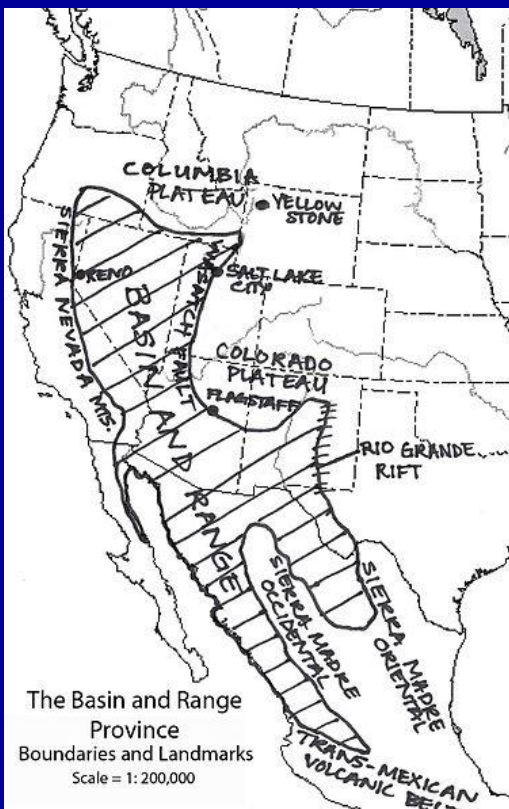
Basin and Range topography

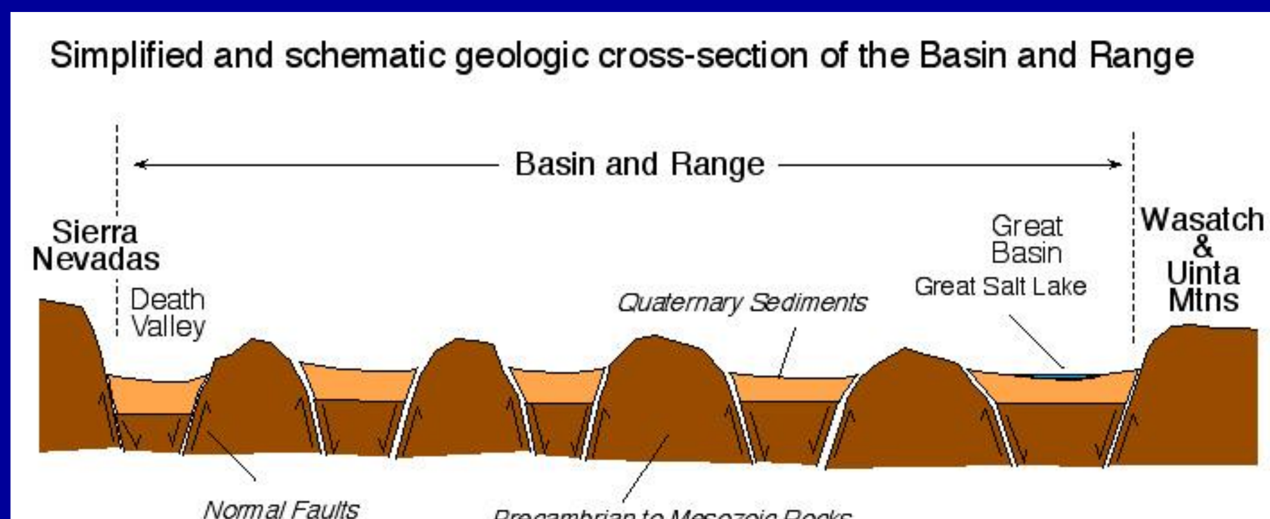
broad extensional faulting

Basin and Range Province



extension and thinning of the lithosphere, listric faults, grabens, horsts

elevated heat flow, geothermal energy

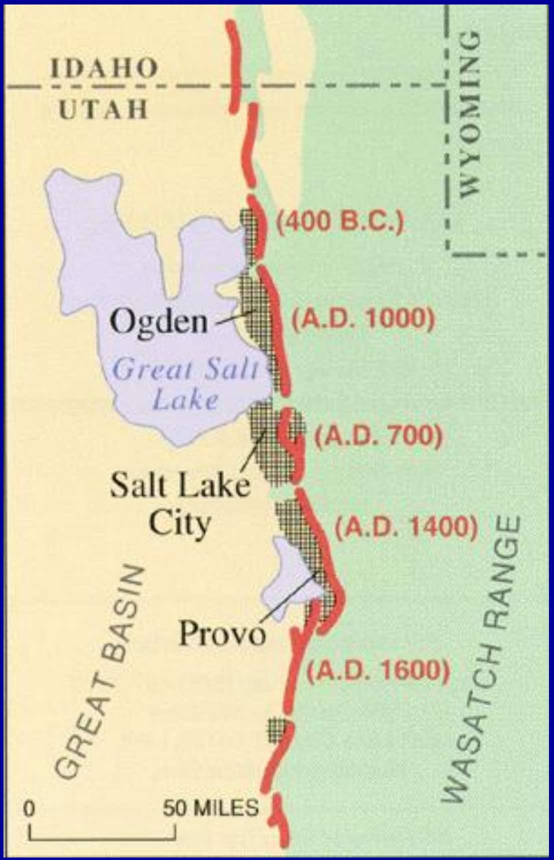


From Sierra Nevada to Wasatch Mts – 800 km

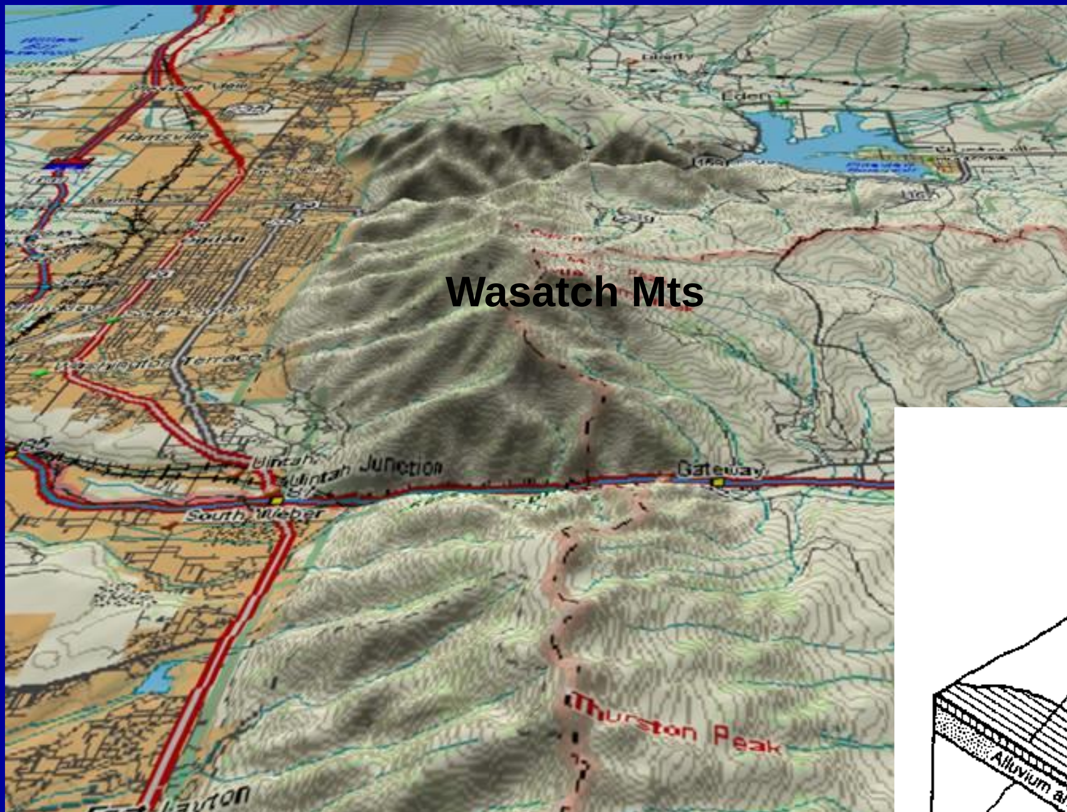
„Local scale„ normal faults

Fault trace of normal faults tends to be short 10-50 km

The **Wasatch fault**, forms the eastern boundary of the Basin and Range geologic province frontal fault are up to 400 km long, composed of separate faults or segments 30 – 60 km long, average of 40 km, each of which can independently produce earthquakes as powerful as local magnitude 7.5

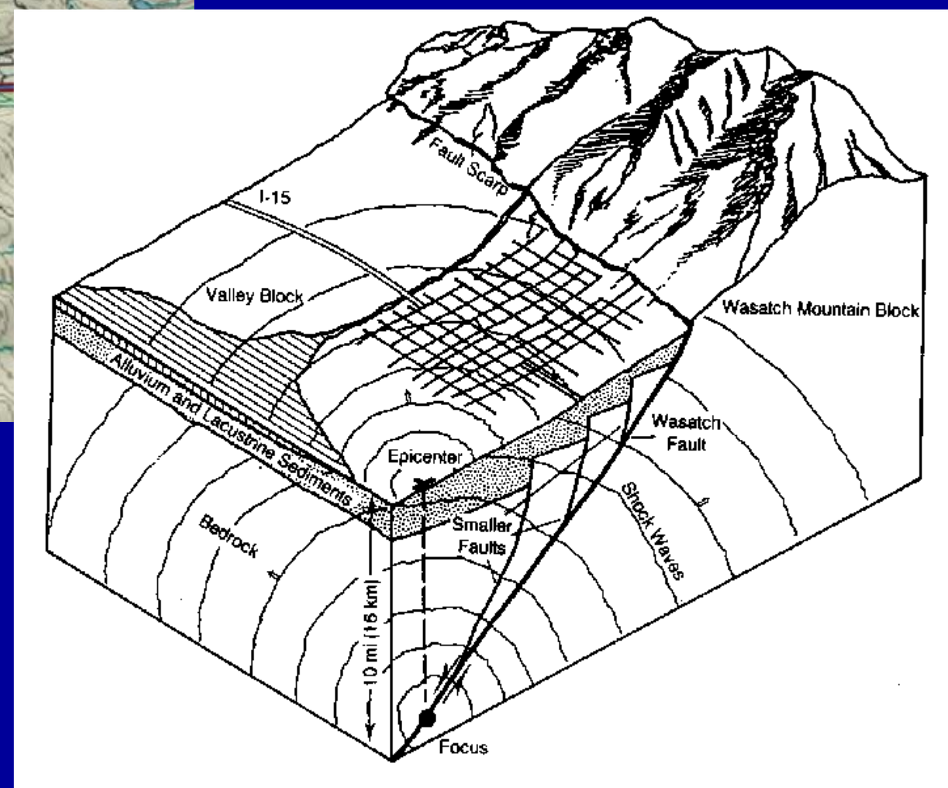


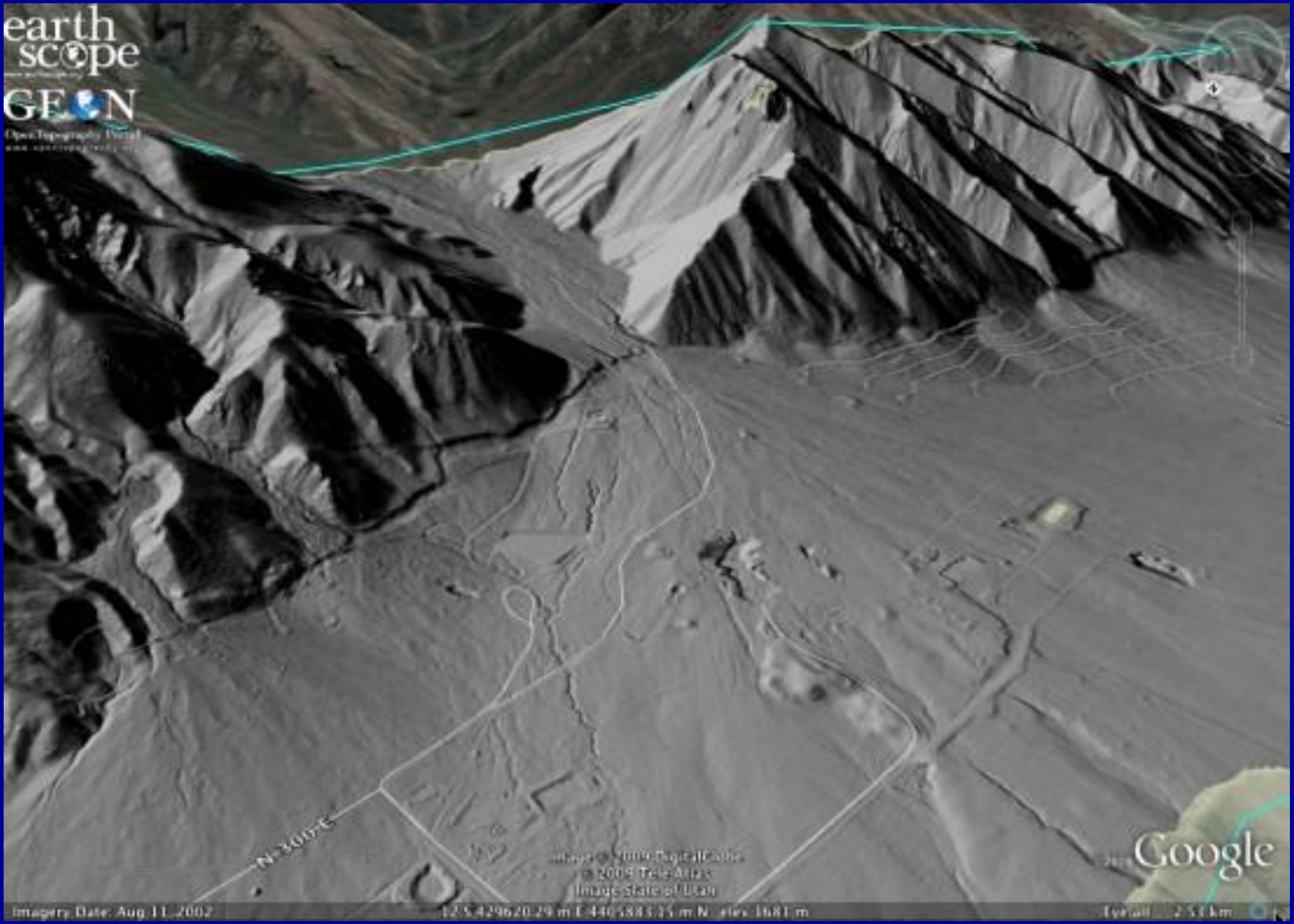
Linear mountain fronts



Linear mountaint front
- repeated earthquakes

The Wasatch Mountains have been uplifted and tilted to the east by movement of the fault. The average rate of uplift along the fault over its history is approximately 1 mm per year.





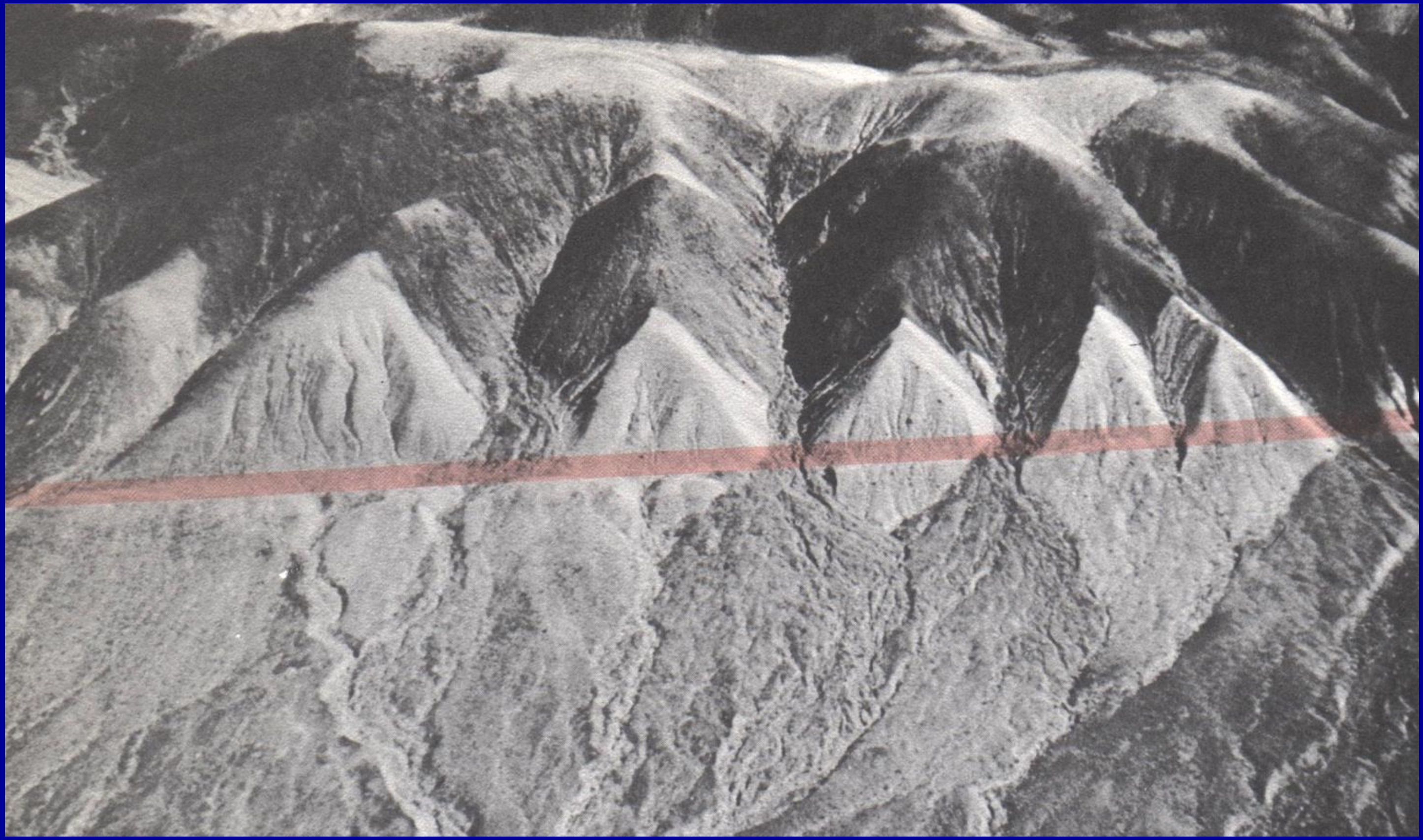
Scarp on the southern part of the Nephi strand of the Wasatch fault:

Wasatch fault

Multiple fault scarps (marked by arrows) cut across 16,000 to 18,000-year-old glacial moraines in Salt Lake County. Some of the scarps are 30 to 40m high, indicating they were formed by repeated large earthquakes (possibly as many as seven to ten events) in the past 18,000 years

Triangular (trapezoidal) facets

- dissected mountain front by rivers, setries of facets - „flatirons“



un-named fault in California, SE from Panamint Valley

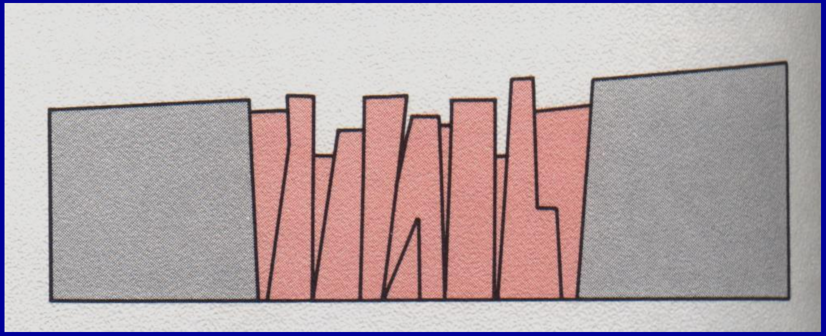
Bloom (1978)

Triangular facets aligned on the fault scarp of Maple Mountain, 15 km south of Provo, Utah. View east. (Photo: H. J. Bissell.)

Subsided blocks

Narrow block subsided between two ridges uplifted by strands of San Andrea Fault

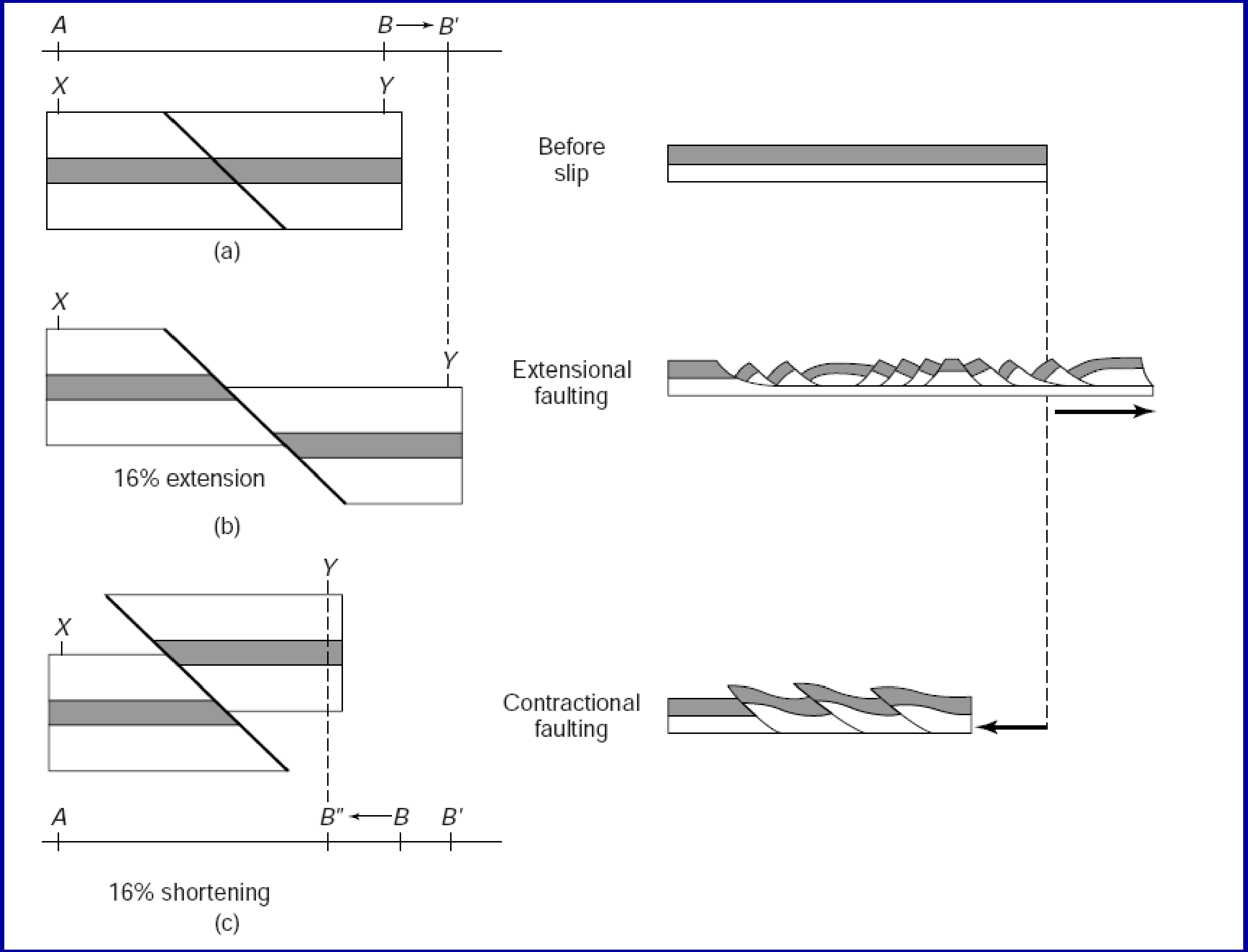
sags and ridges – by uneven blocks uplift



Crustal Shortening :
Reverse Faulting, Folding and Uplifting

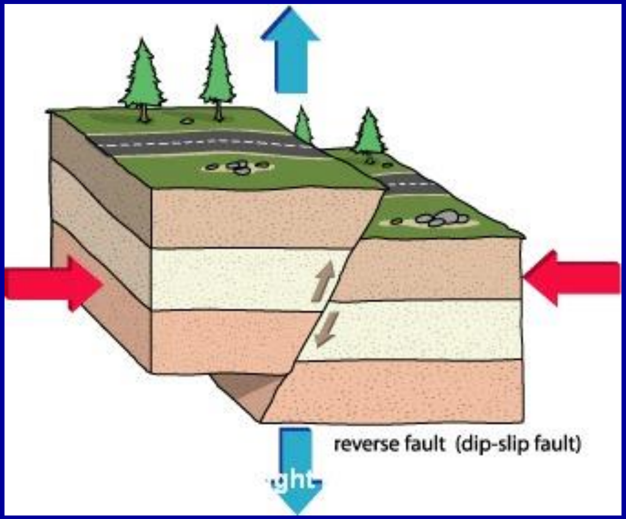
Crustal shortening + thickening

- Crustal shortening is the reduction of the size of the Earth's crust through convergent plate boundary (compression)

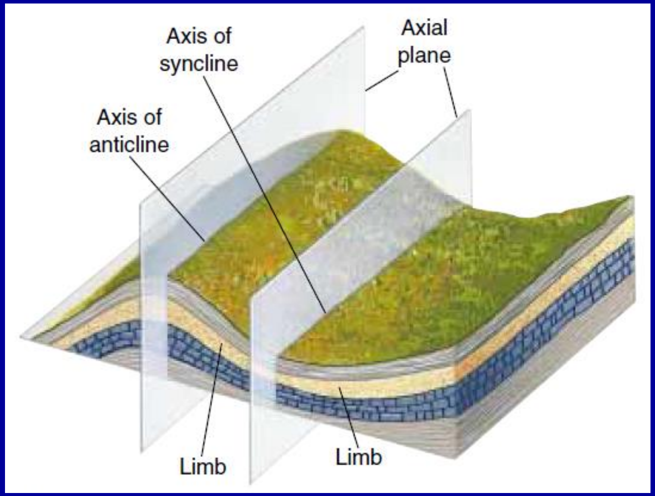


Crustal Shortening

- Implications :
  - Reverse/Thrust Fault

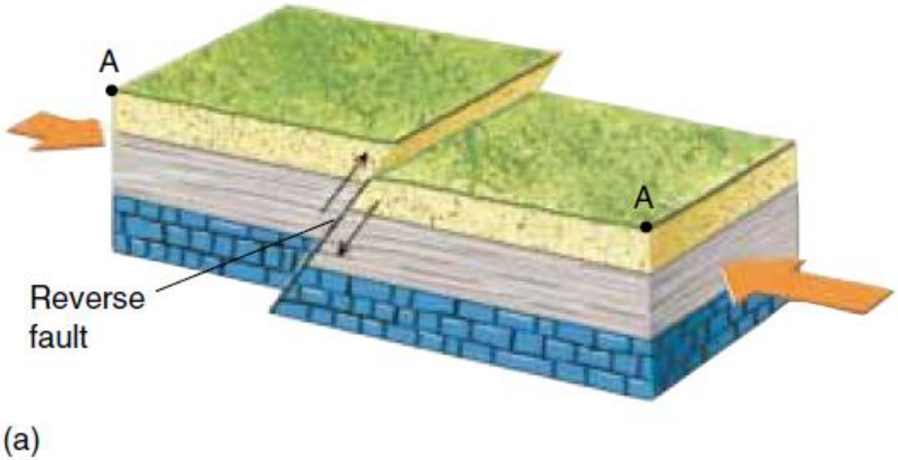


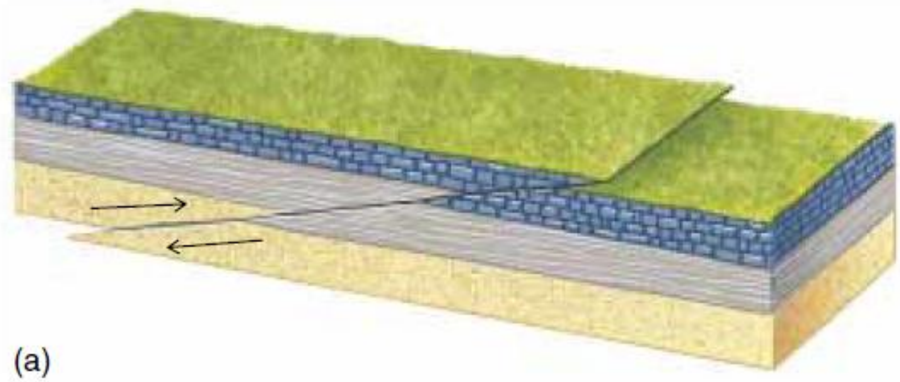
  - Fold



  - Uplift

Reverse – Thrust Fault



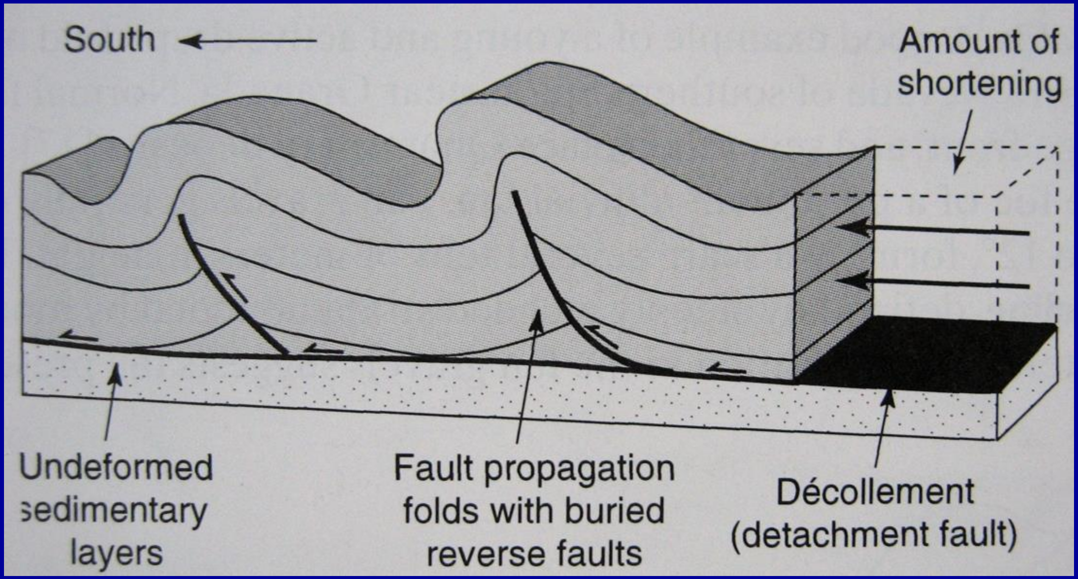


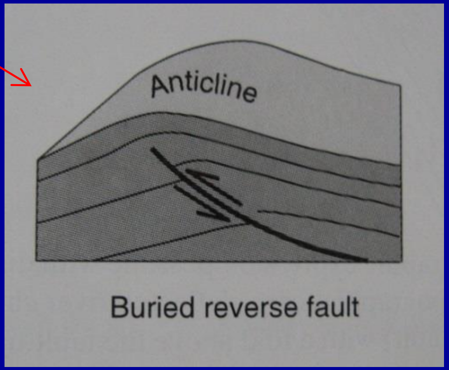
Reverse Fault : > 45^0

Thrust Fault : <45^0

Thrust faults associated with subduction produce a variety of landforms –
- uplifted coastal terraces, anticlinal hills (upwarped) and synclinal lowlands (downwarped)

Thrust faults – often associated with fold - in **fold-and-thrust belts**
- some of the thrusts and reverse fault may **break the surface** or they remain **hidden** in the core of anticline – **blind reverse fault**



