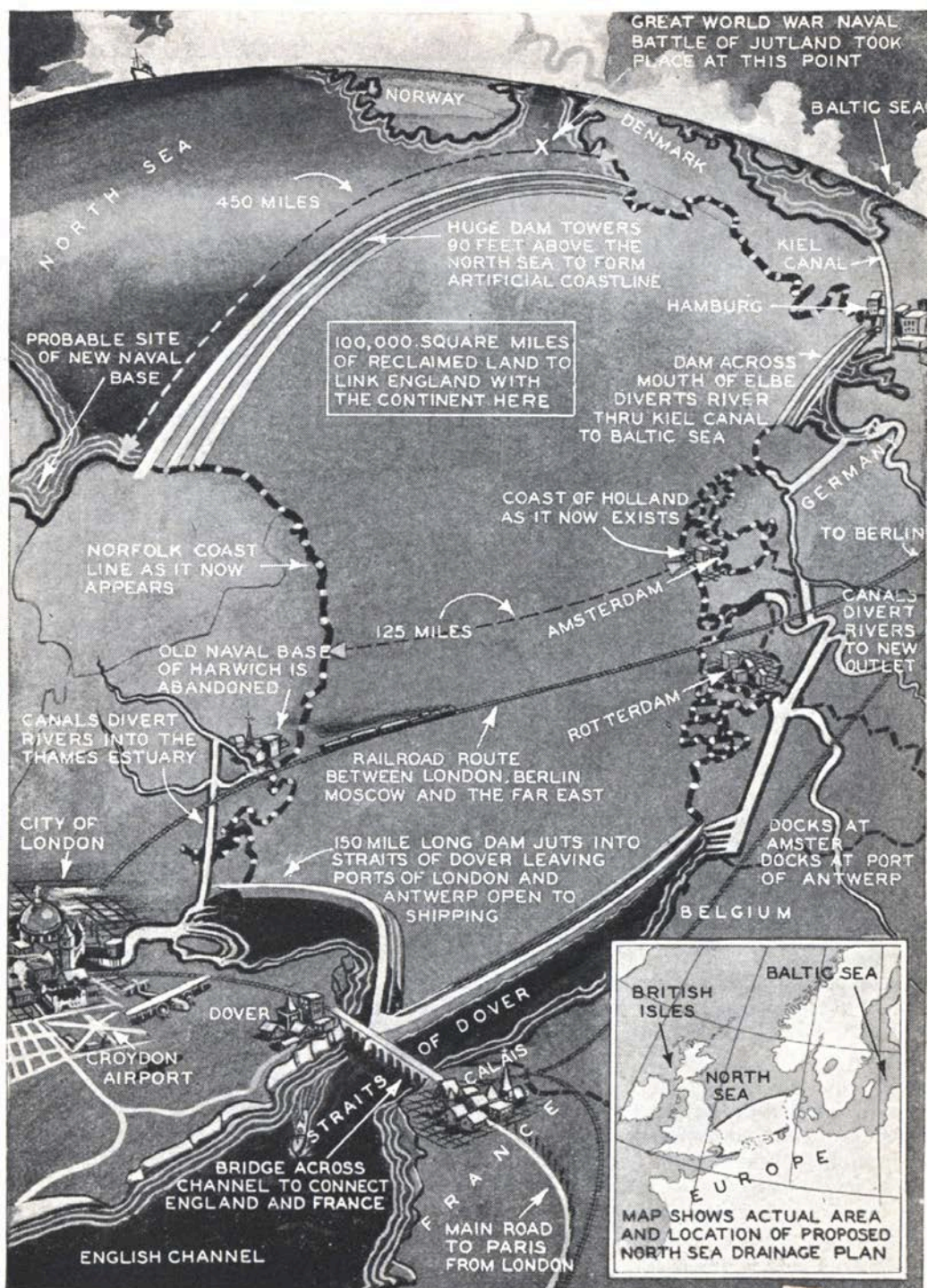
# Simulation of 6 m landslide tsunami

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 Safety Standards

for protecting people and the environment

### Volcanic Hazards in Site Evaluation for Nuclear Installations

Specific Safety Guide  
No. SSG-21



## IAEA Safety Standards

for protecting people and the environment

### Site Evaluation for Nuclear Installations

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



# 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?

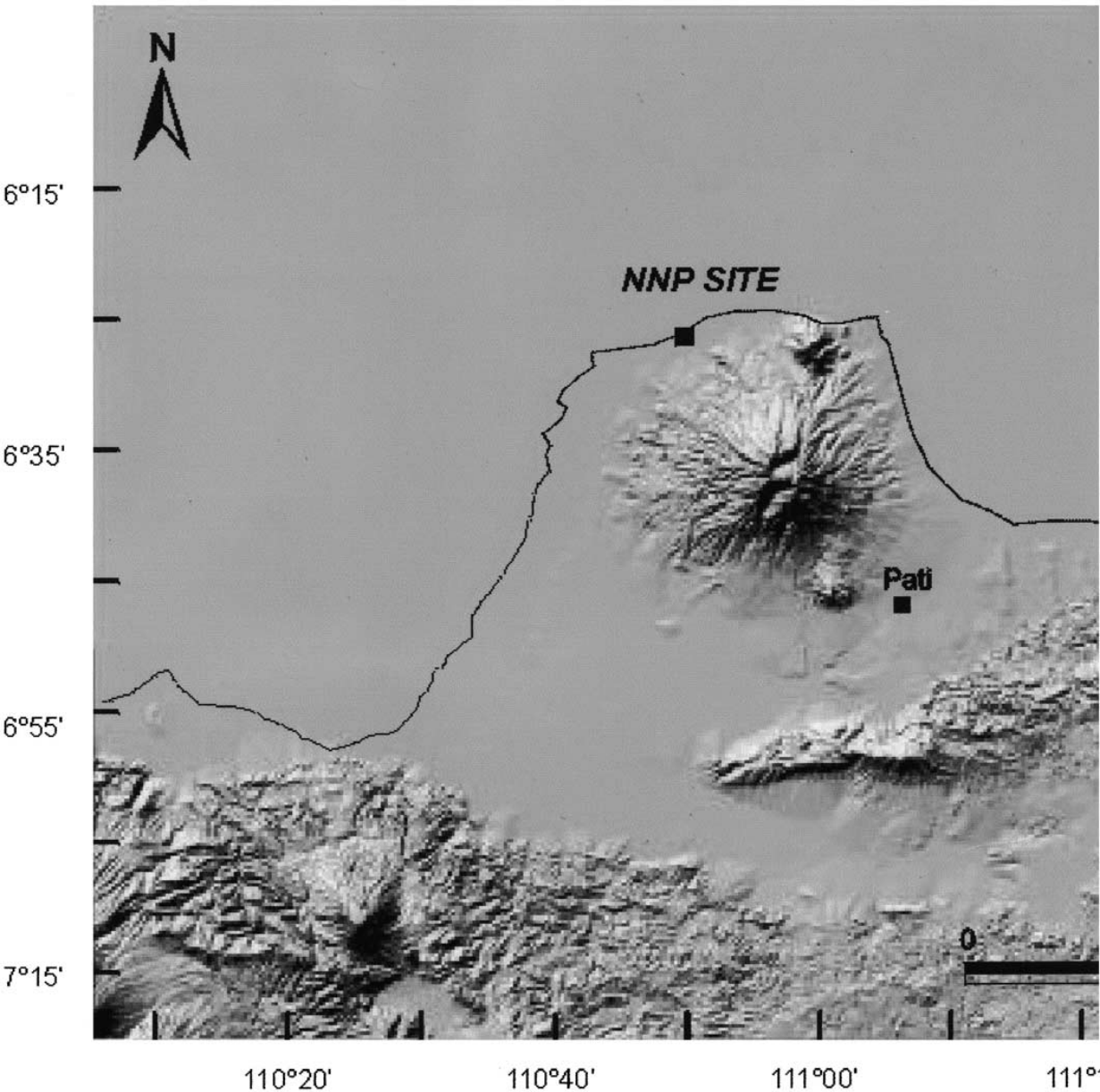
- ash cloud modelling
- probabilistic studies of ash deposition
- lahars
- pyroclastic flows



