Tectonic geomorphology and paleoseismology

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Outline:

1. Definition of active tectonics, tectonic processes and their types related to different tectonic regimes

2. Landforms characteristic for different types of tectonic movements (horizontal or vertical)

3. Tectonic geomorphology, tectonic control on landscape evolution

4. Response of tectonic processes in fluvial systems, asymmetry of river basins, related increased erosion and accumulation, river pattern analysis

5. Analyses of fluvial landforms affected by tectonic movements – river terraces, alluvial fans, analysis of longitudinal river profile and valley cross sections

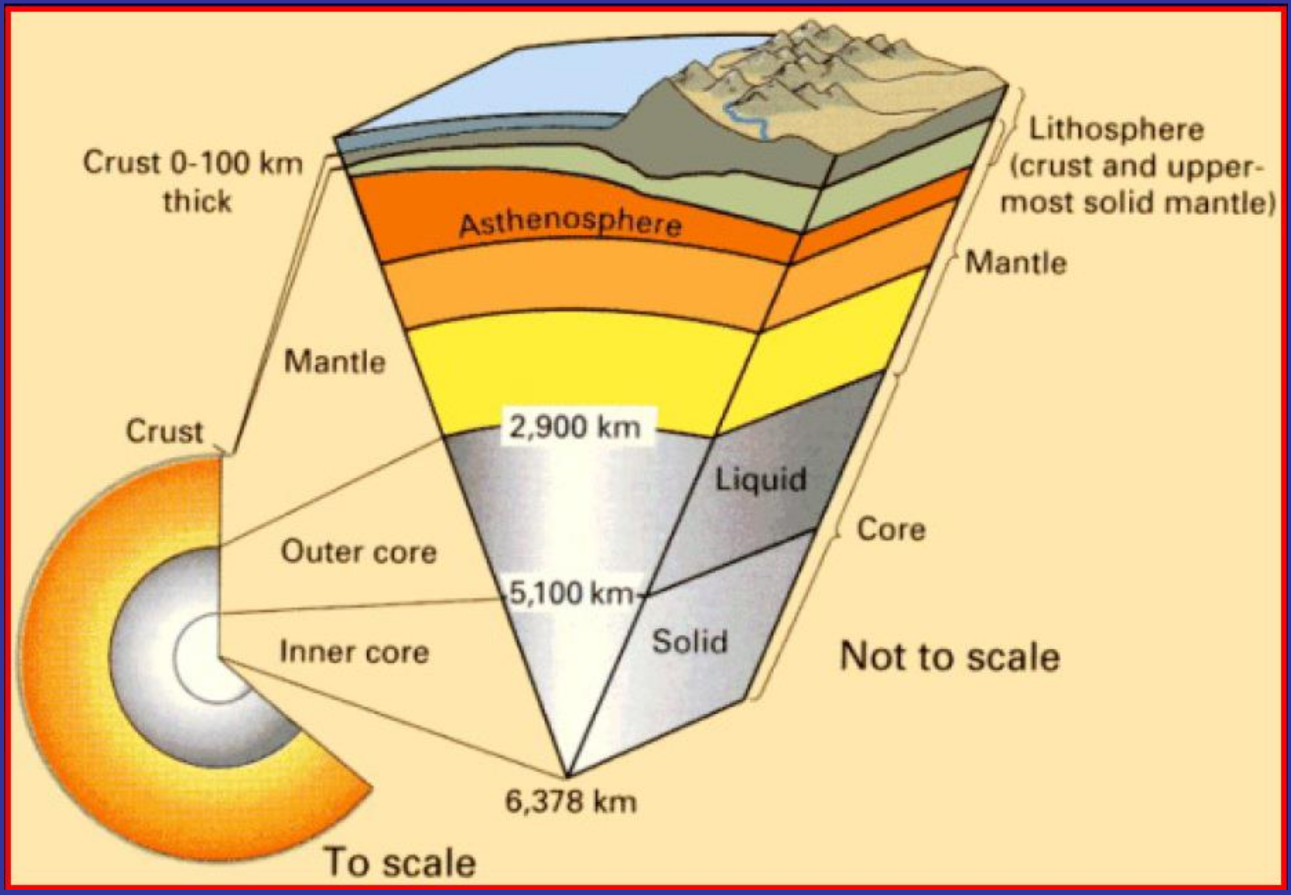
6. Fault scarps, their evolution, erosion

7. Paleoseismology, study of prehistoric earthquakes from geological record, reconstruction of movements

8. Study of paleoseismic parameters of active faults, intensity of movements, average slip rate, spatio-temporal distribution within the fault

Active tectonics, tectonic processes and their types resulting from different tectonic regimes

Tectonics – endogenous processes, structures and landforms associated with Earth´s crust deformation (movements of lithospheric plates)



Lithosphere = solid shell of the Earth (up to 100 km)

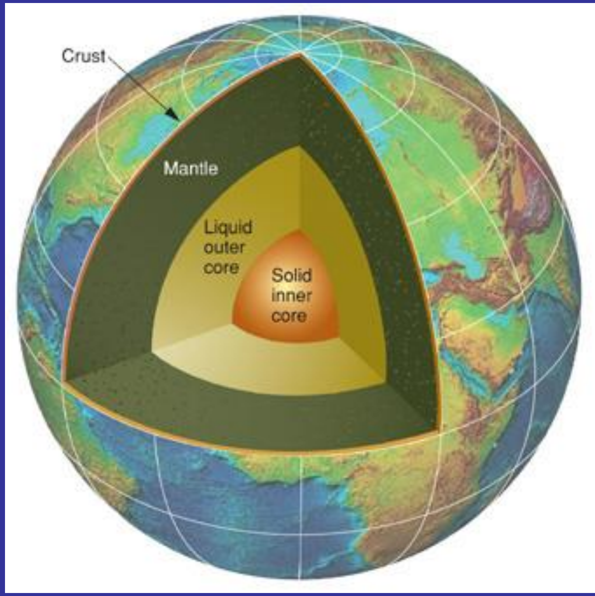
Earth´s crust + uppermost solid mantle

continental crust (30-80km), density 2.7 g/cm^3

Sedimentary, granitic, basaltic layer

oceanic crust (5-10km), density 2.9 g/cm^3

Sedimentary, basaltic layer



direct observations – drills, geologic information (xenolites)

Mohorovičič discontinuity – crust/mantle – density change, higher velocity P-waves

Lithosphere / asthenosphere (semifluid) 3.6 g/cm^3, lower viscosity – below lithospheric plates

– velocity of seismic waves

Seismogenic crust!

Global scale tectonics: origin of continents and ocean basins

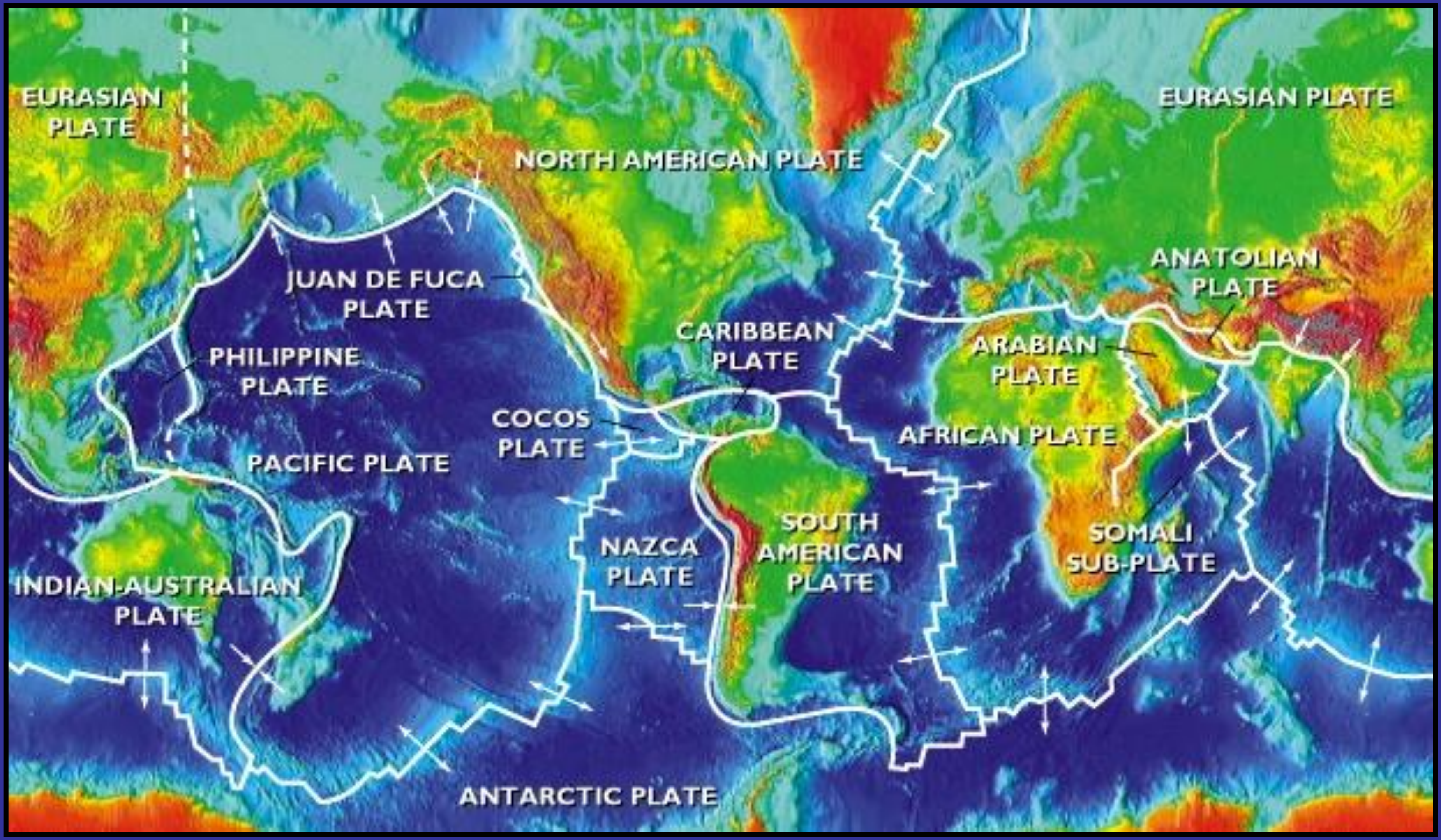
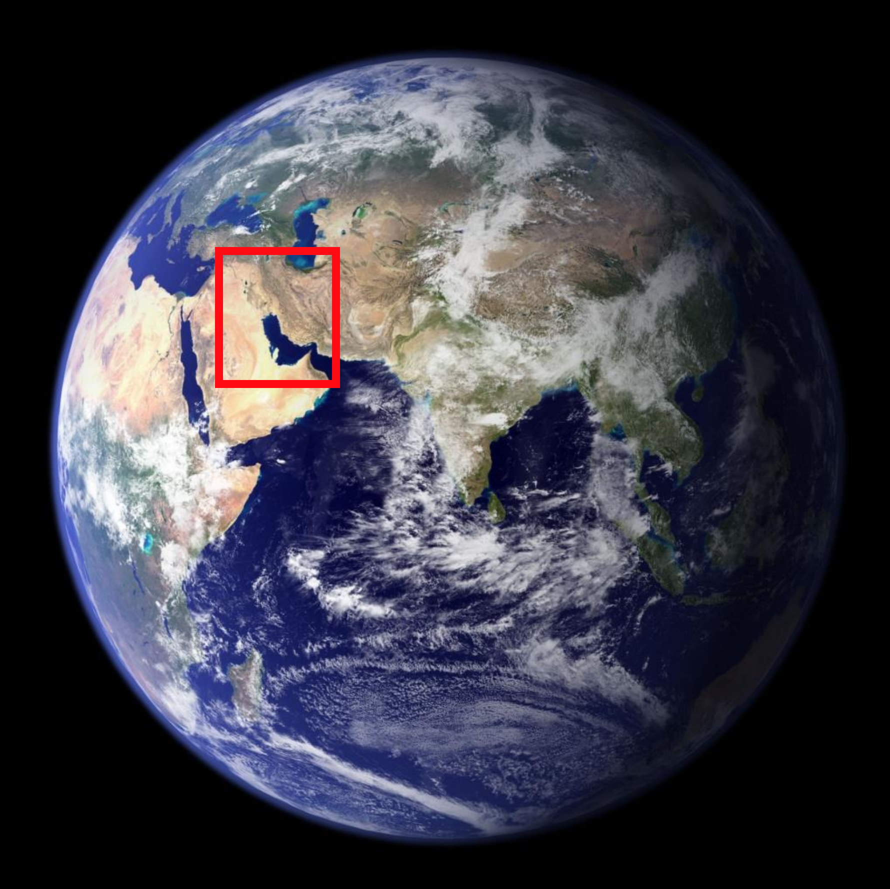


Plate tectonics

Global Neotectonics



10^7 m

10,000 km

Scale 1:100,000,000

Satellite images

microplates

Regional Neotectonics

10^6 m

1000 km

Scale 1:10,000,000

mountain chains

Active Tectonics
Tectonic Geomorphology

10^5 m

100 km

Scale 1:1.000,000

10^4 m

10 km

Scale 1:100,000

10^3 m

1 km

Scale 1:10,000

Local scale: individual landforms such as folds, fault scarps, small hills etc.

satellite images

Structural Geology
Petrology

10^1 m

10 m

Scale 1:100

offset channels

10^0 m

1 m

Scale 1:10

tectonic breccia

10^{-1} m

10 cm

Scale 1:1

outcrop/ hand sample

Time scales of tectonics:

depend on ***spatial scale*** at which the processes act:

Development of continents - thousands of millions years

Large ocean basins - hundreds of millions years

Small mountain ranges - several millions years

Small folds to produce hills - several hundred thousands years

Fault scarps - suddenly during earthquake

***Neotectonics* -** crustal movements starting after the youngest orogenic phase or related to the youngest stress field occurring in the late Neogene and Quaternary

***Active tectonics* –** tectonic processes that caused deformation of

the Earth´s crust of local scale and on a time scale

significant for humans (earthquakes)

Active faults – have moved during last 10.000 yrs – Holocene

(paleoseismology)

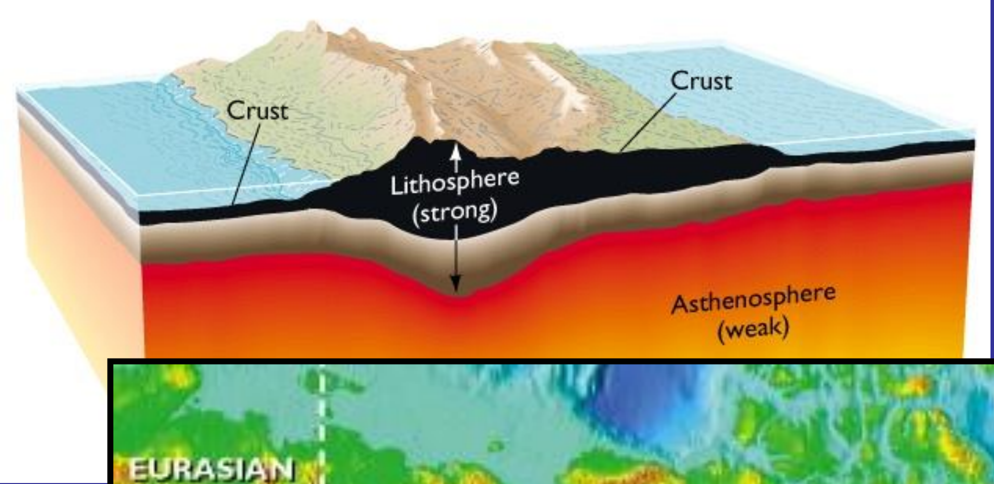
Potentially active faults (capable faults) – have moved during Quaternary

(2.6 million yrs)

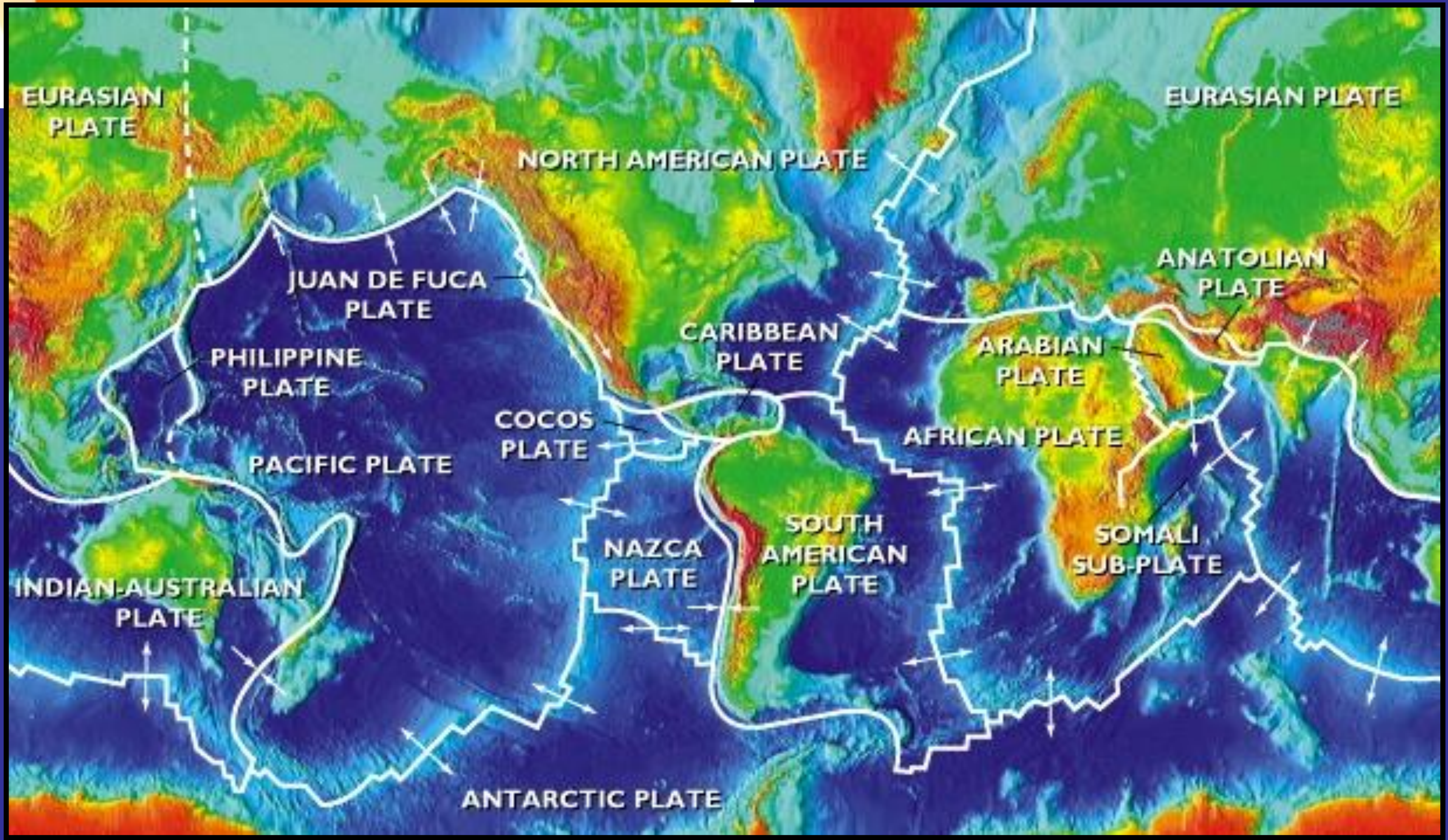
Rates of tectonic processes:

Very variable – 0.00X-X mm/year for fault displacement

X cm/year for movement on plate boundaries



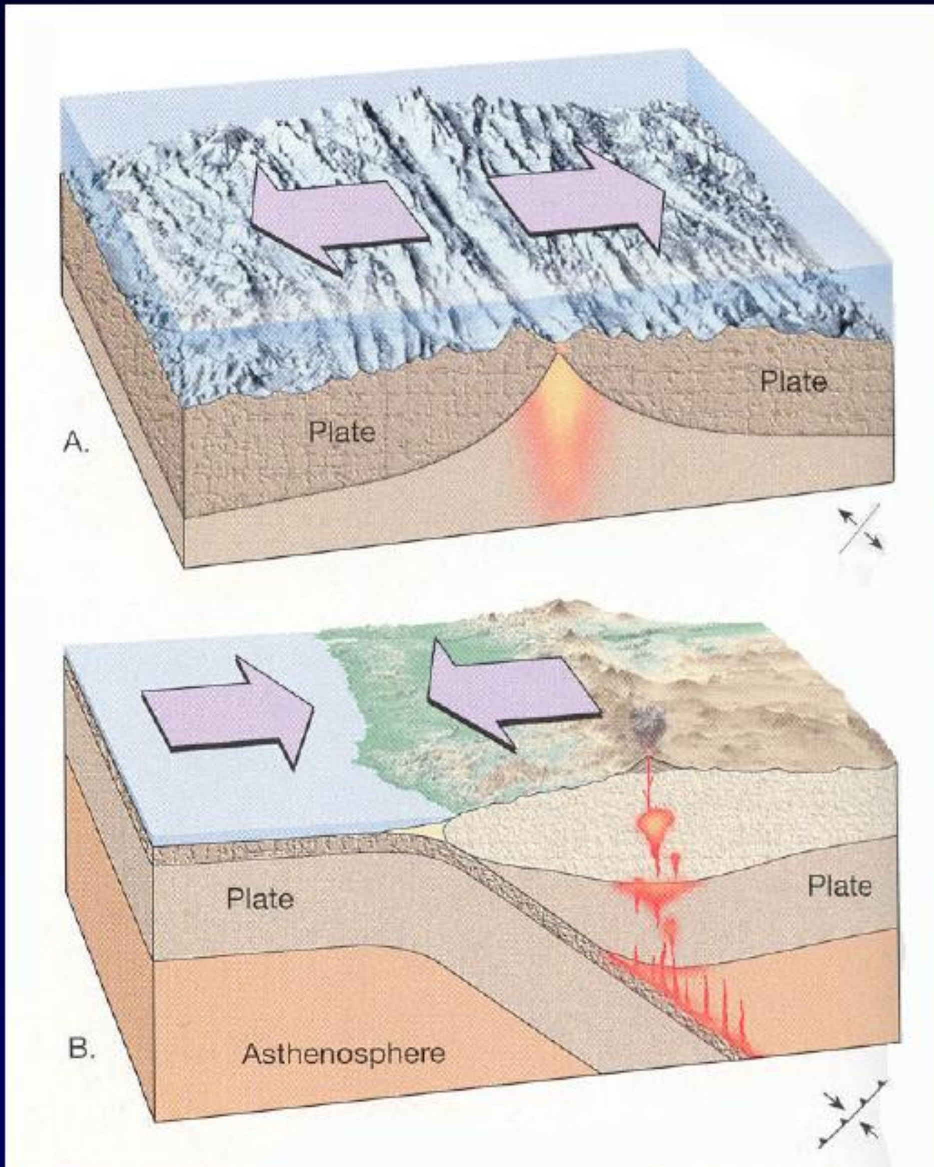
Tectonic processes - driven by forces in the depth that deform the crust => origin of ocean basins, continents, mountains