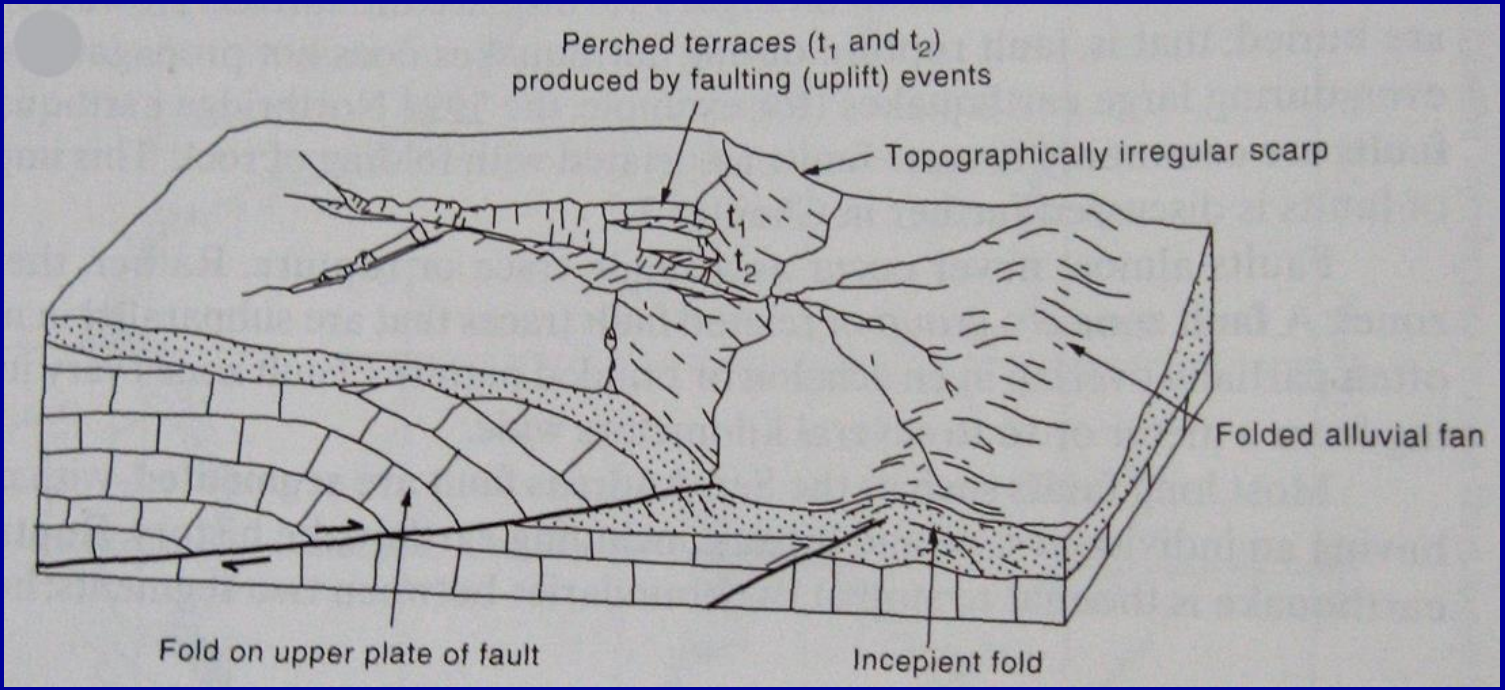


Asymmetric **fault-propagation fold** developed over a décollement

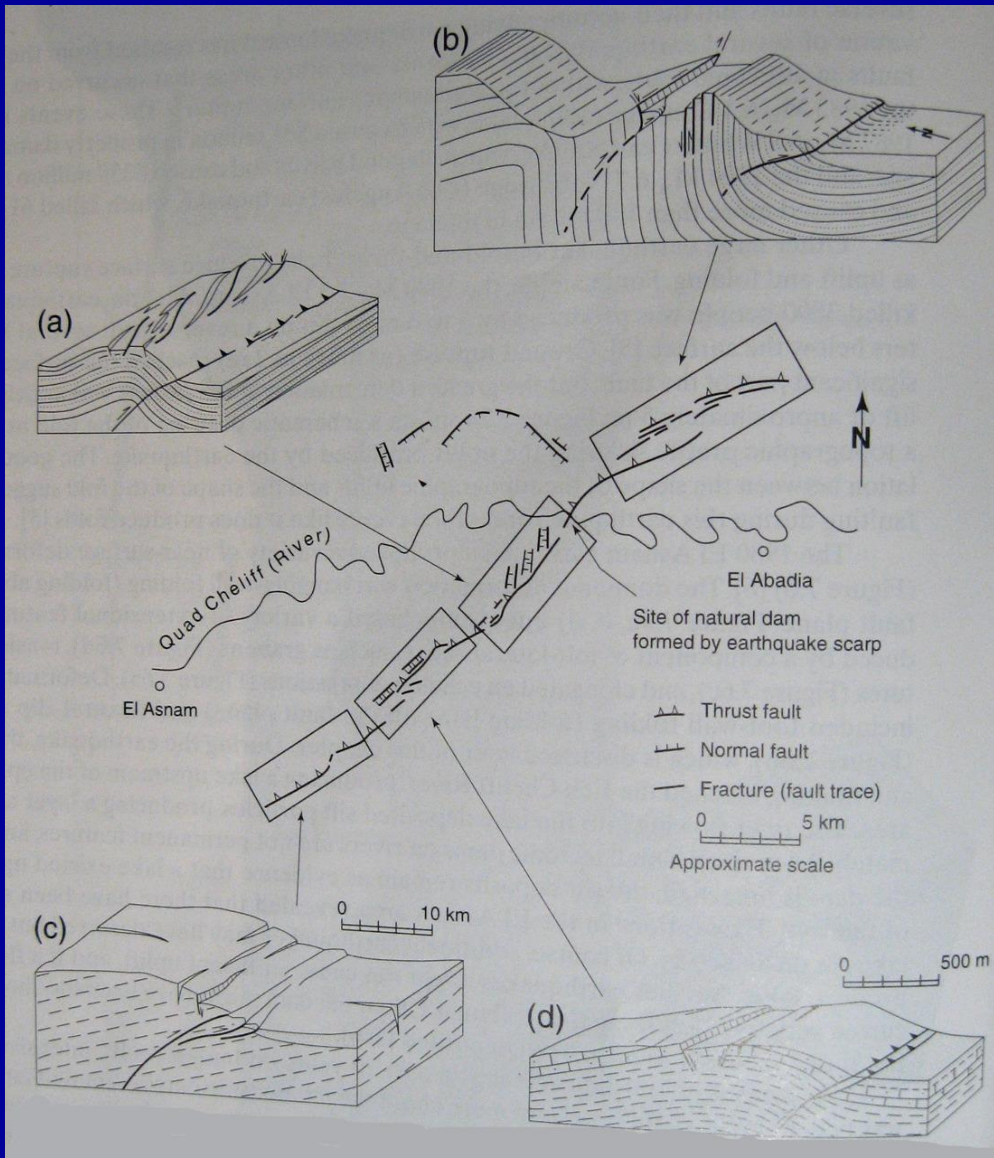
Reverse faults- closely related to folds
Rate of lateral propagation of faults and fold may be sveral times **higher than vertical slip rate** of the fault

Landforms associated with reverse faulting

steep mountain fronts, fault scarps, fold scarps, extensional features, and landslides



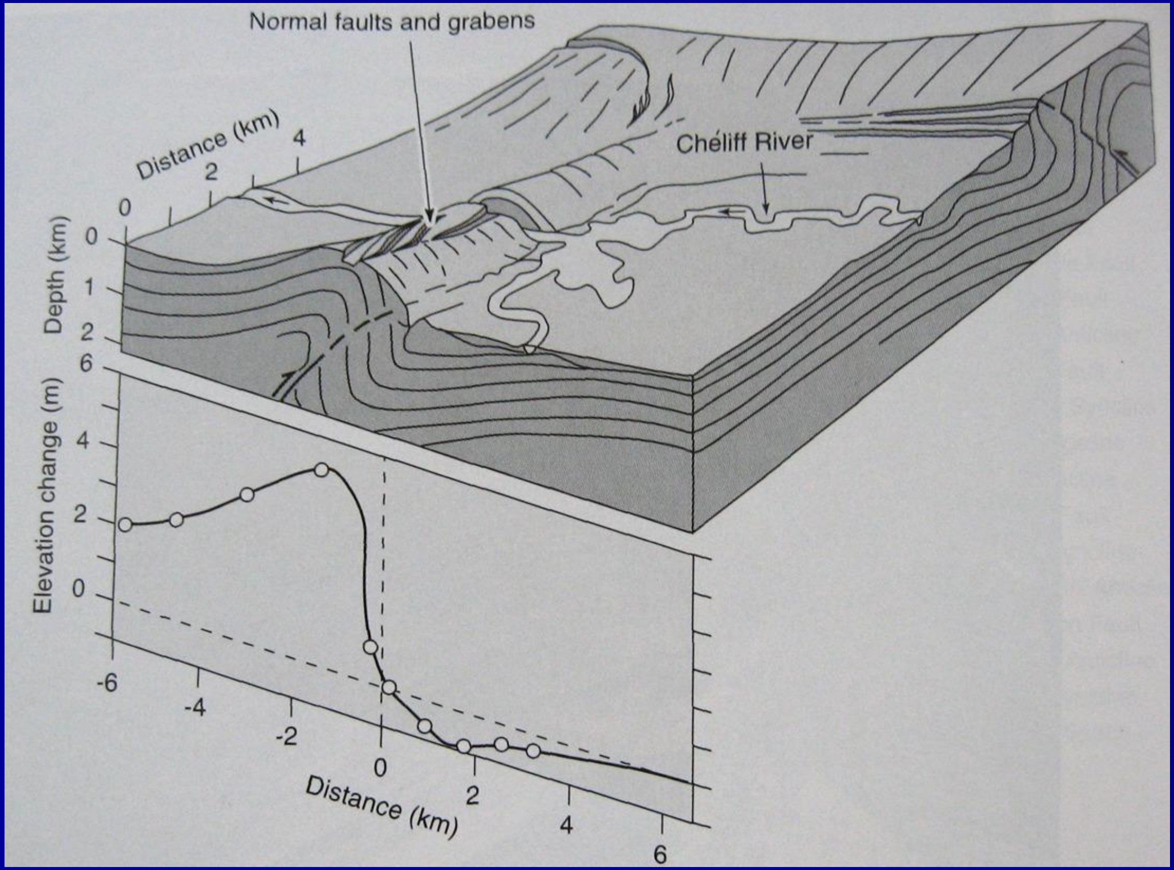
1980 EL Asnam M=7.3, Algeria – fold-and-thrust belt



(Philip, Meghraoui, 1983)

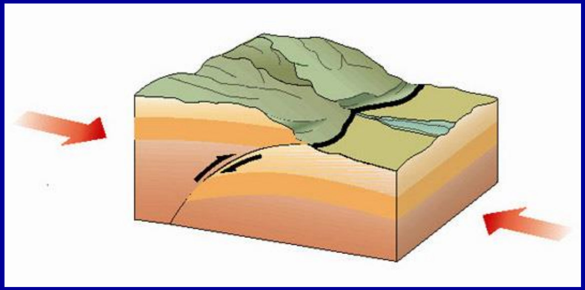
3-6 m slip on reverse fault at the depth,
surface rupture - 2m
mostly anticlinal uplift of 5m
– **seismic folding**

a),b),c) hanging-wall folding
d) extensional features produced by component of left-lateral shear
c) tension fractures
a) elongated en echelon depressions
b) footwall folding and flexural-slip faulting



Graph of surface uplift produced by 1980 El Asnam EQ.
The fold was produced by repetaed earthuqakes

Bolcked river – formation of a lake with deposition of 0.4 m



Fault scarps

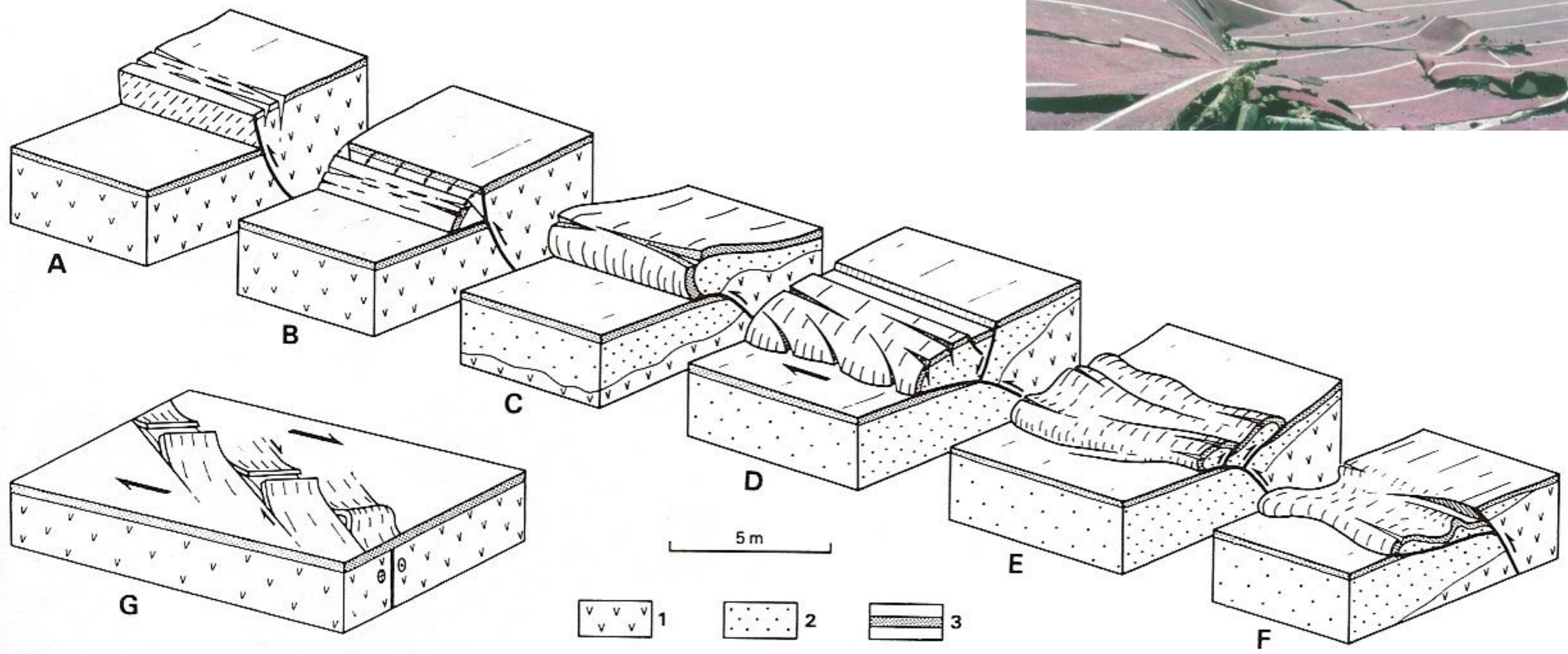
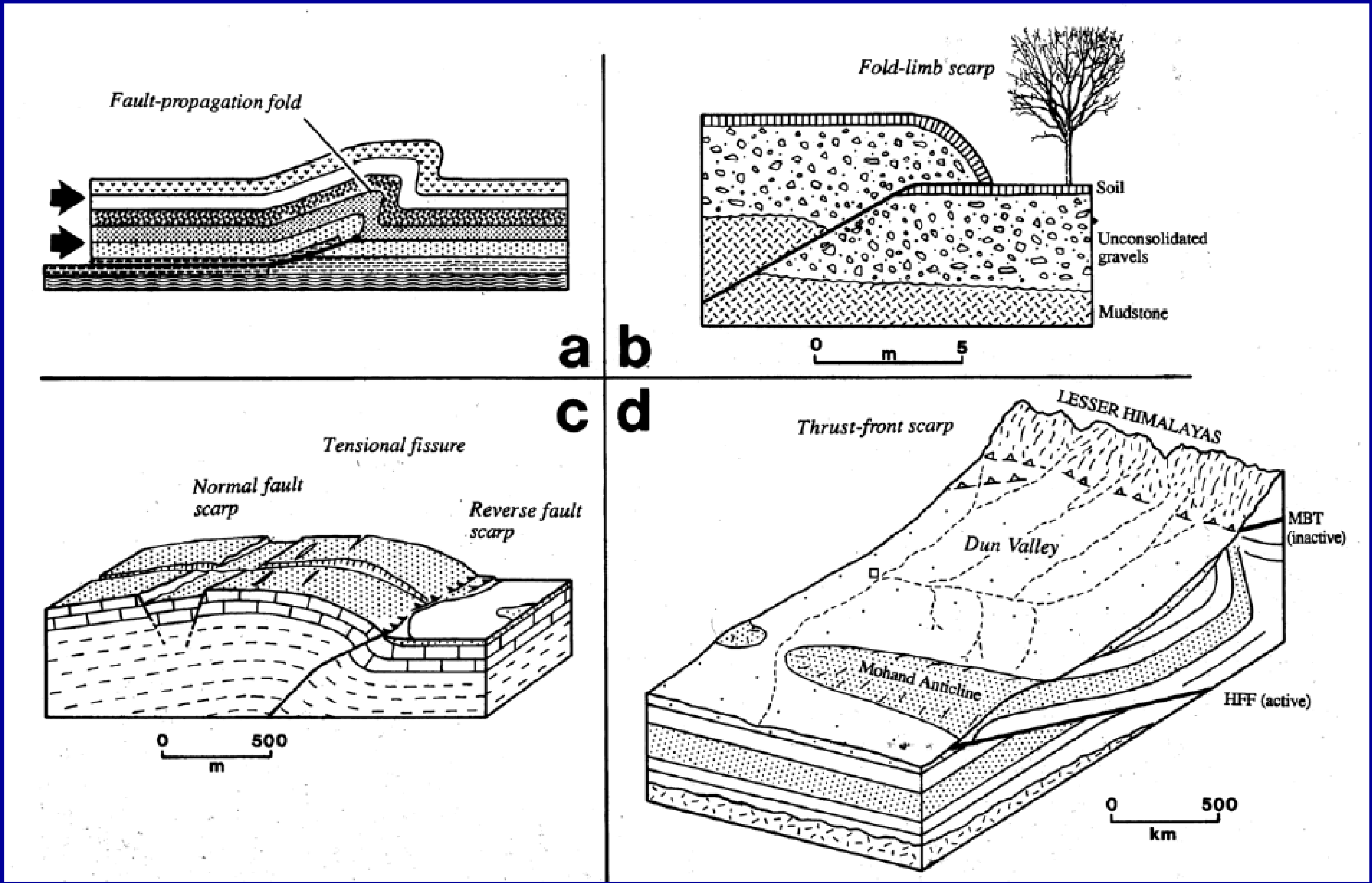


Figure 10–53. Fault-scarp features along the Spitak fault, Armenia. (a) simple thrust scarp; (b) hanging-wall collapse scarp; (c) simple pressure ridge; (d) dextral pressure ridge; (e) back-thrust pressure ridge; (f) low-angle pressure ridge: (g) en échelon pressure ridges. 1, bedrock; 2, soft Quaternary sediment; 3, turf. After Philip et al. (1992).


Fault-propagation fold
a
Fold-limb scarp
Soil
Unconsolidated gravels
Mudstone
b
0 m 5
c
Tensional fissure
Normal fault scarp
Reverse fault scarp
0 500
m
d
Thrust-front scarp
LESSER HIMALAYAS
MBT (inactive)
Dun Valley
Mohand Anticline
HFF (active)
0 500
km

Fold

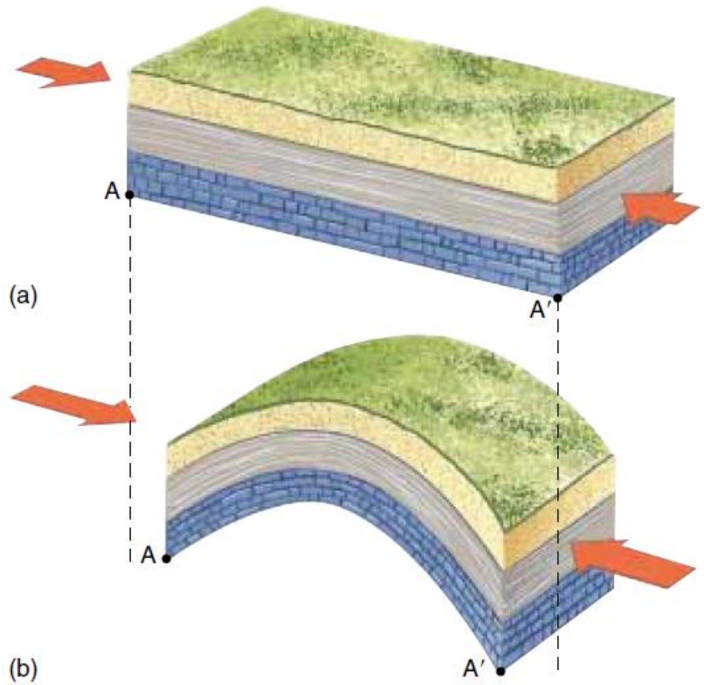
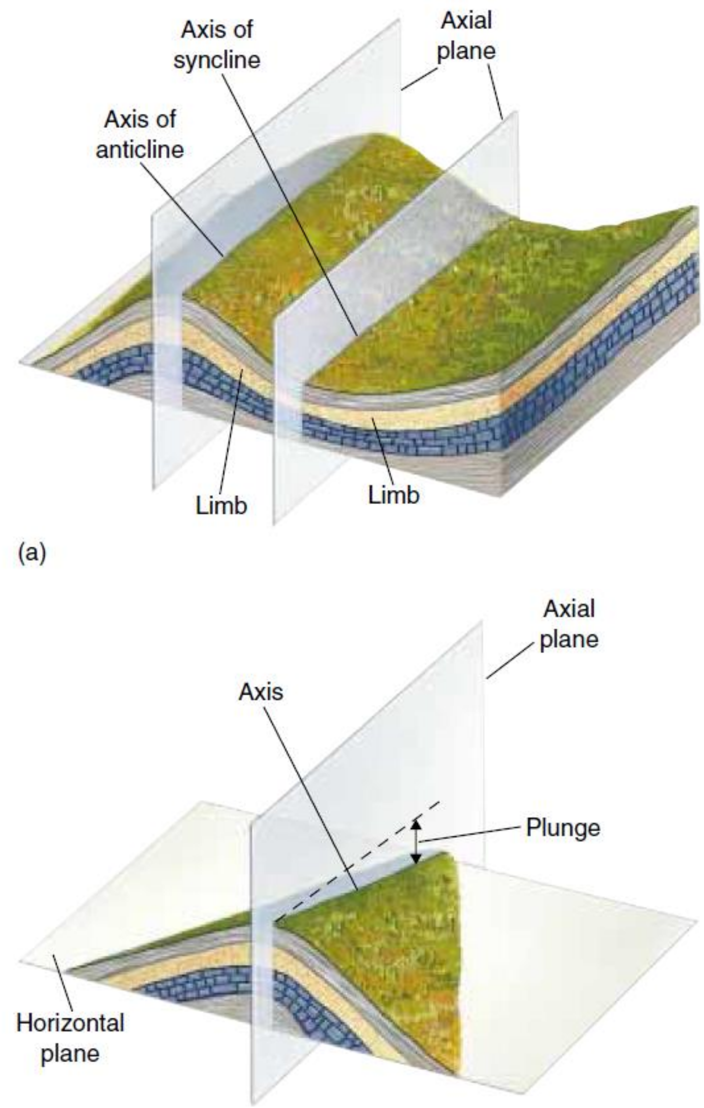
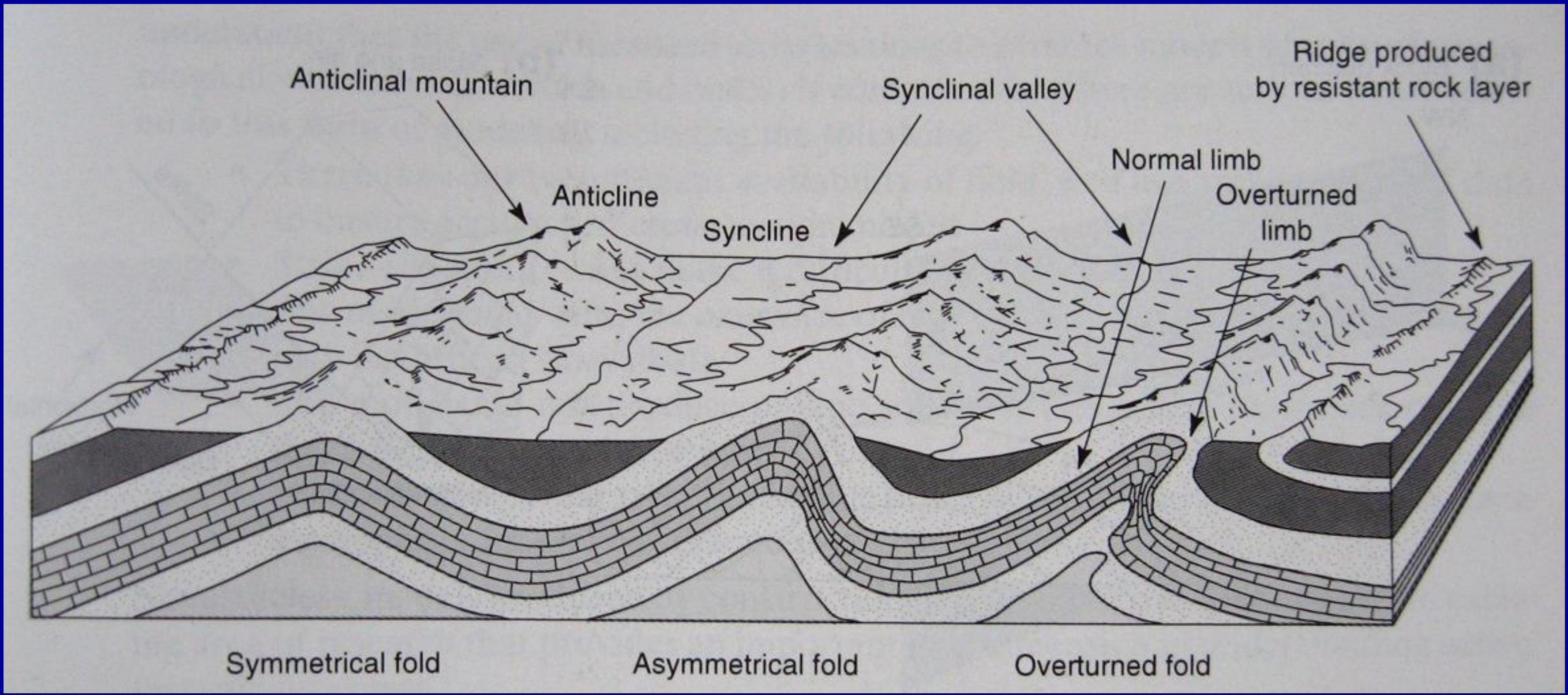


Figure 12–5 (a) Horizontally layered sedimentary rocks. (b) A fold in the same rocks. The forces that folded the rocks are shown by the arrows. Notice that points A and A′ are closer after folding.

1. Folding usually results from compressive stress. For example, tightly folded rocks in the Himalayas indicate that the region was subjected to compressive stress.
2. Folding always shortens the horizontal distances in




Anticlinal mountain
Synclinal valley
Ridge produced
by resistant rock layer
Normal limb
Anticline
Overturned
limb
Syncline
Symmetrical fold
Asymmetrical fold
Overturned fold

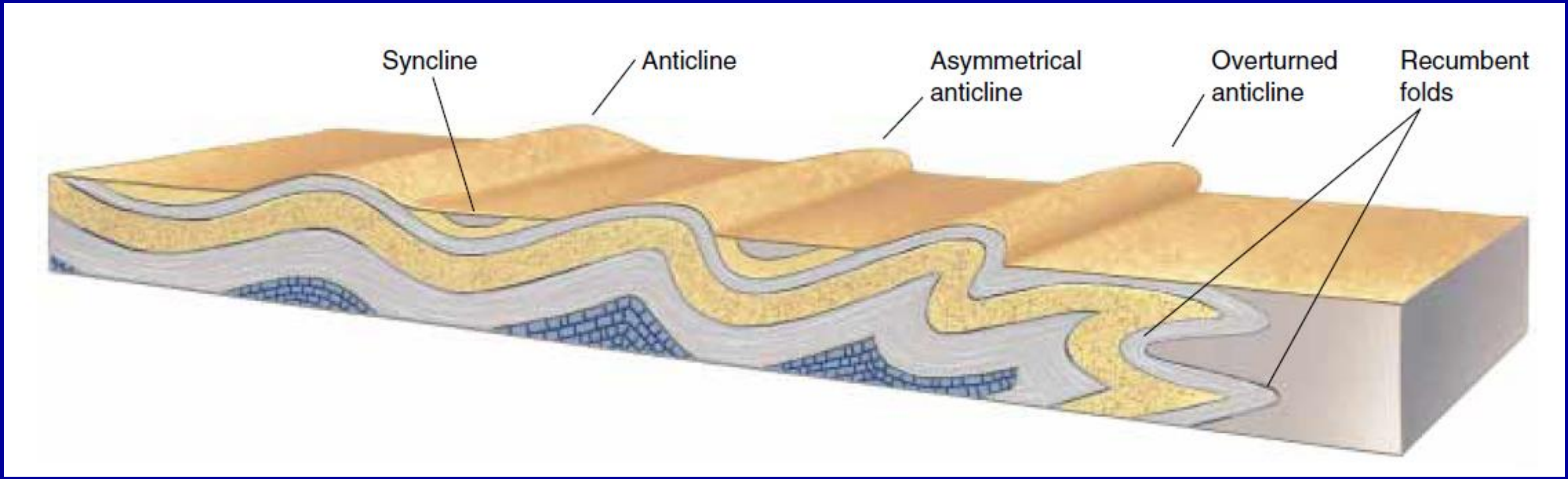

Syncline
Anticline
Asymmetrical
anticline
Overturned
anticline
Recumbent
folds

FIGURE 10.7 An asymmetric, plunging fold (the Sheep Mountain Anticline in Wyoming, USA).