## will it happen - how likely?

- probabilistic studies of volcanic event occurrence





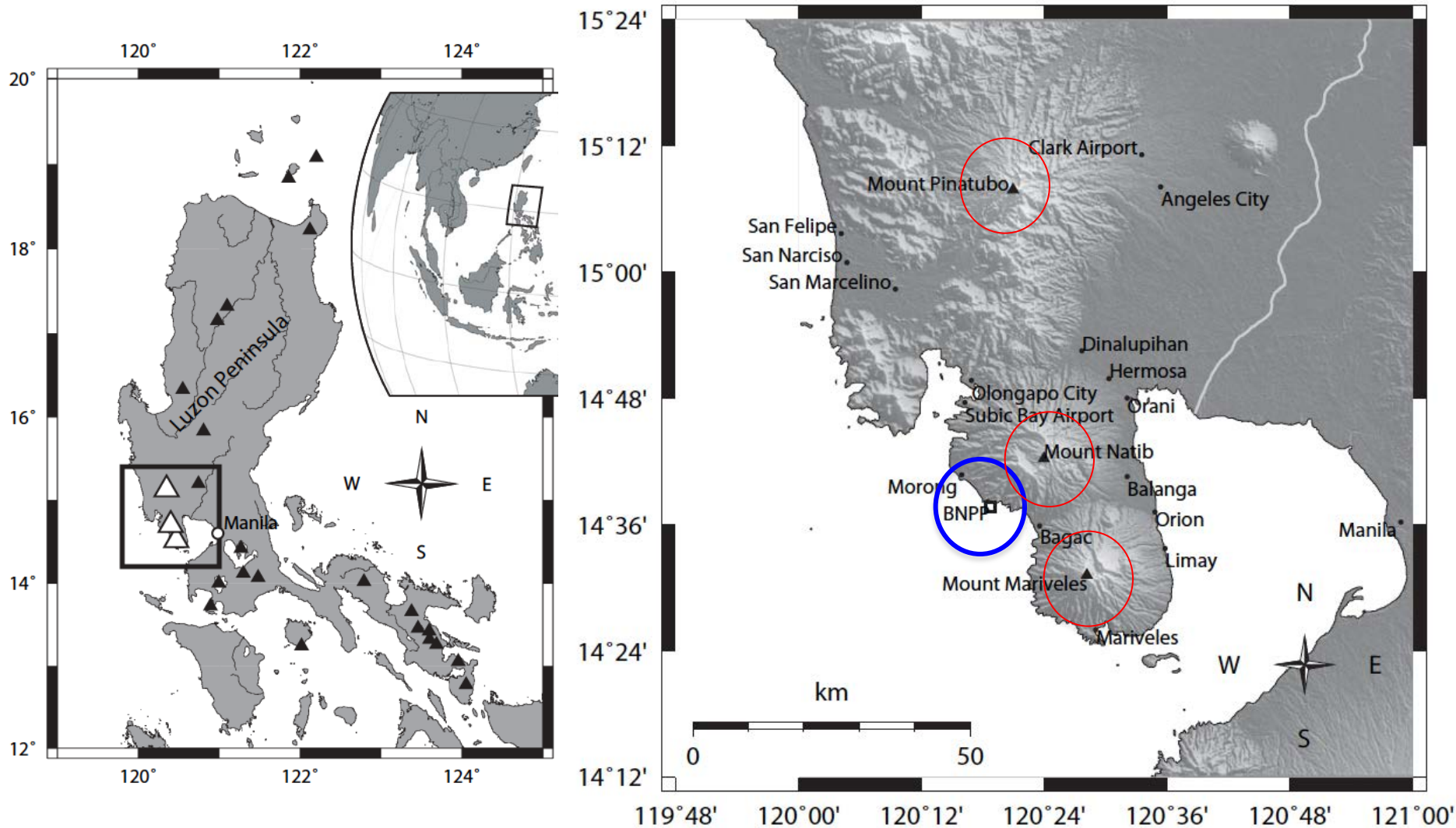
## INDONESIA

### Java: NPP near Muria volcano

Studied by McBirney,  
Connor et al

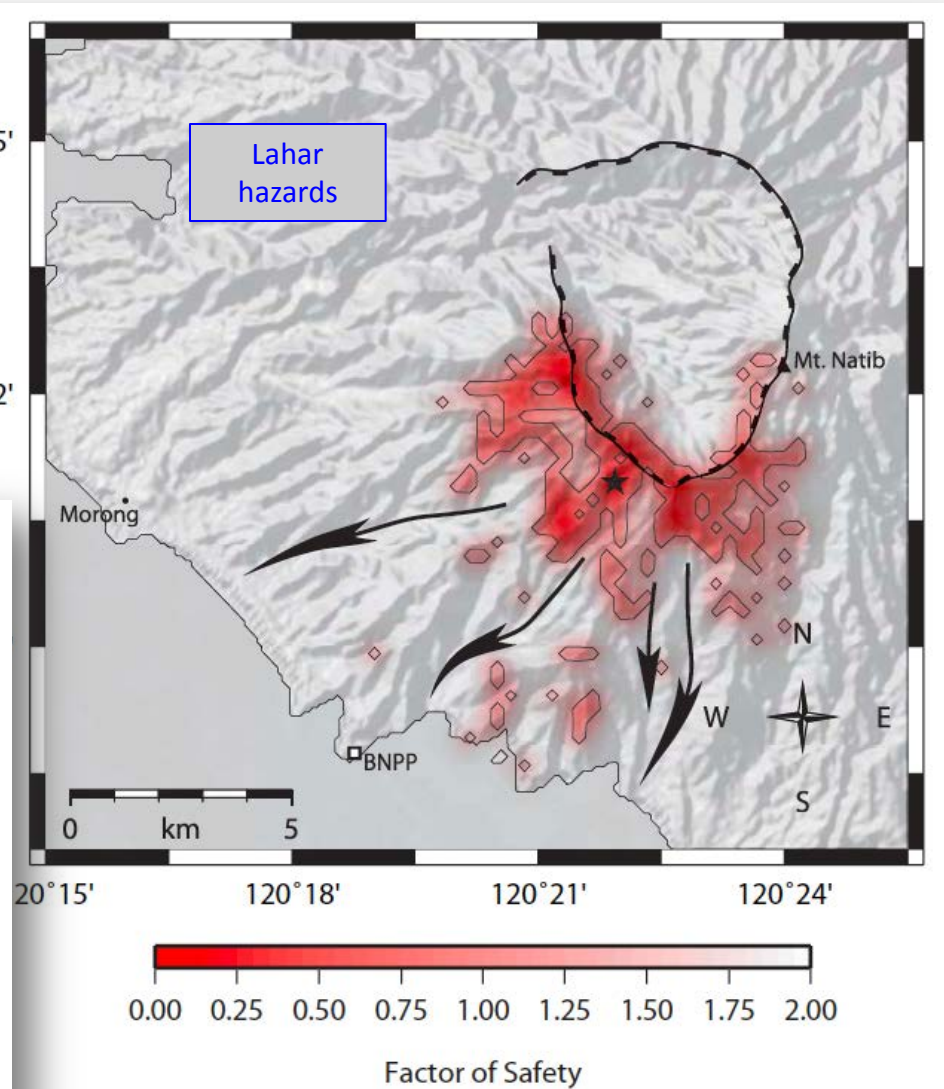
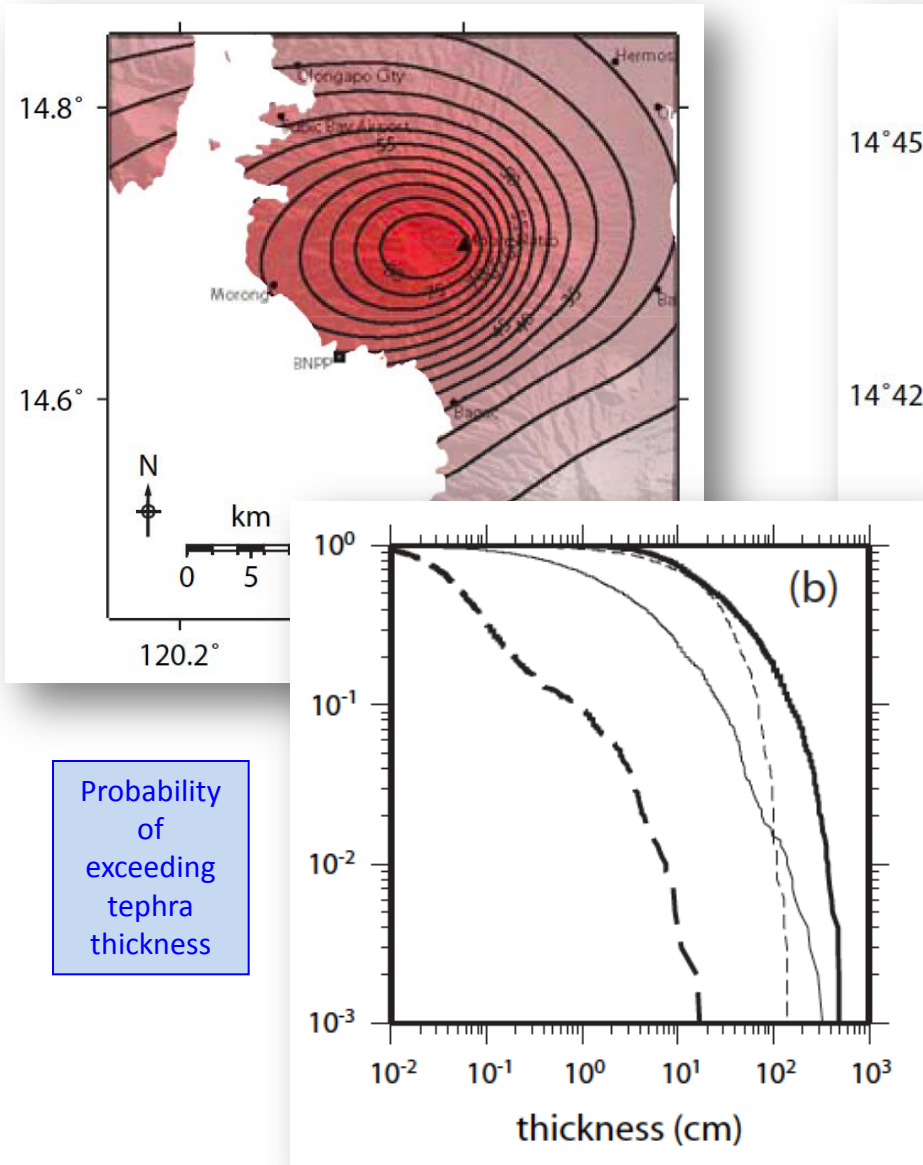
.....probabilities of major  
eruptive episodes impacting  
the site of  $5 \times 10^{-4}$  to  
 $4 \times 10^{-5}$  during the next 100  
years

# Bataan NPP, Philippines



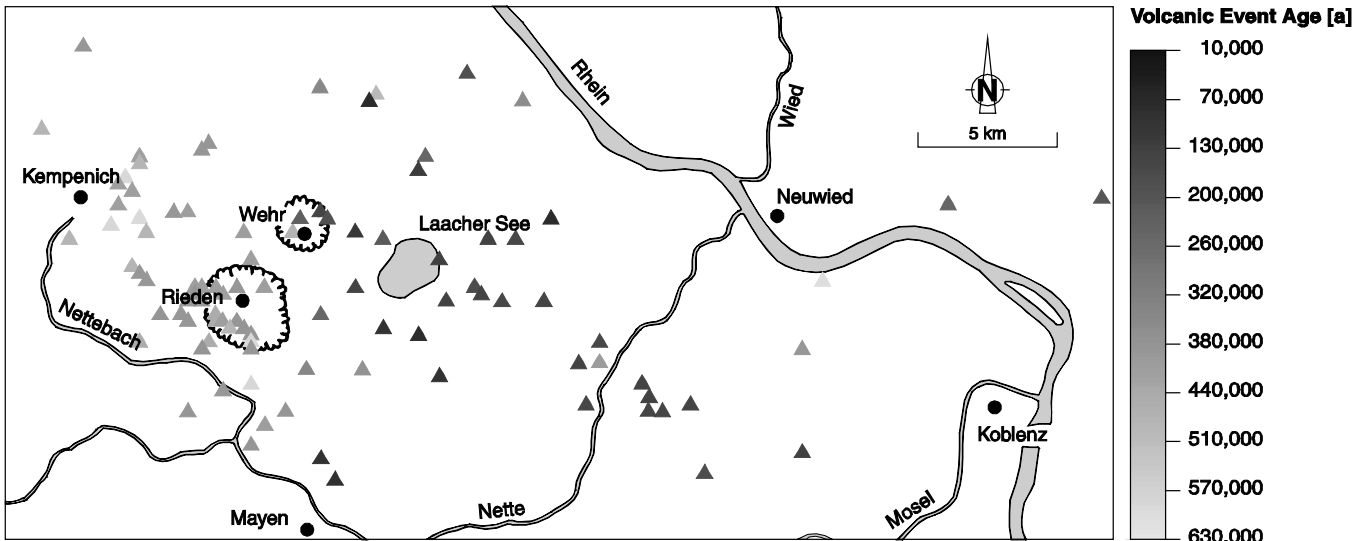
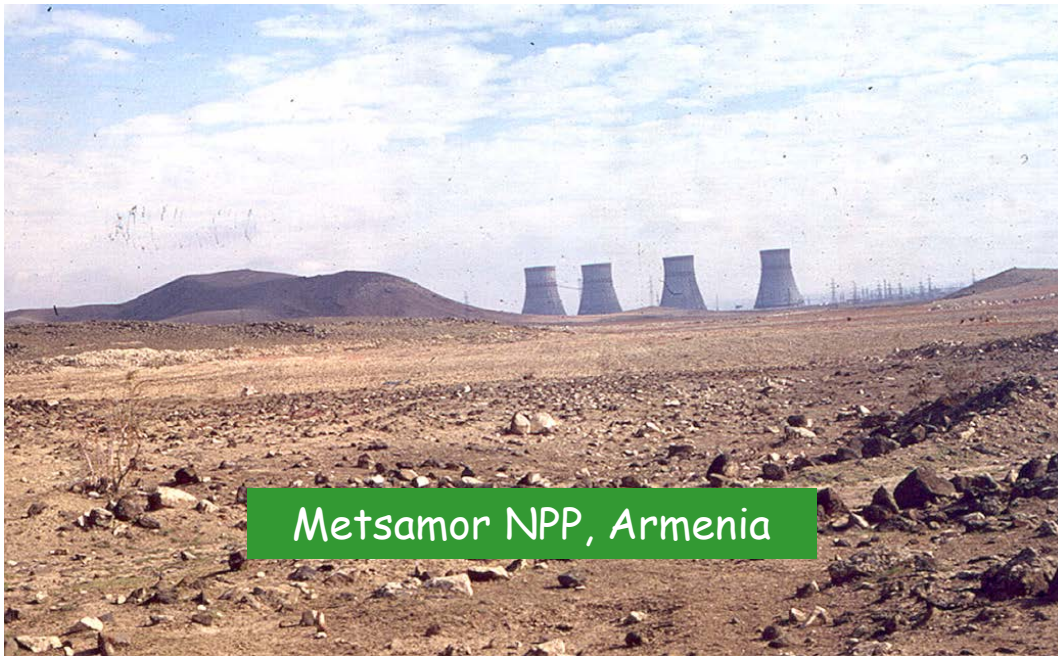
Source: Chuck Connor