Litosphere broken into plates - relatively move; triple junction

Plate Boundaries

A. Divergent boundaries
B. Convergent boundaries
C. Transform boundaries



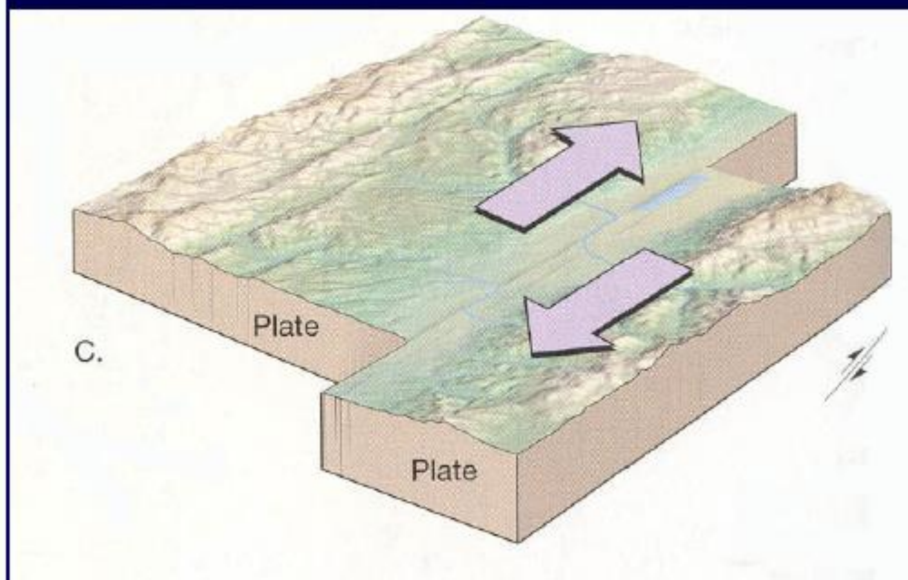
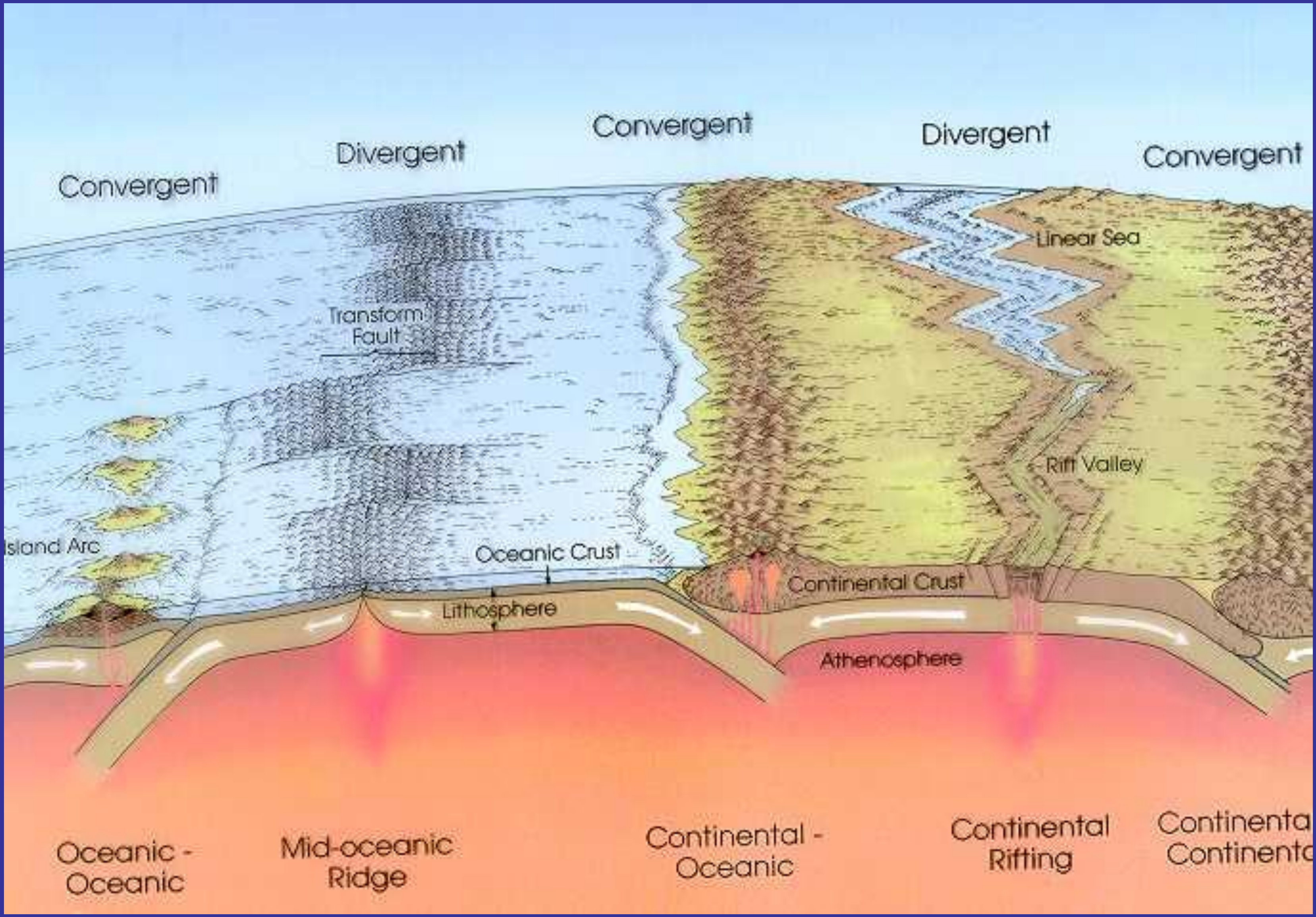


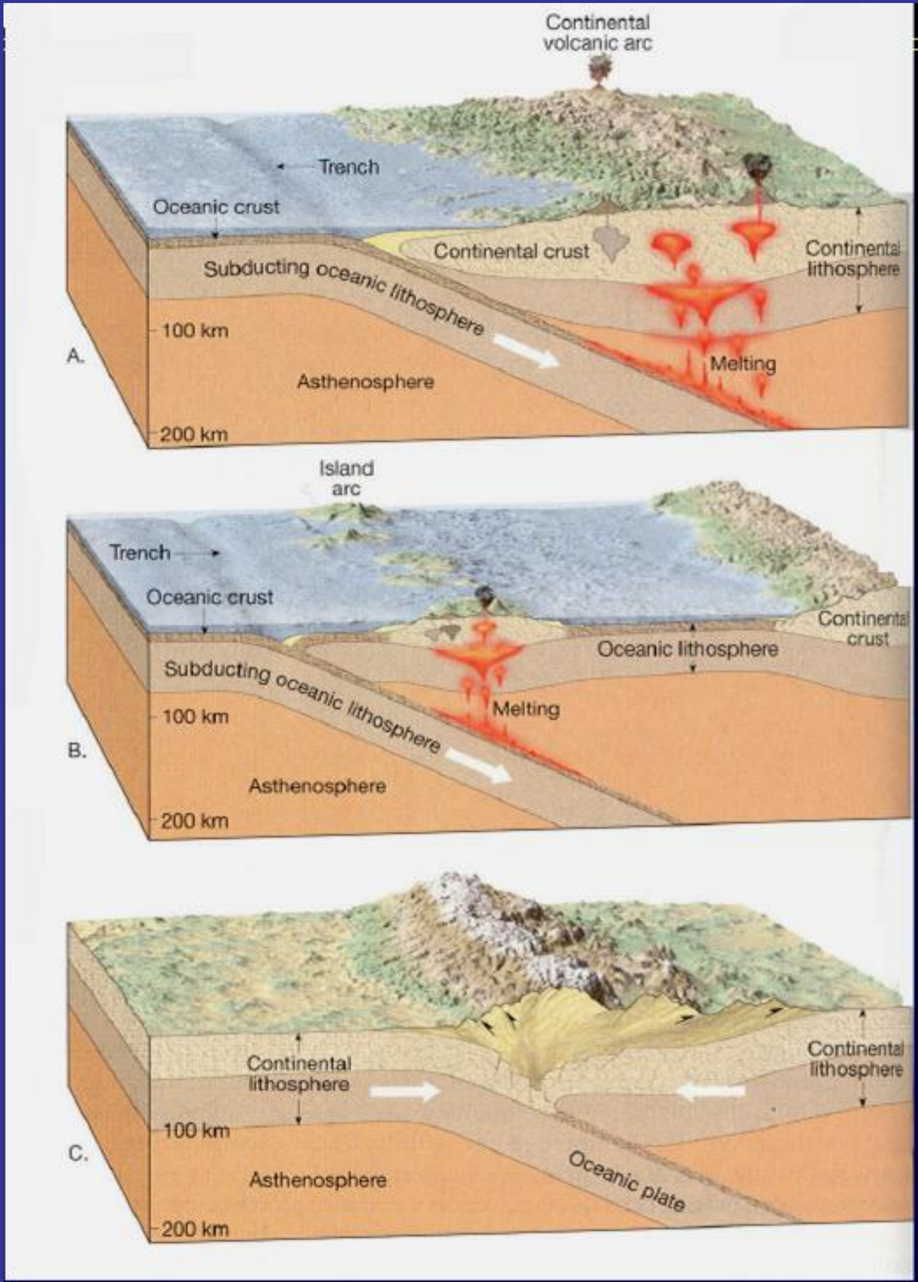
Figure 7.9 The three types of plate boundaries. **A.** Divergent boundary. **B.** Convergent boundary. **C.** Transform fault boundary.

divergent – extension (spreading), convergent – shortening (subduction) video!

Tectonic cycle



Video! Transform faults



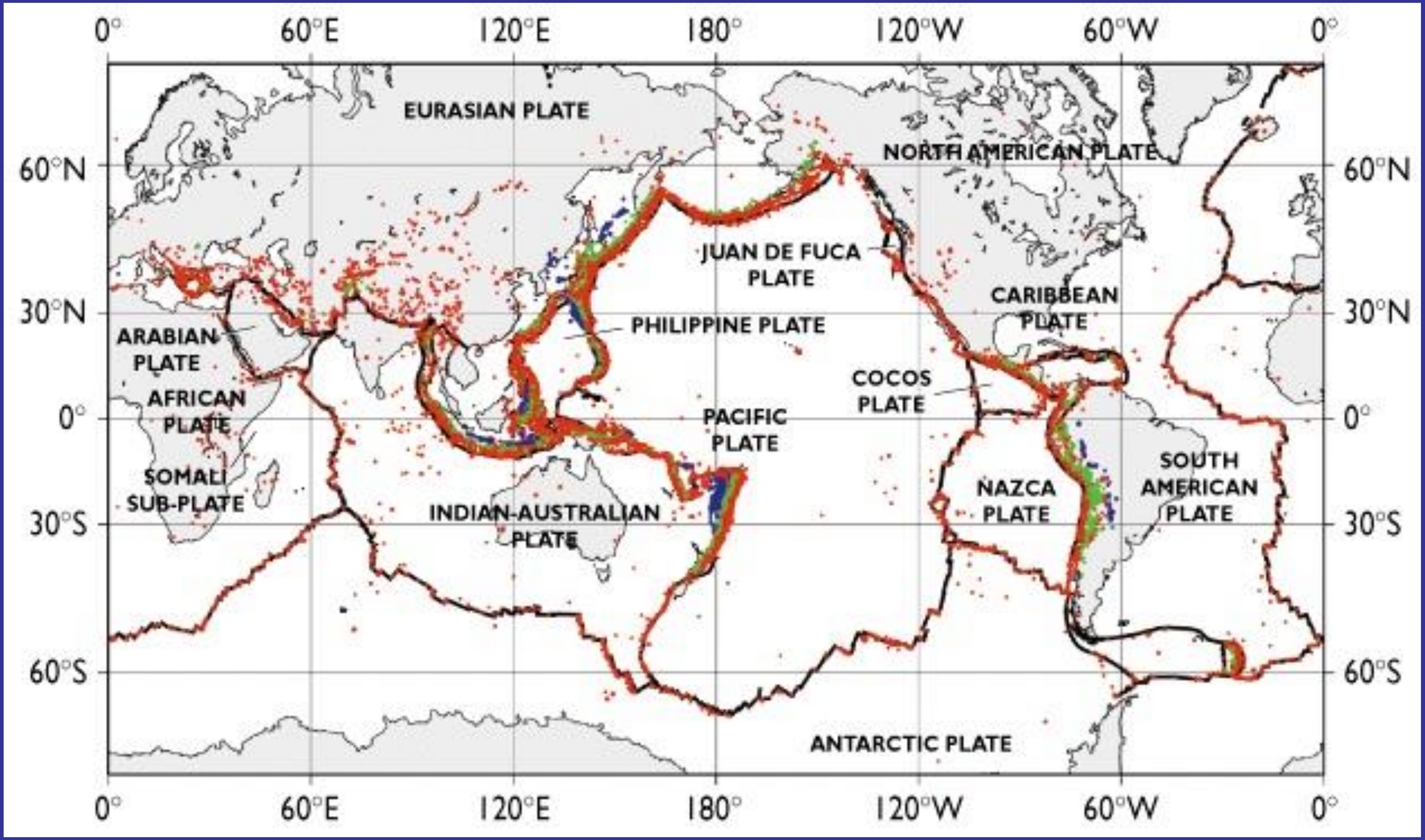
Three types of convergent Plate boundaries :

A. Oceanic-continental
B. Oceanic-oceanic
C. Continental-continental

Video!

Summary video

Active Tectonics: confirmation of plate tectonics…



- Earthquakes
- Volcanoes
- Faults

- Topography
- Surface deformation

World Seismicity, 1963–2000
video

Tectonic movements

- Producing new lithosphere in ocean ridges, subduction of old one and plates sliding along each other – produce stress (force per unit area) and strain (deformation – change in length, volume).

- Seismic movements

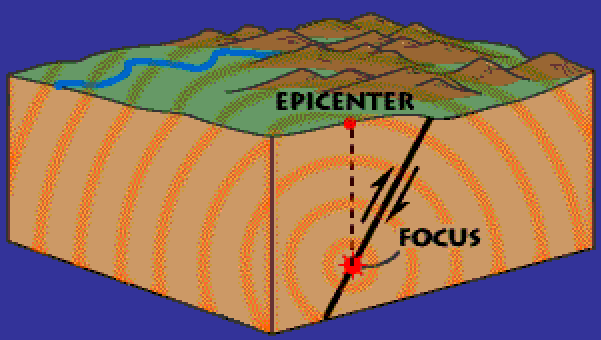
  - accompanied by earthquakes

- Aseismic movements (tectonic creep)

  - more or less continuous movements with minimal seismicity, confined to narrow zone

Seismic tectonic movements

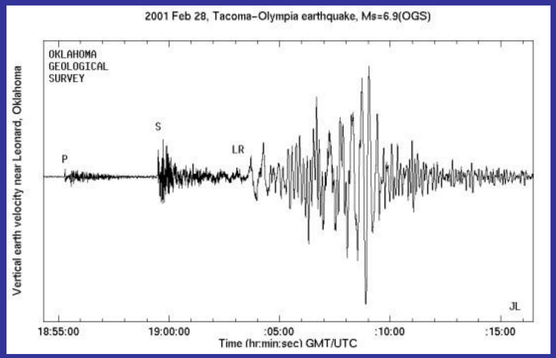
When the stress exceeds the strength of rocks, then rocks fail (rupture), energy is released in a form of an earthquake (elastic seismic waves) and faulting (breaking the rocks, rock deformation).

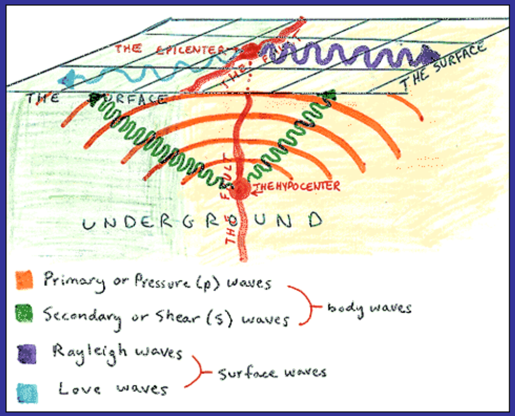


Foreshocks – low intensity

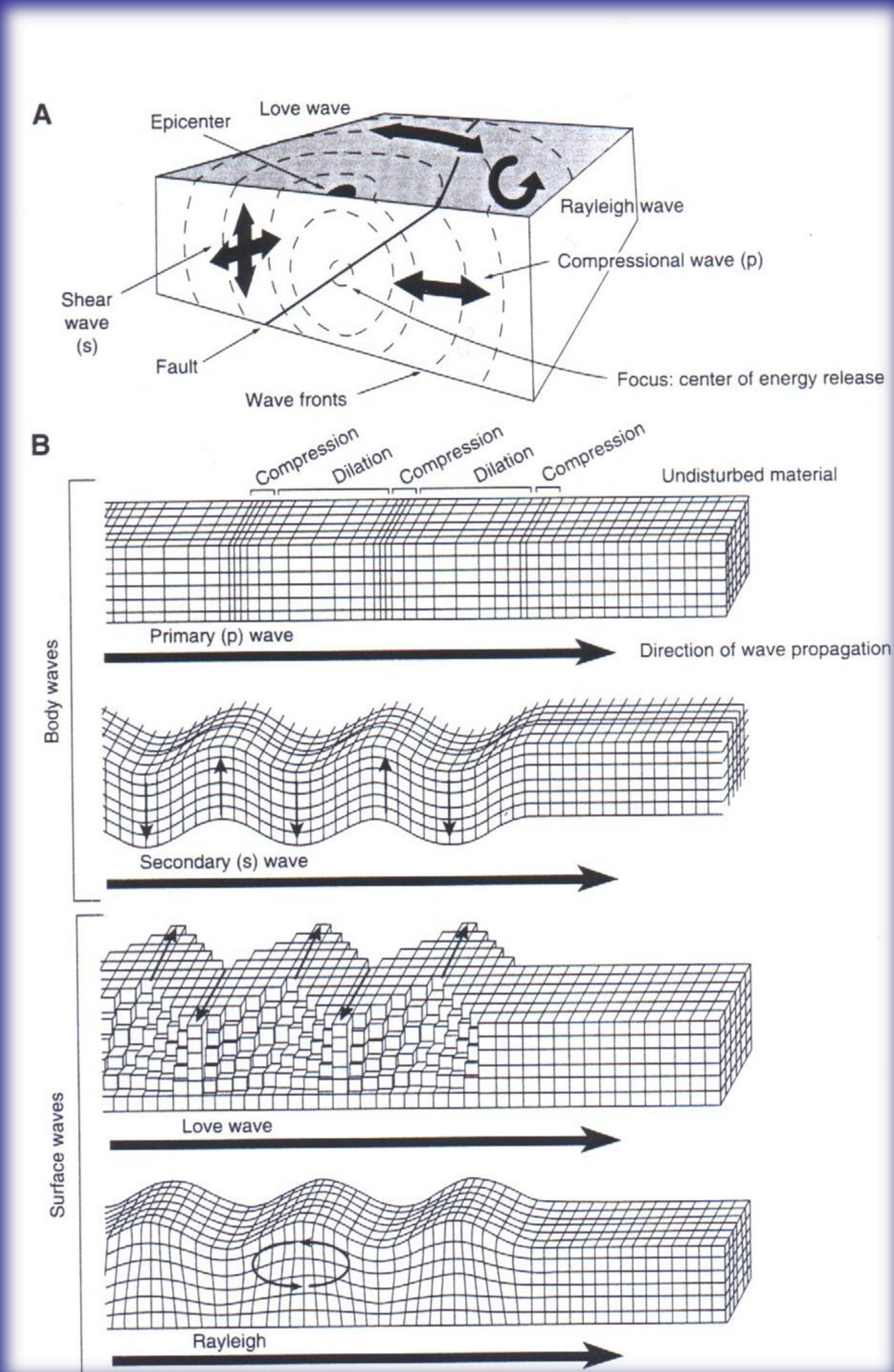
Main shock – tens of seconds to minutes with maximum intensity

Aftershocks – several months with decreasing effects



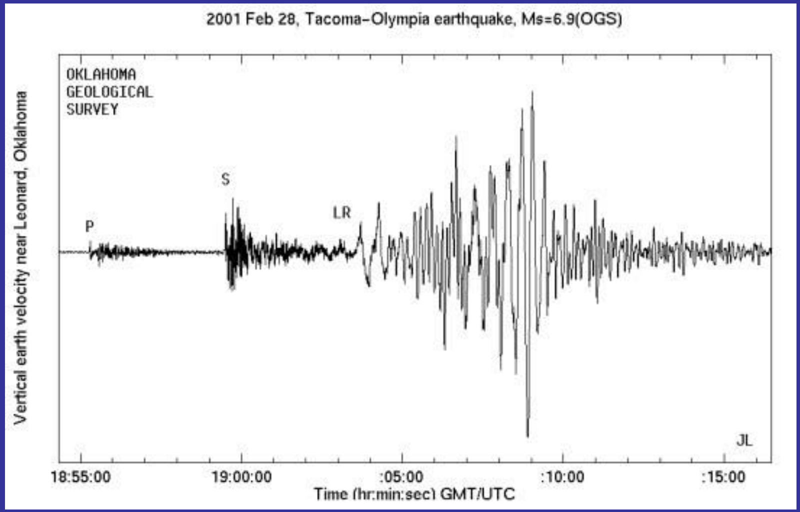


seismograph

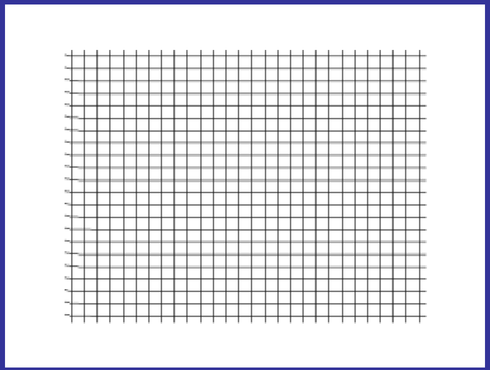


Body waves:
P-waves (primary)
S-waves (secondary, shear waves)
Surface waves – combined –
Love, Rayleigh waves