Thompson and Turk, 1998

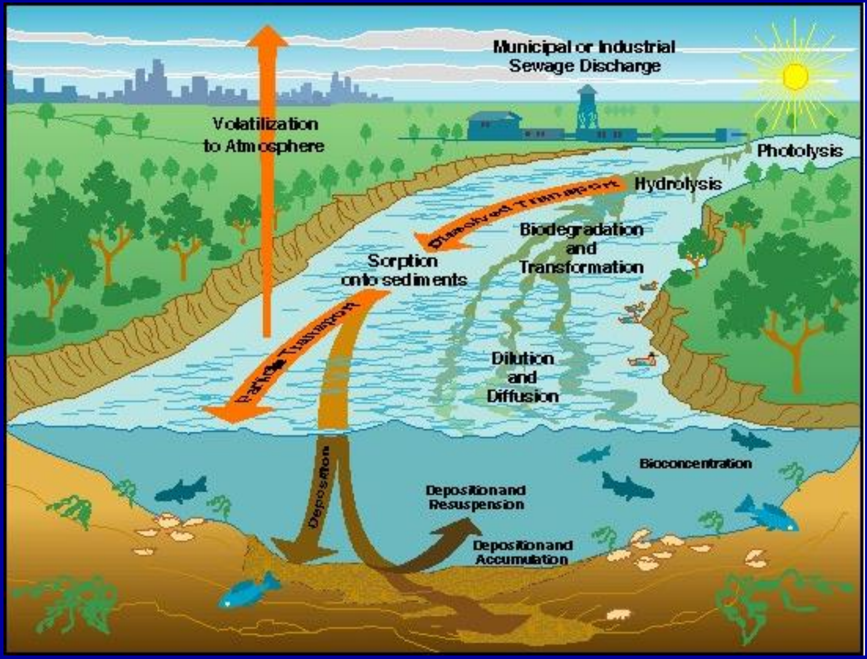
Tectonic landforms versus landforms influenced by tectonics

- Expression of tectonics in river system

- Valley system sensitive to endogenous and also exogenous processes – good information on tectonic movements

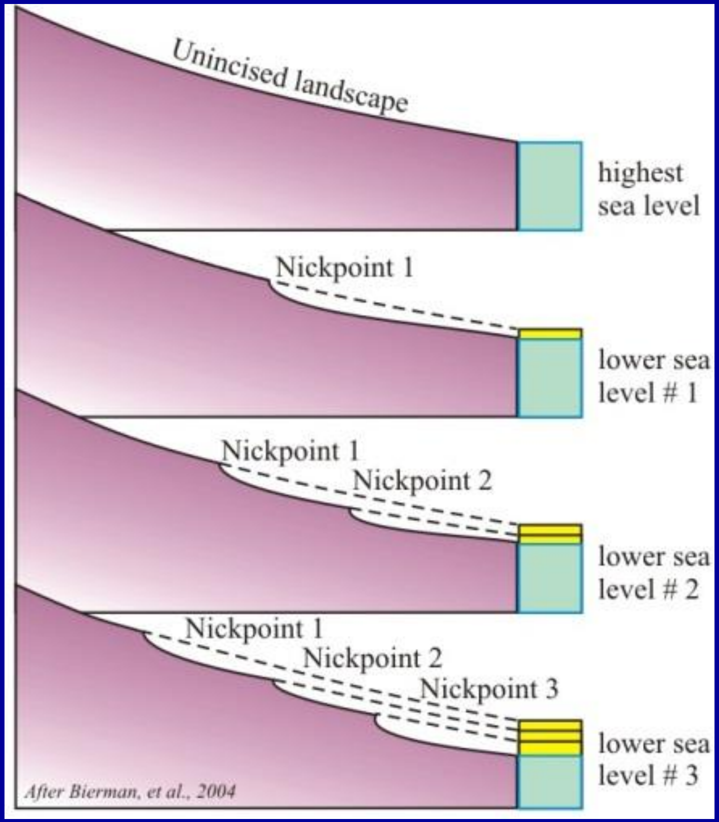
- Streams - parameters: width and depth of the channel, amount of transported material, slope of the channel, channel sinuosity, flow velocity

  These parametres are in balance in river system – sensitive to any changes

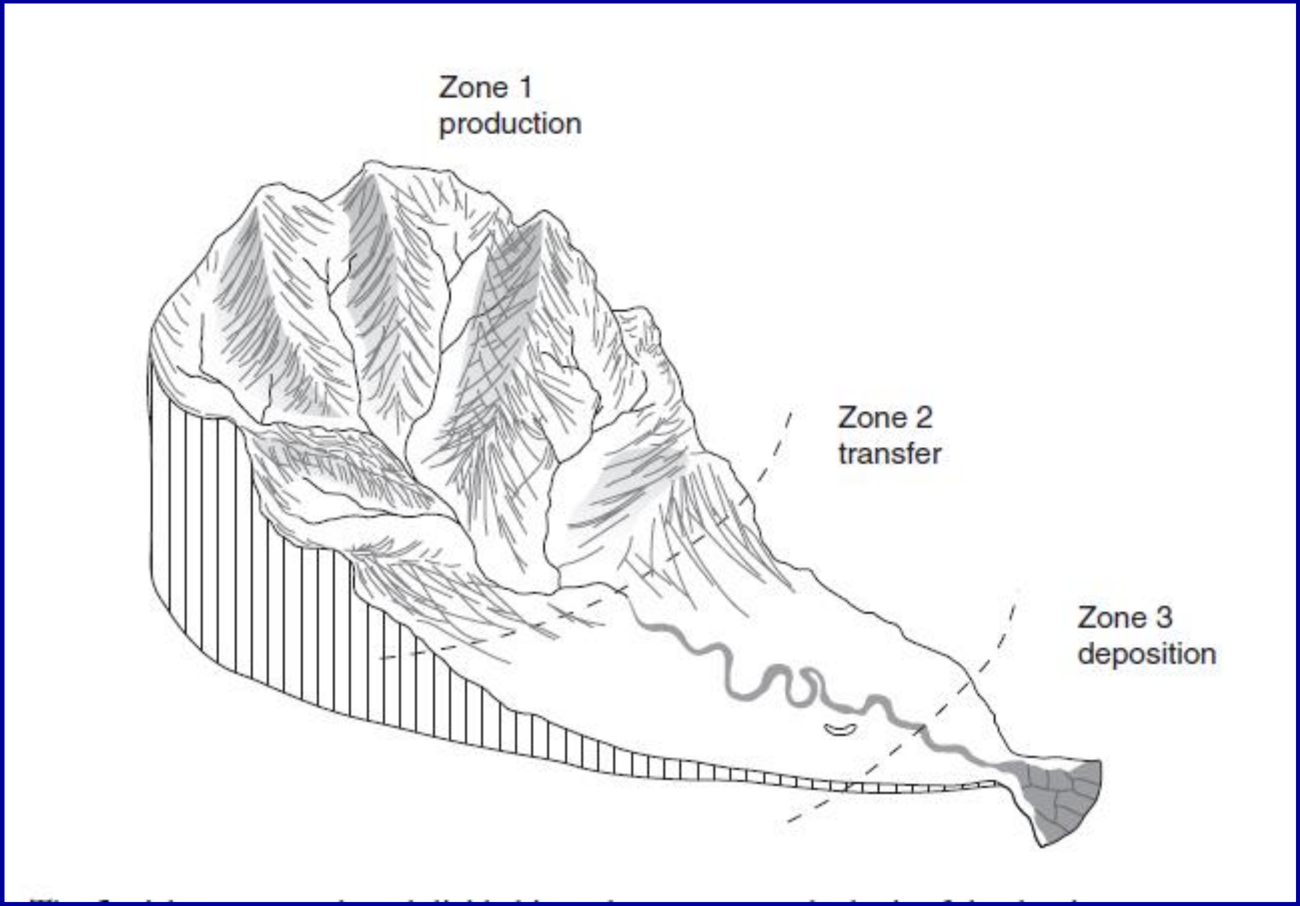


Climate changes in Quaternary (2.6 mil yrs) – large effects on river system – global changes of ocean level – cycles of aggradation (accumulation) and degradation (erosion)

= change of erosion base – the lowermost point of the stream, below this point river cannot erode (local erosional base on stream, sea level)



River actions: erosion, transportation, deposition



1) production of sediments (erosion prevails)
2) transport of material
3) deposition of material

River types based on transported material

- Alluvial rivers – parameters such as roughness of the channel bottom, viscosity, slope of channel etc. don´t allow to transport the material = river flow wittin their own sediments

  - more sensitive to tectonic movements, react to change of any parameter quickly, very young tectonics

- Bedrock rivers – material is transported, rivers erode and flow in exposed bedrock

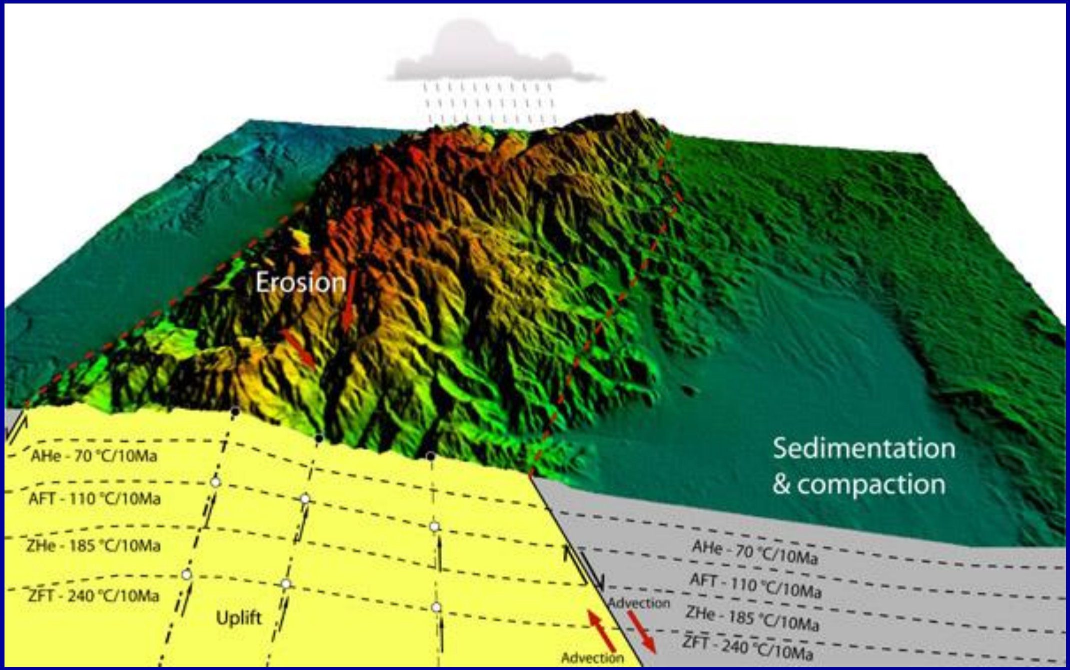
  - less sensitive to tectonics, it takes longer when they are adjusted to tectonics, tectonics is obscured by local differences in lithology

- Graded river – rivers in dynamic balance, onyl transportation, no erosion, no accumulation

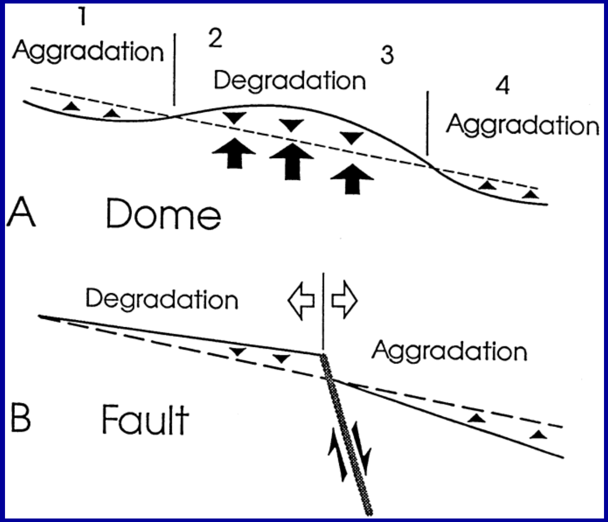
Accumulation and erosion

- Uplift – causes increased erosion or reduction in accumulation

  - higher erosion = higher amount of material, sudden increase of material coarseness in alluvial fan sequences,

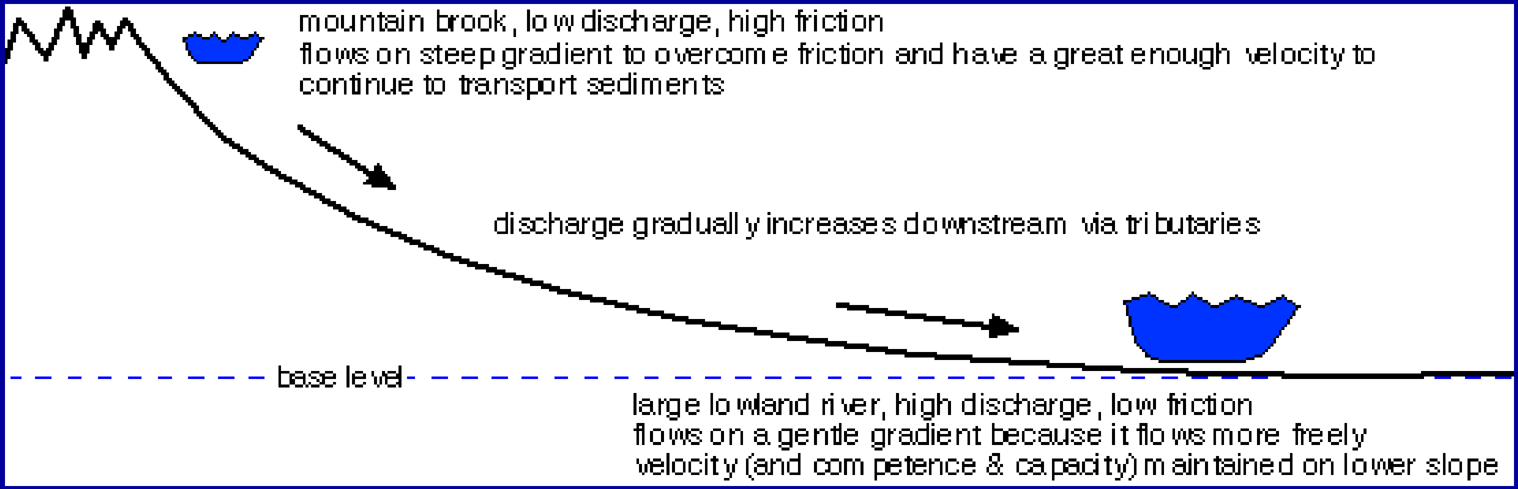


- Subsidence, – favors sedimentation or at least increase existed accumulation



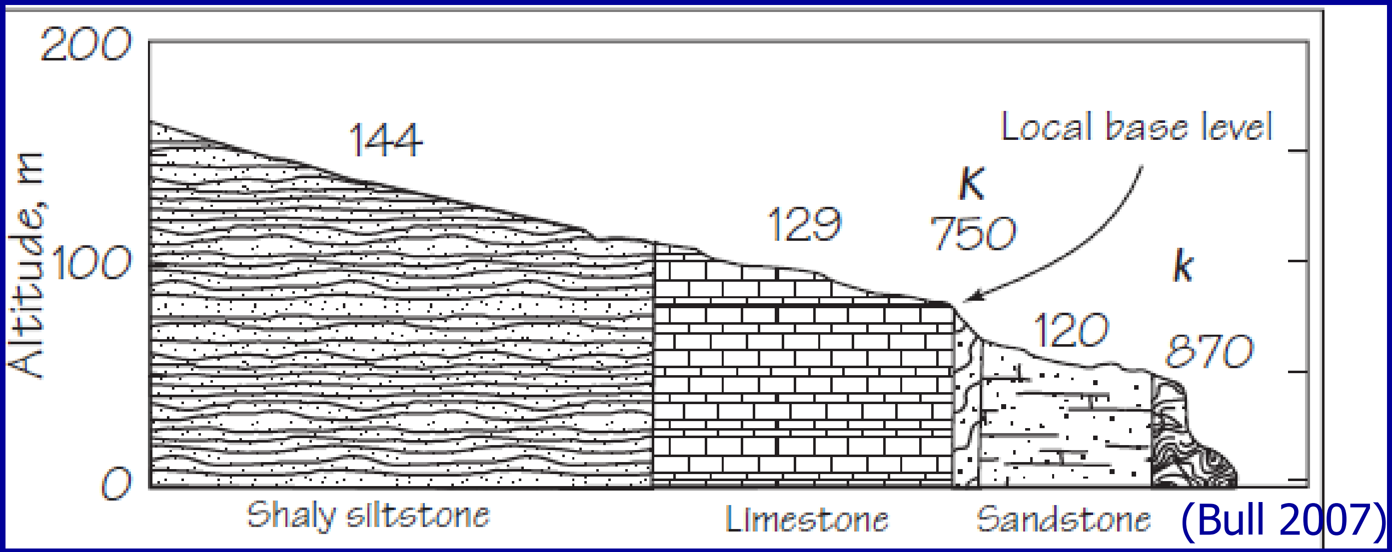
- Changes are expressed in longitudinal river profile
  Tectonics on regional scale – shape of the profile
  local scale– anomalies, knickpoints

Graded river – concave shape

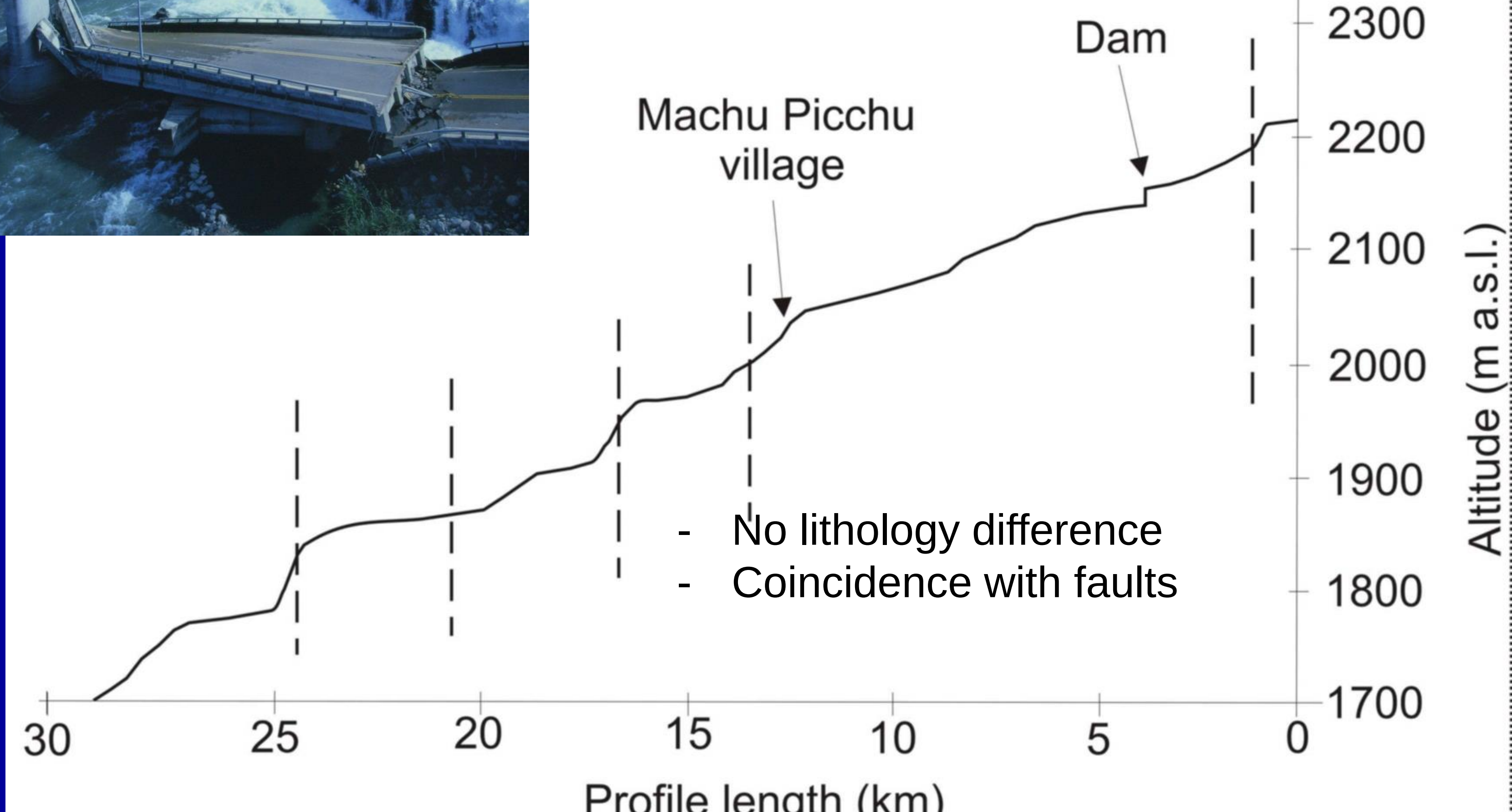


!! Causes of anomalies (knickpoints) in longitudinal river profiles:

- different lithology- more resistant / less resistant
- incision of the main river (hanging valley)
- reach of the headward erosion
- tectonic movements
- change of discharge (e.g. tributary)
- chnage in amount of transported material) (landslide, side erosion)
- antropogenic influence



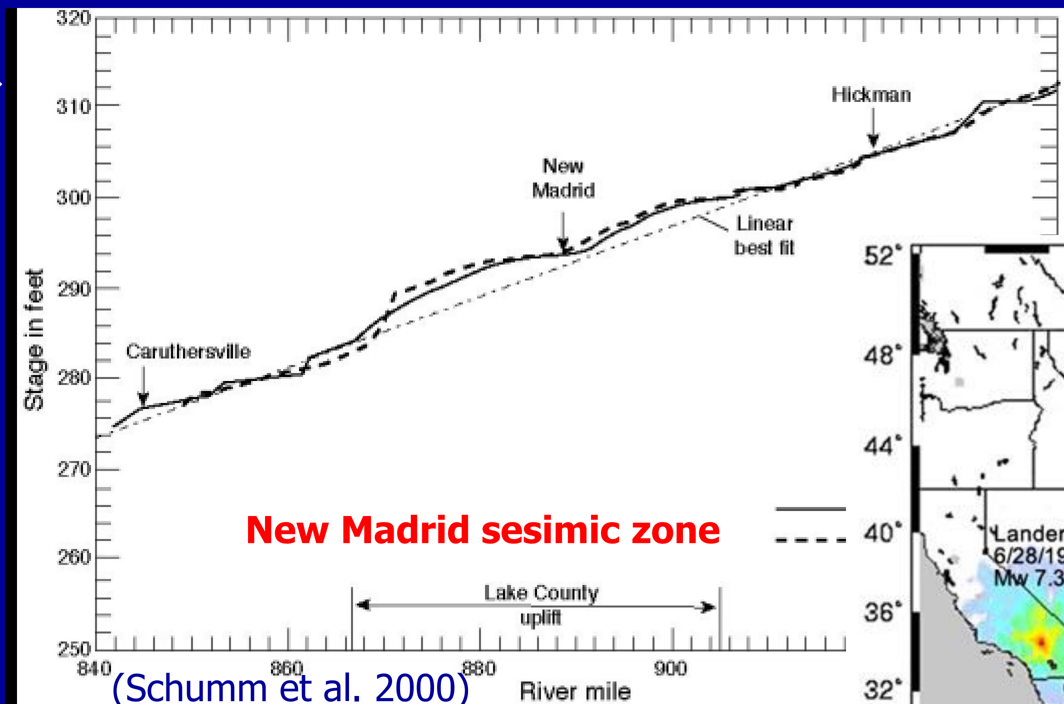
Lithologically controlled knickpoint



- No lithology difference
- Coincidence with faults

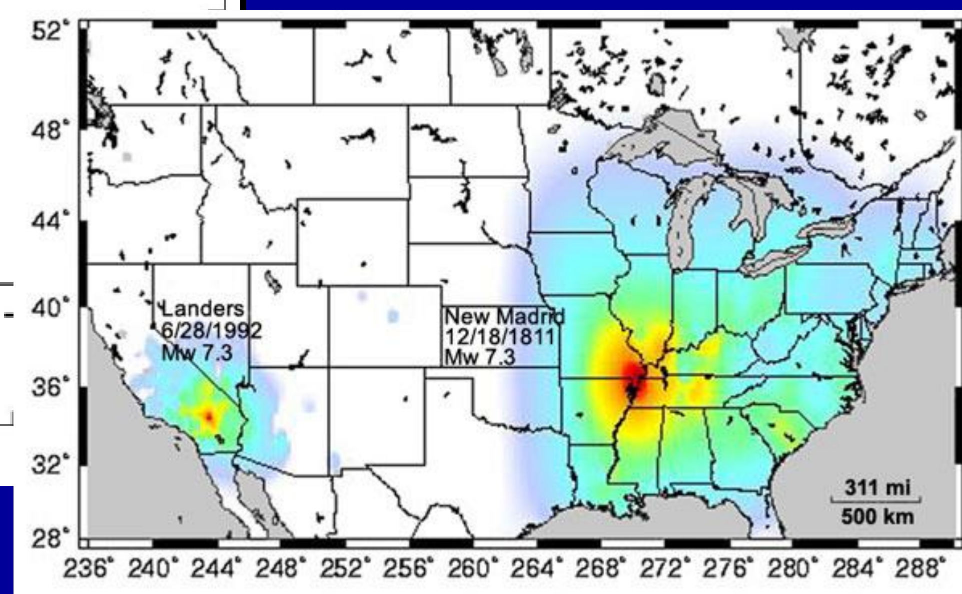
Anomalies tectonically controlled

- New Madrid 1811-1812 – during month 4 large earthquakes M = 7-8
  Large regional changes in landscape – subsidence, uplift, fissures, landslides…

- 

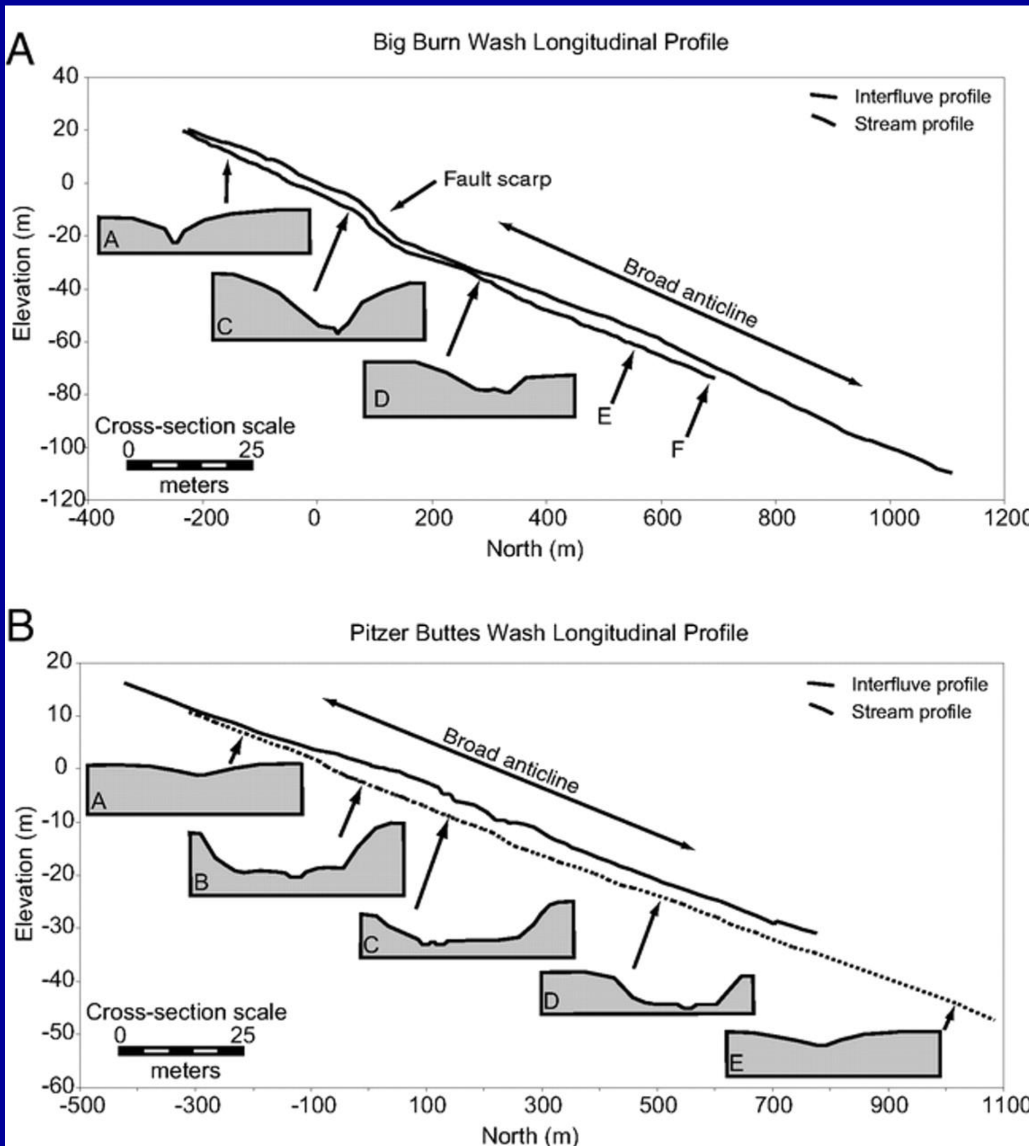
New Madrid sesimic zone

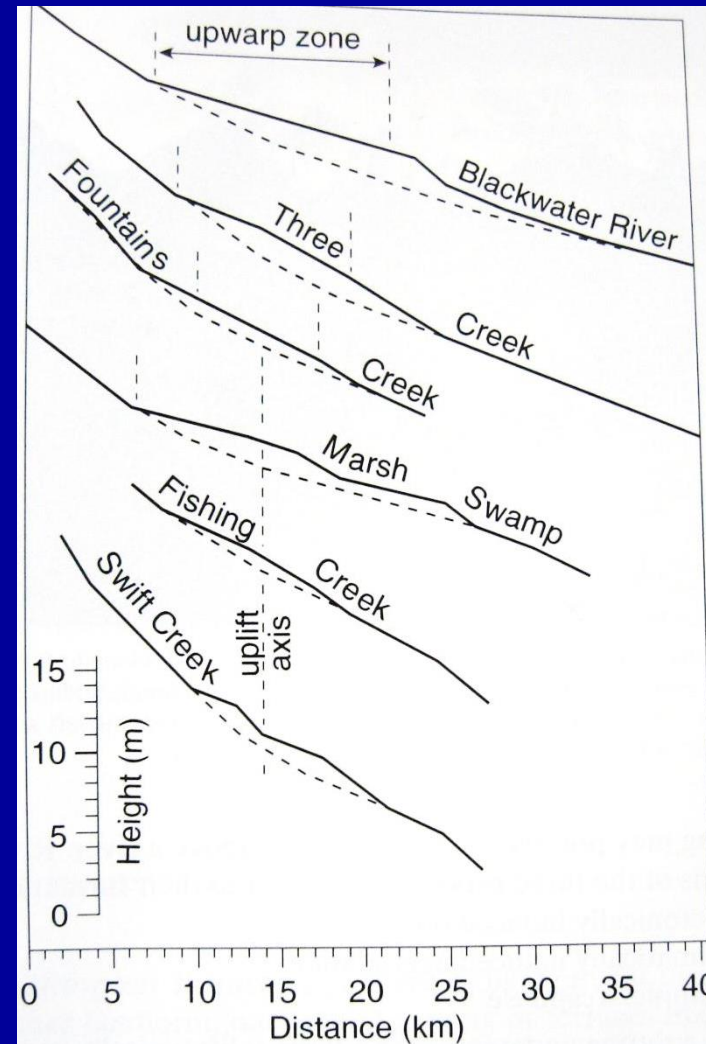
(Schumm et al. 2000)



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.	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VELOCITY	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Present-day longitudinal profile
– response to uplift





Rivers on atlantic coast showing upwarping

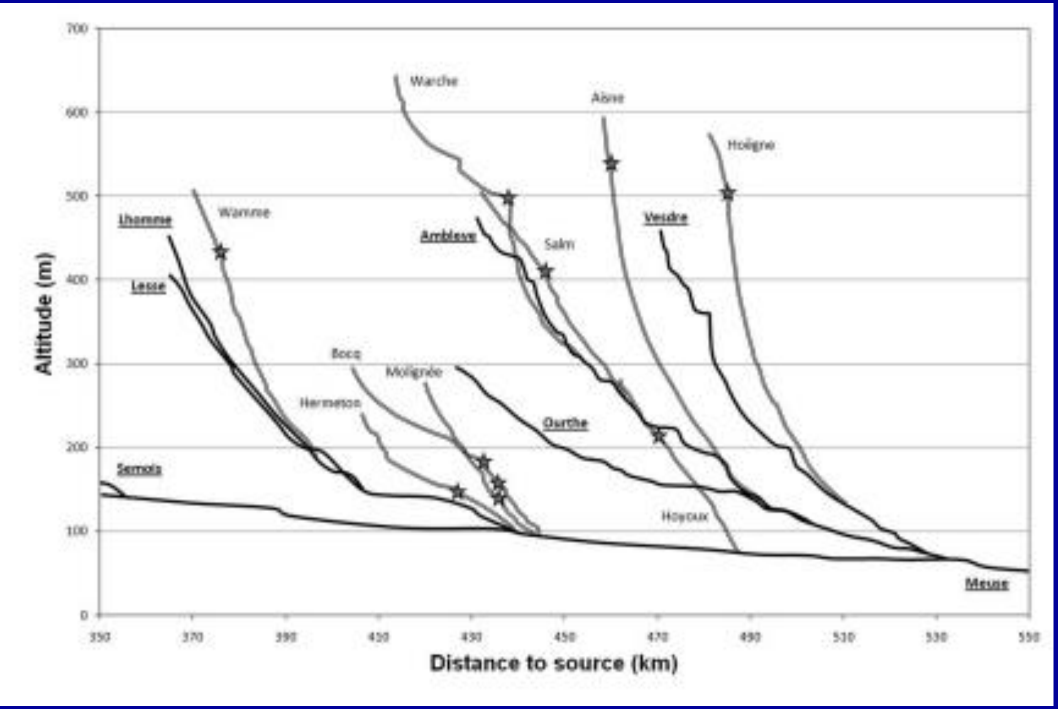
(Marple, Talwani,1999)