# Bataan Volcanic Hazards

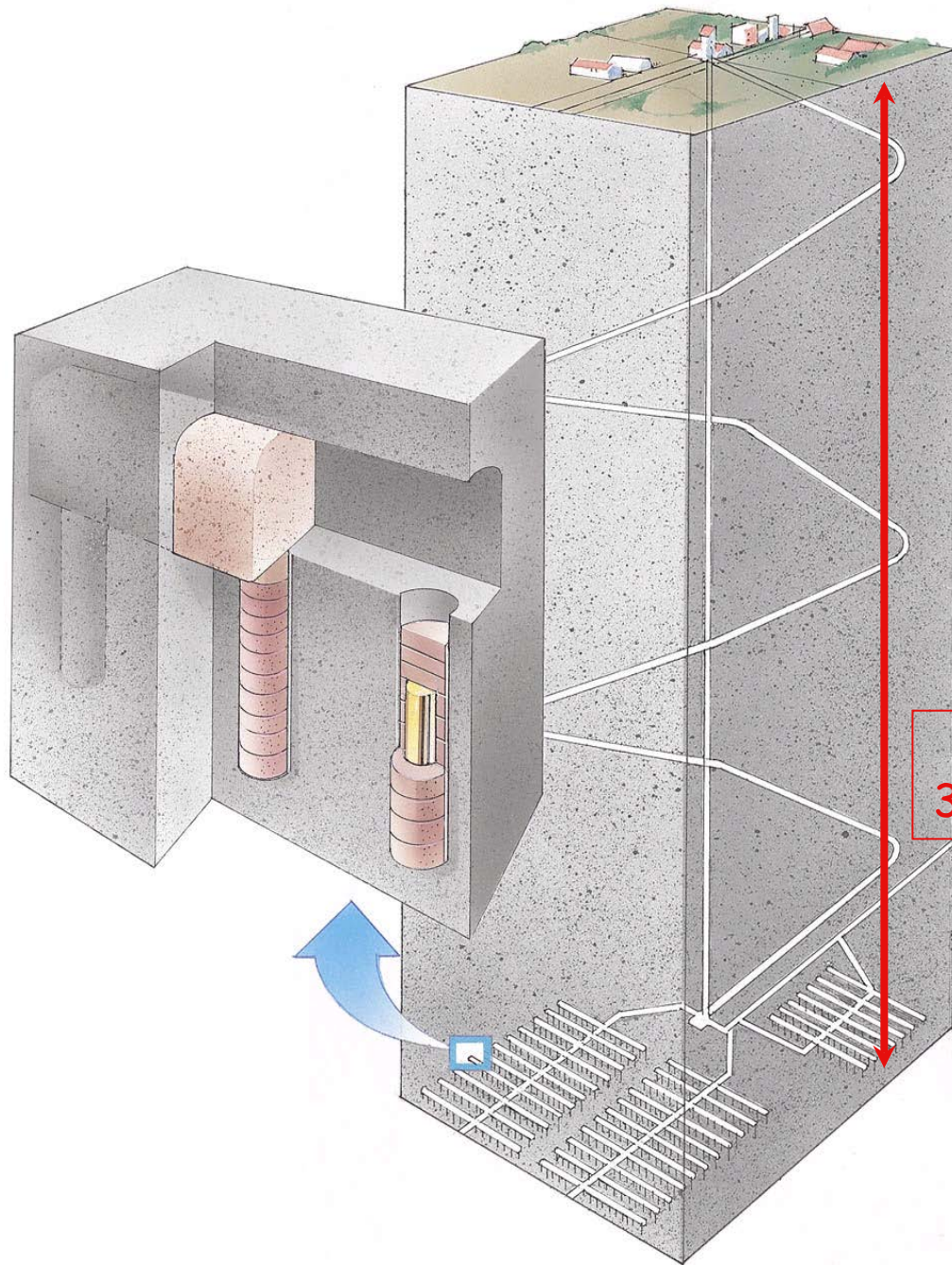


Source: Chuck Connor

# Some NPPs assessed probabilistically for volcanic hazard



Sources: Chuck Connor, Olivier Jaquet

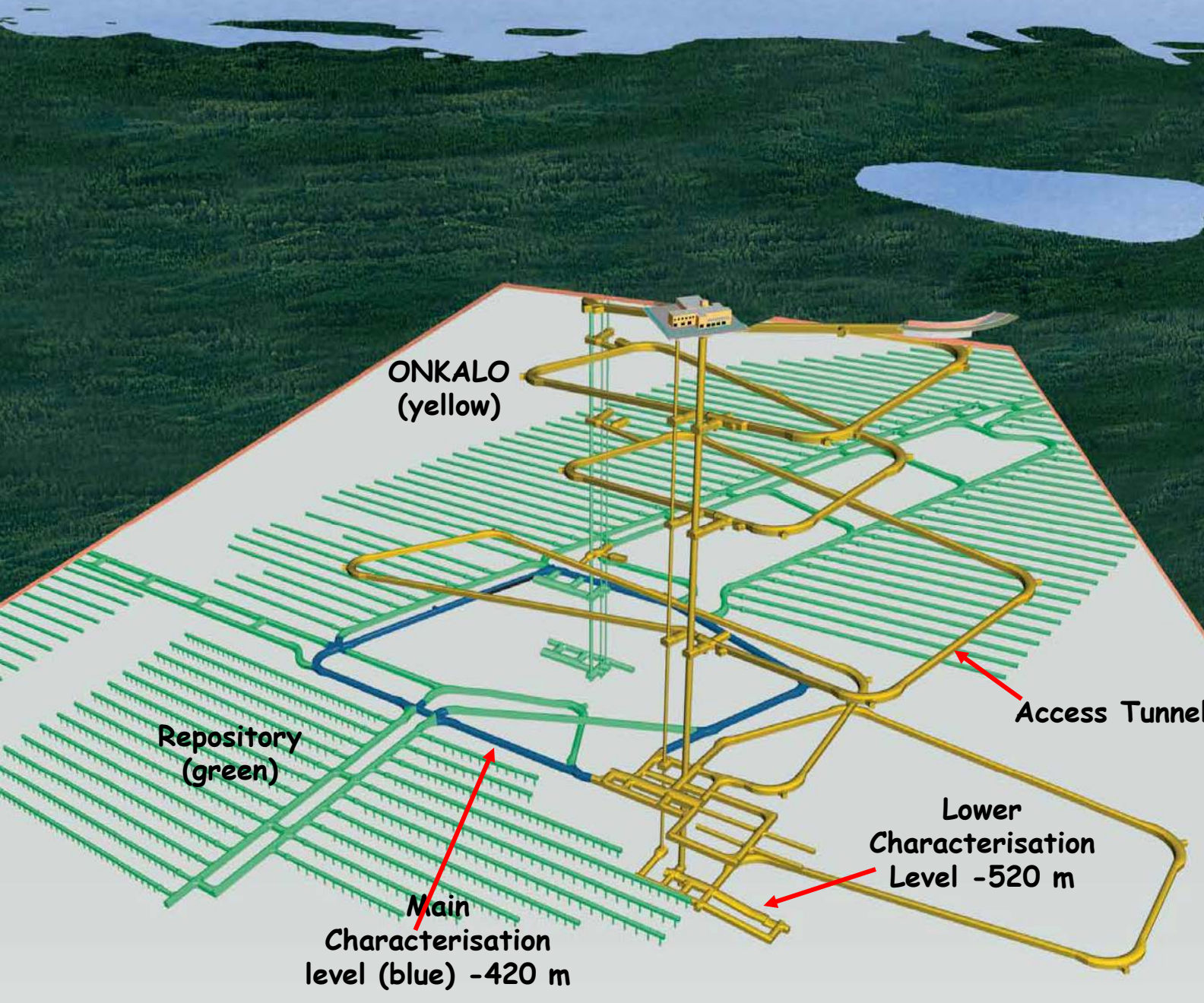


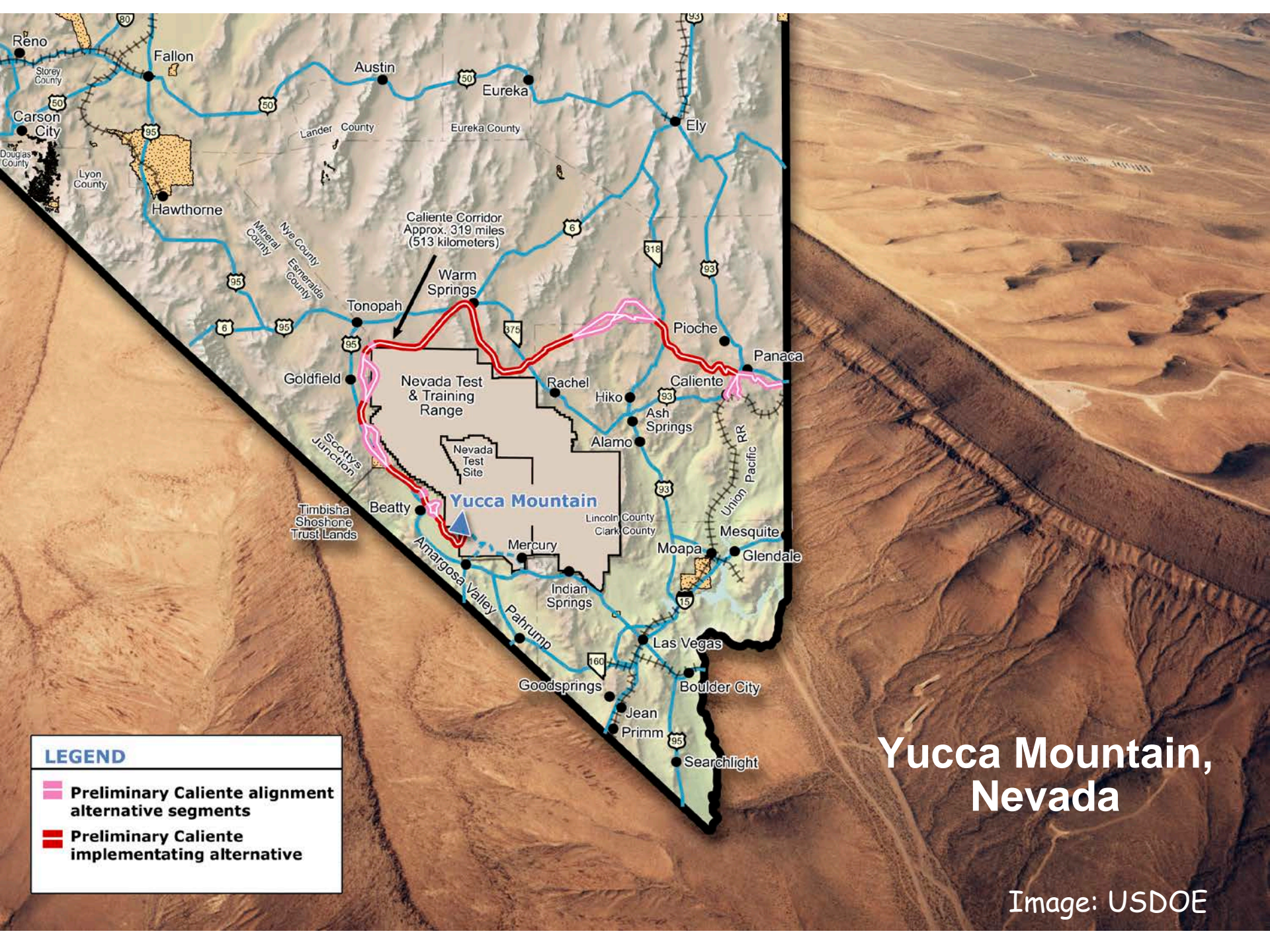
**The much longer term:  
geological repositories  
for long-lived  
radioactive wastes**

**contain and isolate for  
10,000 to 1 million  
