Earth Crustal Deformation Observations from Space using InSAR

How can space technology help us understand our planet?

Howard Zebker

Stanford University

Disasters in the news

An earthquake in Haiti – magnitude 7.0

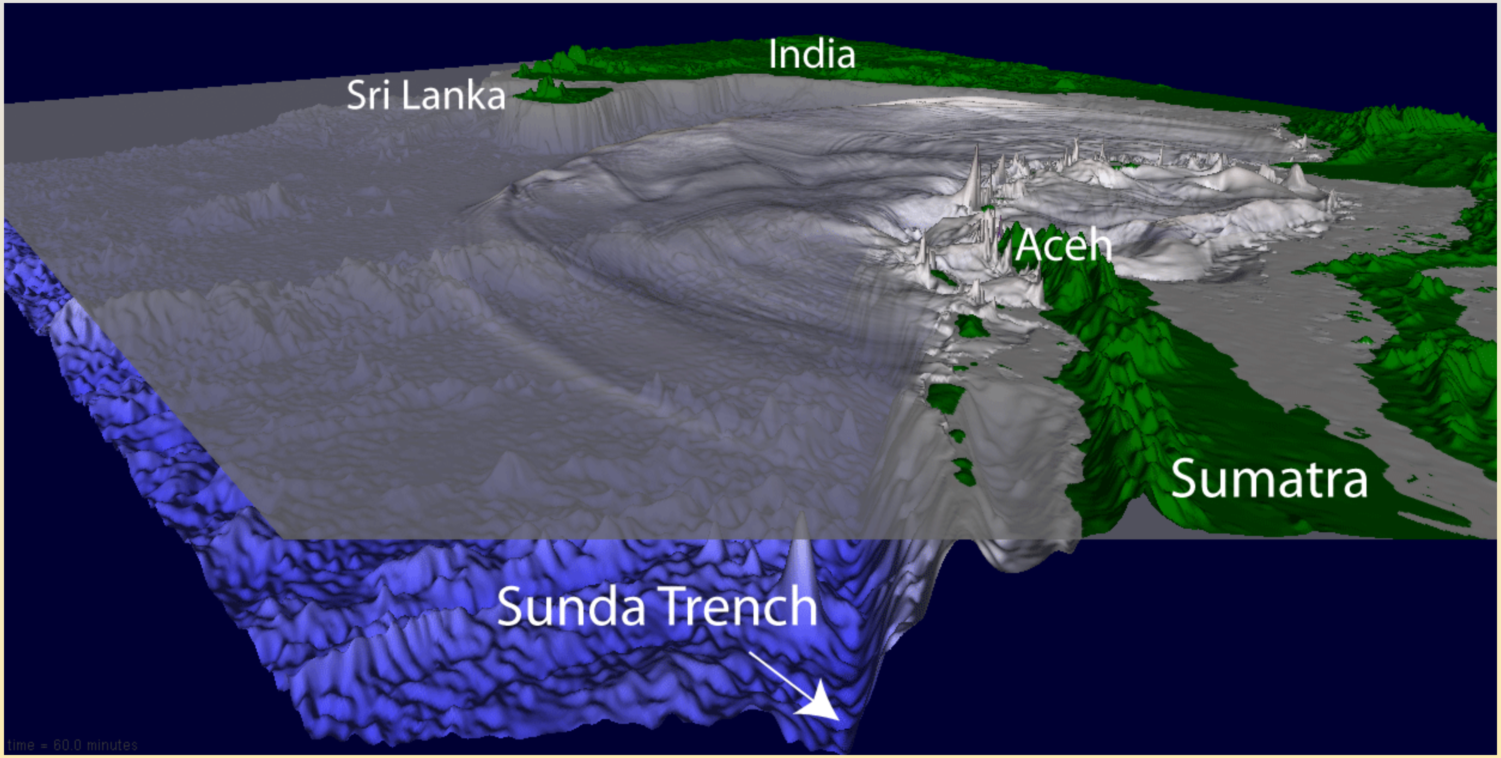
>100,000 killed

1,000,000 homeless

A tsunami in Indonesia

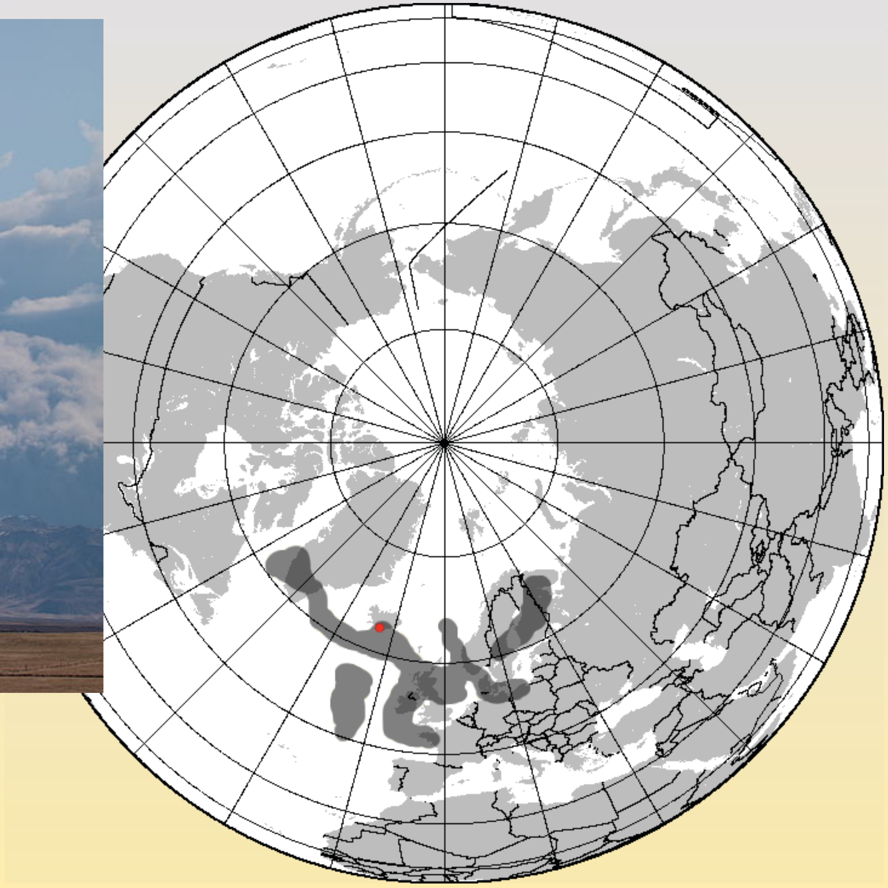
Created by a magnitude 9.2 earthquake under the Indian Ocean

- 230,000 people killed



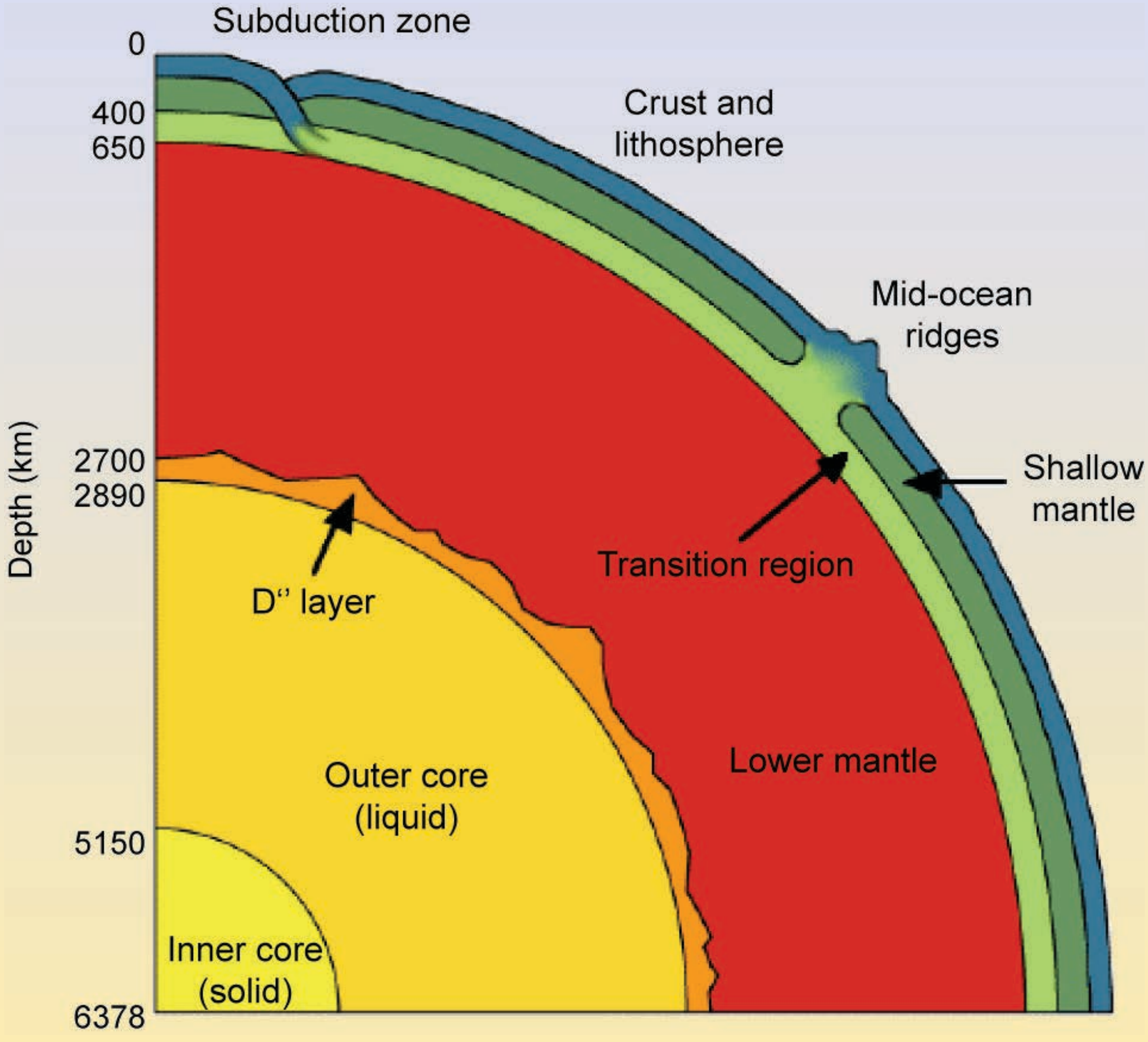
A volcano in Iceland

Fairly small eruption, but disrupted thousands of airline flights



Earthquake and Tsunami in Japan

The ‘Solid’ Earth



Continents and oceans

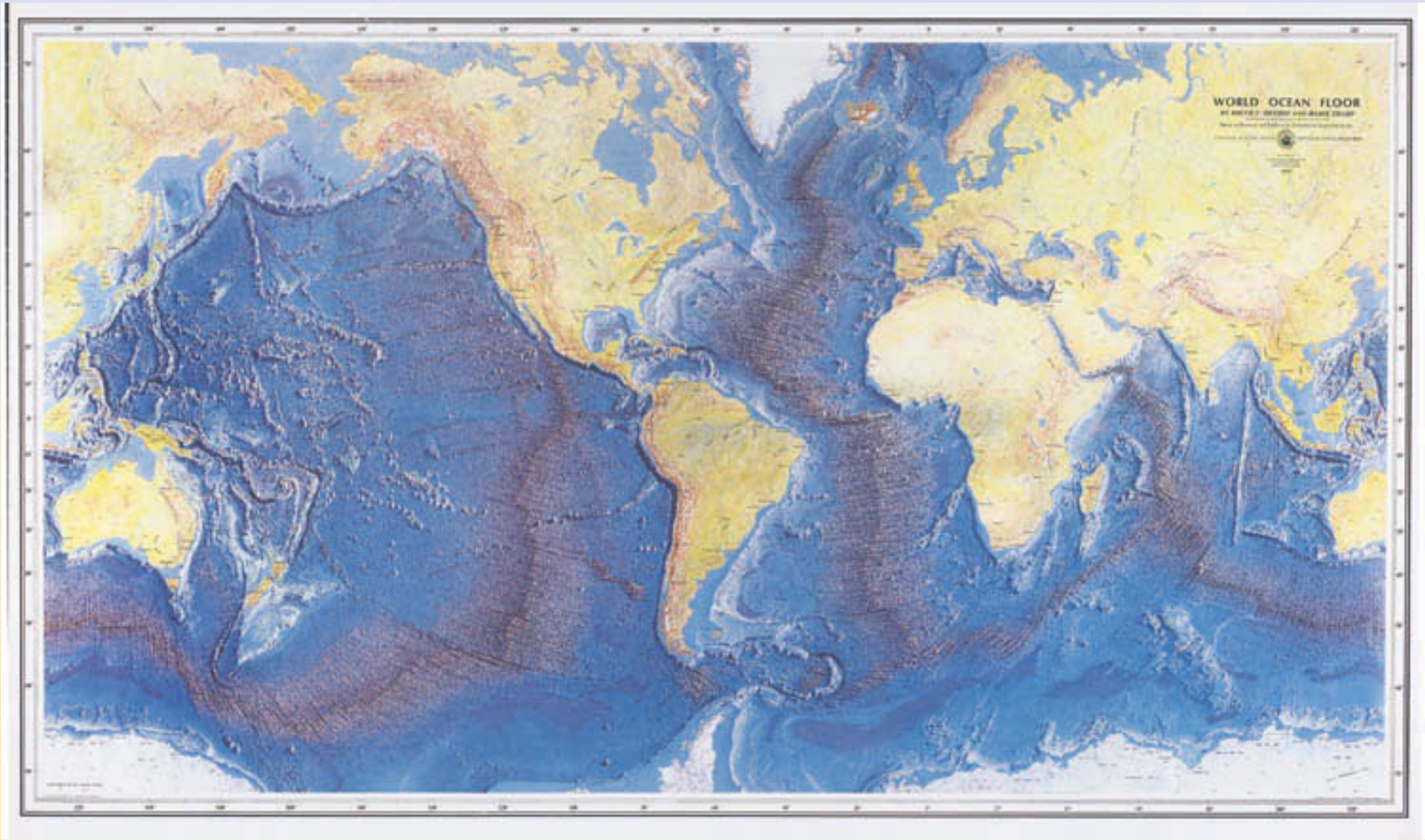


Plate tectonics

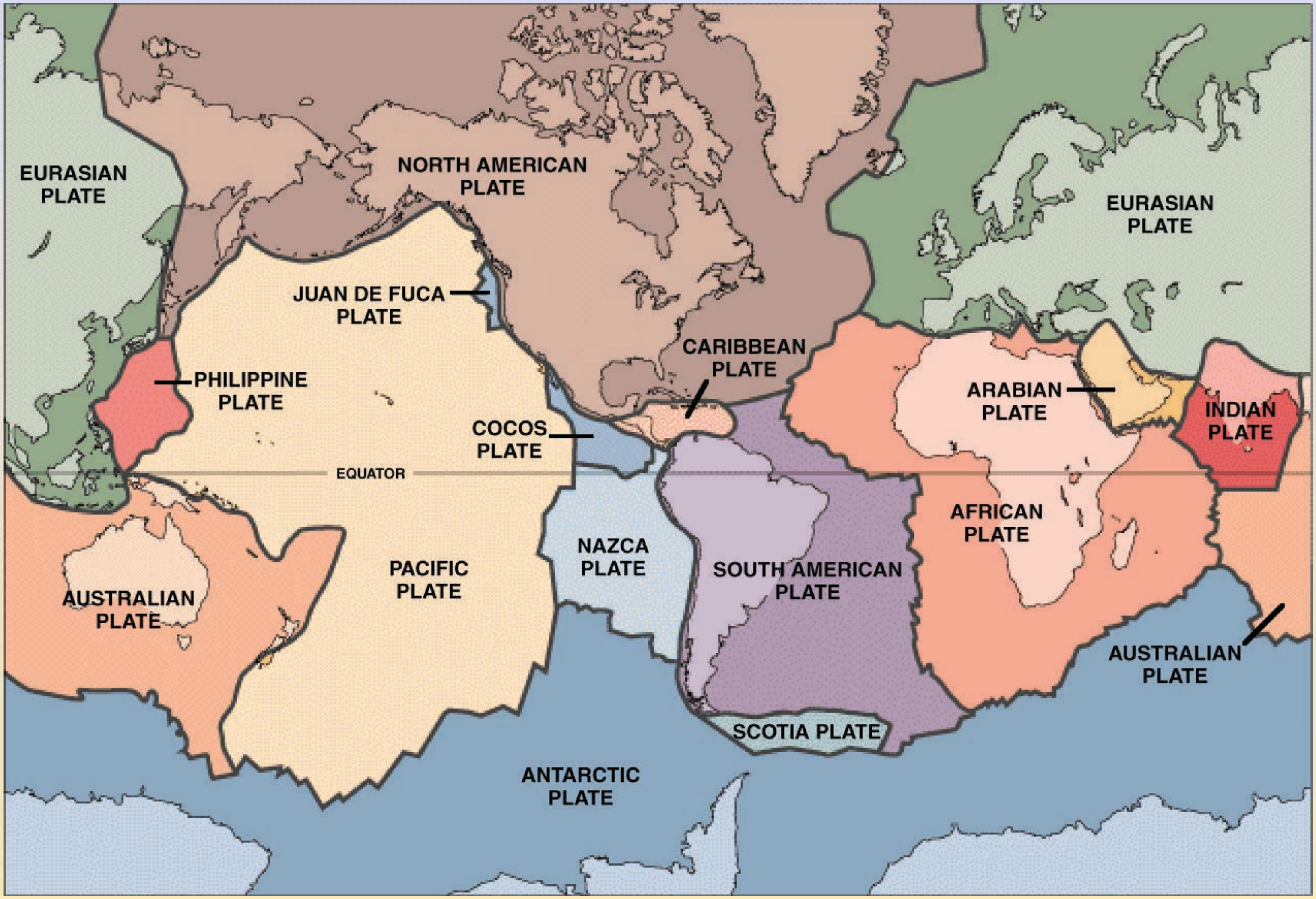
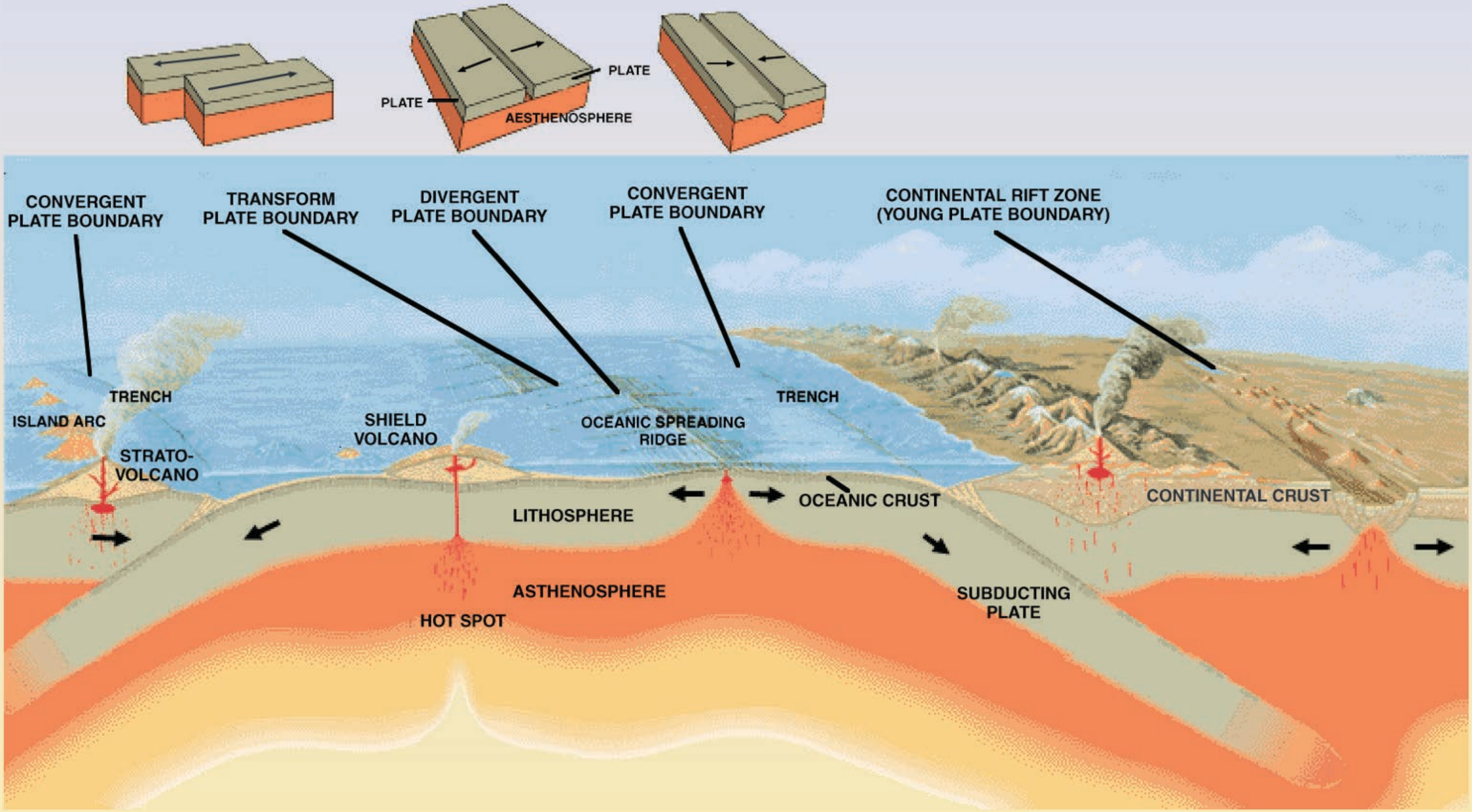
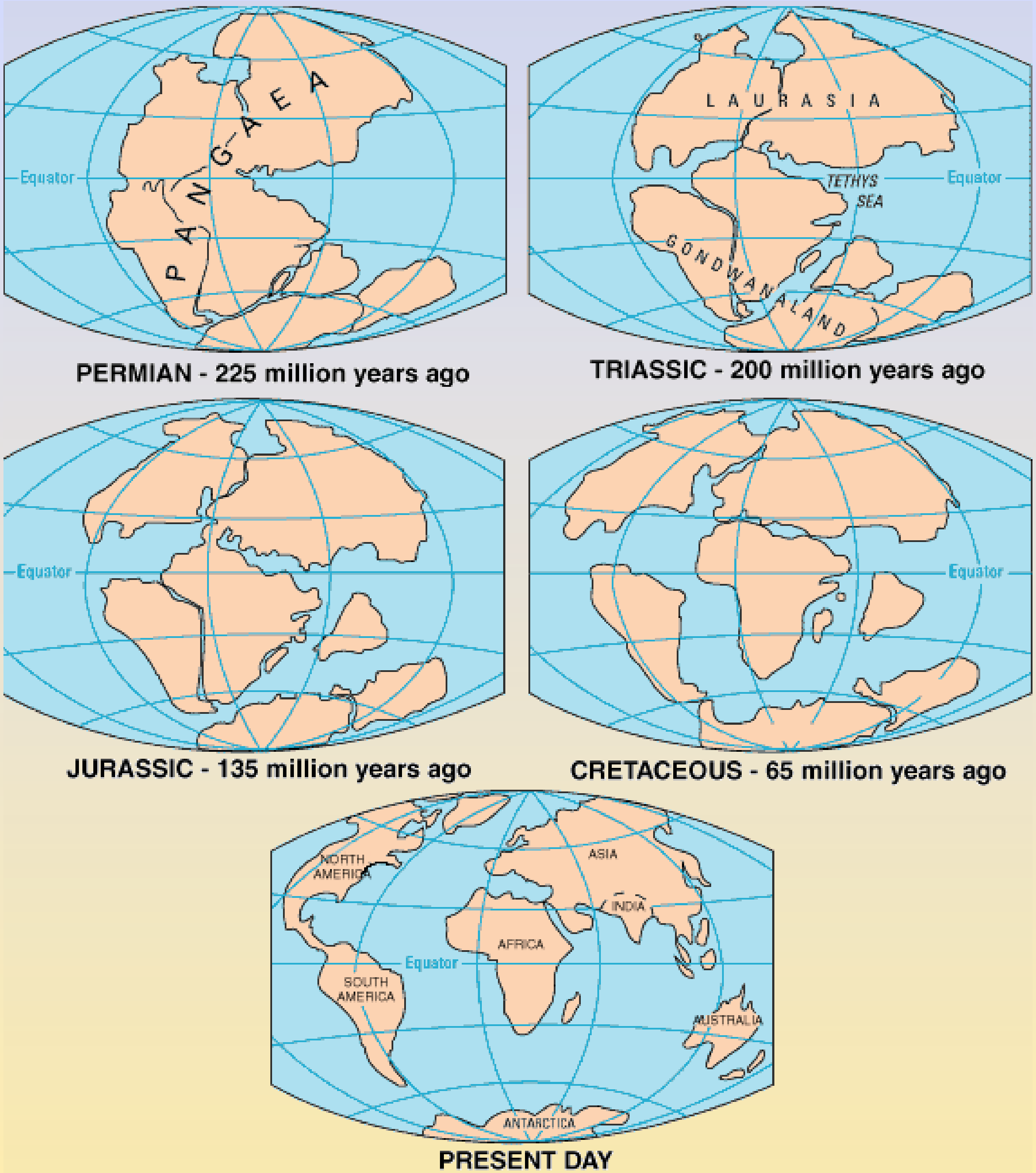


