Terrestrial Planets

Week 11

Professor Olivia Jensen
Earth and Planetary Sciences
FD Adams 131C

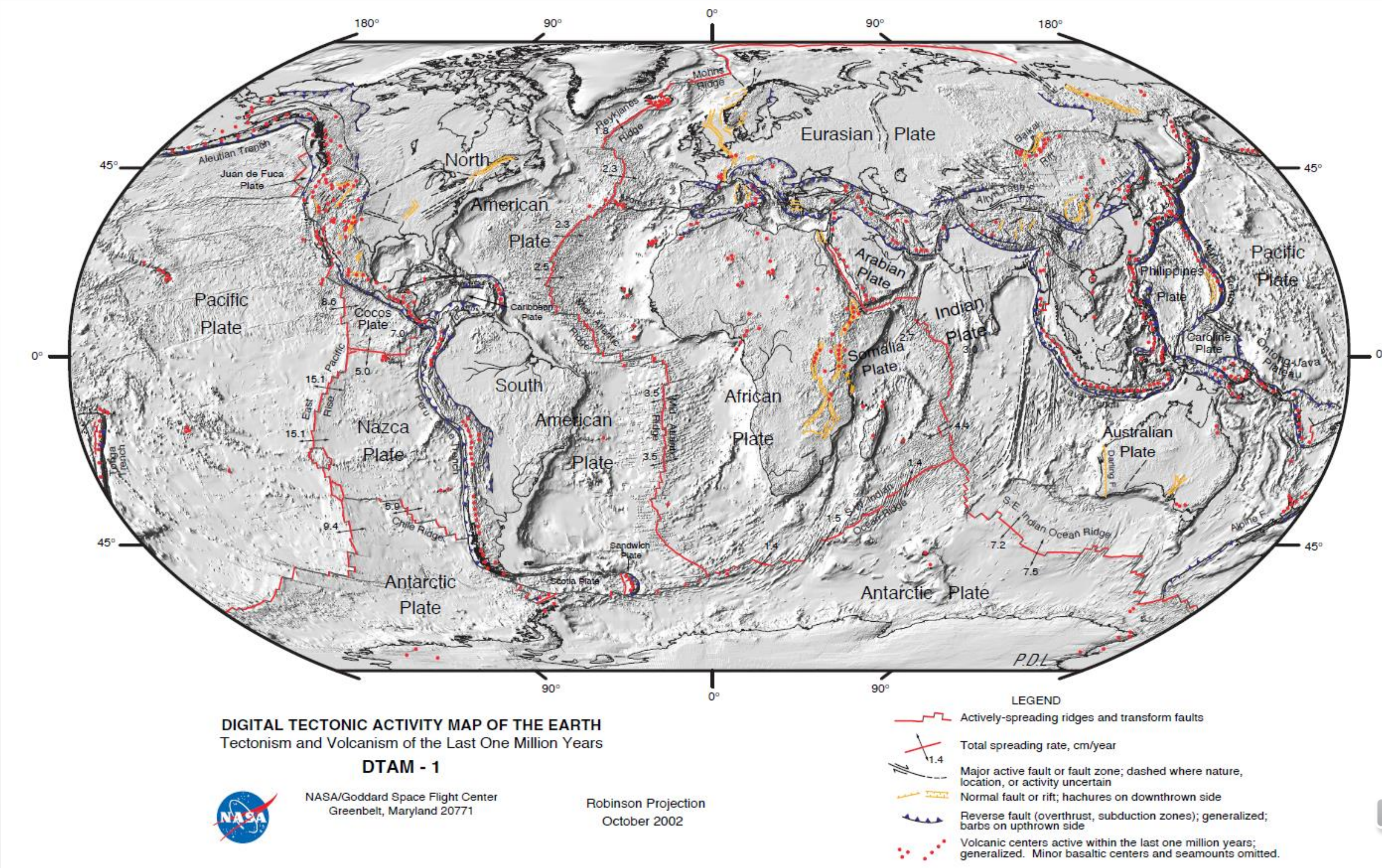
Geological Activity

How would we recognize current and ancient geological activity on other planets and moons?   Evidence?

With Earth as a model, we look for:

- **Plate tectonic topography (deep basins and high continents)**
- **Isostatic violations**
- **Recent and ancient plate tectonic movements – crustal magnetics?**
- **Thrust faulting and ridge spreading**
- **Seismic activity**
- **Volcanism (active and ancient; magma and geysers)**

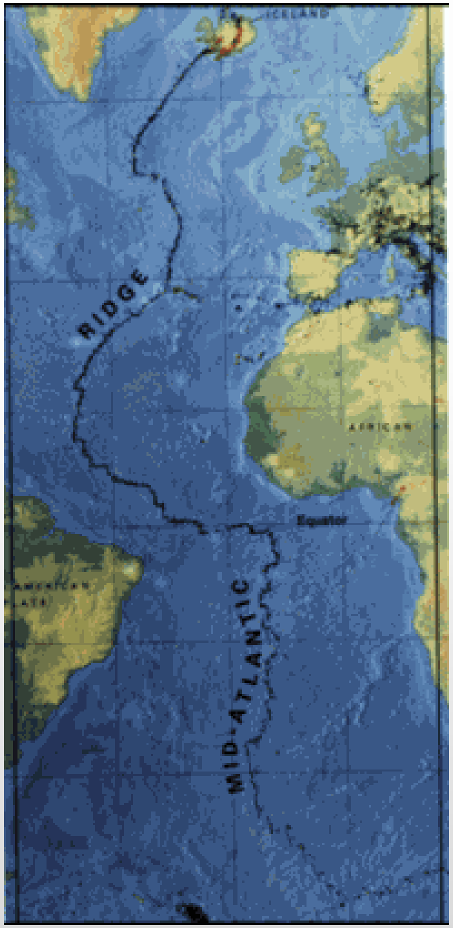
Digital Tectonic Activity Map



Tectonic Plate Boundaries

There are four types of plate boundaries:

<u>Divergent boundaries</u> -- where new crust is generated as the plates pull away from each other.



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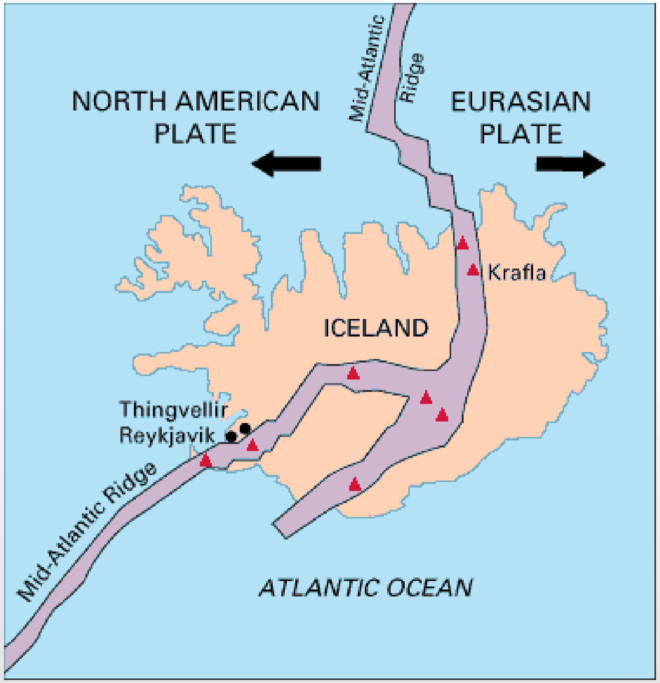

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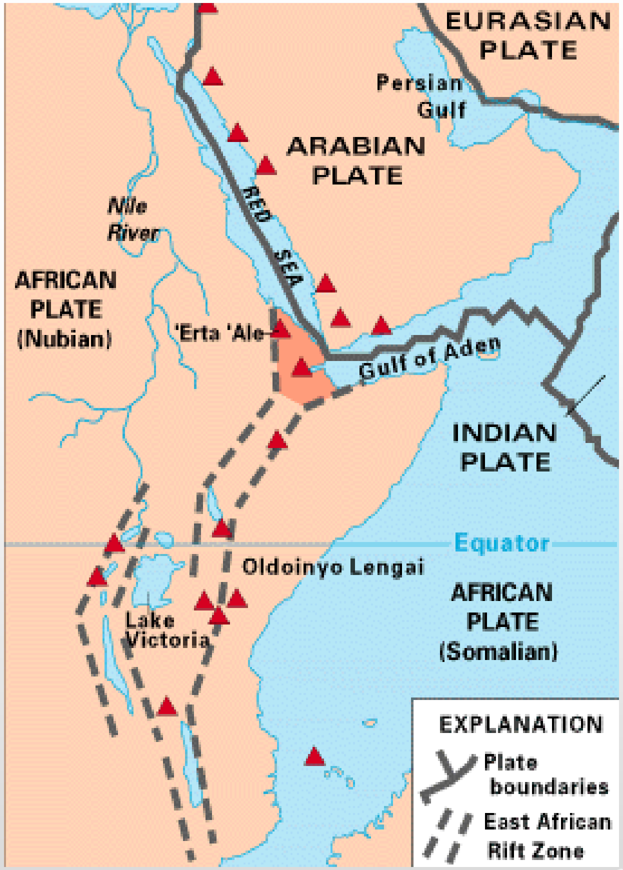

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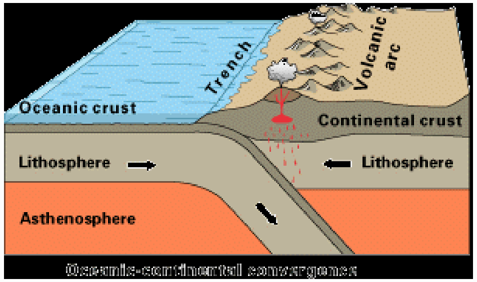
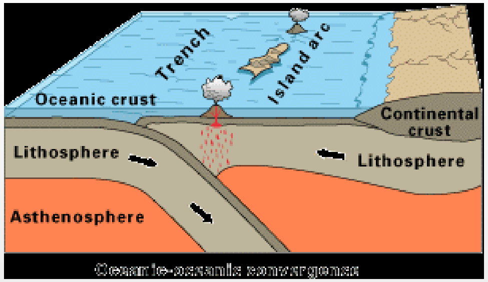
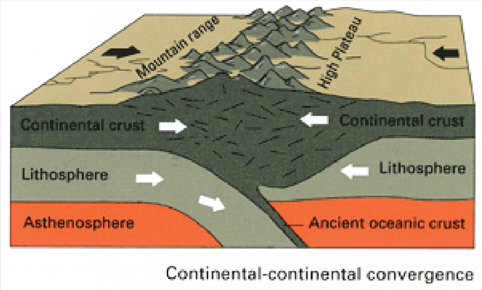


Oceanic-continental convergence



Oceanic-oceanic convergence



Continental-continental convergence

Tectonic Plate Boundaries

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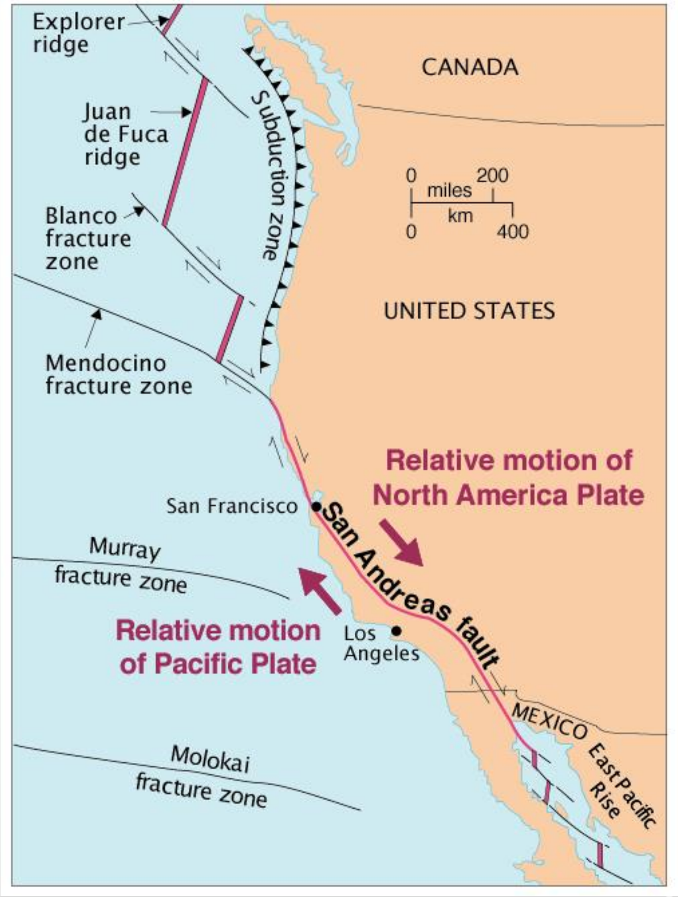
Convergent boundaries -- where crust is destroyed as one plate dives under another.

Transform boundaries -- where crust is neither produced nor destroyed as the plates slide horizontally past each other.



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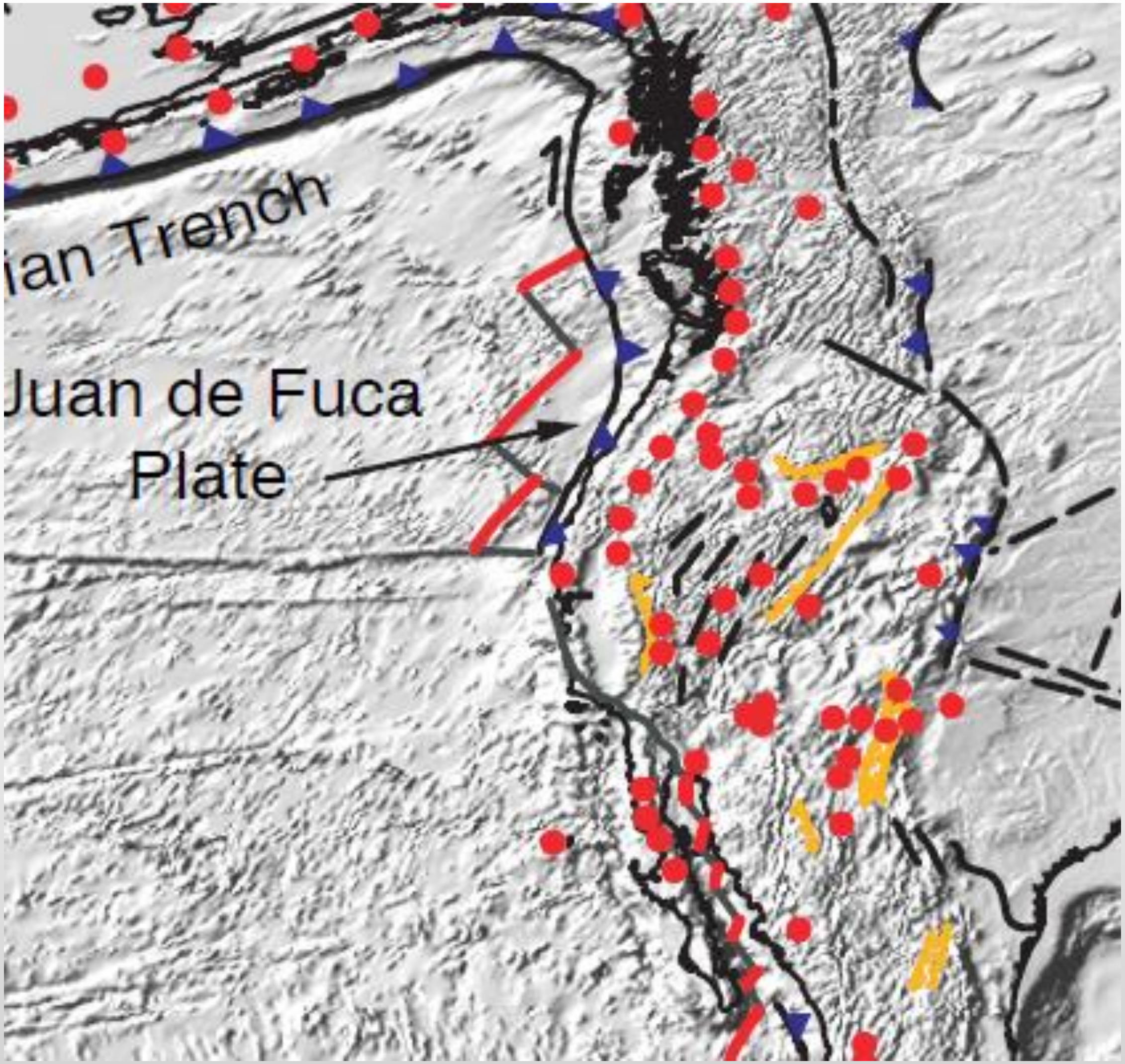
<u>Transform boundaries</u> -- where crust is neither produced nor destroyed as the plates slide horizontally past each other.

<u>Plate boundary zones</u> -- broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.

Sea-floor spreading

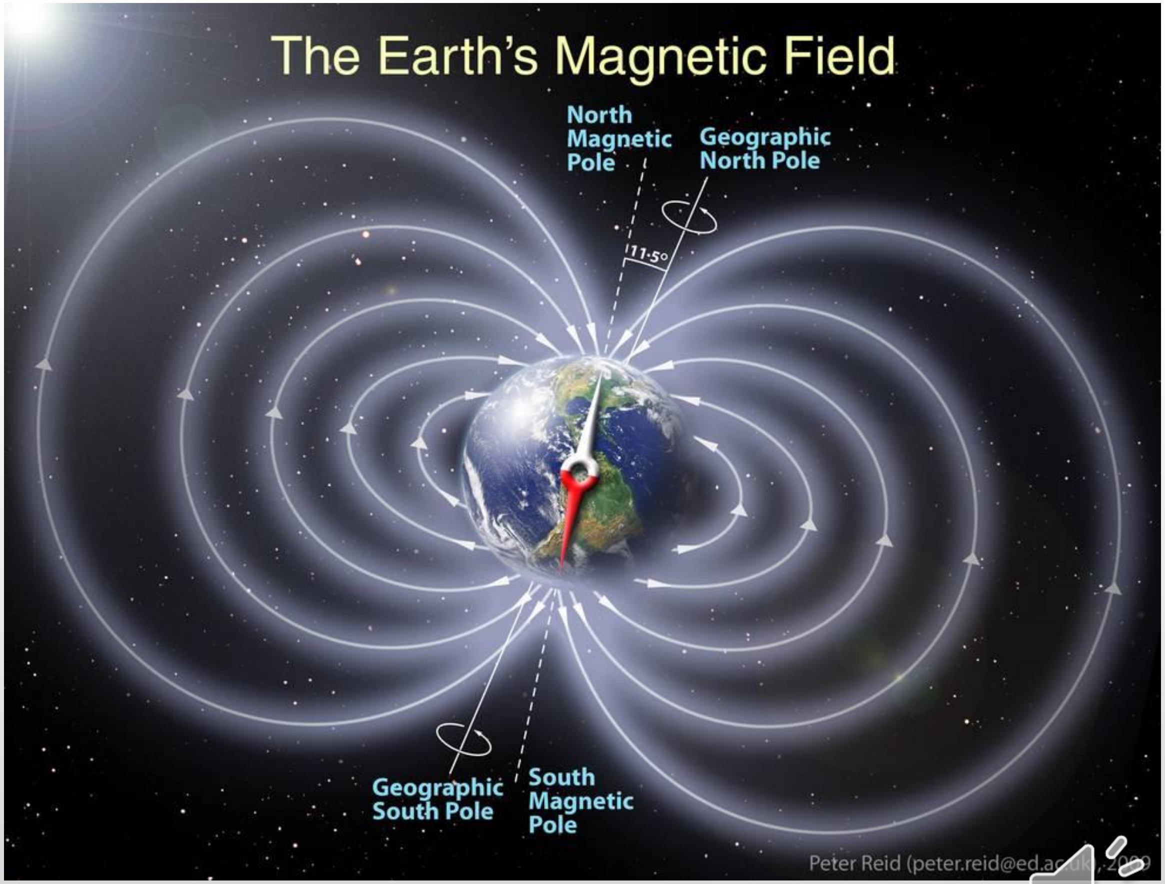


L. Morley and A. Larochelle, in 1962, recognized that a pattern of magnetic striping on the ocean floor southwest of British Columbia showed a symmetry across the ridge between the Juan de Fuca and Explorer Plates. In 1963, **F. Vine and D. Matthews** published their landmark paper in Nature magazine re-iterating the Larochelle-Morley findings for "[Magnetic anomalies over ocean ridges]".

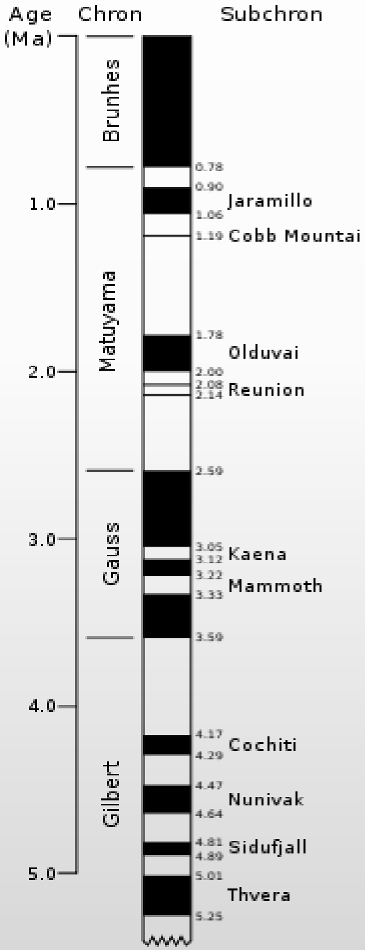
Earth's Geomagnetic Field

The magnetic dipole field generated by Earth's core dynamo aligns with the rotation axis within a few degrees. Since it became well established almost 4 billion years ago, it has undergone aperiodic polarity reversals.