years**



typically,  
300 - 700 m

# Finland: ONKALO and the Spent Fuel Repository





**LEGEND**

-  Preliminary Caliente alignment alternative segments
-  Preliminary Caliente implementing alternative

# Yucca Mountain, Nevada

Image: USDOE

# Proposed Repository at Yucca Mountain

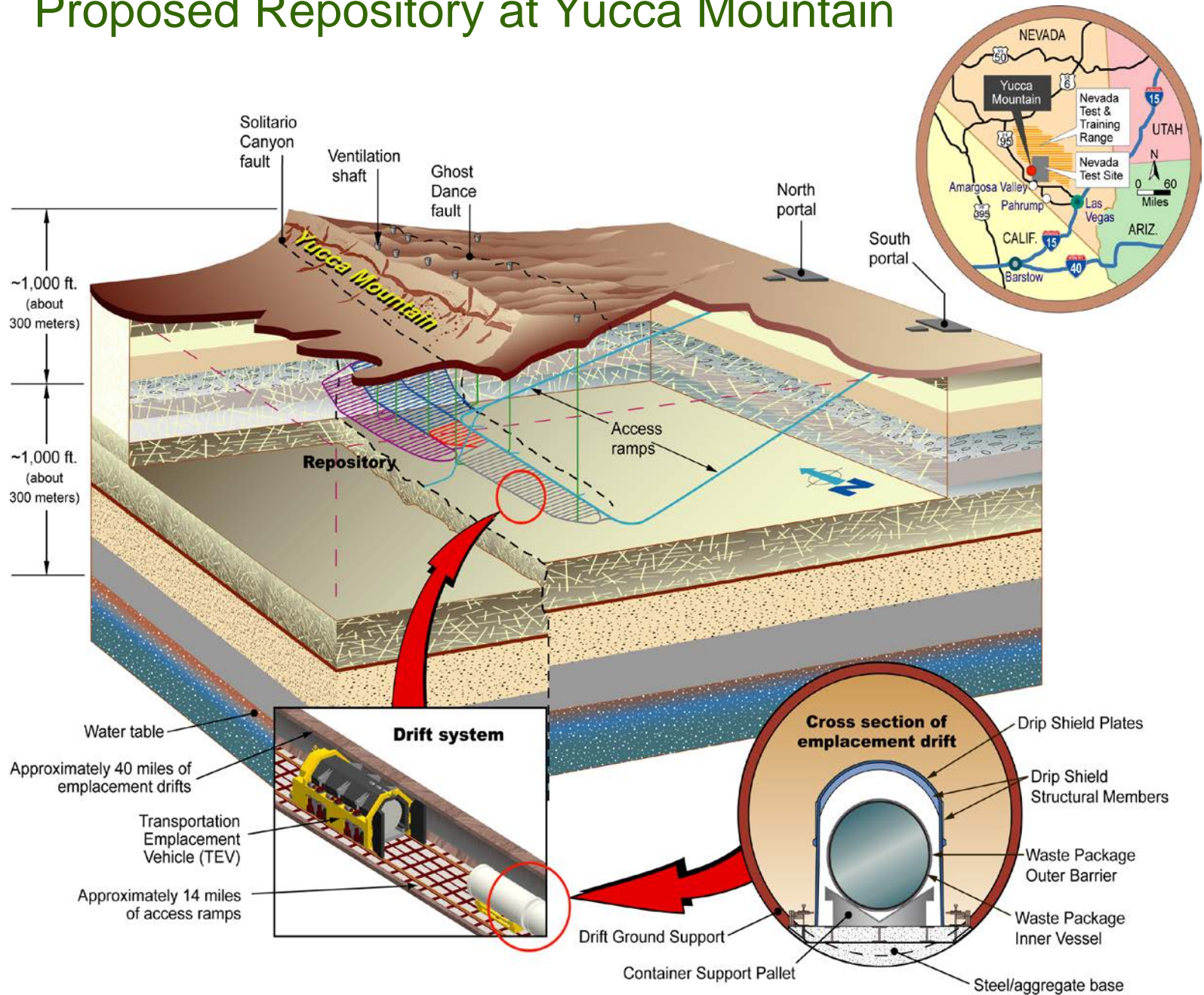
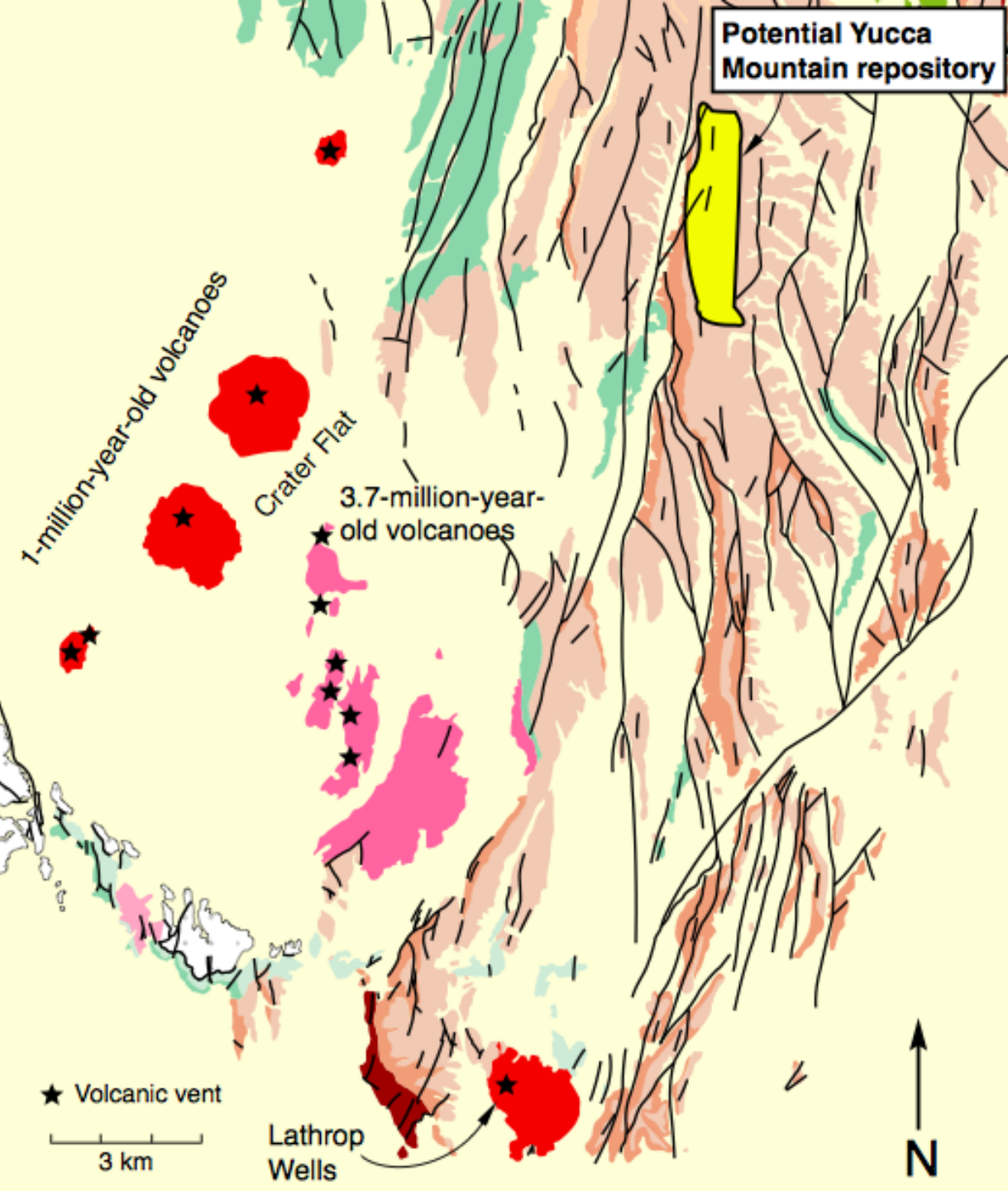