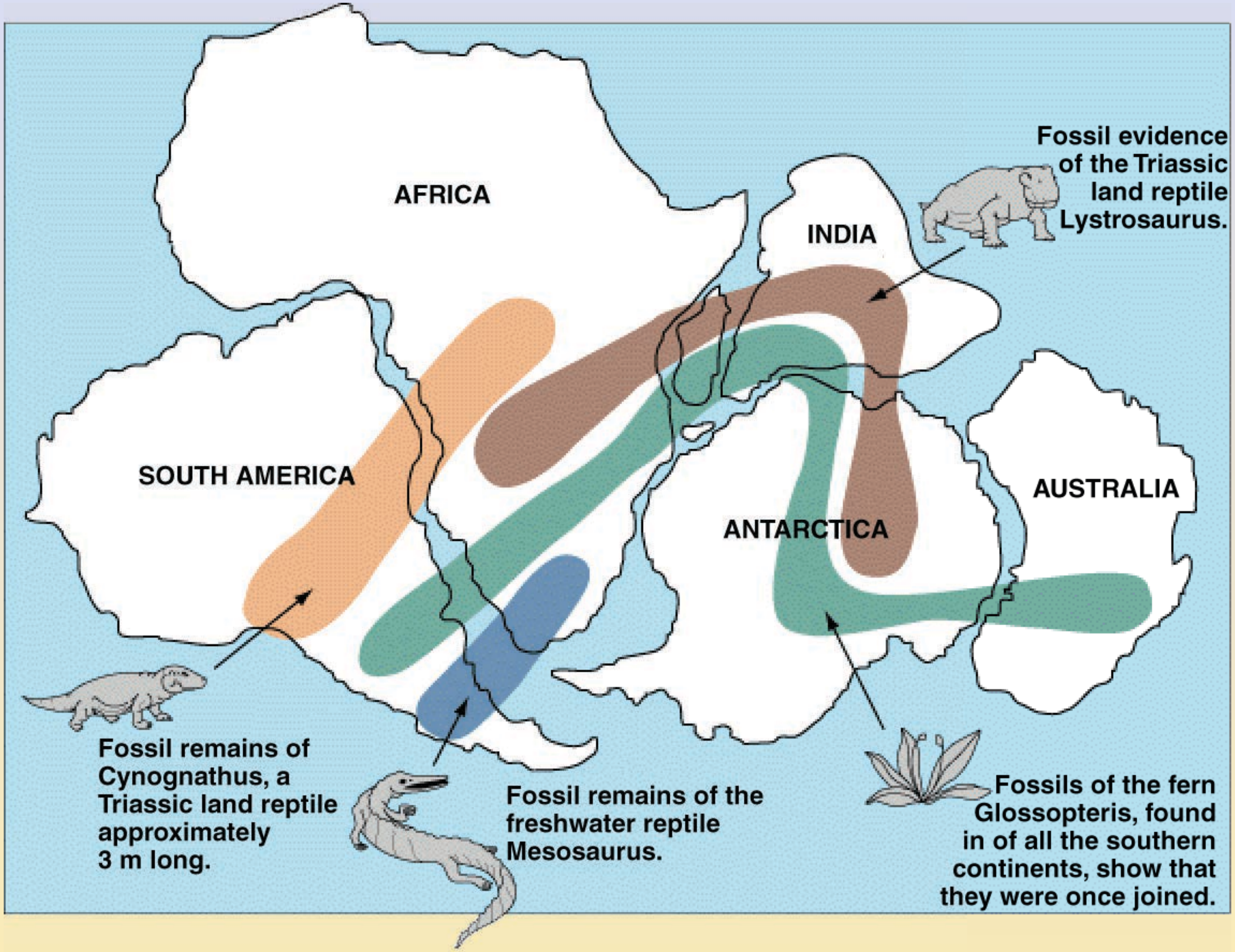
Plate motions



Historical plate motions



Traditional dating of tectonic activity

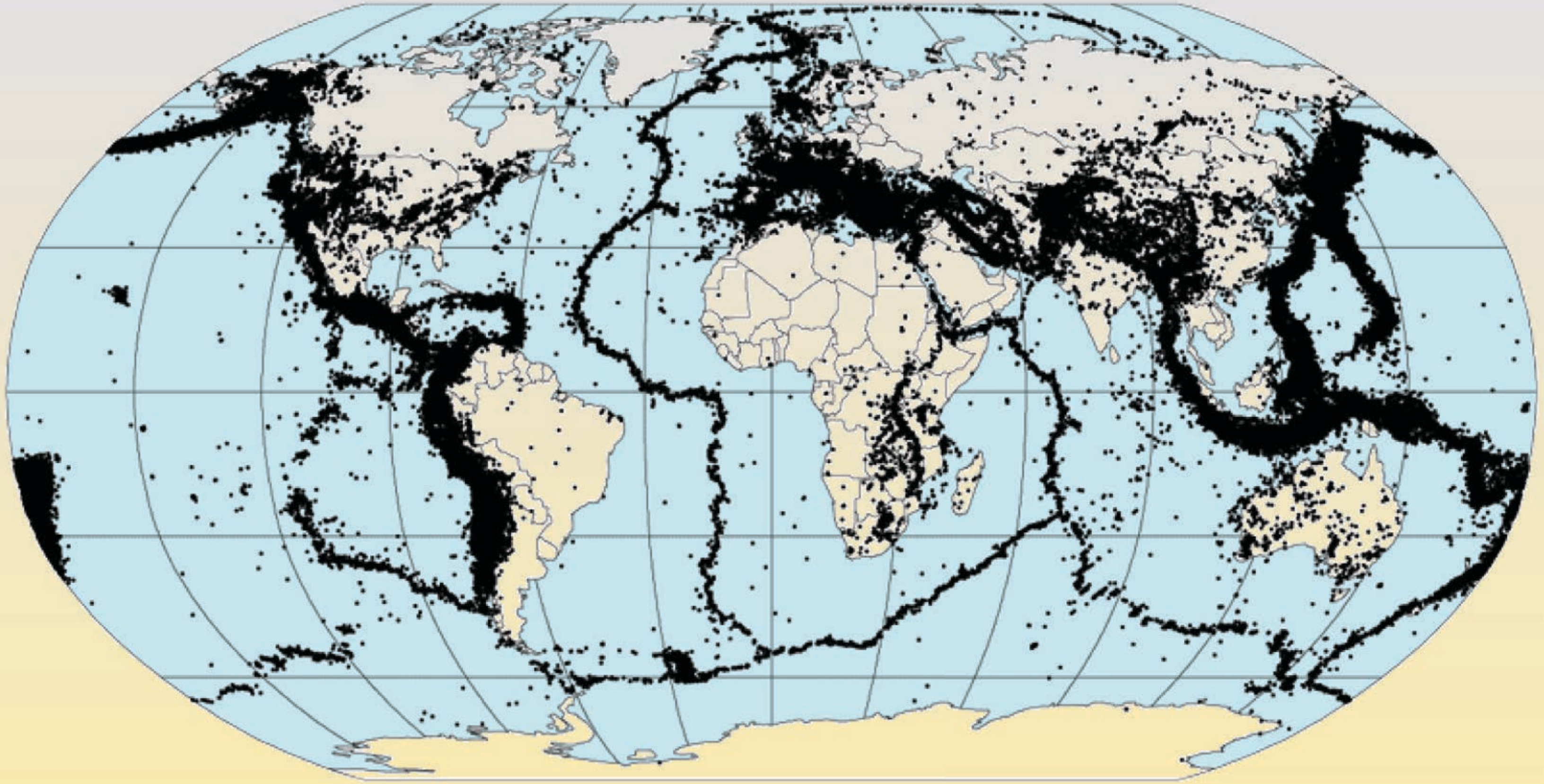


- Similar arguments for isotope/chemical evidence

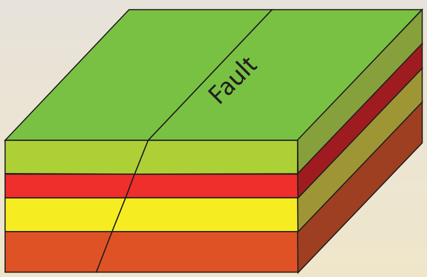
Earthquake basics

Earthquakes mainly occur along plate boundaries where motion is strongest and friction resists the motion

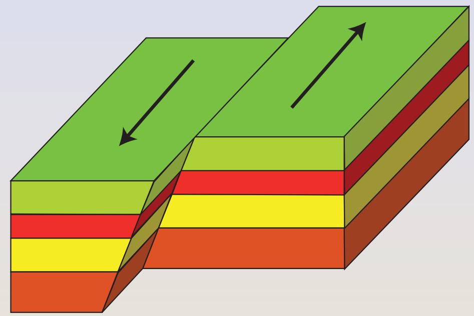
Shown are epicenters of 358,214 events from 1963-1998



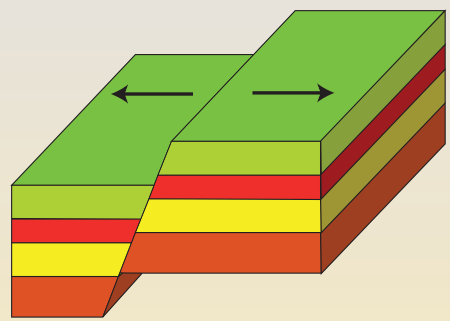
Earthquake types



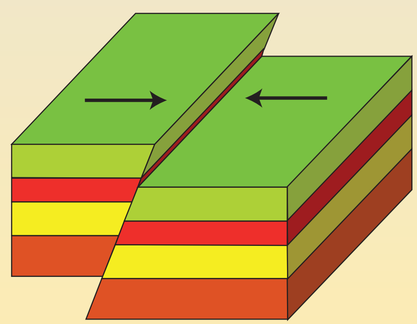
Layered Earth
with a Fault



Strike-slip fault



Normal Fault

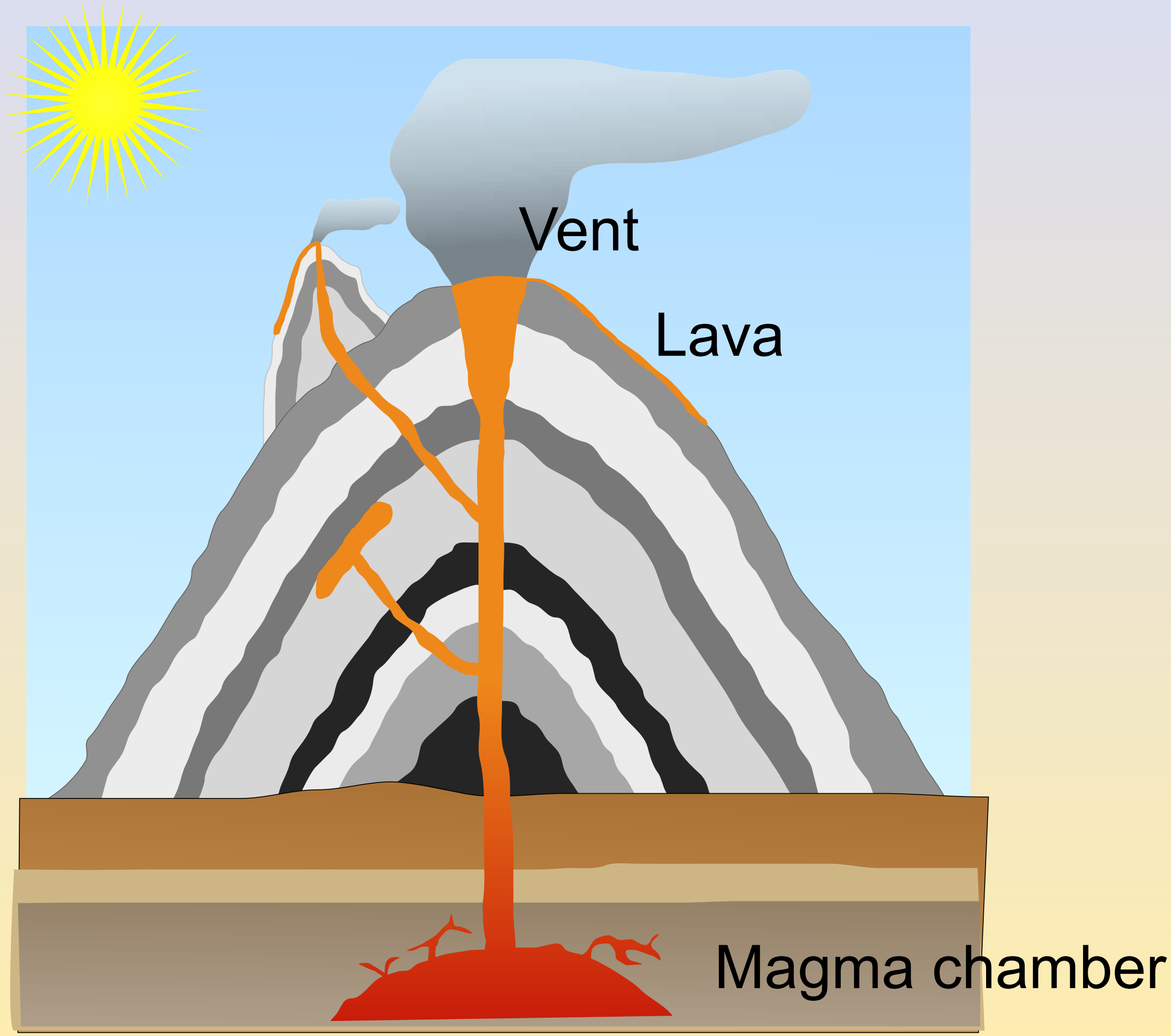


Reverse Fault

Common earthquake myths

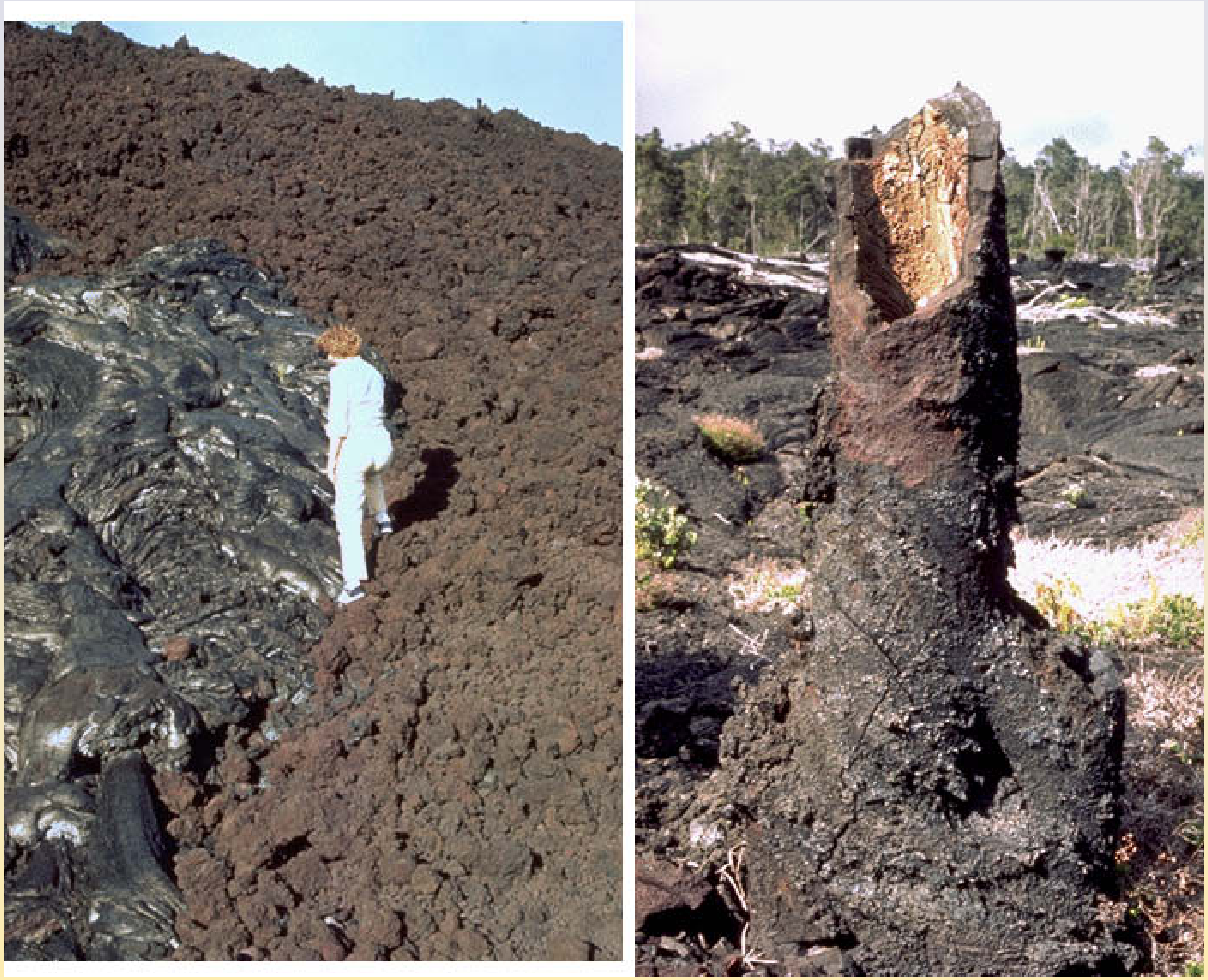
- "Big earthquakes always happen in the early morning"
- "It's hot and dry -- earthquake weather"
- "Beachfront property in Arizona"
- "We have good building codes so we must have good buildings"
- "Head for the doorway"
- "And the earth opened..."