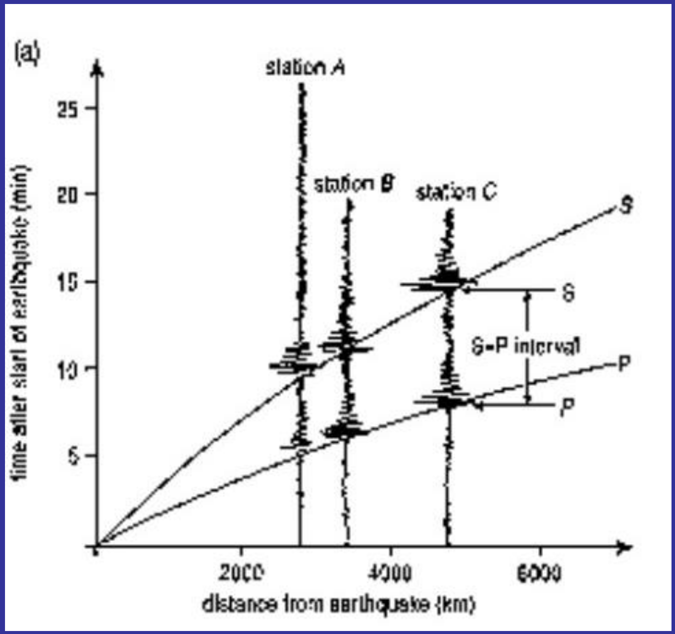
Epicentre location

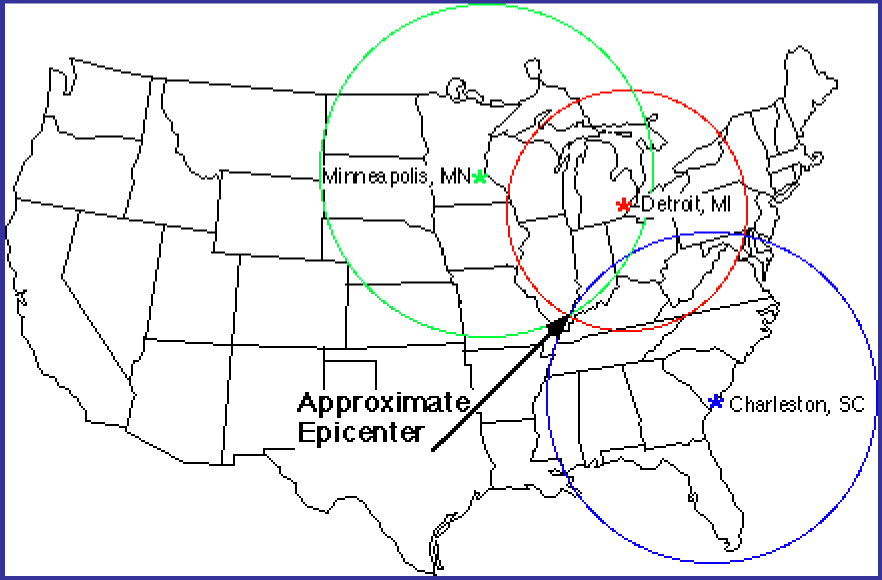


P-waves followed by S-waves



Estimation of epicentre distance - based on time difference between P and S waves





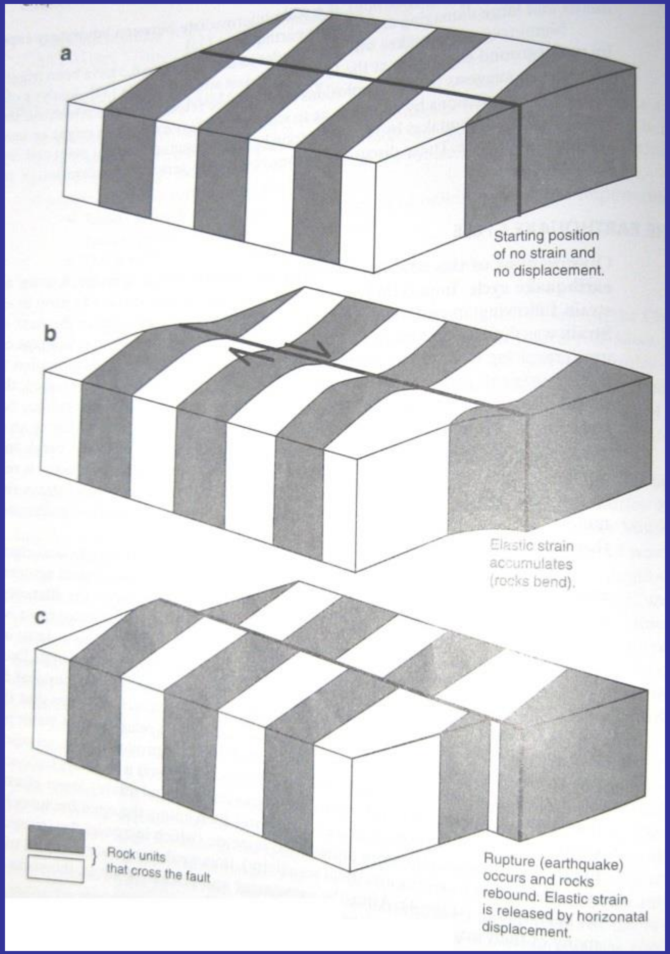
After the earthquake, stress is accumulated again

Earthquake cycle (seismic cycle):

1. accumulation of stress = produces elastic strain (not permanent)

2. during earthquake stress is released when rocks break and permanent displacement occurs, then strain also drops (stress drop)
3. = **elastic rebound** (deformed material in the original shape)

Video!



Magnitude

scale which reflects released energy

Richter´s magnitude

logarithmic scale obtained by calculating the logarithm of the amplitude of waves

$$M = \log a$$

Moment magnitude Mw

$$\boxed{M_\mathrm{w} = \frac{2}{3}\log_{10} M_0 - 10.7,}$$

energy is transformed in

- cracks and deformation in rocks
- heat
- radiated seismic energy E_s

The seismic moment M_0 reflects the total amount of energy that is transformed during an earthquake.

Intensity

It is evaluated based on macroseismic effects

- Damages on buildings, surface, roads etc.
- Subjective – dependent on assessment of amount of damages related to shaking
  - decreases with distance from the epicentre

Rossi – Forel – 10 degrees (1883) the oldest scale

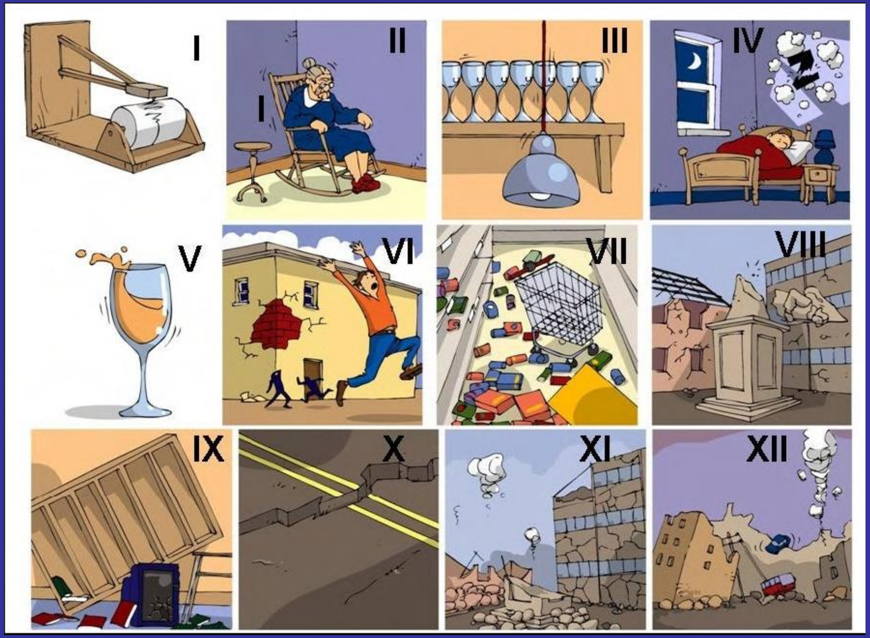
12 degrees scales:

MCS – Mercalli – Cancani - Sieberg (1902)

MSK -64 – Medvedev-Sponheuer-Kárník

MMI – Modified Mercalli (in USA)

EMS-98 - European Macroseismic Scale



I. Not felt	Not felt by anyone.
II. Scarcely felt	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III. Weak	The vibration is weak and is felt indoors by a few people. People at rest feel swaying or light trembling. Noticeable shaking of many objects.
IV. Largely observed	The earthquake is felt indoors by many people, outdoors by few. A few people are awakened. The level of vibration is possibly frightening. Windows, doors and dishes rattle. Hanging objects swing. No damage to buildings.
V. Strong	The earthquake is felt indoors by most, outdoors by many. Many sleeping people awake. A few run outdoors. Entire sections of all buildings tremble. Most objects swing considerably. China and glasses clatter together. The vibration is strong. Topheavy objects topple over. Doors and windows swing open or shut.
VI. Slightly damaging	Felt by everyone indoors and by many to most outdoors. Many people in buildings are frightened and run outdoors. Objects on walls fall. Slight damage to buildings; for example, fine cracks in plaster and small pieces of plaster fall.
VII. Damaging	Most people are frightened and run outdoors. Furniture is shifted and many objects fall from shelves. Many buildings suffer slight to moderate damage. Cracks in walls; partial collapse of chimneys.
VIII. Heavily damaging	Furniture may be overturned. Many to most buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse. Can be noticed by people driving cars.
IX. Destructive	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely. Windows shatter.
X. Very destructive	Many buildings collapse. Cracks and landslides can be seen.
XI. Devastating	Most buildings collapse.
XII. Completely devastating	All structures are destroyed. The ground changes.

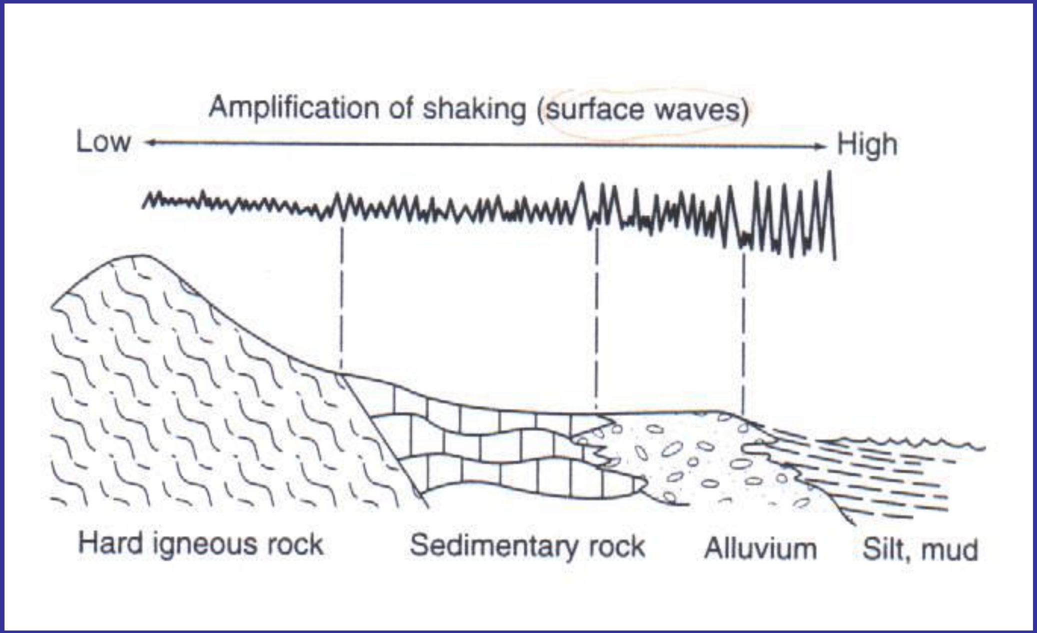
EMS-98

European Macroseismic Scale

Macroseismic effects on the surface controlled by:

- Size of earthquake, focus depth, distance from epicentre, rheology of the surface layers

- Locally – types and physical condition of the rocks,
  ground water level,
  geology - **site effects**



- **Unconsolidated sediments and soil** – shaking is amplified

- **Sediments thickness** above hardrock – amplified if higher thickness

Mexico city 1985, M = 8, epicentre 350km far away, 10,000 casualties

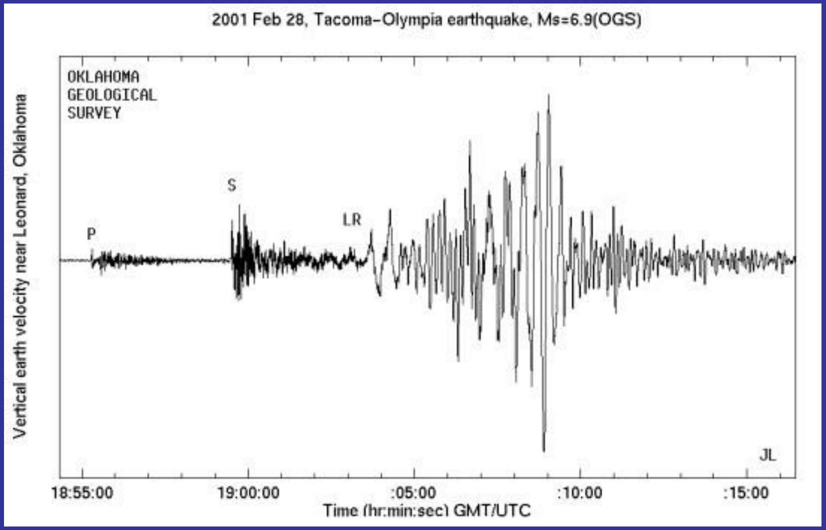
Larger amplitude – worse damages

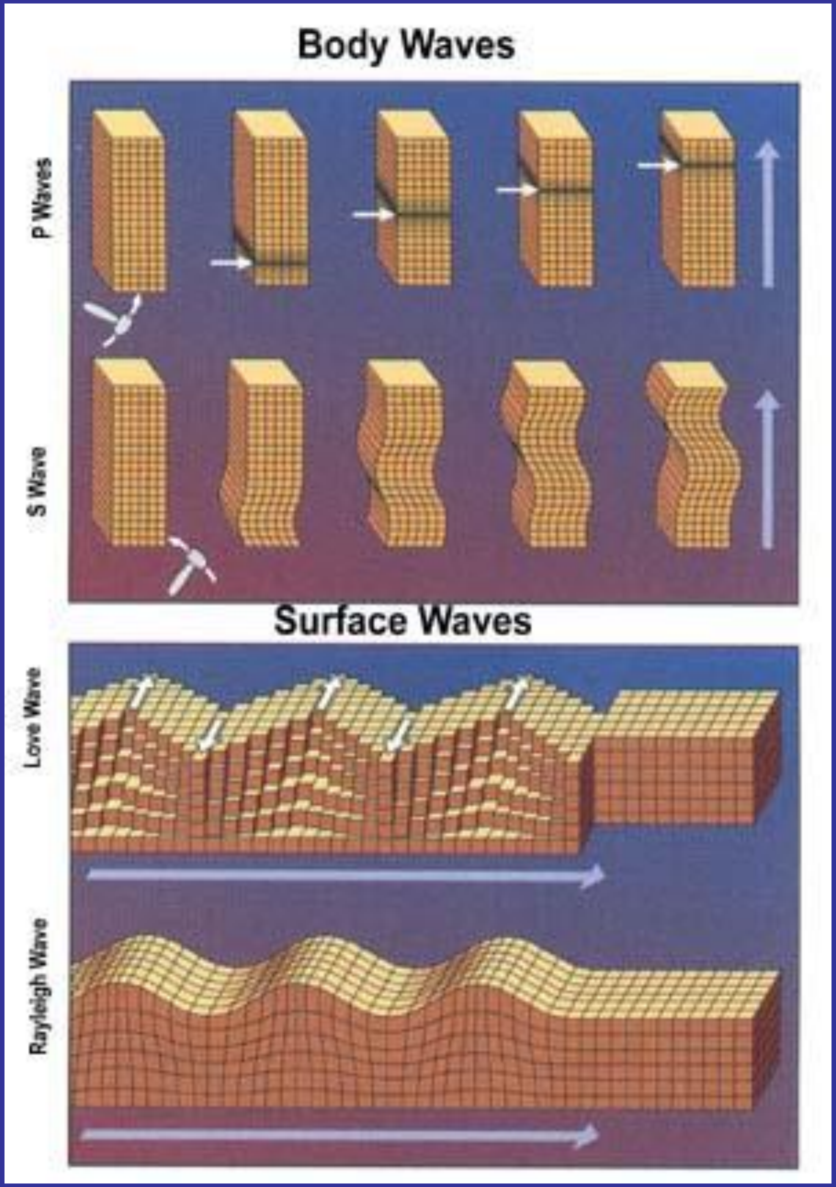
Distance from epicentre

- wave type

P, S body waves – high frequency

Surface waves (Love, Rayleigh) – formed by interference of body waves – low frequency, higher amplitude farther from epicentre (bigger damage)

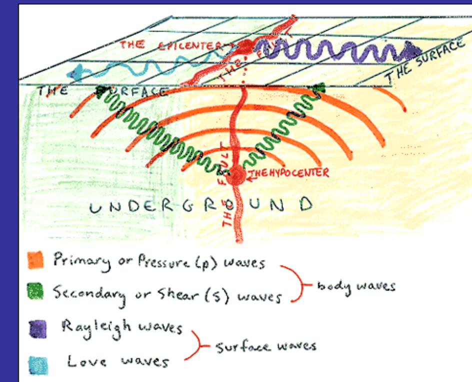




Low buildings – high own frequency

Tall buildings – low own frequency

Ground motion acceleration



Horizontal - peak horizontal ground acceleration
– crucial building codes
(Probabilistic hazard assessment - PHA)
Vertical (amplitudes over 50% lower than horizontal)

Magnitude	Area Felt Over (square kilometers)	Distance felt (kilometers)	Intensity (maximum expected Modified Mercalli)	Ground Motion: (Average peak horizontal acceleration g = gravity = 9.8 meters per second per second)
3.0–3.9	1,950	25	II–III	Less than 0.15 g
4.0–4.9	7,800	50	IV–V	0.15–0.04g
5.0–5.9	39,000	110	VI–VII	0.06–0.015g
6.0–6.9	130,000	200	VII–VIII	0.15–0.30g
7.0–7.9	520,000	400	IX–X	0.50–0.60g
8.0–8.9	2,080,000	720	XI–XII	Greater than 0.60g

Magnitude versus intensity relation

Tohoku 2011 M=9 (2.7g); Christchurch 2011 M=6.4 (2.13g); Kobe 1995 M=6.8 (0.8g)

Effects of earthquakes

Primary effects: ground-shaking motion and rupture of the surface

(shear or collapse of large buildings, bridges, dams, tunnels, pipelines)

Chi-chi EQ Taiwan 1999 with M=7.6

Landers EQ, Emerson fault, CA 1992, M=7.3

Secondary effects:

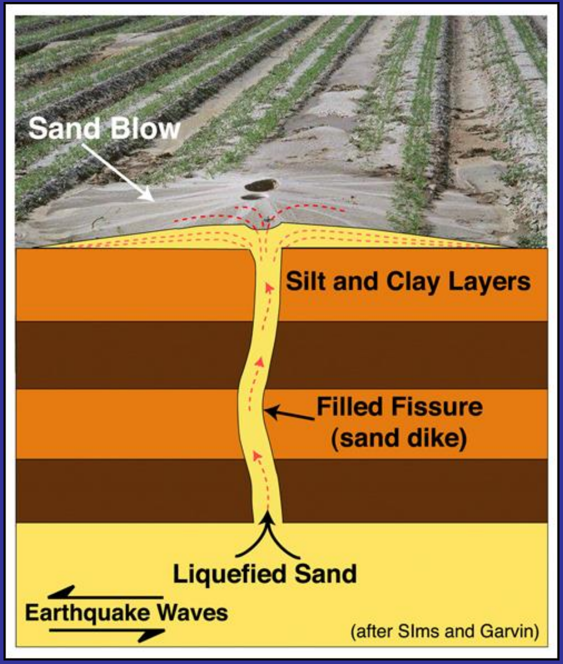
Liquefaction – water-saturated material transforms to liquid state (loose soil into mud) during shaking, compaction causes an increase of pore-water pressure = material loses shear strength and flows. video

Water under the soil rises and the ground sinks causing extensive damage to buildings, roads and other structures.

Buildings tilted due to soil liquefaction,1964 earthquake, Japan.

Liquefaction

Loma Prieta , 1989



Layers of sand below the ground surface liquefy and, under the pressure of the overlying sediments, they exploit any fissure or other line of weakness to flow upwards and burst out on the ground surface as an eruption of sand and water.

Sand volcanoes, sand dykes

Seismites

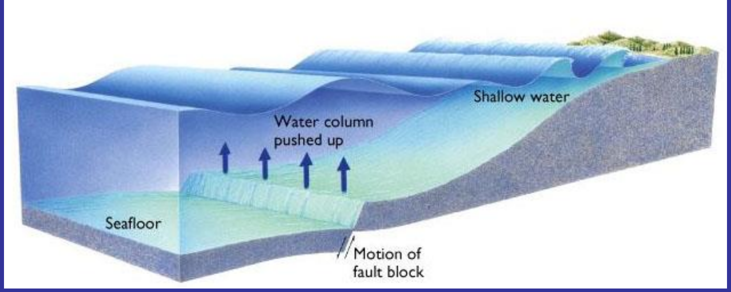
Escape structures

Landslides

Costarica, 2009, Mw=6.2, depth 6km, 550 foreshocks, 180 landslides

Video – no rain, only landslide + pore water

Tsunami - seismic seawaves



Floods – following collapse of dams

Fires

Long-term effects

Regional subsidence,
Change in groundwater level

Change of coastal morphology

subsidence

Ghost forest

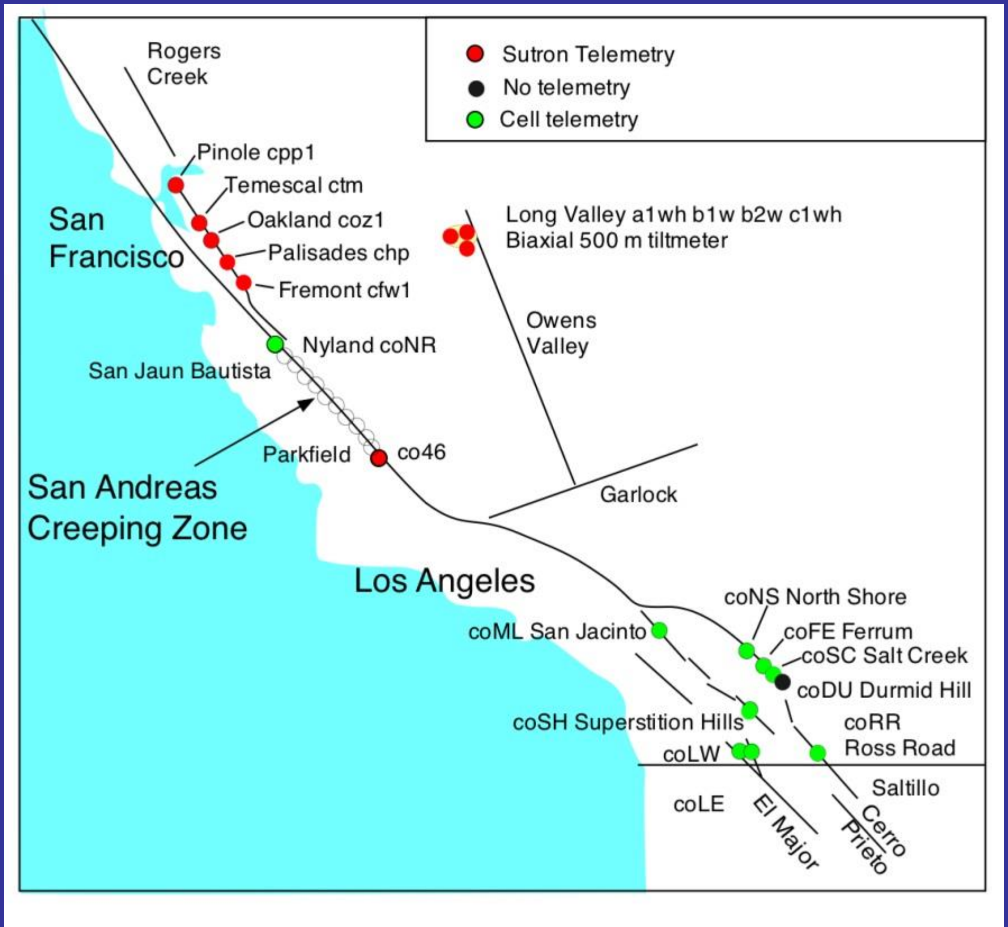
Tectonic creep – aseismic movements

Displacement along a fault zone **accompanied by minimal earthquakes**, **more or less continuous, confined to narrow zone**

Geodetically detectable (GPS, InSAR, creepmeter etc.....)