Image: USDOE



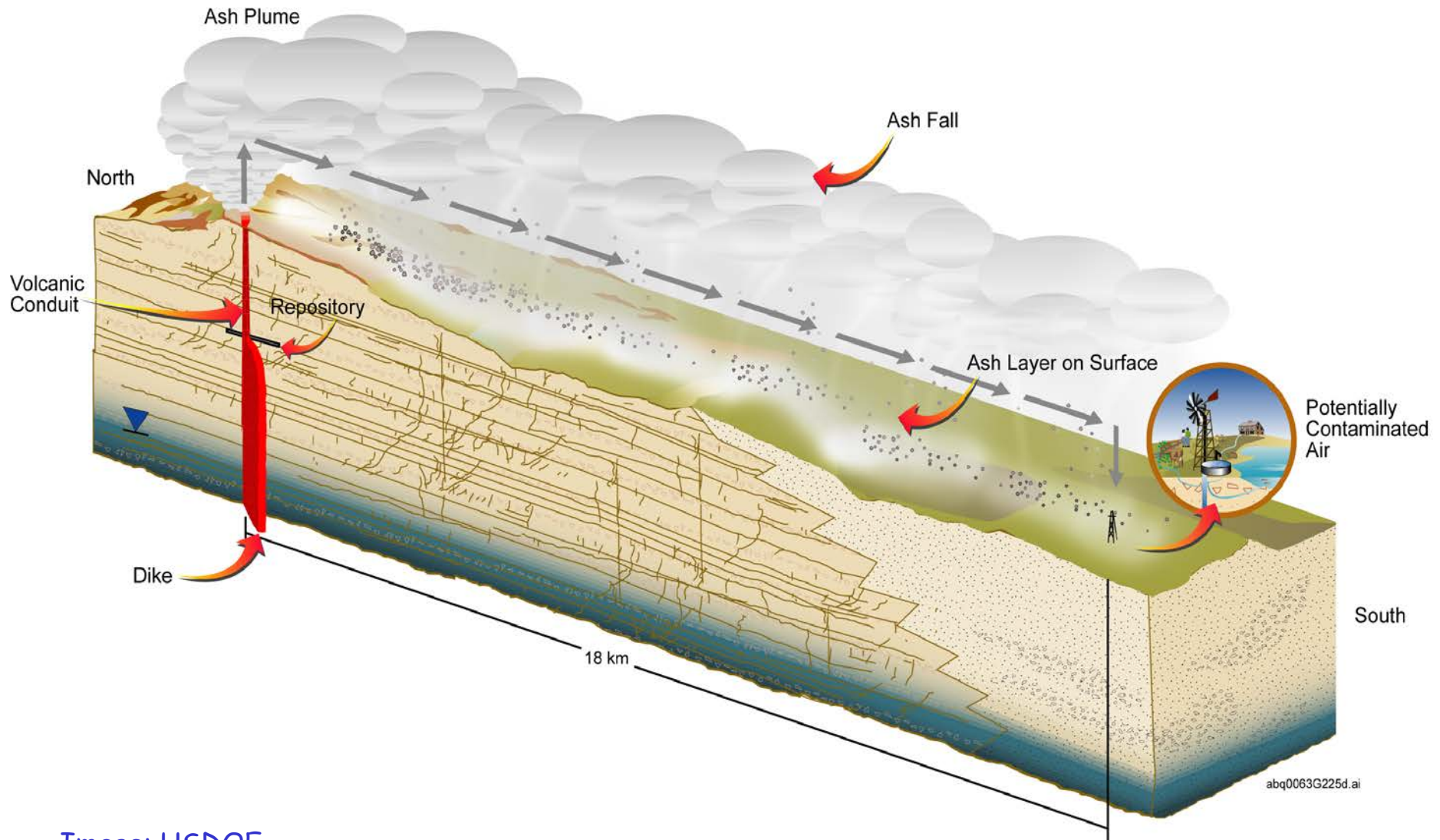


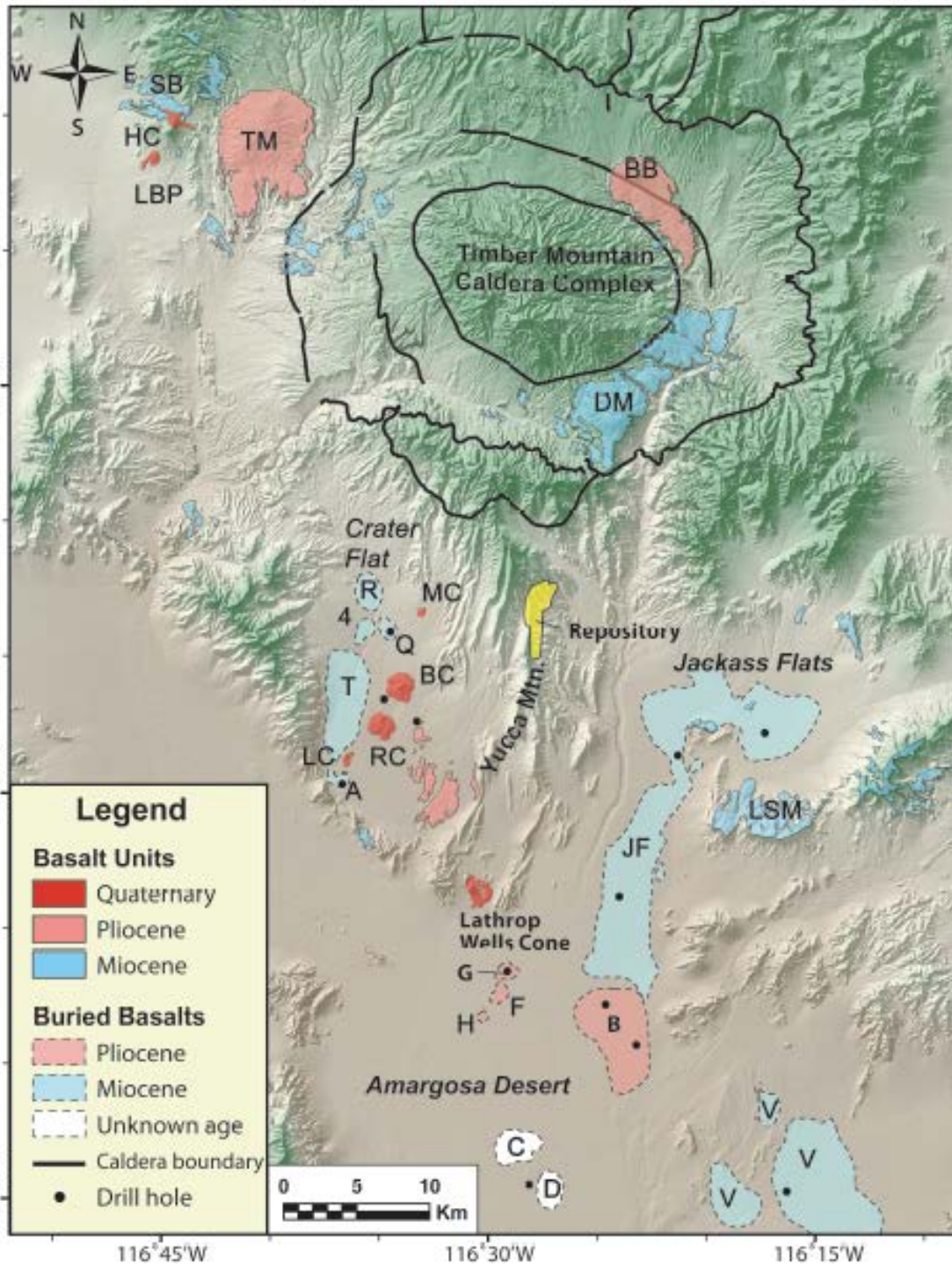
Potential Yucca Mountain repository

## Volcanism around Yucca Mountain

Source: Los Alamos National laboratory

# Volcanic Eruption through the Yucca Mountain repository?

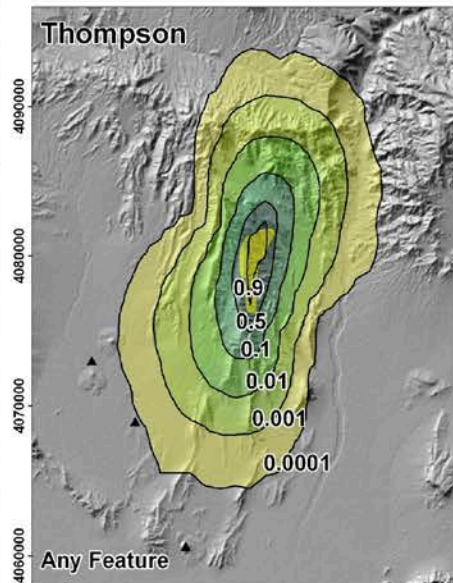
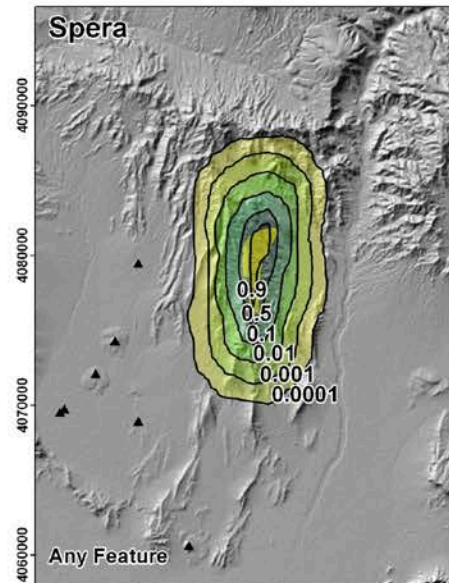