Volcanos



Lava eruptions

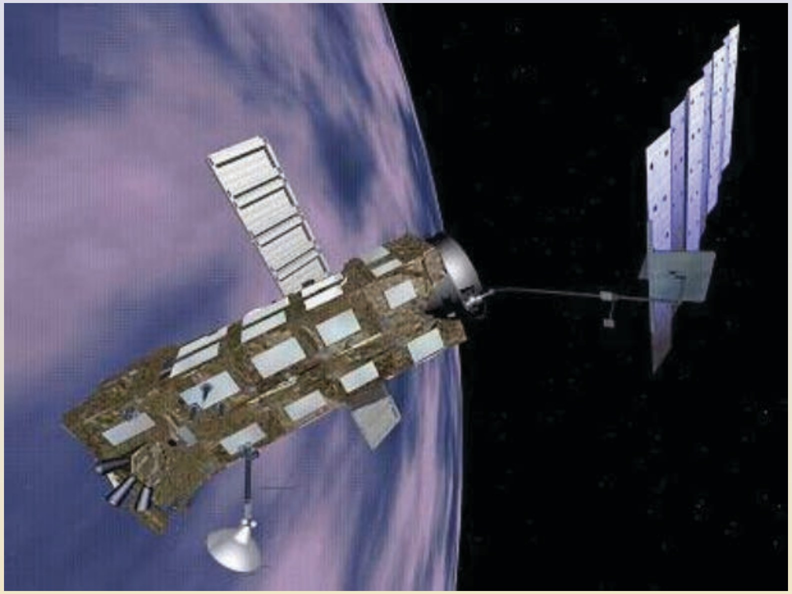
Lava flow forms



Mt. St. Helens before and after 1980 eruption

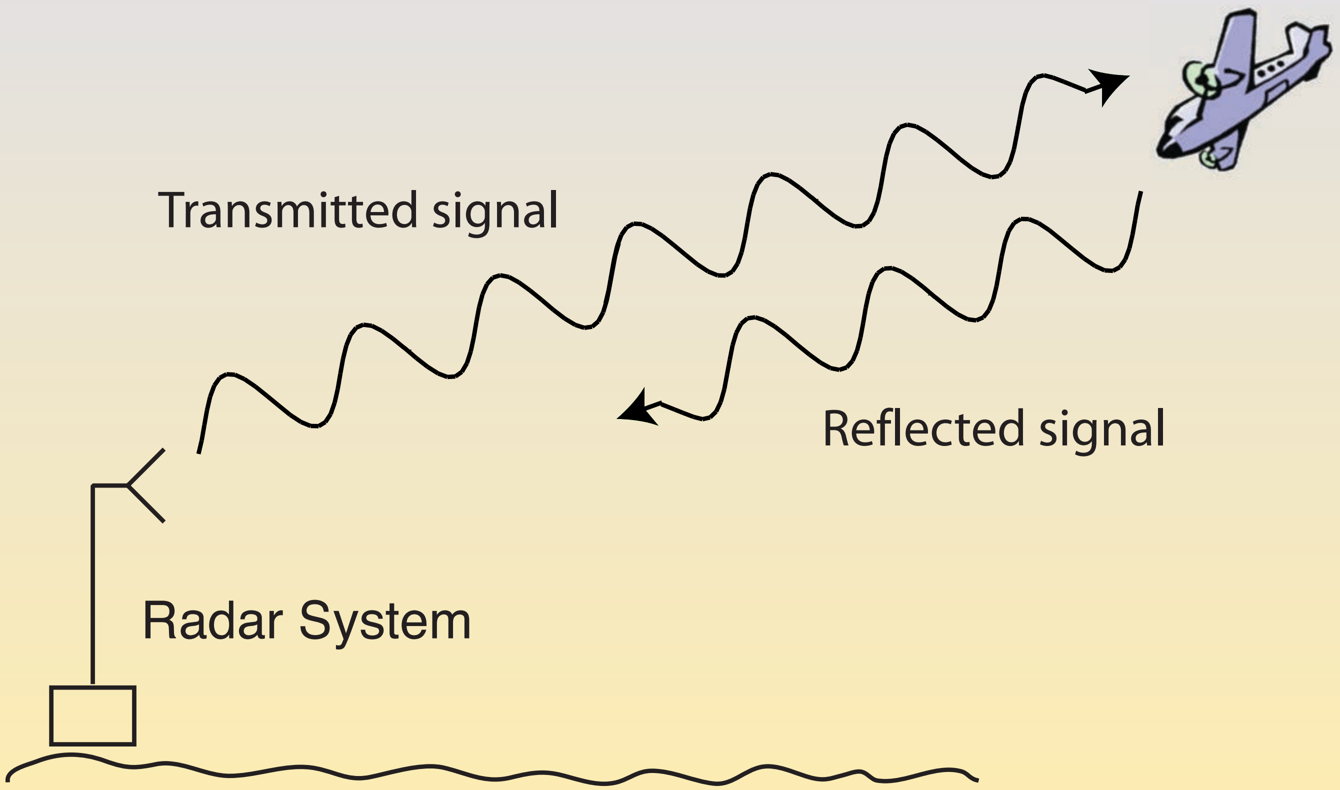
Mt. St. Helens eruption - 1980

Studying Earth from Space

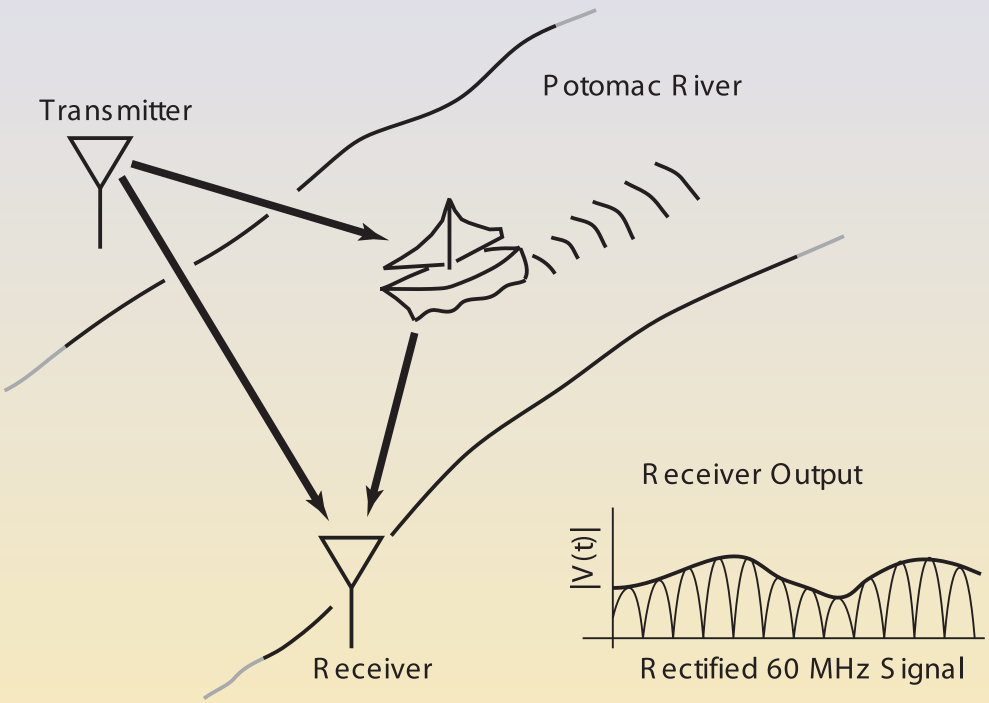


What is a radar?

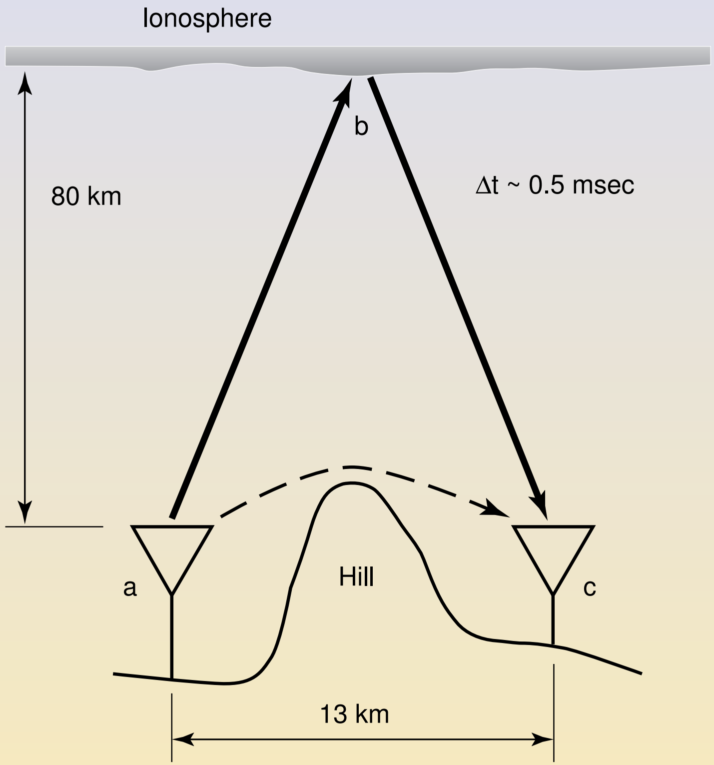
- Radar: Radio Detection and Ranging
- Measures time of flight of EM pulses



Early radars

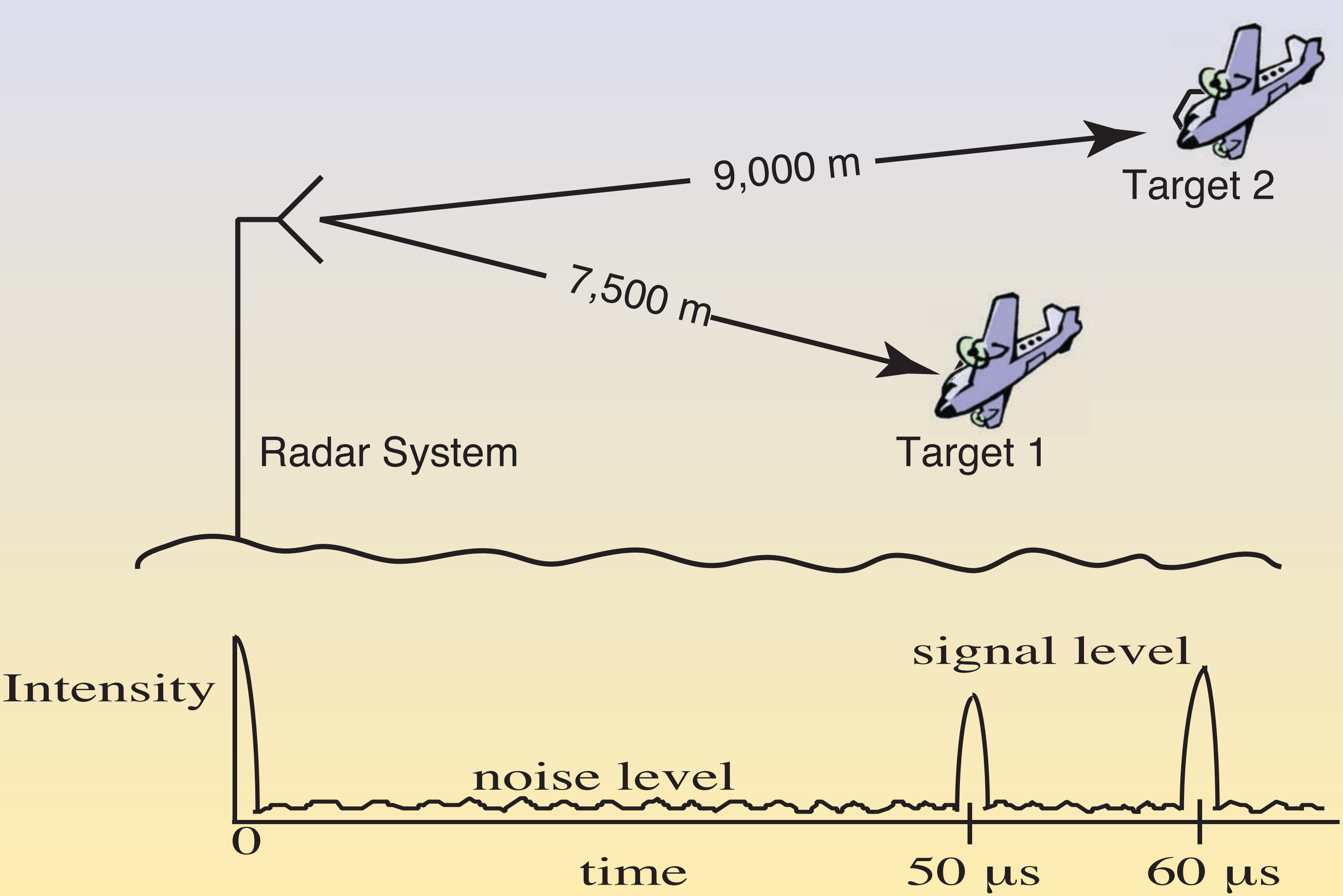


Taylor and Young (1922)

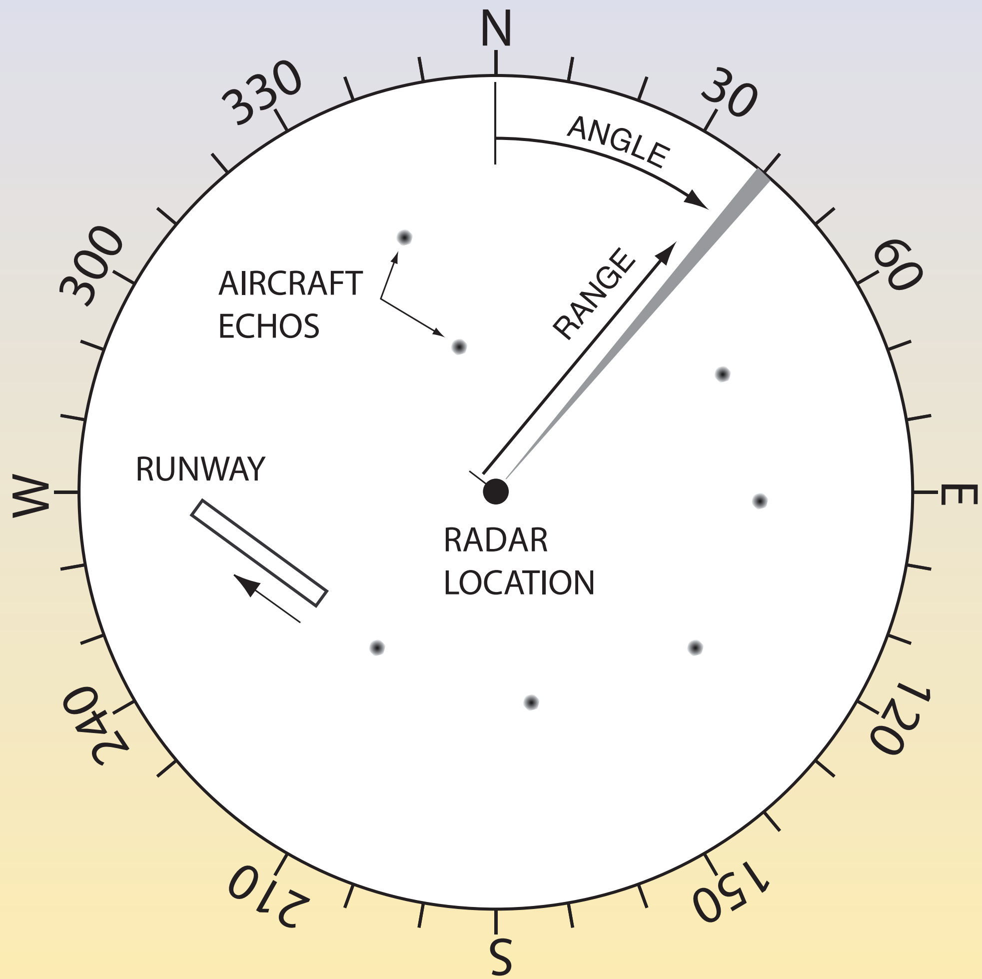


Breit and Tuve (1925)