We can use these reversals to determine the timing of lava freezings… Freezing lavas are imprinted by the field as they cool through the **Curie Temperature**



Magnetostratigraphy

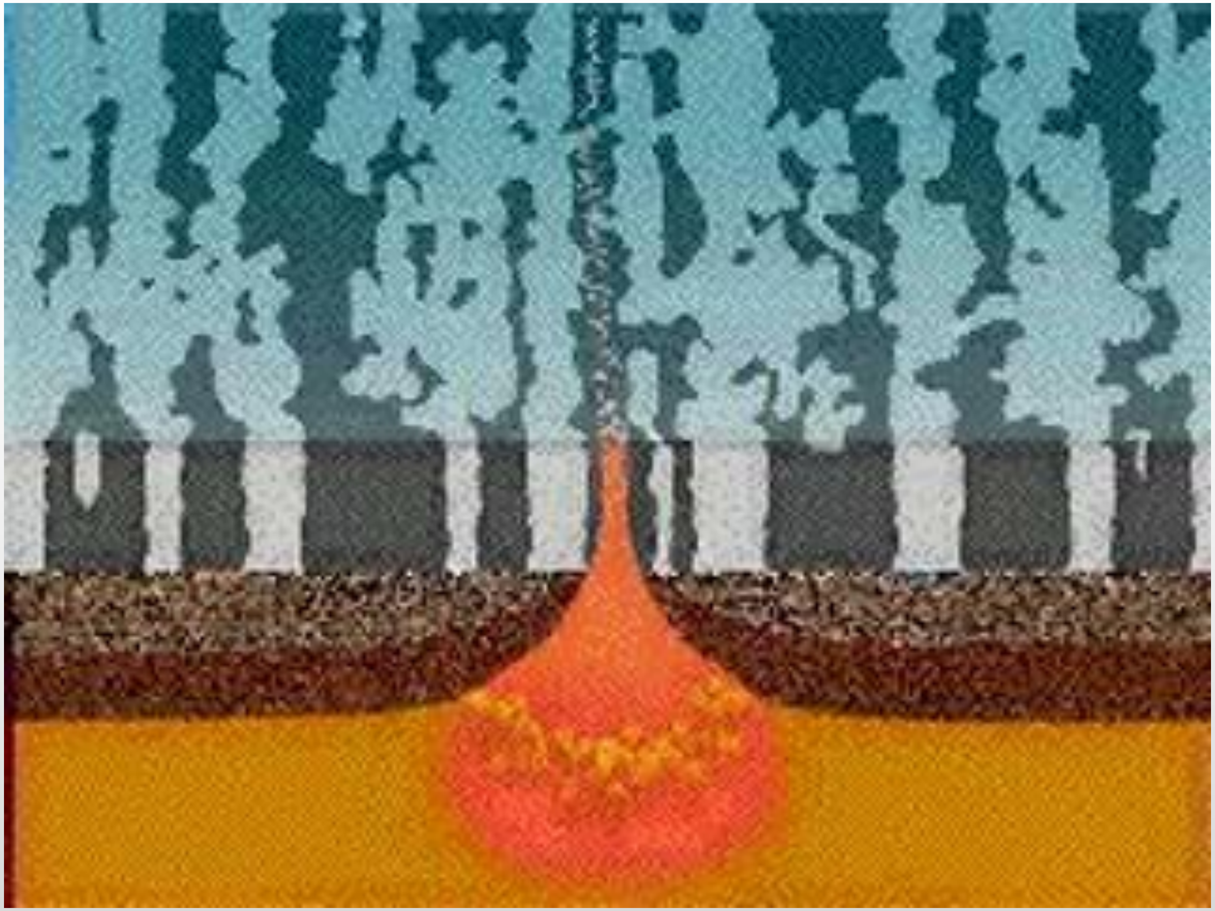


Timing reversals and determining local latitude

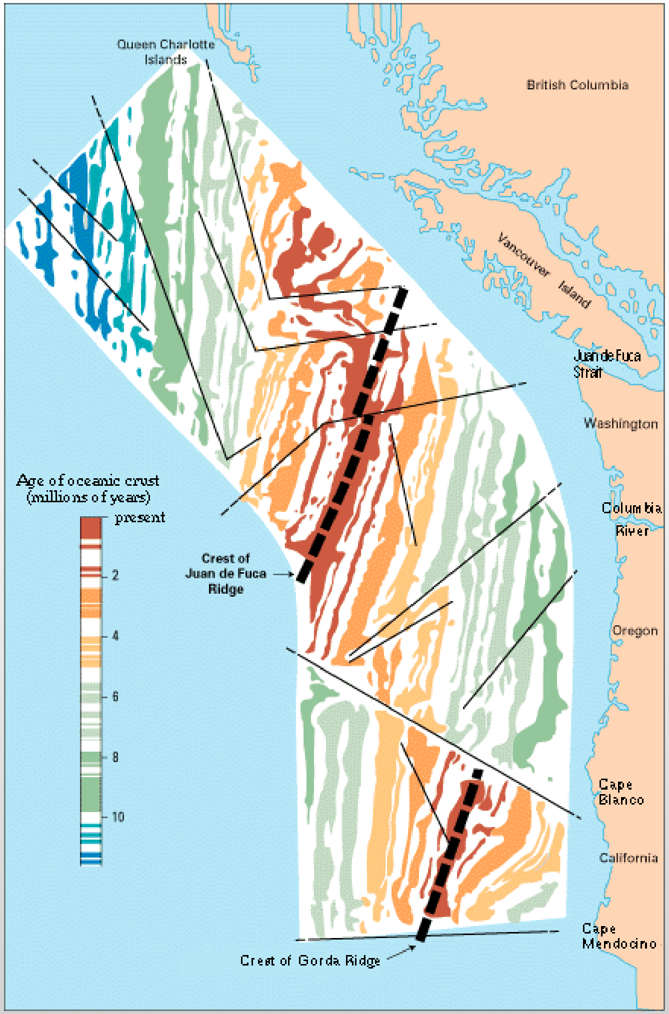
Cores are first analyzed in their natural state to obtain their natural remnant magnetization (NRM). Taken to a lab, the NRM is then stripped away using thermal or alternating field demagnetization techniques to reveal the stable magnetic component which is that frozen in during deposition.

Magnetic orientation of the stable component is measured to determine a relative (to sample) latitude for the Virtual Geomagnetic Poles (VGP). Cores are age-dated to accord their VGP and polarity with time. Polarity data are reported as a magnetostratigraphic column (left).

Magnetic imprinting of oceanic crust



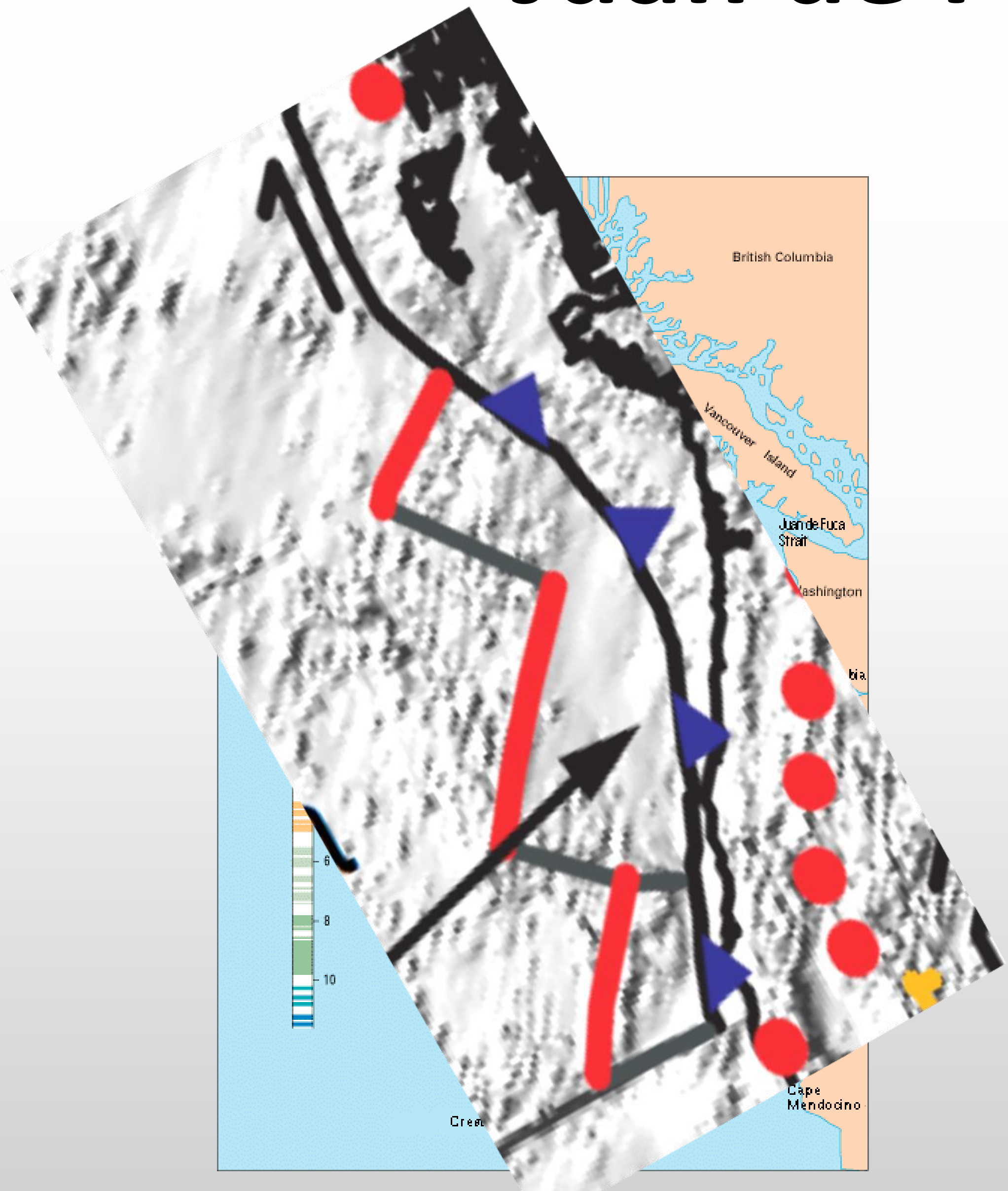
Juan de Fuca ridge



Sea-floor spreading from the Juan de Fuca ridge separates the **Juan de Fuca** and **Gorda Plates** (east side of ridge) from the **Pacific Plate** (west). The rate of spreading from the ridge is measured to be about **3 cm/year**. The Juan de Fuca and Gorda plates collide with the **North American Plate** moving to the west at about **1.2 cm/year**. At the **Cascadia Subduction thrust fault**, they collide at about 4 cm/year.

From ridge to the trench takes up to 10 million years.

Juan de Fuca ridge



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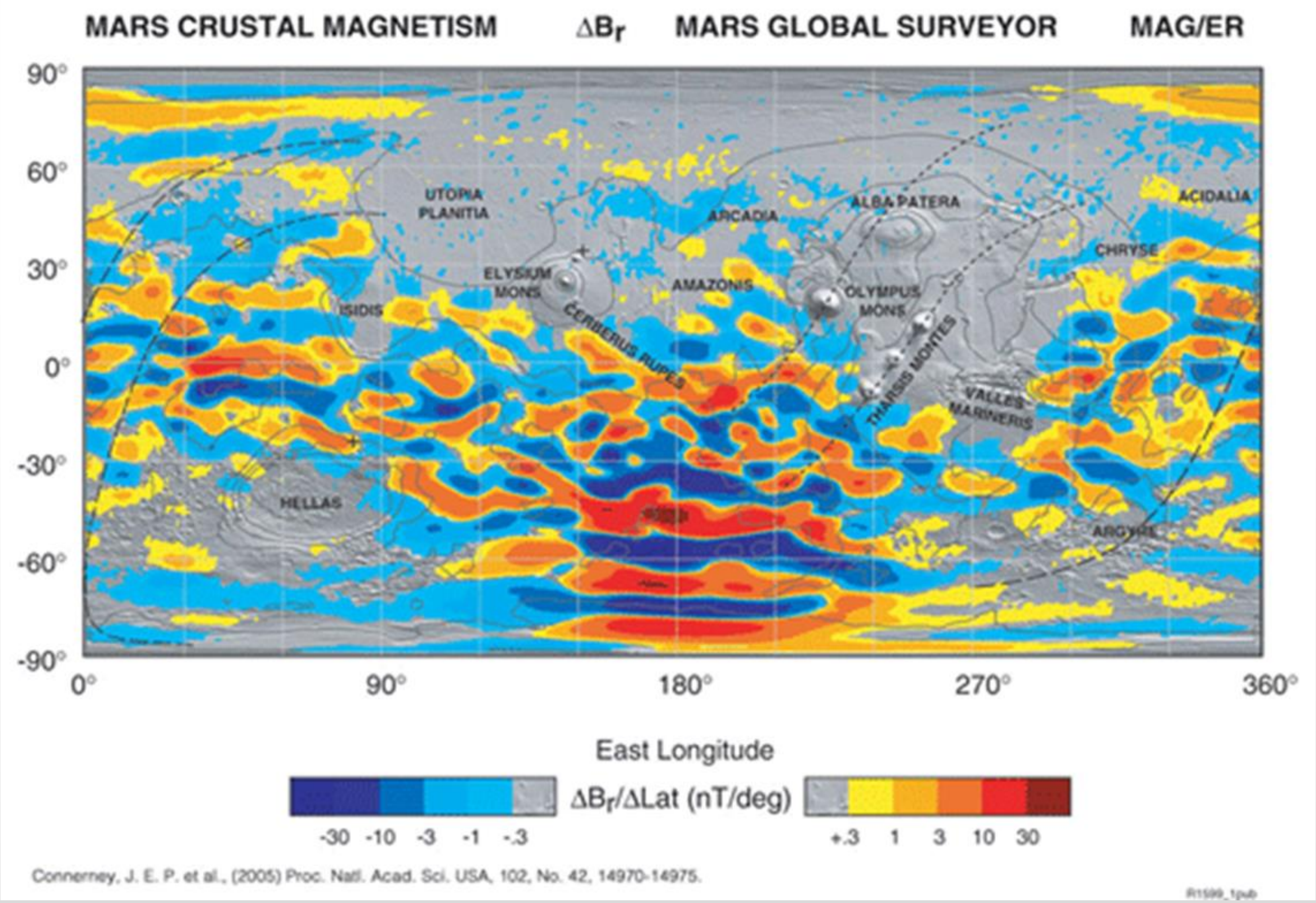
Magnetics – Mars?

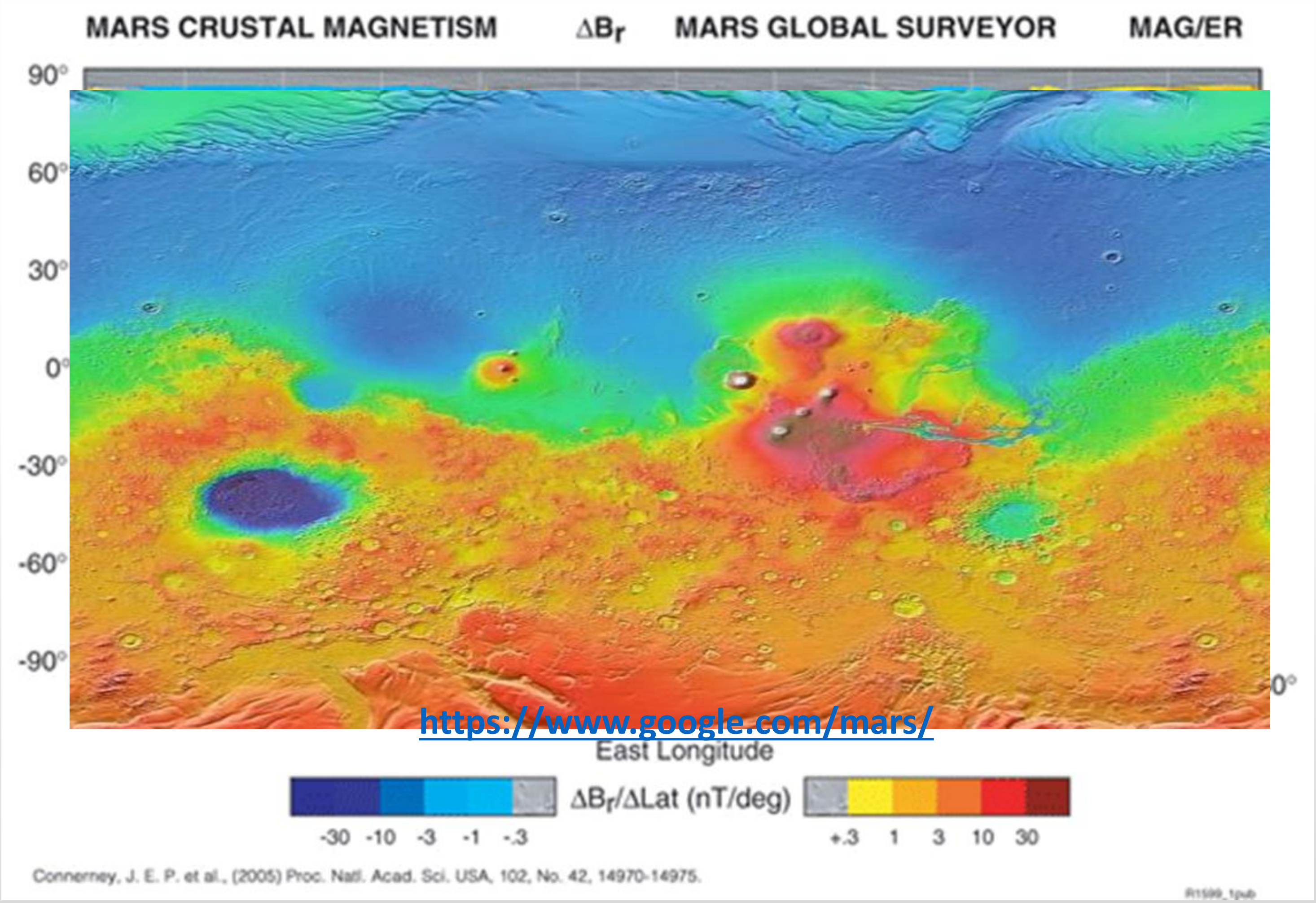
While Mars now has no internally generated magnetic field, there is evidence in the imprinted remnant magnetism in the crustal rock that such a field once existed. In the highlands of the southern hemisphere, that oldest terrain on Mars, magnetic striping even suggests that 4Ga, a field did exist. Moreover, the striped character of the imprinted field suggests some kind of tectonics… plate tectonics?

Magnetics



https://www.nasa.gov/mission_pages/mars/news/mgs_plates.html

Magnetics



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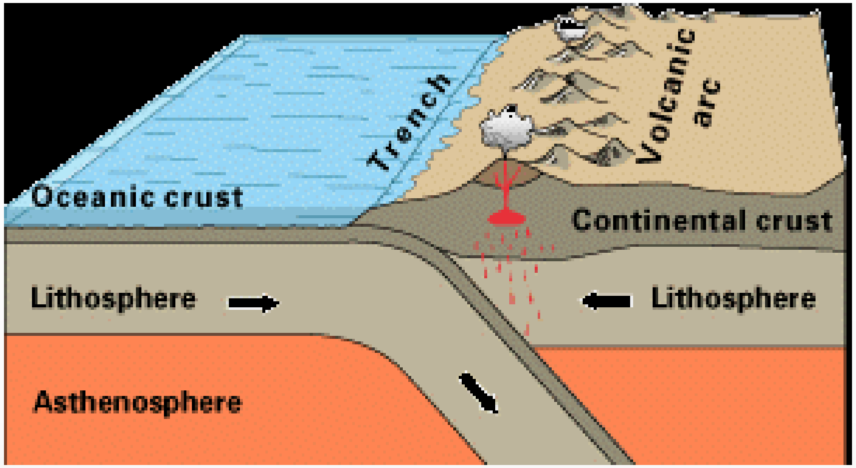
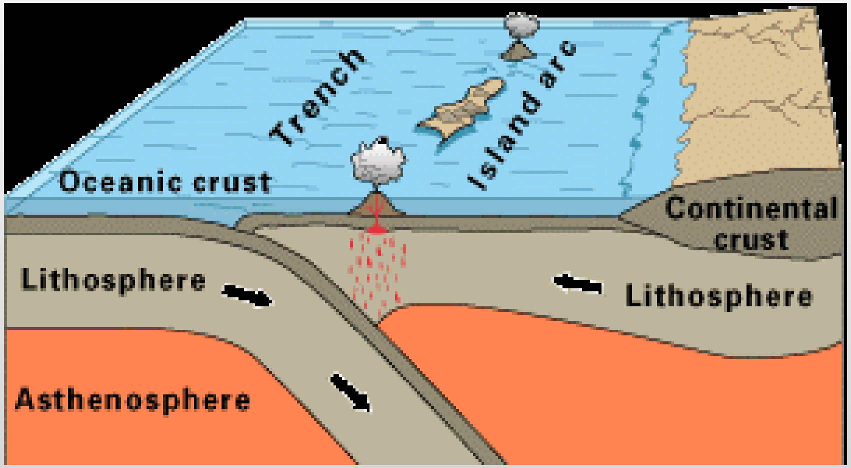
Subduction zones

The oceanic crust and lithosphere that is created at the spreading ridge is recycled back into the mantle at subduction zones. The process is a stick-slip process that is evidenced by often large subduction earthquakes and chain volcanism.





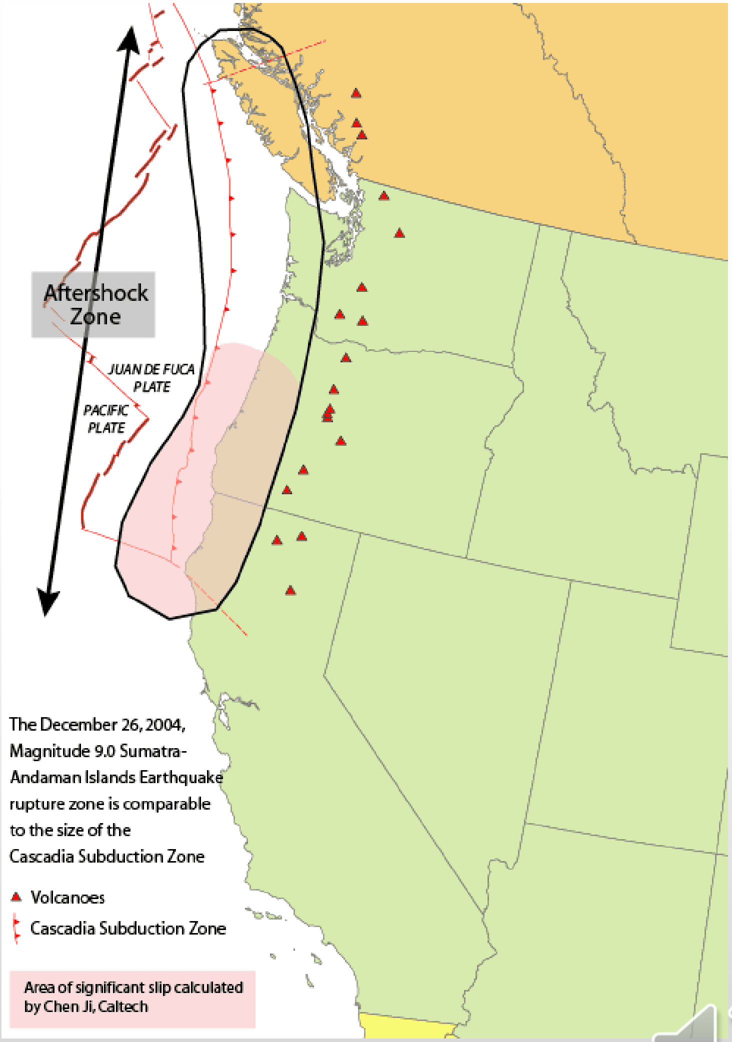
If the lithospheric plate subducts under a continental plate (like the NA plate), the continental plate is up-lifted and foreshortened. Subduction under another oceanic lithospheric plate creates Island Arc Volcanism like Japan and the Aleutian Islands.

https://pubs.usgs.gov/gip/dynamic/understanding.html

Cascadia Megathrust Event

At **about 9:00PM on January 26, 1700, the Cascadia Thrust Fault fractured** in what is one of the largest earthquakes known to have occurred on Earth. We have no instrumental records of the event but many indications of its occurrence and scale.

The [Cascadia Subduction Zone (CSZ) Megathrust Earthquake](https://upload.wikimedia.org/wikipedia/commons/3/38/Cascadia_subduction_zone_USGS.png) **M_w ~ 9+**.



https://upload.wikimedia.org/wikipedia/commons/3/38/Cascadia_subduction_zone_USGS.png

Tsunami

The tsunami generated by the 1700 CSZ event was first recognized as a "***orphan tsunami***", one which was not caued by a local Japanese earthquake. Around midnight on January 27, 1700, a mysterious tsunami stole through several villages on theeastern coast of Japan.