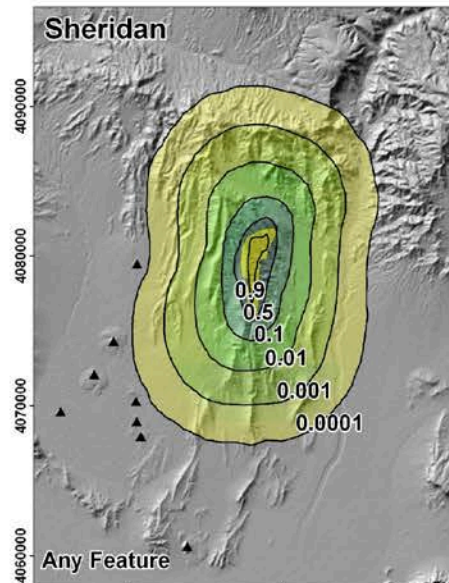
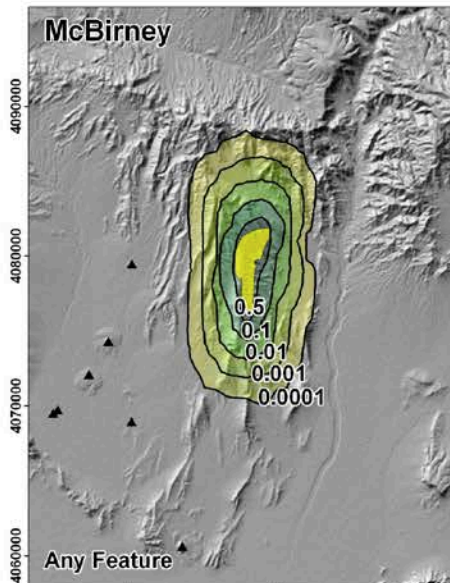
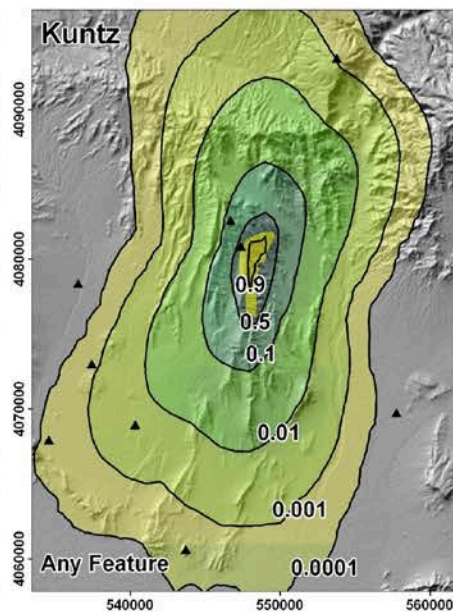
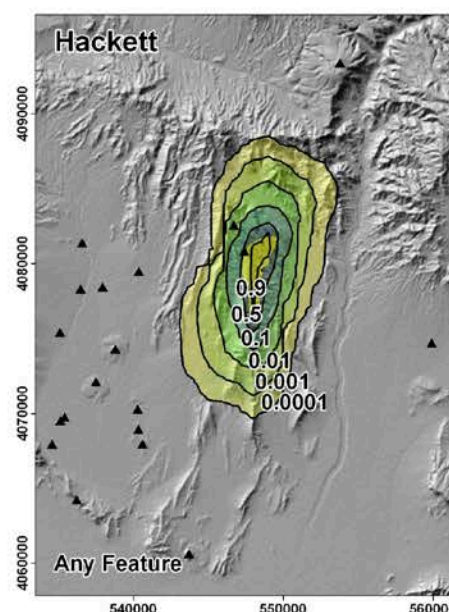
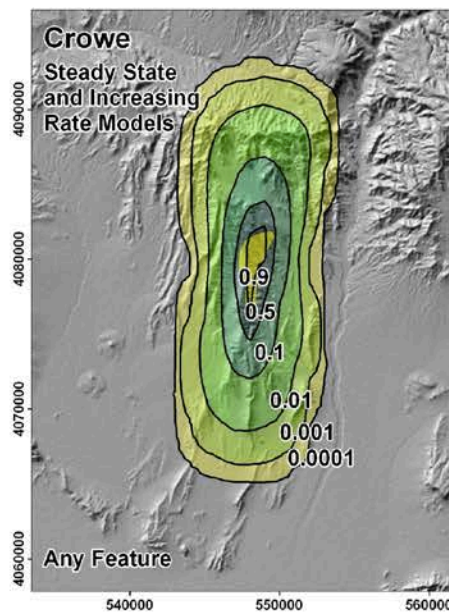
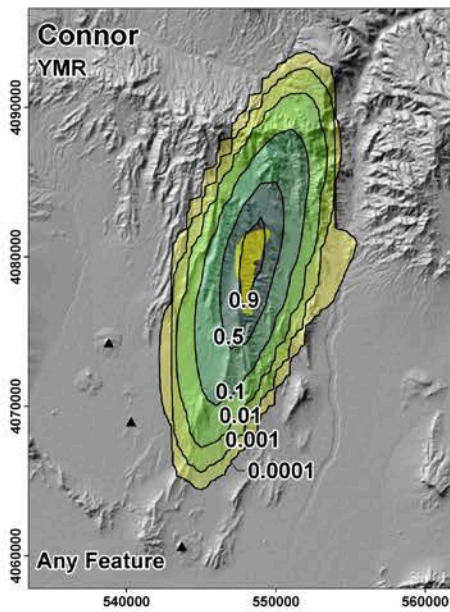




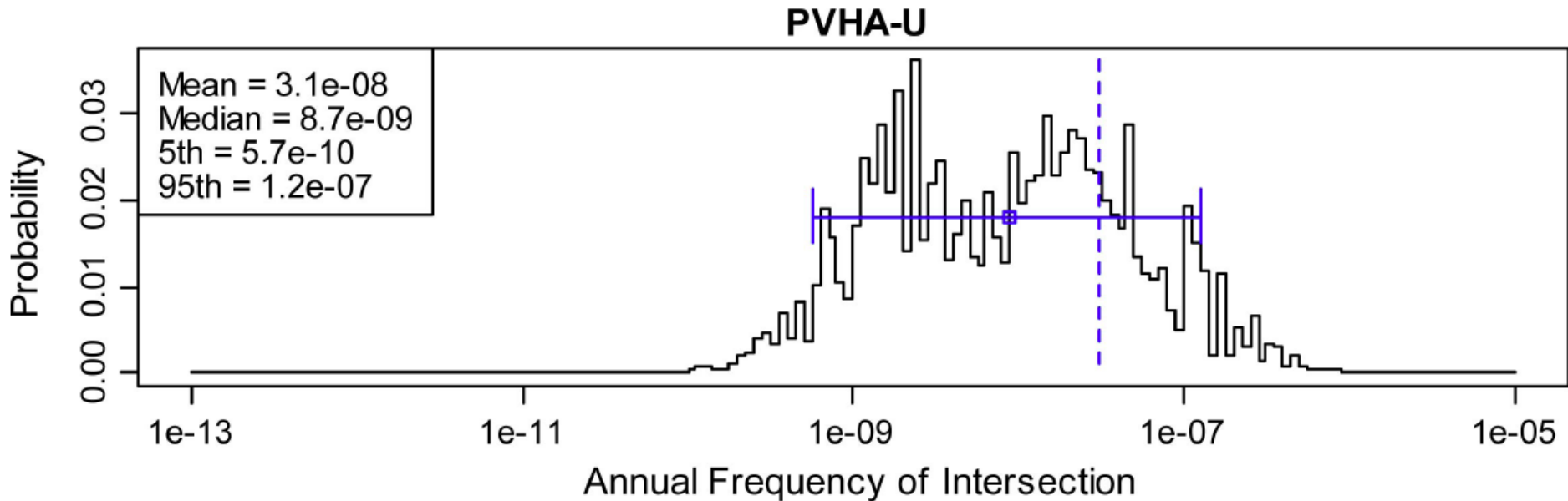
## Comprehensive Probabilistic Volcanic Hazard Assessment