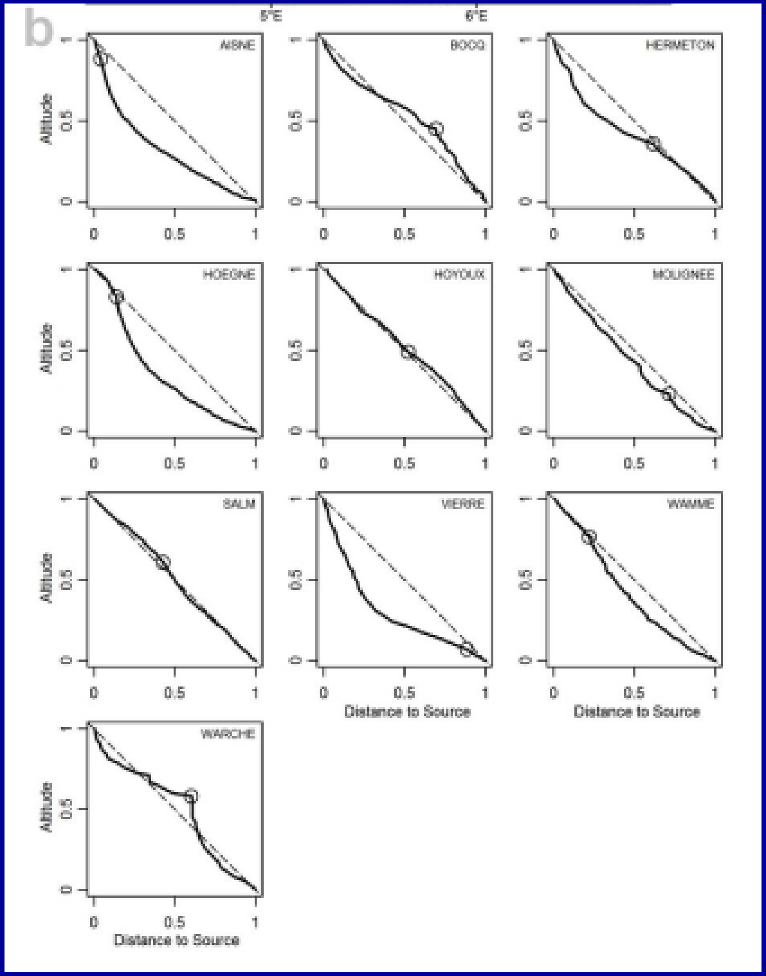
Shape of longitudinal profile – reflects regional tectonics

profile convexity

River not afftected by tectonics – concave profile

- variabilties: lithology, different uplift rate





(after Demoulin)

Normalized river profiles

River terraces

- Former floodplain

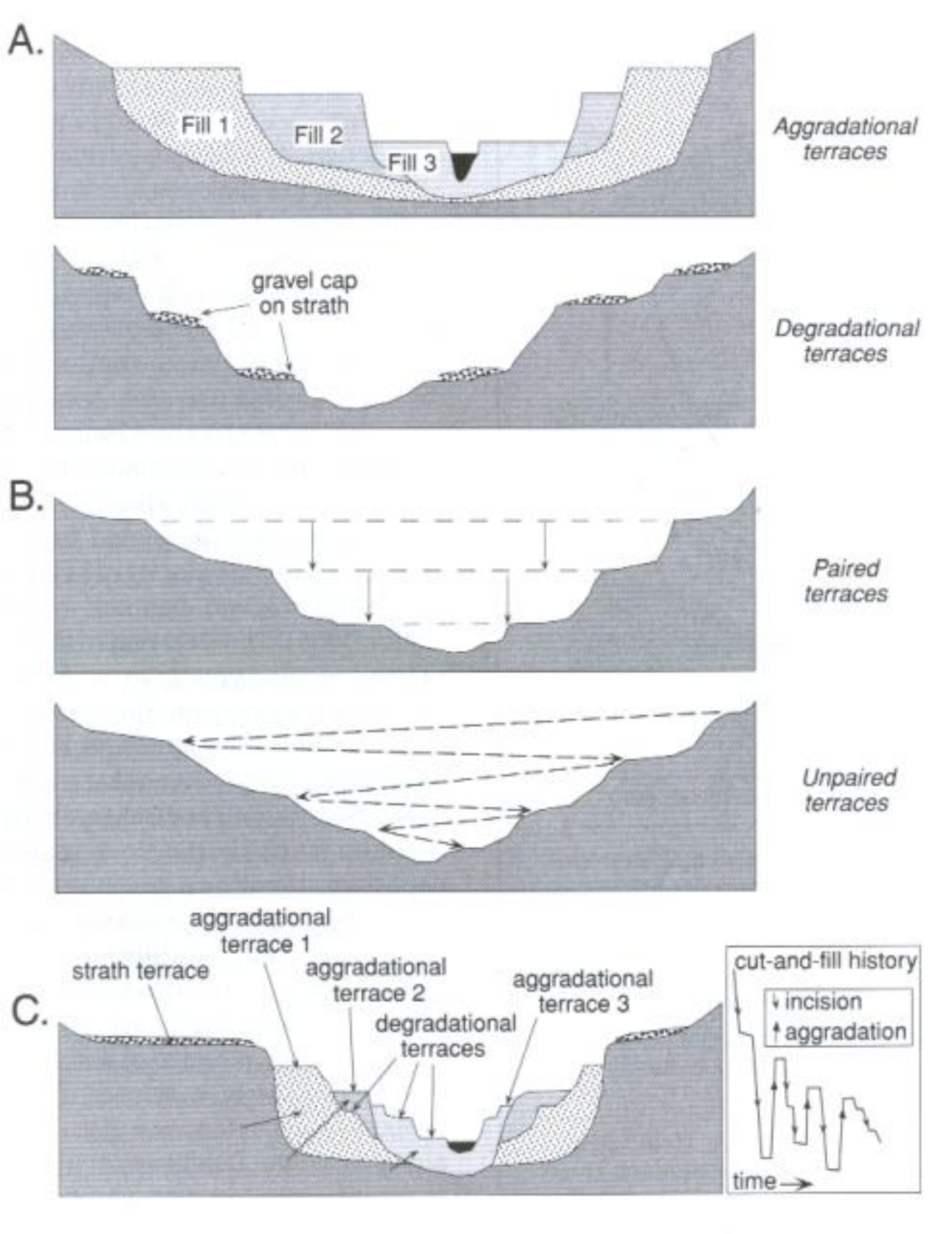
➩ Terraces origin– complex response, many causes

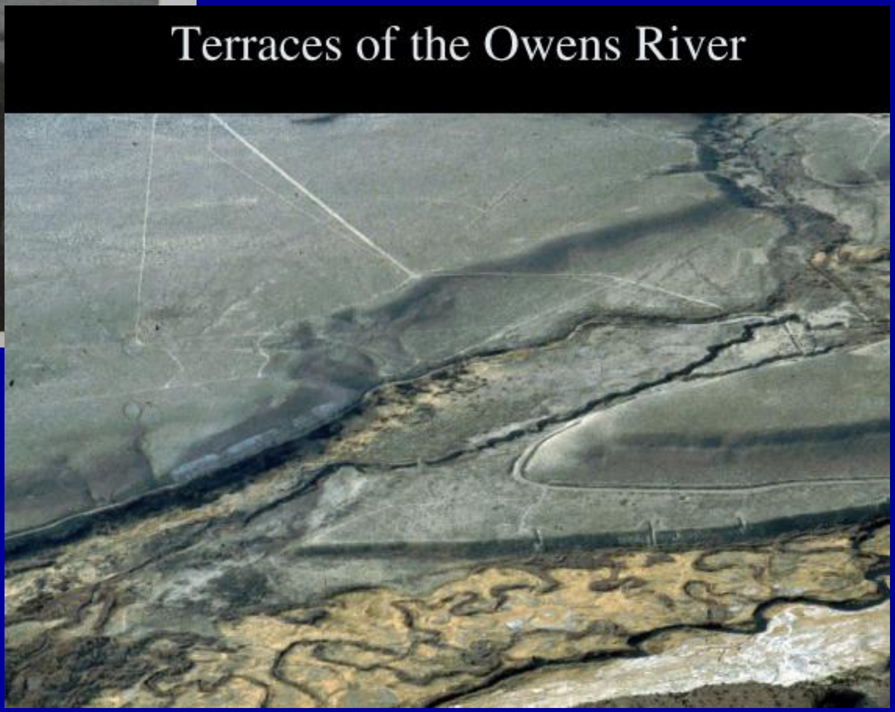
- Repeated tectonic uplift

- Slow continuous uplift combined with alternating of glacial period and interglacial period

- Climate influence - =/= plus drop of the erosional base

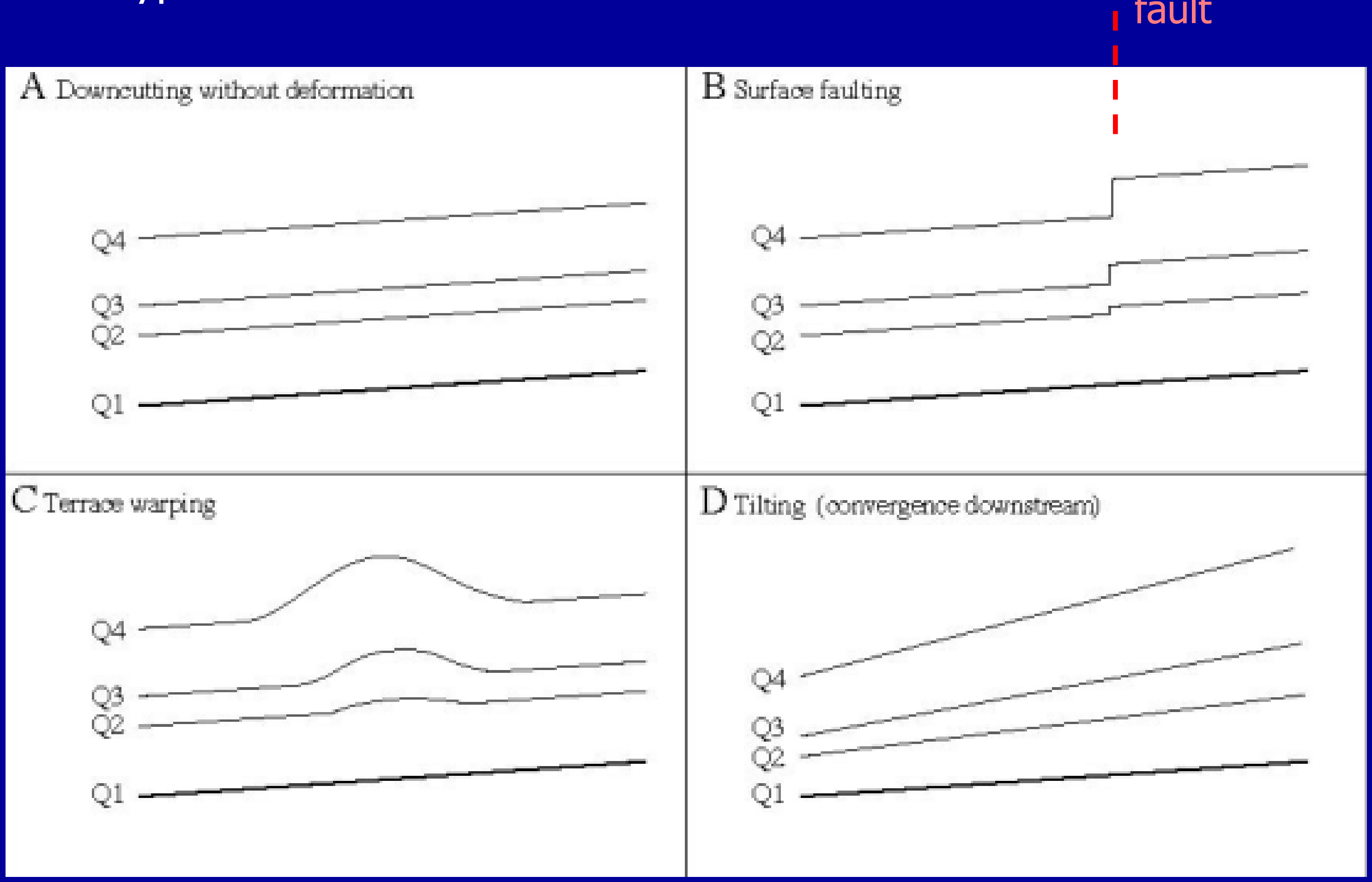
➩ Terraces – important ptential indicator of tectonic activity
  - more to the past





Terraces of river Mijar in Kyrgyzstan
– Trans Alai Range

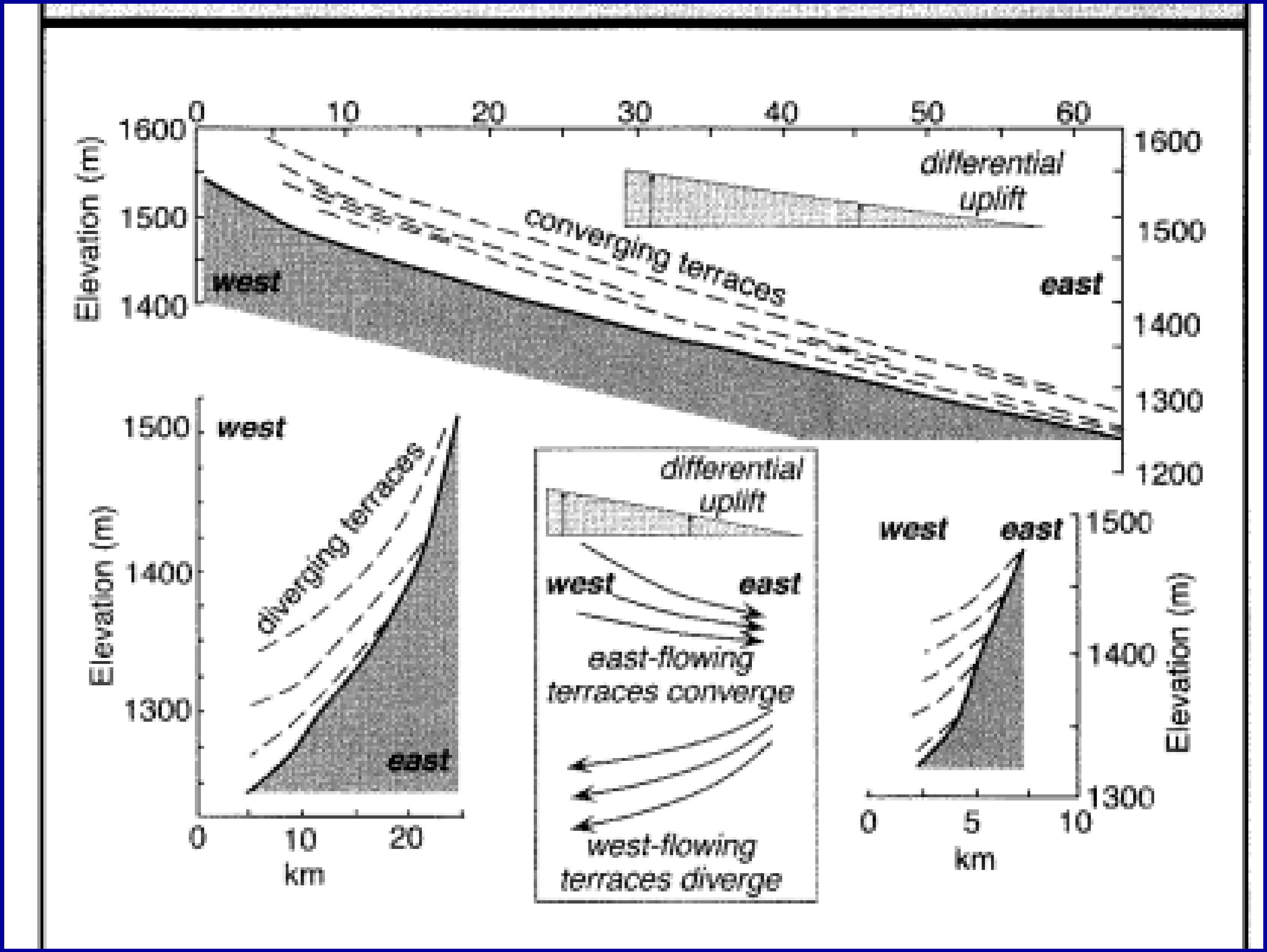
Four types of tectonic deformation of fluvial terraces



(Keller, Pinter 2001)

up-warping

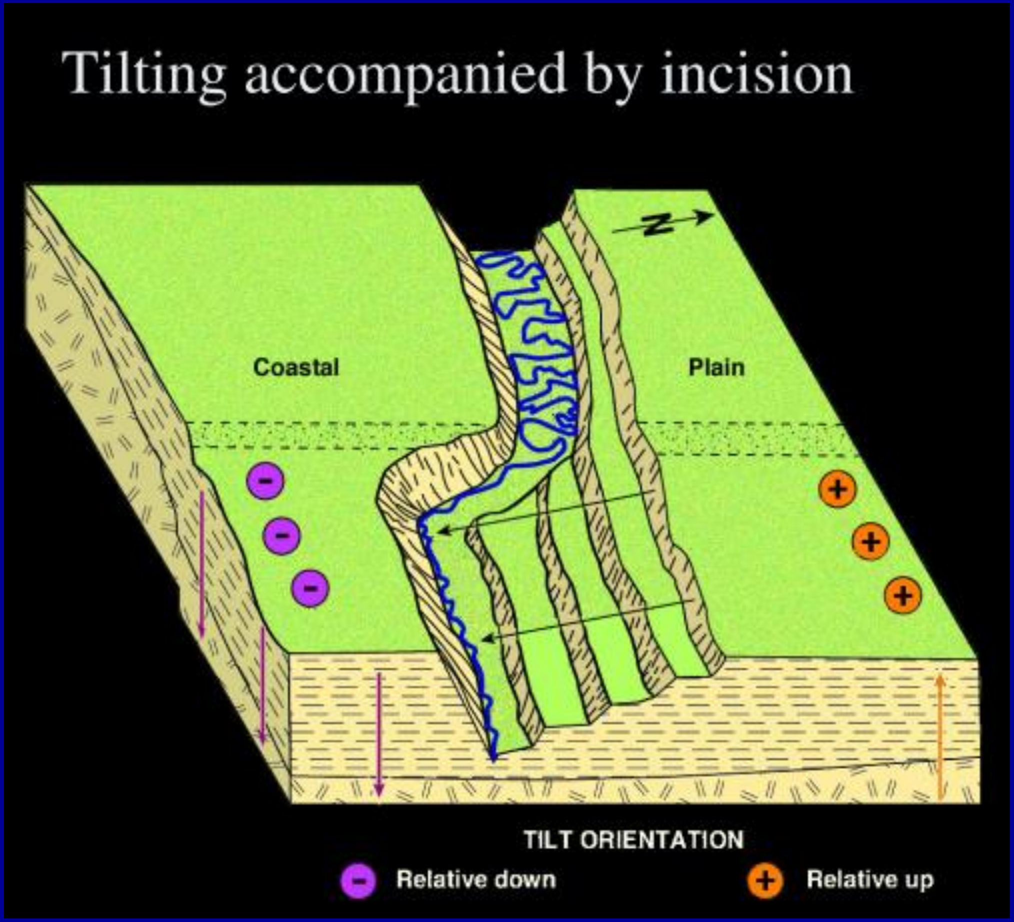
tilting



Convergent terraces down to the river – uplift of lower part
Divergent – subsidence in the lower part

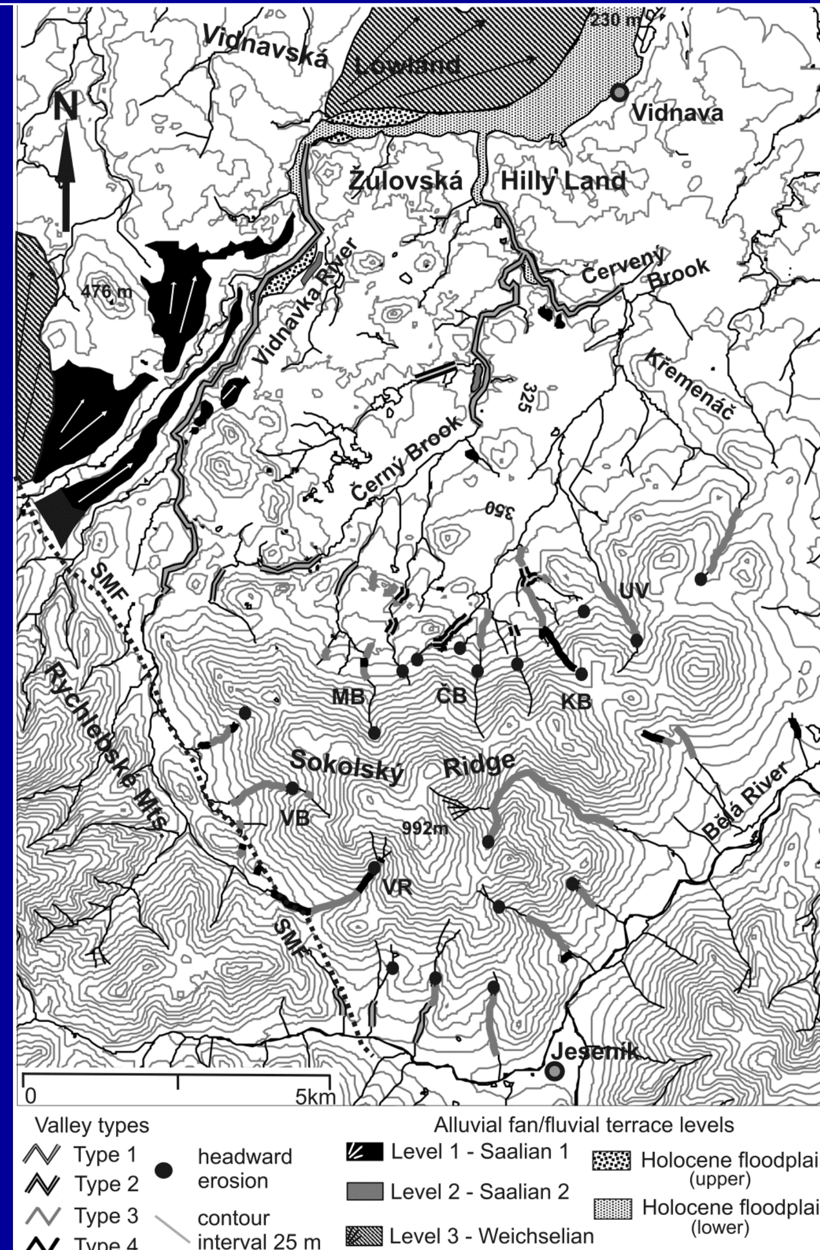
Burbank, Anderson 2001

Transversional tilting – unpaired terraces



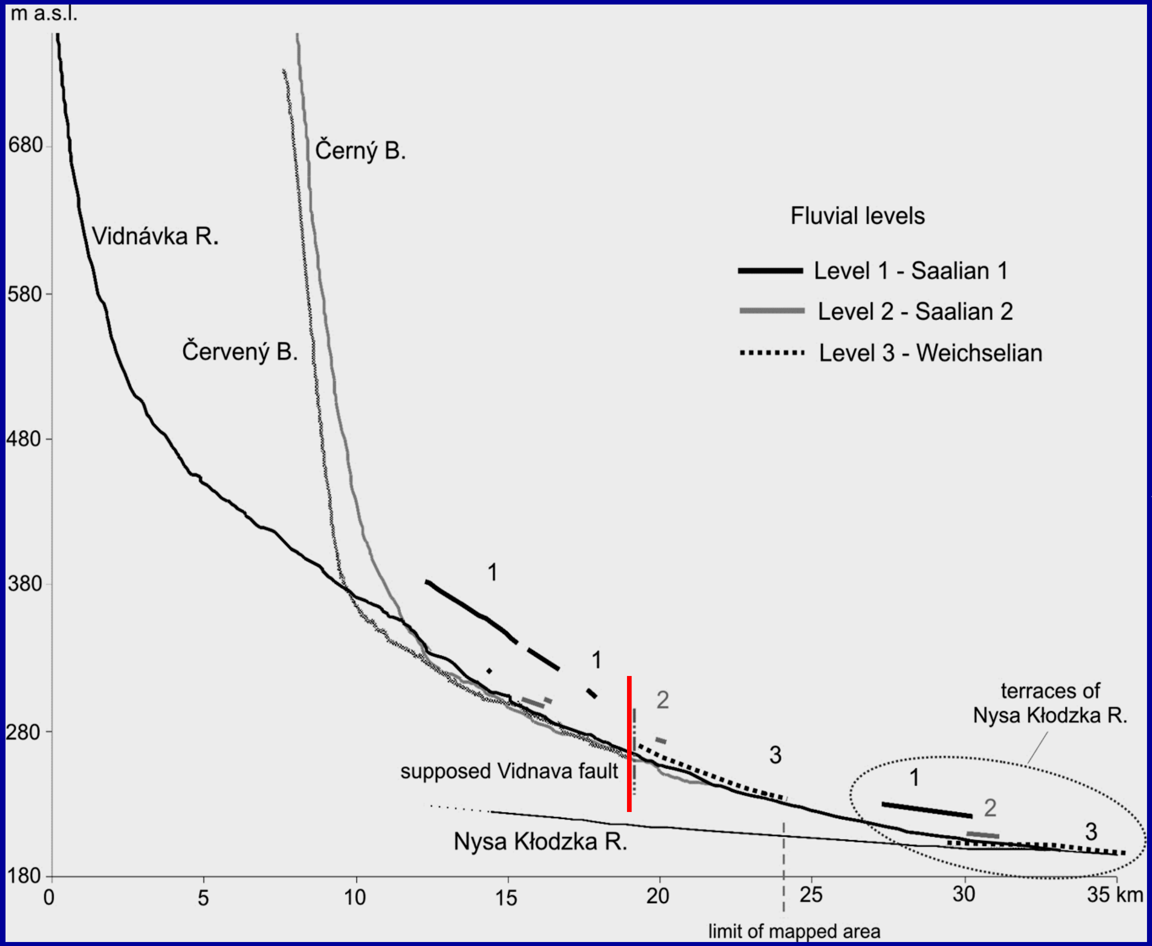
River terraces of Vidnavka river

Terraces of tributaries – usually lower relative height above the river than in the main river



Uplift of Žulovská Hilly Land
(?glacioisostasis)

Fluvial sediments -3 post-glacial (po deglaciaci) Pleistocene terrace level and alluvial fan



Úroveň 1 – Saale 1 Upper Terrace

Vidnavka - 38 – 48m (relative height)

Černý potok - 20m

Červený potok - 35 – 40m

Úroveň 2 – Saale 2 Middle Terrace

Černý potok - 13 – 22m

Úroveň 3 – Weichselian Lower Terrace

Vidnavka - 4 – 8m

Anomaly in river terraces profile (Kladská Nysa)

Level 1 – difference 20m

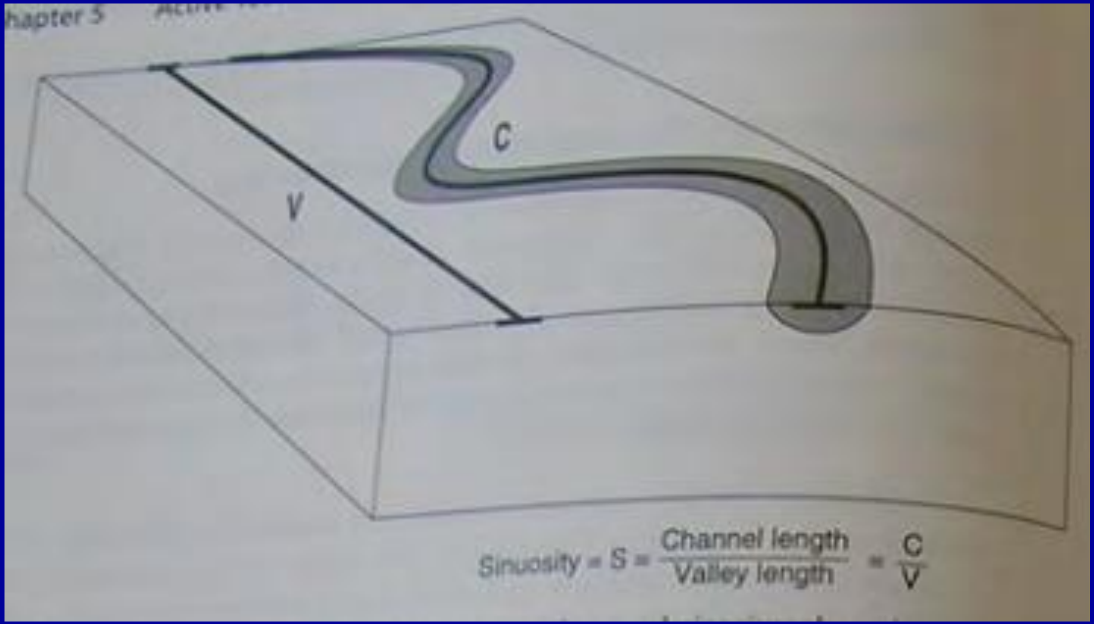
Level 2 – difference 8m

Level 3 – difference 2-3m

Stream sinuosity

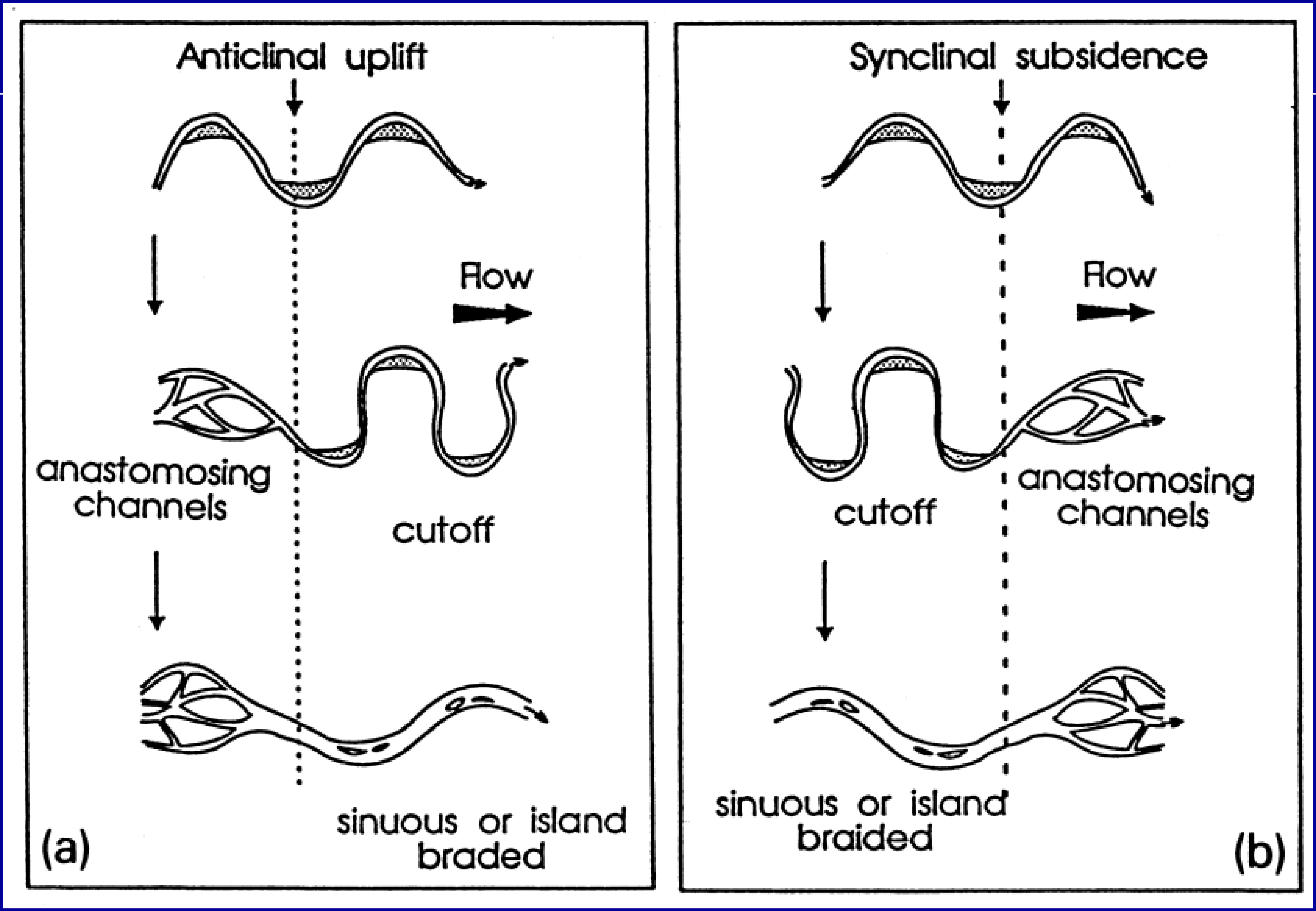
- Rivers are meandering to balance the slope of the channel with discharge and transported material