Less damage from creep – generally along narrow fault zones subject to slow movements,

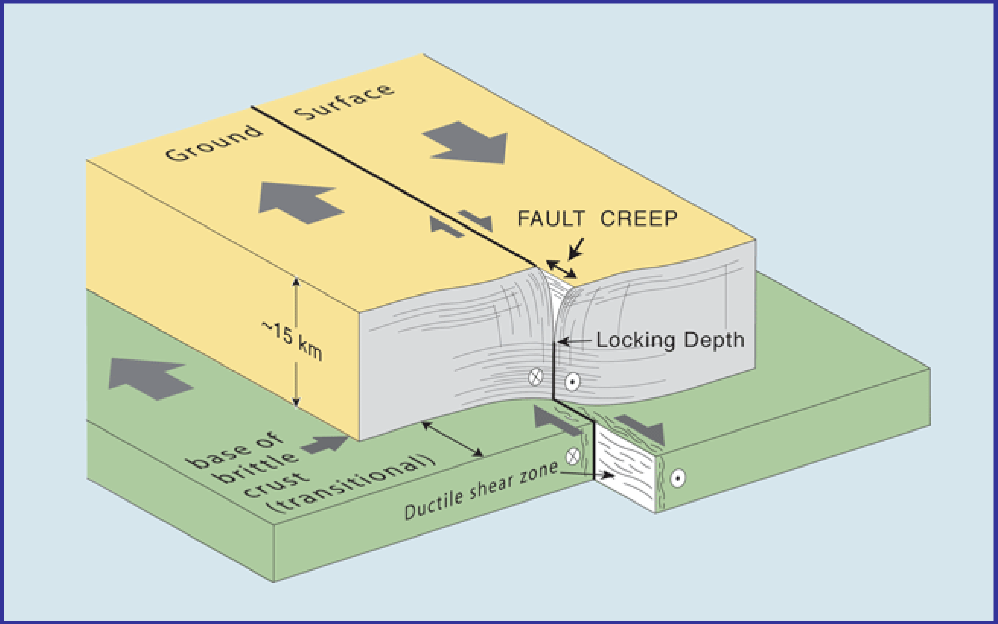
Not much studied – no seismic hazard



Creepmeters

Hayward fault – SAF zone, San Francisco Bay area

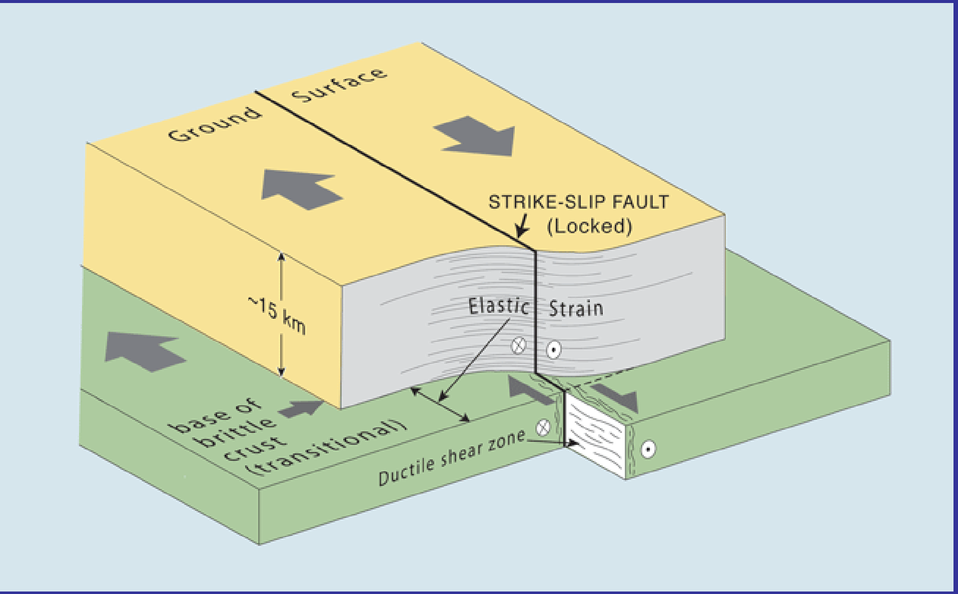
Creep rate measured by creepmeter installed across the fault – typically 5 mm/year, max in Fremont 7.8 - 8.5 mm/year



Between 5 and 12 km in depth is believed to slip entirely in earthquakes, but the surface and deepest part of the fault also slips by a process of aseismic creep.

Creep since 1896 large EQ, the creep partially releases the strain energy on the fault

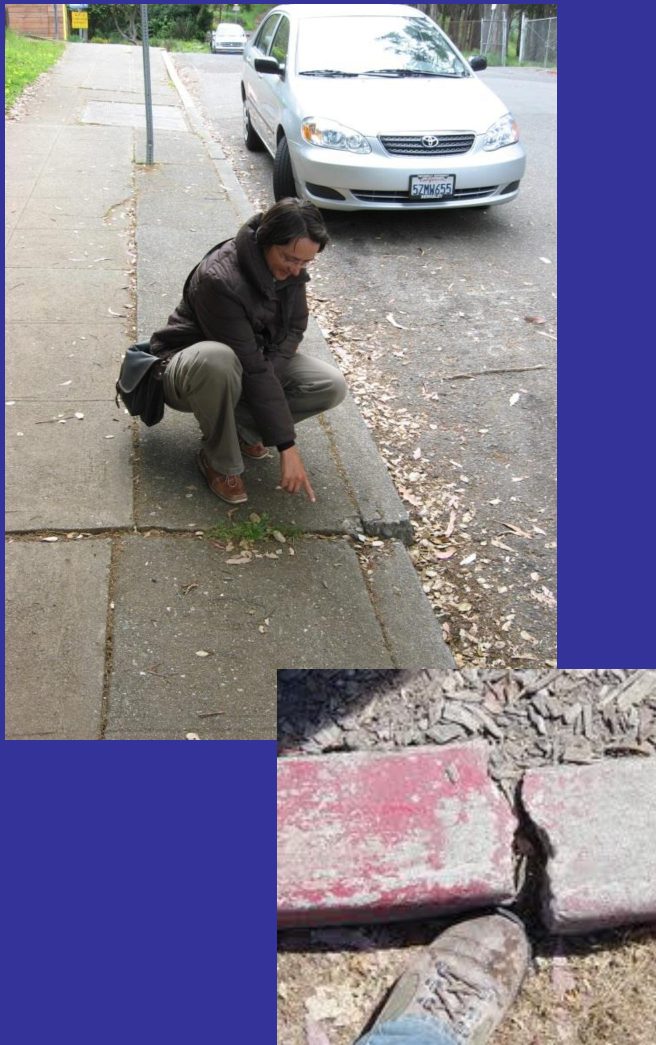
High rate: slow damage of roads, sidewalks, building etc.



Hayward faults

Berkeley – Memorial stadium

3.2 cm in 11 years,
periodic repairs needed



Berkeley, offset sidewalk

Contra Costa, deformed road

Hayward, offset fence

Higher creep rate:

Calaveras fault (SAF zone)

Creep rate – varies
1910-1929 no creep, based on offset in two sidewalks constructed in 1910 and 1929, and pipeline laid in 1929
1929 ......- creep commenced, with 8 mm/yr (average)
1961 - 1967, slip rate about 15 mm/yr
1979....2 sites monitored in Hollister with 6.6 mm/yr and 12 mm/yr (2.3km NW)

Hollister, twisted house

20.000 earthquakes a year - small, strain not accumulated and it is released by slow creep – not able to produce a large earthquake

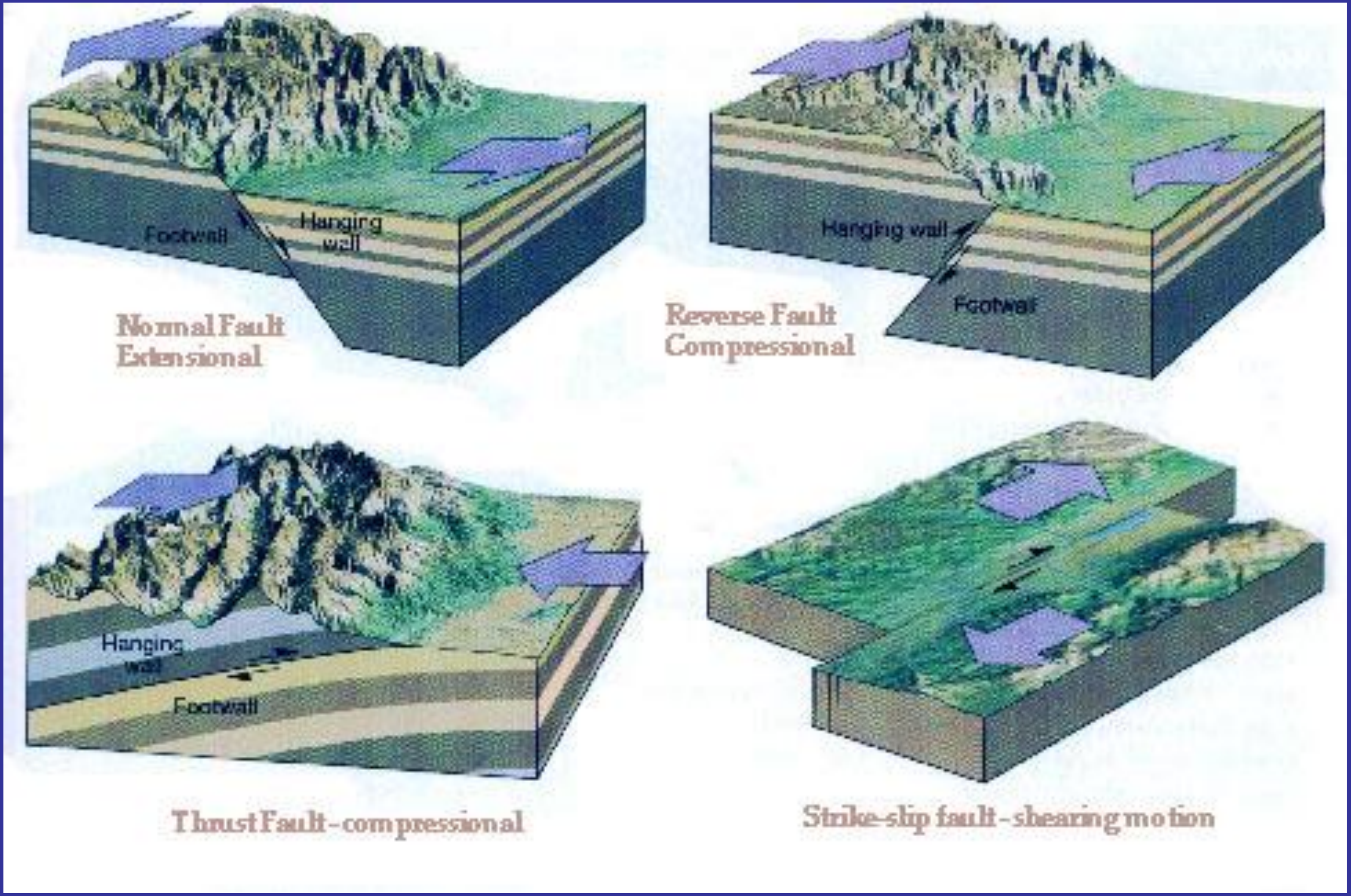
Calaveras fault - winery

Calaveras fault

Creeping tree

Faults

3 types of faults – in various stress regime: normal faults, reverse faults, strike-slips; cumulative earthquake or creep – relief formation



video!

normal fault

strike-slip

thrust fault

reverse fault

Landforms related to different types of movements

Change in landscape caused by change in landscape process

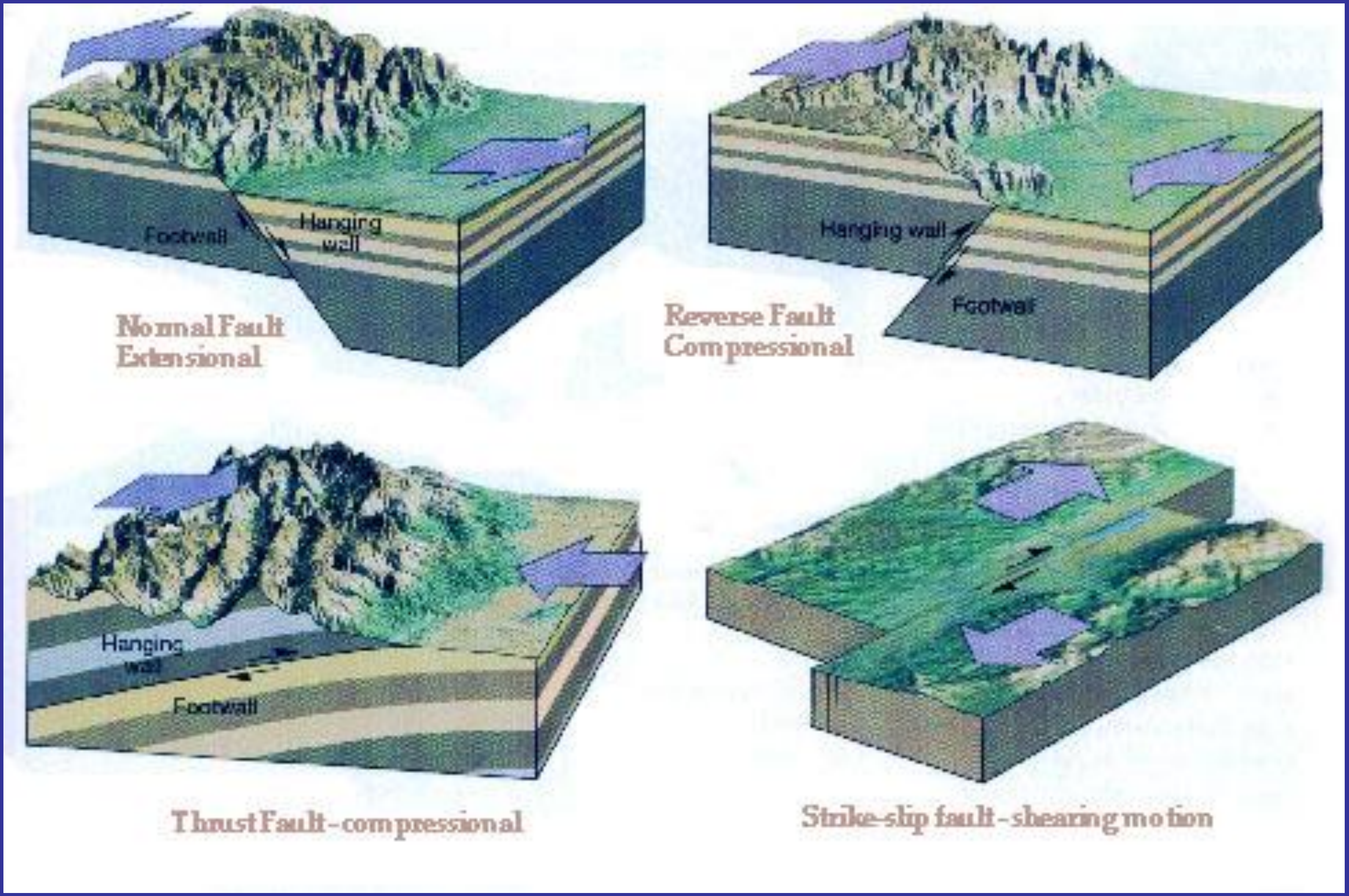
Look for **morphological anomalies** – surfaces warped, tilted, uplifted, fractured

Some features indicate the presence of a fault, but say little about activity or type of movements

Vegetation alignments, springs, fault scarps, other lineaments

Faults

3 types of faults – in various stress regime: normal faults, reverse faults, strike-slips; cumulative earthquake or creep – relief formation



video!

normal fault

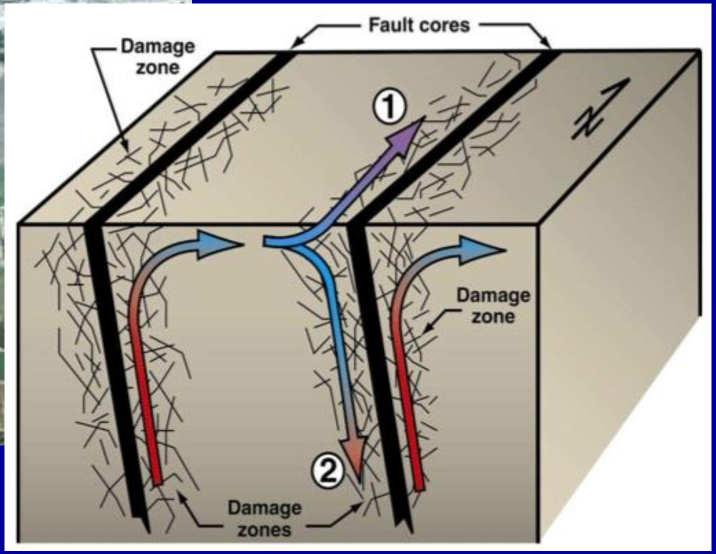
strike-slip

thrust fault

reverse fault

All Fault Types Have Potential to Disrupt Groundwater Flow/Create Scarps

- Springs – fault gouge can be an effective barrier



Gilman Hot Springs, San Jacinto Valley

- Vegetation Lineaments (arid areas)

San Andreas Fault - Thousand Palms Oasis, Indio Hills, California

Scarps – all fault types, all scales

Northward across Coyote Creek Fault, San Jacinto Fault Zone

Scarp on Strike-Slip (oblique slip)

A young scarp!! TINY!

Carboneras fault, Spain

Coyote Mts, Elsinore fault, CA

Scarps on normal fault

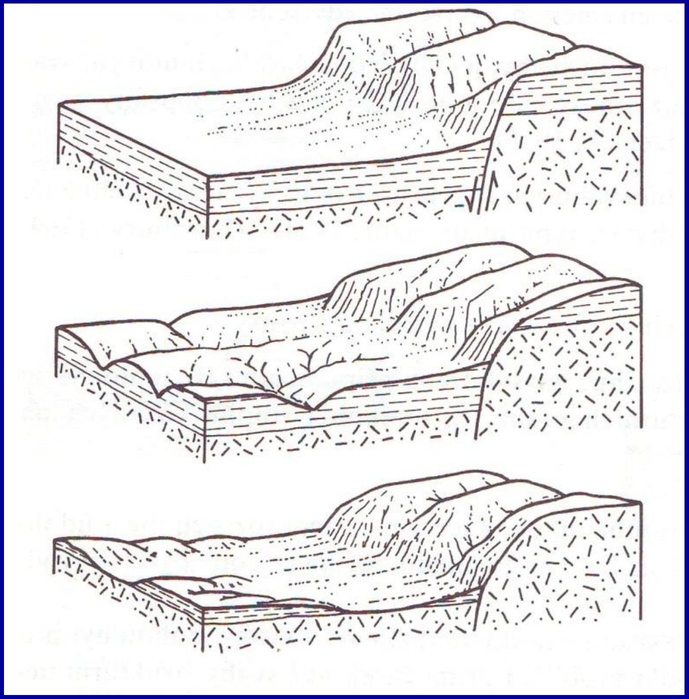
Krupnik fault , Bulgary, 1904 M=7,8

Scarps on thrust fault

Chichi earthquake 1999, Taiwan

Active or Inactive?

- Differential weathering along inactive faults can produce features that resemble features produced by active faults
  - Vegetation lineaments,
  - Linear valleys
  - Scarps
    - Known as "**Fault-Line Scarps**"



Sometimes these features exist, but they are not associated with any active faulting!! (differential erosion)

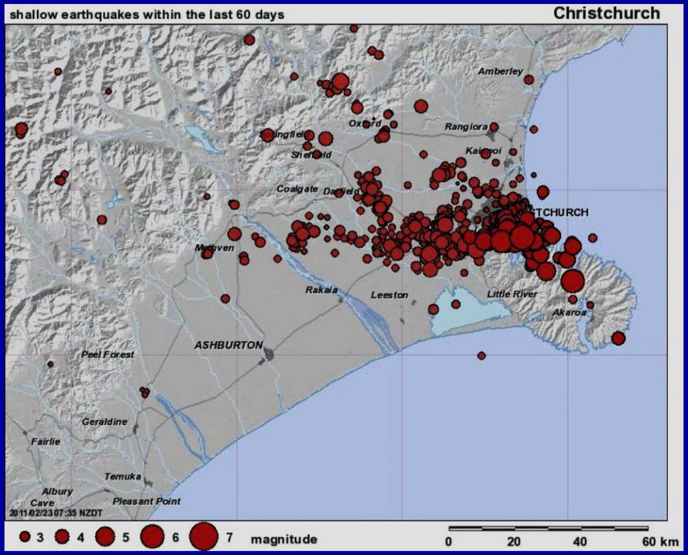
Some geomorphic features clearly indicate **young activity** (usually Holocene to late Quaternary)

- If it is expressed in the geomorphology, it is likely active (unless you can demonstrate that the features are totally erosional in nature)
  - scarps in alluvium, deflected drainages, sags, shutter ridges, side-hill benches

A general rule is that active faults produce alluvium so they bury themselves, so locally, the evidence for activity may be obscured along some portions of the fault

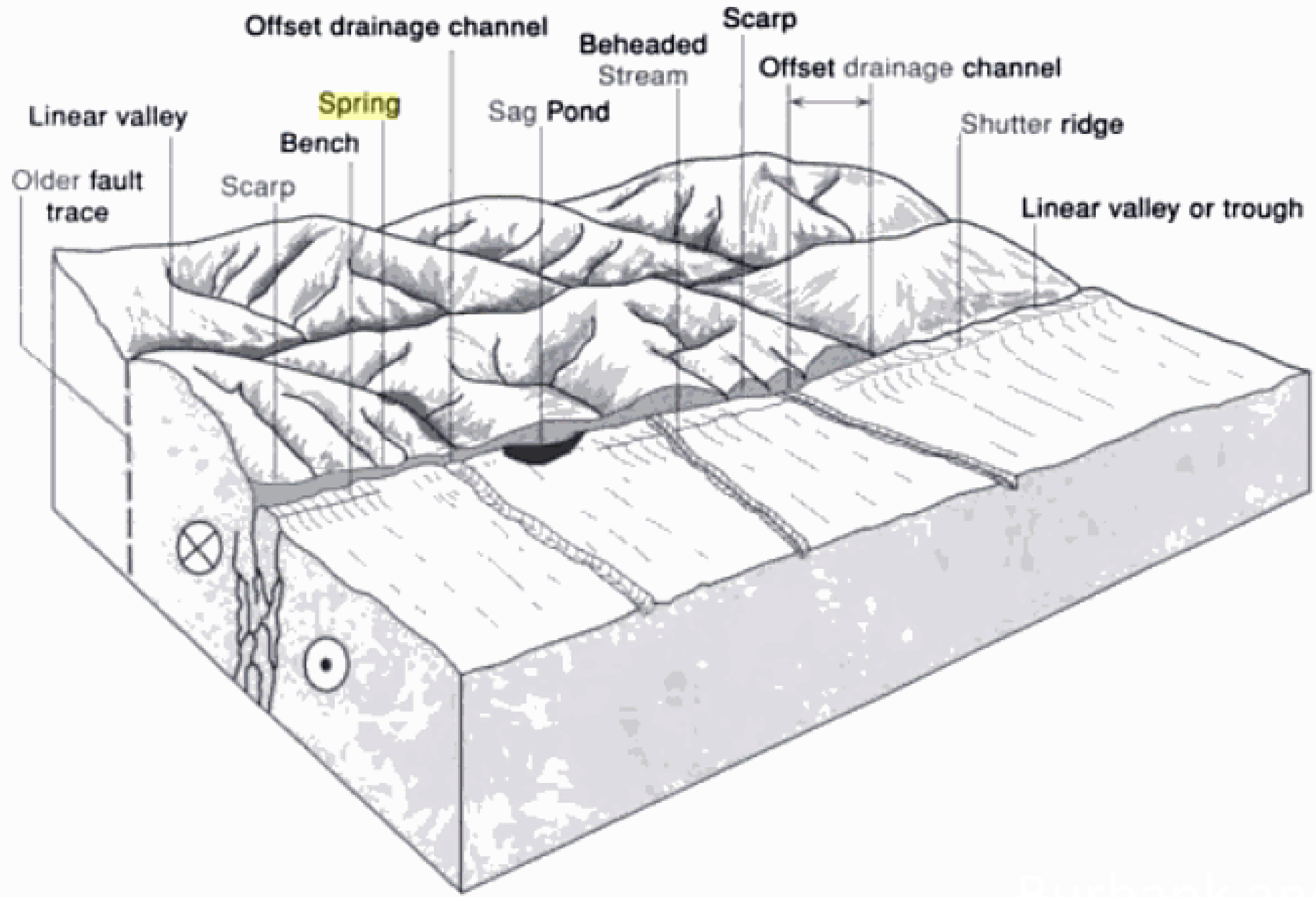
Christchurch EQ 21.2. 2011, M = 6.3, NZ

- **unknown fault,** uplift of Southern Alps – 10mm/year =high sedimentation, sediments obscure the fault trace



Active Strike-Slip Fault Geomorphology

FIGURE 4.18. Overview of strike-slip geomorphology



A linear trough along fault, sag ponds, shutter ridges, offset ridges and drainages, springs, scarps, and beheaded streams are typical geomorphic features indicative of strike-slip faulting. The older, abandoned fault trace displays analogous, but more erosionally degraded features. Modified after Wesson et al. (1975).