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

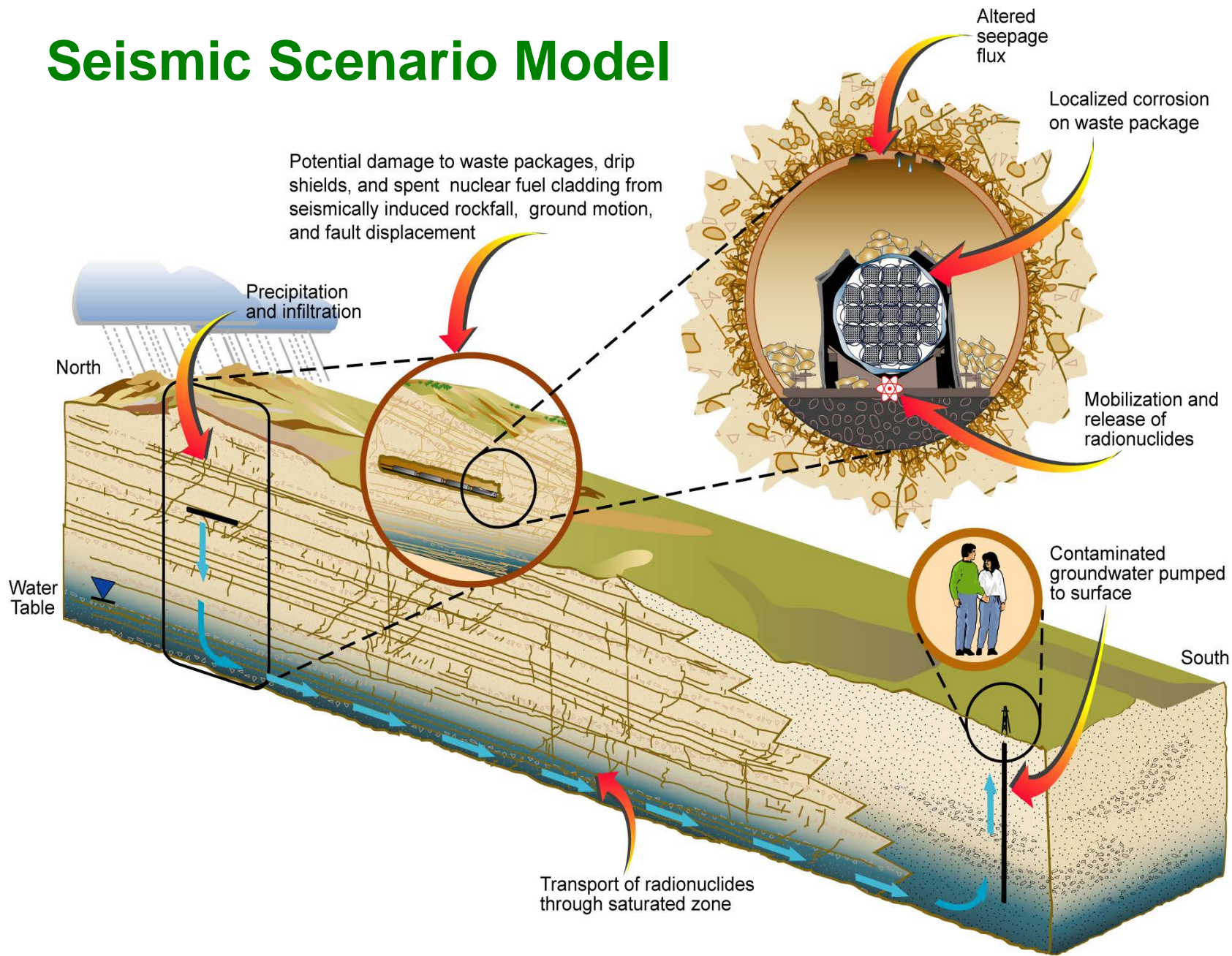


# Probability of disruption in 1 million years



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

# Seismic Scenario Model



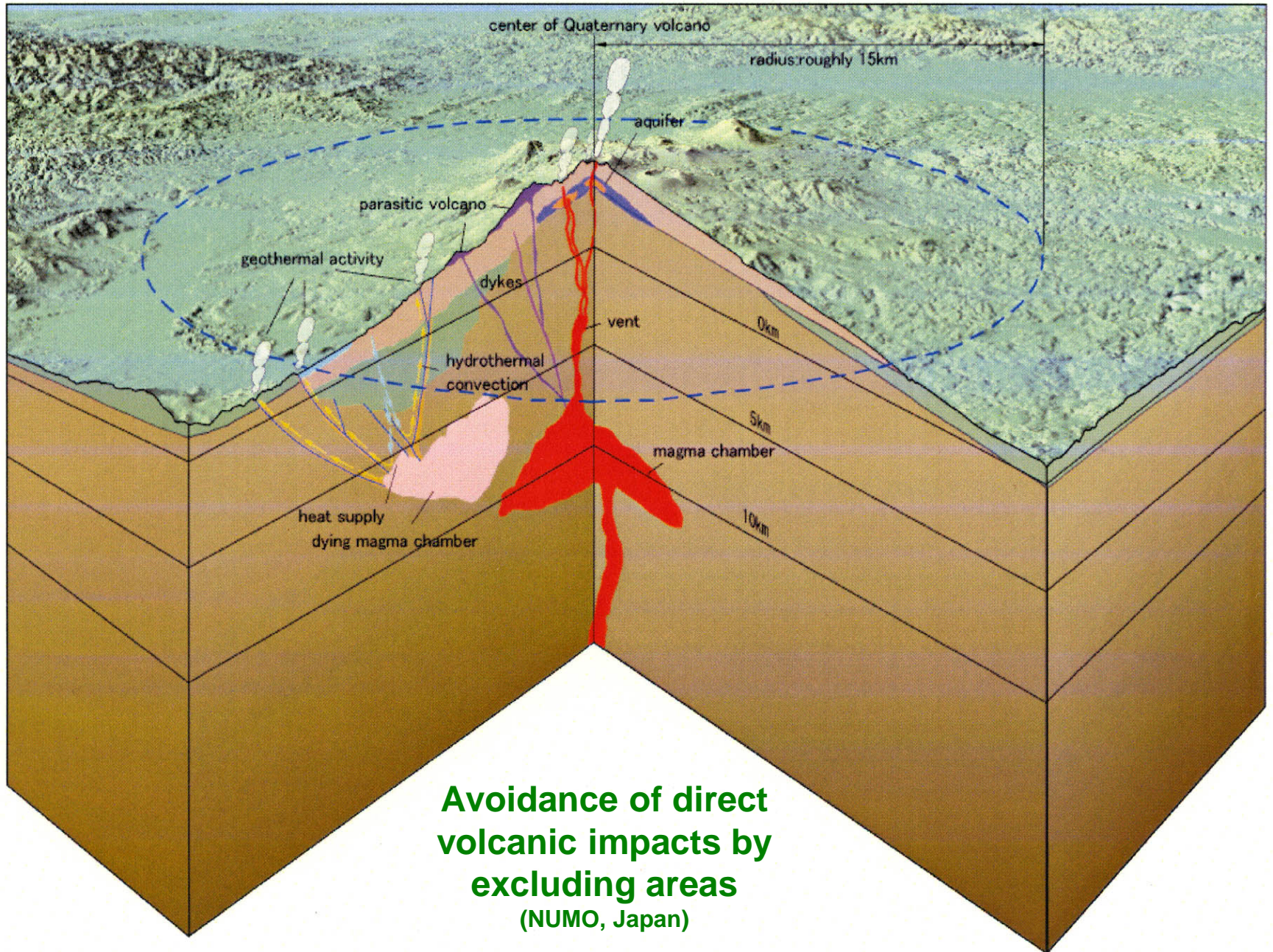


# Yucca Mountain

## Precariously balanced rocks

Exposed surfaces dated using cosmogenic isotopes

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

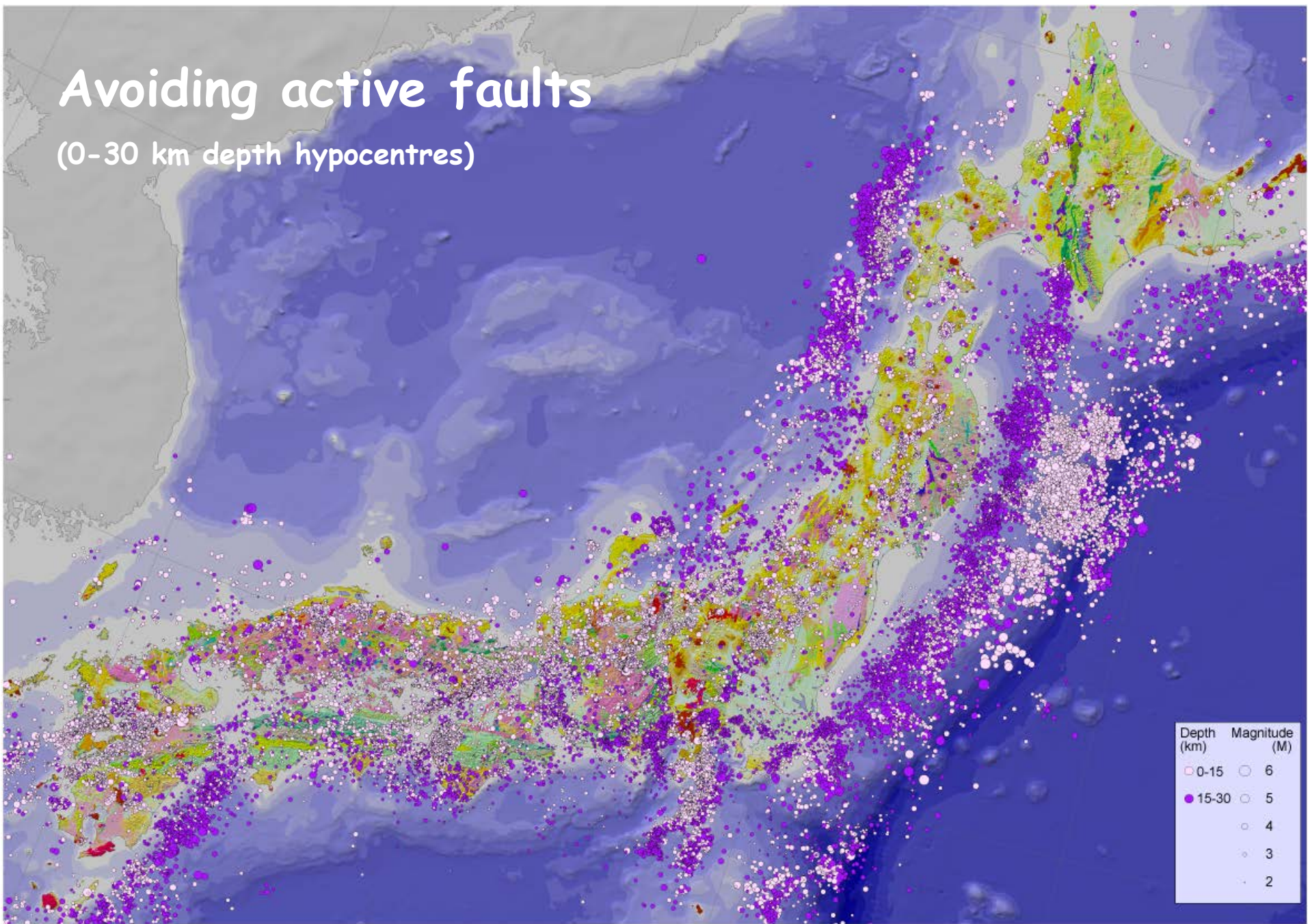


**Avoidance of direct  
volcanic impacts by  
excluding areas  
(NUMO, Japan)**



# Avoiding active faults

(0-30 km depth hypocentres)