Sinuosity = channel length : valley length



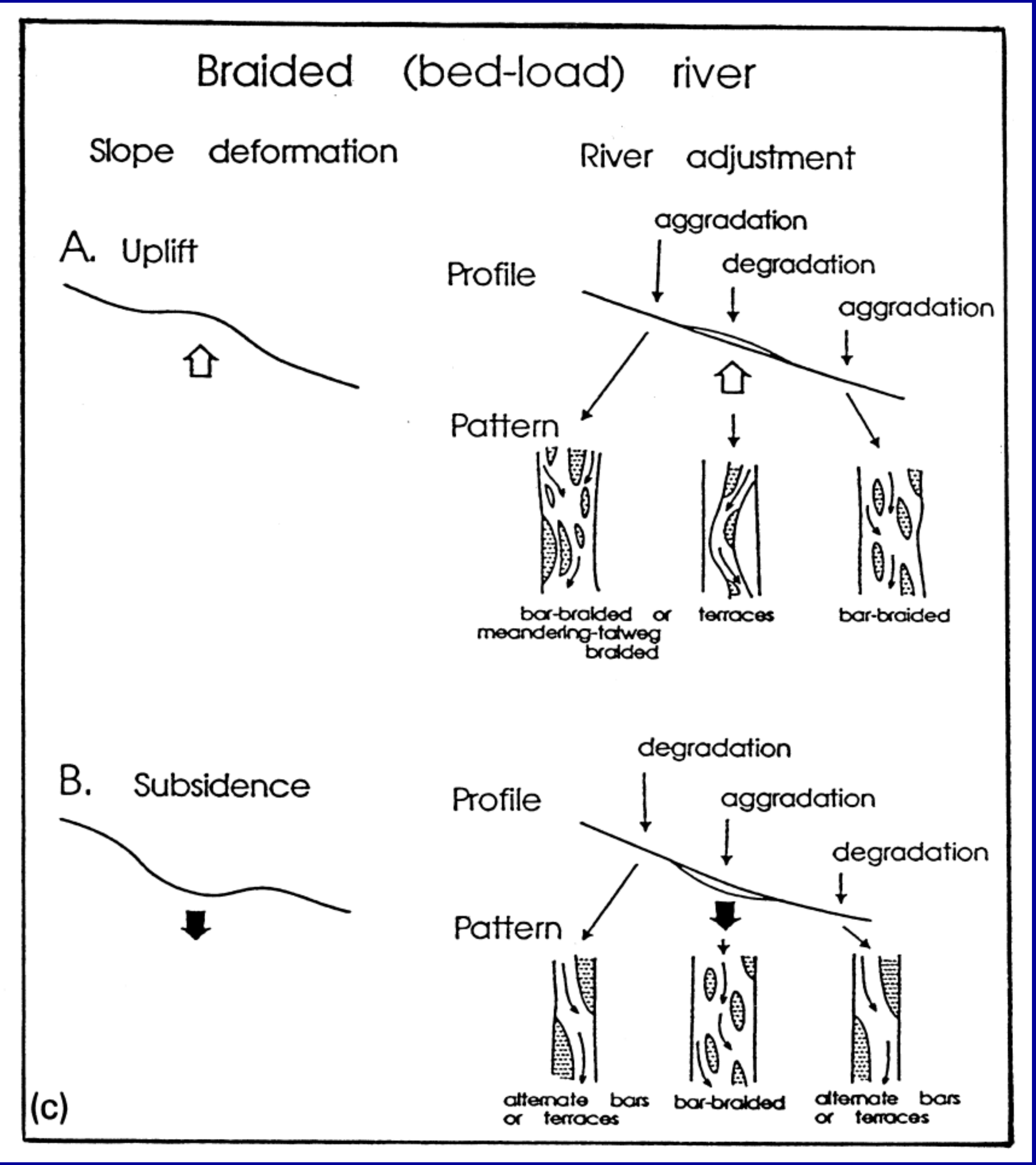
River meanders when the valley length is too steep to keep the balance
- Meandering (curving) decreases the channel slope (stream is longer – less steep profile)

During flowing through upwarping area – on the higher part – less curved, in the lower part more curved



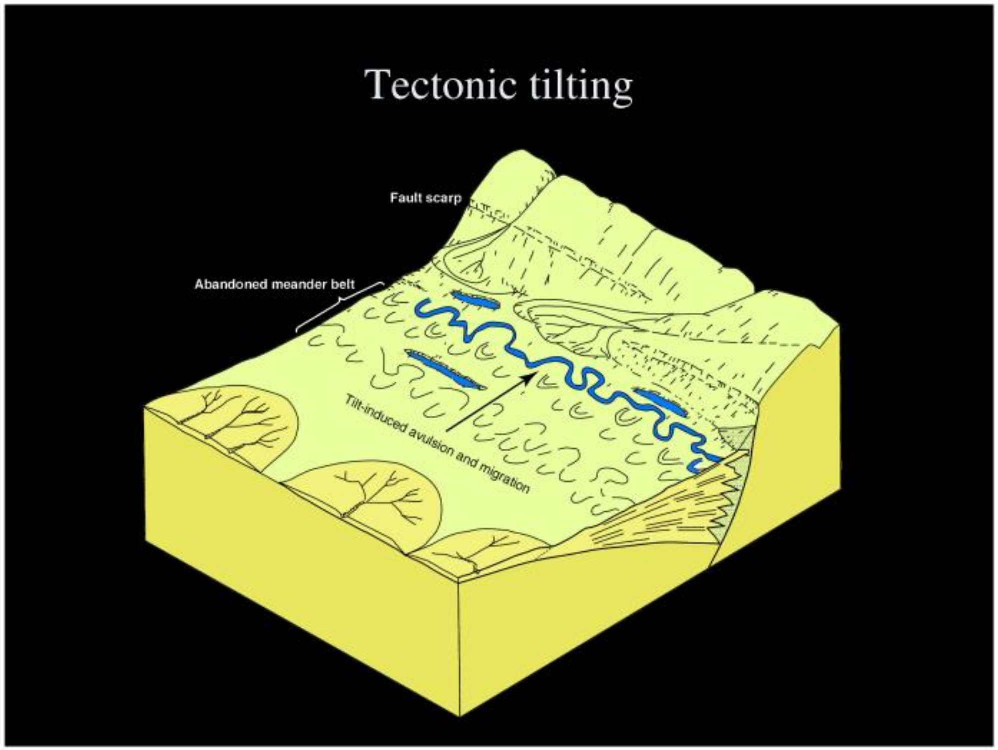
Response of meandering or straight stream in uplifted area (A) or subsided (B)

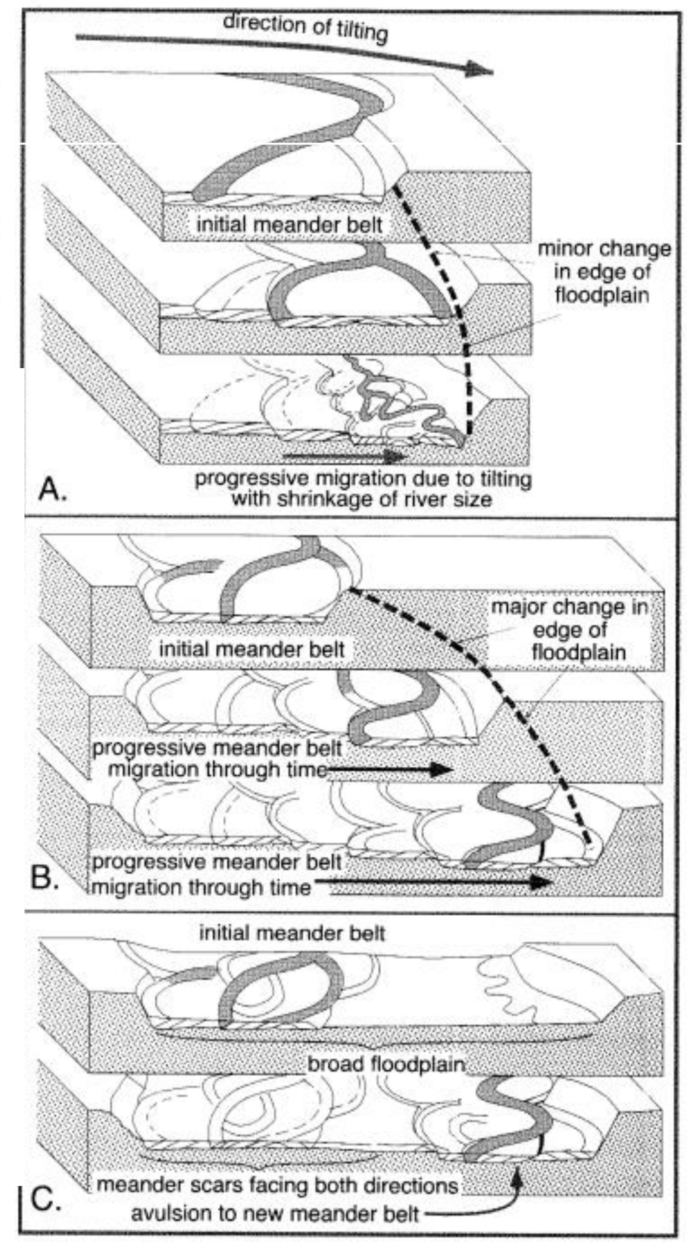
(Schumm et al, 2002)



Response of braided streams (C) (Ouchi, 1983)

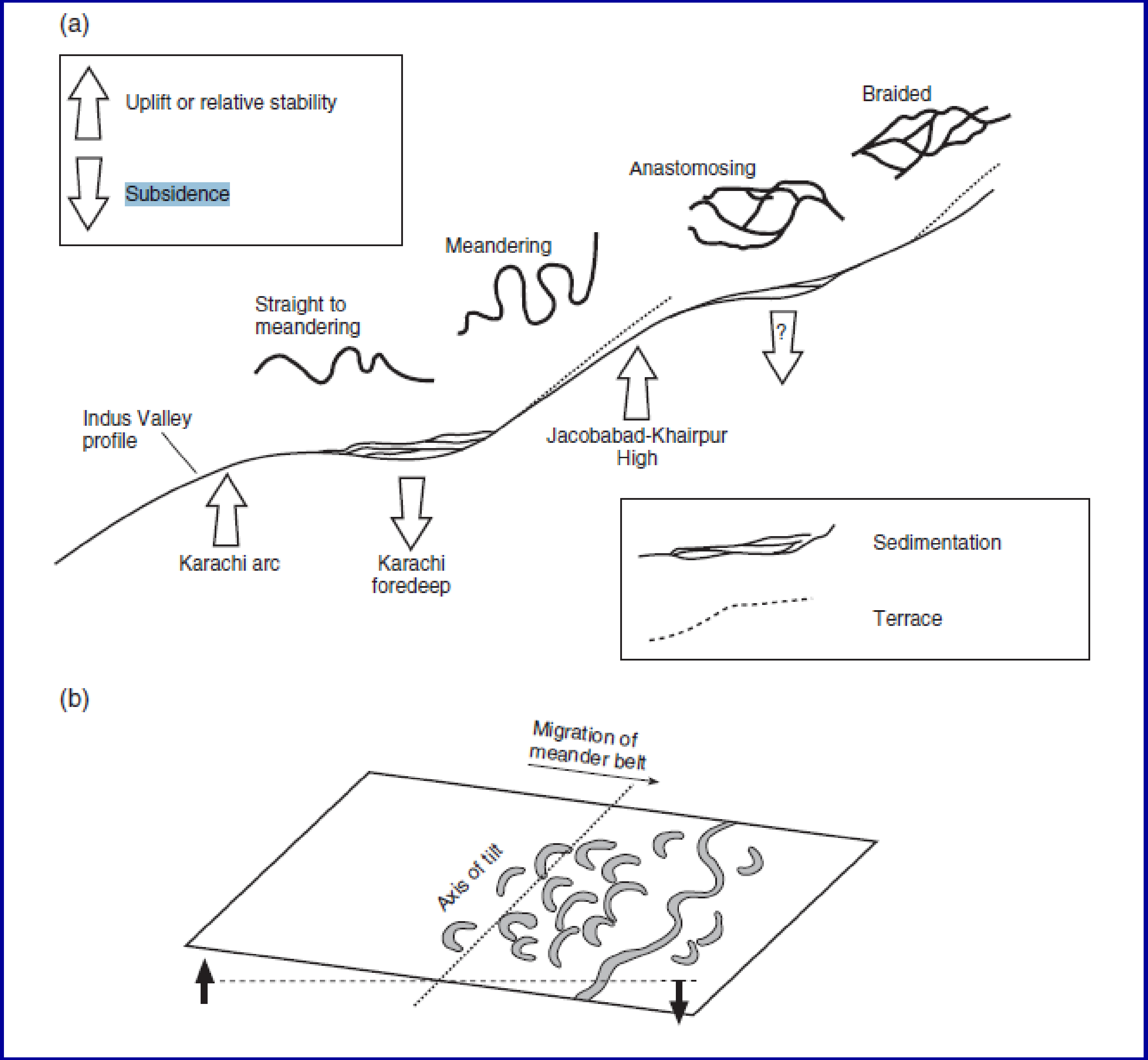
Cross sections





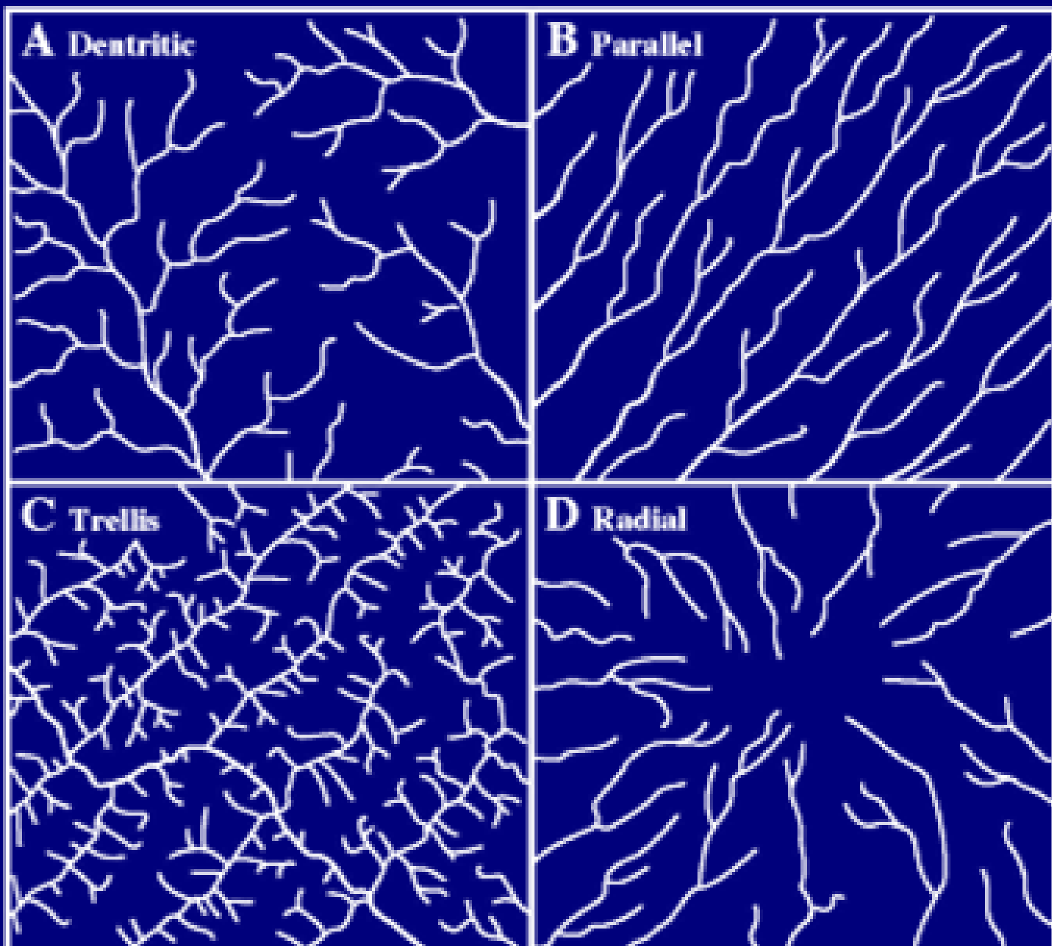
A. Steady tilting with shrinkage of river size.
B. Steady tilting and migration. C. Abrupt tilting and avulsion across a floodplain. Modified after Alexander et al. (1994).

Tectonically deformed river

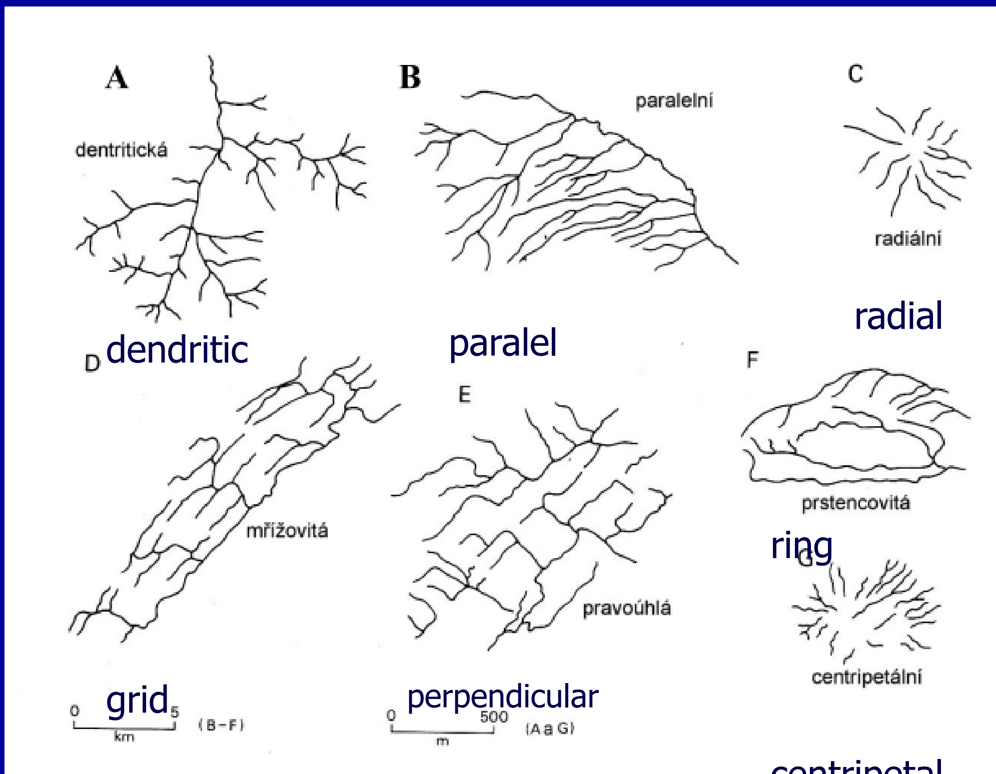


(Jorgensen et al. 1993)

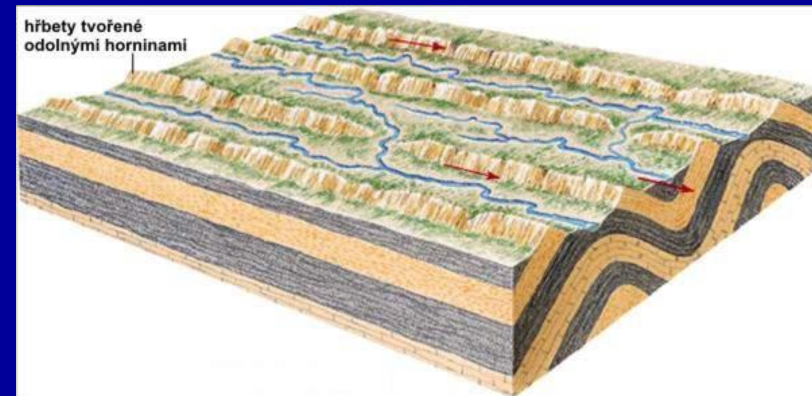
Changes in drainage and stream pattern



Dendritic	This drainage pattern forms on homogeneous bedrock or loose sediments in areas with gentle regional slopes.
Parallel	Parallel drainage pattern forms on steep slopes and where bedrock or landforms trend parallel to the regional slope.
Trellis	Pattern forms where underlying rock has one or more planes of weakness oblique to regional slope, such as on folded sedimentary rocks, or where linear landforms like beach ridges control drainage.
Radial	Pattern forms around structural high points such as volcanoes, salt domes, or tectonic upwarps.



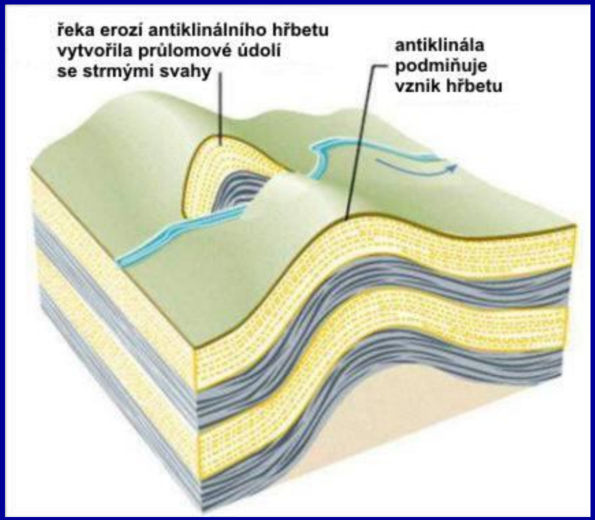
Obr. 3.8 Typy říční sítě dle Summerfield (1991).

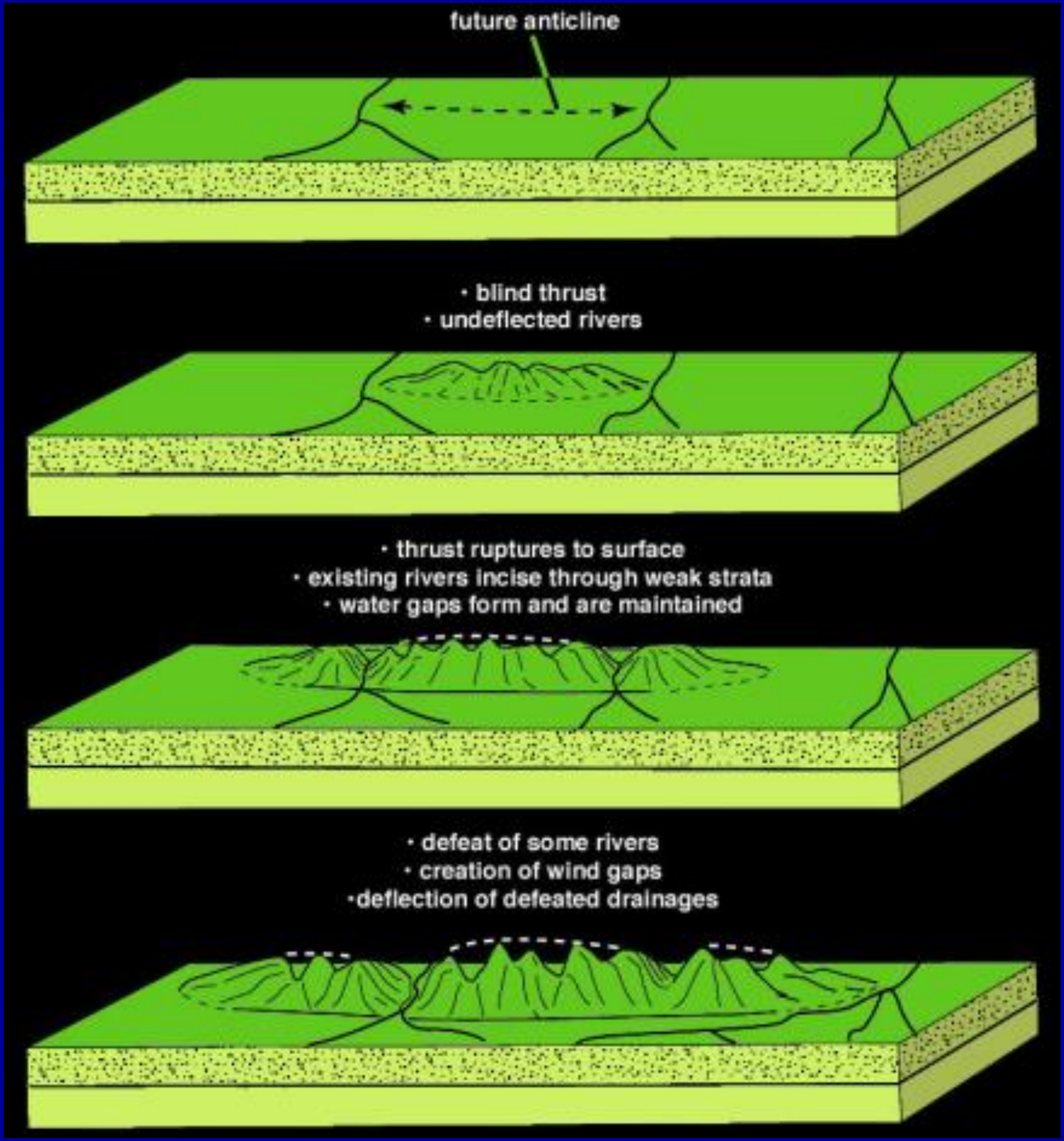


paralel

Changes in river pattern – response to uplift and erosion

- Antecedent valley
  - water gap
- Abandoned valley
  - wind gap
- Stream deflection/diversion
- River capturing

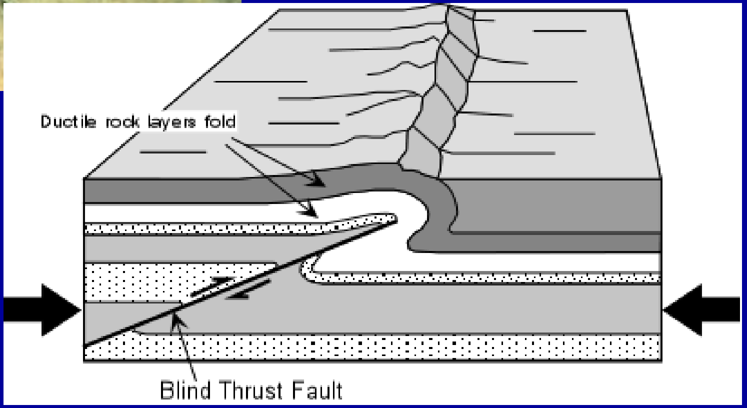




Burbank et al. 1999

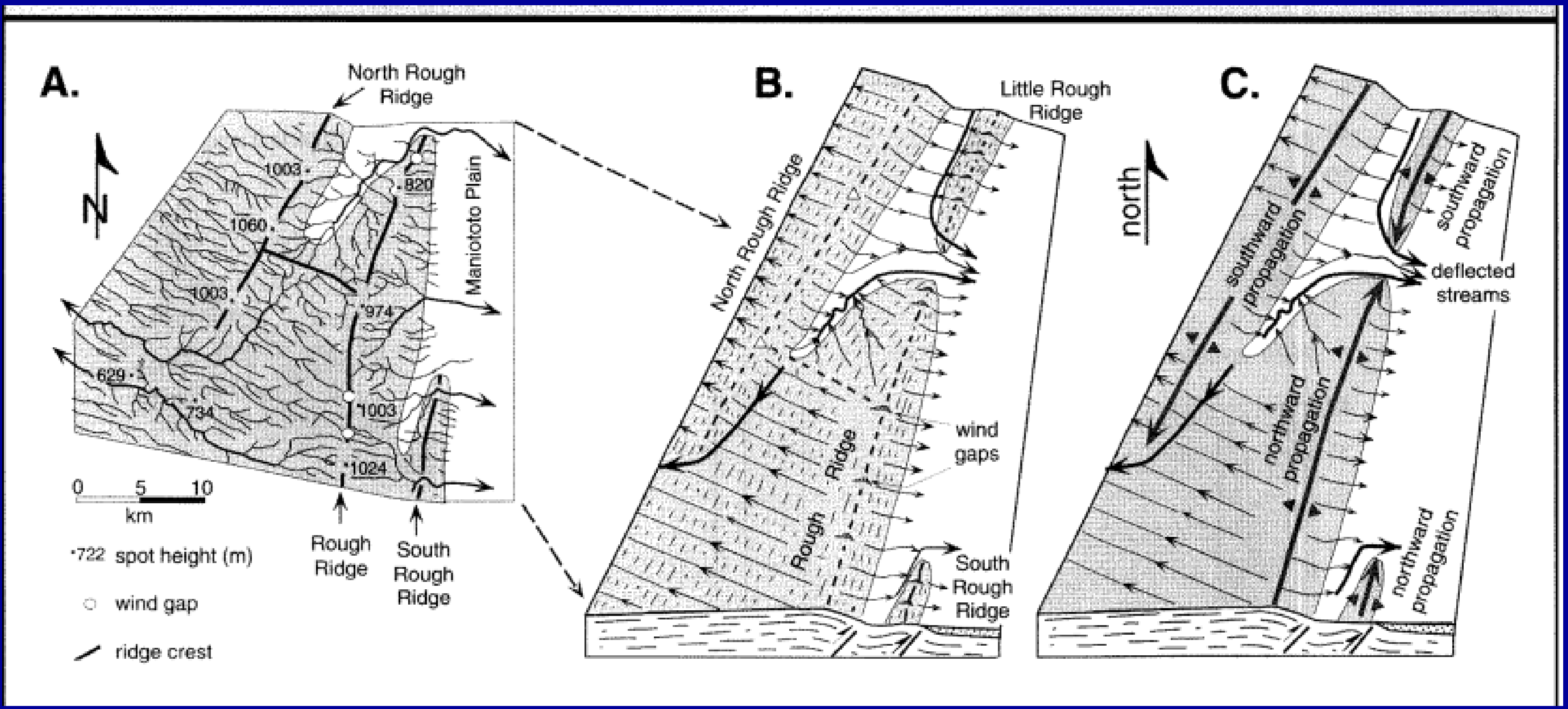
Active folding

Fault-propagation fold
- fault related fold



„**Blind thrust fault** that does not rupture all the way up to the surface so there is no evidence of it on the ground. It is "buried" under the uppermost layers of rock in the crust“. USGS