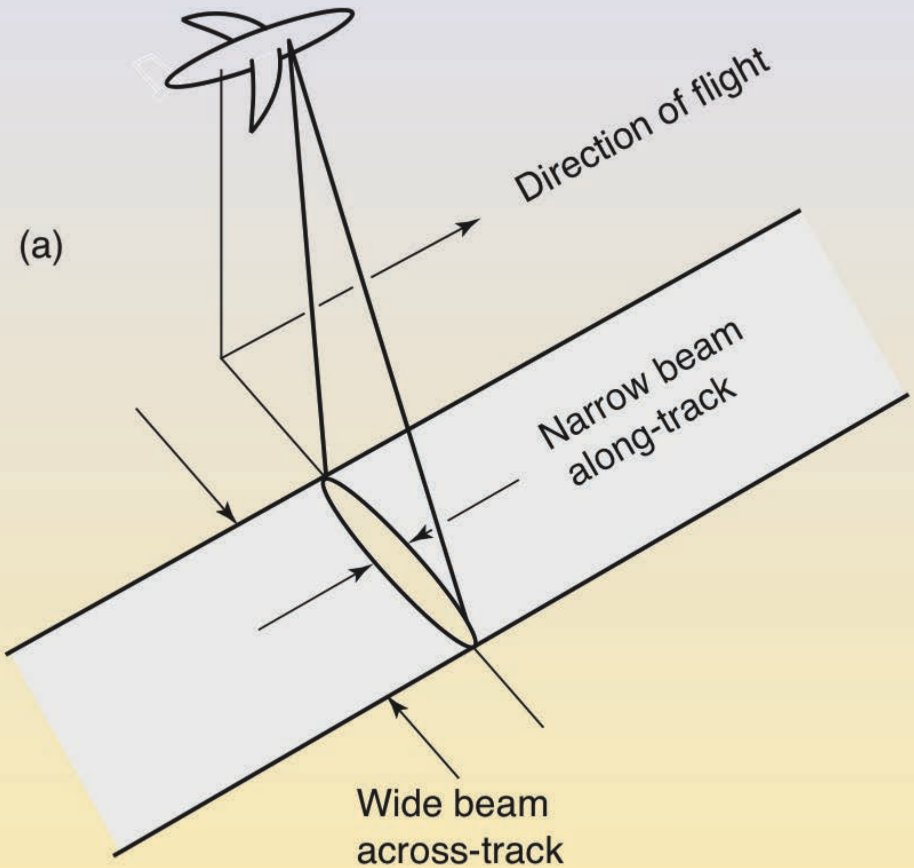
Distance measurements

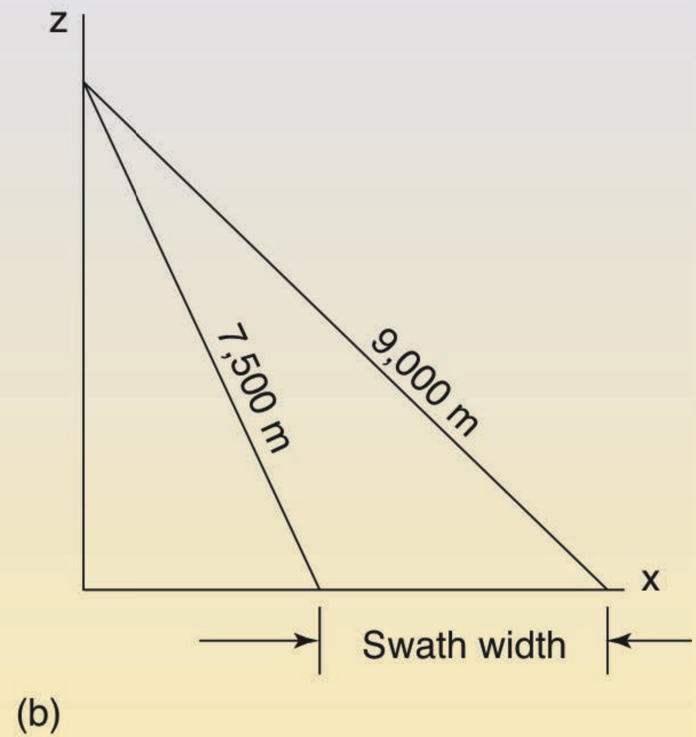


Mapping multiple objects - ppi

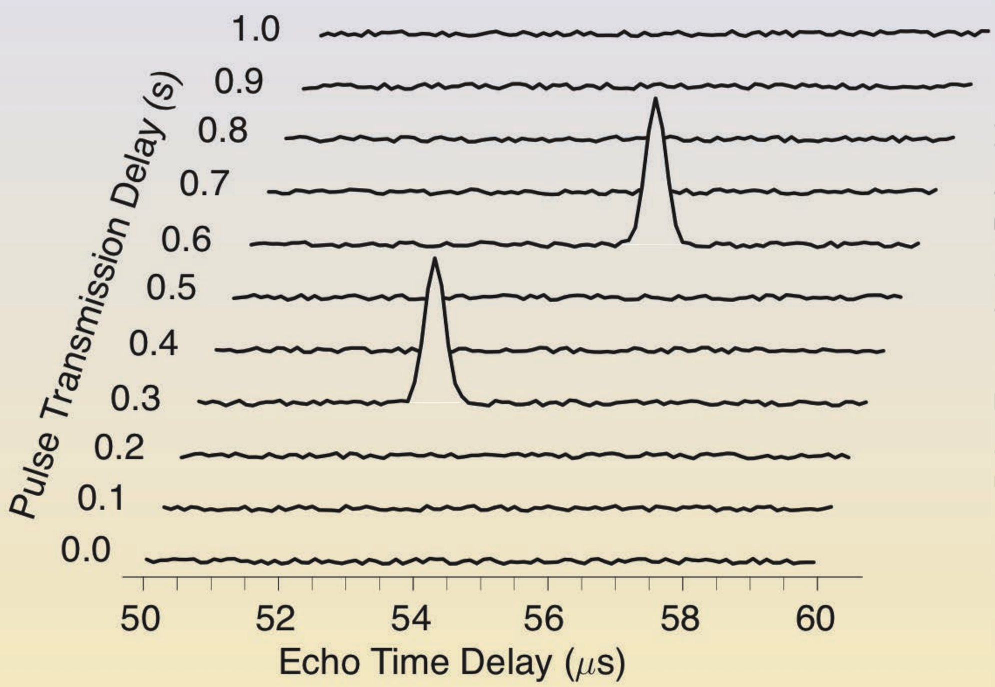


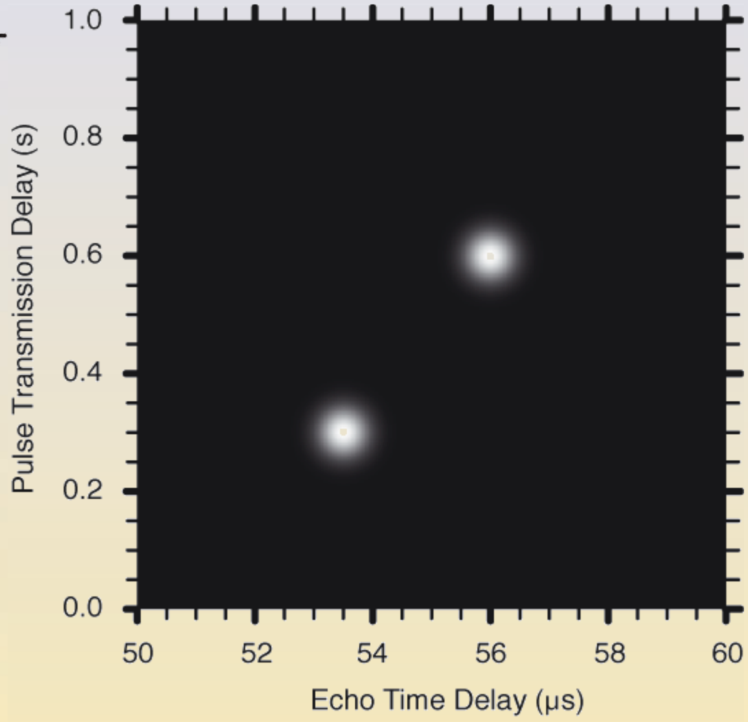
Imaging geometry



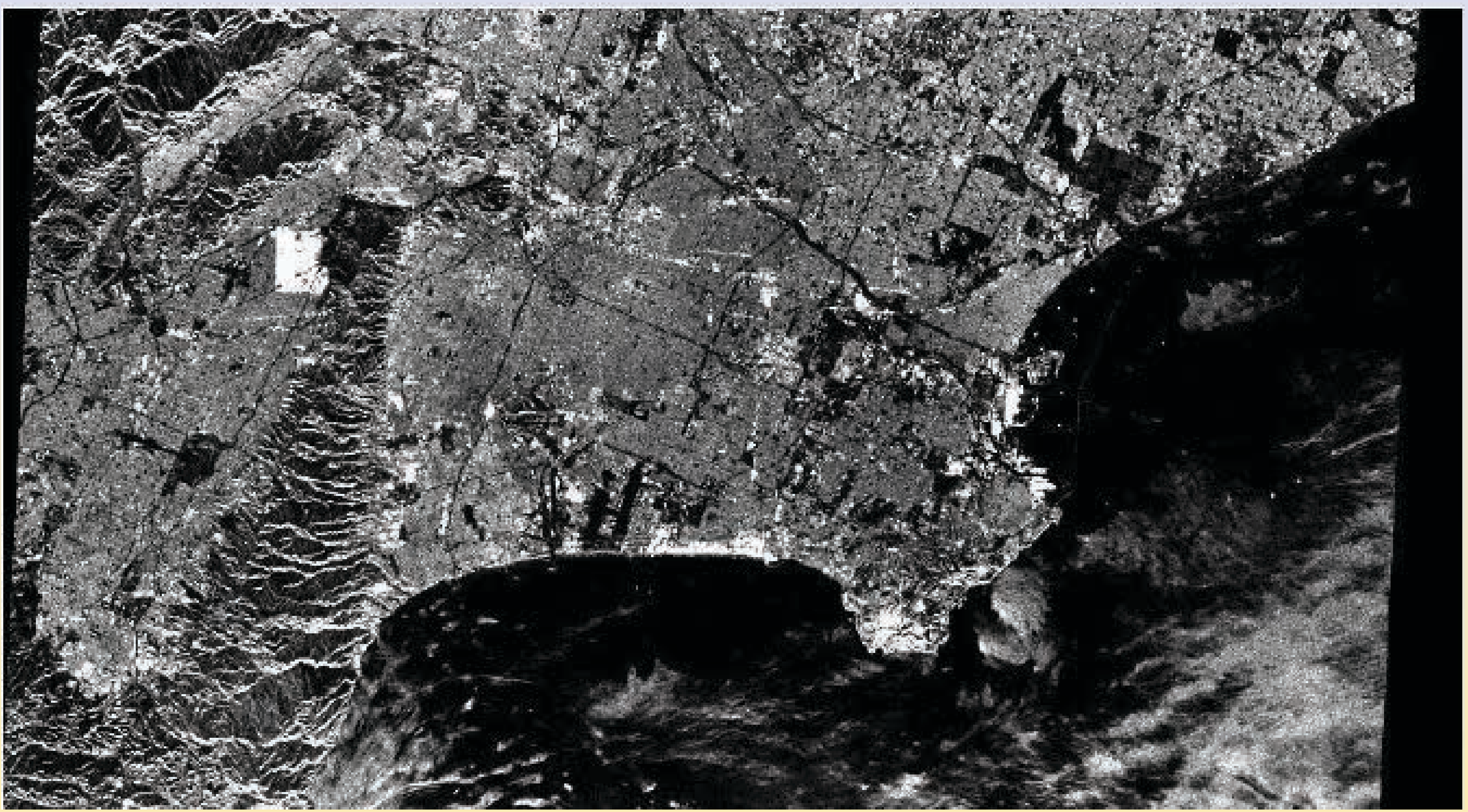


Forming an image

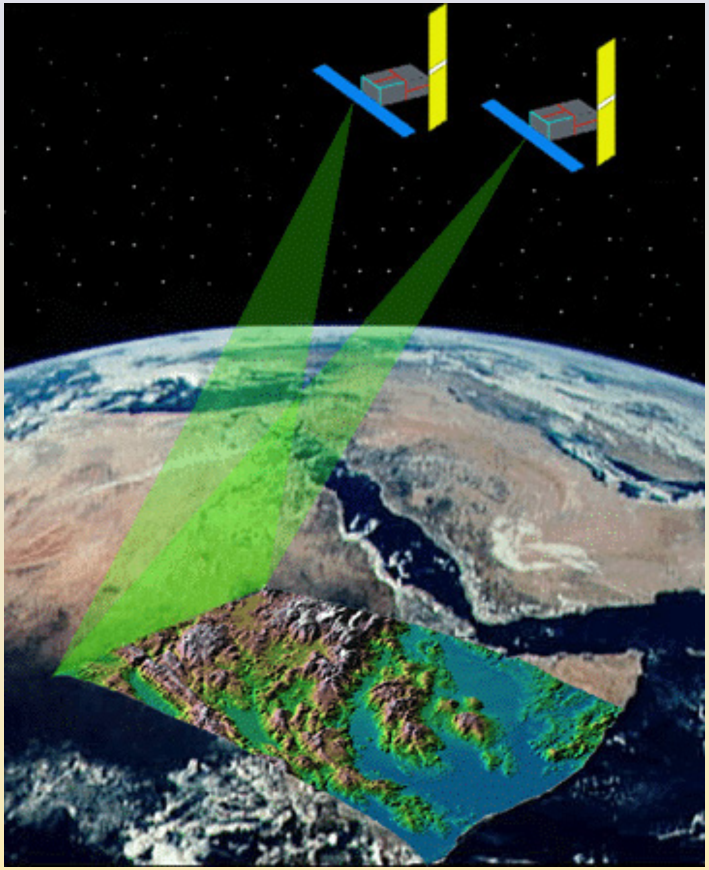


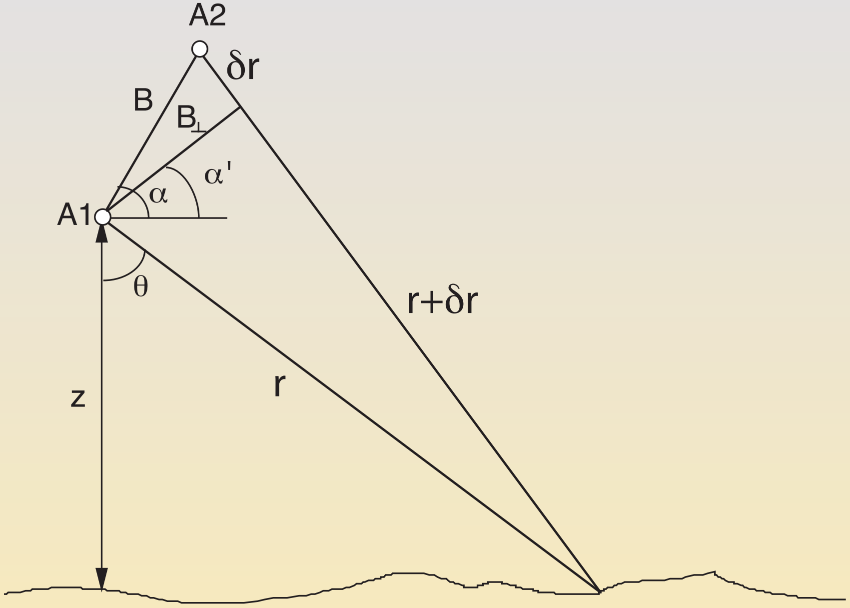


Seasat – First satellite imaging radar, 1978

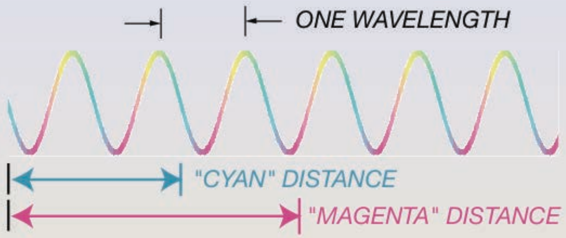


Interferometric Synthetic Aperture Radar (InSAR)

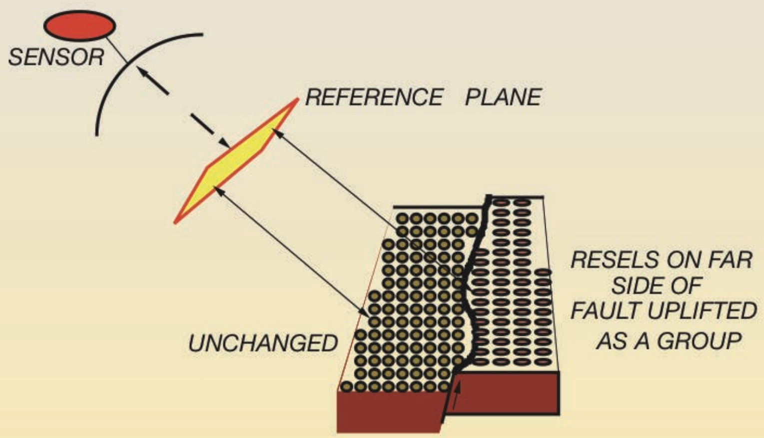




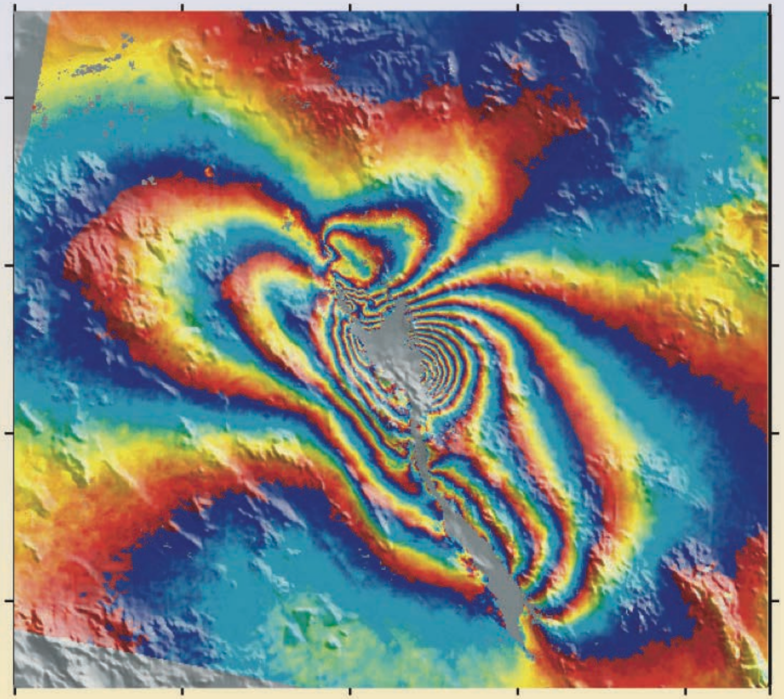
InSAR measures distance by measuring signal phase



1. Distances measured as signal phase



2. Mapping change in phase gives deformation



3. Radar interferogram

InSAR phase observables

Topography term

$$\delta r = \frac{\lambda\phi}{4\pi}$$

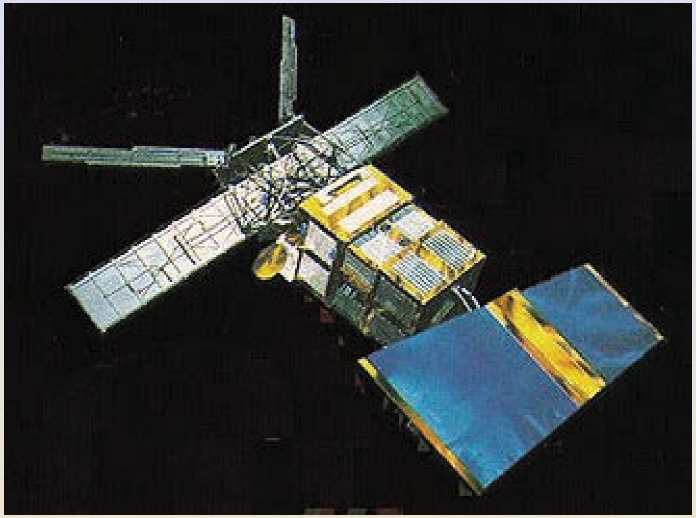
$$\sin(\alpha - \theta) = \frac{(r + \delta r)^2 - r^2 - B^2}{2rB}$$

$$\mathrm{z(y) = h - r\cos}\theta$$

Deformation term

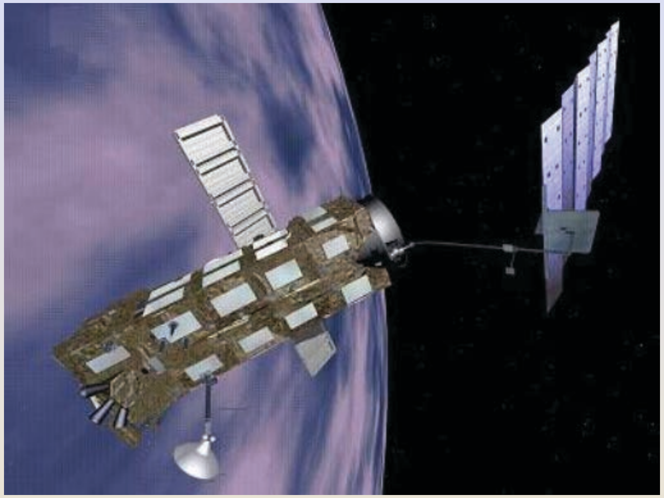
$$\phi = \frac{4\pi\,\Delta r}{\lambda}$$