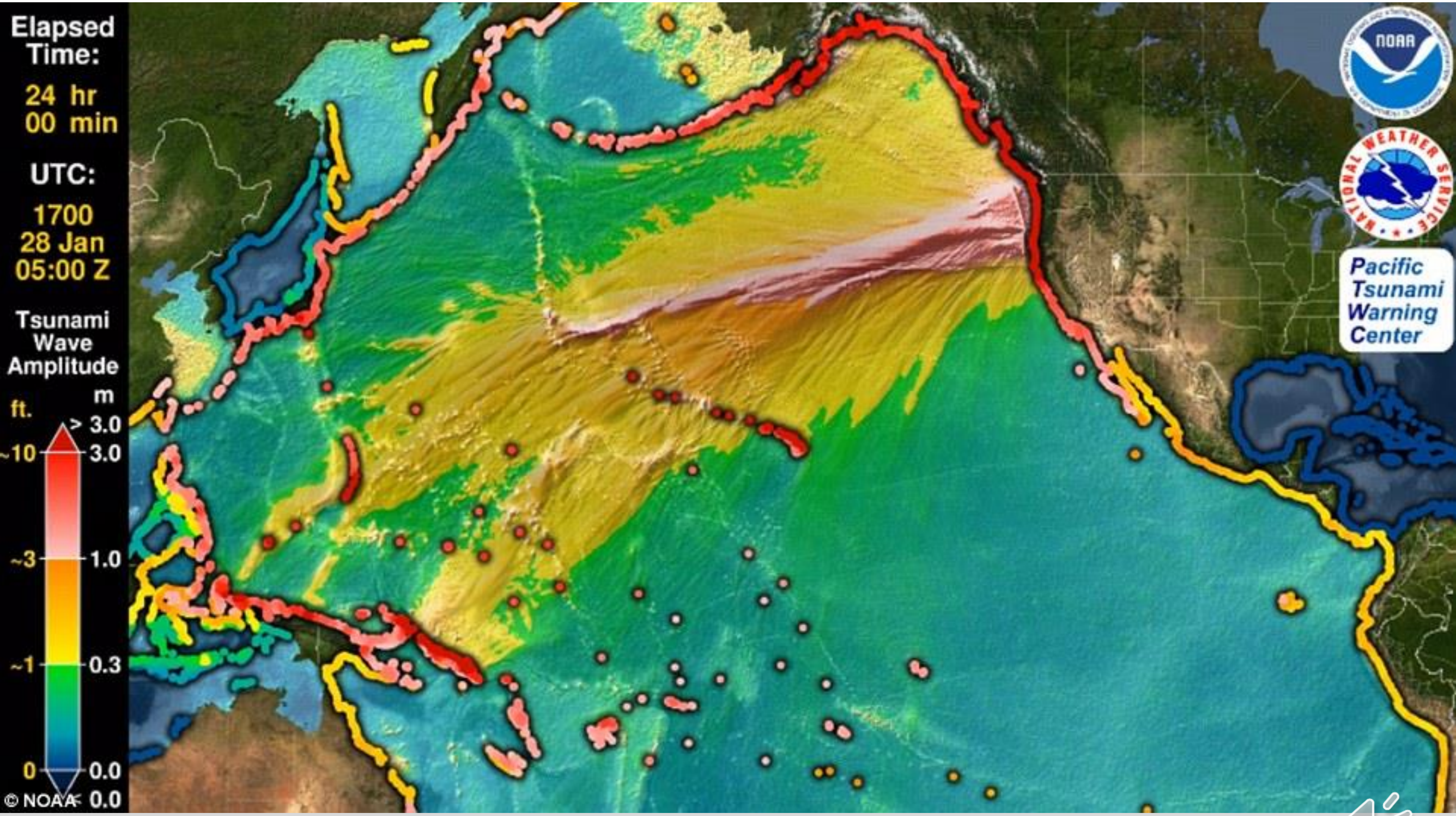
The waves reached as high as 4 metres and flooded rice paddies, washed away buildings and damaged fishing shacks and salt kilns. Sleeping villagers awoke startled and wet and had to hastily scramble to high ground. The waters knocked down oil lamps and started a fire in one village and destroyed 20 houses in another.

The waves pounded the villages all through that night and into the late morning of the next day.

Local effects were later recognized on the coasts of BC, Washington and Oregon.

Simulations of what might be expected locally when the next Mw 9 CSZ event occurs: **Low resolution**, **medium resolution**.

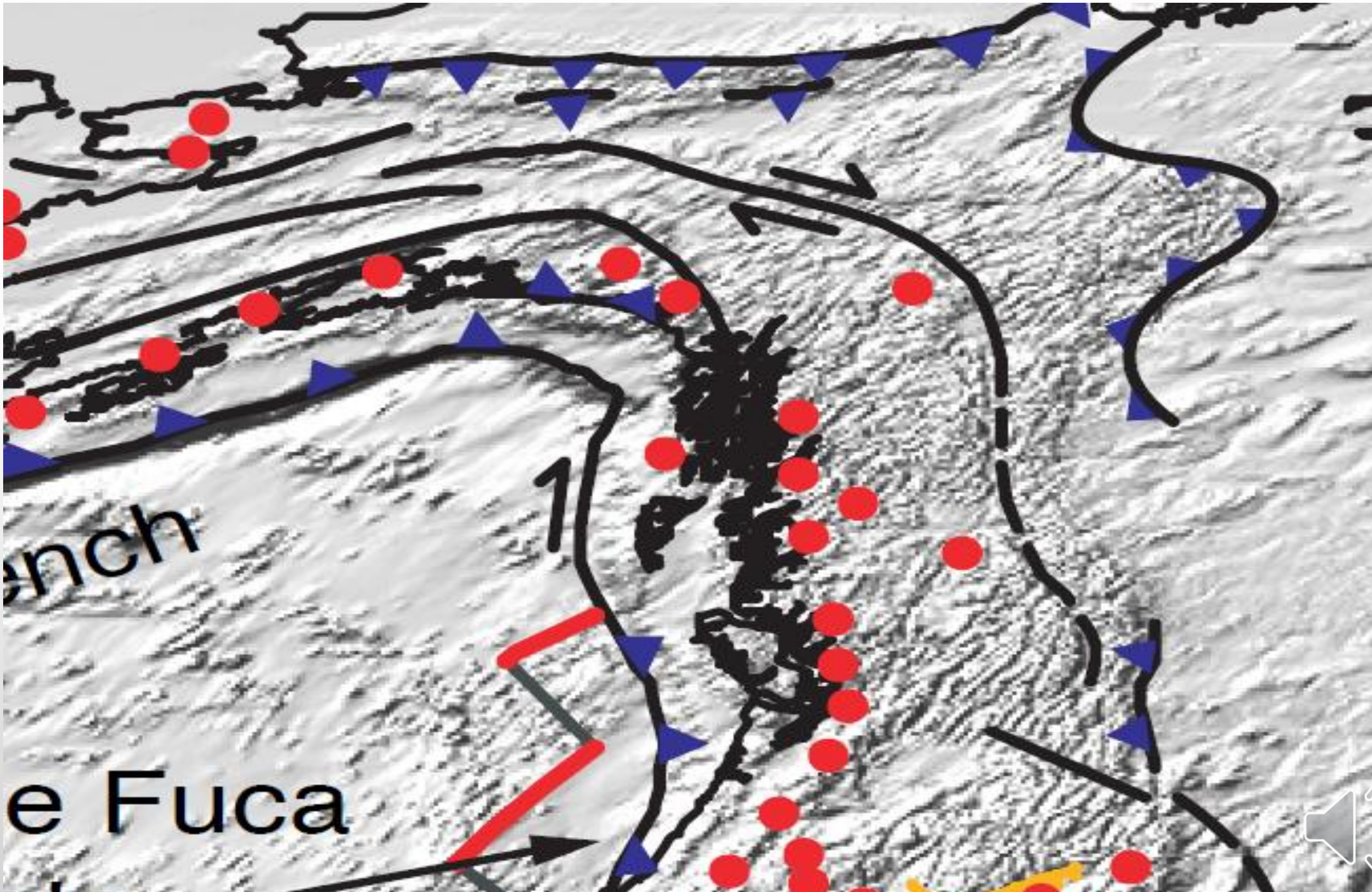
Tsunami



Elapsed Time:
24 hr
00 min
UTC:
1700
28 Jan
05:00 Z
Tsunami Wave Amplitude
ft.
m
> 3.0
~10
3.0
~3
1.0
~1
0.3
0
0.0
© NOAA
< 0.0
NOAA
NATIONAL WEATHER SERVICE
Pacific Tsunami Warning Center

Tsunami Cascadia 1700

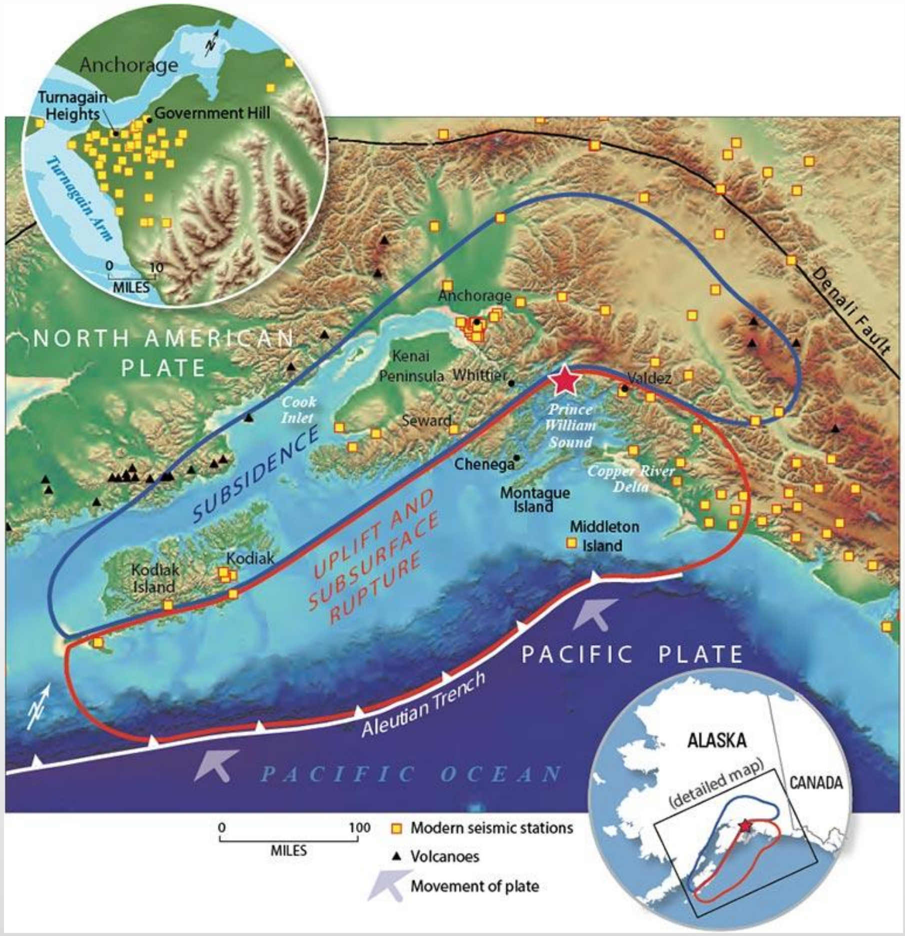
Alaska 1964



Alaska 1964

On Good Friday, March 27, 1964, the second largest (M_w 9.2) earthquake that we have so-far recorded with seismic instruments occurred in [Prince William Sound, Gulf of Alaska.]

Ground shaking devastated Anchorage. [Tsunami] spread worldwide, causing serious inundations in Hilo, Hawaii and along the west coast of North America. The hardest hit region of Canada was Port Alberni BC where the harbour infrastructure was devastated.



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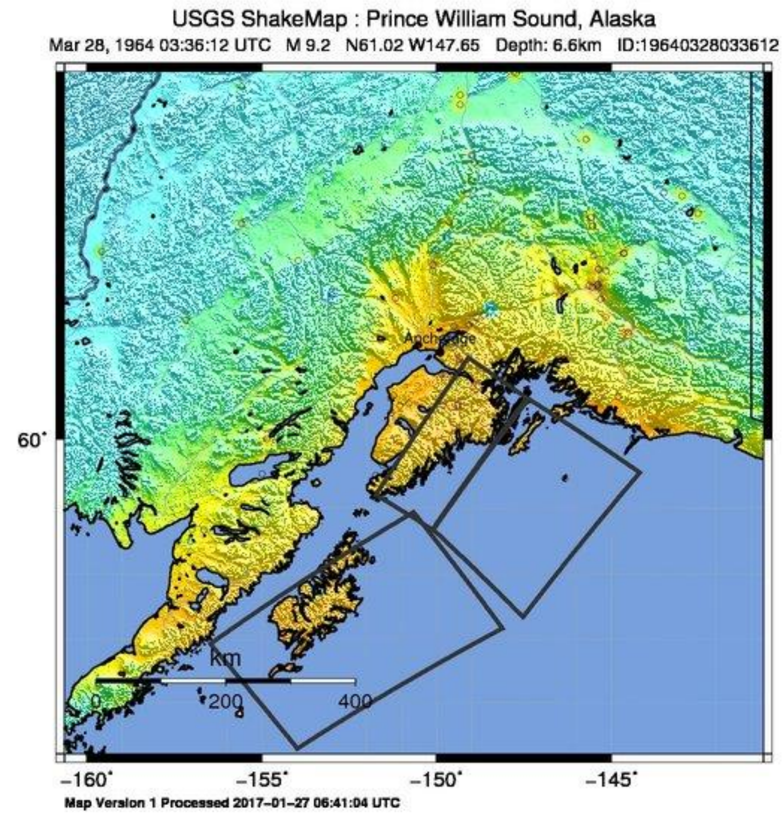

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Tsunami Alaska 1964

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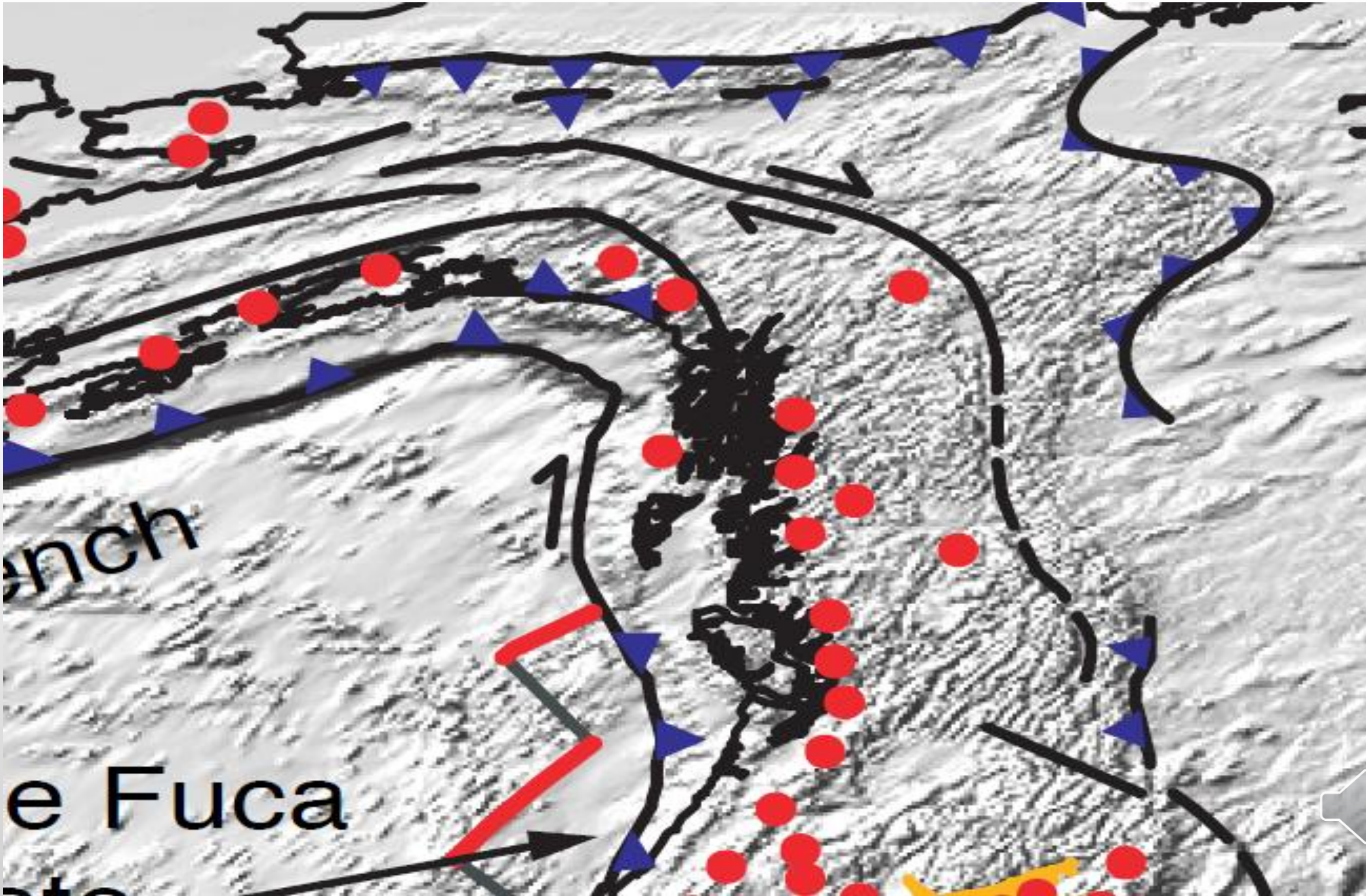
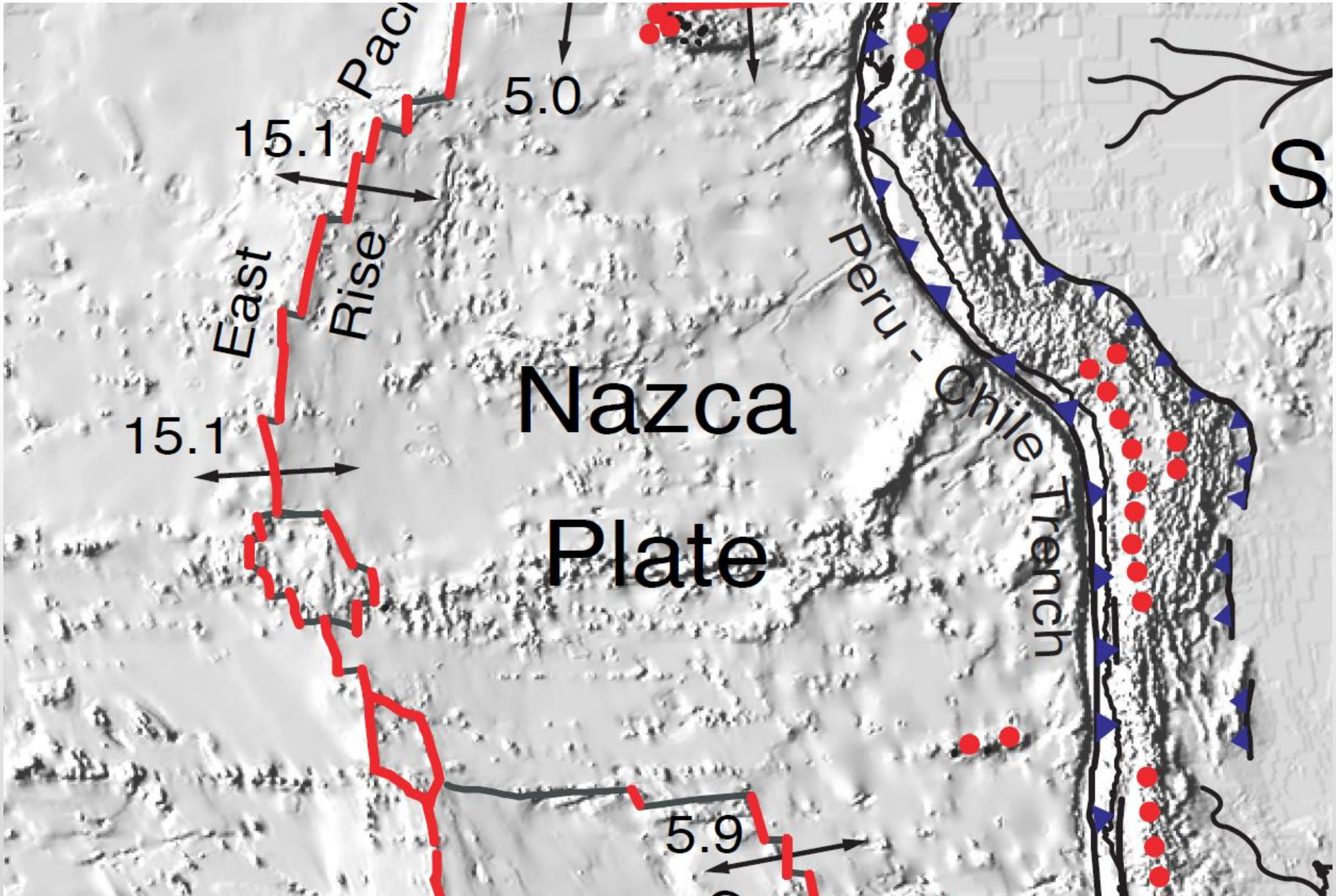


Nazca Plate – Chile-Peru 1960



https://commons.wikimedia.org/wiki/File:Tsunami_travel_time_Valdivia_1960.jpg#filelinks

Nazca Plate – Chile-Peru 1960

Offshore from the west coast of South America, under Peru, Bolivia and Chile the Nazca Plate which is spreading away from the East Pacific Rise (a ridge) about 4000km to the west is subducting under the South American Plate.

Along this convergent margin, the largest earthquake, in terms of its magnitude ever instrumentally recorded on Earth, the M_w 9.5 **1960 Chile-Peru (Valdiva) Megathrust event** occurred along this convergent margin.

Tsunami spreading away from that earthquake travelled across the Pacific to Japan, reflected from the Asian coastline and then travelled back across the Pacific again to South and North America.