Basin asymmetry in active folding-faulting region

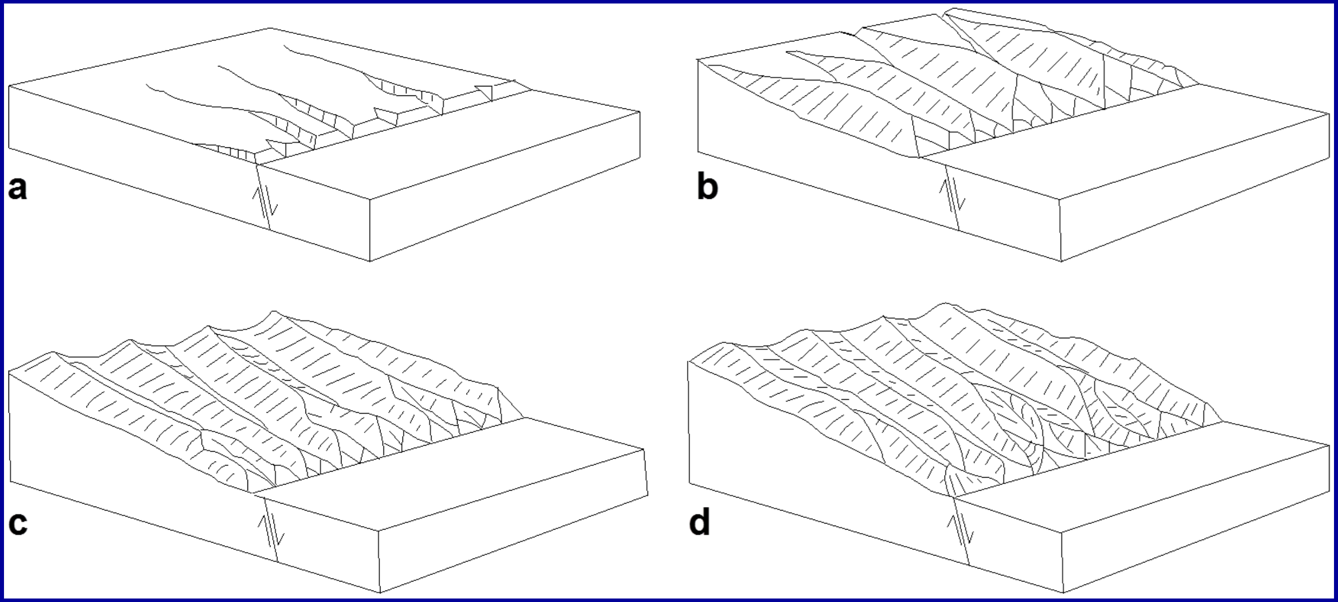


Limb axis tilted – water gap, altitude decreases, river streams diversion close to fold limit

(Burbank, Anderson 2001)

Mountain front – fault scarps, active mountain margins,

Several generation of facets – evolution of mountain front



Anderson (1977)

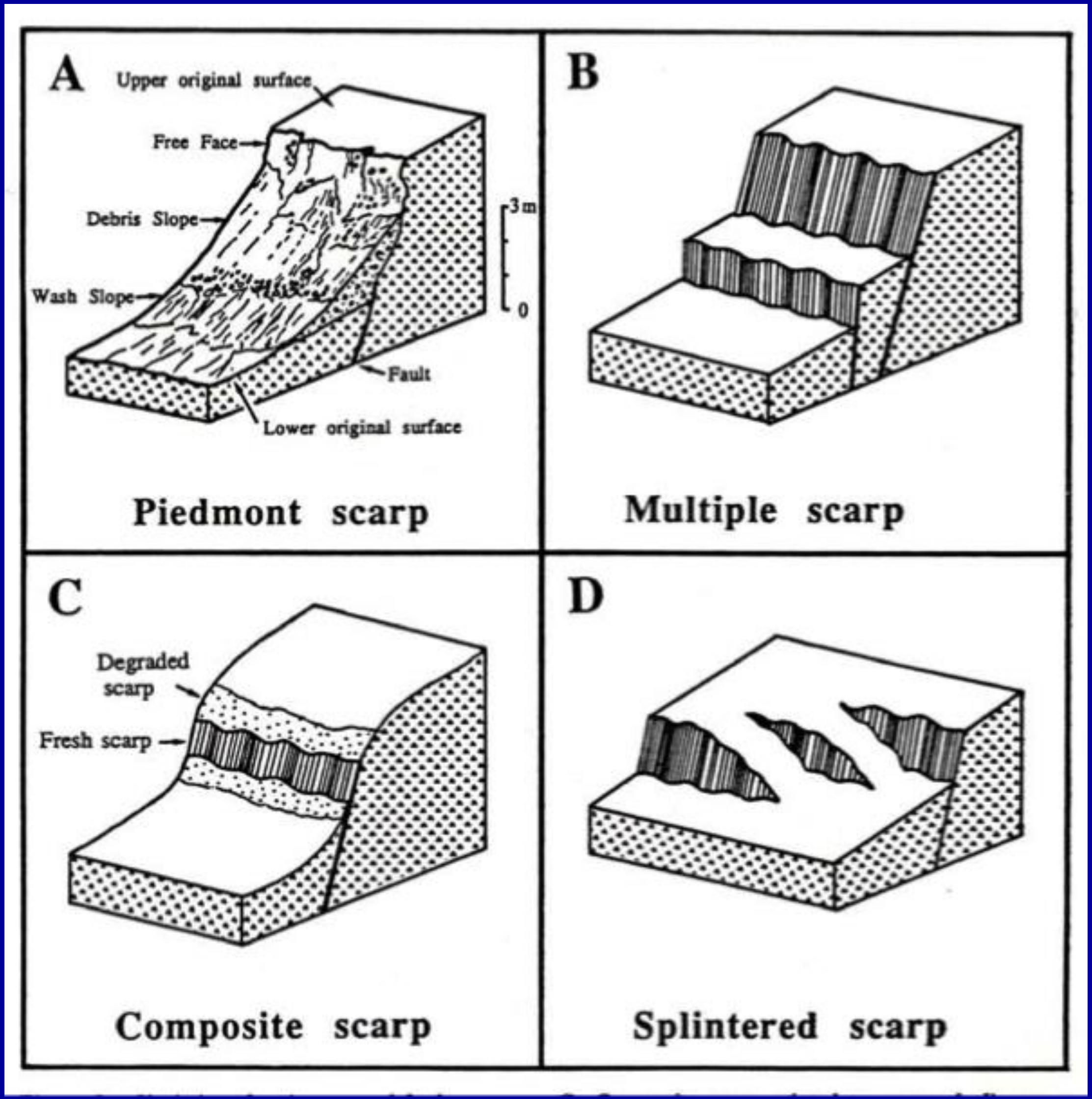
Repeated episodic movements - origin

➢n–hundreds meters high fault scarp

➢ fault-controlled mountain front – hundreds kilometers long, up to 1 km high (Stewart, Hancock 1994)

Fault scarps

Fault scarp – tectonic landform coinciding with fault plane



Stewart, Hancock 1990

Piedmont scarp – formed during one movement in unconsolidated sediments

Multiple scarp

- Formed on parallel faults or branches of the fault during one movement

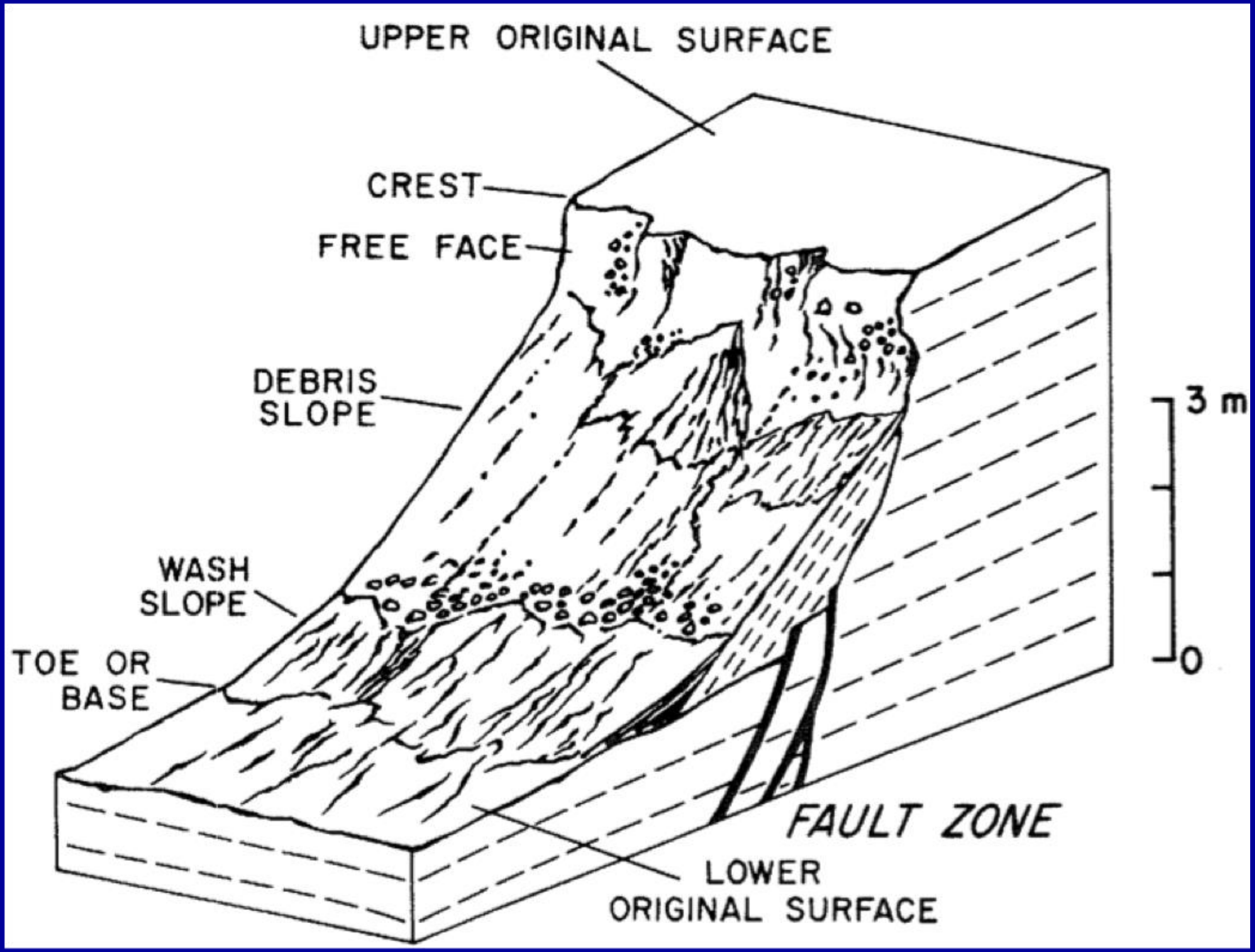
Composite scarp (combined)

- Formed by reactivation and by degradation of the former free face

Splintered scarp – formed - during movement distriuted on en échelon fault segments

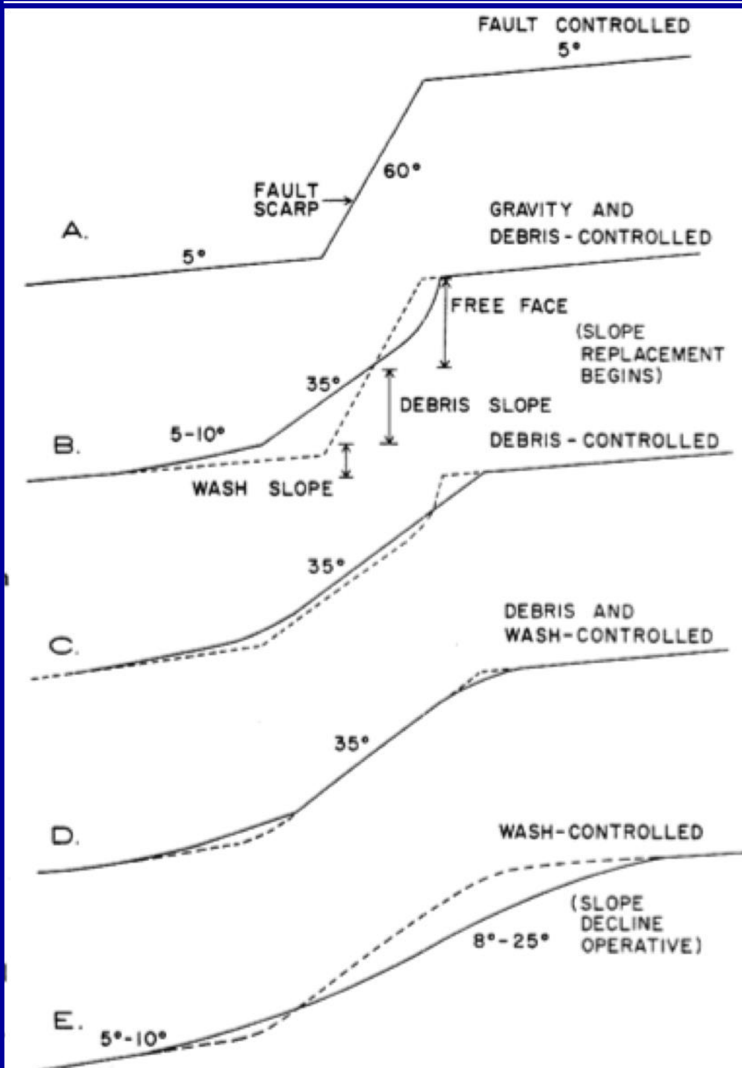
Fault scarp anatomy

- *Toe* and *crest* - upper and lower limit of fault scarp
- *Free face* - sub-vertical part, exposed alluvial fan deposits or slope deposits formed by movements – can keep the shape 10-1000 years
- *Debris slope* – scree cone accumulated bellow the free face by gravitation
- *Wash slope* – part of slope on the toe controlled by fluvial erosion or accumulation

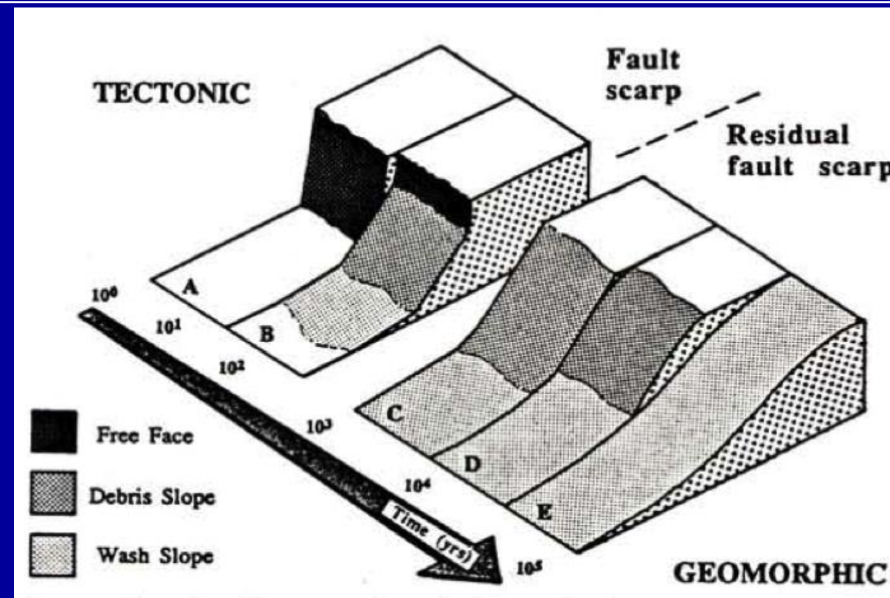


Wallace 1977

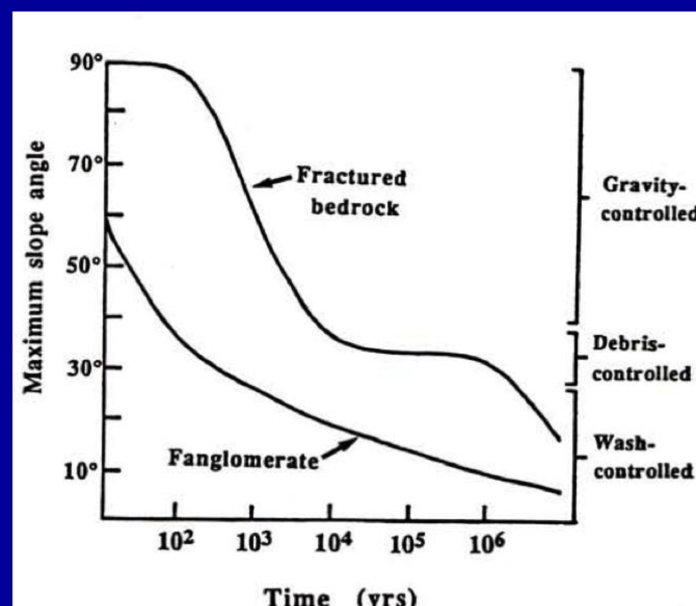
Fault scarp degradation



Wallace, 1977

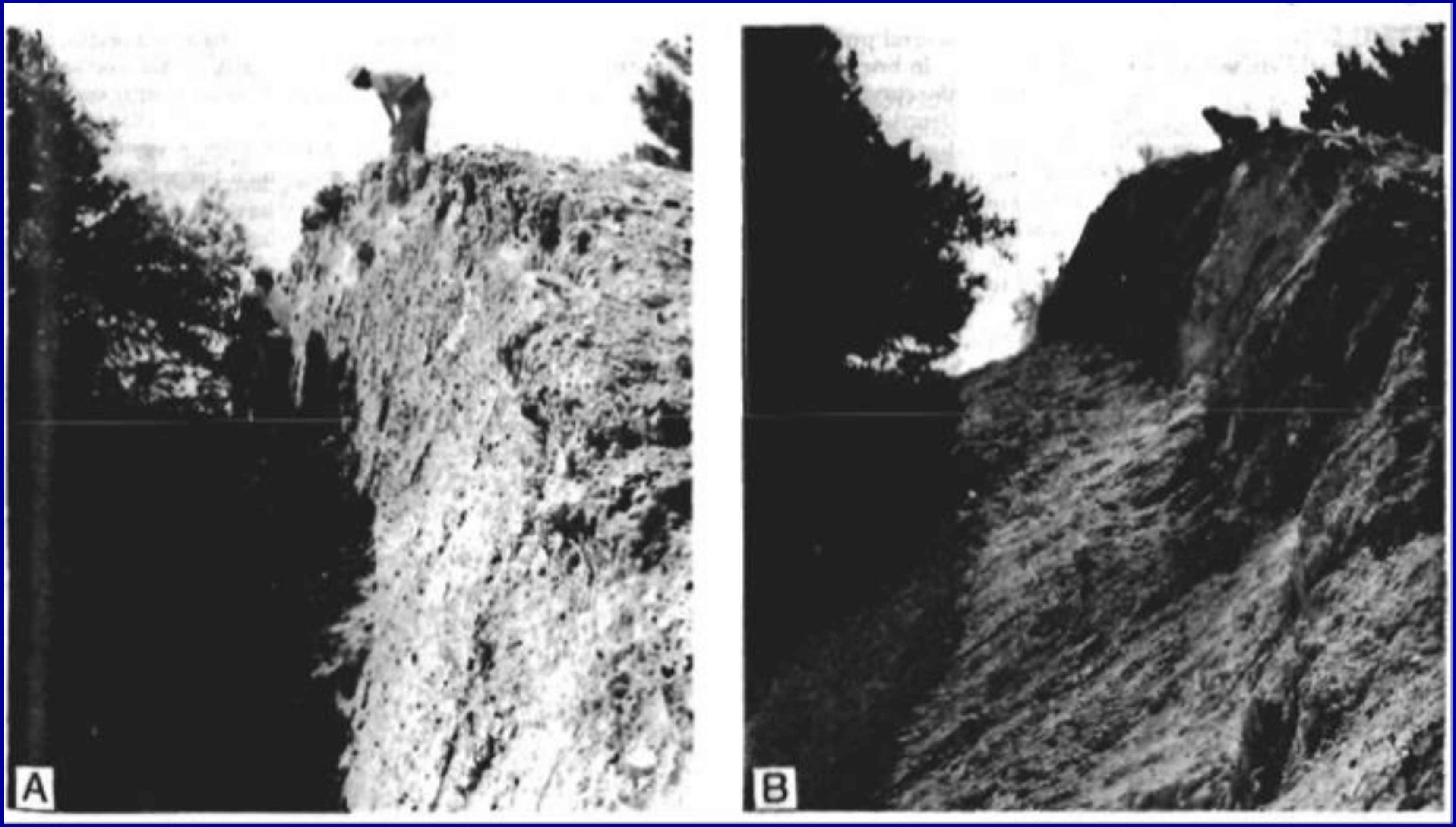


Stewart, Hancock, 1990



Wallace, 1977

Fallon-Stillwater earthquake, July 6th, 1954 M 6.6



Wallace, 1977

Pictures taken from 1954 and 1974 show several meters of retreat from the free face, forming a debris-slope.

Paleoseismology, methods and examples

Paleoseismology

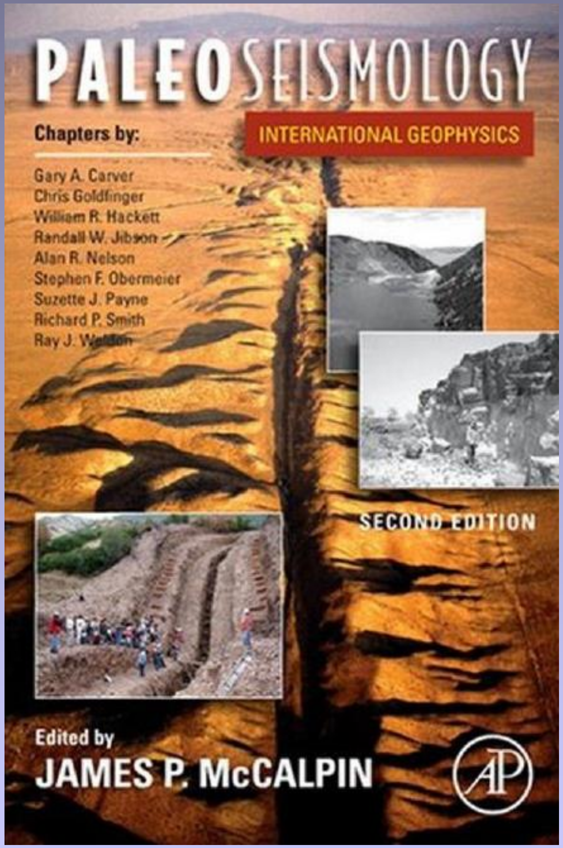
- behaving of seismogenic fault in geological history

Paleoseismology studies **prehistoric** earthquakes - in space, in time, size

Seismologists - data measured instrumentally during EQ

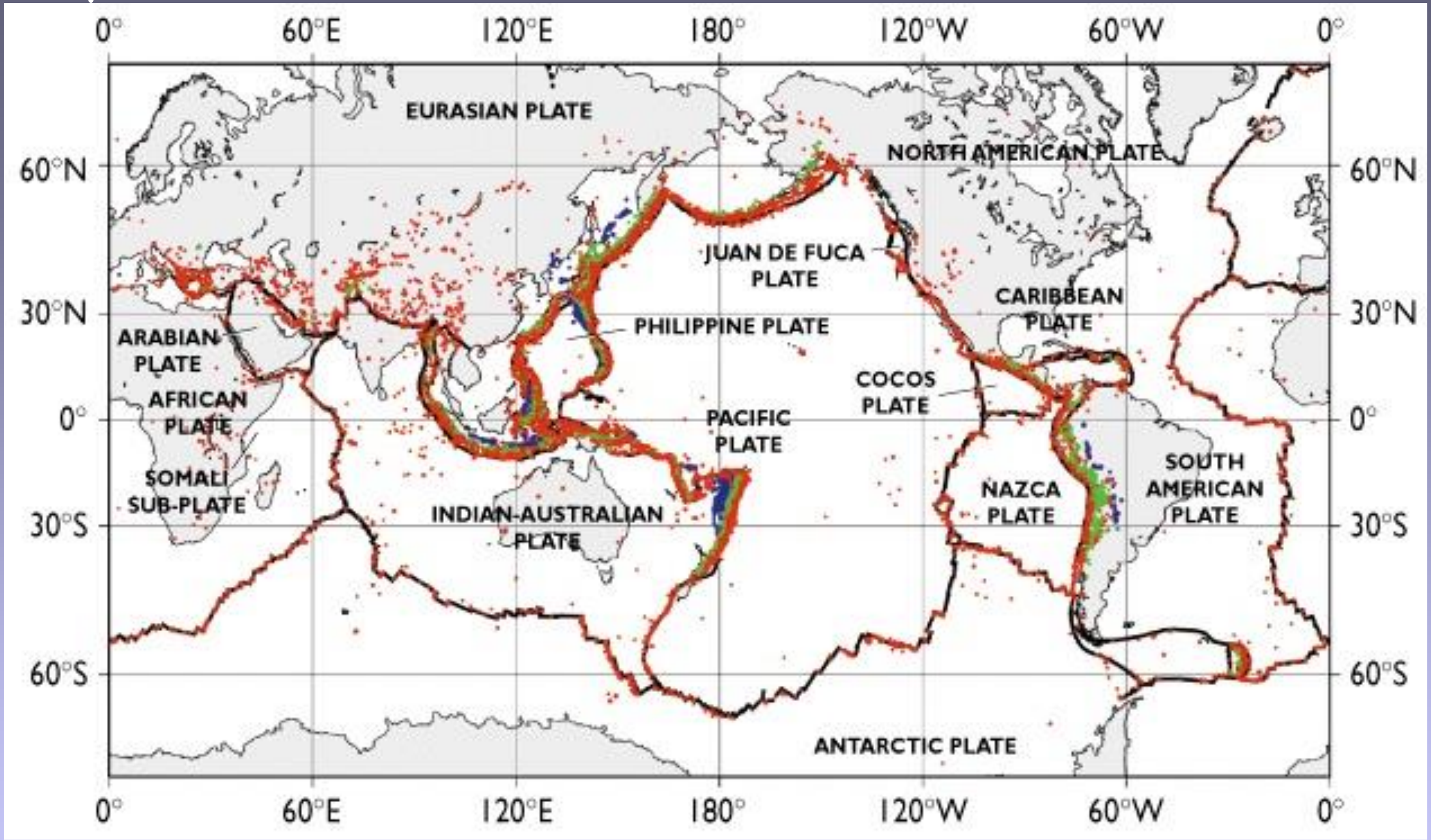
X

Paleoseismologists interpret **geological phenomena** accompanied by individual EQs



McCALPIN, J. (2009). *Paleoseismology.* San Diego: Academic Press.

Why?



Present day seismicity – plate boundaries, intraplate regions
Catastrophic Eqs – sometimes in areas with faults with no present day seismicity, - seismic cycle – longer reccurence interval (China, New Zealand)

Most areas – record of historical EQs only several hundred yrs (historical and instrumental seismicity)

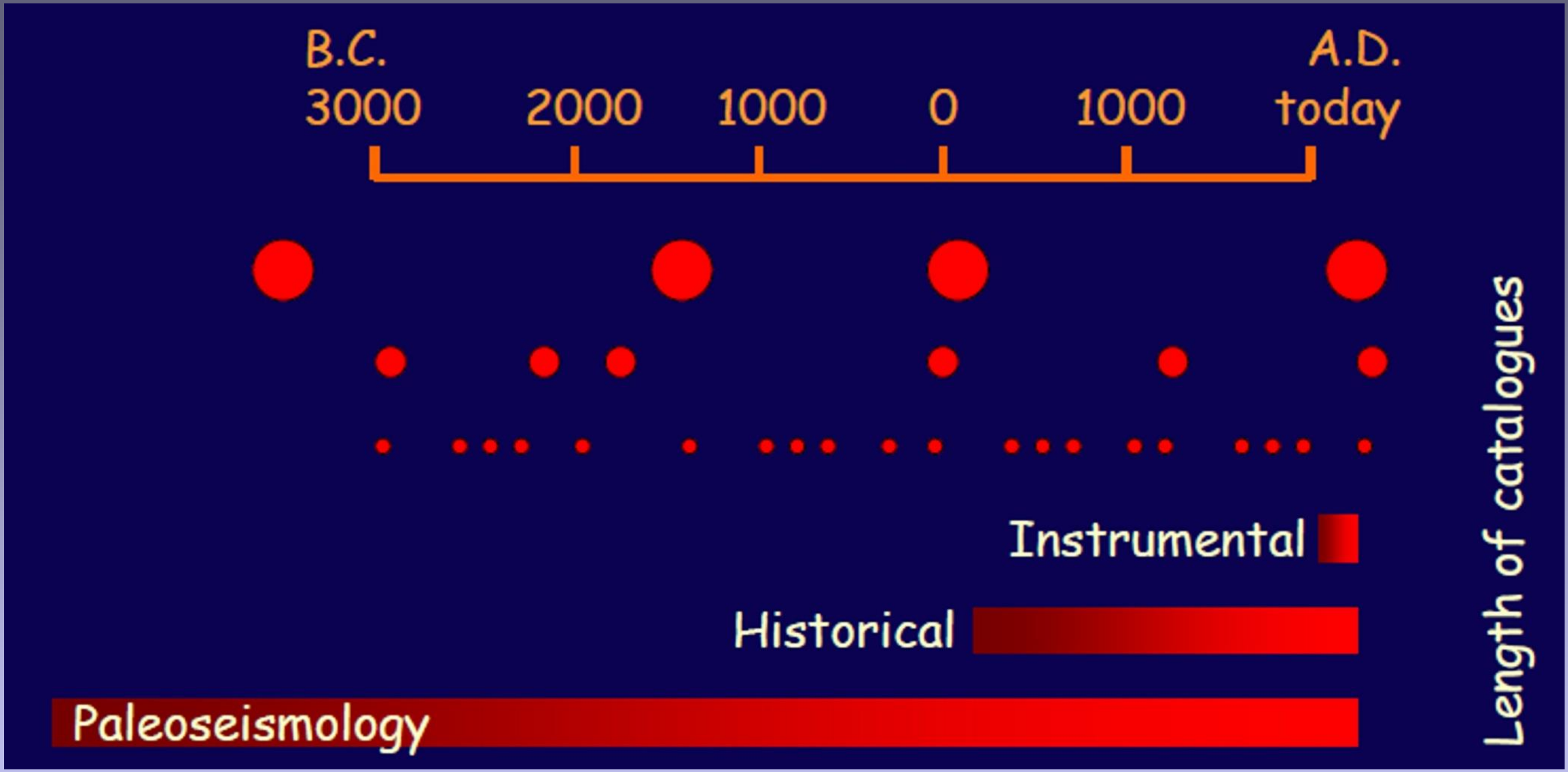
X some active faults expressed in morphology and geology – no historical seismicity or large EQs

China and Middle-East – record thousands yrs and more, still not long enough; fault active millions yrs – 3,000 yrs – only little part of faulting history

Seismic hazard assessment – based on very short period of record of historical EQs, it may cause 2 problems:

❖ overestimation of probability of future EQs based on historical large EQs, but with long recurrence interval (seismic energy is released)