InSAR Satellites

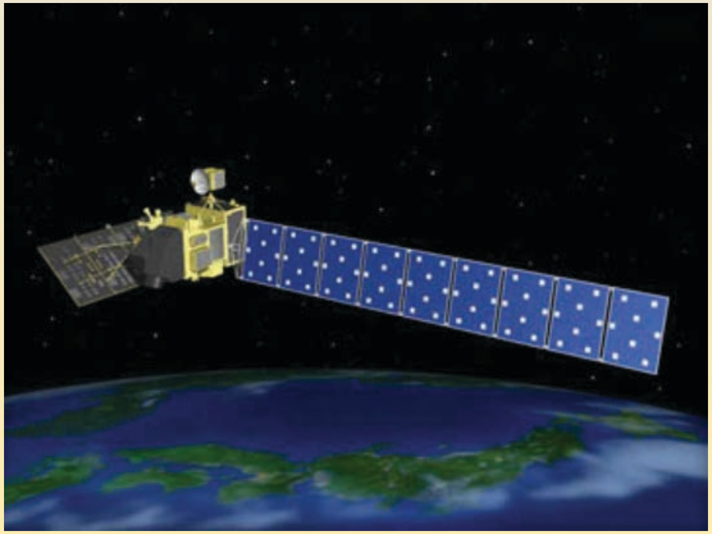


ERS

Envisat



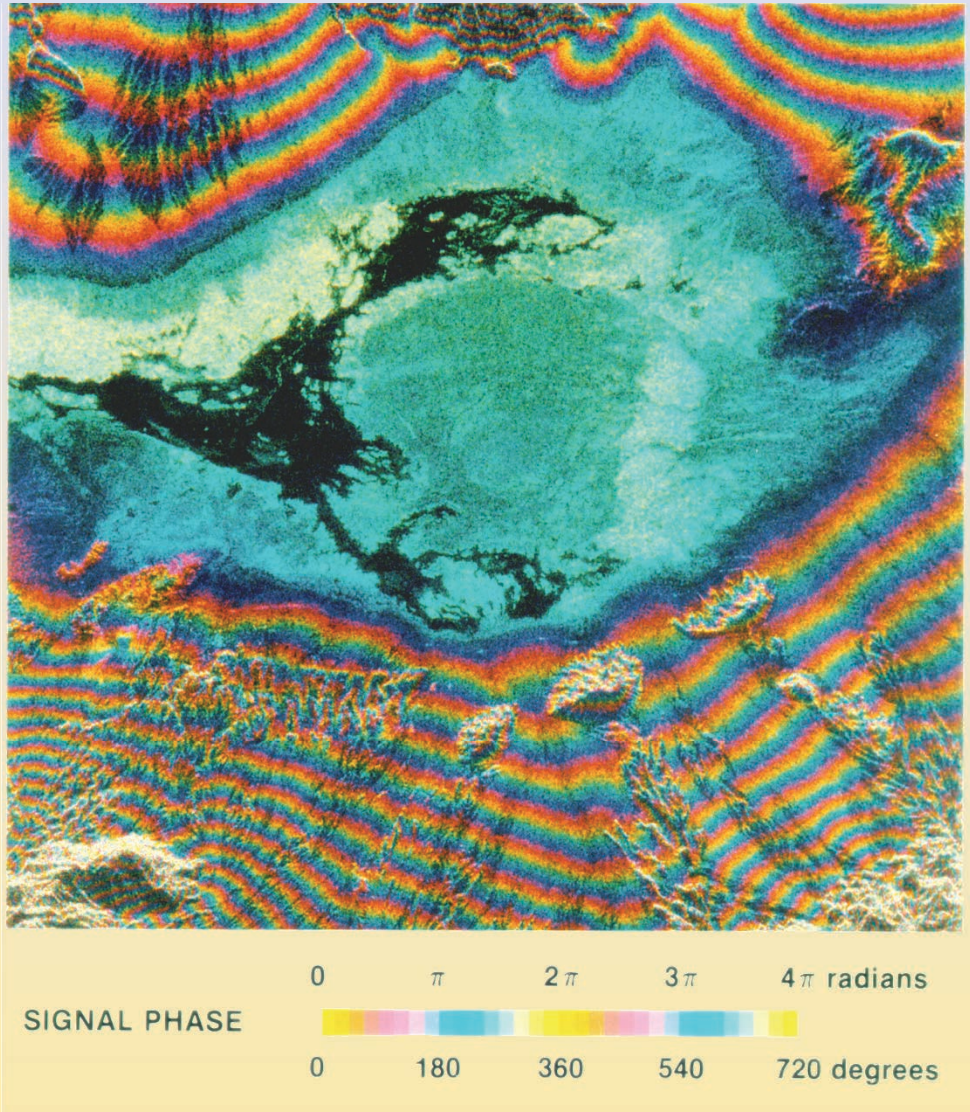
ALOS



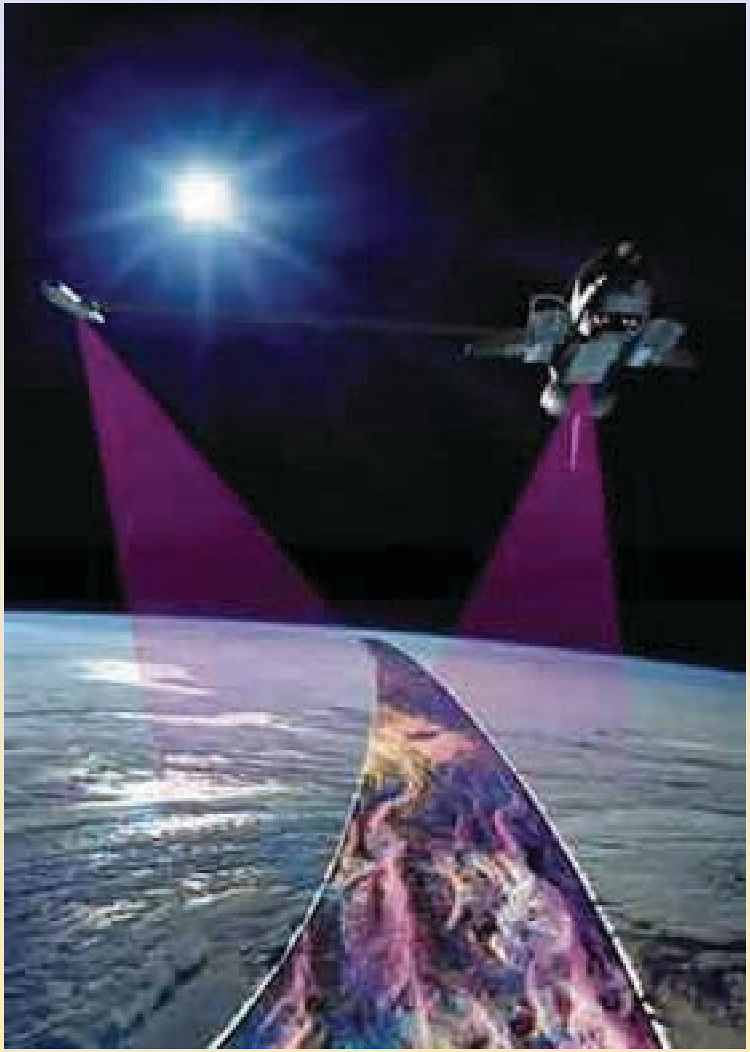
Radarsat

Seasat also produced the first interferometric fringes

- Topographic map of Death Valley, CA



InSAR topography - SRTM



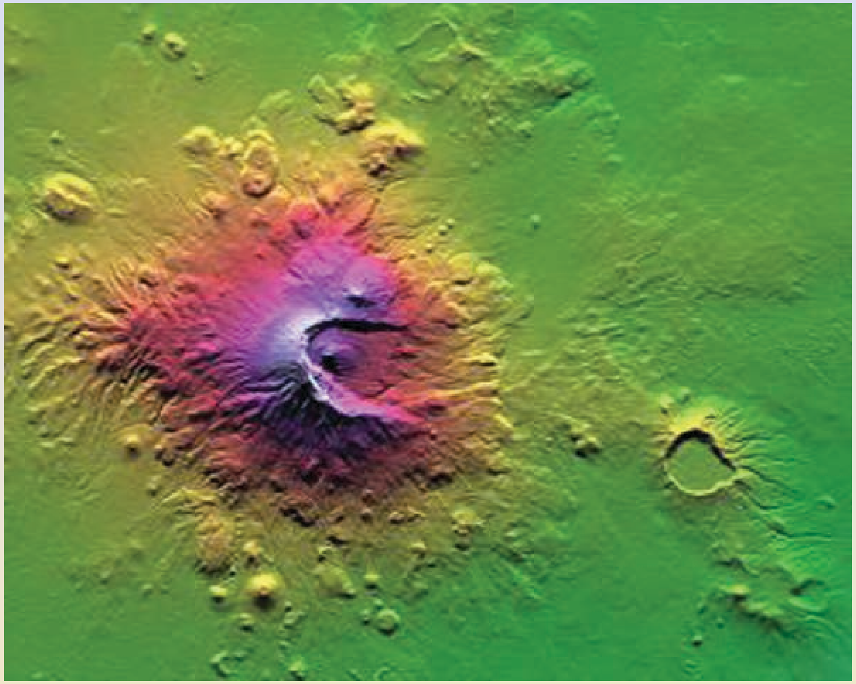
JPL SRTM Project

First (and only) worldwide, consistent model of elevation

World mapped at 30 m posting, 10 m elevation accuracy

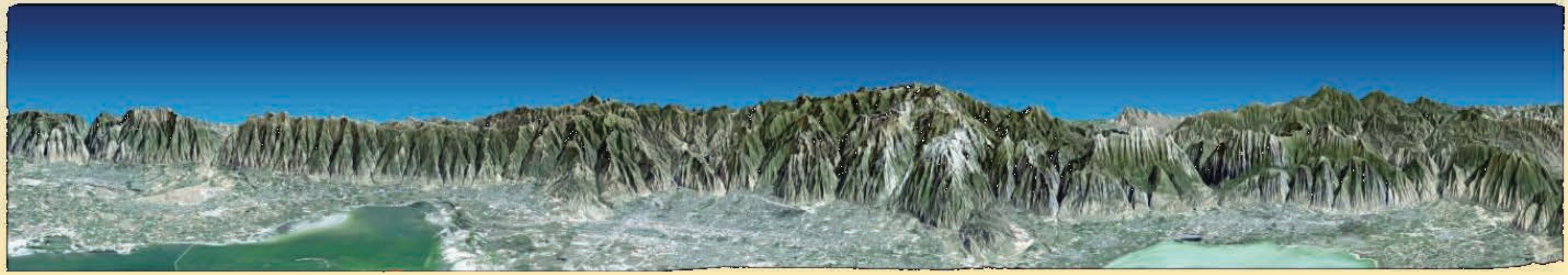
90 m data available for Earth

InSAR topography - Examples



Mount Meru, Tanzania

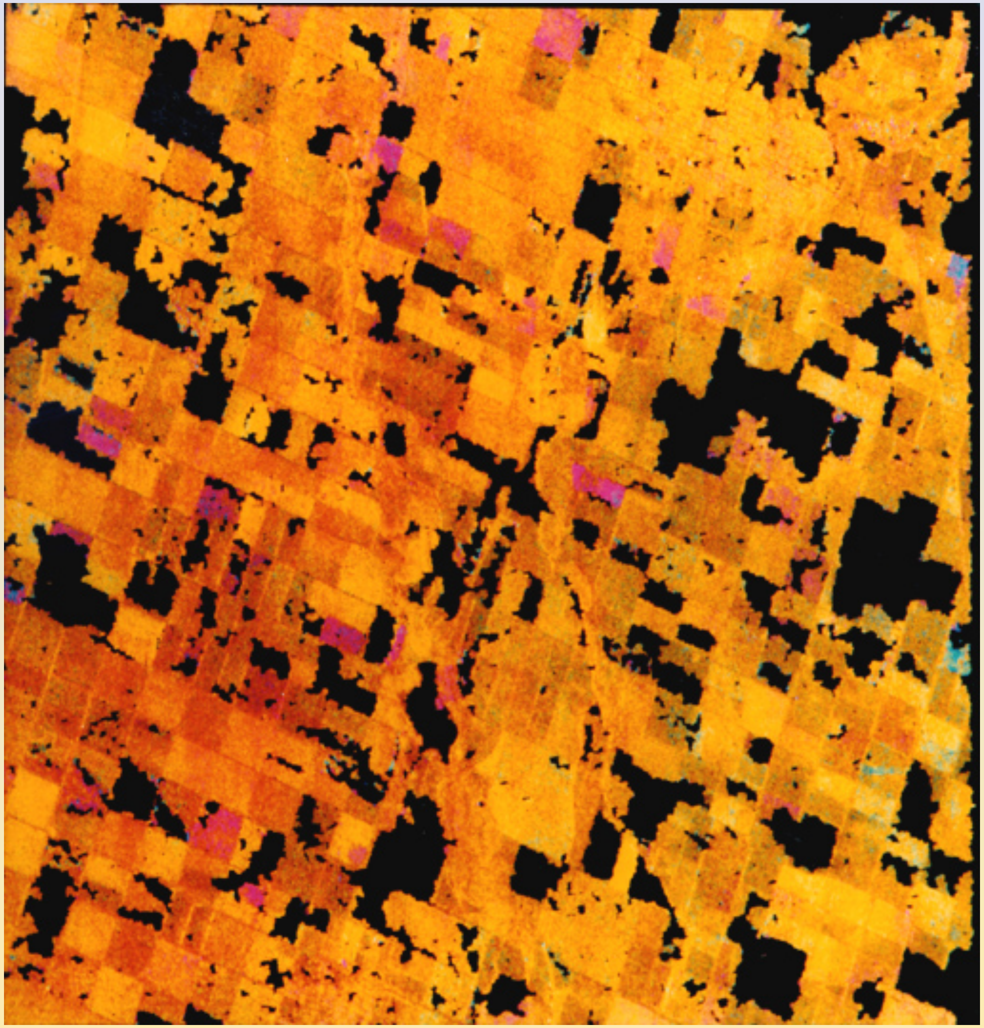
Utah front range



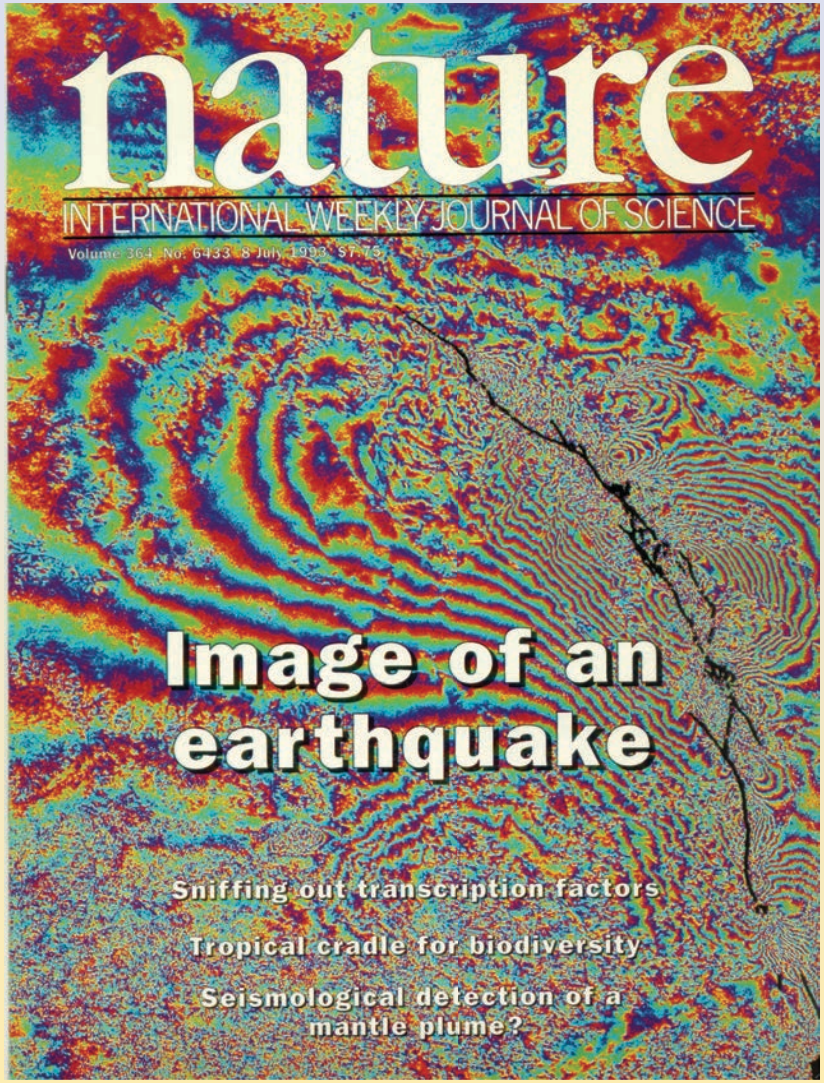
JPL SRTM Project

Seasat deformation observations

- Local uplift and subsidence near Salton Sea, CA

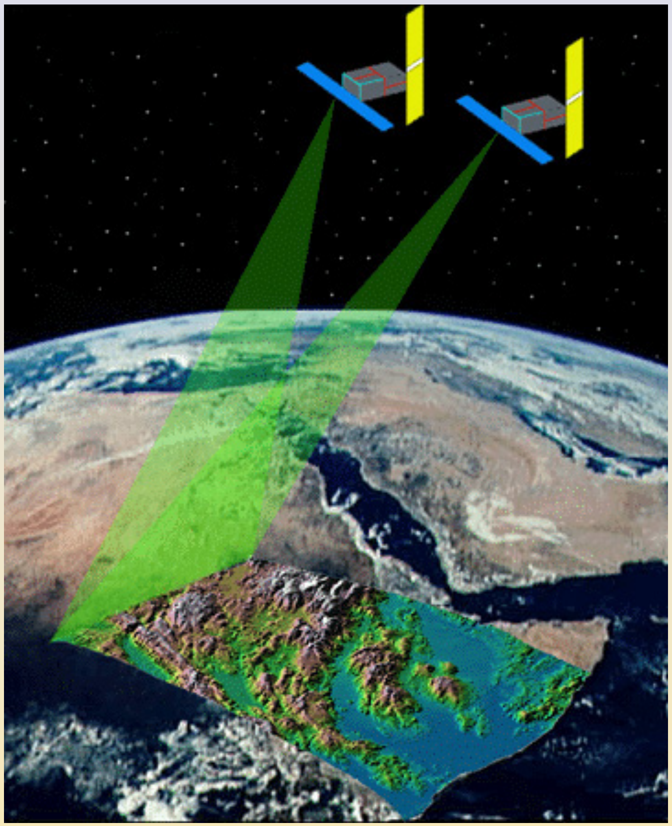


ERS radar measured first earthquake from space



Geodesy – Precise measurement of Earth shape

InSAR



GPS

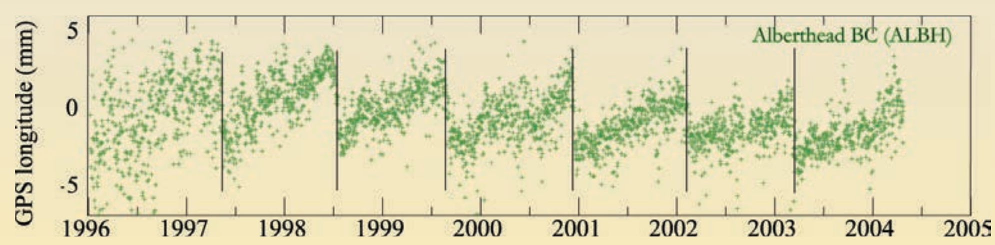
GPS aseismic (‘slow’) earthquakes

Melbourne and Webb, 2003

Cascadia subduction zone

Slow events occurs in many subduction zones around the Earth

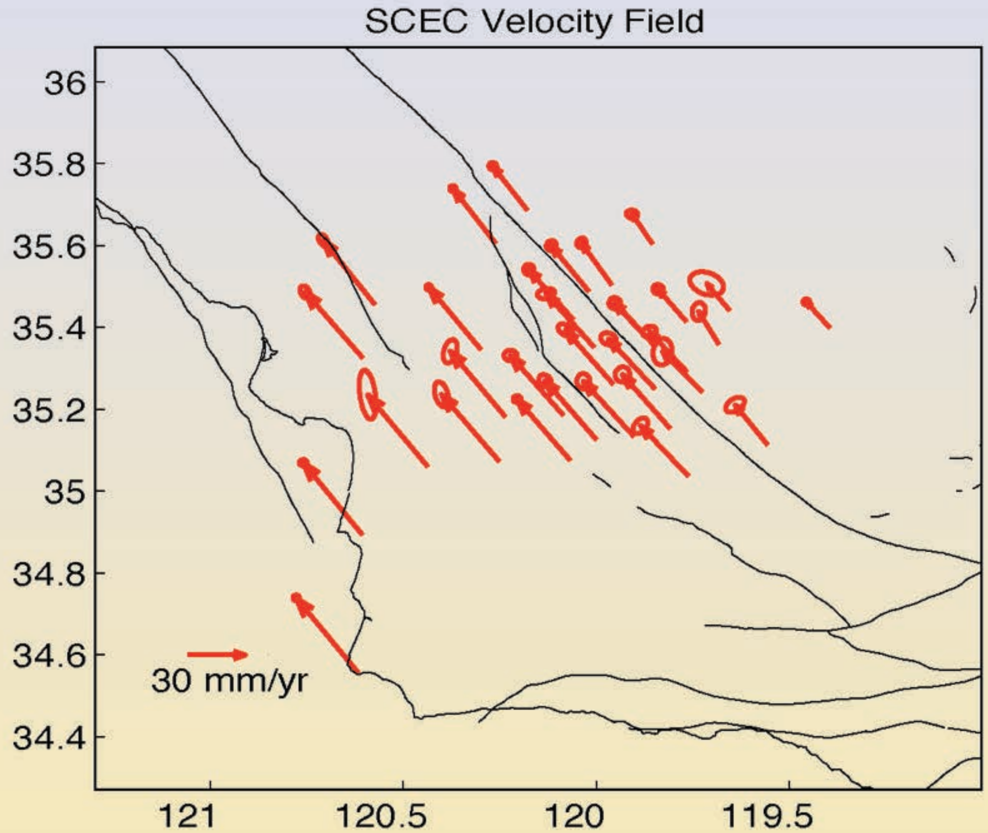
Slow earthquakes are adding stress to subduction fault