Effects on Stream Channels

Offsets

- Implies a previously straight, now-curved channel as a result of displacement
- the bend in the channel must agree with the sense of slip!

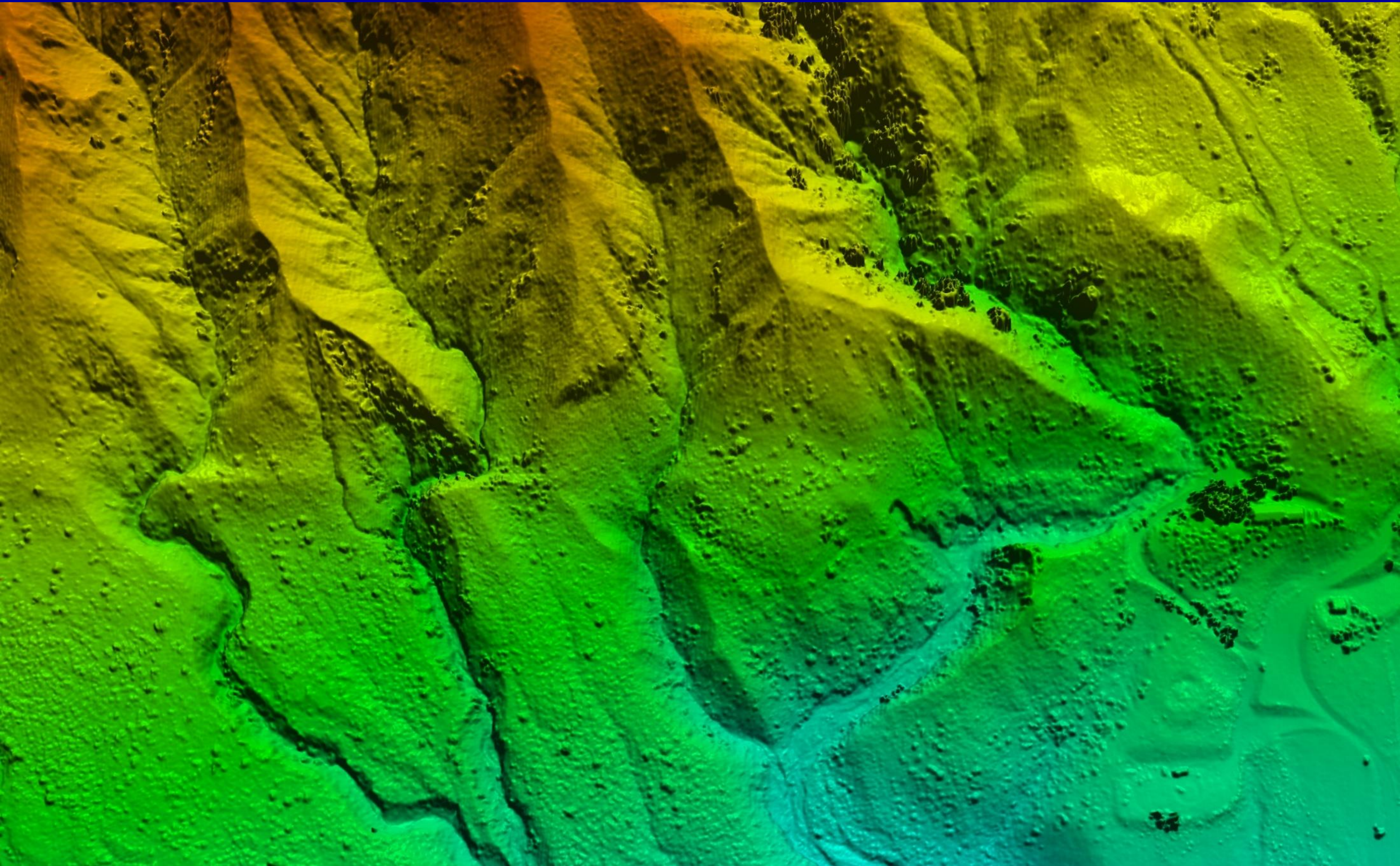
Deflections

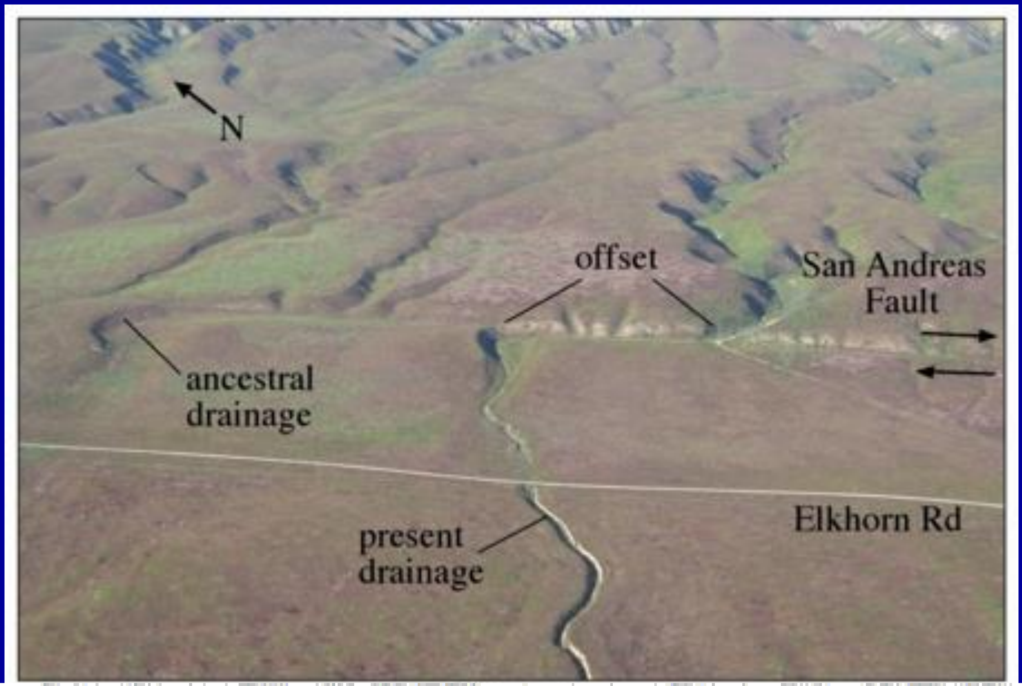
- The curve in the channel can be with or against the sense of slip
- Result of drainage capture
  - (water will take the easiest path downhill, alluvial fans)

All offsets are deflections, but not all deflections are offsets!