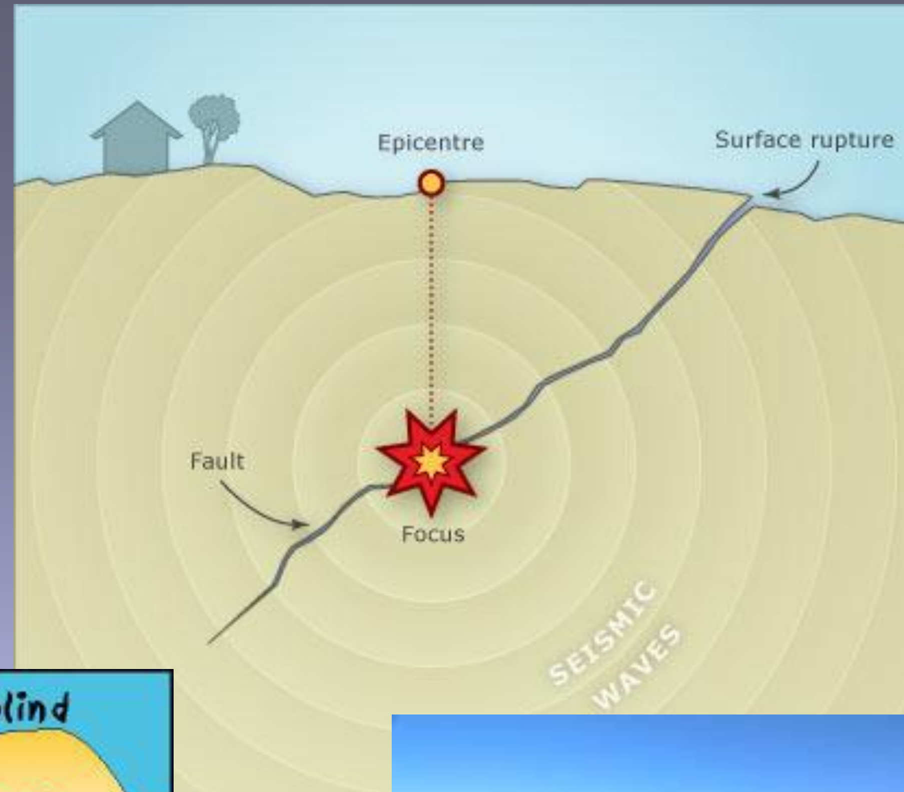
❖ underestimation – in areas with seismogenic faults but no historical record (strain accumulation)

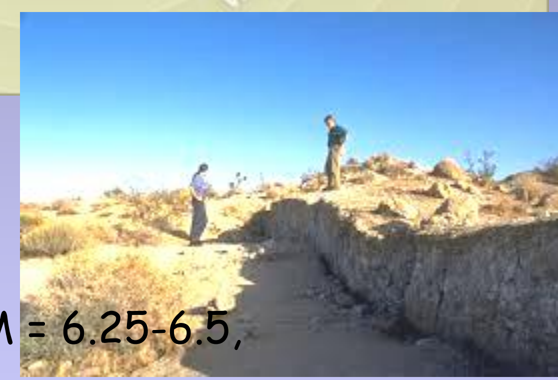


Paleoseismology extends record of EQs into the geological past

EQs catalogues too short

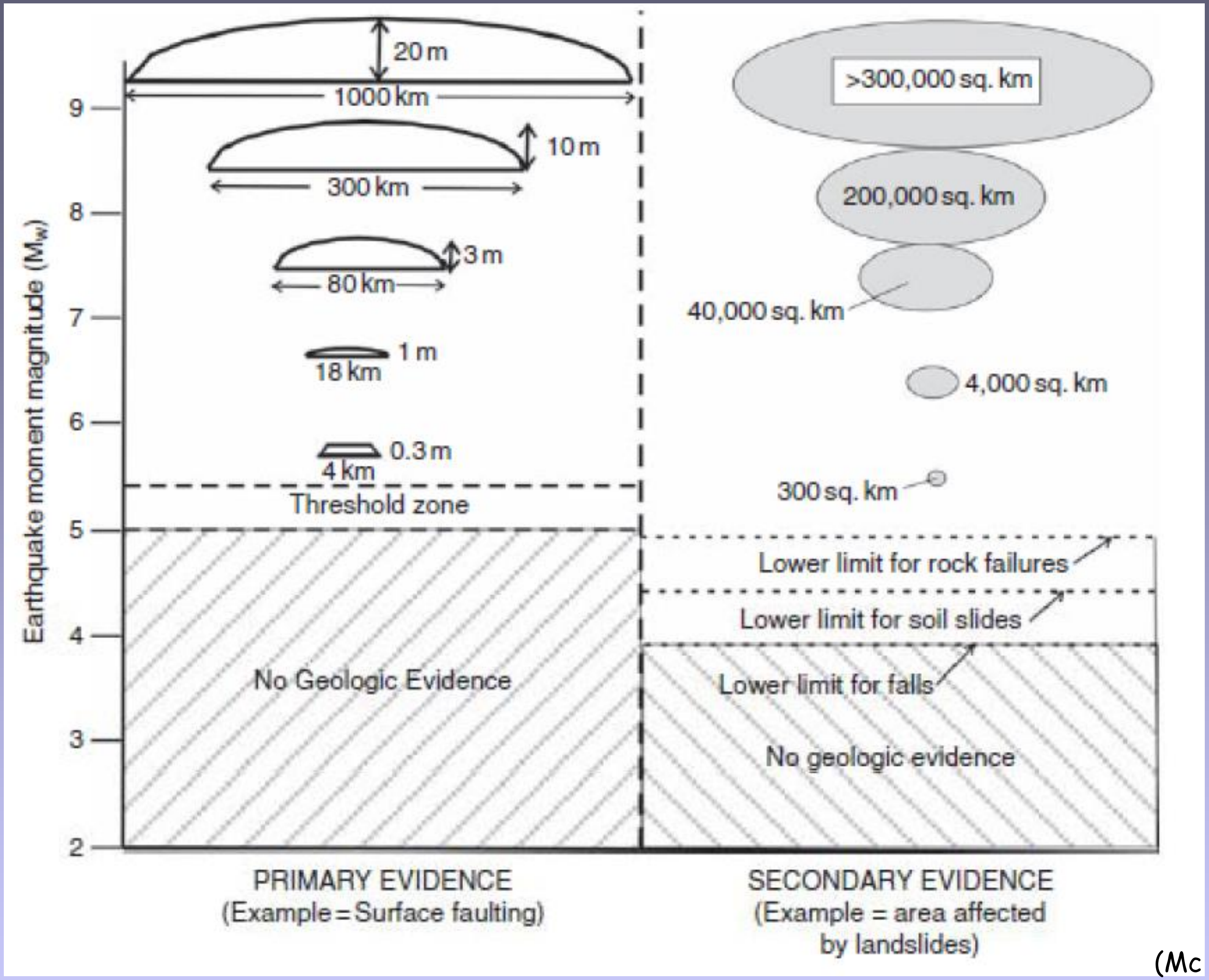
Premise – EQ only larger M > 6 can create permanent deformation on the surface → topografic instability → new processes erosion and accumulation → new landforms and sturctures → geological record of EQ





Smaller EQ - rarely geological expression created or survives
Fault type – normal faults $M \geq 6{,}3$; strike-slips – California i – $M = 6.25$-6.5,
Depth of seismogenic crust – deeper needs higher magnitude

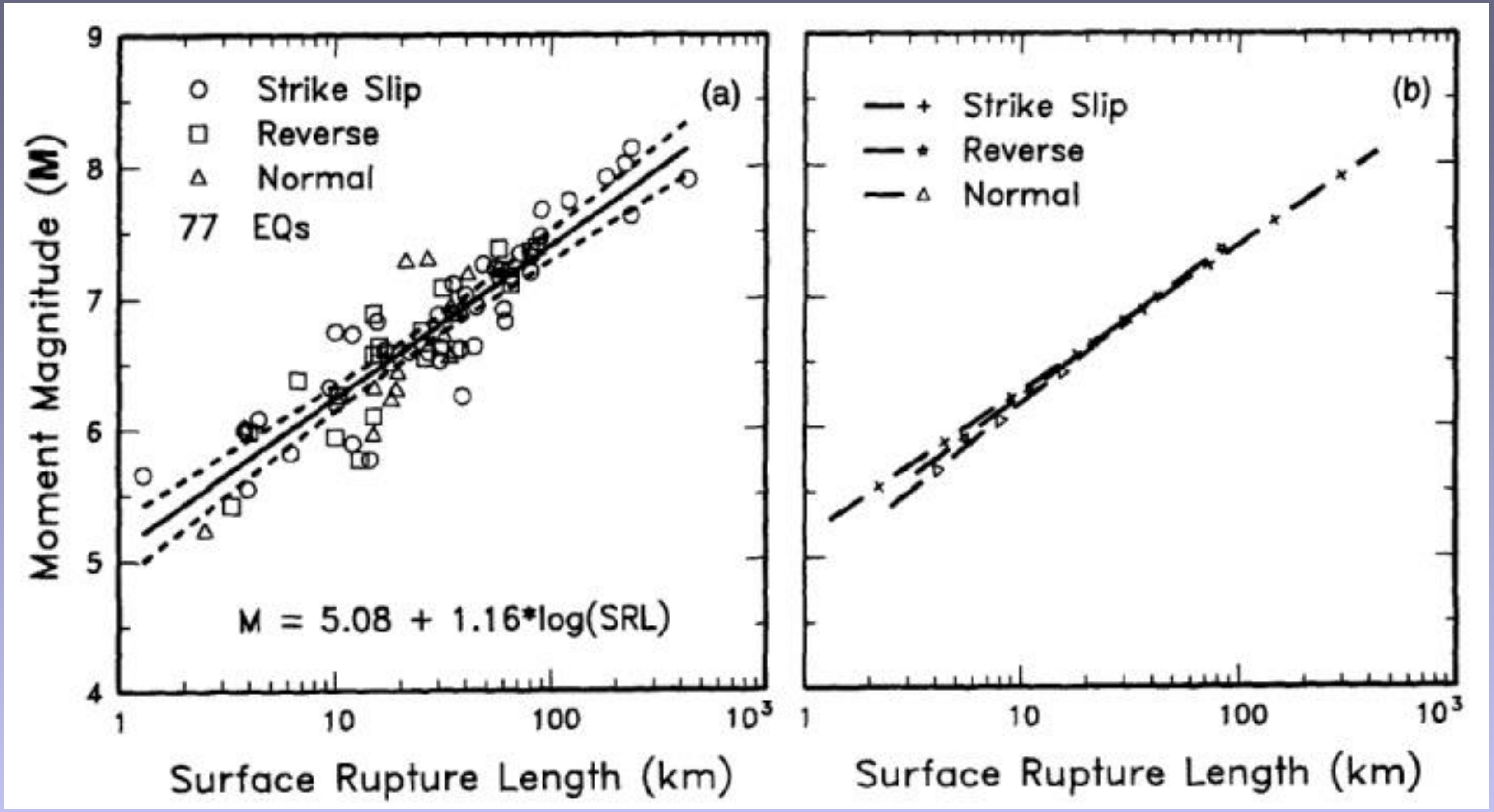
Loma Prieta 1989 M=6,9, 2m slip in depth 3-18km, no surface rupture
Gujarat 2001 M=7.7, blind fault, 1-4m in depth 9-15km,



(Mc Calpin 2009)

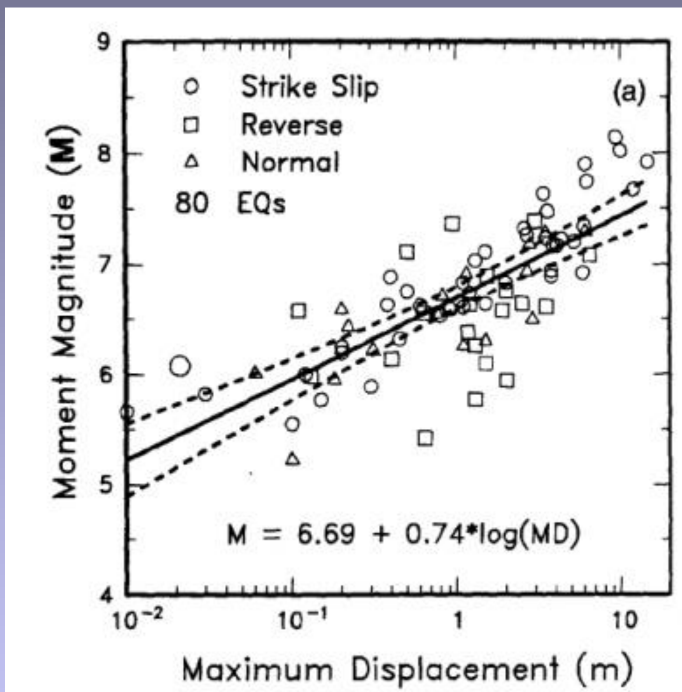
Empirical relationships based on observation from historical EQs

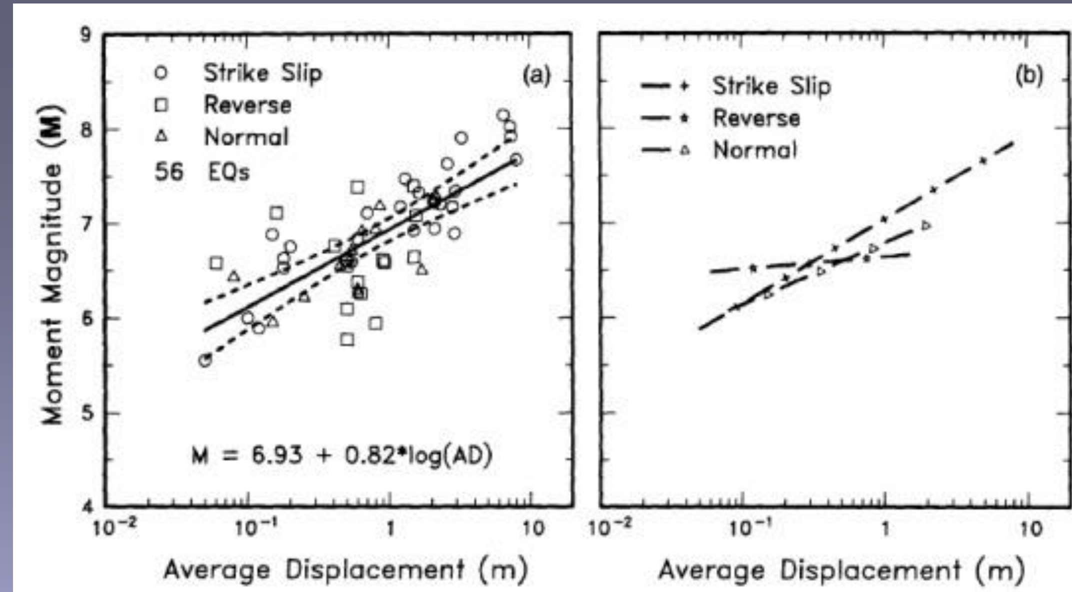
Relationships: fault length, amount of displacements, size of Magnitude
e.g. fault 80km long can generate EQ Mw=7.5 and displacement 3m



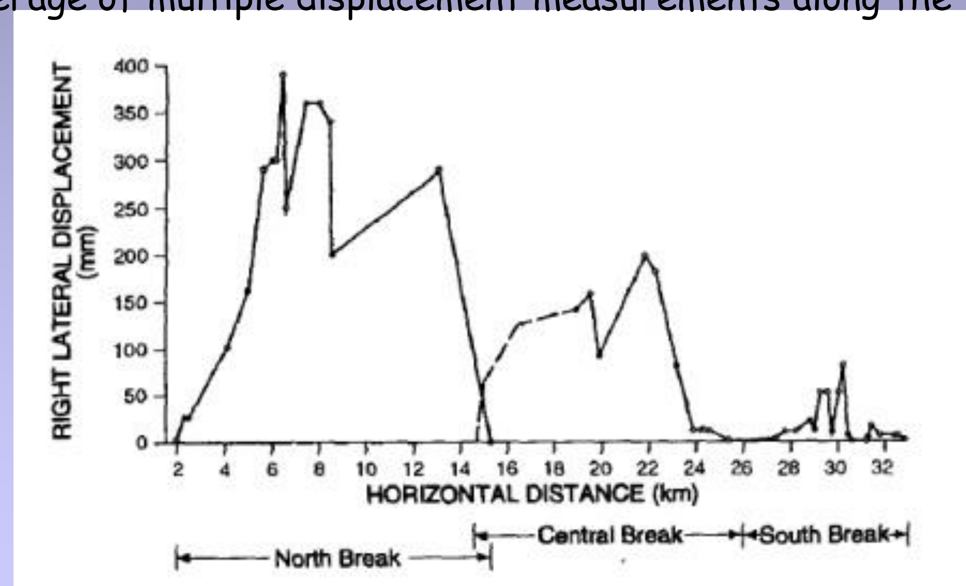
Empirical relationships – historical EQs (421), focis depth ‹40km, Mw › 4.5

Wells, and Coppersmith 1992





Average of multiple displacement measurements along the fault



9. 4. 1968, Borego Mts, CA

Paleoseismological study of faults

- Localisation and geometry (geomorphology, geological mapping)
- Slip rate – faulting velocity (= displacement/time)
- Slip per event – characteristic displacement during individual EQs
- Recurrence period – (repeated EQ, frequency EQ)
- Elapsed time – time from the last EQ
- Maximum potential magnitude

Chronological reconstruction of movements

- stratigraphic, structural, geomorphological, biological, archeological evidence
- dating of displaced features or movement indicators


Fig. 21


Fig. 22

- dating of multiple movements (EQs) - recurrence interval, long-term slip-rate, vaiability of movements during EQs

→ predict localisation and magnitude of future EQs

Methods

– direct observations od dislocated objects – on the surface or in **trenches**, outcrops

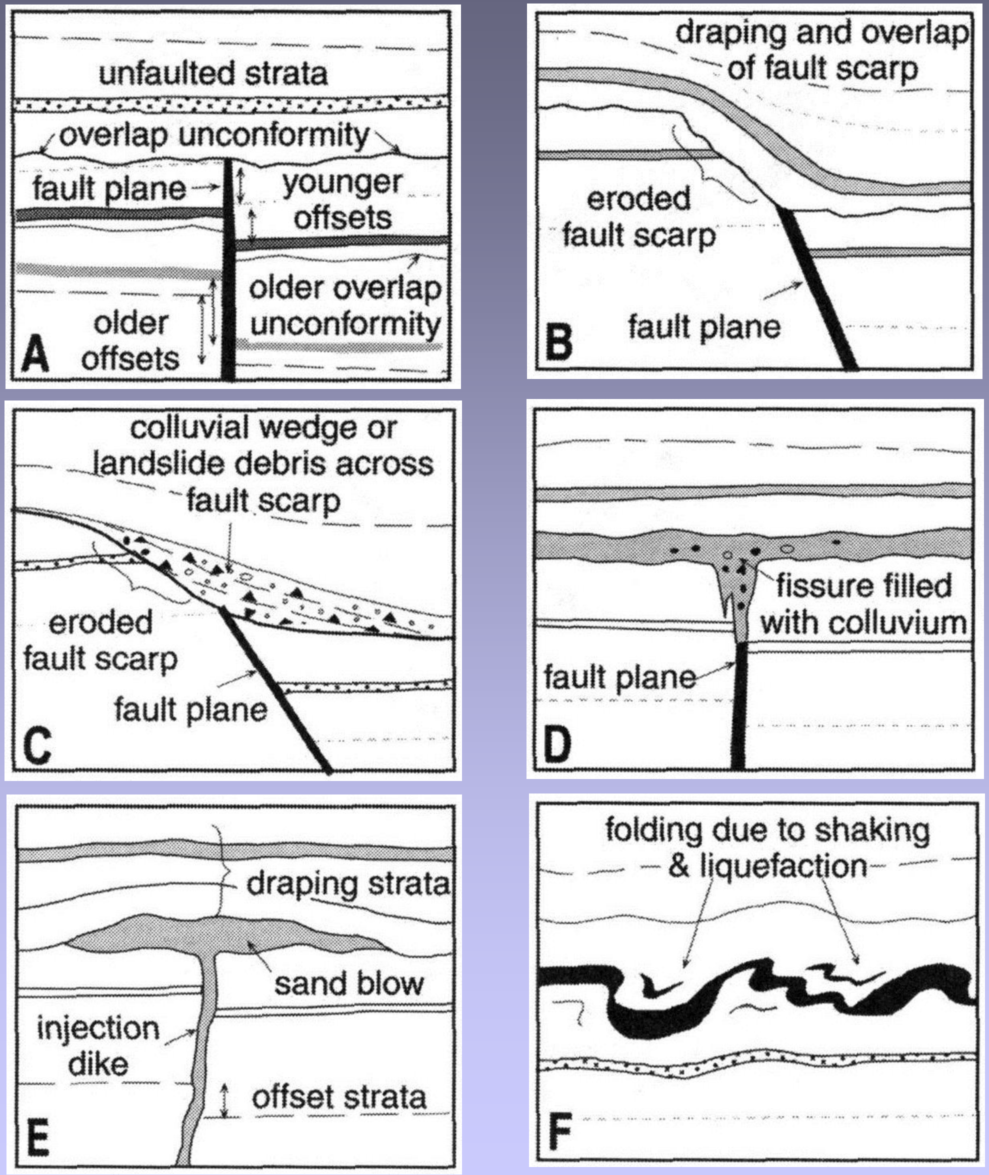
- young sediments, fine grained, stratified - well recognizable displacemnt of layers, not thick

  Alluvial fans, lake sediments X debris flow

- datable material– chronology of movements

Evidence of EQs in trenches

- Difference in cumulative offset
- Buried fault scarp
- Coluvial wedge- typical for sudden movement
- Filled fissures by overlying material
- Sand dykes
- Liquefied layers



Allen (1986)

Repated EQs

- Difference in cumulative offset

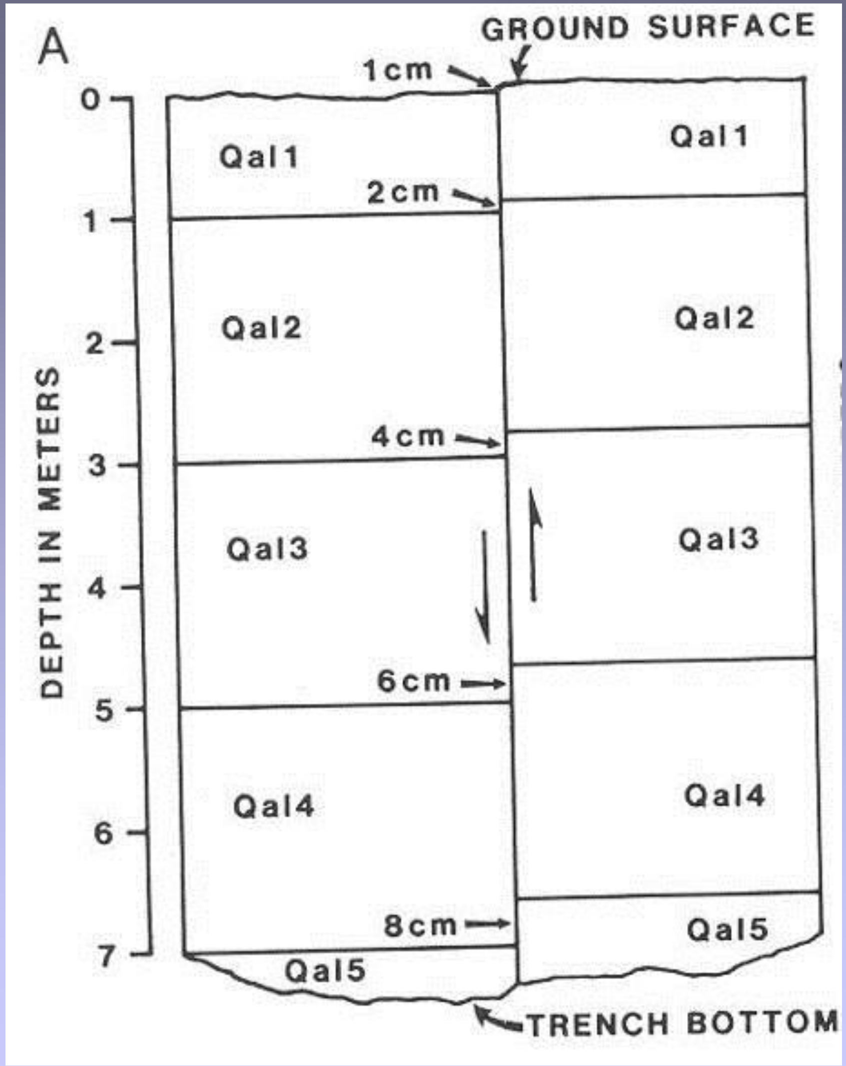
? How many: retrodeformation

4 events – vertical offset 2cm

Oldest layer - (Qal5) all 4 events, cumulative 8cm

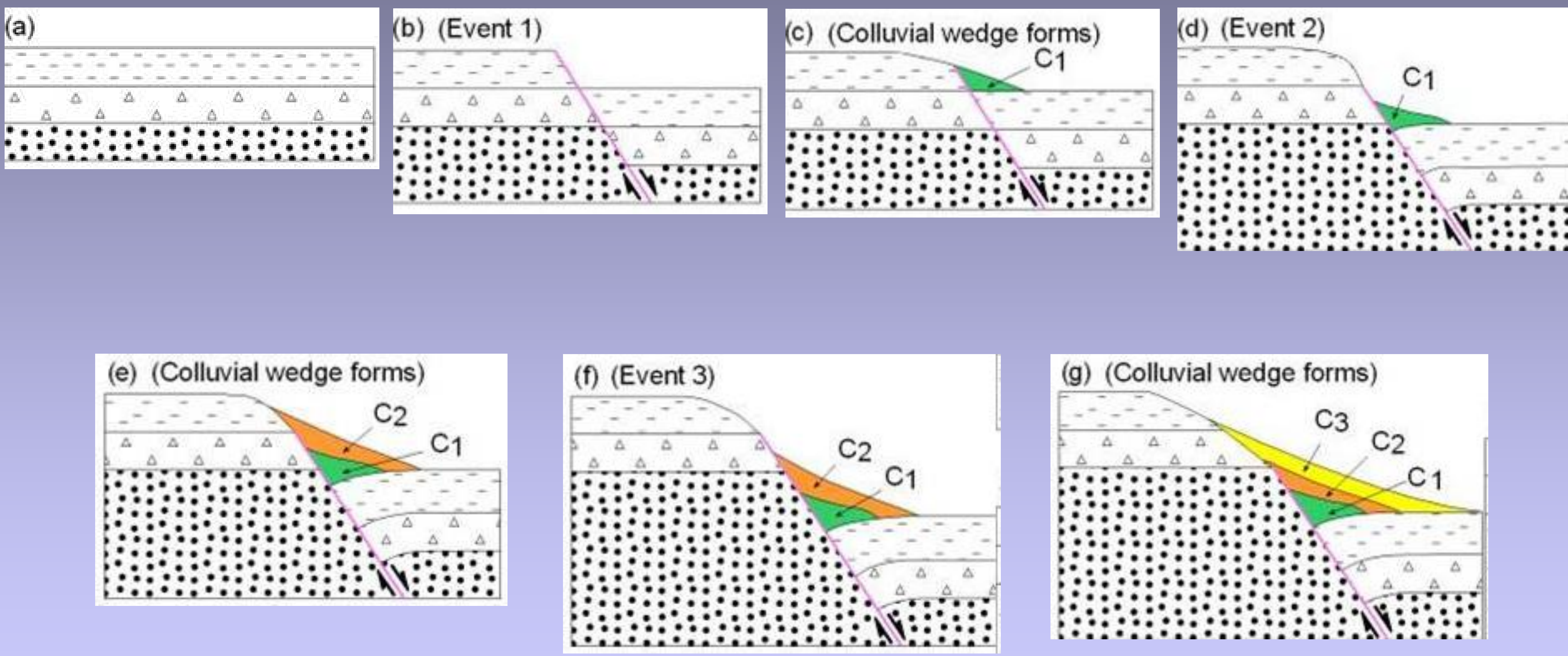
Youngest (Qal1) has experienced only 1 event → 2 cm on the layer base, but 1 cm on the surface!