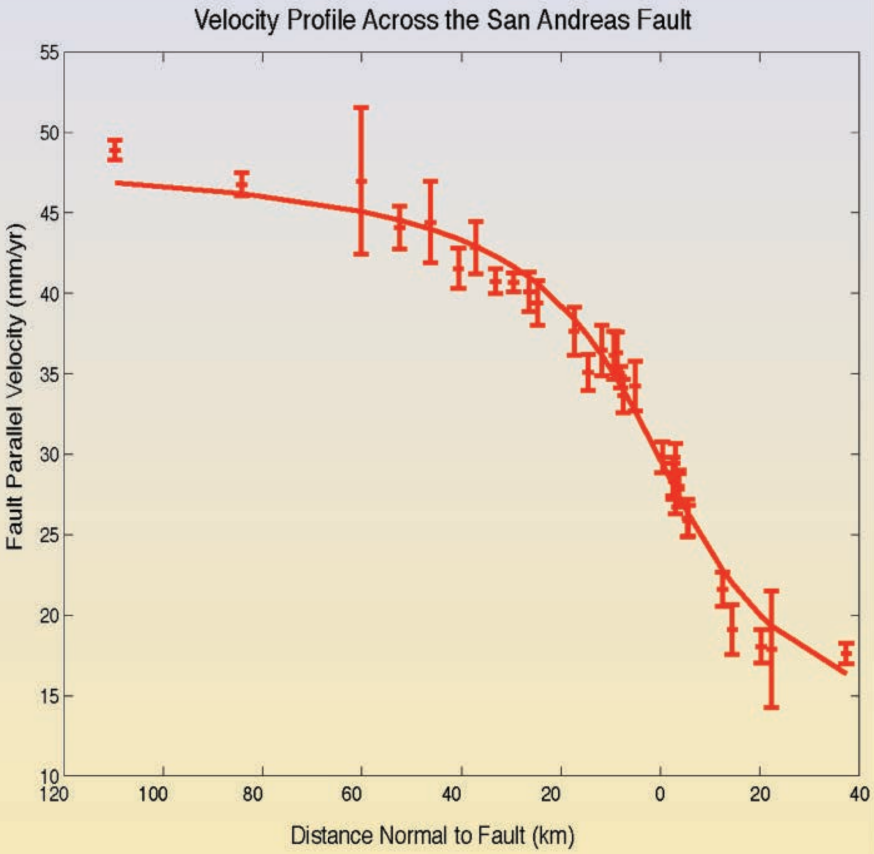


GPS time series

GPS views interseismic velocity field

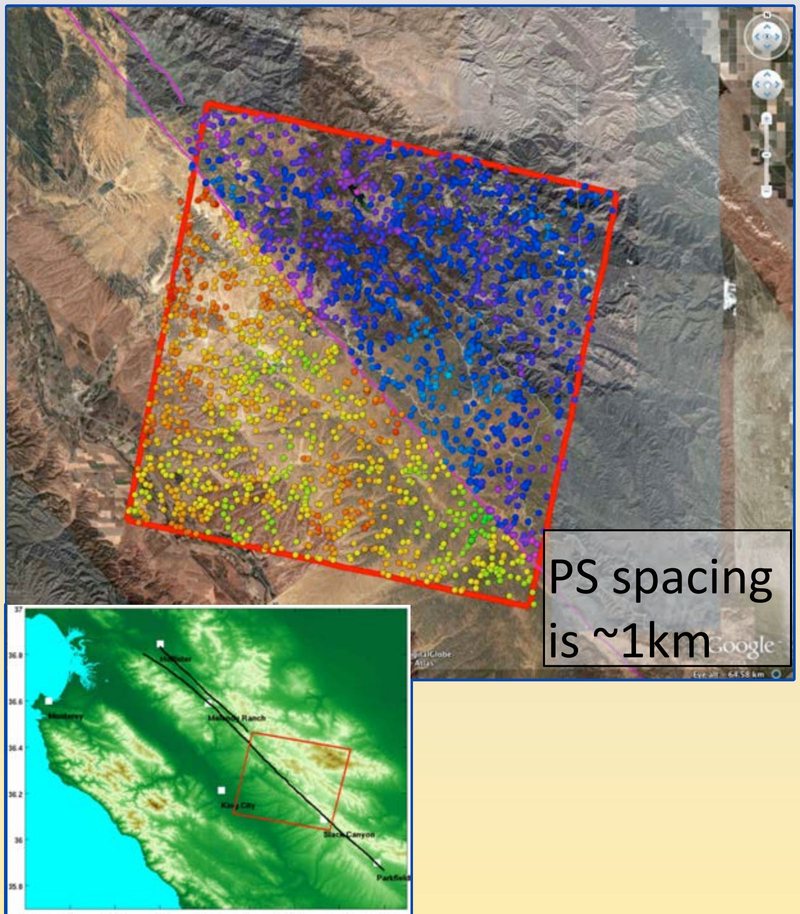
Central California / San Andreas fault



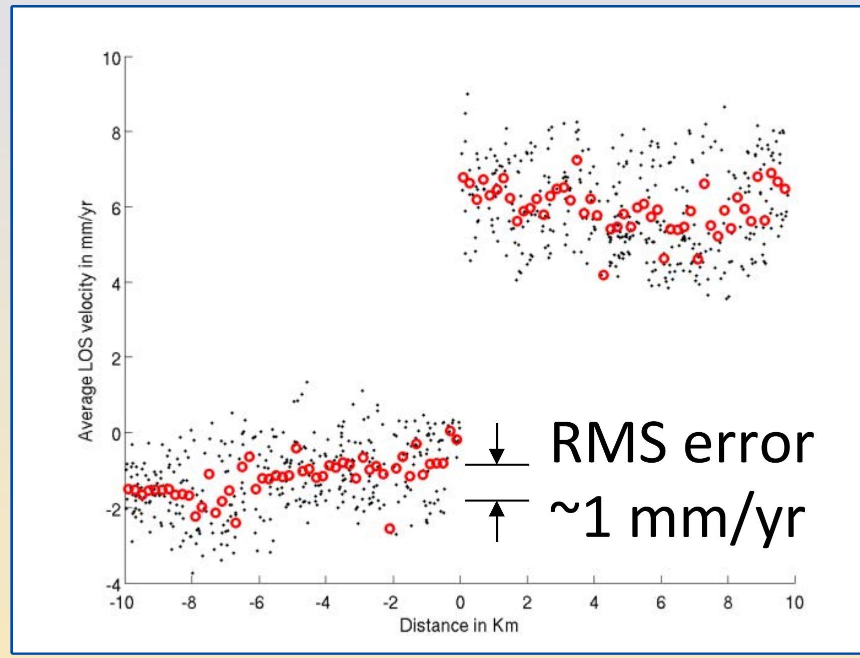


InSAR Persistent Scatterer method

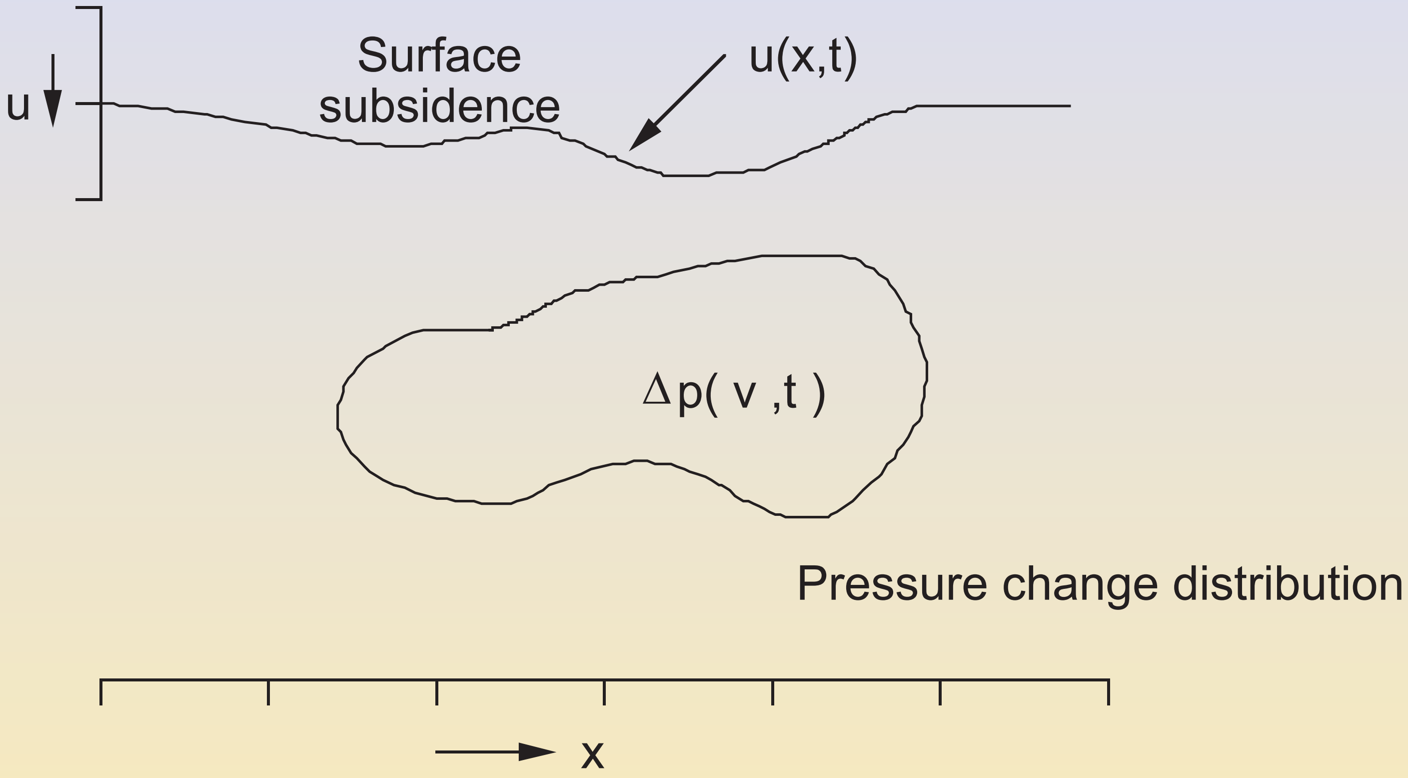
PS image of San Andreas Fault - ERS satellite



PS performance

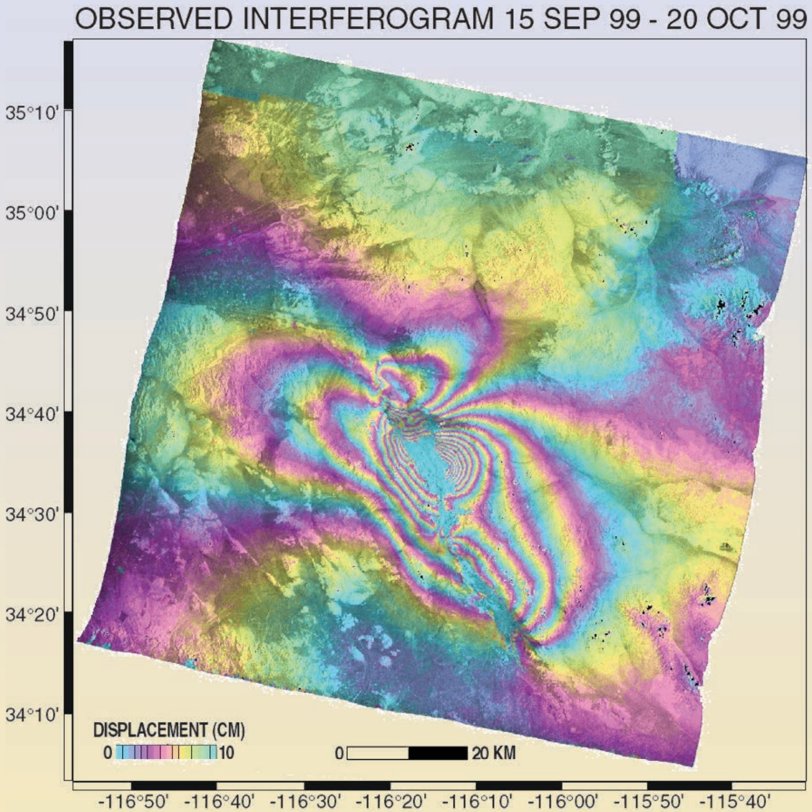


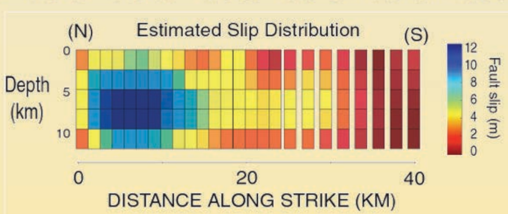
Integral inversion yields pressure or movement from surface subsidence

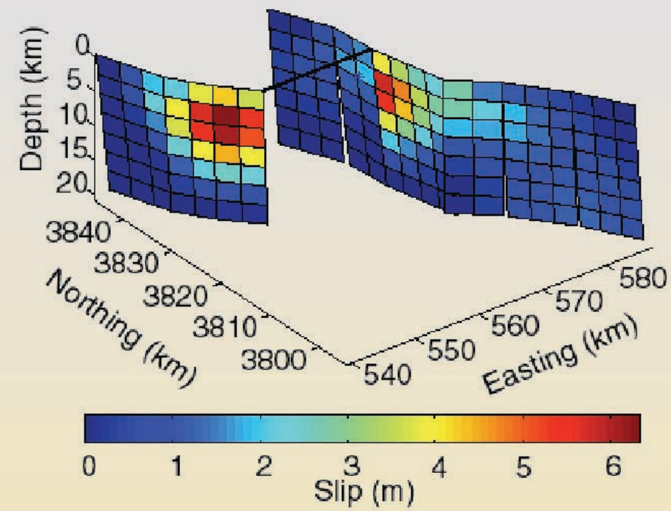


$$u(x,t) = \frac{\alpha(1-2\nu)}{2\mu\pi(1-\nu)} \int_{dv} \Delta p(v,t)\ g(x,v)\ dv$$

Hector Mine earthquake and fault slip solution

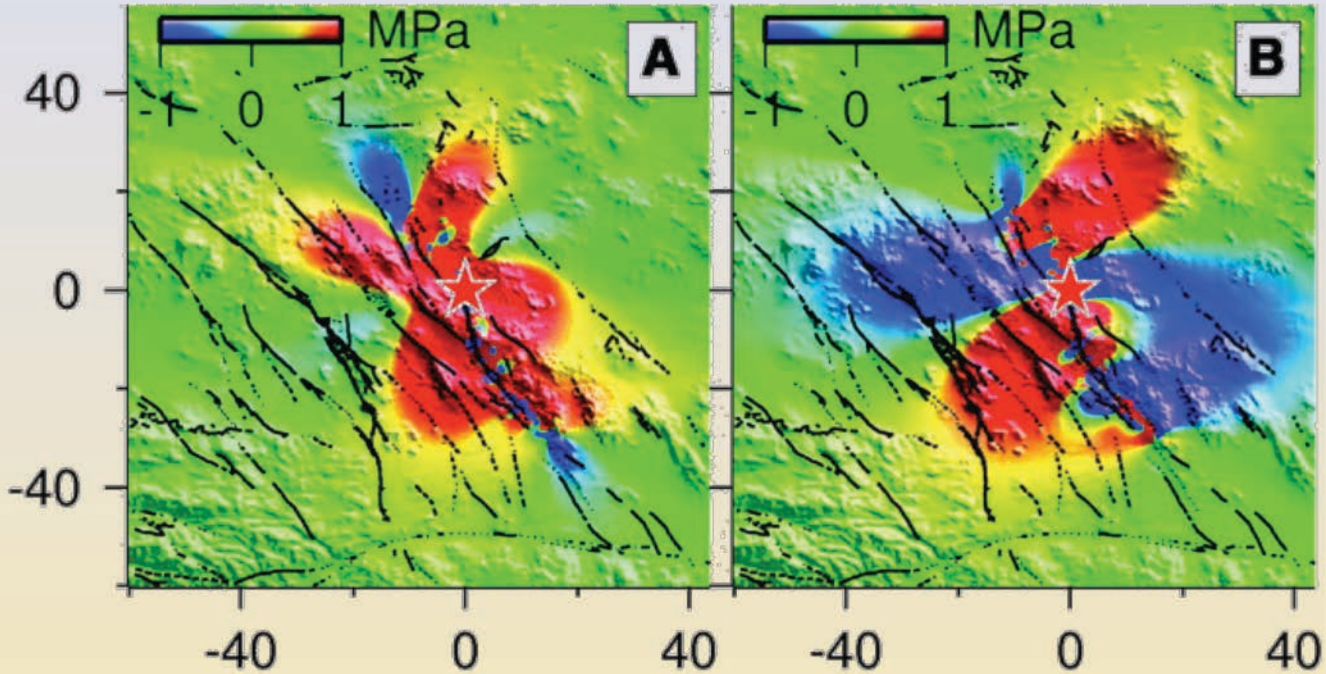






Inference of stress change
Hector Mine Earthquake

Fialko et al., 2002

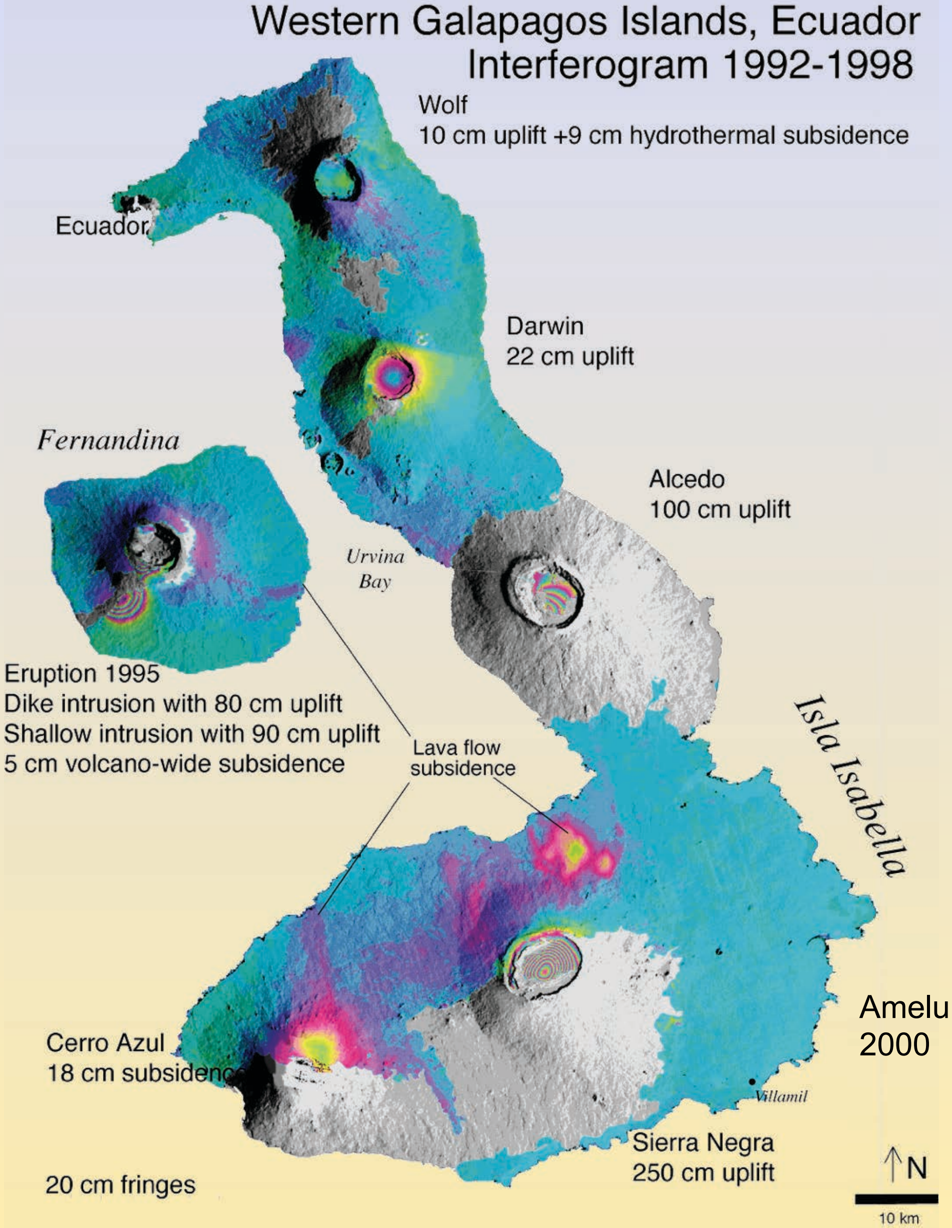


Static shear stress change   Static normal stress change

Volcanic deformation

Some volcanic regions, such as Galapagos islands, are extraordinarily active

How do widespread volcanoes communicate?