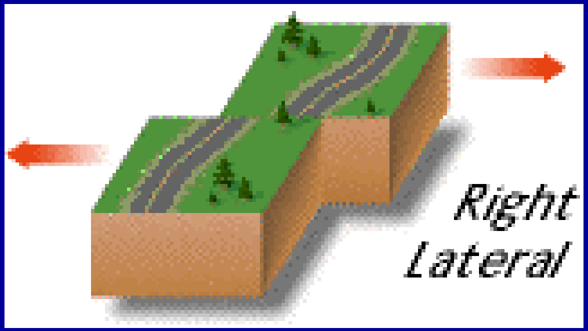
Offset channels

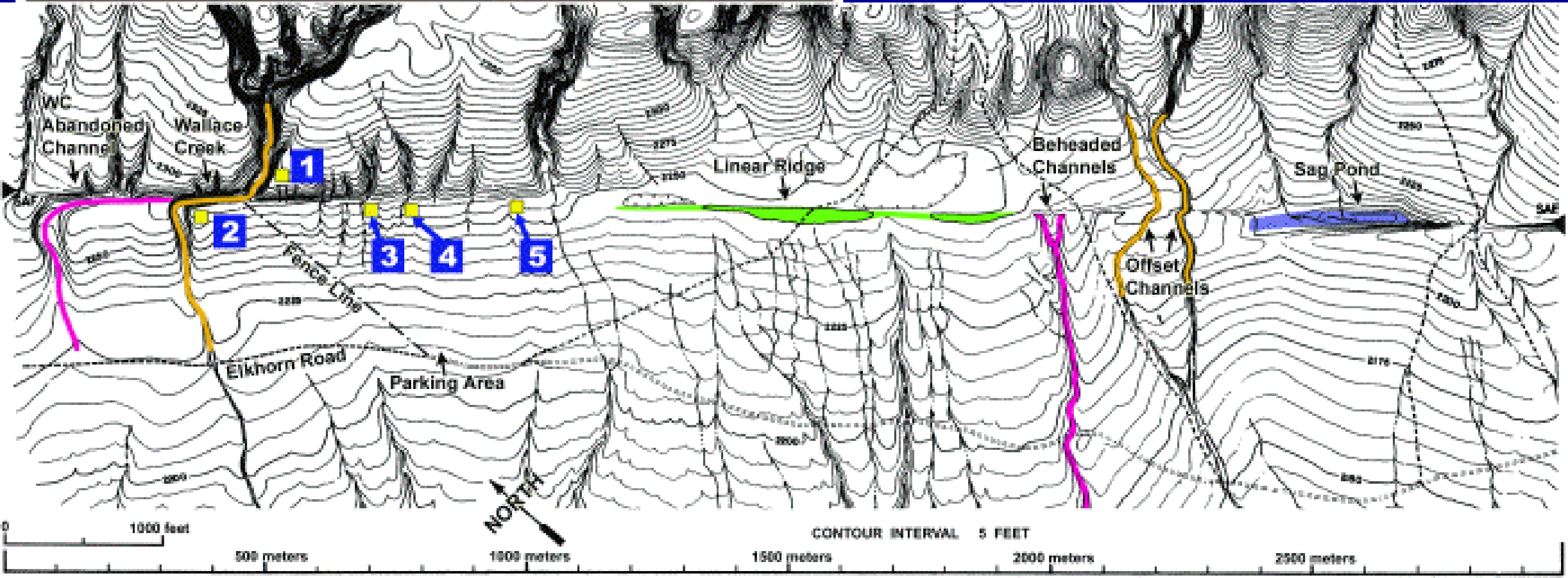
Pitman Canyon ~ 46 - meter offsets





San Andreas Fault,
Carrizo plain, CA



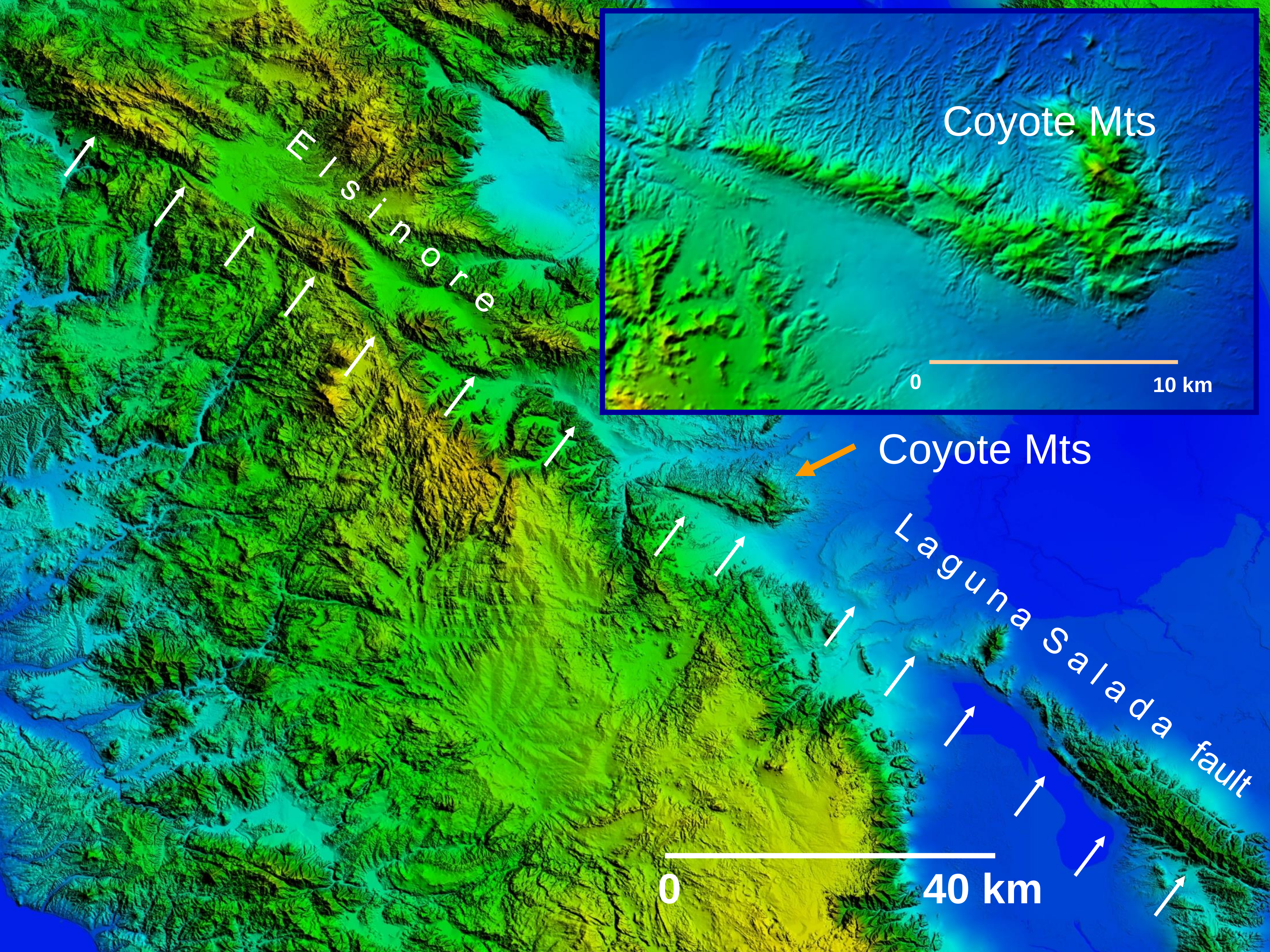


Wallace creek

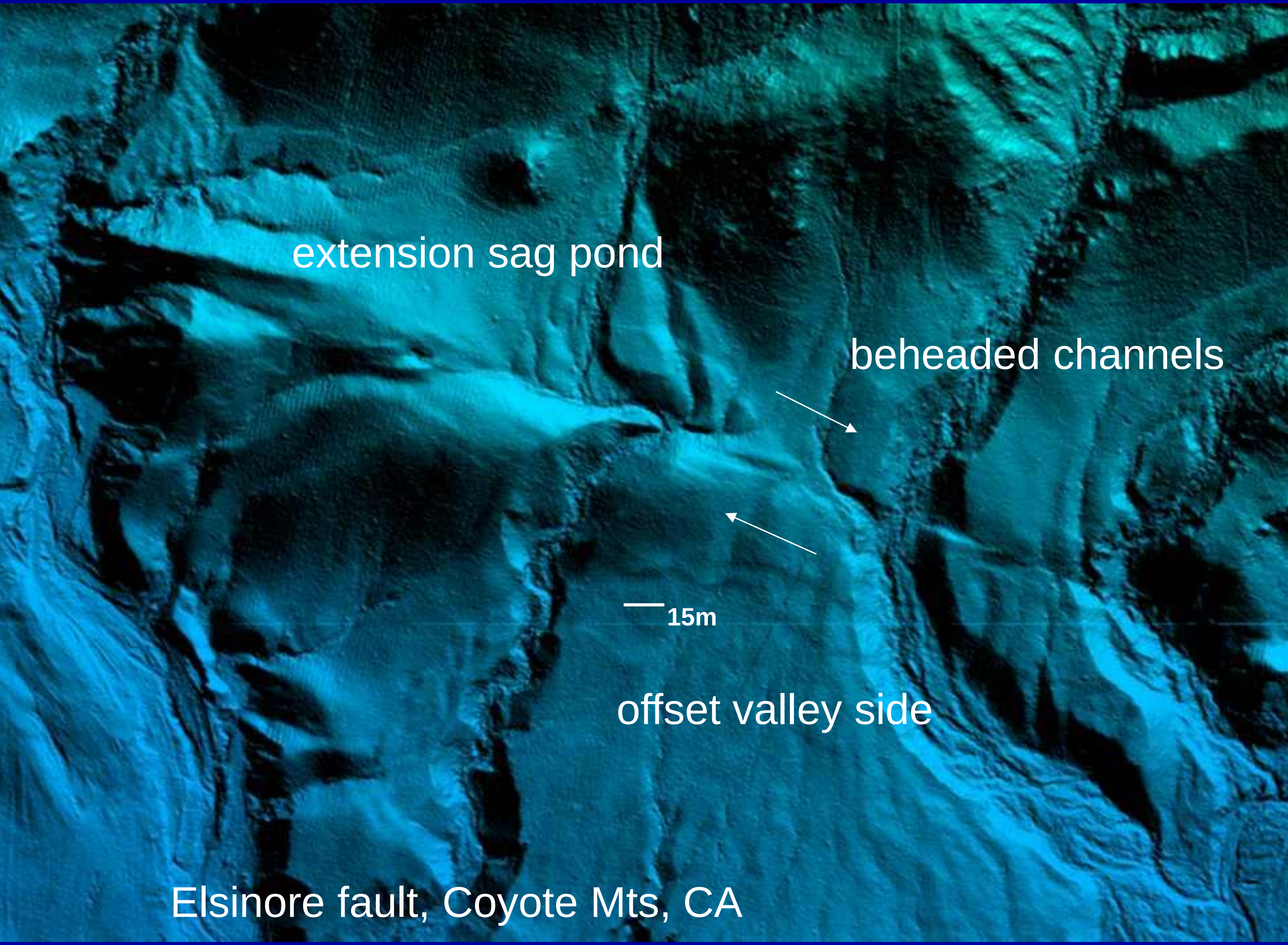
Offset channels

Carizzo plain

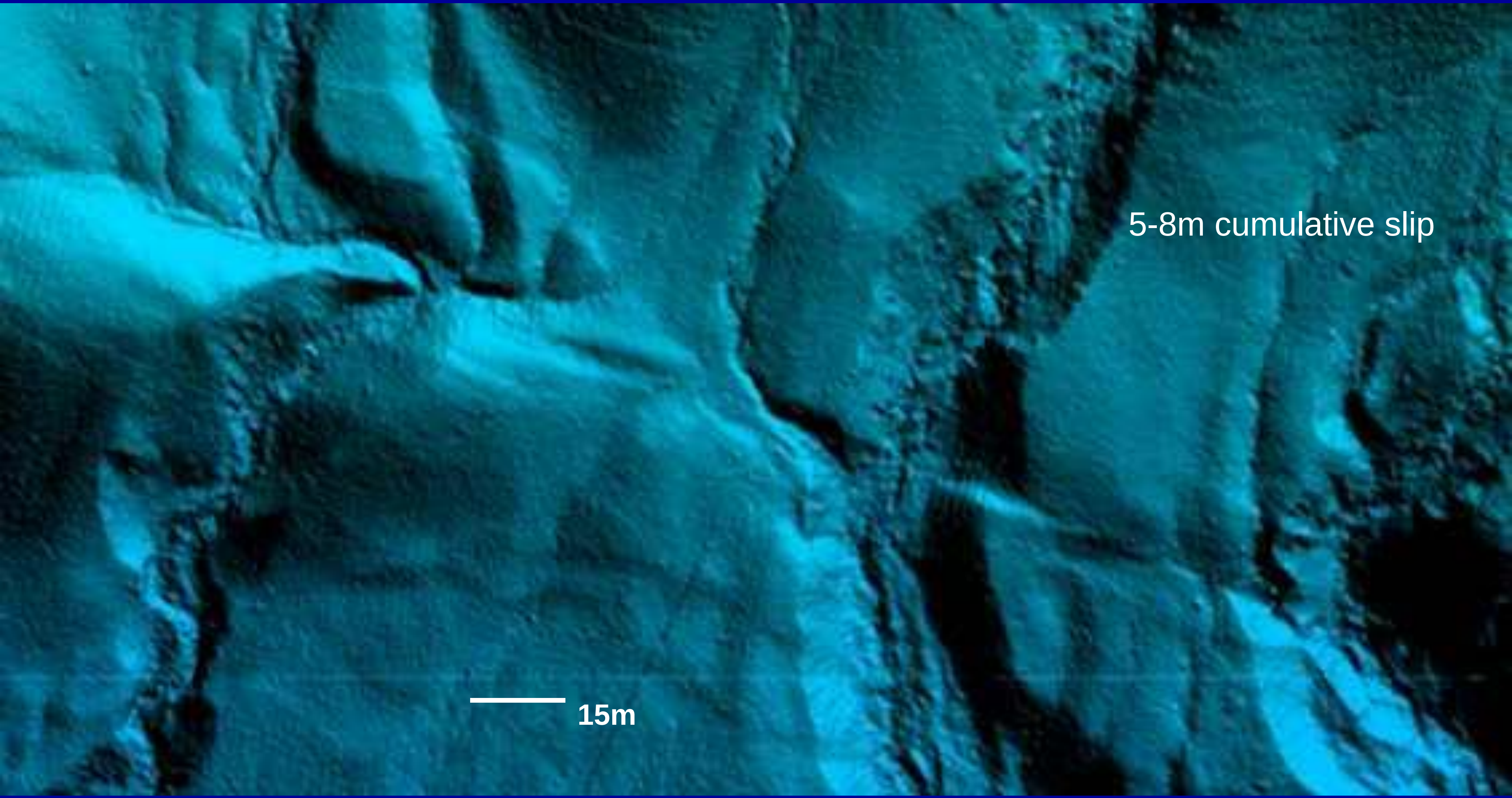
Elsinore fault

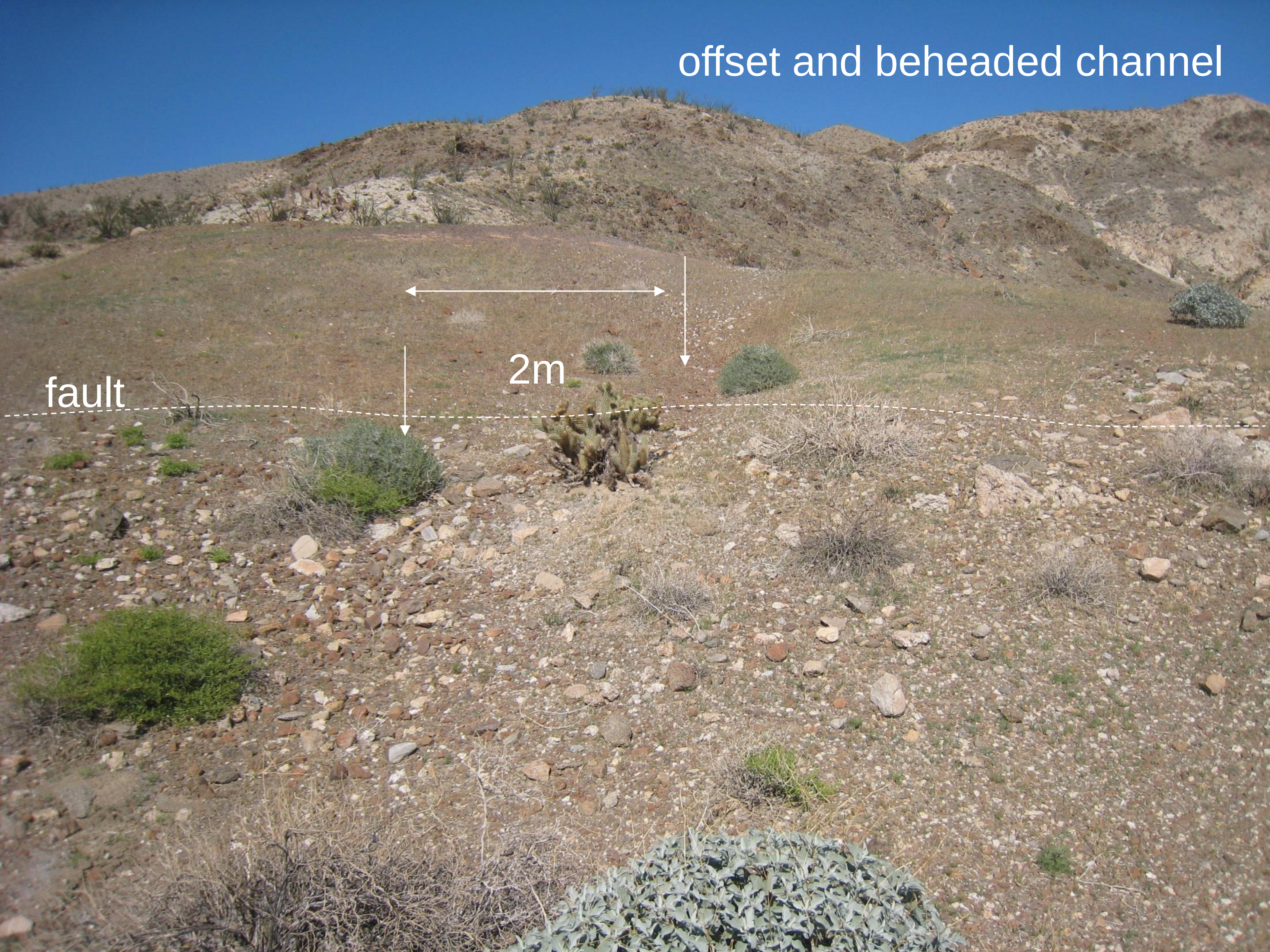


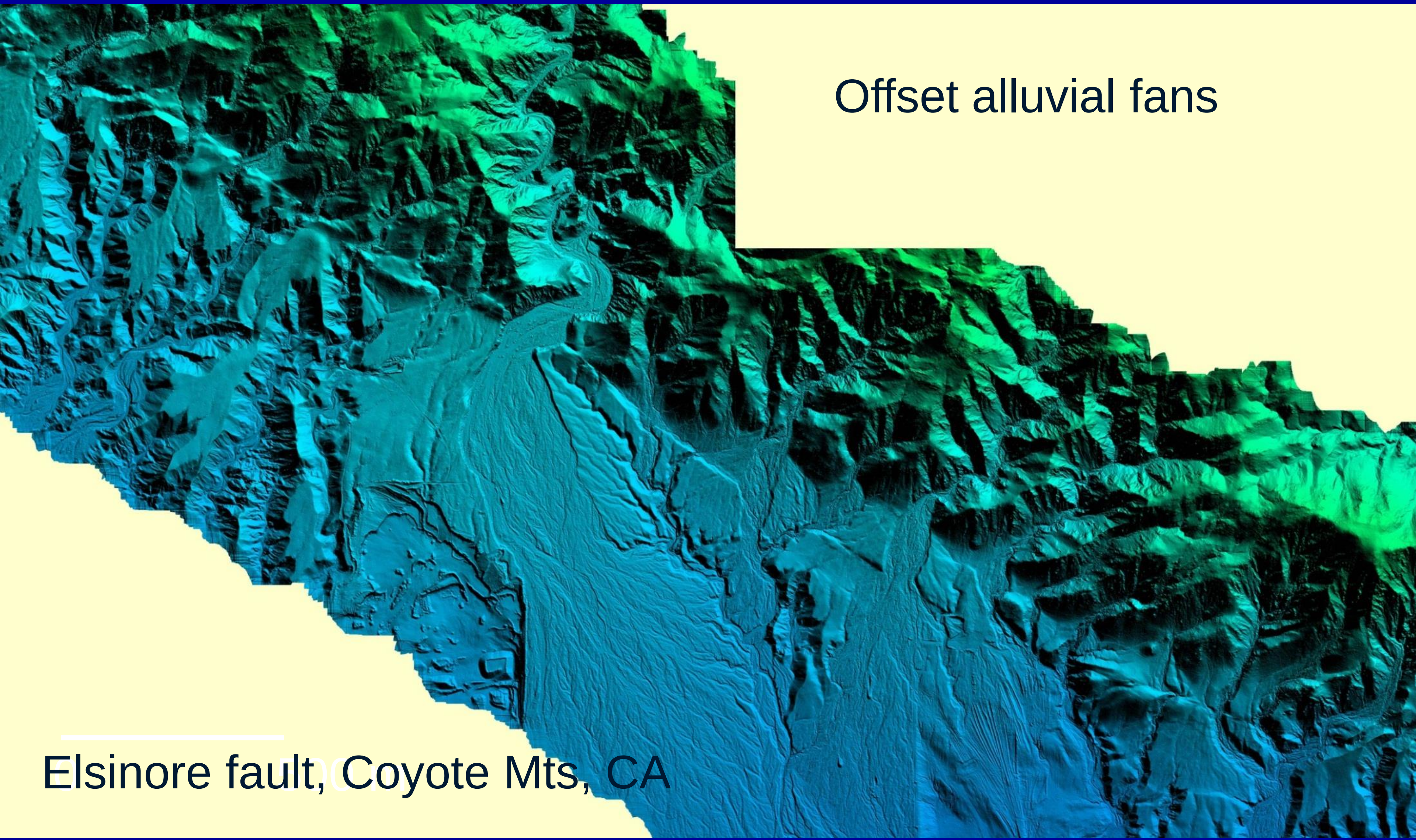
Elsinore
Coyote Mts
0
10 km
Coyote Mts
Laguna Salada fault
0
40 km


extension sag pond
beheaded channels
15m
offset valley side
Elsinore fault, Coyote Mts, CA