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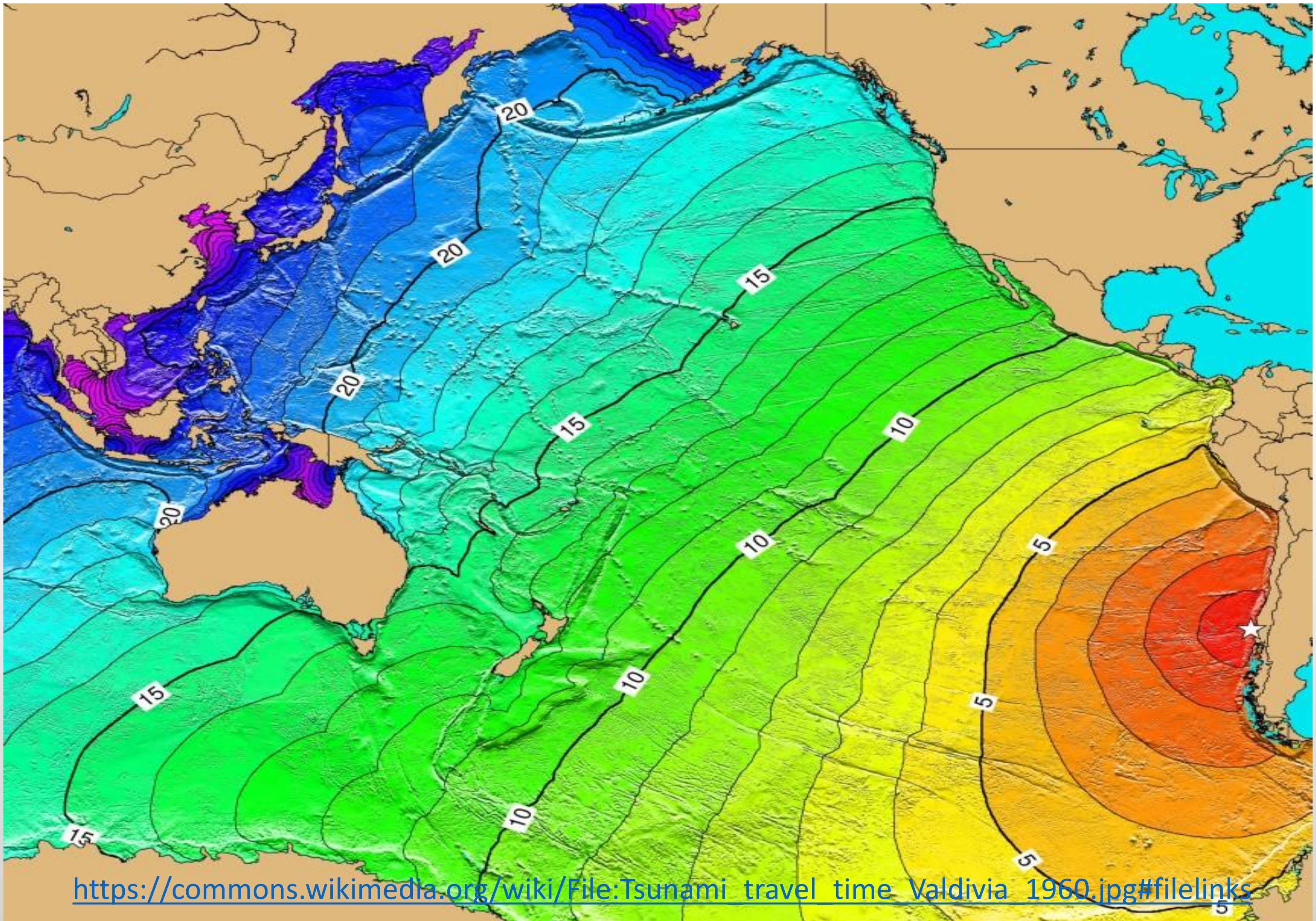

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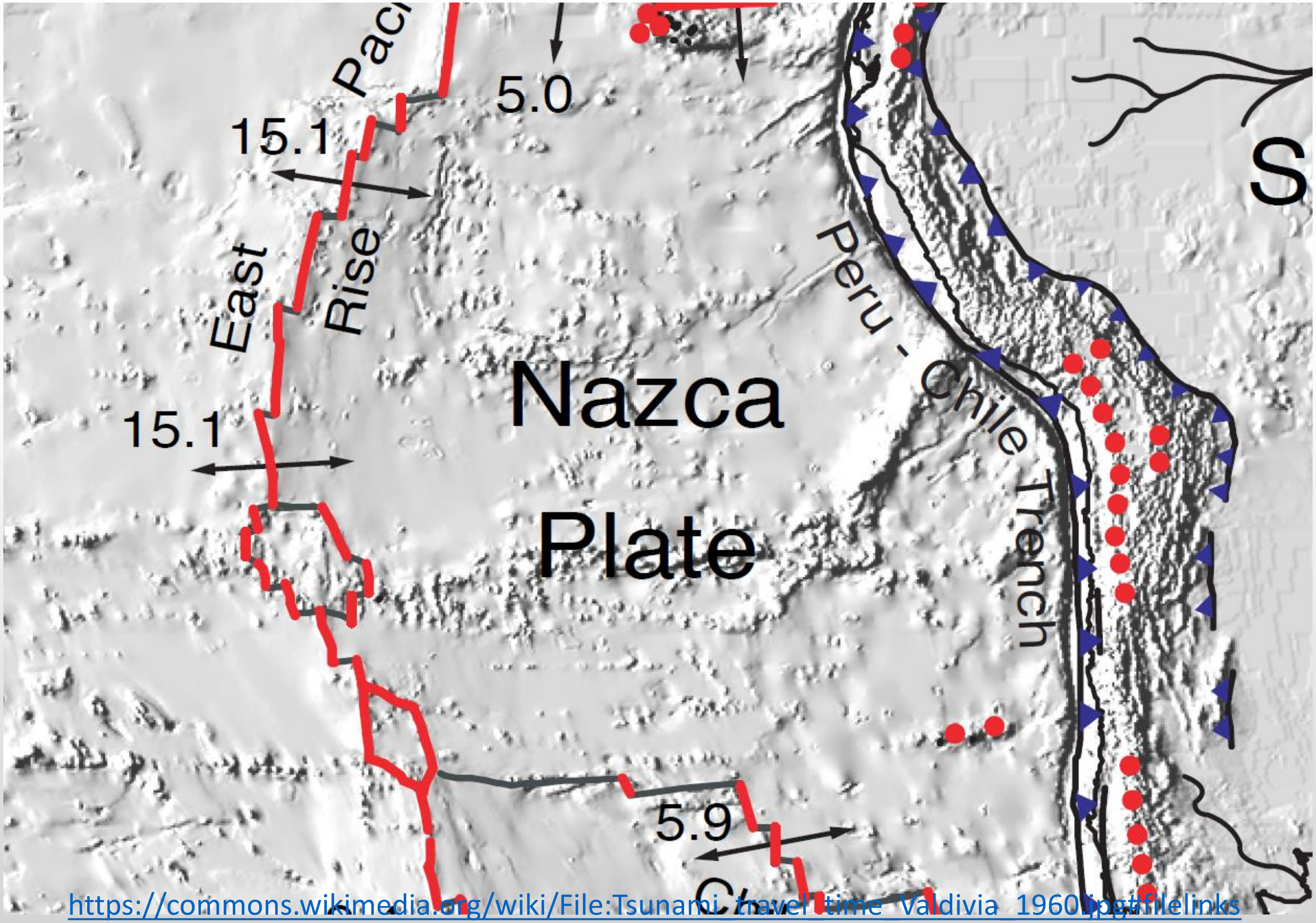

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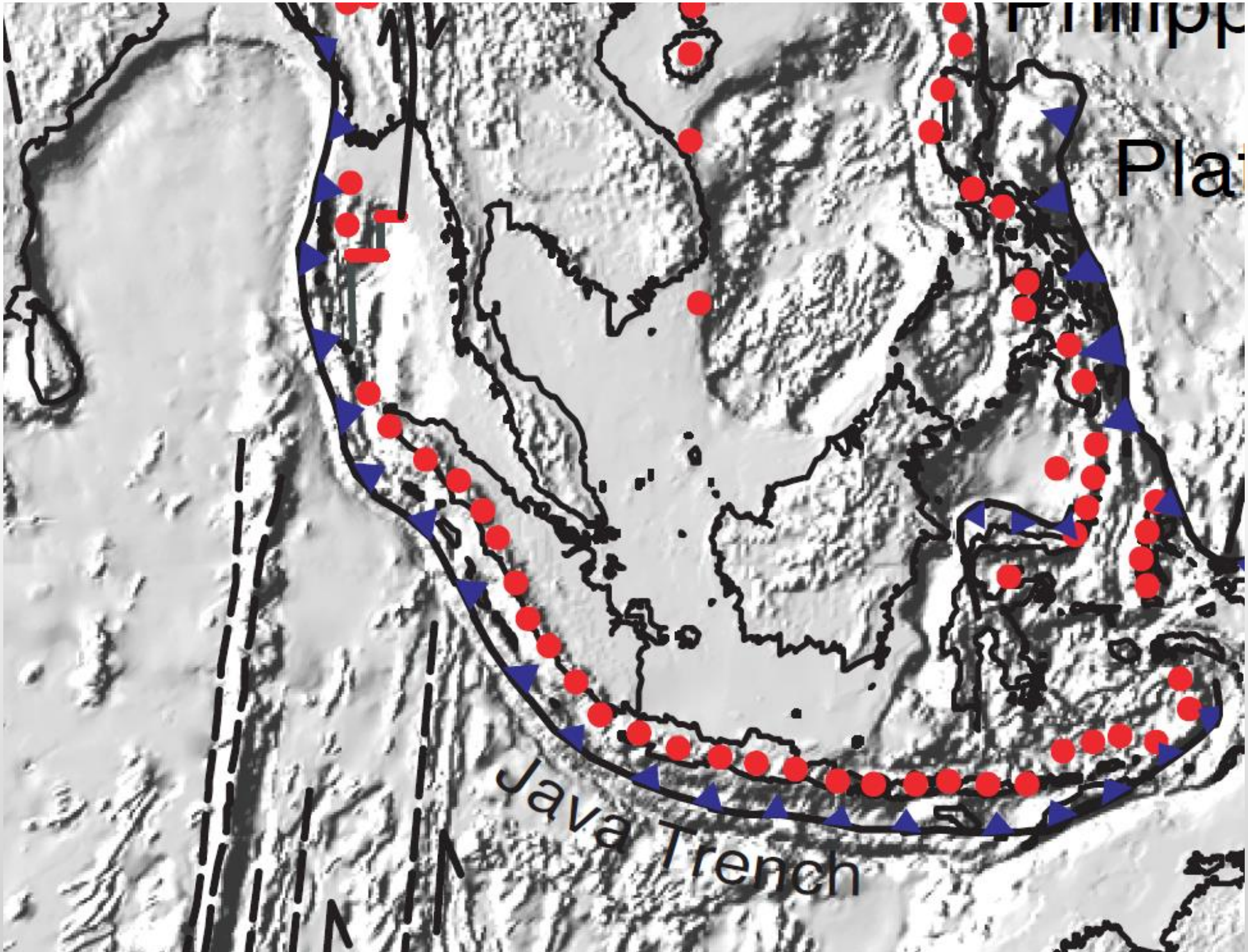
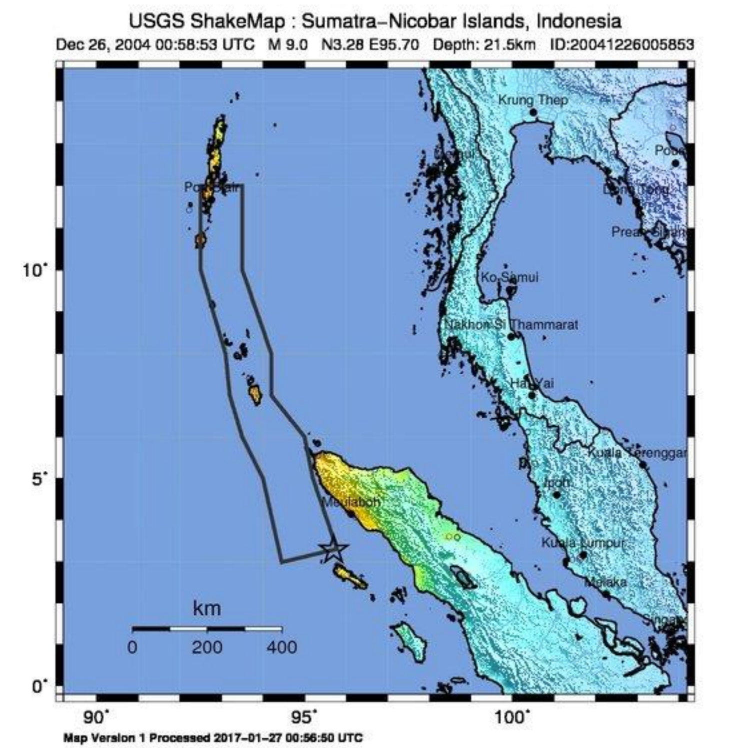
Sumatra (Andaman) 2004



Sumatra (Andaman) 2004

On December 26, 2006, the **Mw 9.2 Sumatra-Andaman subduction megathrust event** occurred off the west coast of Sumatra, Indonesia.

Direct seismic shaking produced little damage but the **tsunami** caused by this event led to more deaths and casualties than any earthquake in the previous 50 years. More than 200000 people were killed along the coastal regions of the Indian Ocean with significant casualties as far away as Madagascar.



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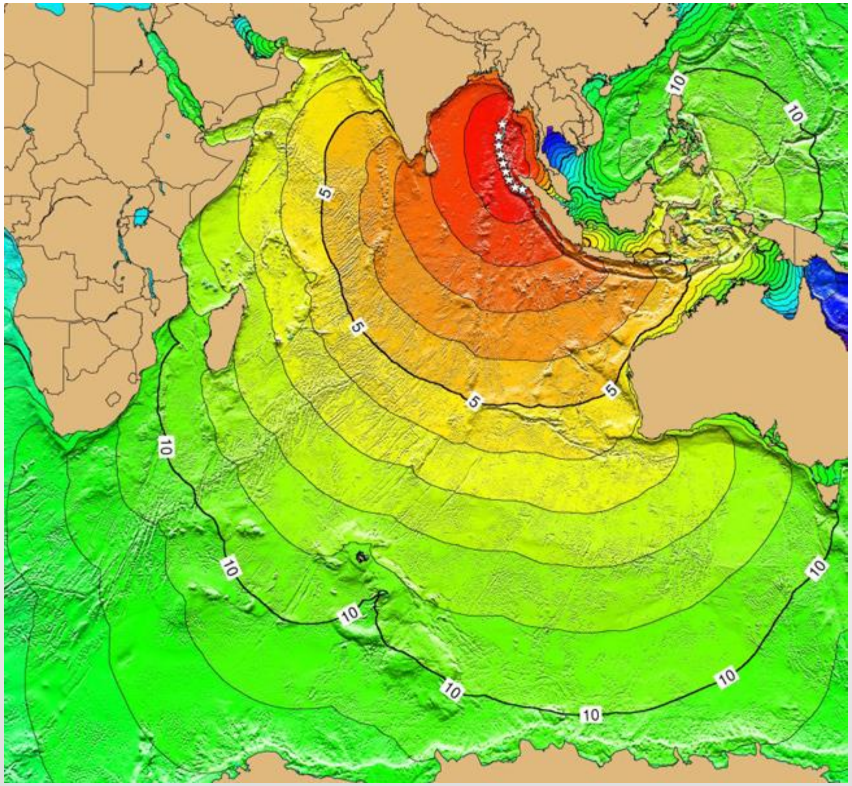

Tsunami Sumatra 2004

Tsunami Sumatra 2004
Global

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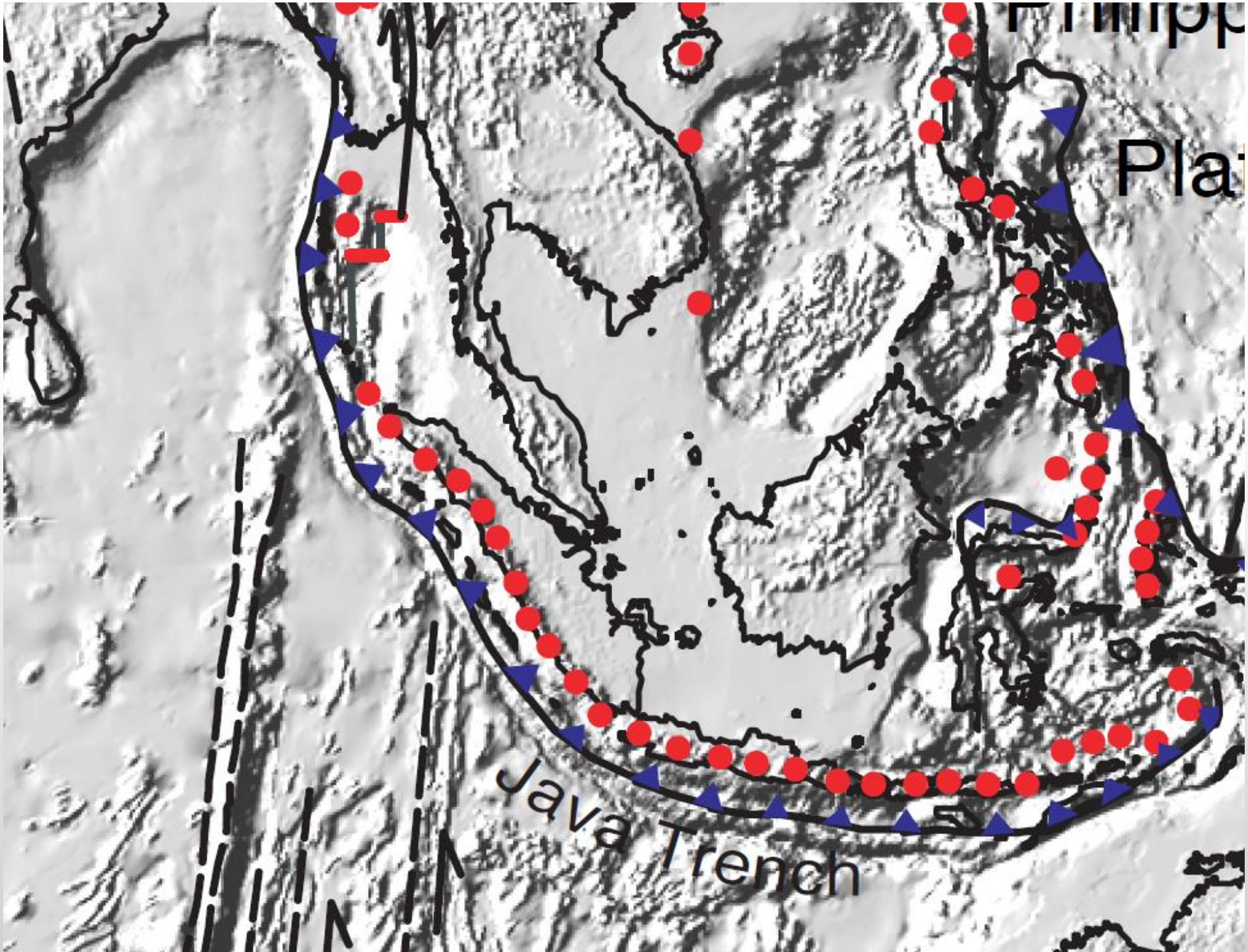
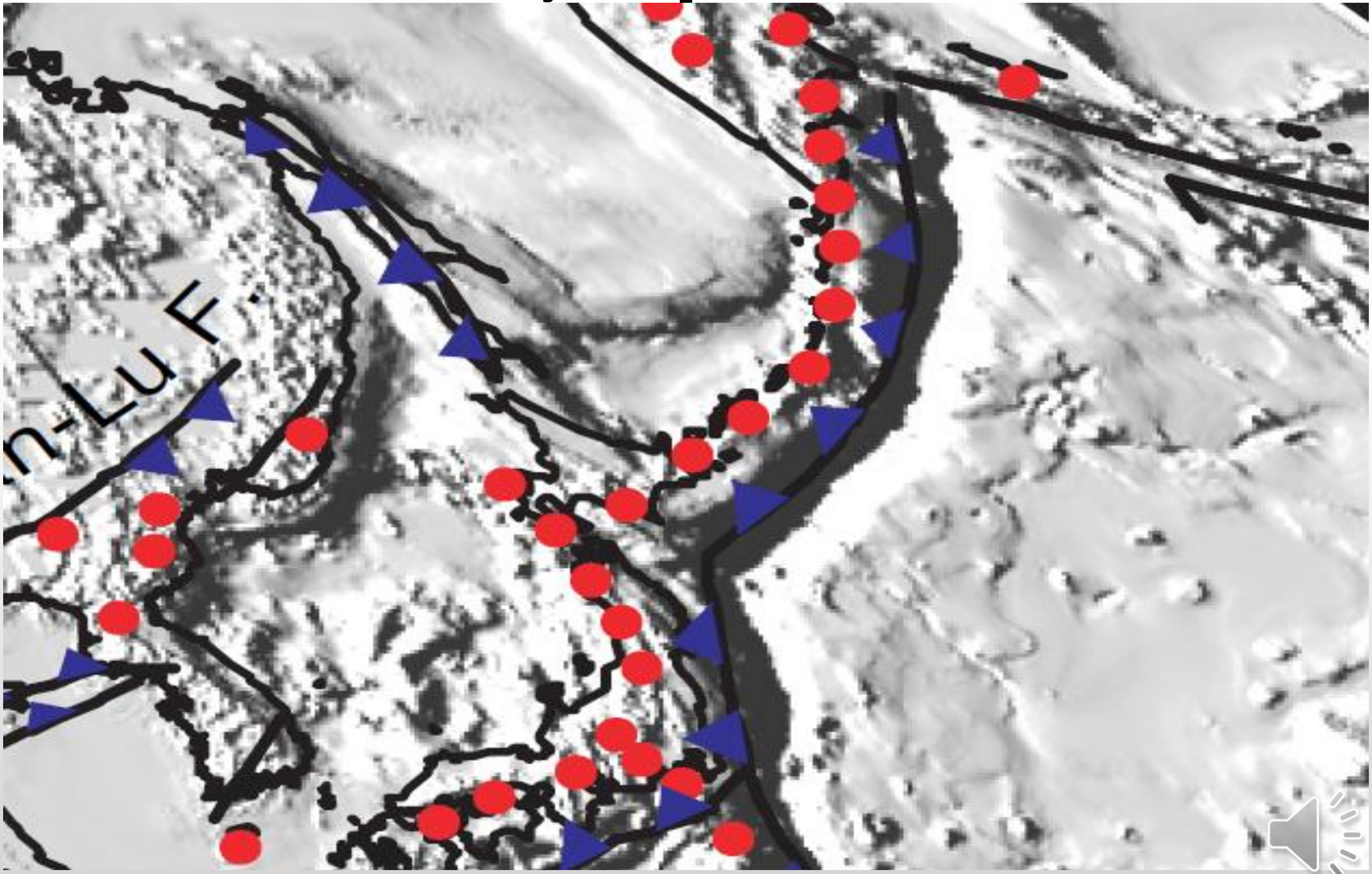


Tohoku, Japan 2011

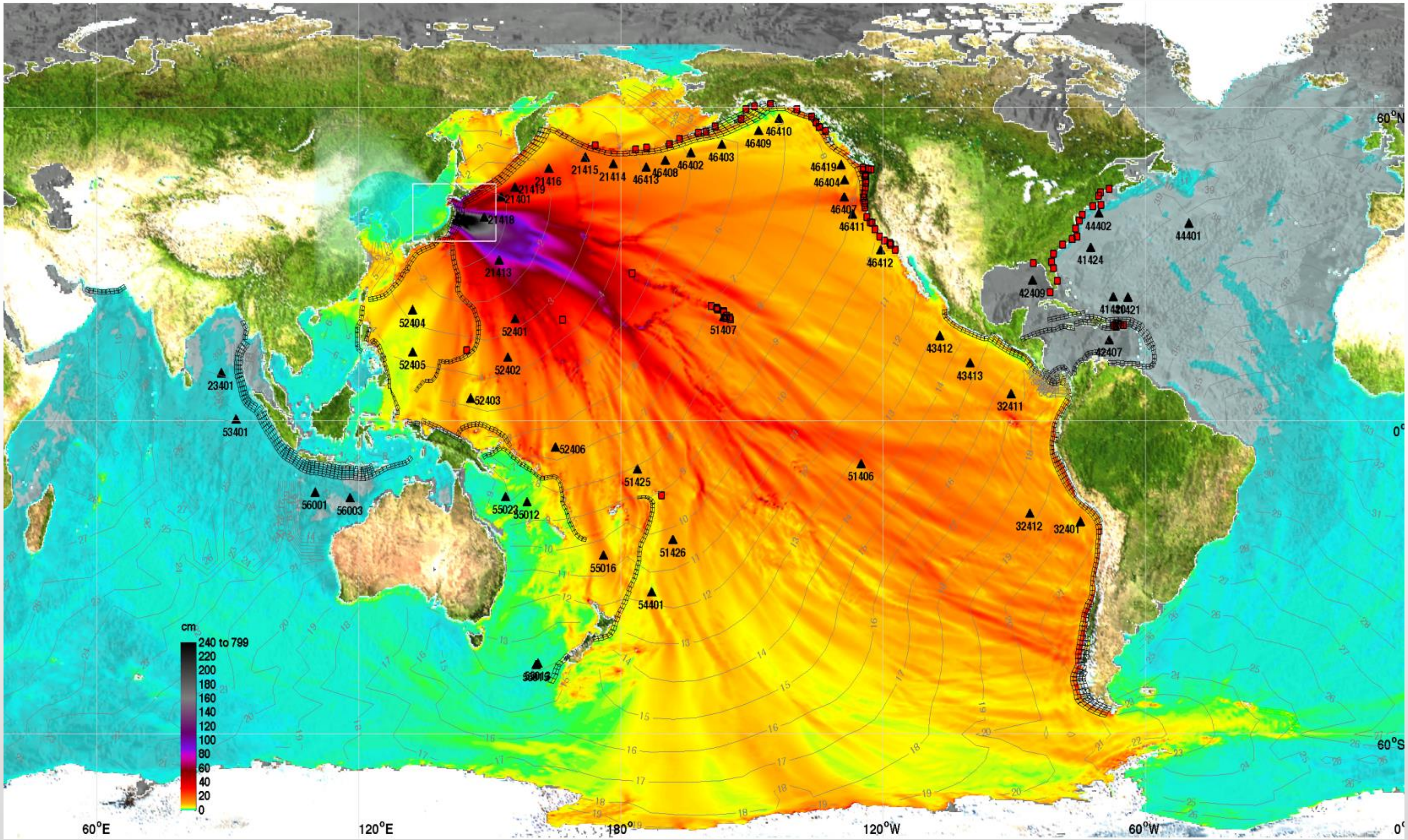


Tohoku, Japan 2011

The **M_w 9.1 Tohoku earthquake of March 11, 2011** was, perhaps, that that produced the most structural damage so-far this century. The Tokyo Electric Company's Fukishima Nuclear Reactor installation was destroyed and radioactive wastes distributed over a large region which remains closed to human habitation and agriculture.