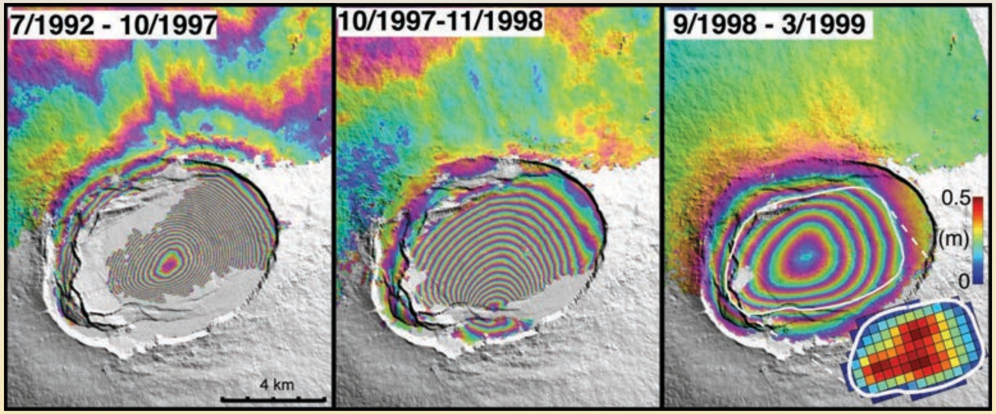
Amelung et al., 2000

Volcanic deformation

Multiple deformation processes occur simultaneously

Sierra Negra

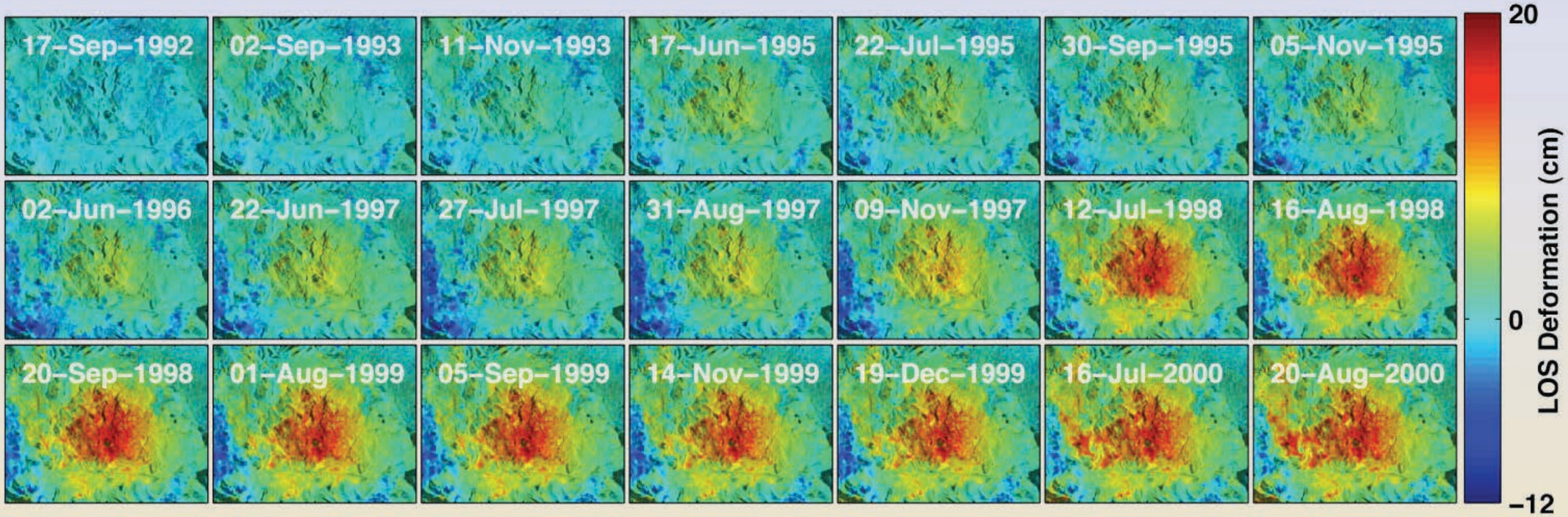
- Continuous inflation from an oblong sill
- Trap-door faulting occurs episodically

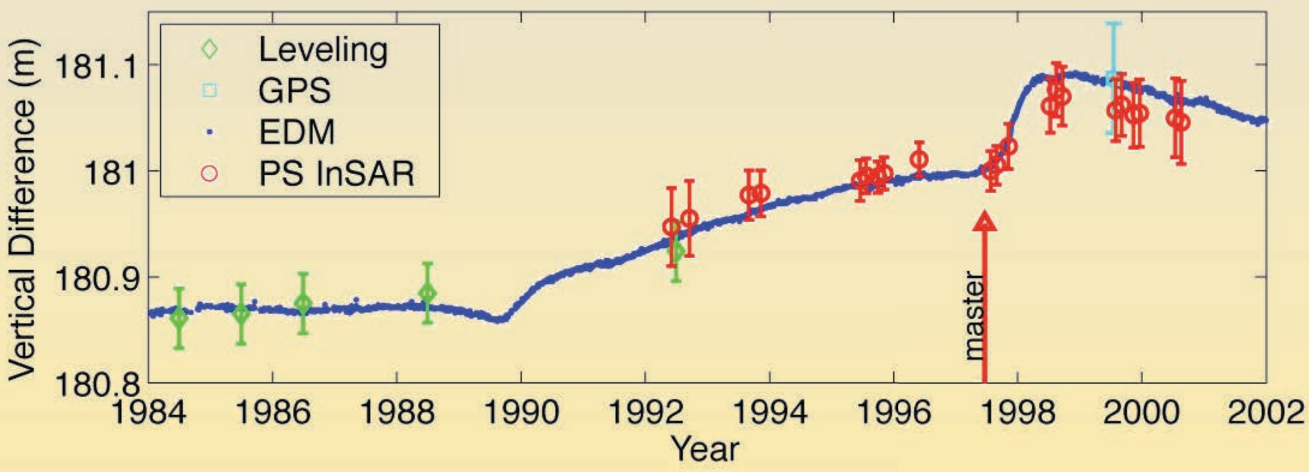


Jonsson et al., 2005

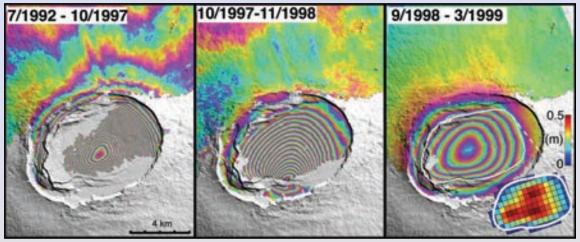
Time series resolves temporal deformation