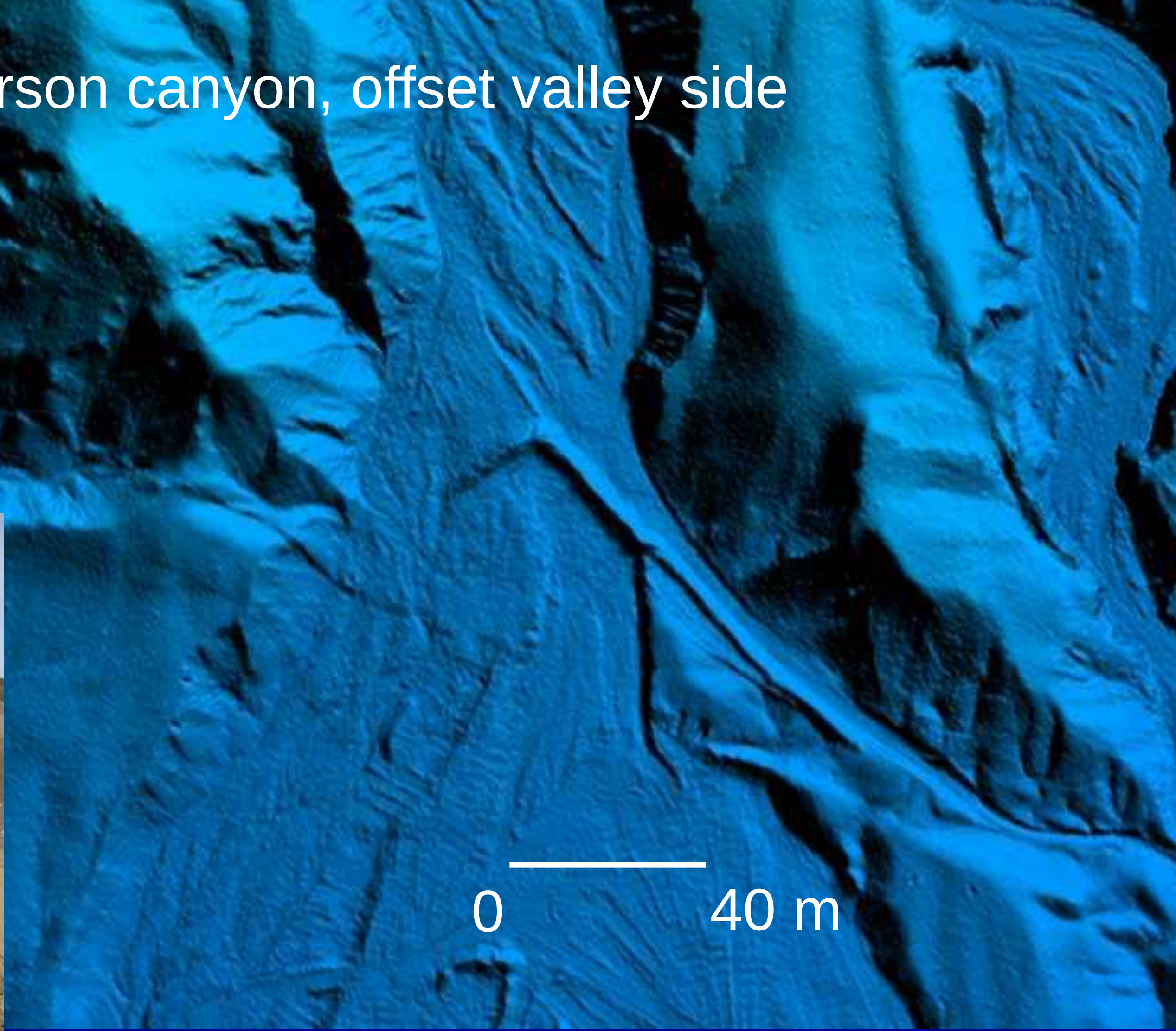
beheaded channels

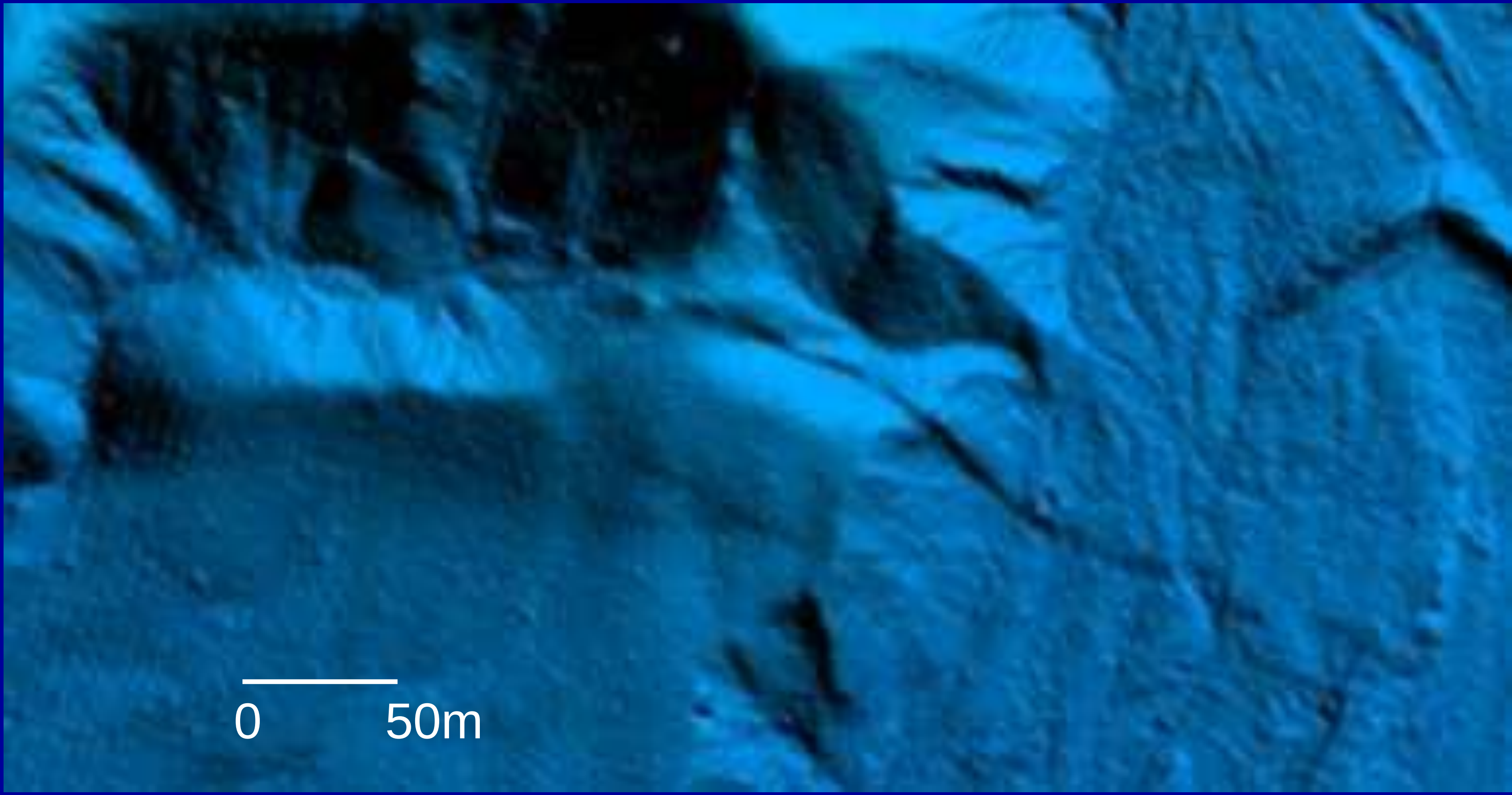



offset and beheaded channel
2m
fault


Offset alluvial fans
Elsinore fault, Coyote Mts, CA

Alverson canyon, offset valley side

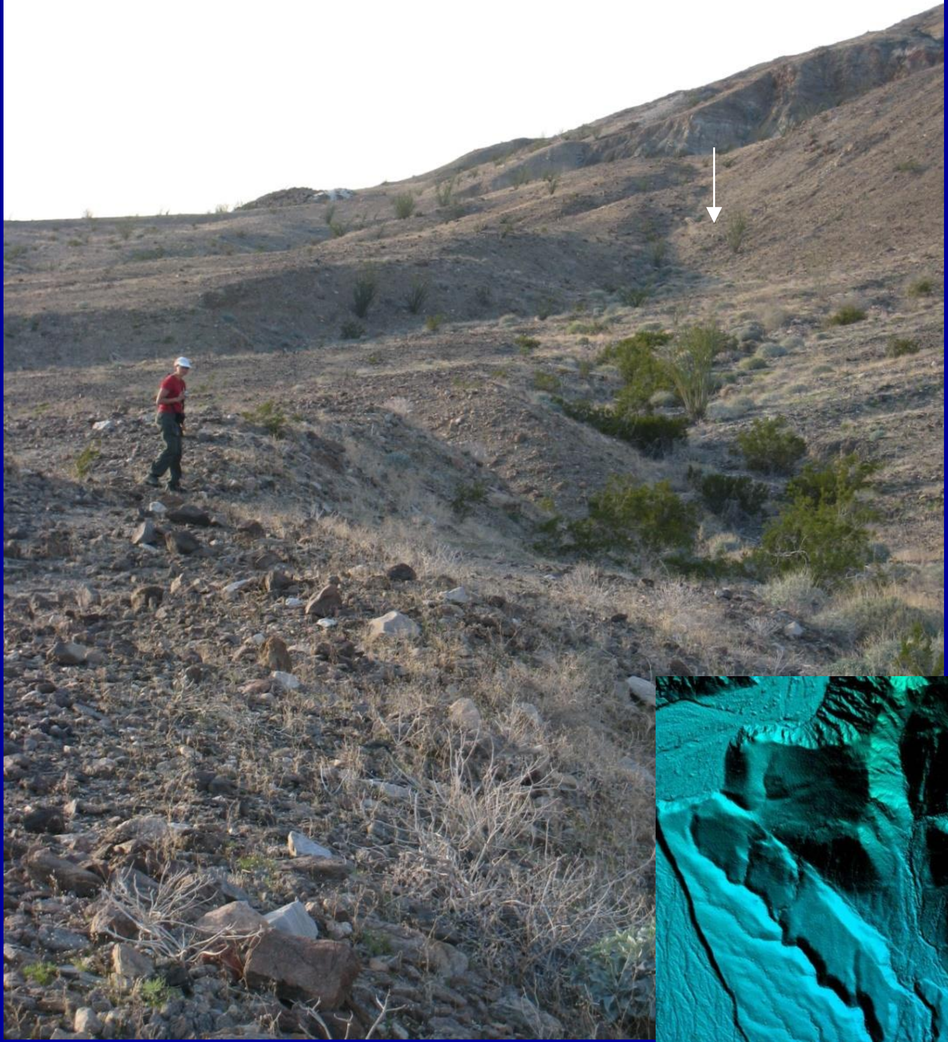


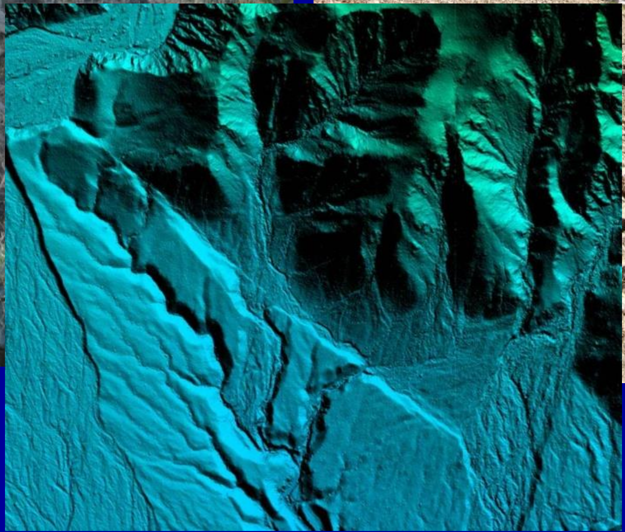

0
50m


offset channels and bars

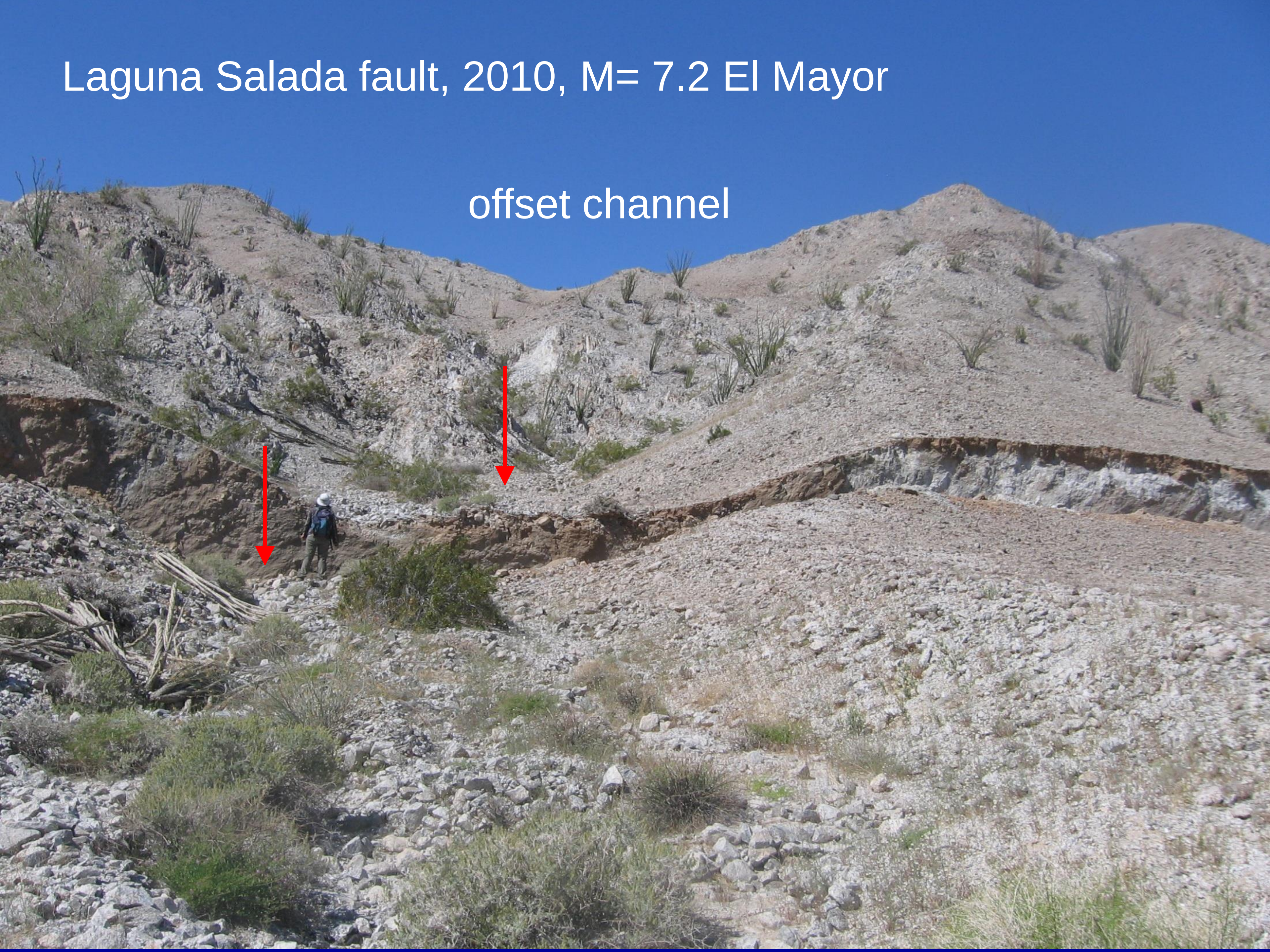
offset channel bars

offset alluvial fan



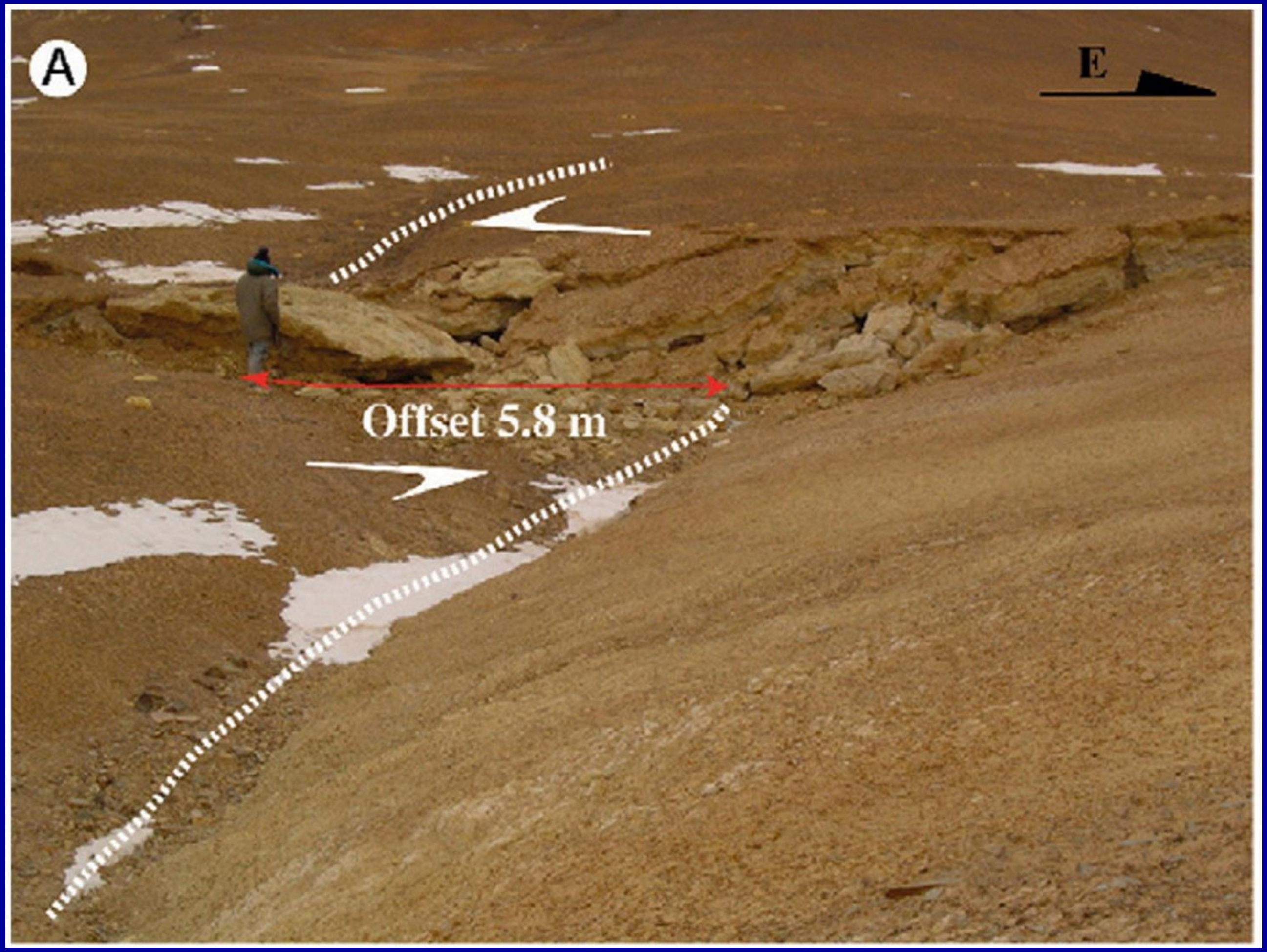


Different lithology – tells us about the amount of offset


Laguna Salada fault, 2010, M= 7.2 El Mayor
offset channel


offset channel


offset valley side



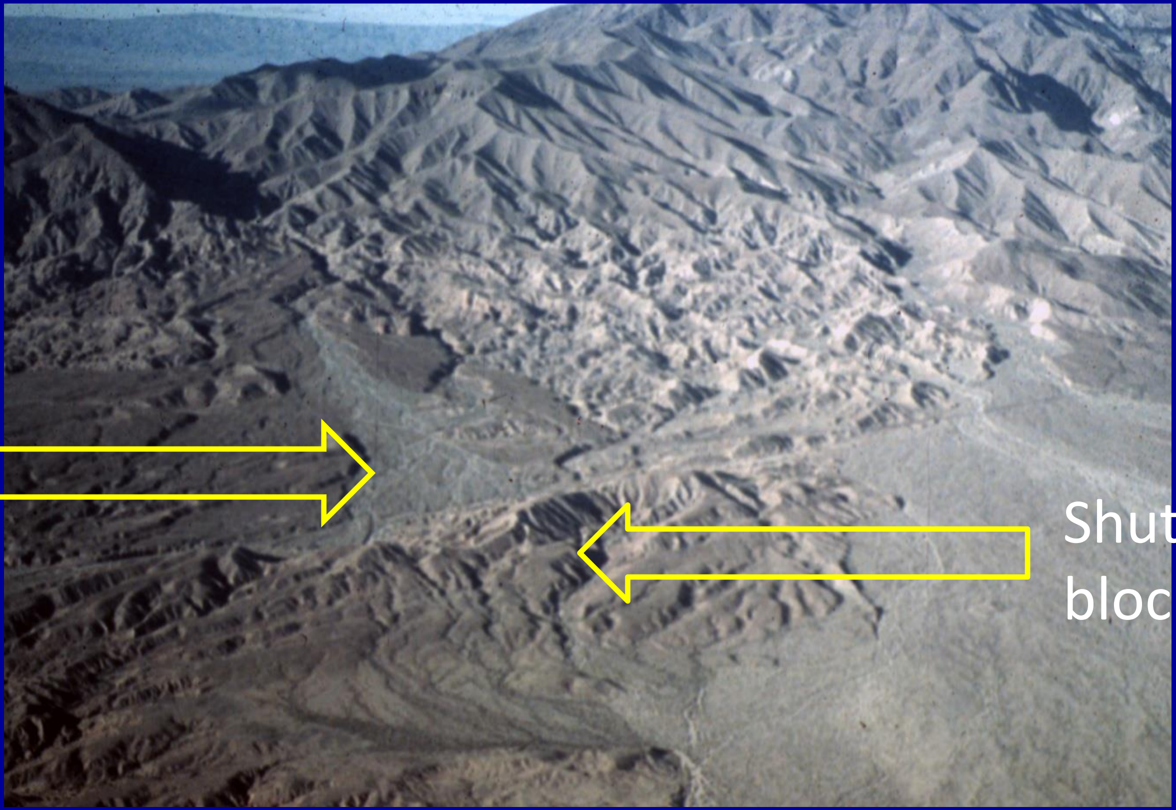
Kunlun fault, Tibet, 2001   M = 7.8

San Jacinto Fault, Southern California


sag
piercing/matching points
Offset channel margin
sag
Denali fault. Photo: Lloyd Cluff, 1973

Shutter Ridge

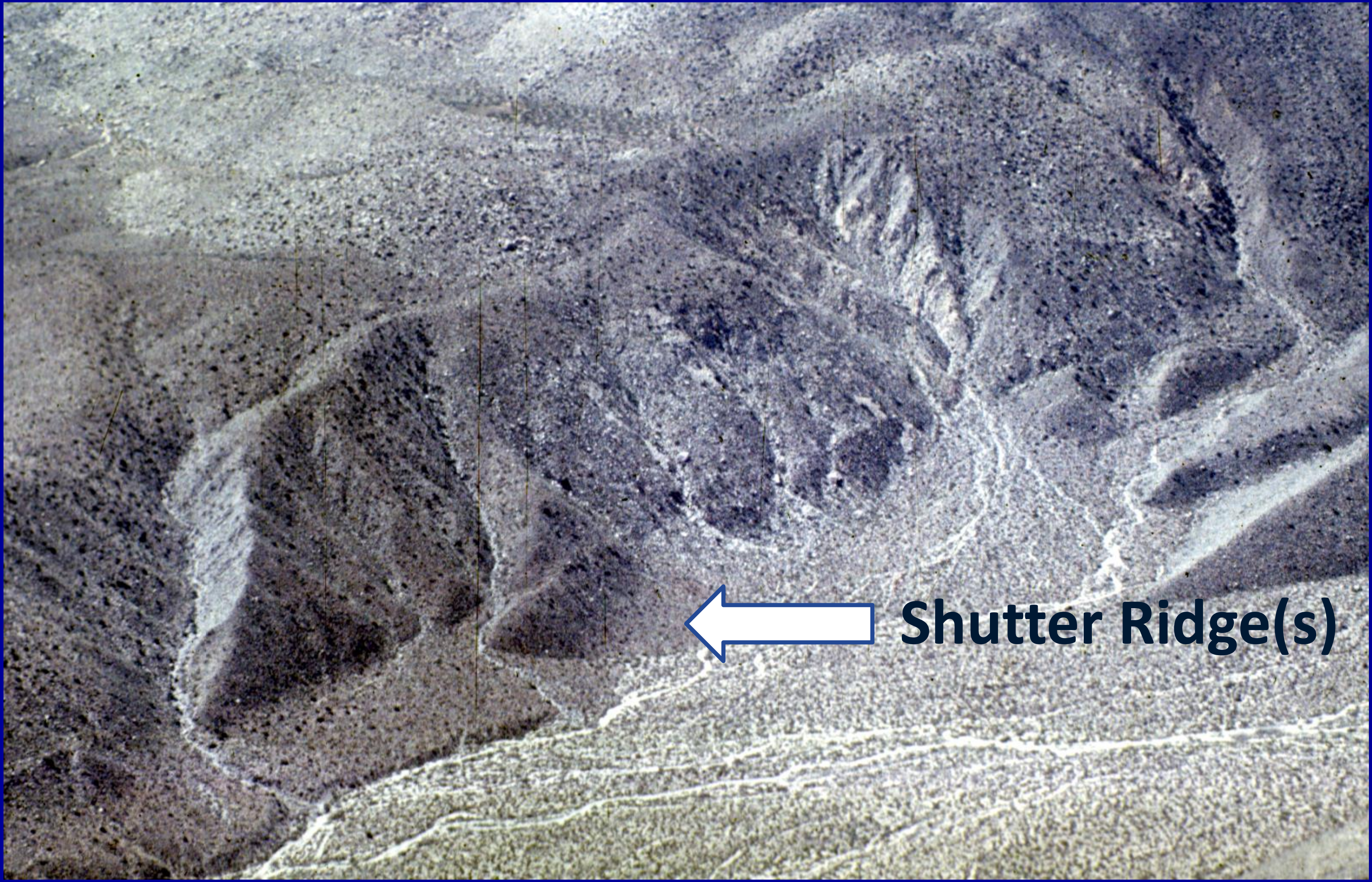
- Hřbet, který se pohyboval podél horizontálního zlomu a zablokoval odtok, údolí



Clark strand of the San Jacinto

Hector Mine Rupture, 1999

San Jacinto Fault, Southern California



Linear valleys

Linear valleys - related to faulting or just fault-line eroding crushed fault zone rocks

Transtension/Transpression

- Both occur at all scales!   Local to regional features
- Controlled by bends in SS fault (local), or overall convergence/divergence along a SS fault (regional)

Transtension

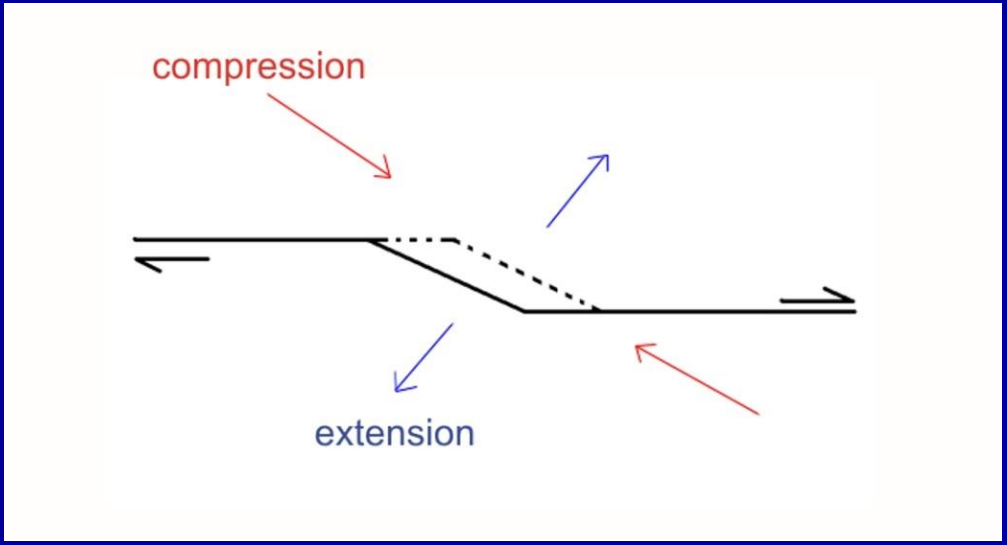
- Simultaneous occurrence of strike-slip faulting and extension

Transpression

- Simultaneous occurrence of strike-slip faulting and shortening

Transtension

- Component of divergence along SS fault (strike-slip)
- Right steps in Dextral SS fault
- Left steps in Sinistral SS fault



Opening causes a “sag,” or pull-apart basin

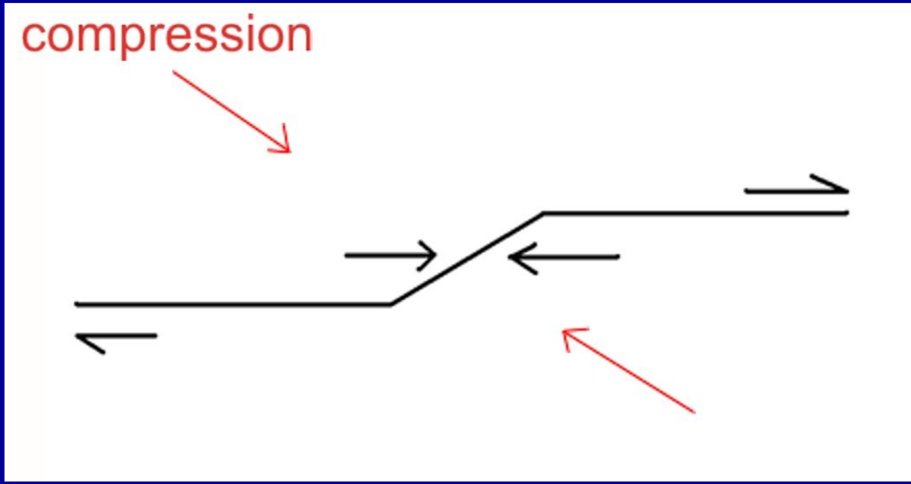
Sag Ponds

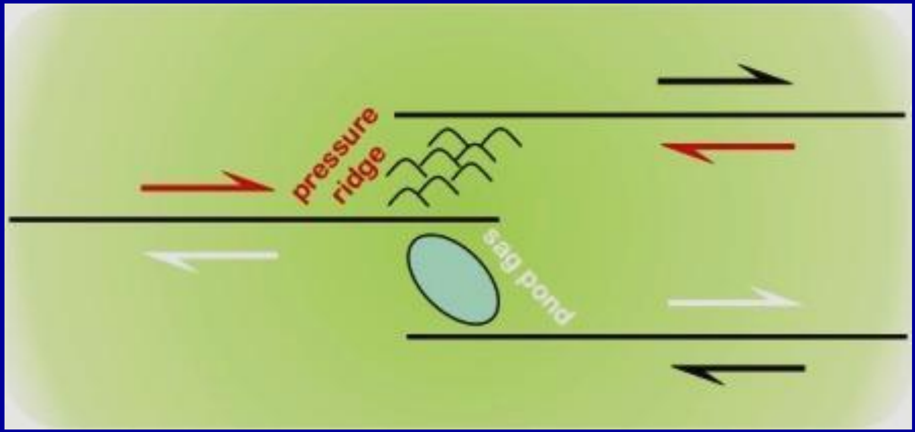
San Andreas

Topographic depression produced by extensional bends or stepovers along a strike-slip fault. It may or may not contain water year-round. Synonymous with pull-apart basin.

Transpression

- Component of convergence along SS fault
- Left step in Dextral SS fault
- Right step in Sinistral SS Fault





Right-step causes a space problem, and a “pressure ridge” is formed

Pressure ridge

A topographic ridge produced by compressional bends or stepovers along a **strike-slip fault**

Small pressure ridge along SAF in Cholame Valley

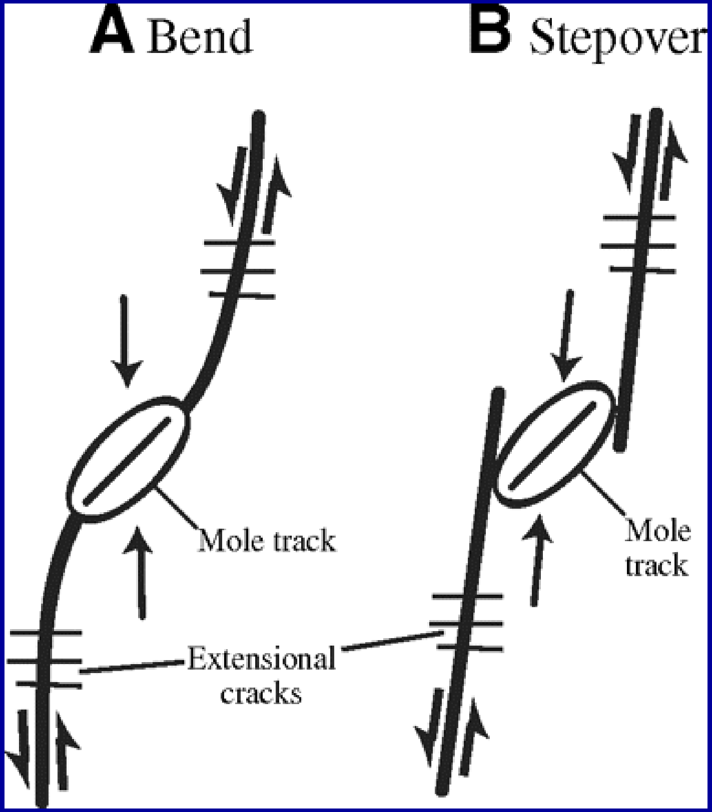
Dragon’s Back Pressure Ridge System along the San Andreas

Pressure ridge

Thousands Palms – Indio Hills, San Andreas fault

„Mole track“ structure

Material is extruded along the fault by pressure

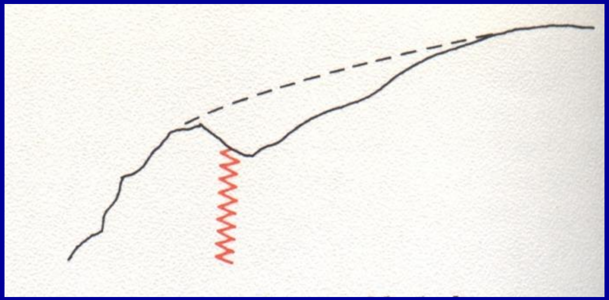


Kunlun fault, Tibet, 2001   M = 7.8

SAF, San Francisco 1906, M = 7.9

Denali fault, Alaska

Side-Hill Benches/Valleys



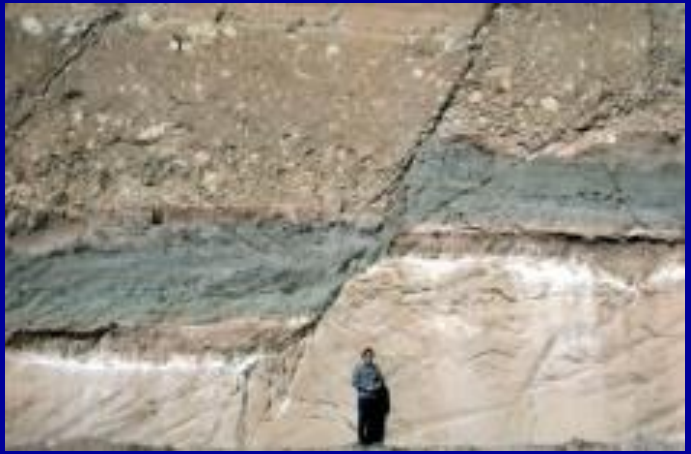
Parallel faults, Kresna Gorge, Bulgary

Slope inflection along San Andreas Fault

Flat step on the slope

Geomorphology of Extensional Faulting: normal fault

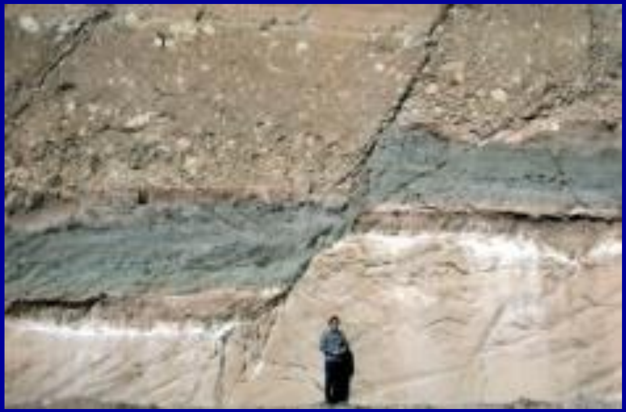
Zanjan. Iran

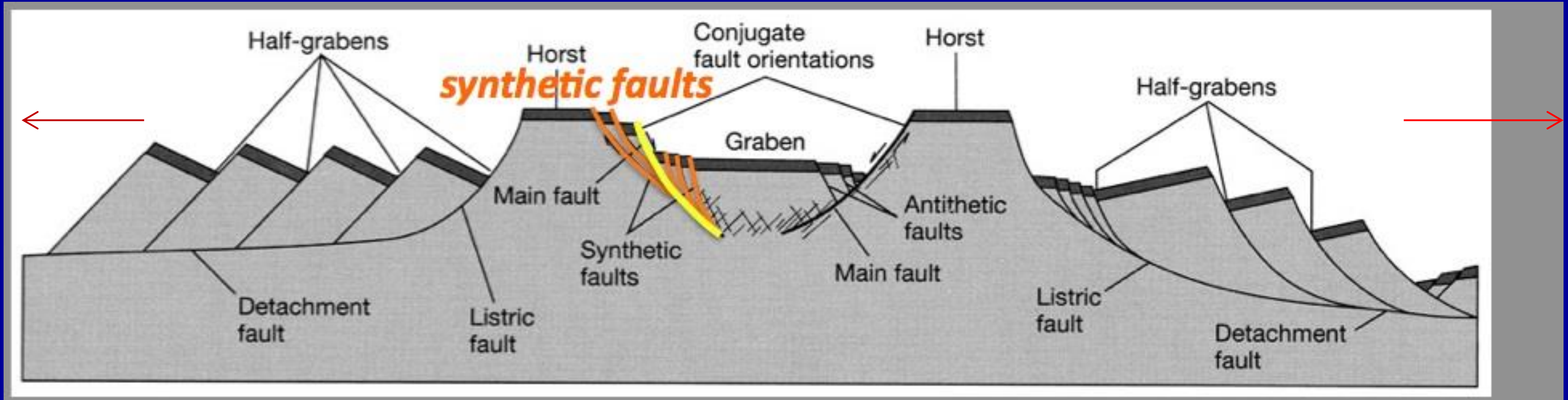


Extensional Faulting

Displacement accommodated in normal faults
- Single, Parallel synthetic, Antithetic