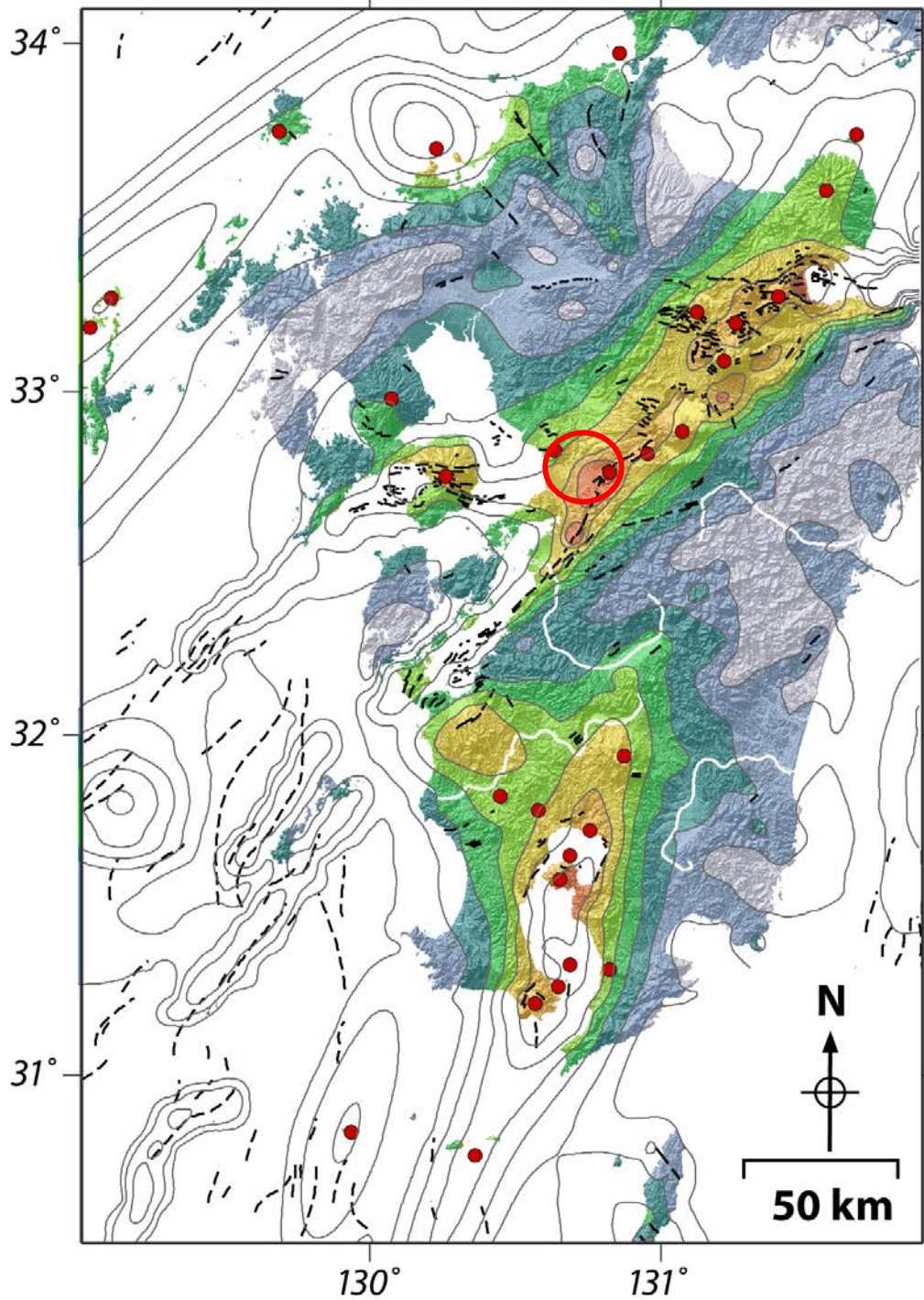




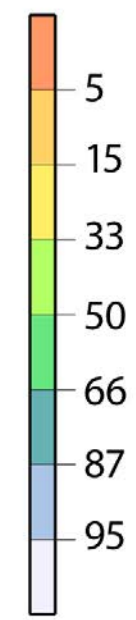
**Neodani fault at Midori,  
October 1891, M8 event**

**6m vertical, 3m horizontal  
displacement**

**Photo: B Koto**



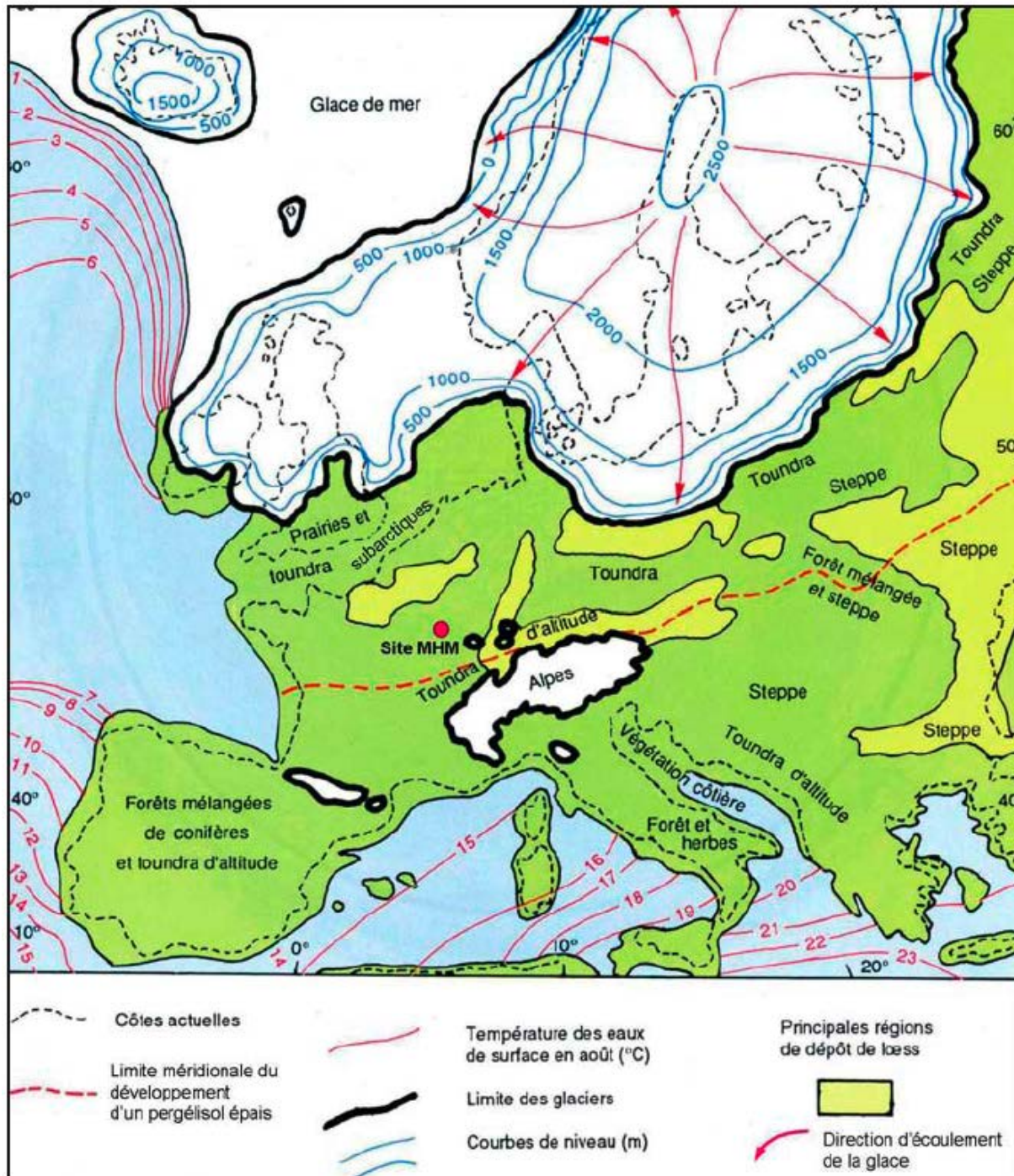
Relative Hazard  
from  
Volcano  
Spatial Density  
+  
Combined  
Tectonic Strain  
(gps, fault, seismic)  
(%)



**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

Geoscientists worldwide are developing and applying methodologies to estimate geologic hazards associated with the siting of nuclear facilities, including nuclear power plants and underground repositories for long-lived radioactive wastes. Understanding such hazards, particularly in the context of the long functional lifetimes of many nuclear facilities, is a challenging task. This book documents the current state-of-the-art in volcanic and tectonic hazard assessment for proposed nuclear facilities, which must be located in areas where the risks associated with geologic processes can be quantified and are demonstrably low.

Specific topics include overviews of volcanic and tectonic processes, the history of development of hazard assessment methodologies, description of current techniques for characterizing hazards, and development of probabilistic methods for estimating risks and uncertainties. Examples of hazard assessments are drawn from around the world, including the United States, Great Britain, Sweden, Switzerland, and Japan.

This volume will promote much interest and debate about this important topic among research scientists and graduate students actively developing methods in geologic hazard assessment; geologists and engineers charged with assessing the safety of nuclear facilities; and those with regulatory responsibility to evaluate such assessments.



Cover illustration (front): elevated view of nuclear power plant on California, Avila Beach, California, USA, photograph by Larry Dale Gordon, November 2002; courtesy gettyimages.com. (back): Mt. Fuji, an active volcano in Japan.

Cover designed by Hart McLeod

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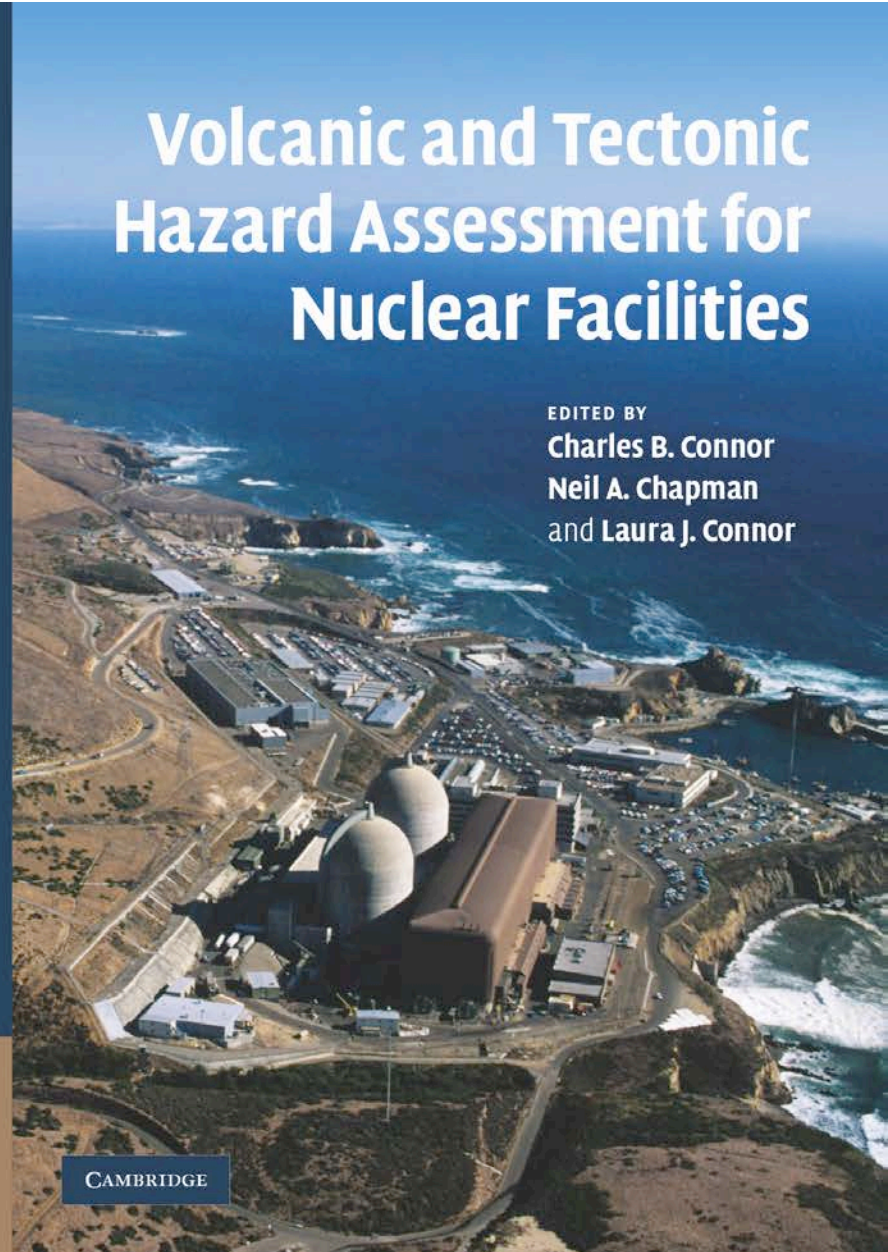


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Connor, Chapman  
and Connor  
**Volcanic and Tectonic Hazard  
Assessment for Nuclear Facilities**

## Volcanic and Tectonic Hazard Assessment for Nuclear Facilities

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and Laura J. Connor**



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