Long Valley Caldera



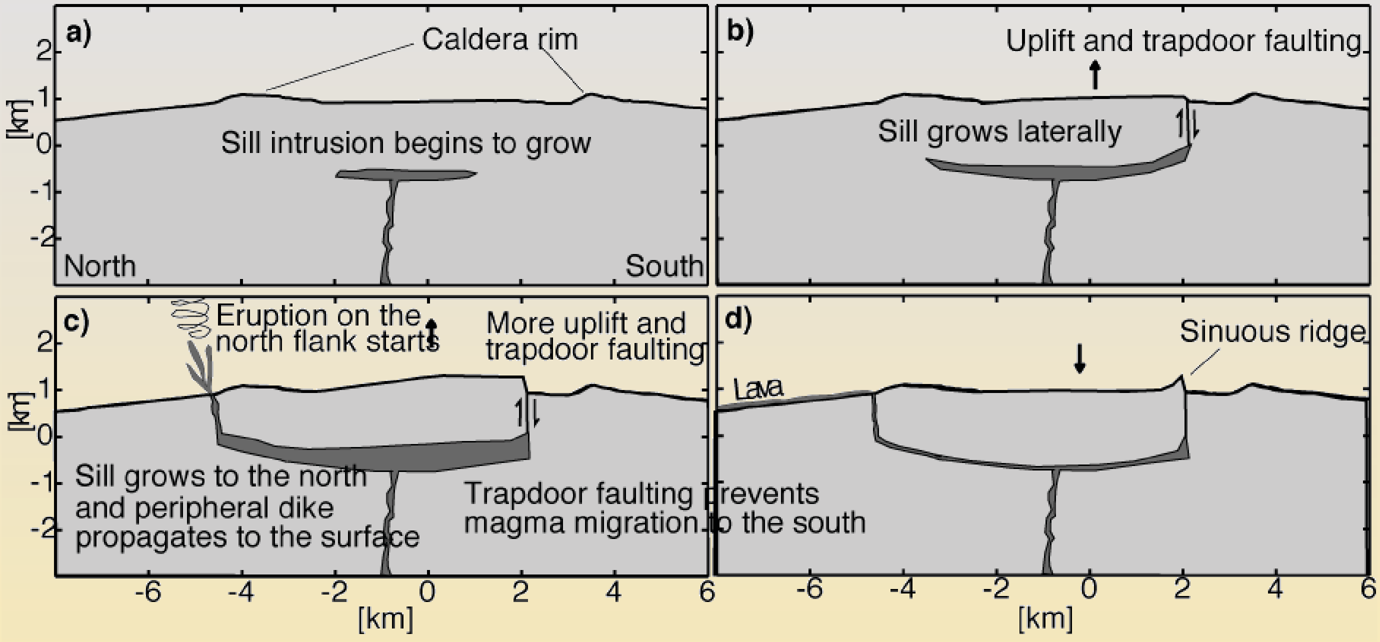


Volcanic mechanical modeling



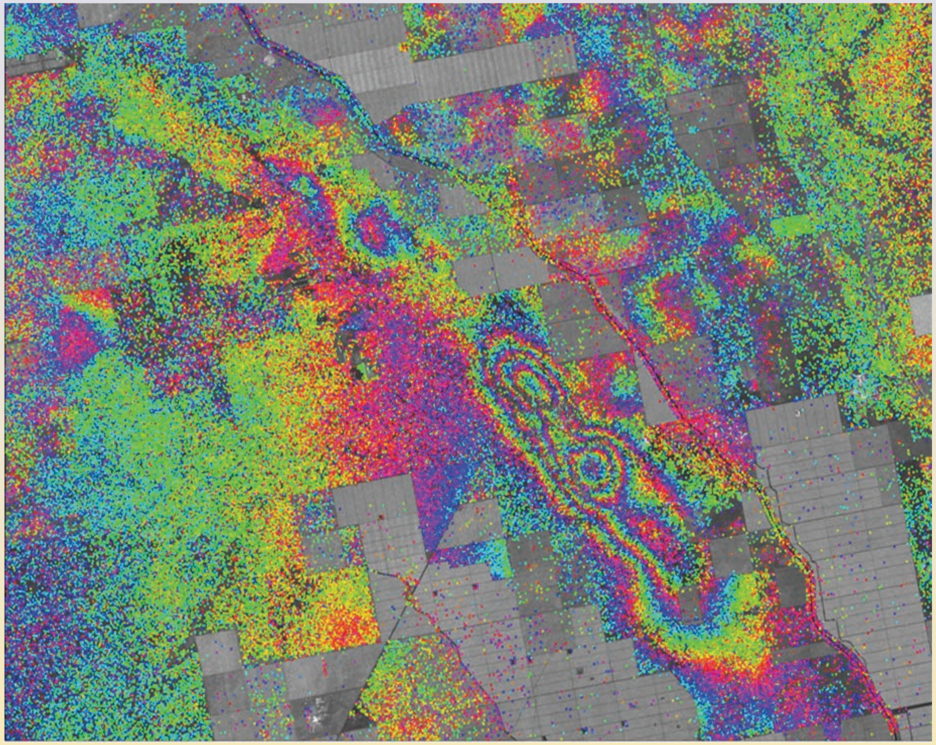
Space measurements

Jonsson et al., 2005

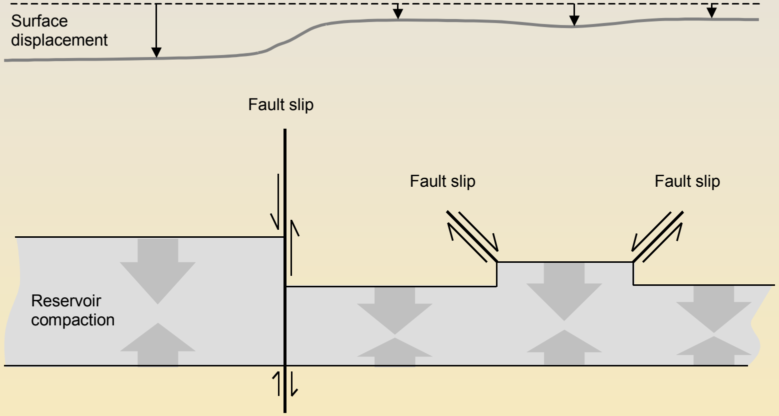


Mechanical model - Sierra Negra

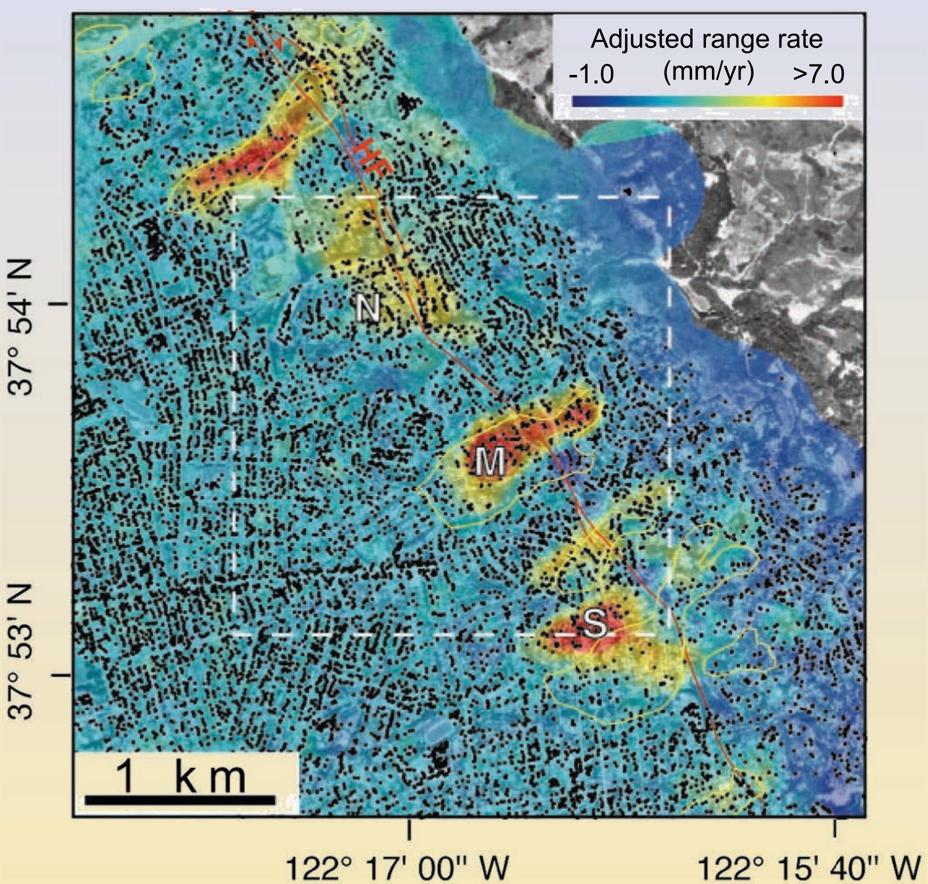
Energy resource management



Subsidence from petroleum extraction – Lost Hills, CA



Landsliding in Berkeley Hills, CA

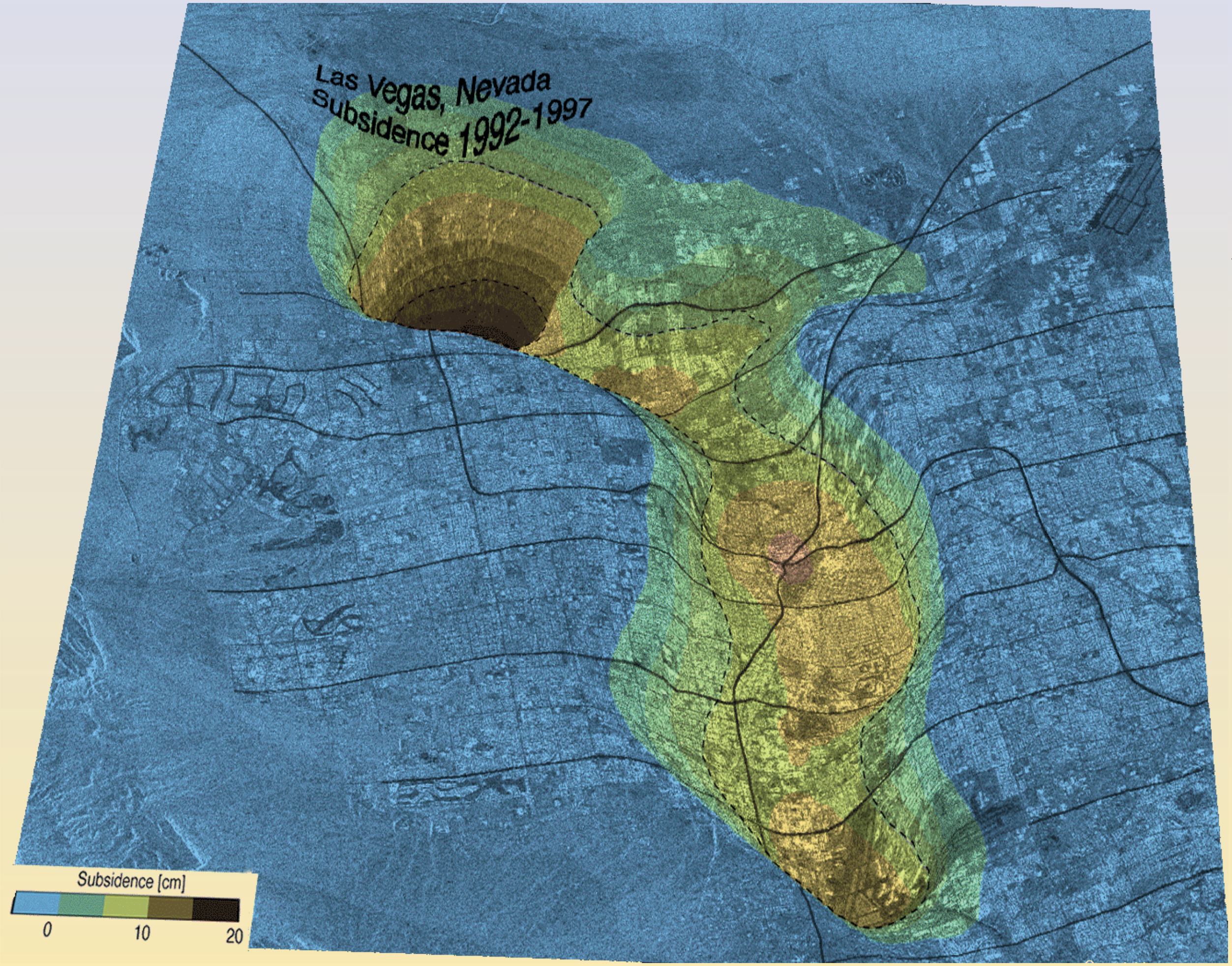


Landslides appear clearly in InSAR maps

Rates increase in years with greater precipitation

Can be mapped by small (<1 mm) motions

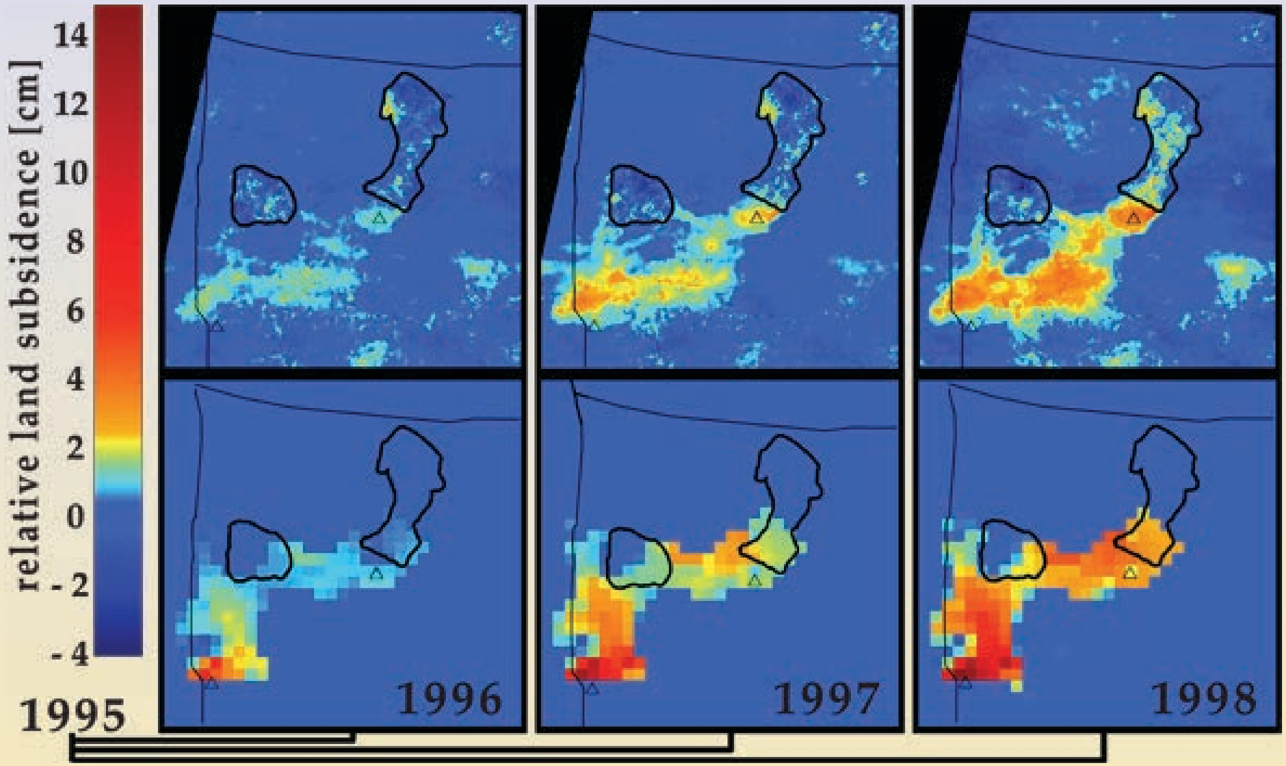
Groundwater management



Subsidence in Las Vegas Valley, 1992-97

Falk Amelung

Groundwater modeling



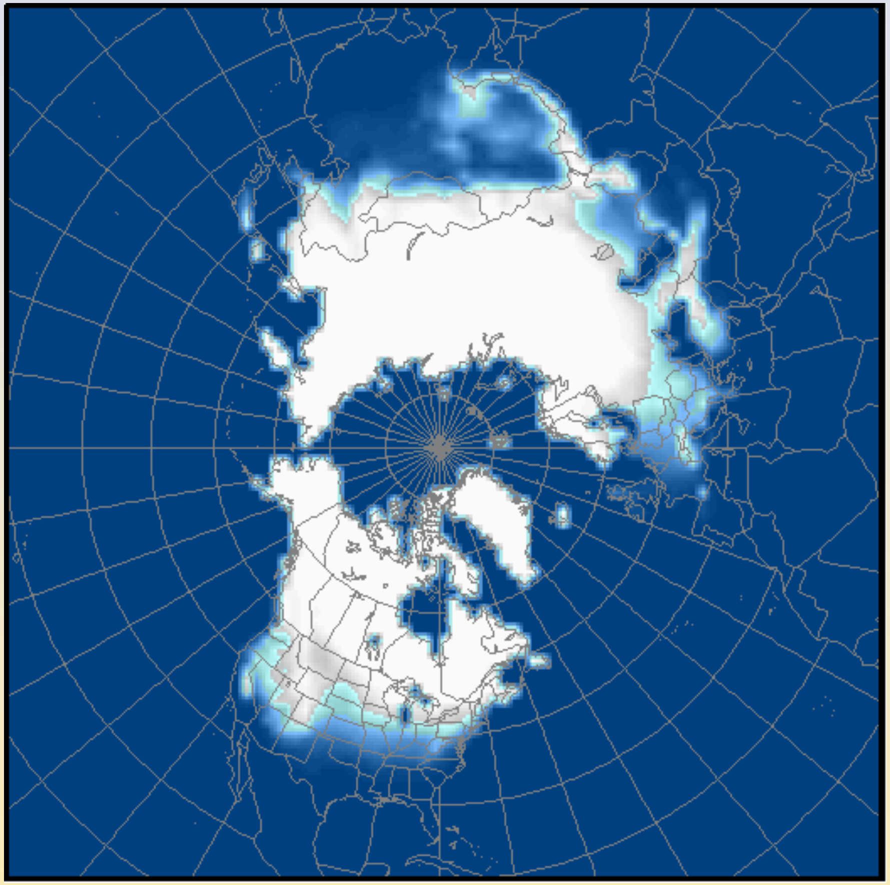
Hoffmann et al., 2003

Aquifer storage extent, Antelope Valley, 1995-98

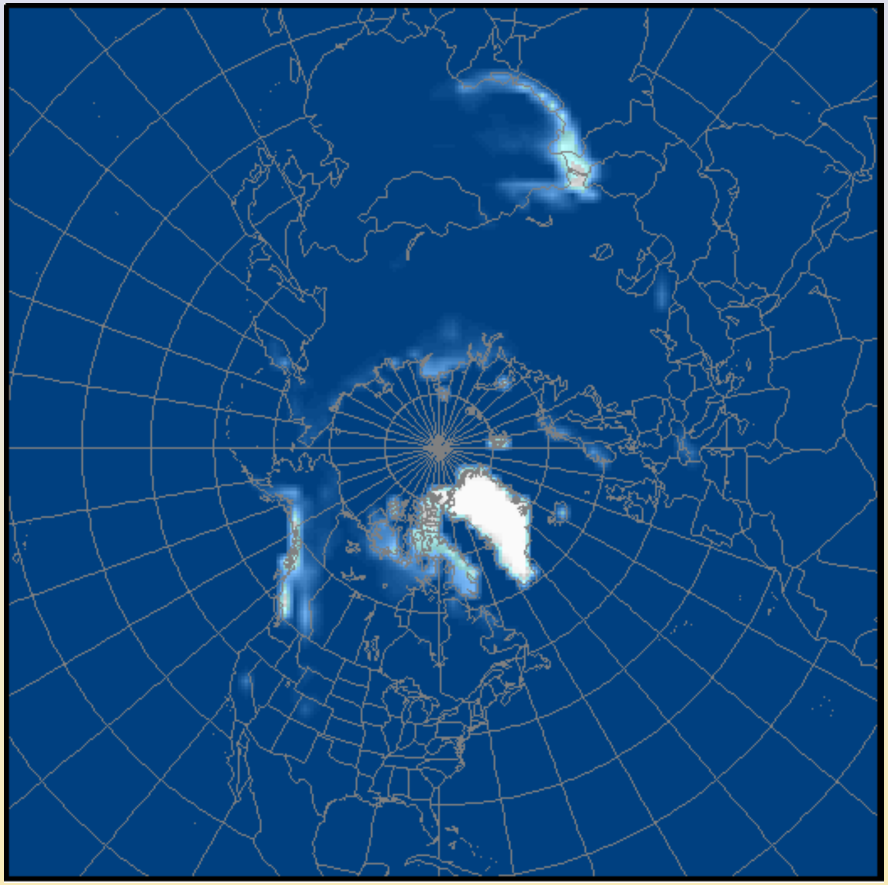
By Peter Shuger / courtesy USACE

Sea Level Rise: a Serious Problem if Global Ice Sheets Melt

January



July



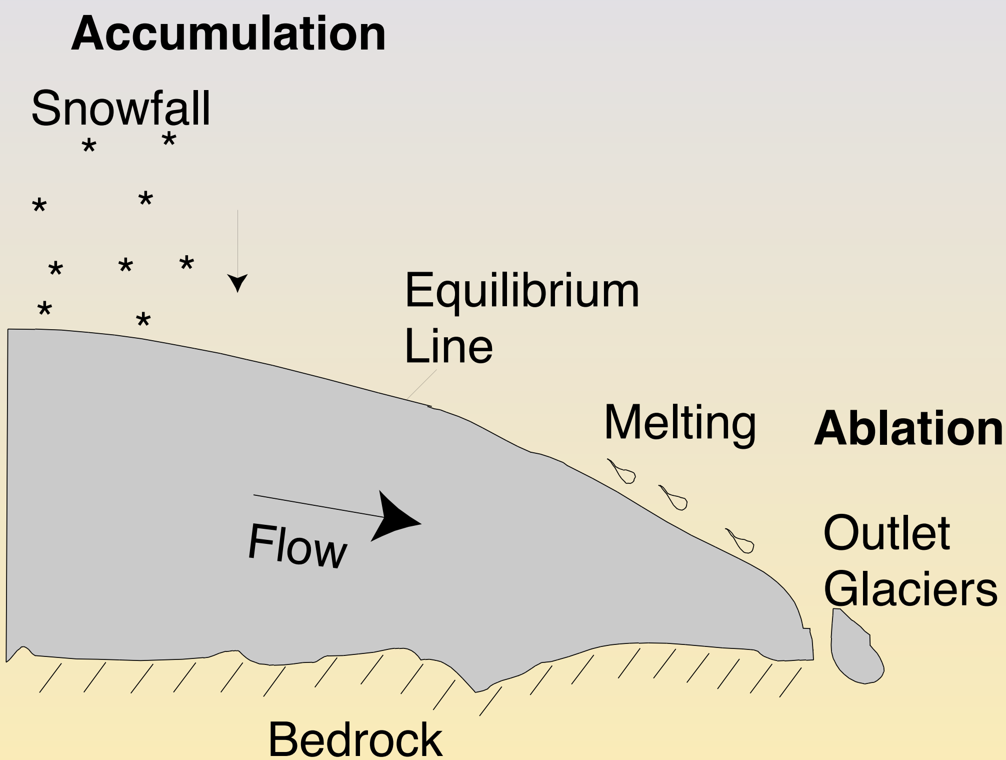
Global View of Dynamic Ice Motion and Mass Balance

Glacial retreat marks worldwide climate change

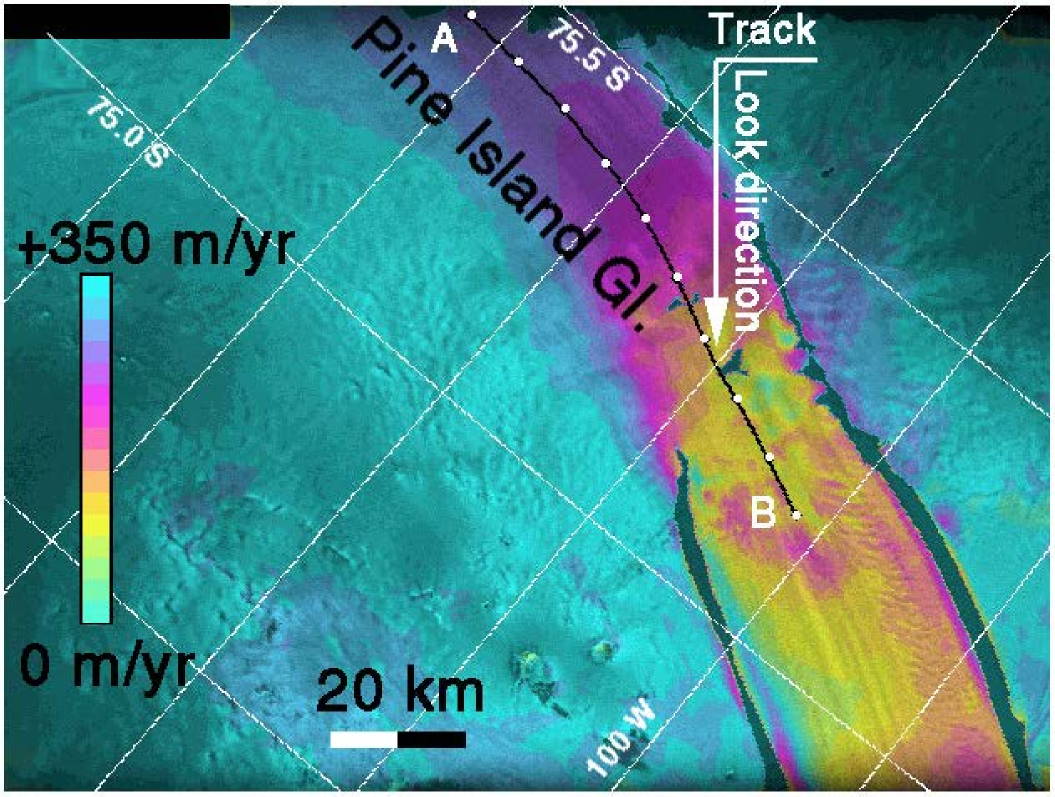
Portage Glacier, Alaska

Mass balance

Physical processes driving mass balance



Climate change and the polar regions



Rignot, 2001

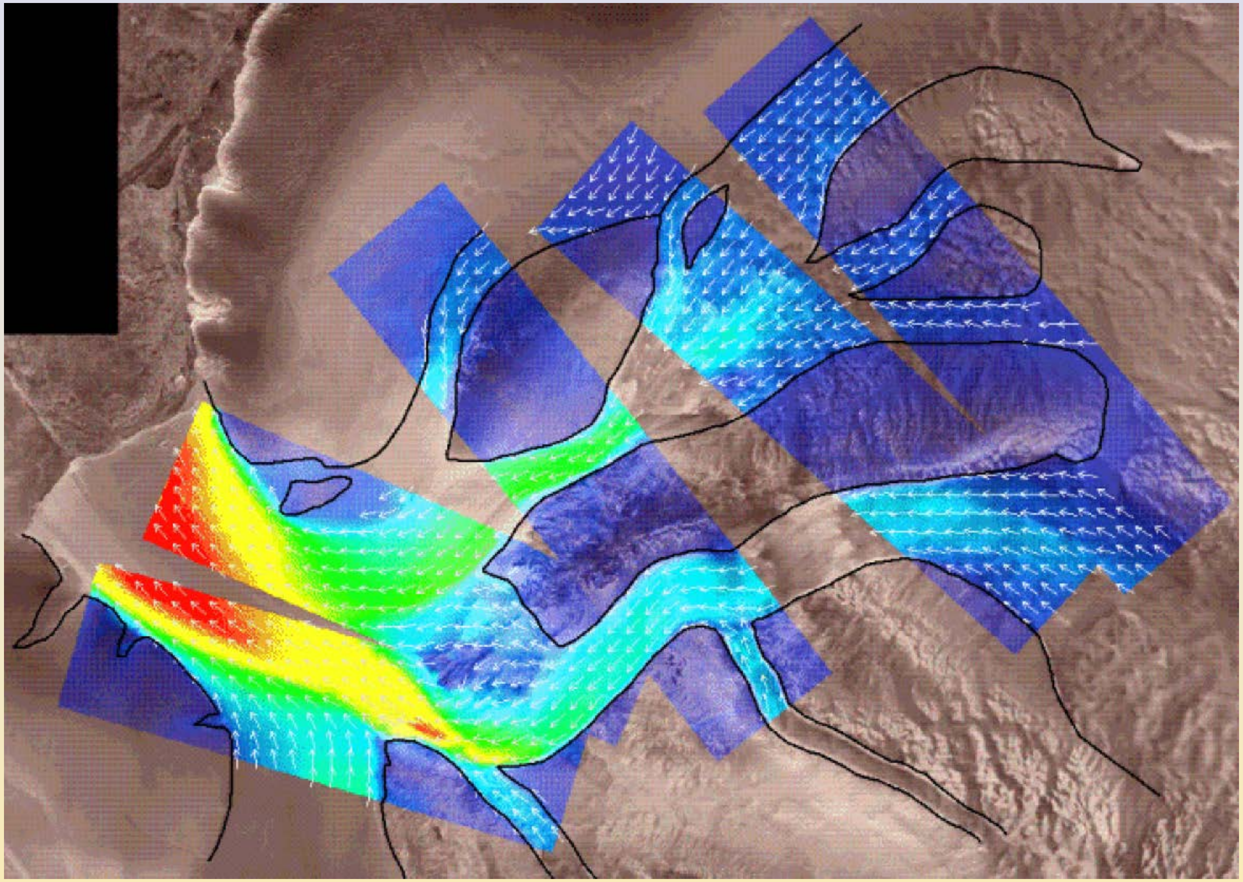
Ice velocity mapping -
Pine Island Glacier

InSAR Observations of Ice Flow

Ice Streams in Antarctica

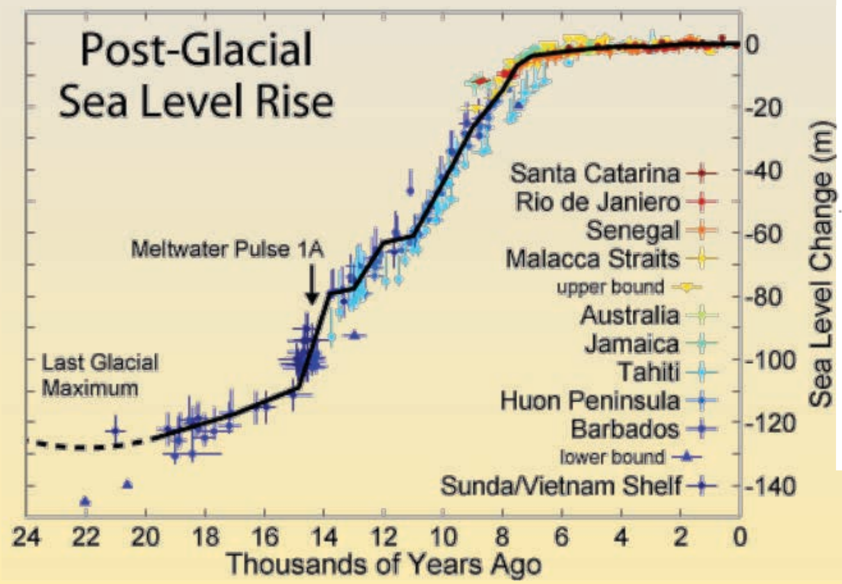
Blue
<10 m/yr

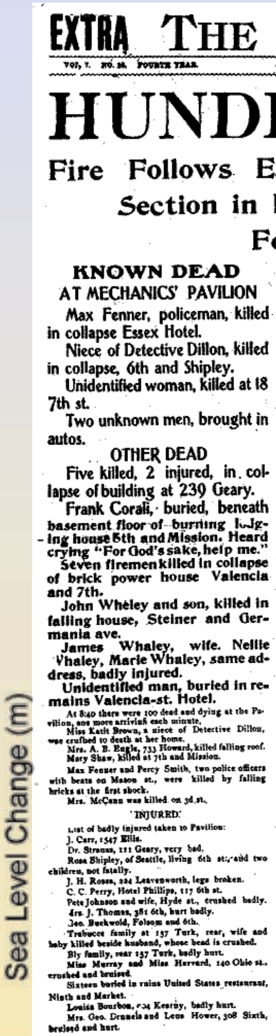
Red
>1000 m/yr



Natural hazards and global change

- Seismic cycle
- Volcanoes
- Climate change
  - Ocean circulation
  - Atmospheric circulation
  - Distribution of glaciation
- Sustainability





EXTRA THE DAILY NEWS EXTRA

HUNDREDS DEAD!

Fire Follows Earthquake, Laying Downtown Section in Ruins--City Seems Doomed For Lack of Water

KNOWN DEAD
AT MECHANICS' PAVILION

Max Fenner, policeman, killed in collapse Essex Hotel.

Niece of Detective Dillon, killed in collapse, 6th and Shipley.

Unidentified woman, killed at 18 7th st.

Two unknown men, brought in autos.

OTHER DEAD

Five killed, 2 injured, in collapse of building at 239 Geary.

Frank Corali, buried, beneath basement floor of burning lodging house 5th and Mission. Heard crying "For God's sake, help me."

Seven firemen killed in collapse of brick power house Valencia and 7th.

John Wheley and son, killed in falling house, Steiner and Germania ave.

James Whaley, wife. Nellie Whaley, Marie Whaley, same address, badly injured.

Unidentified man, buried in remains Valencia-st. Hotel.

At 8:40 there were 100 dead and dying at the Pavilion, one more arriving each minute.

Miss Katie Brown, a niece of Detective Dillon, was crushed to death at her home.

Mrs. A. B. Engle, 733 Howard, killed falling roof.

Mary Shaw, killed at 7th and Mission.

Max Fenner and Percy Smith, two police officers with beats on Mason st., were killed by falling bricks at the first shock.

Mrs. McCann was killed on 3d st.

INJURED.

List of badly injured taken to Pavilion:

J. Carr, 1547 Ellis.

Dr. Strauss, 111 Geary, very bad.

Rosa Shipley, of Seattle, living 6th st., and two children, not fatally.

J. H. Ross, 224 Leavenworth, legs broken.

C. C. Perry, Hotel Phillips, 117 6th st.

Pete Johnson and wife, Hyde st., crushed badly.

Mrs. J. Thomas, 381 6th, hurt badly.

Geo. Buckwold, Folsom and 6th.

Trabucce family at 157 Turk, rear, wife and baby killed beside husband, whose head is crushed.

Bly family, rear 157 Turk, badly hurt.

Miss Murray and Miss Harvard, 140 Ohio st., crushed and bruised.

Sixteen buried in ruins United States restaurant, Ninth and Market.

Louisa Bourbon, 524 Kearny, badly hurt.

Mrs. Geo. Drunels and Lena Hower, 308 Sixth, bruised and hurt.