The earthquake was a classical subduction zone megathrust event. It may be that this event produced more thrust slippage (50-70 metres) than any earthquake that we have observed since 1900. It produced **Tsunami** that was observed Pacific-wide and globally. Though most of the tsunami damage was restricted to Honshu Island, Japan, there was coastal damage as far away as Hawaii.

Tohoku, Japan 2011



Tsunami Tohoku 2011

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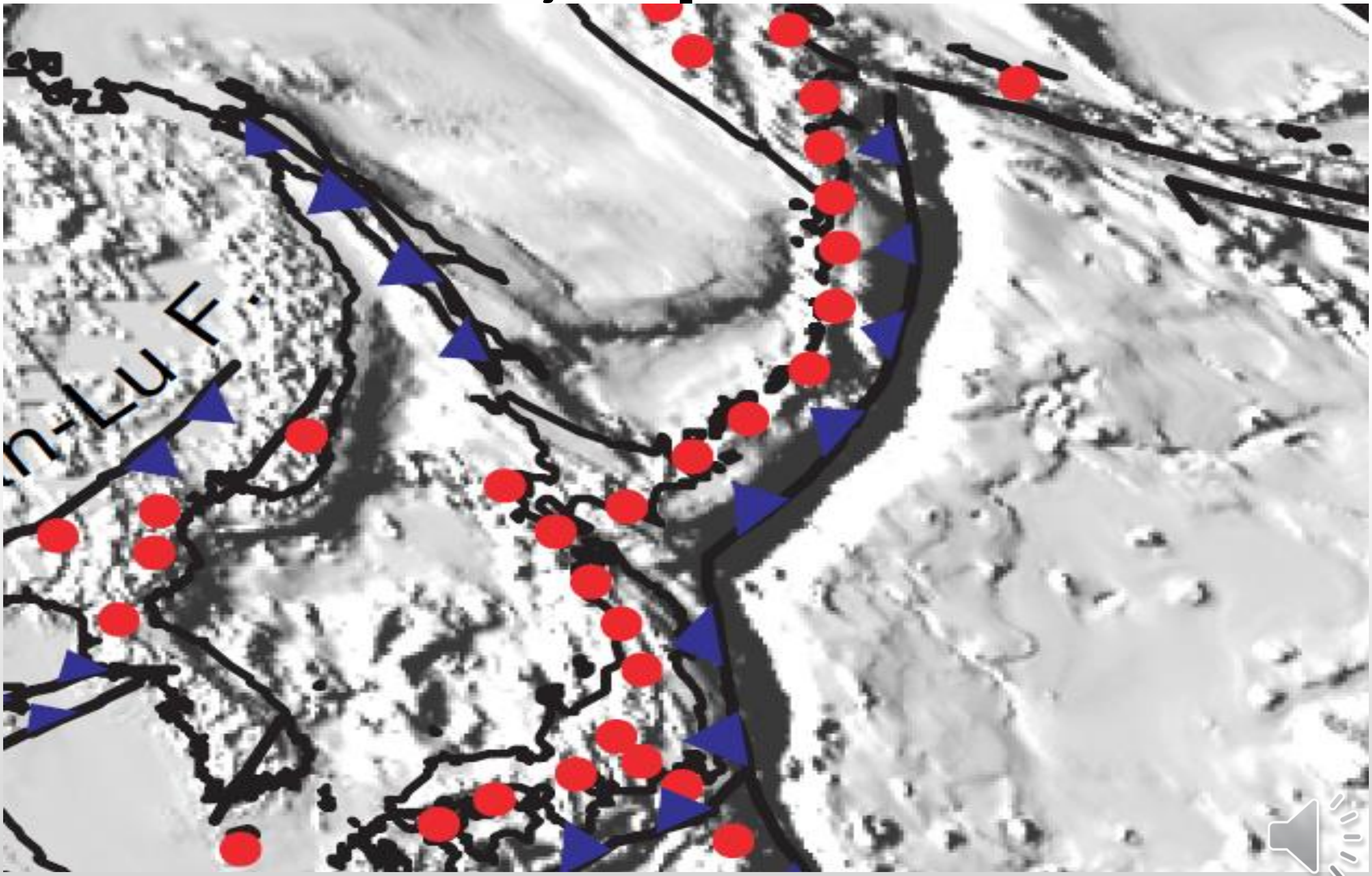
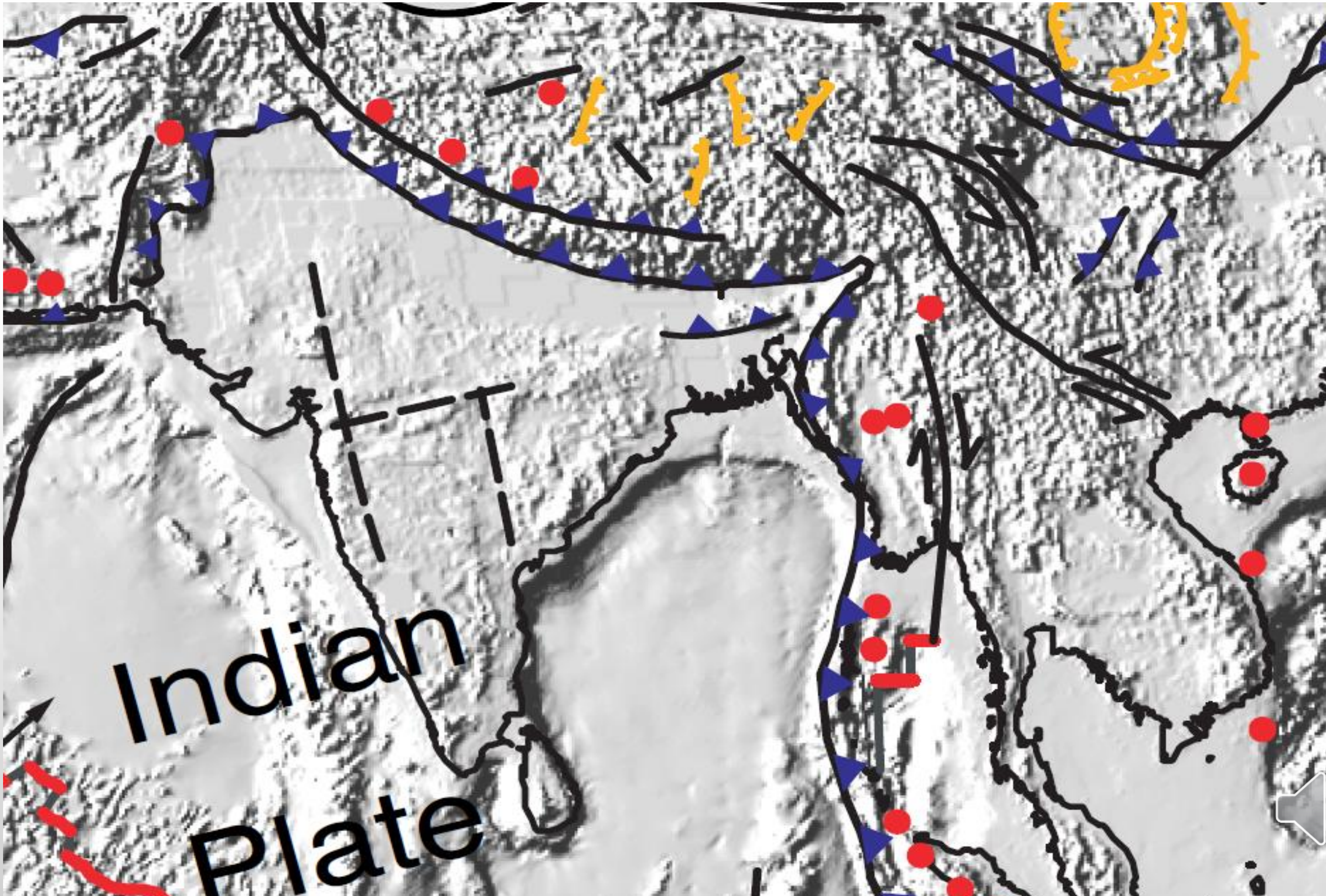


Nepal 2015



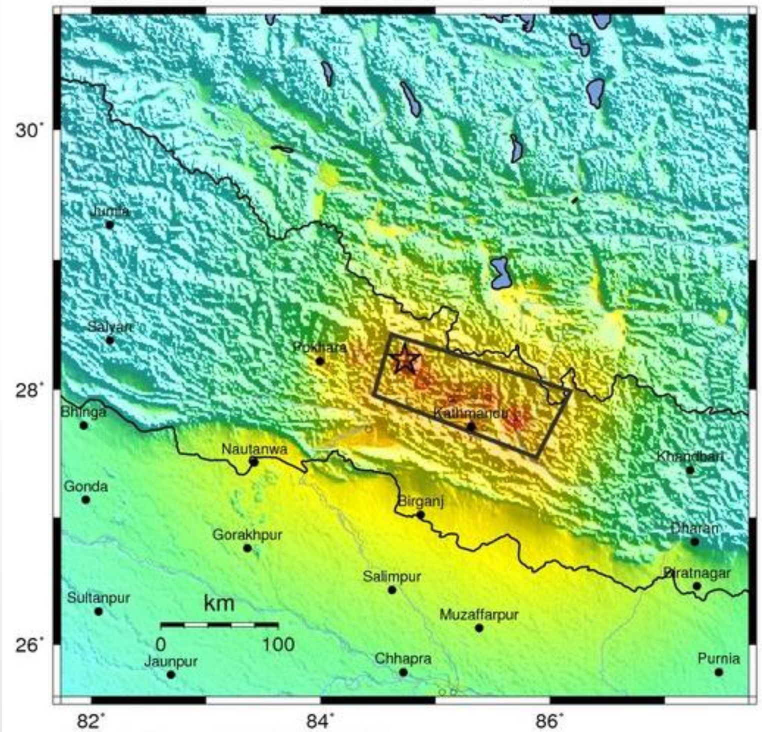
Nepal 2015

As the Indian subcontinental plate continues to intrude on the Eurasian plate, the continental-continental collision lifts the Himalayas. Large-to-major earthquakes occur relatively frequently along the southern arc of the Himalayas and within the Indian subcontinent. The [M_W 7.8, Khudi, Nepal, April 25, 2015] earthquake was the most recent large event.

Kathmandu was devastated. Village populations in the high mountain valleys were isolated for months. While the total death toll has not been finally tabulated, it is estimated that between 10000 and 20000 fatalities were directly attributable to the earthquake and to subsequent isolation.

USGS ShakeMap : NEPAL

Apr 25, 2015 06:11:25 UTC M 7.8 N28.23 E84.73 Depth: 8.2km ID:us20002926



Map Version 9 Processed 2015-07-02 22:51:16 UTC

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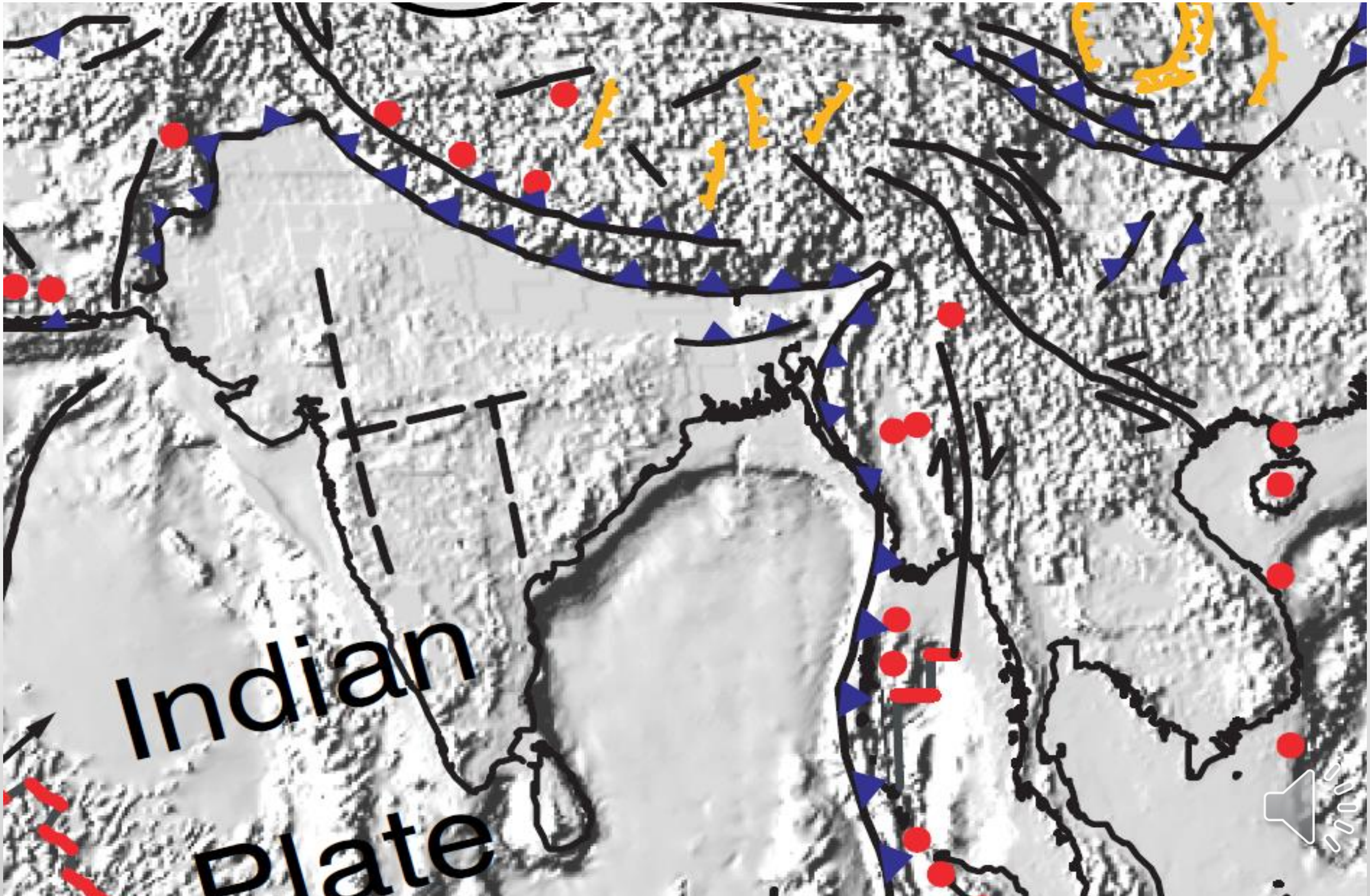


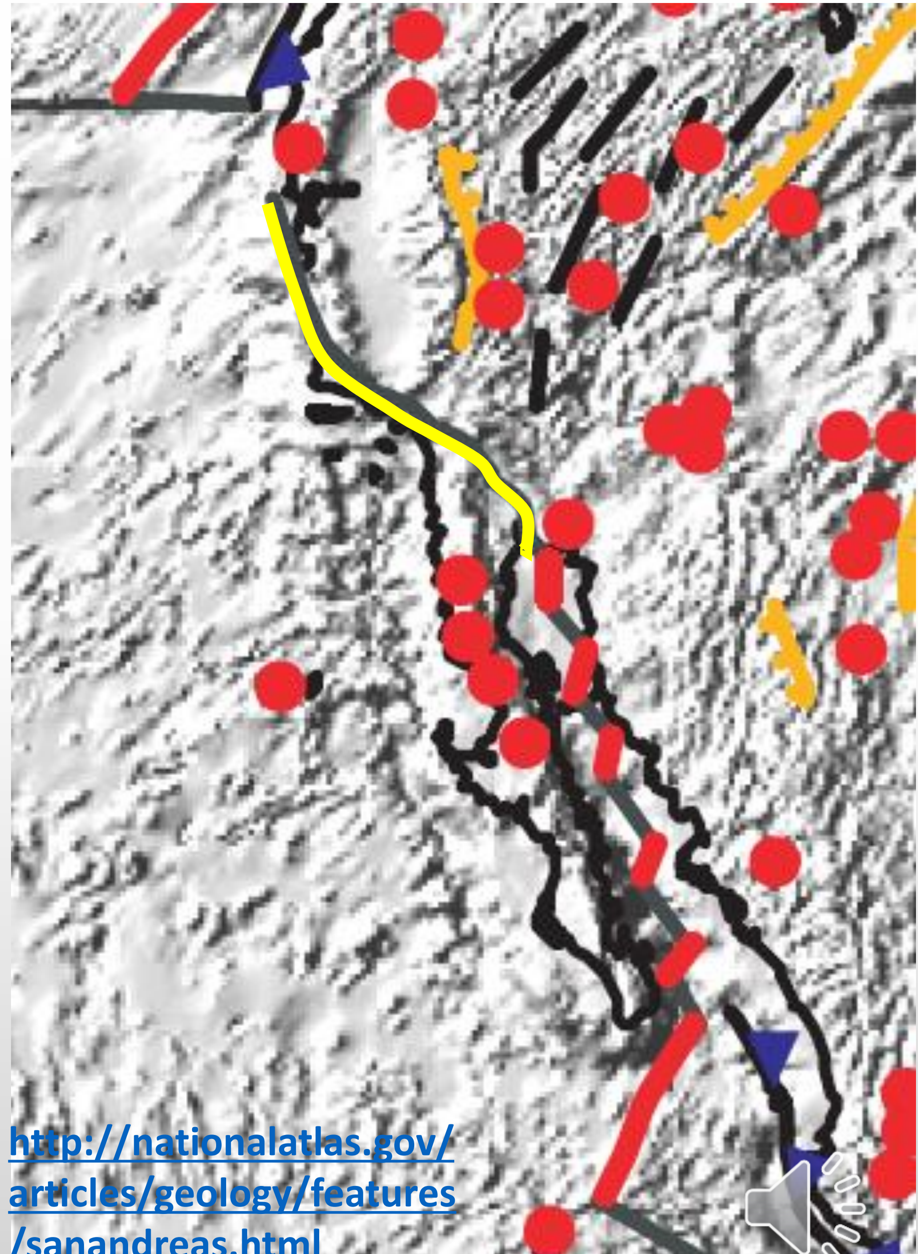
Transform Faults

Subduction zone megathrusts and some continental collision events produce the ***major earthquakes***, those with $M_w > 8.5$.
There have been, however, many very large earthquakes that occur, largely restricted to the upper 30km of crust along **transform faults**. The 1906 Great San Francisco earthquake (M_w 7.8-8.0) is the best known of them.

San Andreas Fault

Although it is not the largest nor most damaging earthquake of the past century, the [Great San Francisco earthquake of 1906] was singularly important in alerting geophysicists to the threat of large events on the San Andreas Fault and elsewhere.

[San Andreas] is a transform fault, separating the Pacific Plate (sliding relatively NW) from the North American plate. It's southern boundary is on the northward extension of the East-Pacific rise in the Gulf of California; its northern boundary at Cape Mendocino transform fault zone that forms the southern boundary of the Juan de Fuca system.