Primary normal fault (60-70°)
- Crustal penetrating fault
- Often has km of displacement
- Separates linear mountain range from adjacent basin
  - Up-faulted block (horst)
  - Down-faulted block(graben)

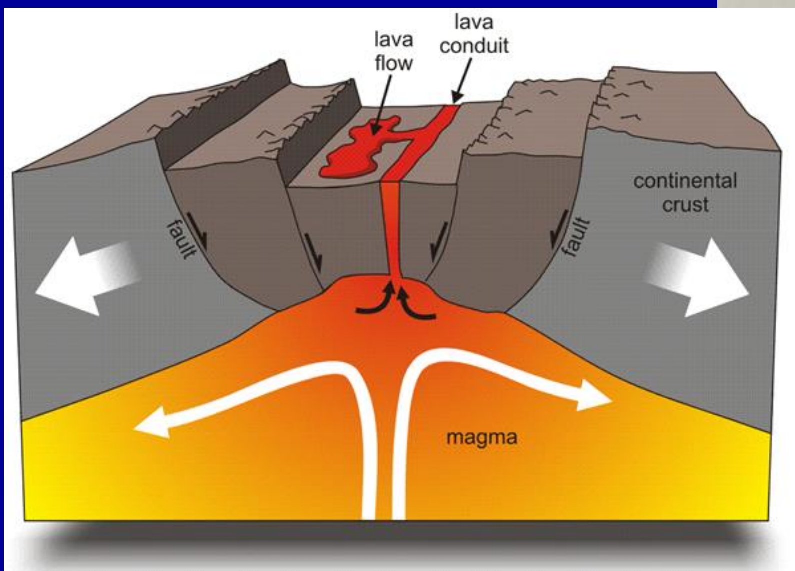


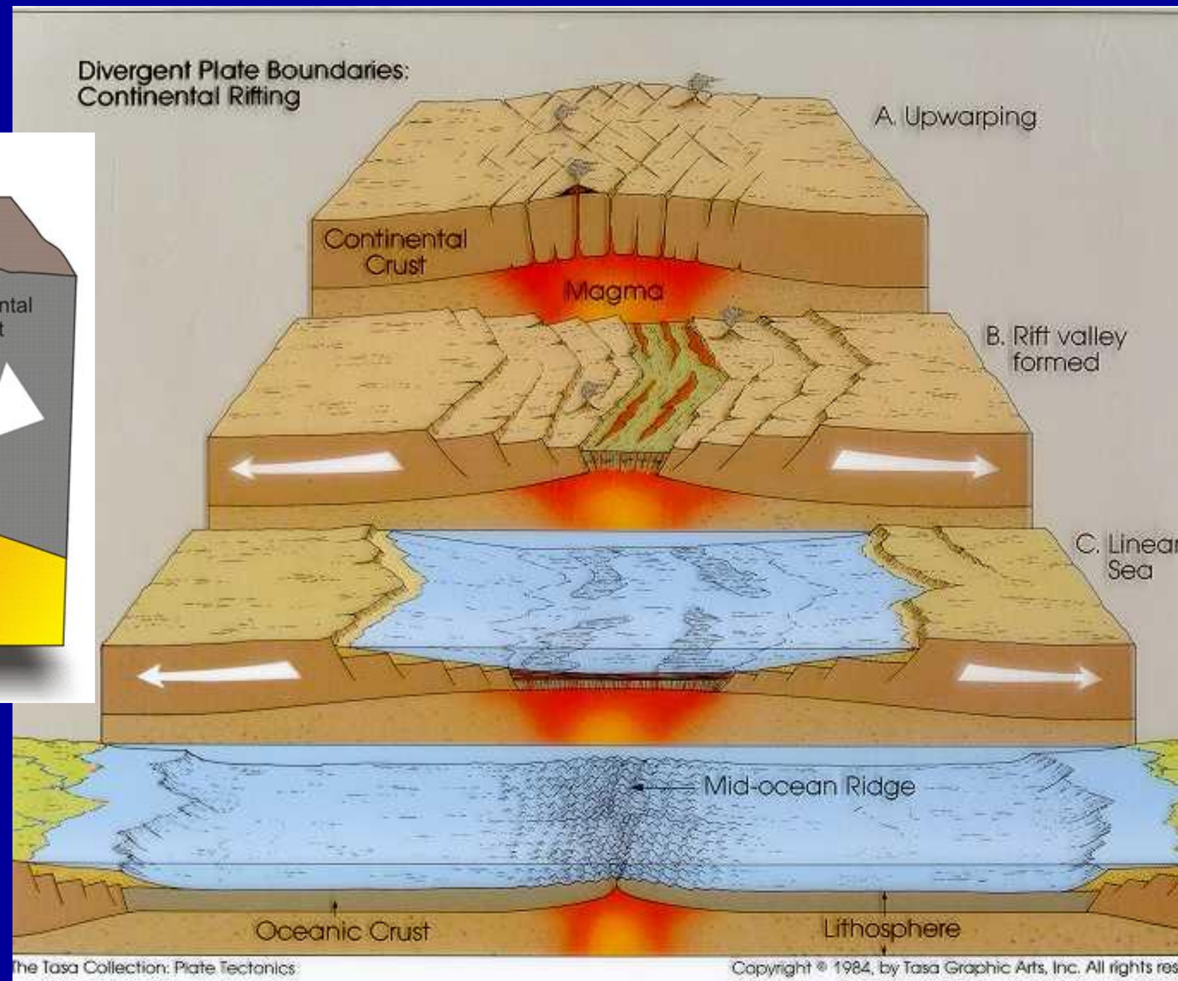


- Subsidiary faults dipping in the same direction as the major fault are synthetic. Those dipping opposite to the major fault are antithetic.

Crustal extension and normal faults – related to the most remarkable topography at regional scale

Rifts valleys

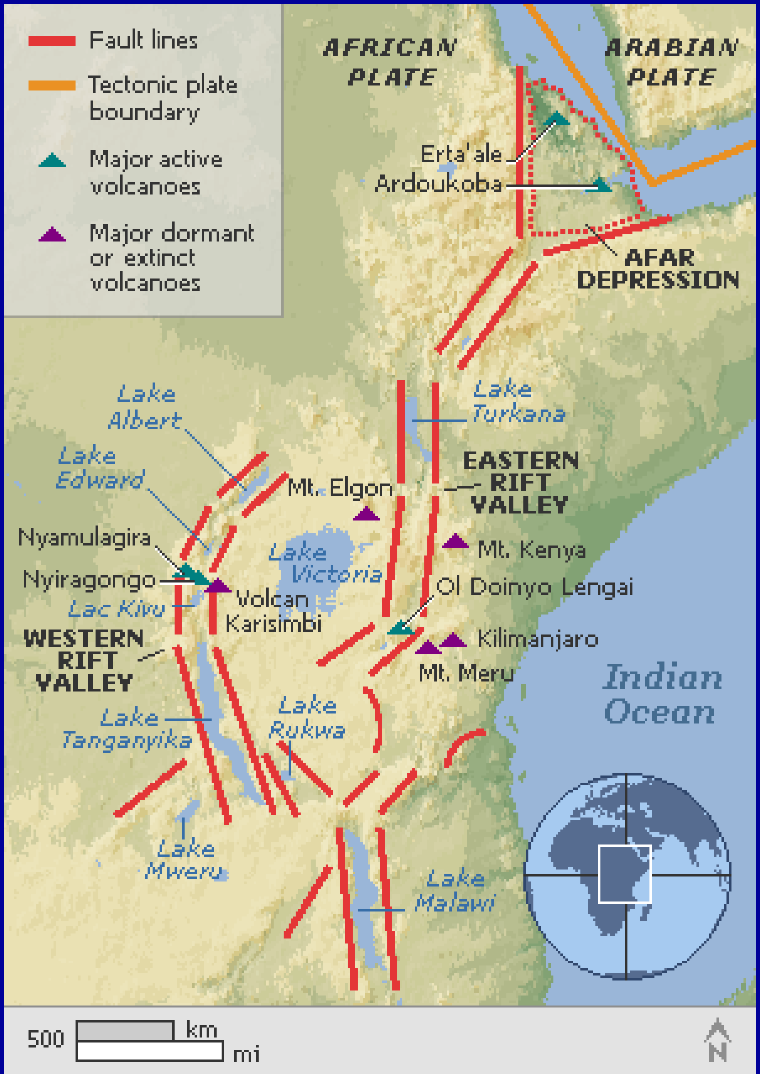


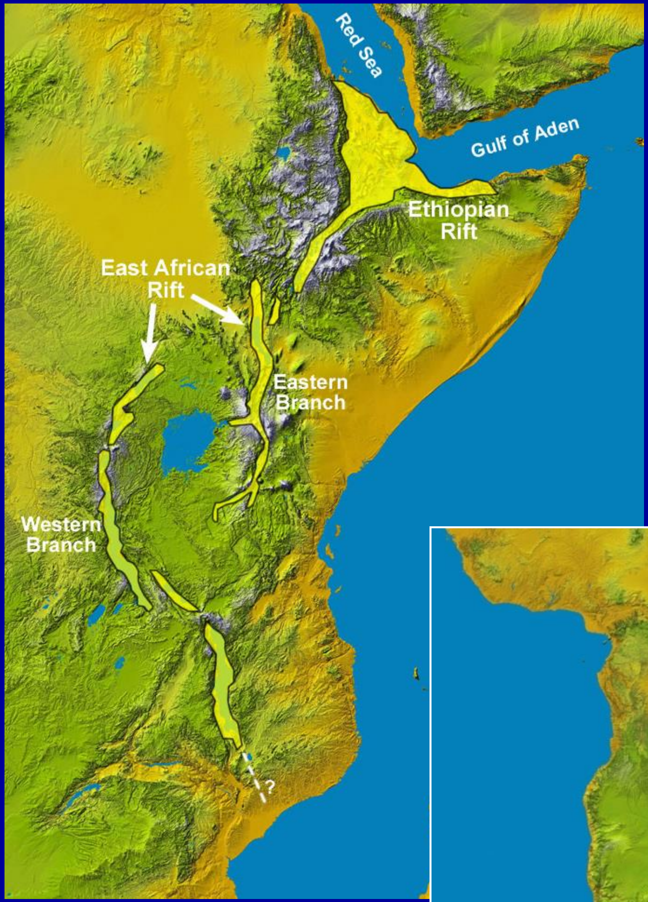


rift – elevated heatflow,
vertical compression,
horizontal extension

East African Rift Valley

active divergence, rift – numerous of normal faults





East African rift in 20 mil years

Hayli Gubbi, shield volcano, crater inside caldera, Afar region, Ethiopia

Normal faults disecting the volcanos, Afar

Massive fissure splits open in the Ethiopian Desert

Rift activity 2009

Escarpments

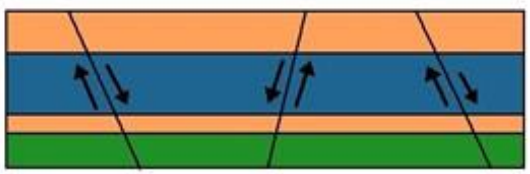
Rift Valley - Tanzania

Main Ethiopian Rift Valley

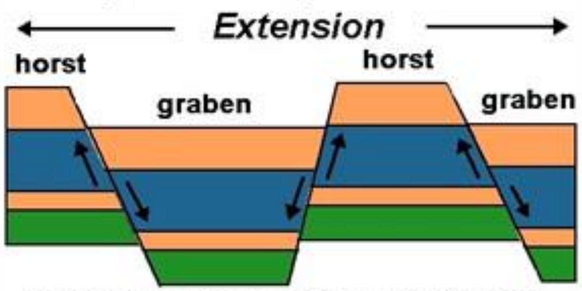
They has been formed during millions years

Textbook horst and graben formation

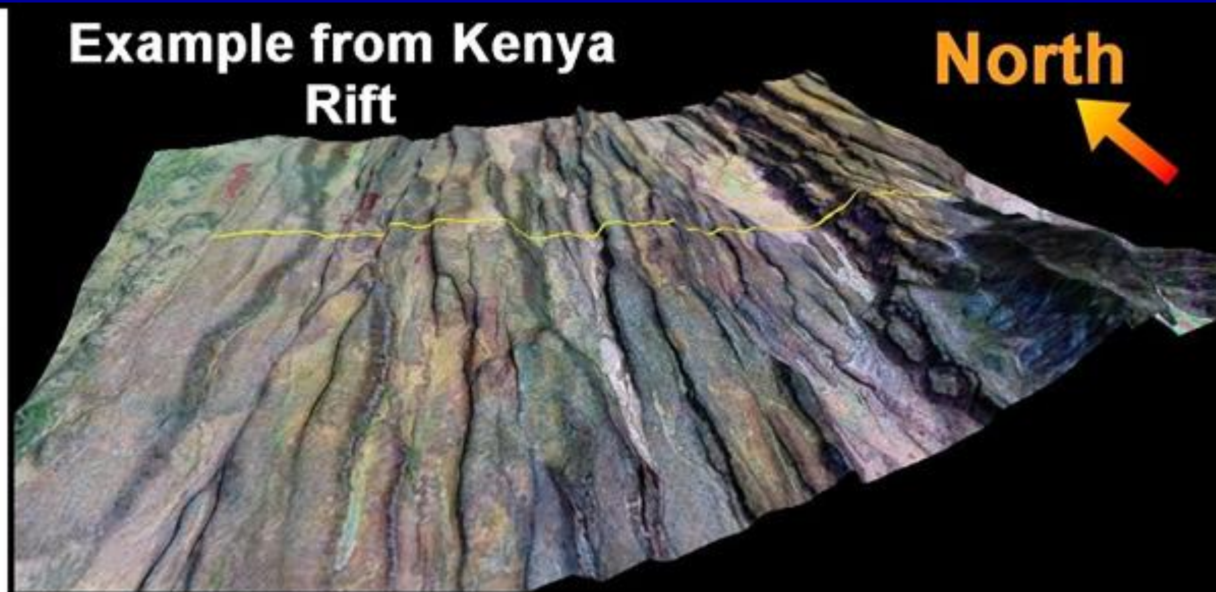
1. Layered rock units



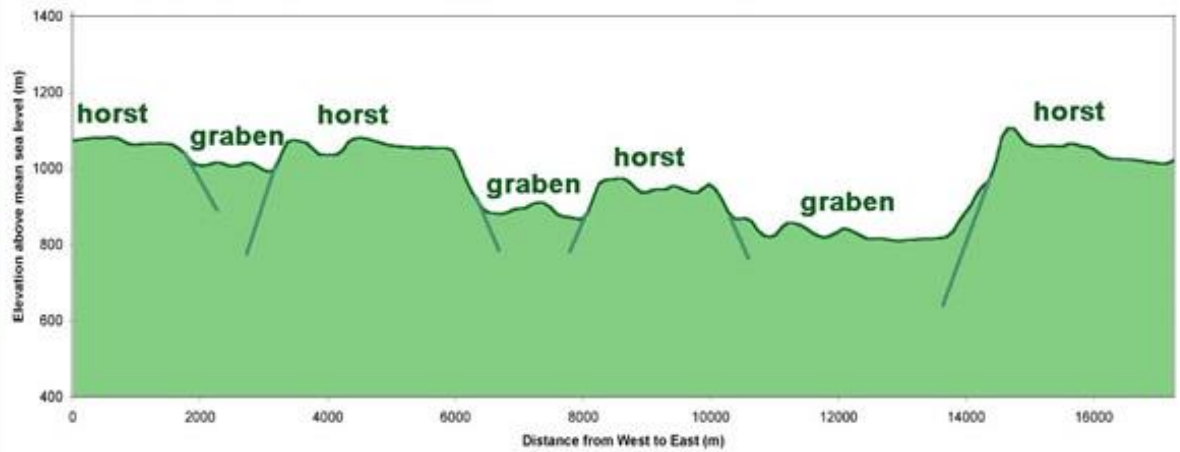
2. Layers are cut by normal faults



3. Down-dropped blocks are grabens, and upthrown blocks are horsts, note that the extension that occured.



Topographic profile along yellow line showing horst and graben structures

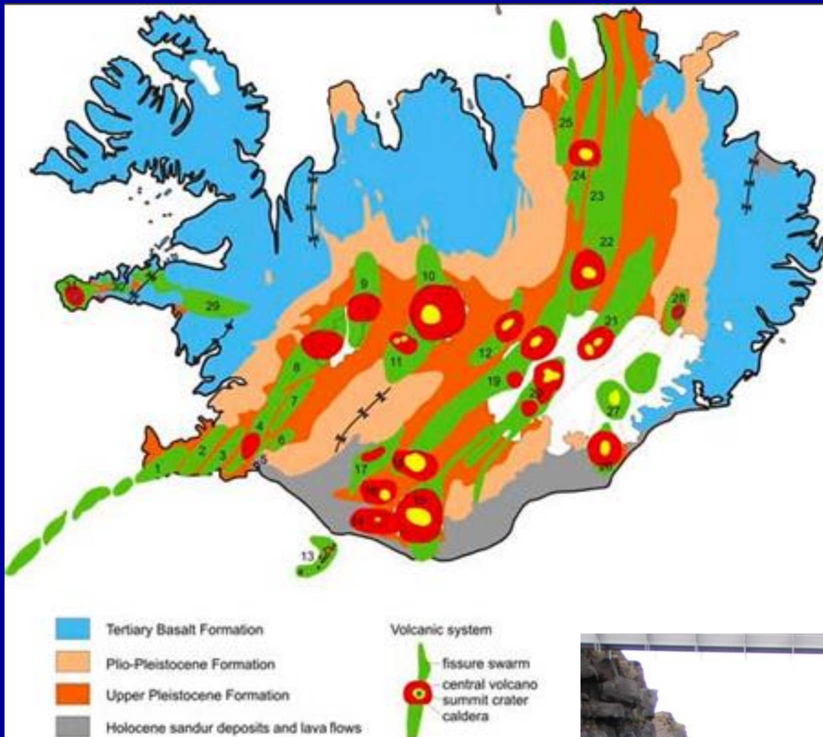


Iceland – Rift Valley

ridge represents submarine segments of the mid-ocean ridge

Image Source:
http://commons.wikimedia.org/wiki/File:Iceland_Mid-Atlantic_Ridge_Fig16.gif

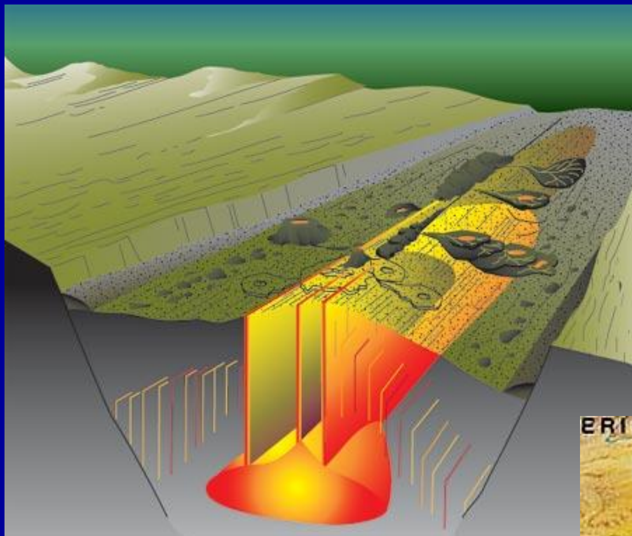
Iceland - shaded area shows the Icelandic Basalt Plateau, red points the migration of the hot spot and orange lines are the rifts, both active and inactive.



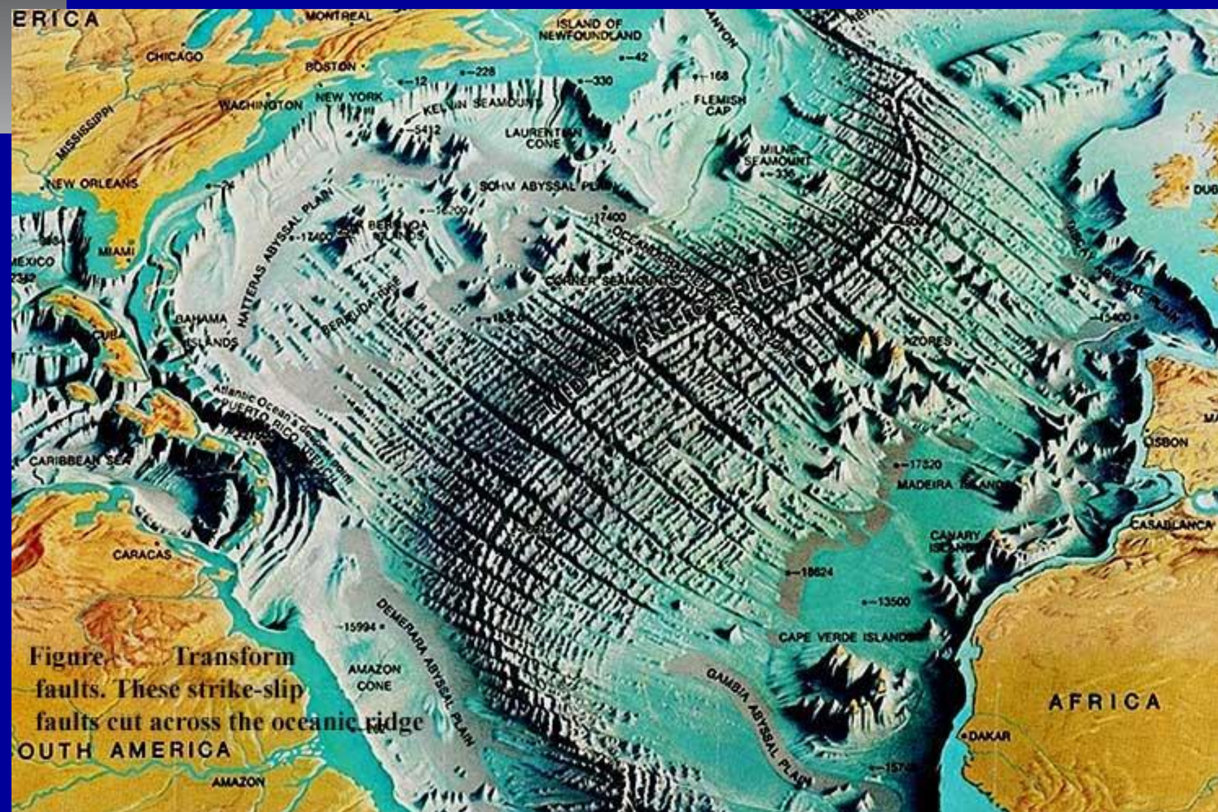
Geological map of Iceland - volcanic systems and volcanic zones and the division of the isla into formations.

Each volcano with the typical lifetime of 0.5-1.5 my. Around 30 active volcanic systems in Iceland.

Rift valley, Thingvellir national park, Iceland



Ocean ridge – basaltic oceanic crust



Mid-Atlantic oceanic ridge