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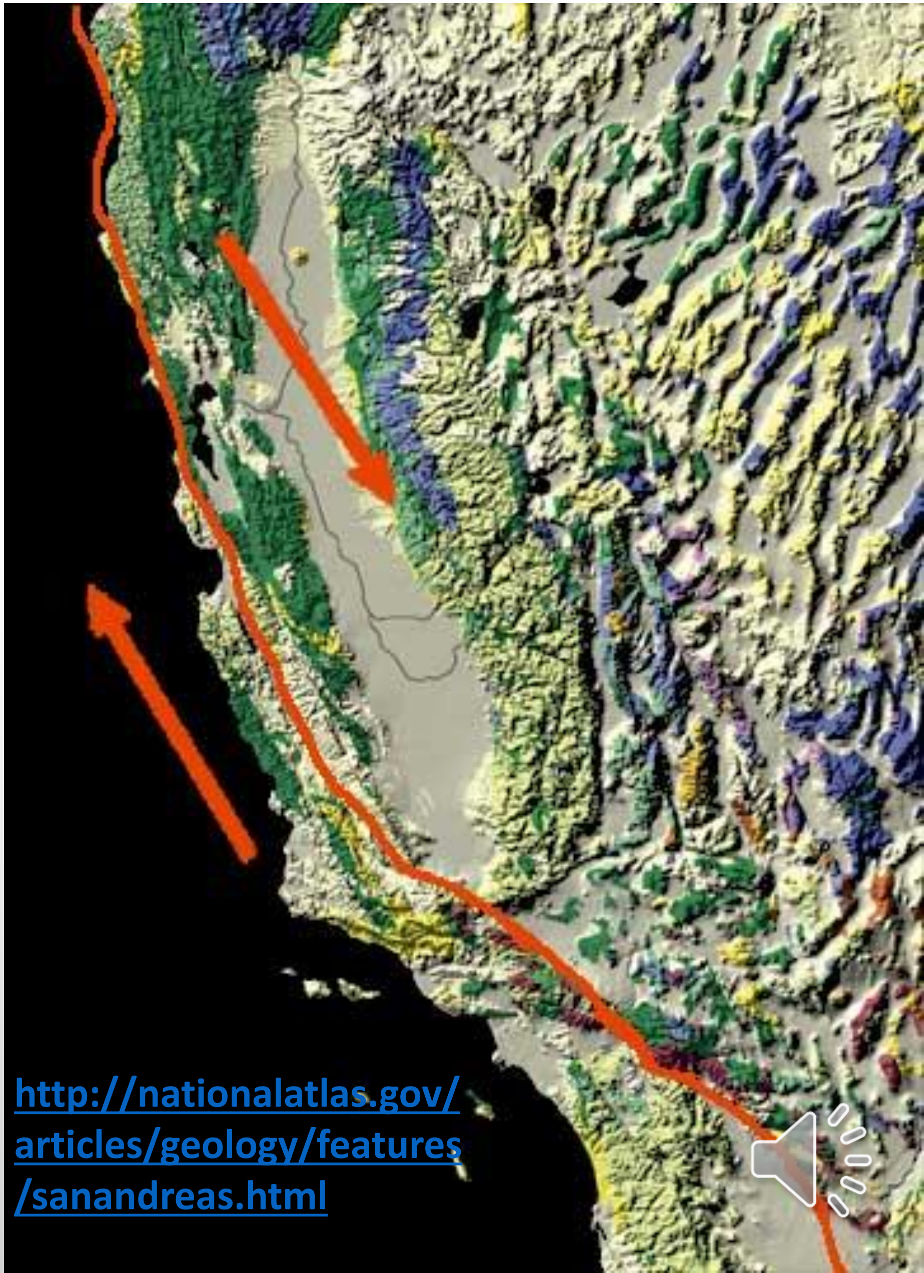
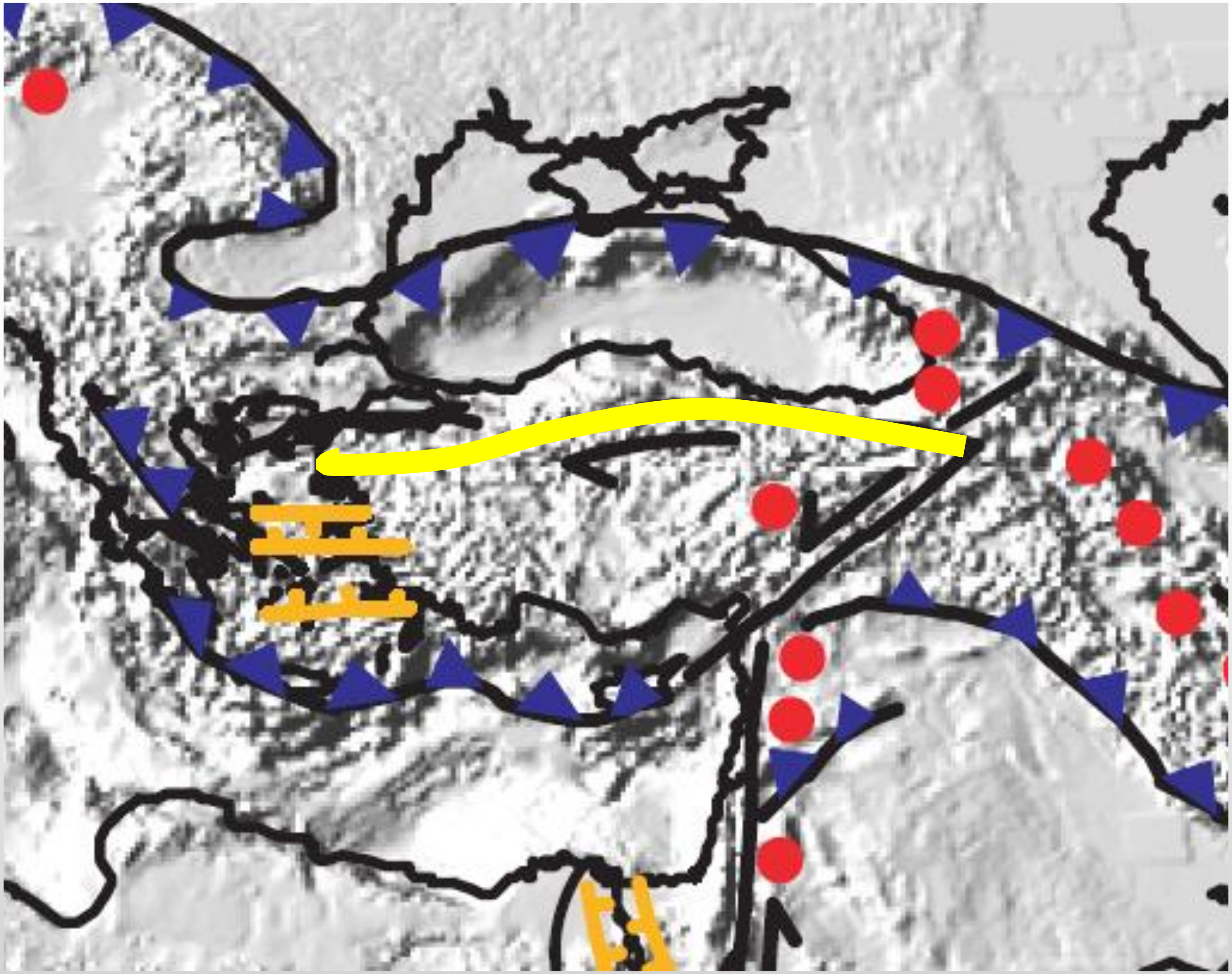
Although it is not the largest nor most damaging earthquake of the past century, the Great San Francisco earthquake of 1906 was singularly important in alerting geophysicists to the threat of large events on the San Andreas Fault and elsewhere.

San Andreas is a transform fault, separating the Pacific Plate (sliding relatively NW) from the North American plate. It’s southern boundary is on the northward extension of the East-Pacific rise in the Gulf of California; its northern boundary at Cape Mendocino transform fault zone that forms the southern boundary of the Juan de Fuca system.



http://nationalatlas.gov/articles/geology/features/sanandreas.html

North Anatollian Fault

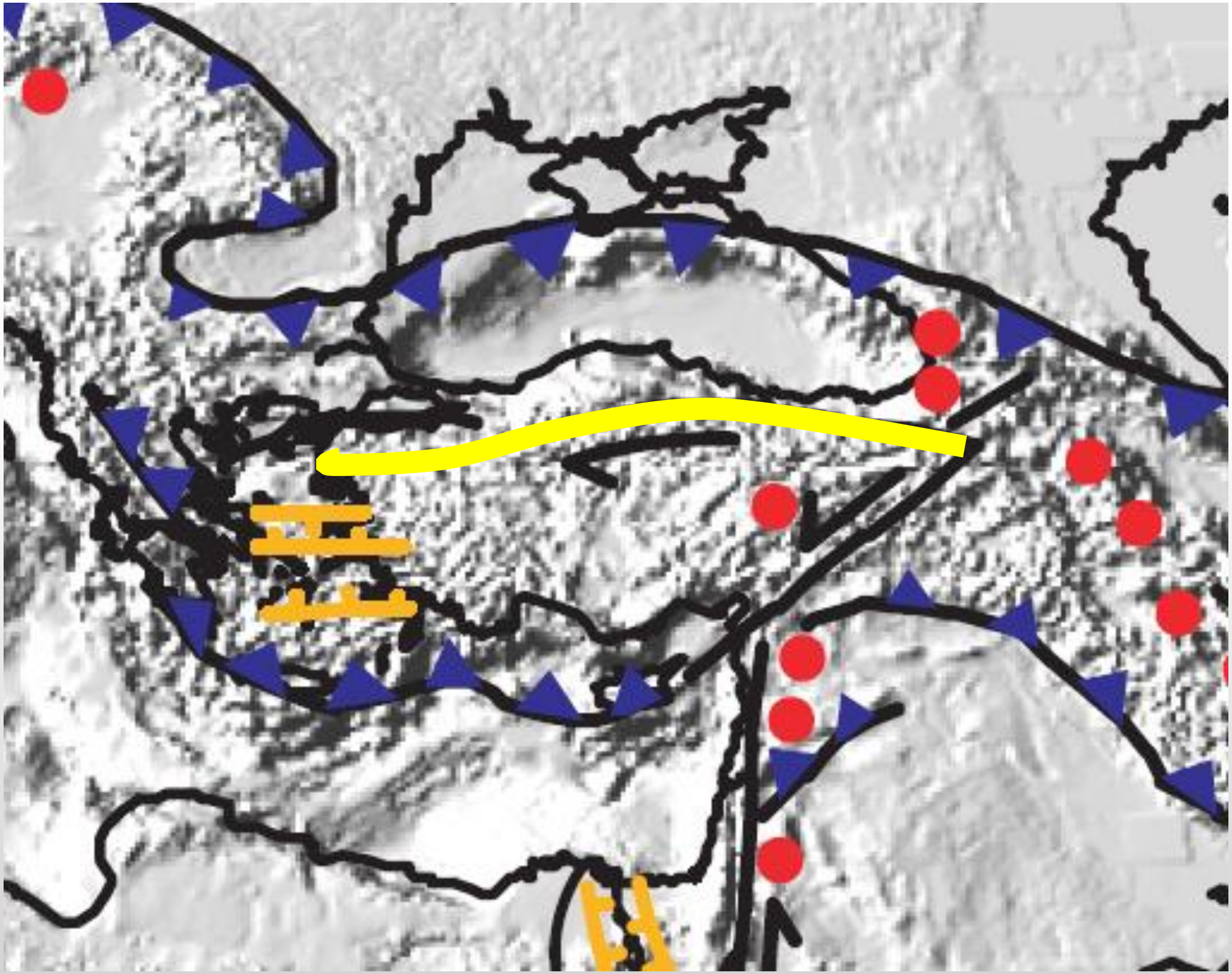


North Anatollian Fault

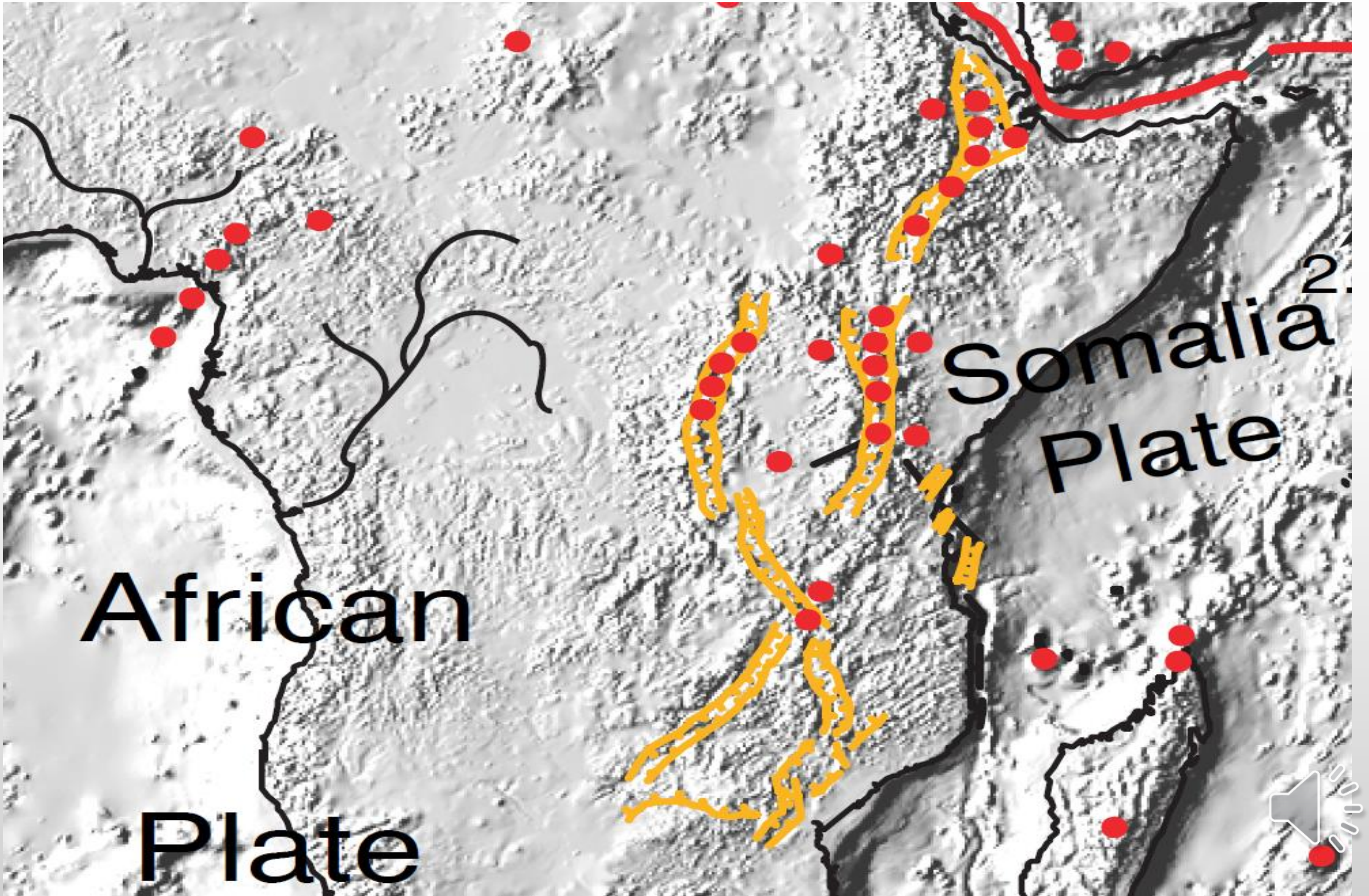
Across northern Turkey, the North Anatollian Fault shears the length of land. This fault is a ***dextral transform fault*** like the San Andreas.

Interestingly and historically, earthquakes have fractured this fault almost cyclically, starting in far eastern Turkey and then over a period of 60 years successively marching eastward toward Istanbul. The **M_w 7.6 Īzmit Earthquake of 1999** was the last of the sequence. We might worry about another nearer Istanbul in the next very few years.

North Anatollian Fault



Continental Rifting

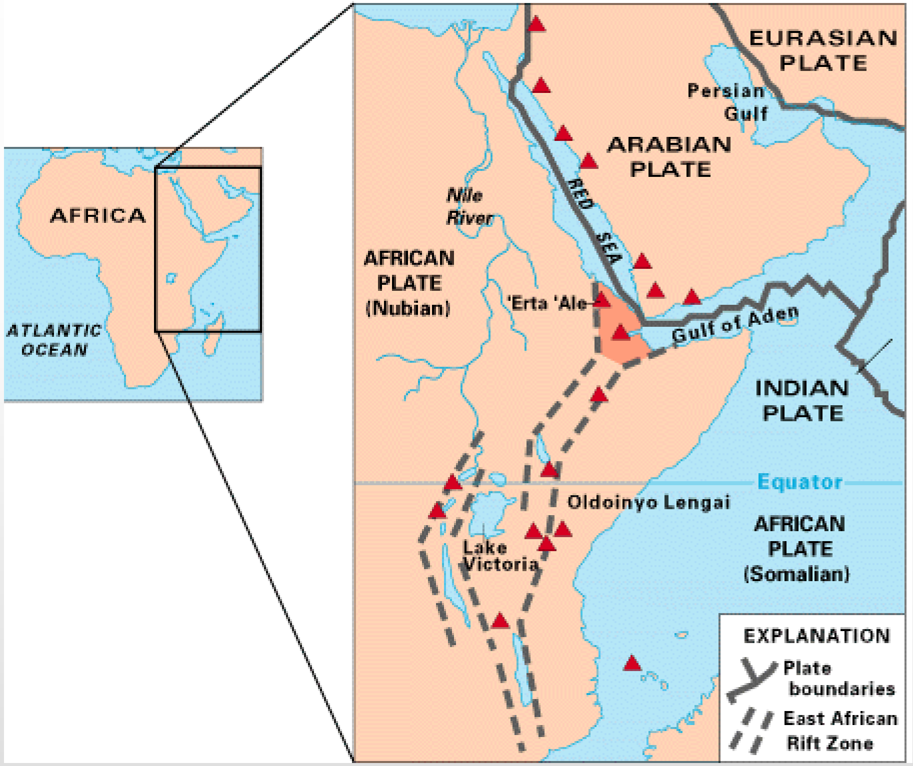


Continental Rifting

Continental rifting is caused by spreading along **divergent boundary zones** in continental crustal blocks and the underlying lithosphere. The most famous of these zones is the East-African Rift Valley.

Normal faulting along such rifts often produces large earthquakes.

Lake Tanganyika (M_w 6.8) Dec. 5, 2005



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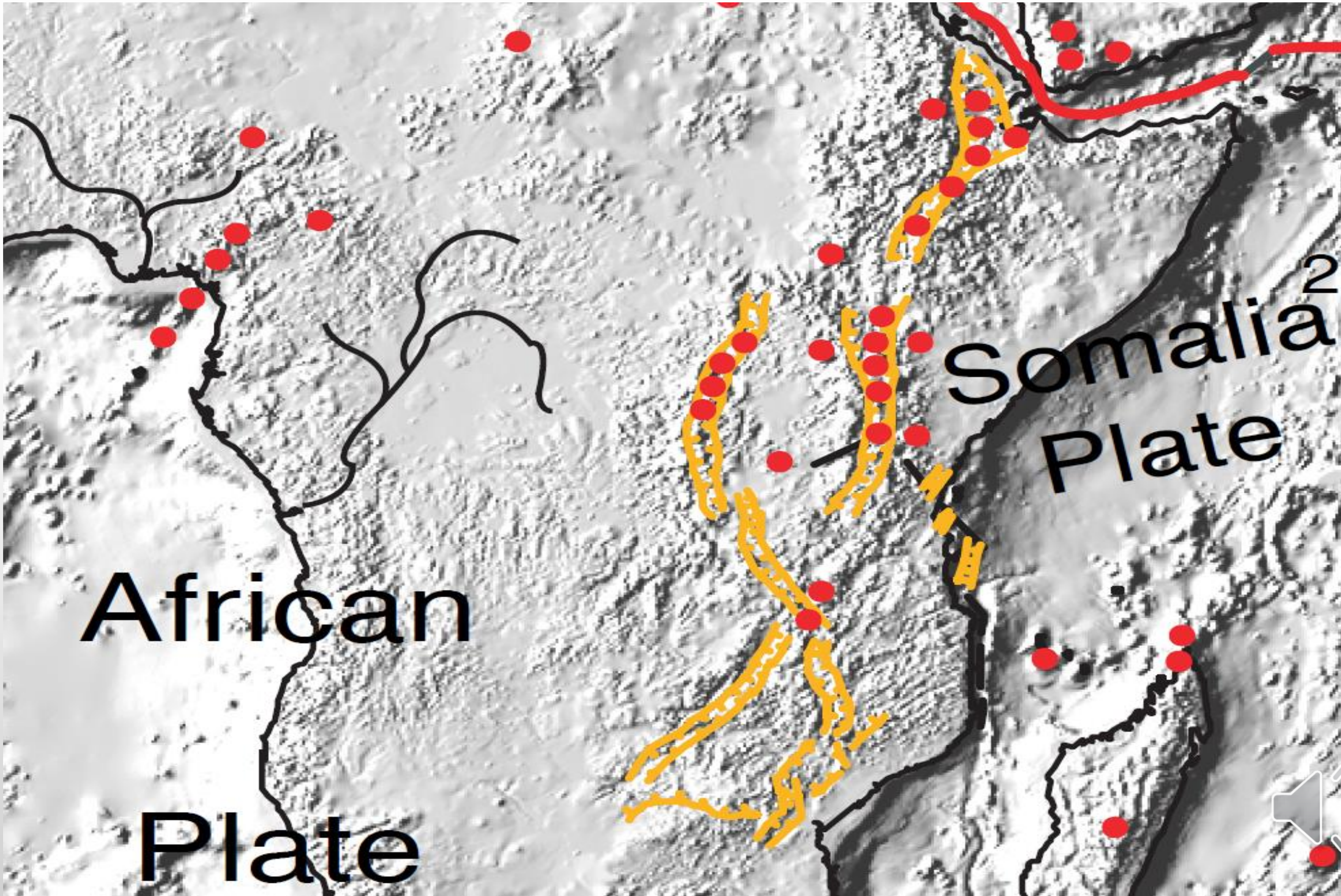
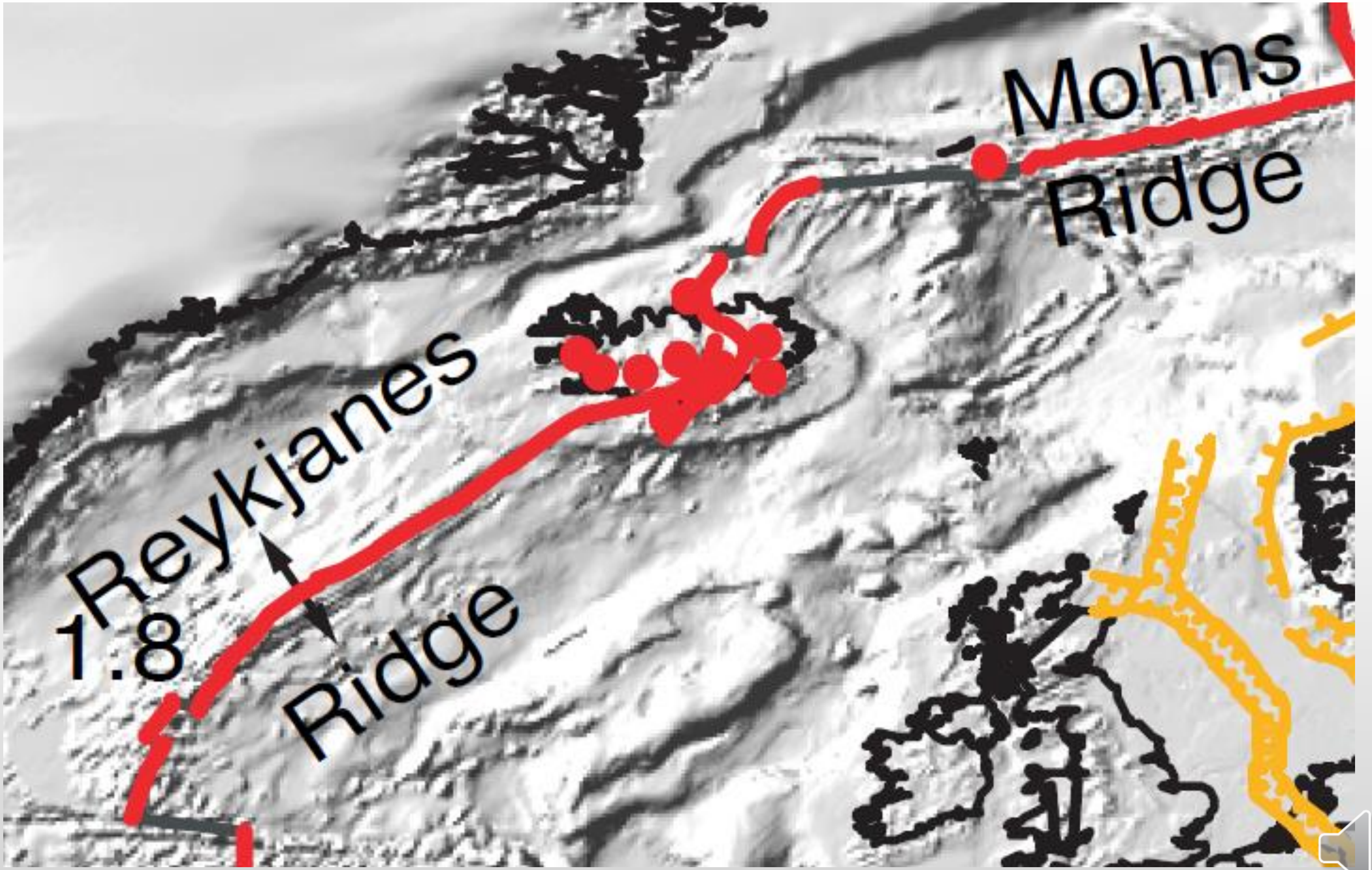


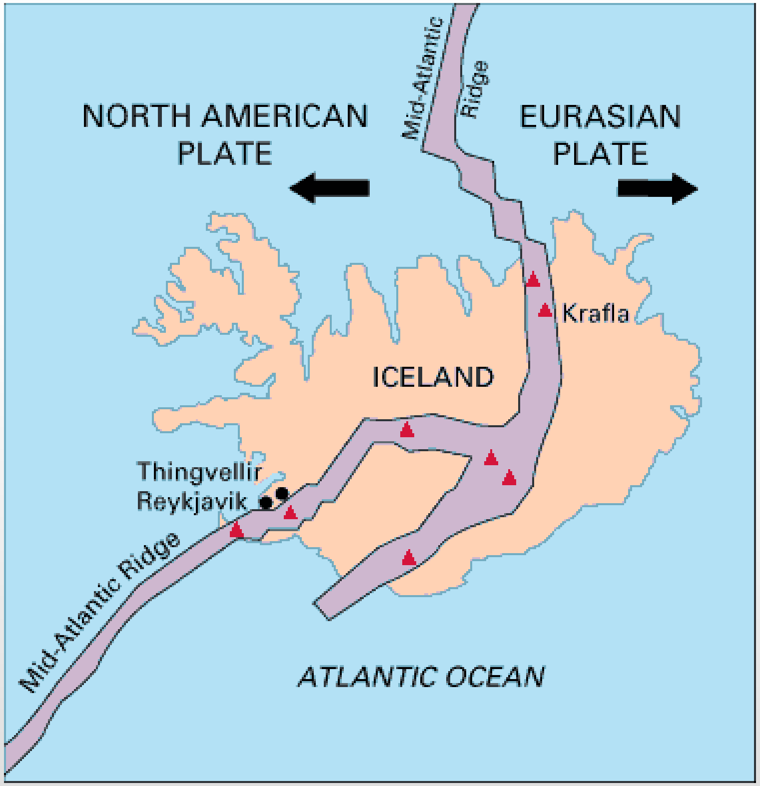
Sea-floor Rifting



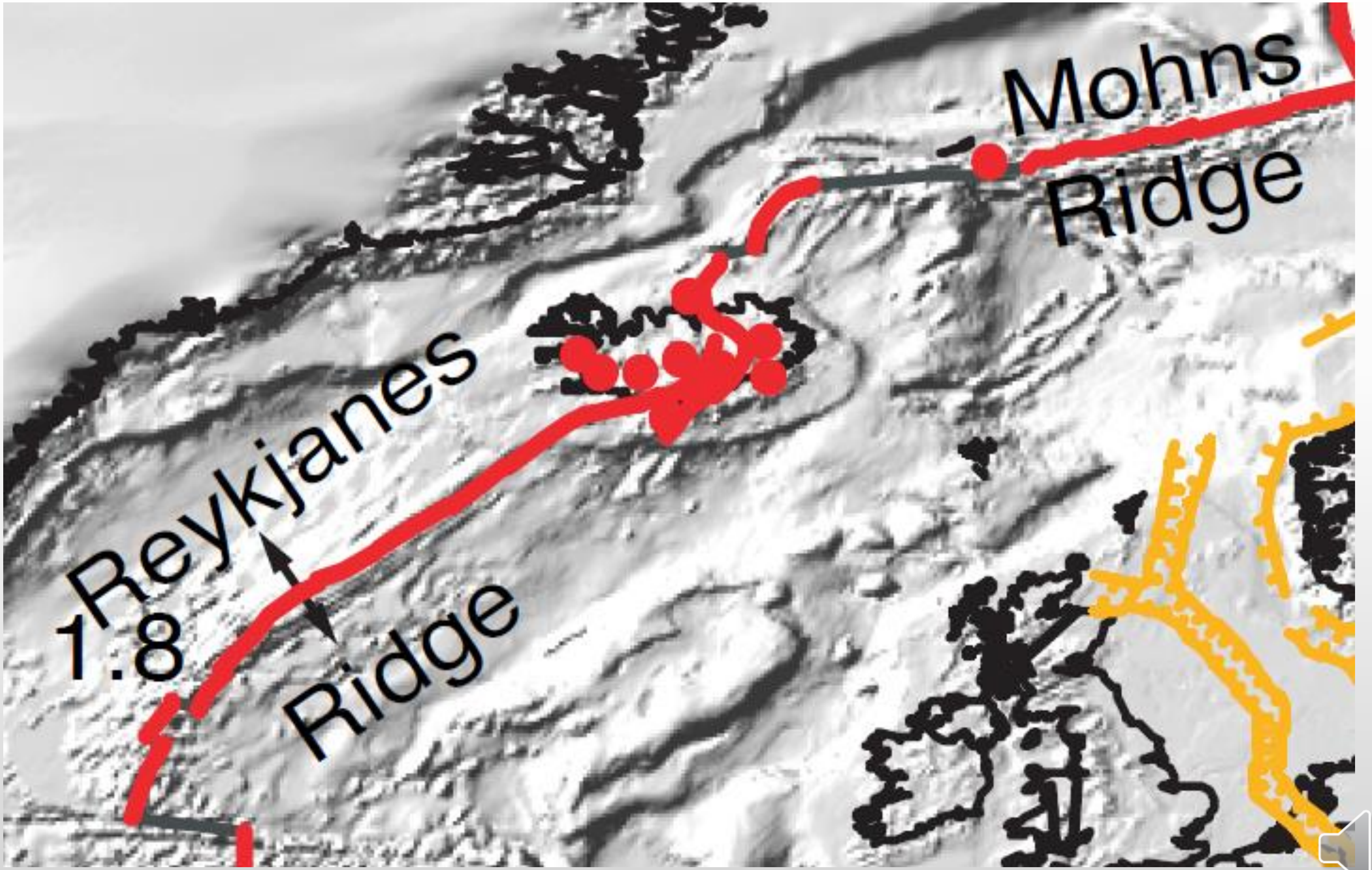
Sea-floor Rifting

Sea-floor rifting is episodic on short time scales; the rifting episodes produce earthquakes. These events are typically of moderate magnitude, less than M_w 6.

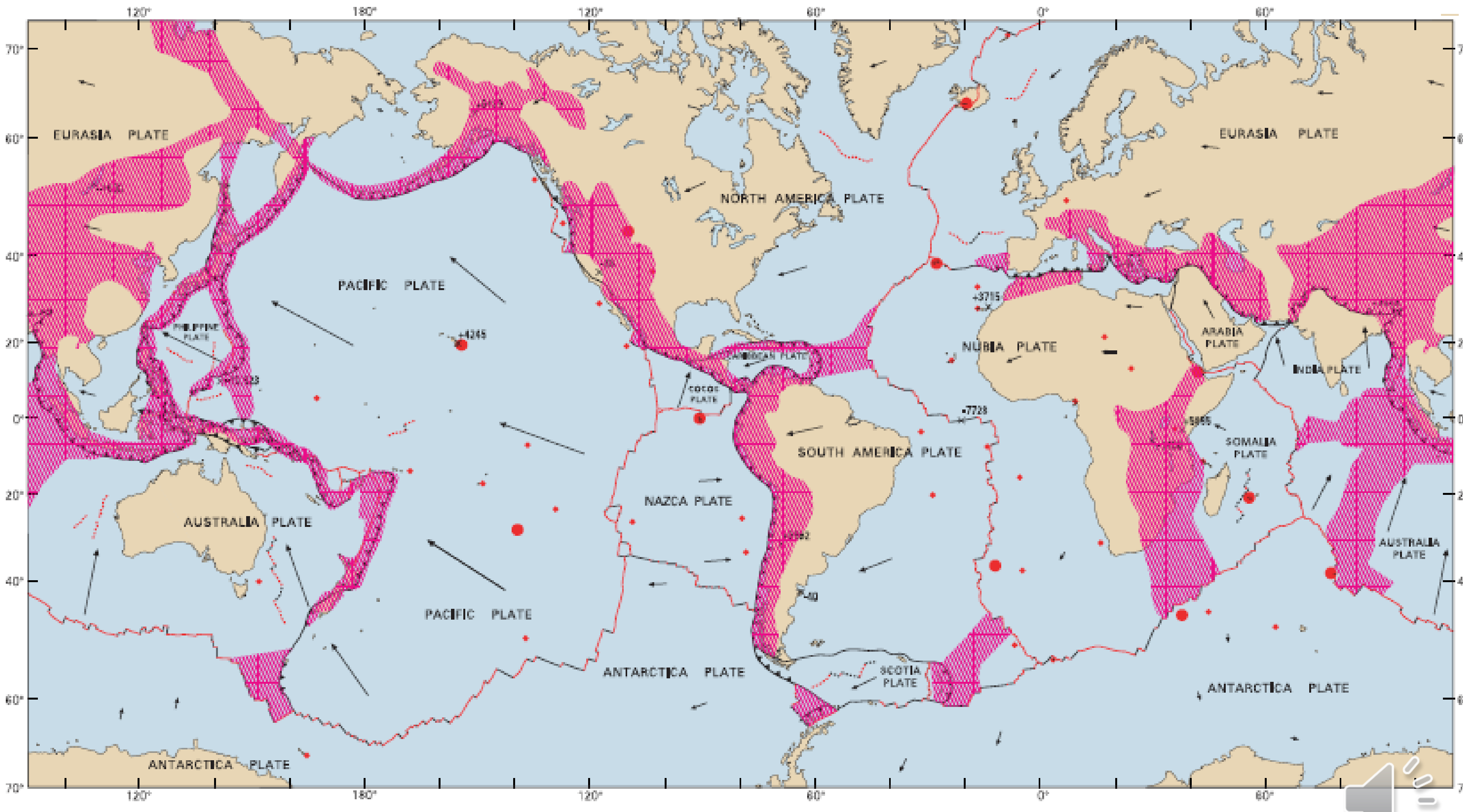
Frequent small earthquakes associated with magma eruptions are monitored by the Iceland Met Office.



Sea-floor Rifting



Global Tectonic Stress Fields



INTERPRETIVE MAP OF PLATE TECTONICS

Where do large earthquakes occur?

- Top 20 Largest
- Magnitude 8+
- Magnitude 7+
- Special Earthquake Studies

Source: https://earthquake.usgs.gov/earthquakes/

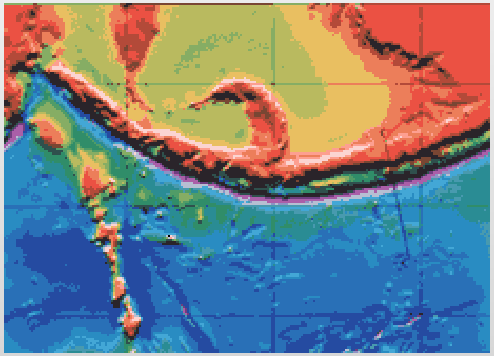
On other planets and moons

Extraterrestrial plate tectonics?

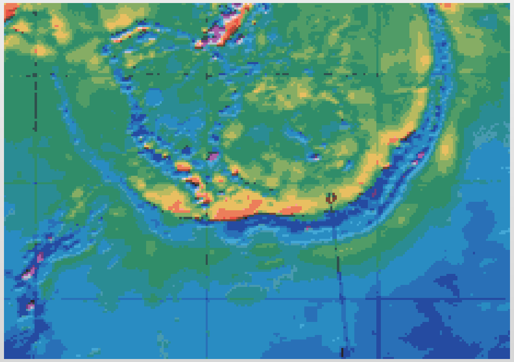
- Global distribution of small thrust faults on Mercury! ***Planetary shrinkage!***
- Pioneer-Venus spacecraft measured a high amount of sulfur in the upper atmosphere of the planet; the sulfur amount then decreased over the next few years. ***A volcanic eruption?***

The Magellan spacecraft revealed dramatic volcanic features and long, deep valleys similar in size and shape to oceanic trenches on Earth. ***Subduction?***

Aleutian Trench, Earth



Artemis Corona, Venus



https://pubs.usgs.gov/gip/dynamic/unanswered.html#anchor19928310

‘Quakes on other planets?

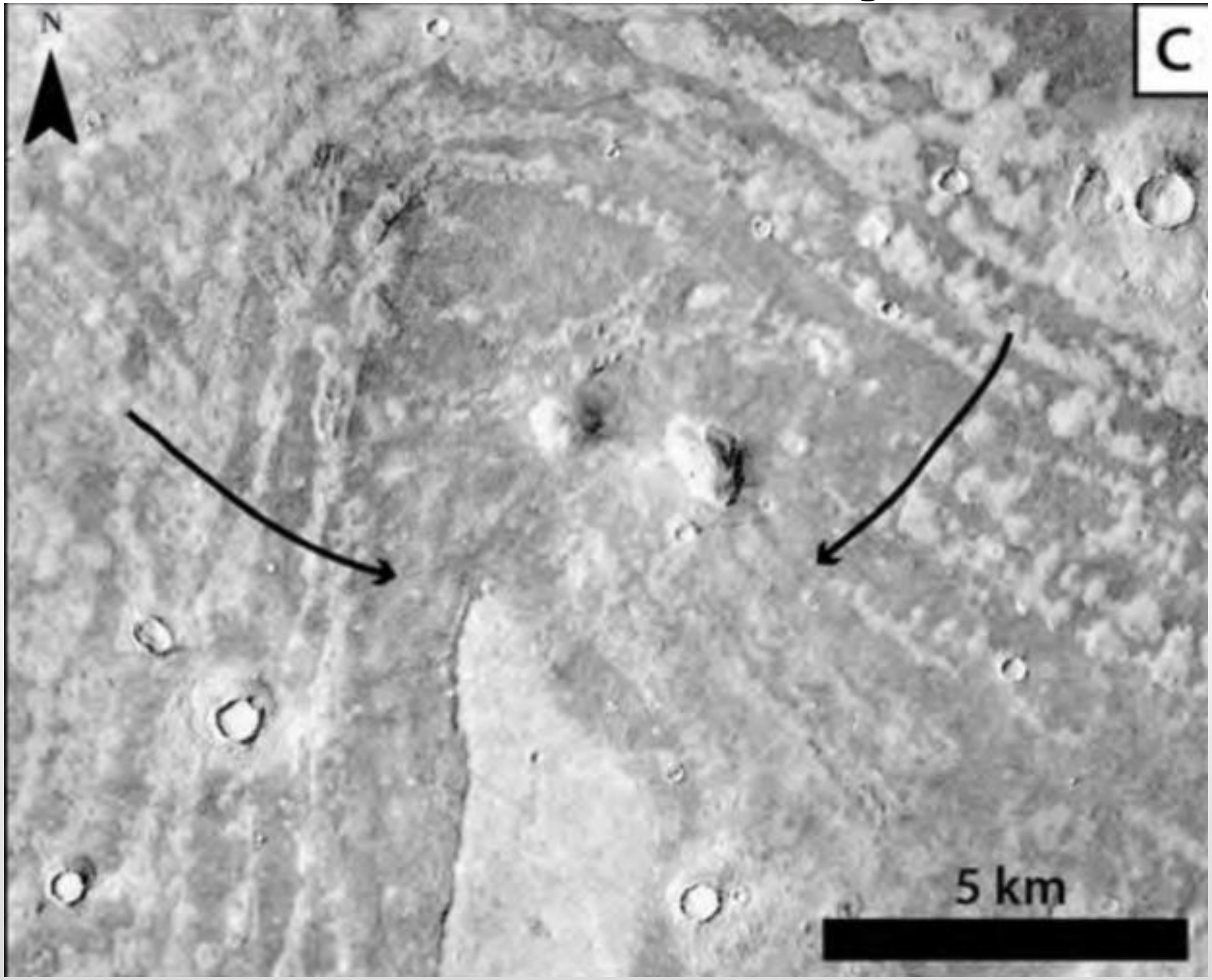
The ***Apollo Moon program*** placed seismometers on the Moon (1969 – Apollo 11) and during the 18 months that they were recording, many “***moonquake***s” were recorded. These appear to be due to tidal flexing of the body of the moon rather than proper geological activity.

In 1976, Viking 1 and Viking 2 landed on Mars with seismic instruments. While it remains in some debate, it is generally thought the seismometers detected no “***marsquakes***”… Now, we await detections by the **InSight SEIS** instrument.

Recently, it has been argued that there is evidence of Tsunami on Mars.   The evidence does not imply large “***marsquakes***”; the characteristic tsunami deposits point to a major impact in what is thought to have been an ancient ocean covering much of the northern hemisphere of Mars.

‘Quakes on other planets?

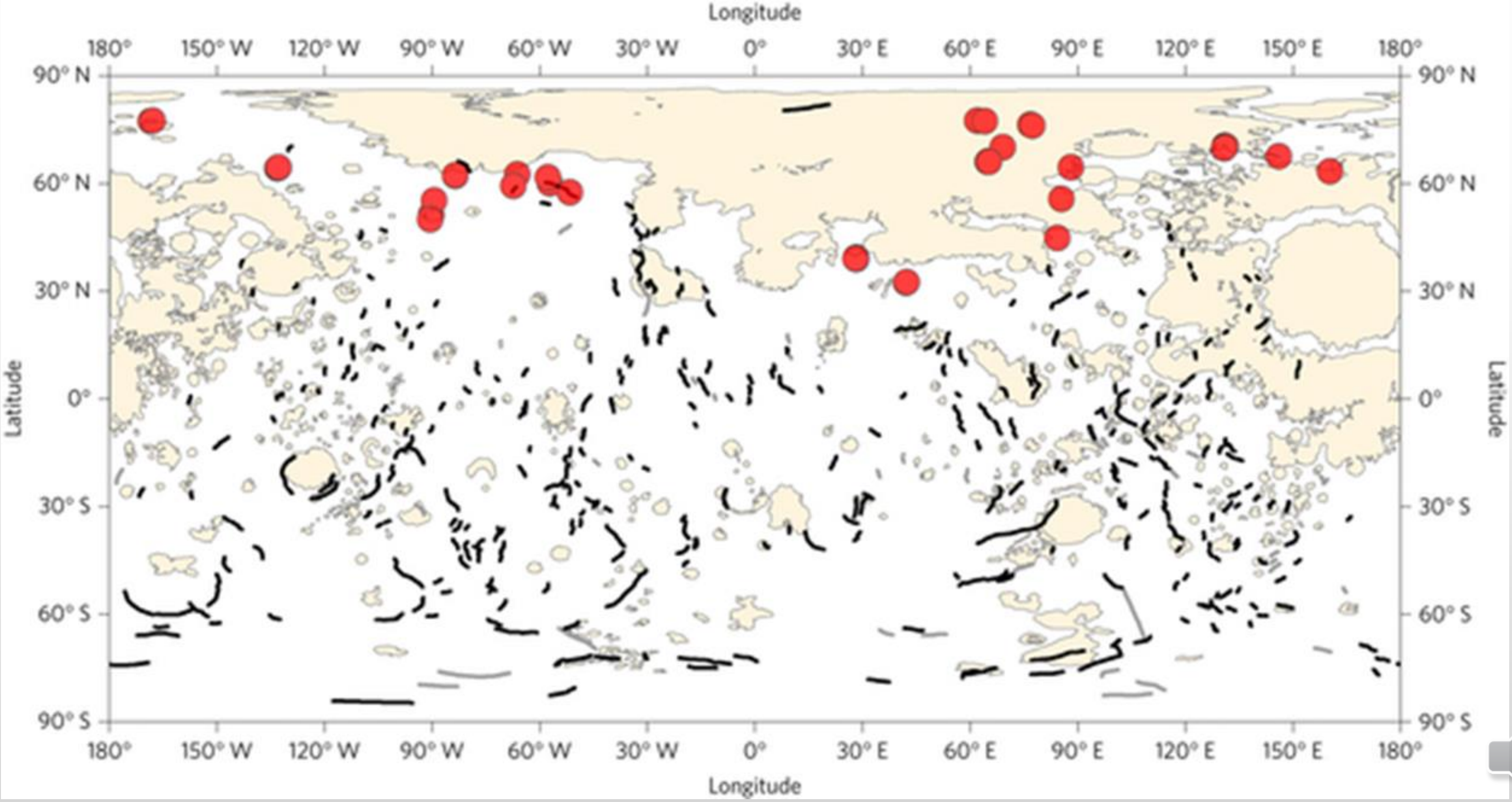
‘Quakes on other planets?



This recent story (BBC) reports the study: **Impact crater linked to Martian tsunamis**

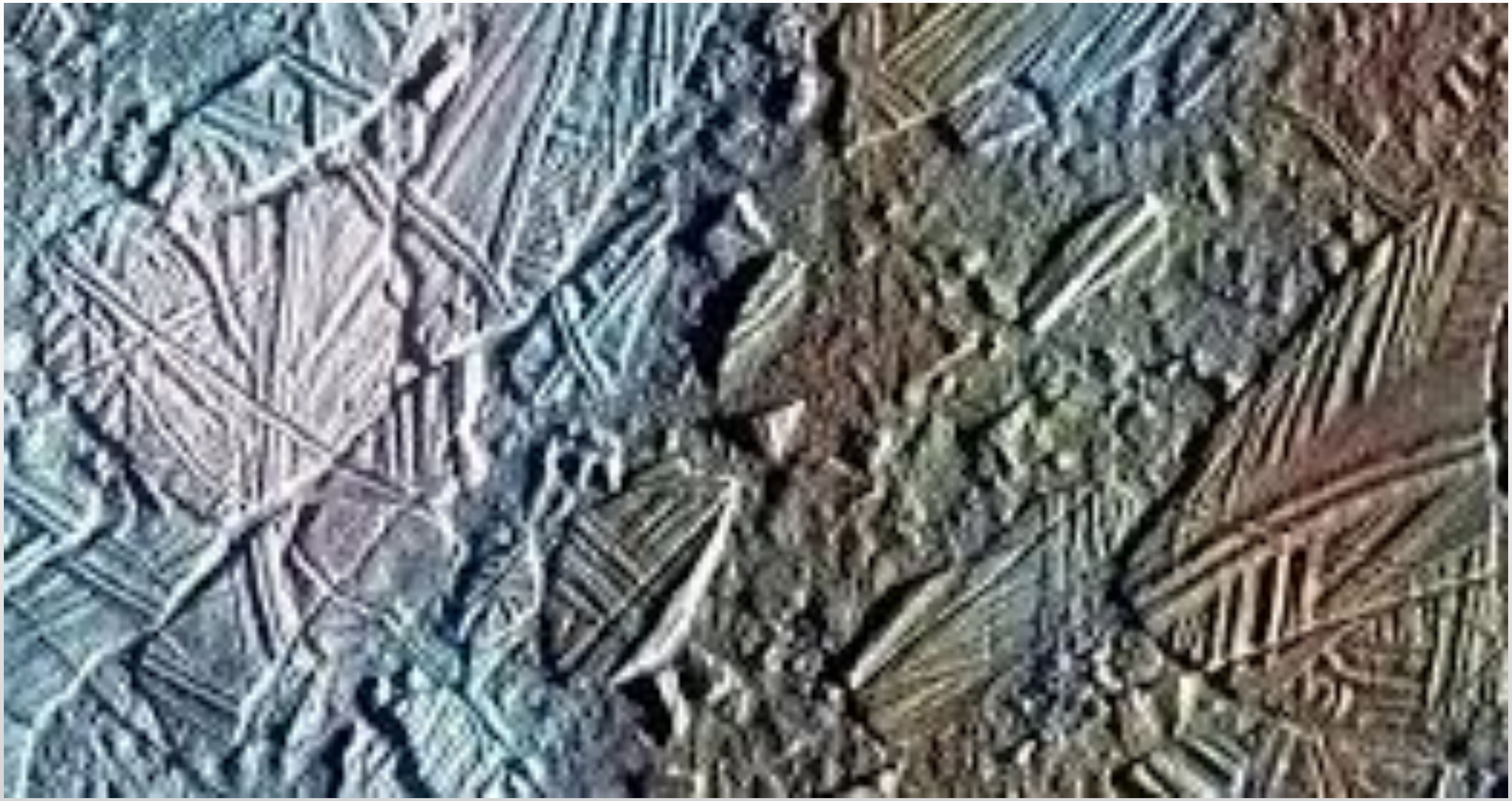
Mercury’s thrust faults

Mercury’s thrust faults indicate past geological activity.
Plate tectonics?



Europa’s ice plates

Europa’s thick ice plates show tectonic activity, cracking, re-cementing, faulting. It is a unique plate-tectonic style. It shows the evidence of a mobile sub-ice ocean.



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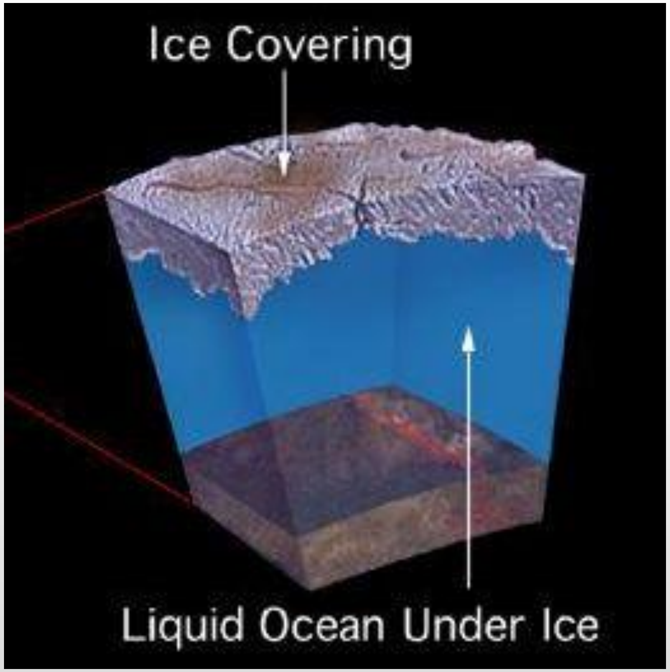
Interpretation for internal structure: surface ice plates 10-20km thick floating on a deep (perhaps more than 100km) ocean lying over a rocky (warm?) mantle.



Volcanism – Andes Chain

We have seen that lineation of volcanism along subduction margins of continents is indicative of a plate-tectonic process. Subduction forms strato-volcanoes that are “felsic” (low in silica, $Si0_2$) in their effusive eruptions of tephra and lavas that form the mountains.

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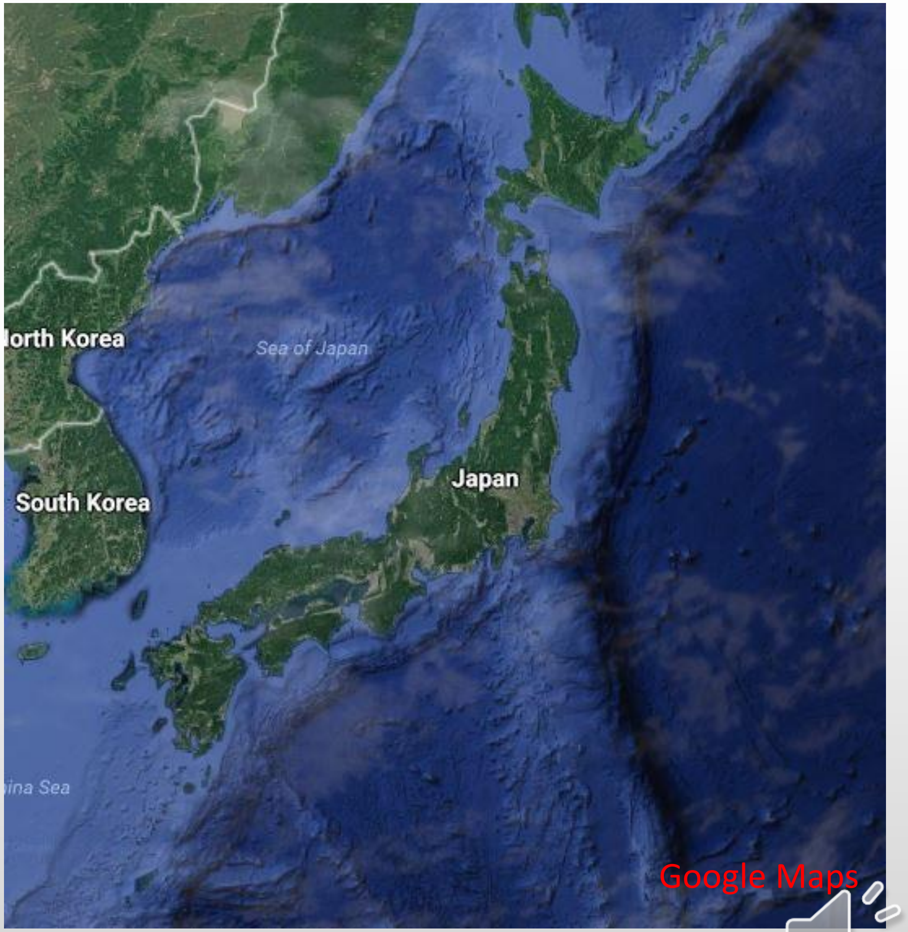
Villarrica volcano, Chile

https://en.wikipedia.org/wiki/Villarrica_(volcano)

Volcanism – Japan Arc

We have also seen that linear island arcs of volcanism form where an oceanic plate subducts under another oceanic lithospheric plate.



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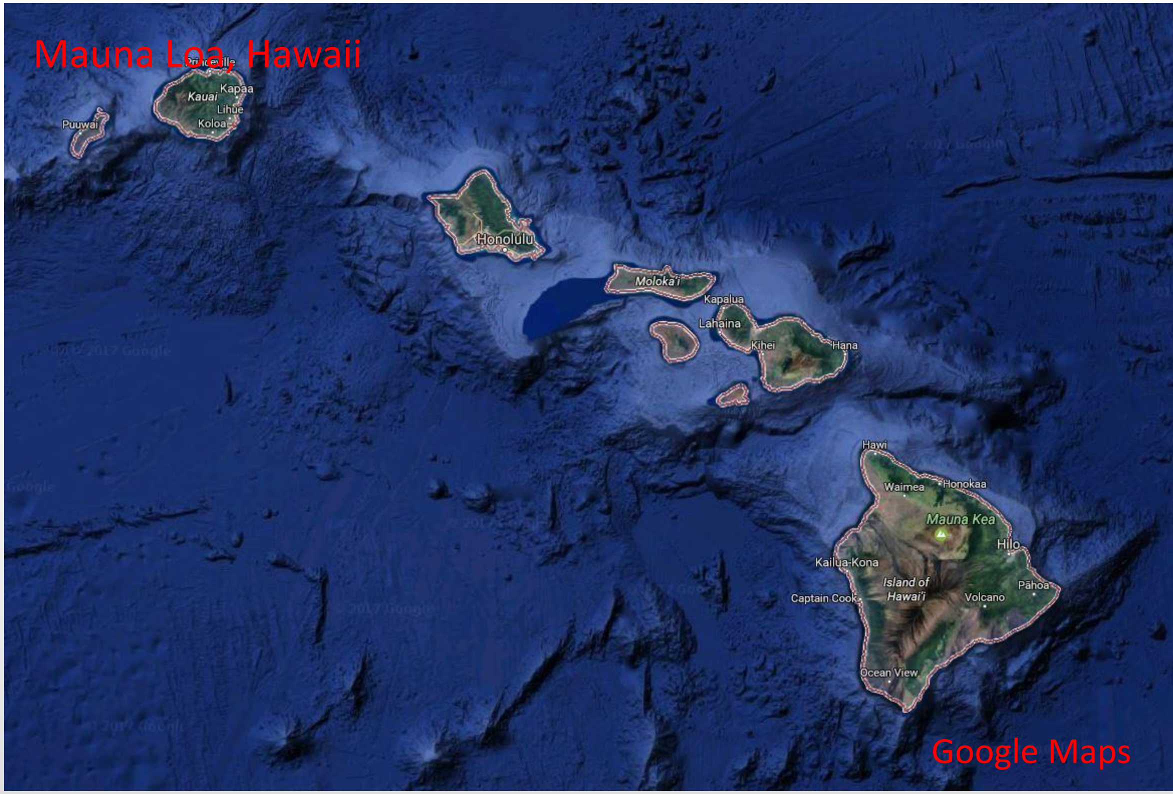
https://en.wikipedia.org/wiki/Mount_Fuji

Hawaiian Chain

We have also seen where chains of volcanoes form as the lithosphere moves across what appears as an eruptive hotspot that penetrates to the surface.

The Hawaiian volcanism is basaltic, low viscosity, low in SiO_2 and so flows easily on low-angle slopes of ***shield volcanoes***.



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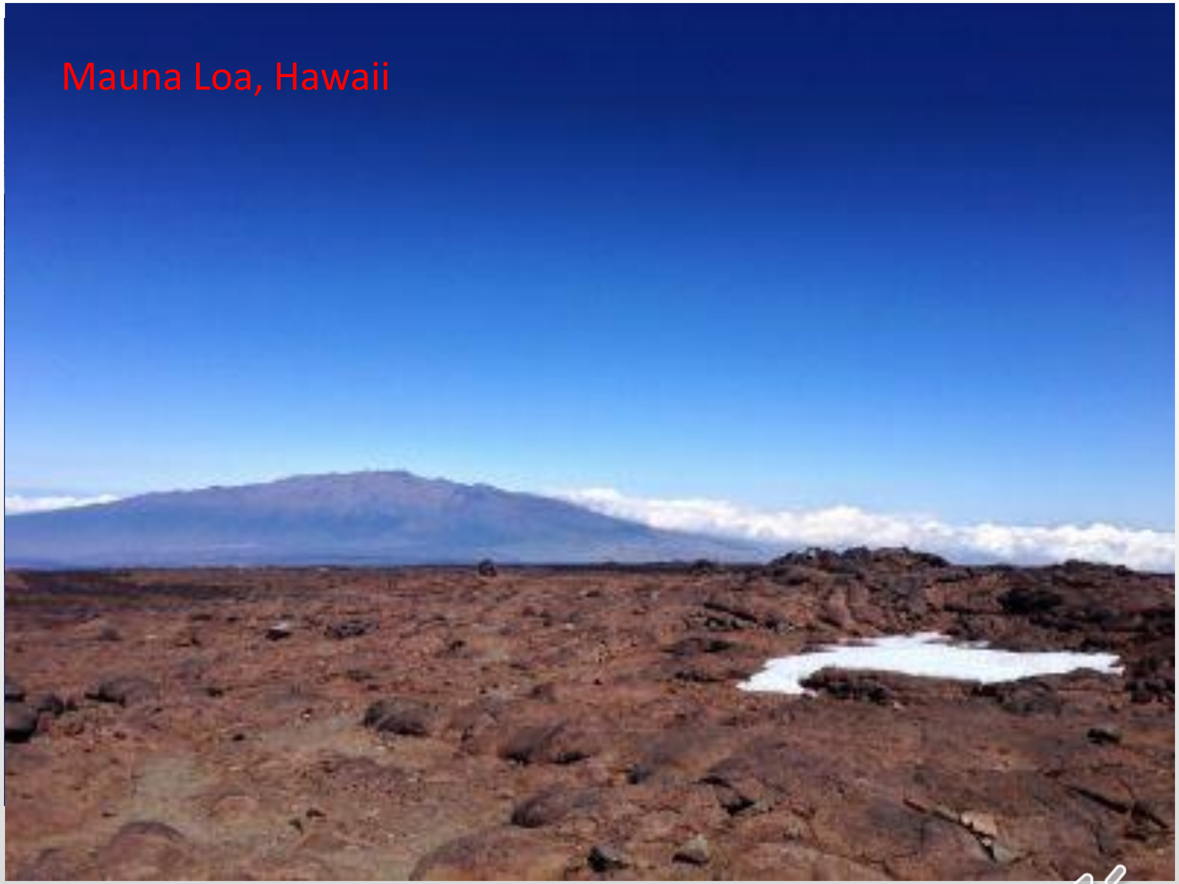

https://en.wikipedia.org/wiki/Mauna_Loa

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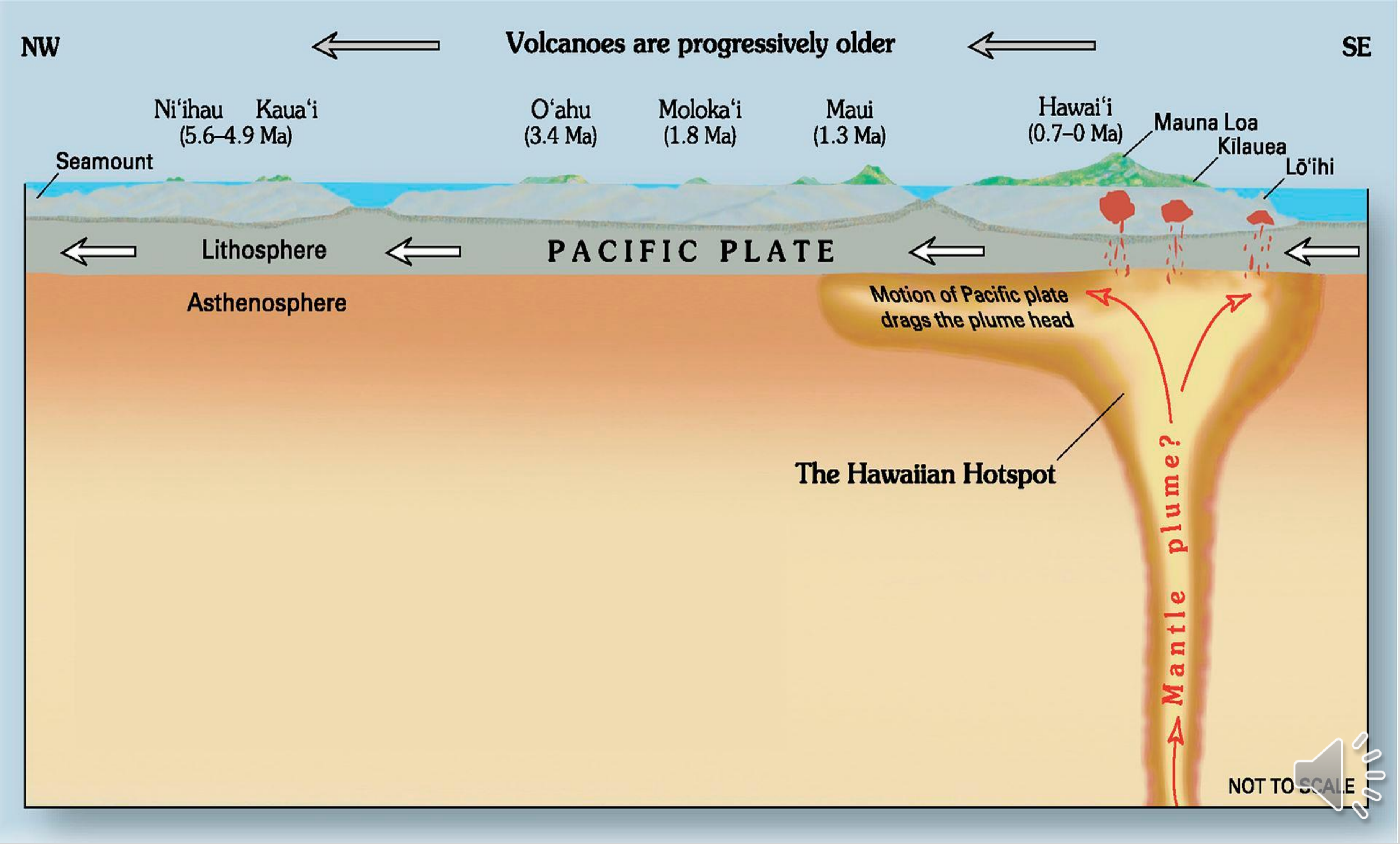


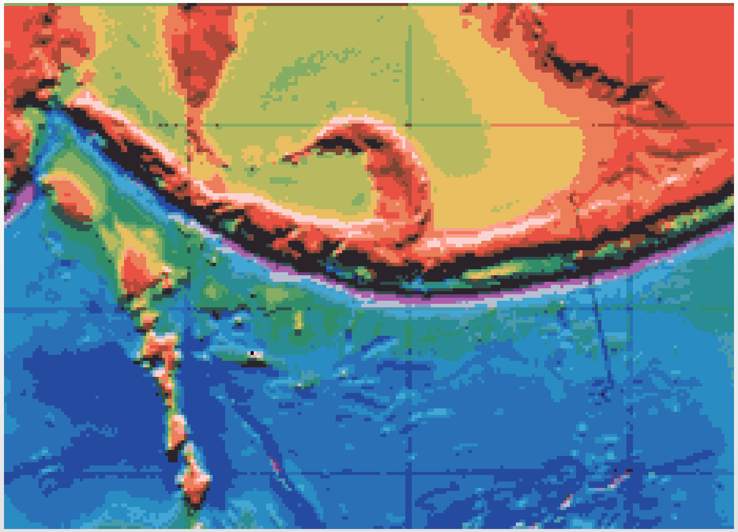
Active Volcanism

We have seen that several bodies in the Solar System are volcanically active:

- **Io:** The most volcanically active body in our Solar System. Explosive outflows **of sulfurous materials and rock magma erupt from as many as 40 volcanoes** on Io at present. Magmas have been radiant temperature measured to be hotter than the basaltic magmas of Hawaii.
- **Enceladus:** Fissures in this small moon's southern hemisphere allow **eruptions, geysers, of water**.
- **Titan:** With its surface of water-ice rocks being eroded by channelled rivers of methane-ethane, the moon is, at least, climatalogically active. There are indications that **methane-ethane is also erupted in geysers** from the surface.
- **Triton:** This moon of Neptune is much larger and more massive than Pluto. Orbiting Neptune in a direction opposing Neptune's rotation suggests that it is a captured Kuiper object. **Eruptions of geysers of liquid nitrogen** were observed by Voyager in 1989. They are interpreted as sub-ice (probably water ice) volumes of liquid nitrogen being heated by the faint Sun penetrating the ice to vapourization. Liquid-to-vapour nitrogen temperature is about 80 K.

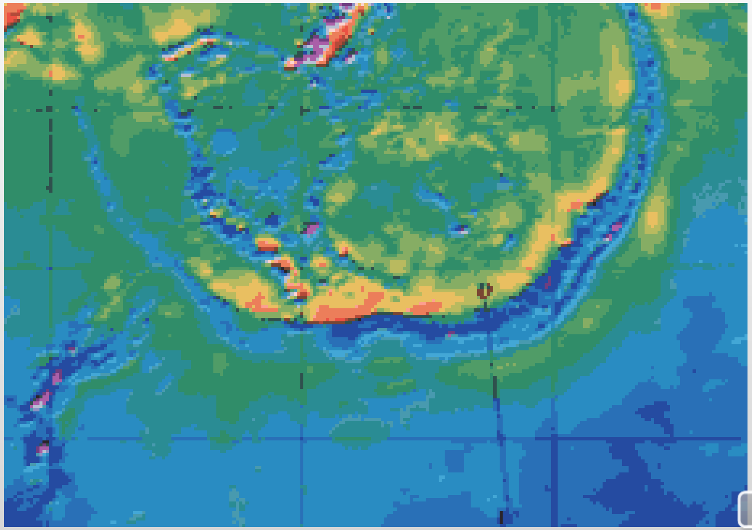
Volcanic chains?

Do we see chains of volcanoes indicative of plate motions even possibly active on other planets or moons? Do we see evidence of subduction zones?



Aleutian Trench, Earth

Artemis Corona, Venus



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Past Volcanism

Large shield volcanic edifices on Mars and Venus, some larger than those on Earth, attest to the geological activity of these planets in their past.

Venus: Dating the surface by counting of impact craters suggests that Venus completely renewed its surface in a globe-wide flood of lavas between **400Ma** and **700Ma** ago. The largest volcanoes, **Maat Mons** and **Sif Mons** are larger than **Mauna Loa** from its deep water base to peak. The distribution of volcanoes does not argue for long subduction zones that would be expected of a planet with plate-tectonics.

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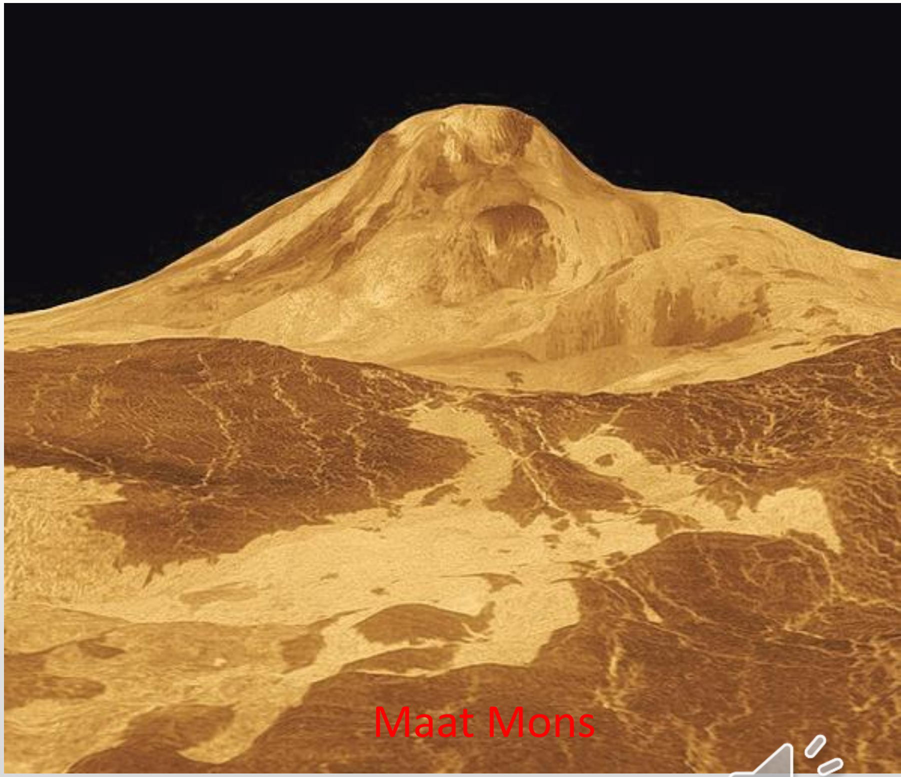

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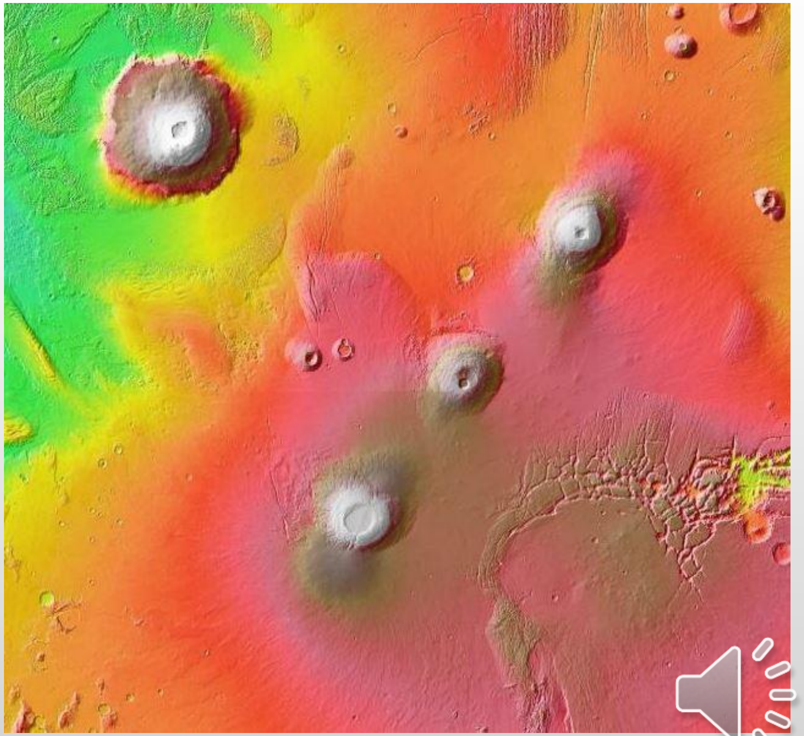

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