Surficial erosion



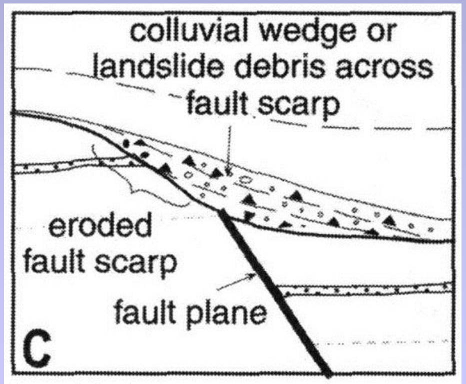
Normal faulting

Coluvial wedge

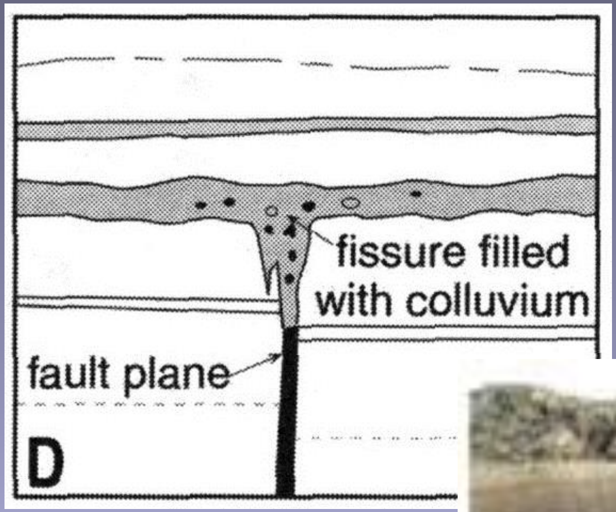


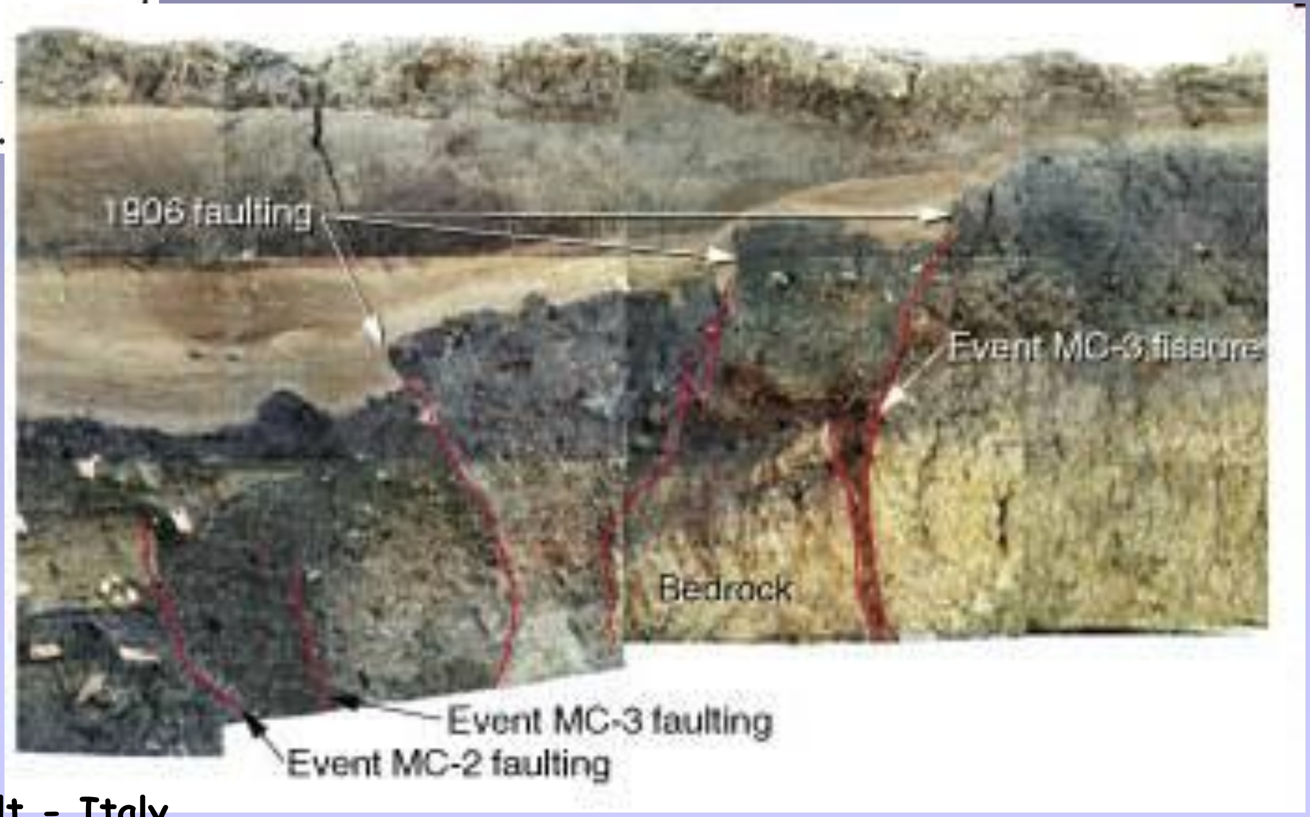
Gravitational instabilty

Fault scarp derived material - wedge



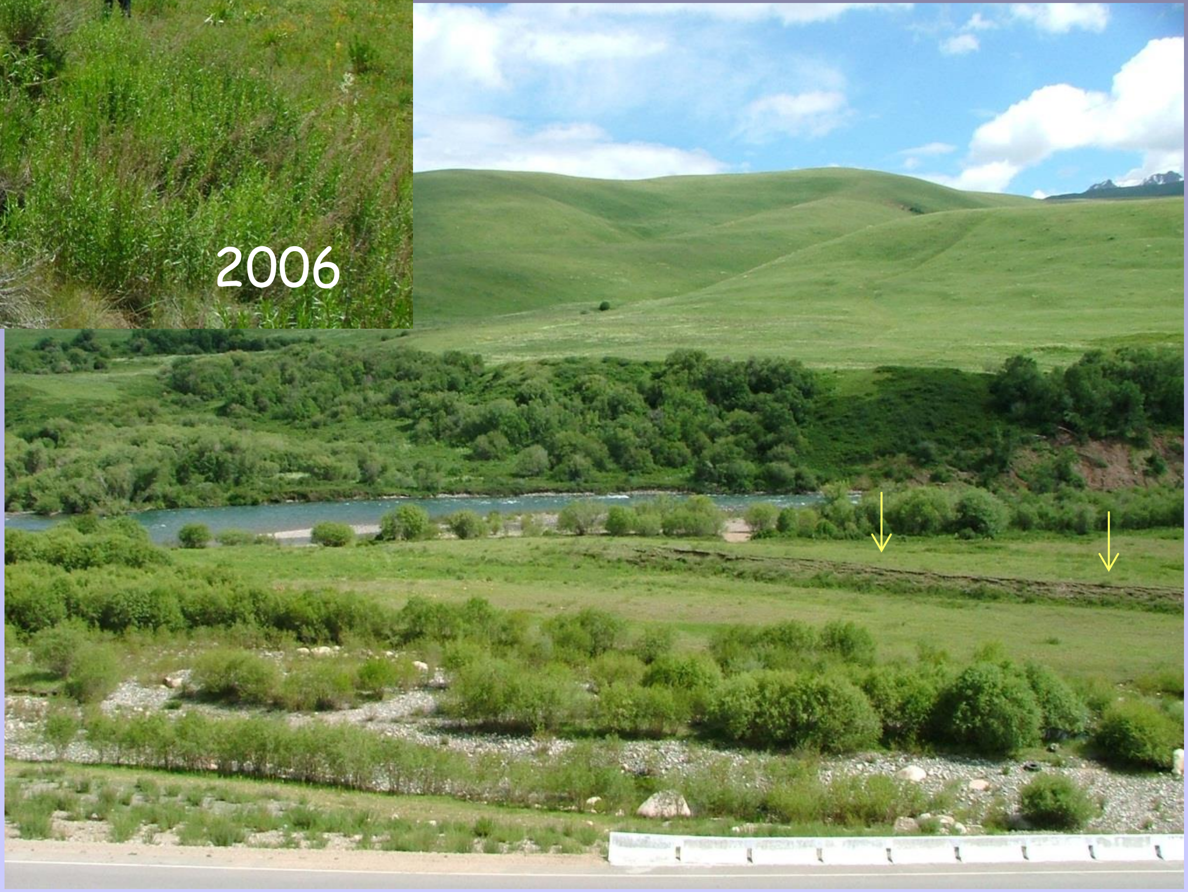
- **Filled fissure**





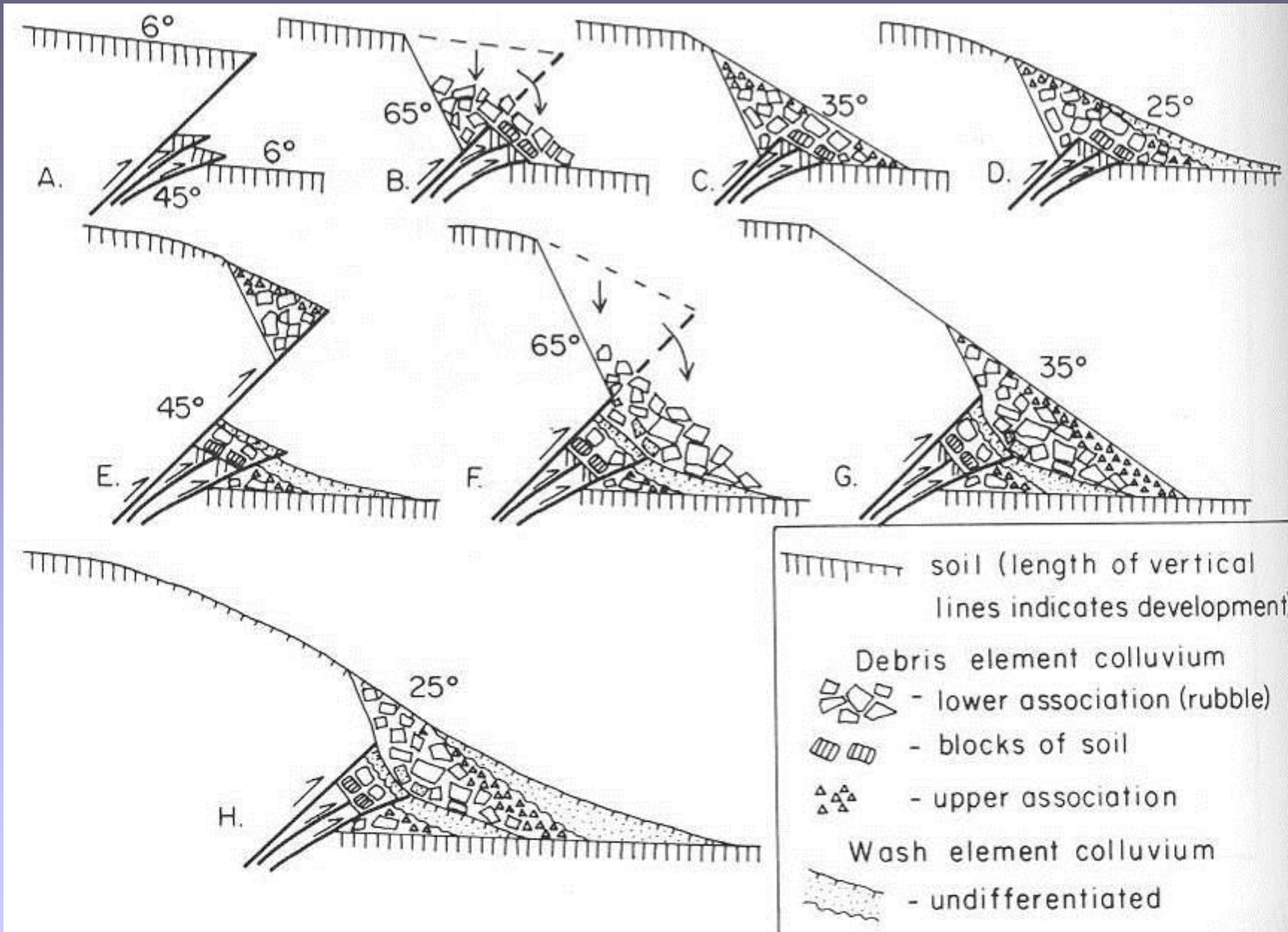
Aremogna-Cinquemiglia fault - Italy

Reverse faulting

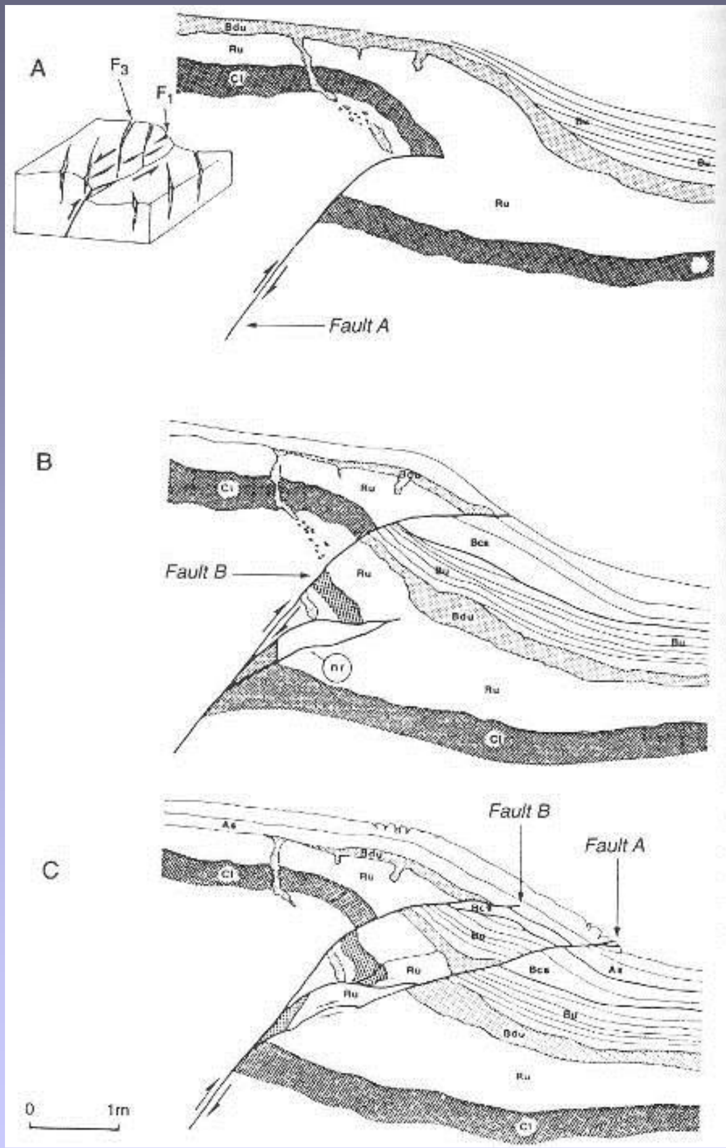


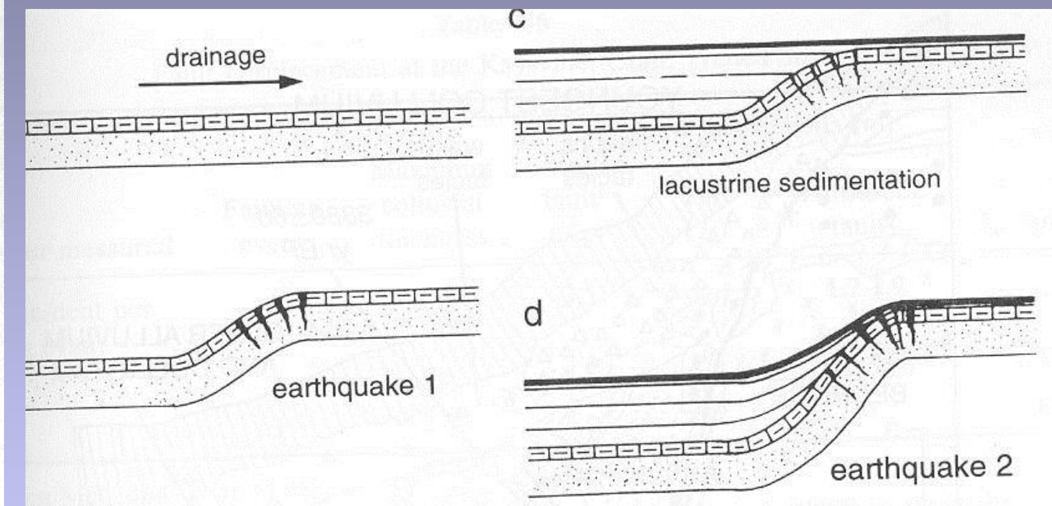
Suusamyr, 1992, M=7,4
Kyrgyzstan

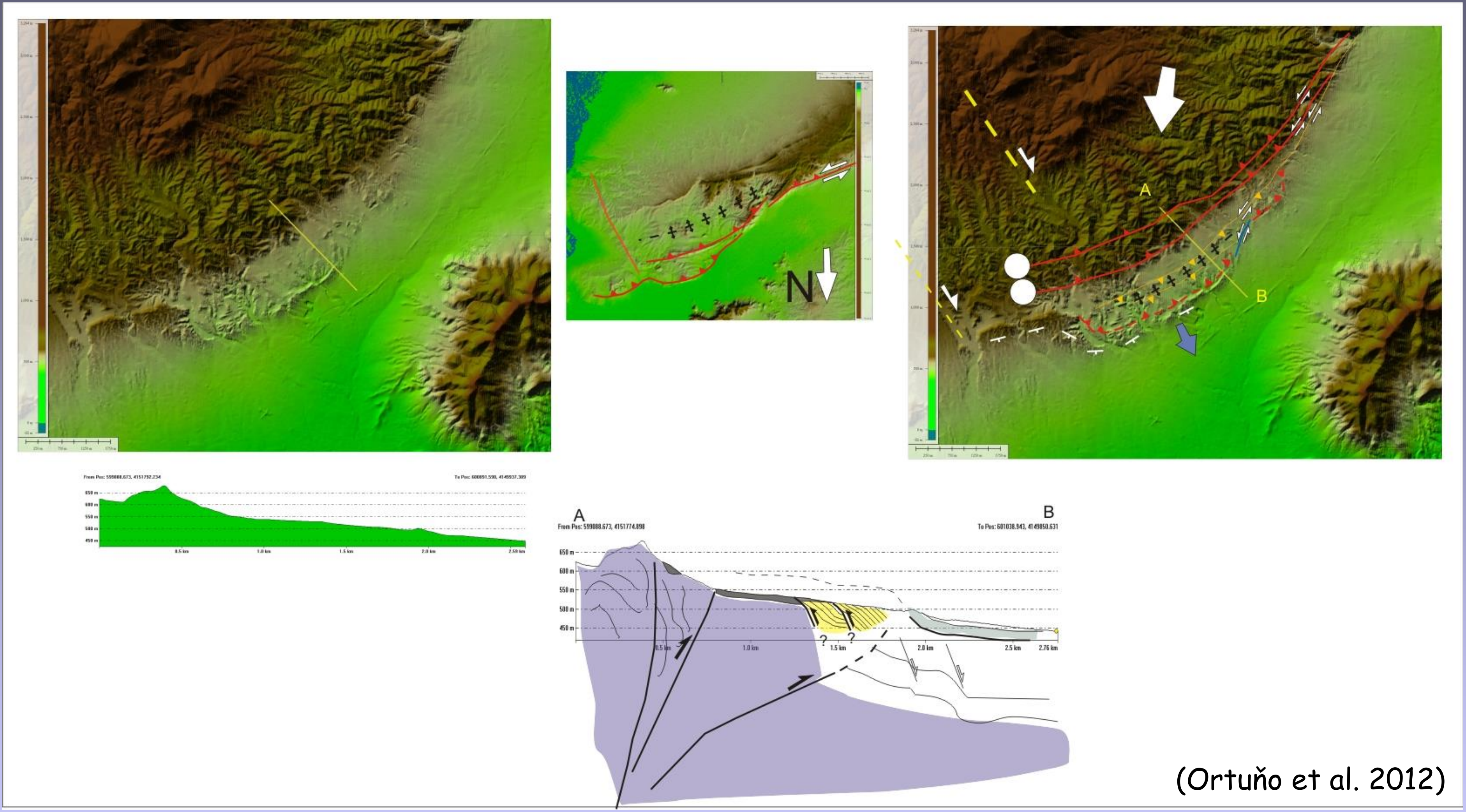
Reverse faults – colluvial wedge



Reverse faults

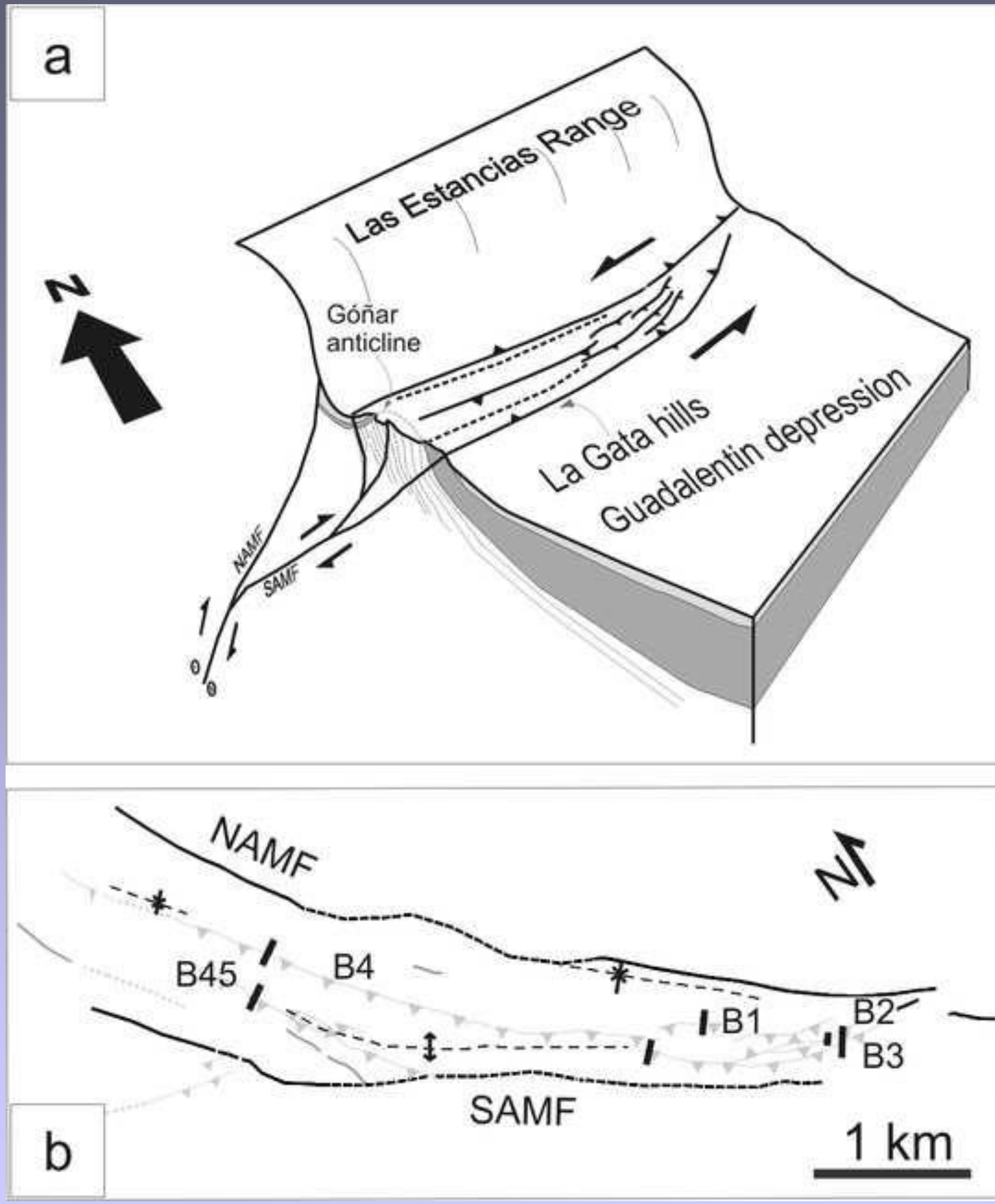




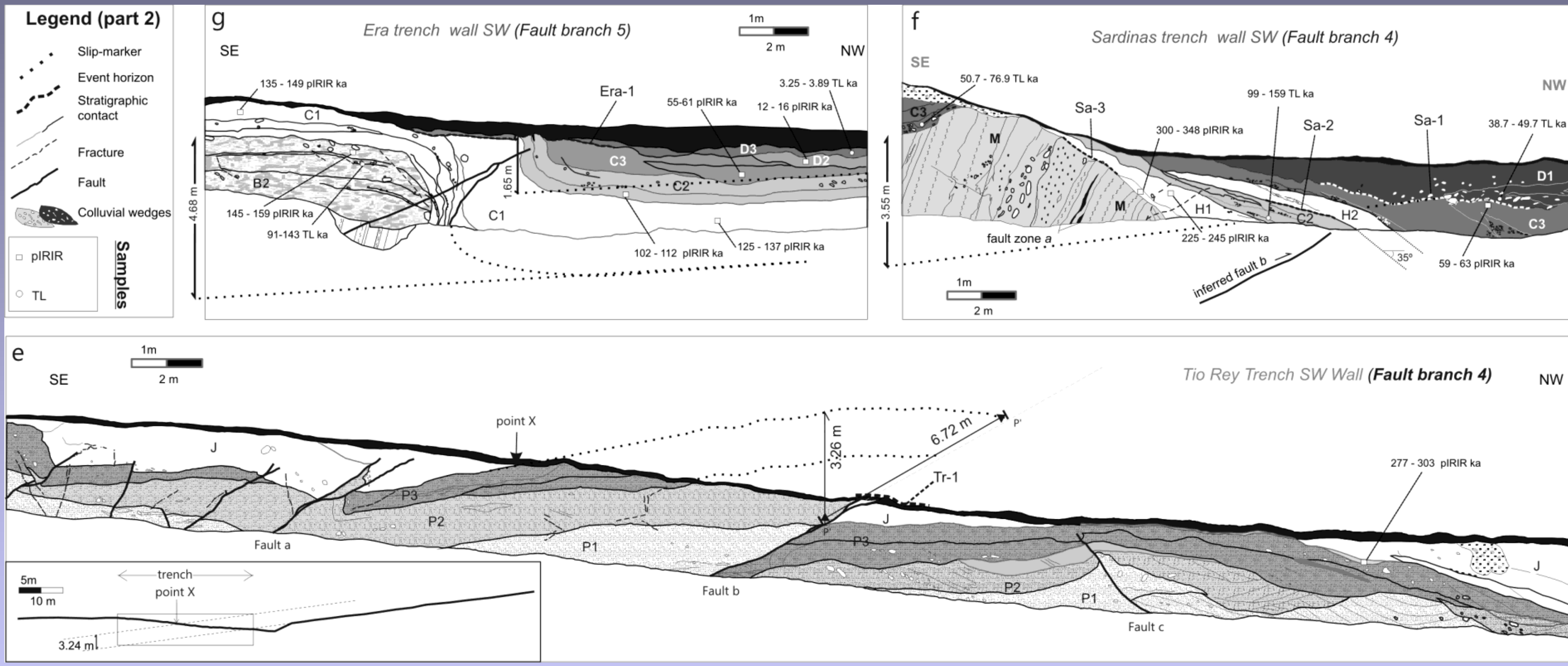


Alhama de Murcía fault, Spain

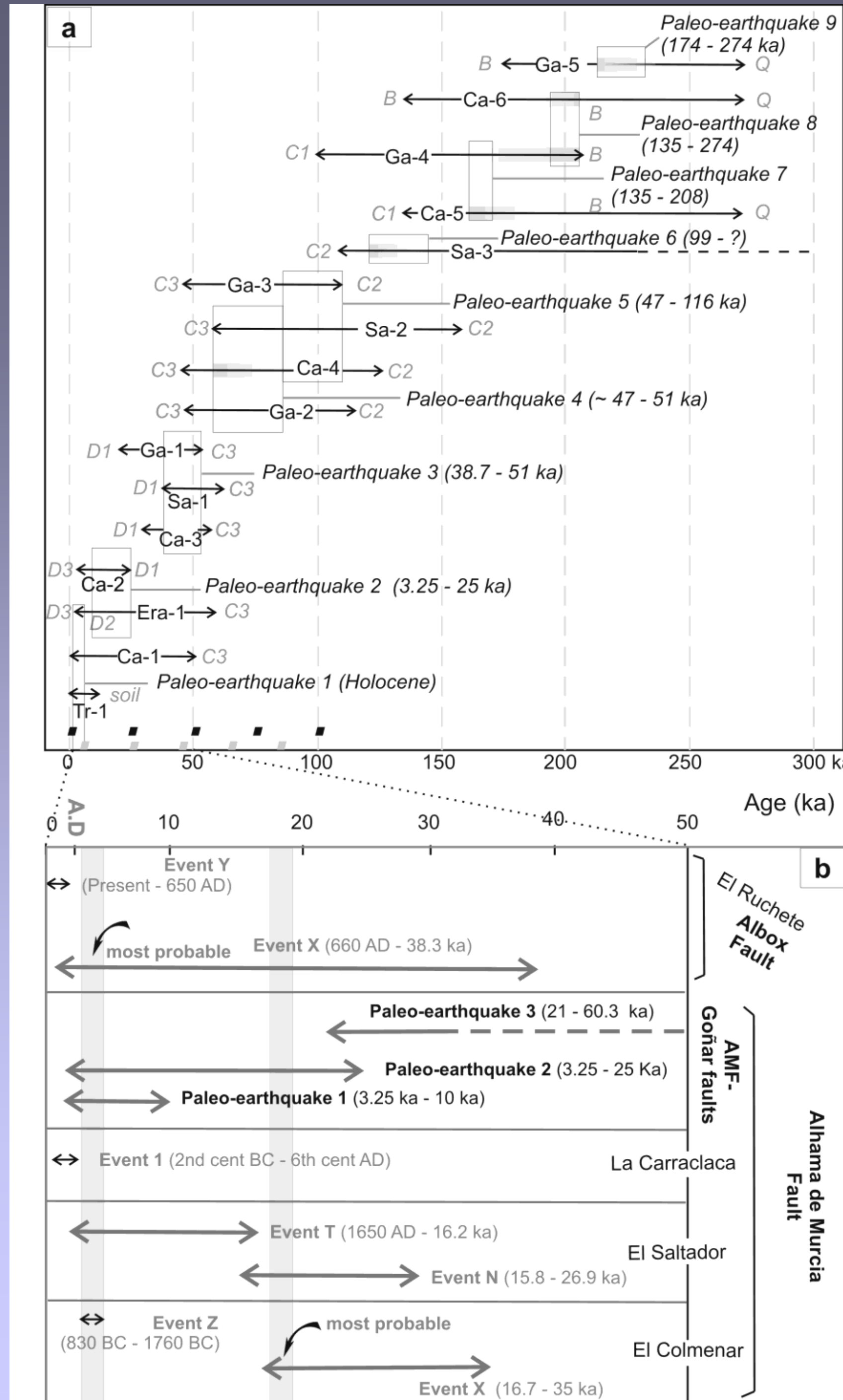
Different kinematics based on stress orientation


a
Las Estancias Range
N
Góñar
anticline
La Gata hills
Guadalentin depression
NAMF
SAMF
b
NAMF
N
B45
B4
B1
B2
B3
SAMF
1 km

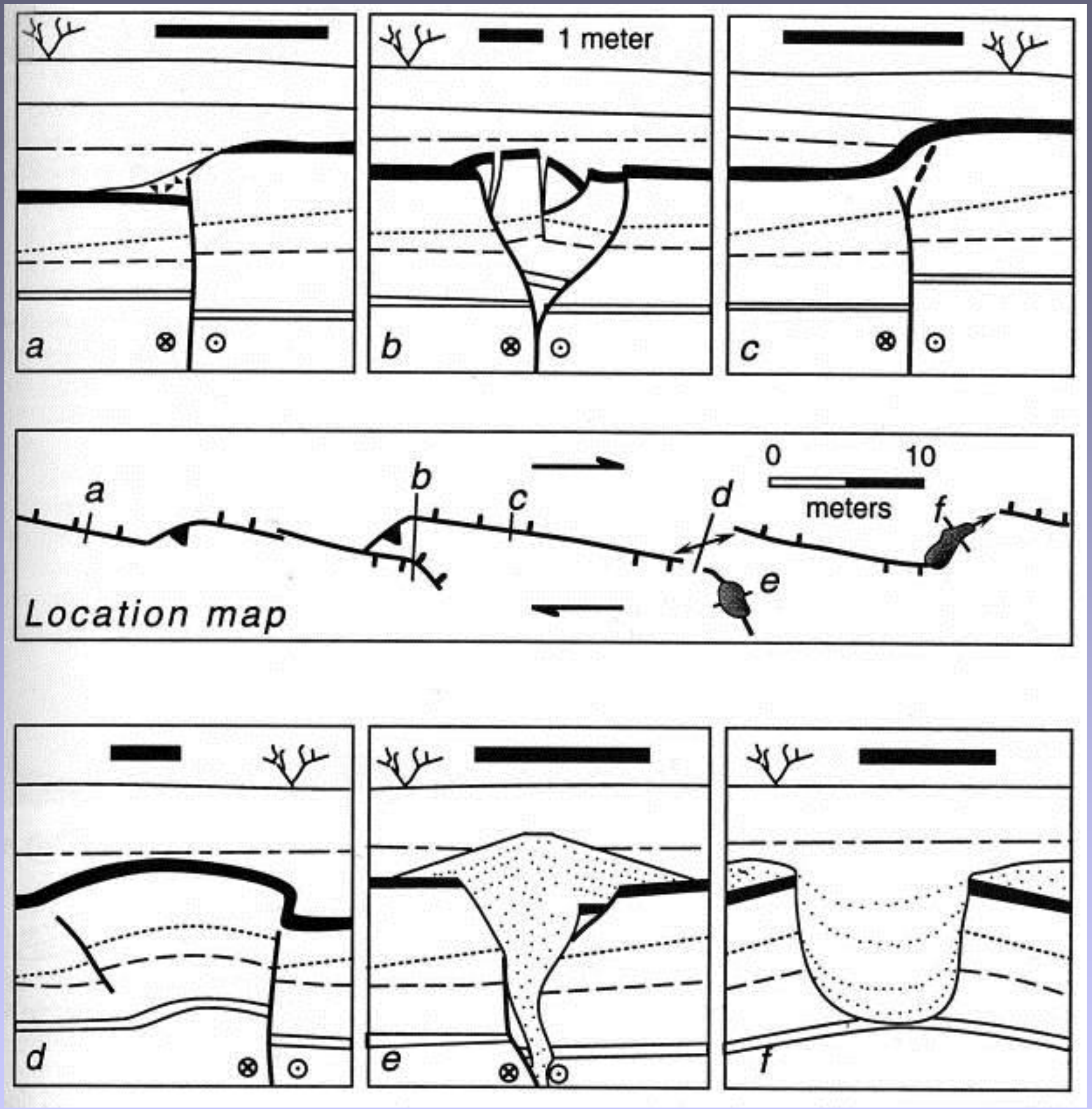




Legend (part 2)
Slip-marker
Event horizon
Stratigraphic contact
Fracture
Fault
Colluvial wedges
pIRIR
TL
Samples
g
Era trench wall SW (Fault branch 5)
SE
NW
1m
2 m
135 - 149 pIRIR ka
Era-1
55-61 pIRIR ka
12 - 16 pIRIR ka
3.25 - 3.89 TL ka
C1
C3
D3
D2
C2
B2
4.68 m
1.65 m
145 - 159 pIRIR ka
91-143 TL ka
C1
102 - 112 pIRIR ka
125 - 137 pIRIR ka
f
Sardinas trench wall SW (Fault branch 4)
SE
NW
50.7 - 76.9 TL ka
C3
Sa-3
M
99 - 159 TL ka
Sa-2
Sa-1
38.7 - 49.7 TL ka
300 - 348 pIRIR ka
D1
3.55 m
M
H1
C2
H2
C3
fault zone a
225 - 245 pIRIR ka
35º
59 - 63 pIRIR ka
inferred fault b
1m
2 m
e
1m
2 m
Tio Rey Trench SW Wall (Fault branch 4)
SE
NW
point X
J
3.26 m
6.72 m
P'
Tr-1
277 - 303 pIRIR ka
P3
P2
J
P'
P3
P1
Fault a
Fault b
P2
P1
J
Fault c
5m
10 m
trench
point X
3.24 m



(Ortuňo et al. 2012)



Yeats et al (1997)

Imperial fault, 1940 M=7, 6m offset, 60km length

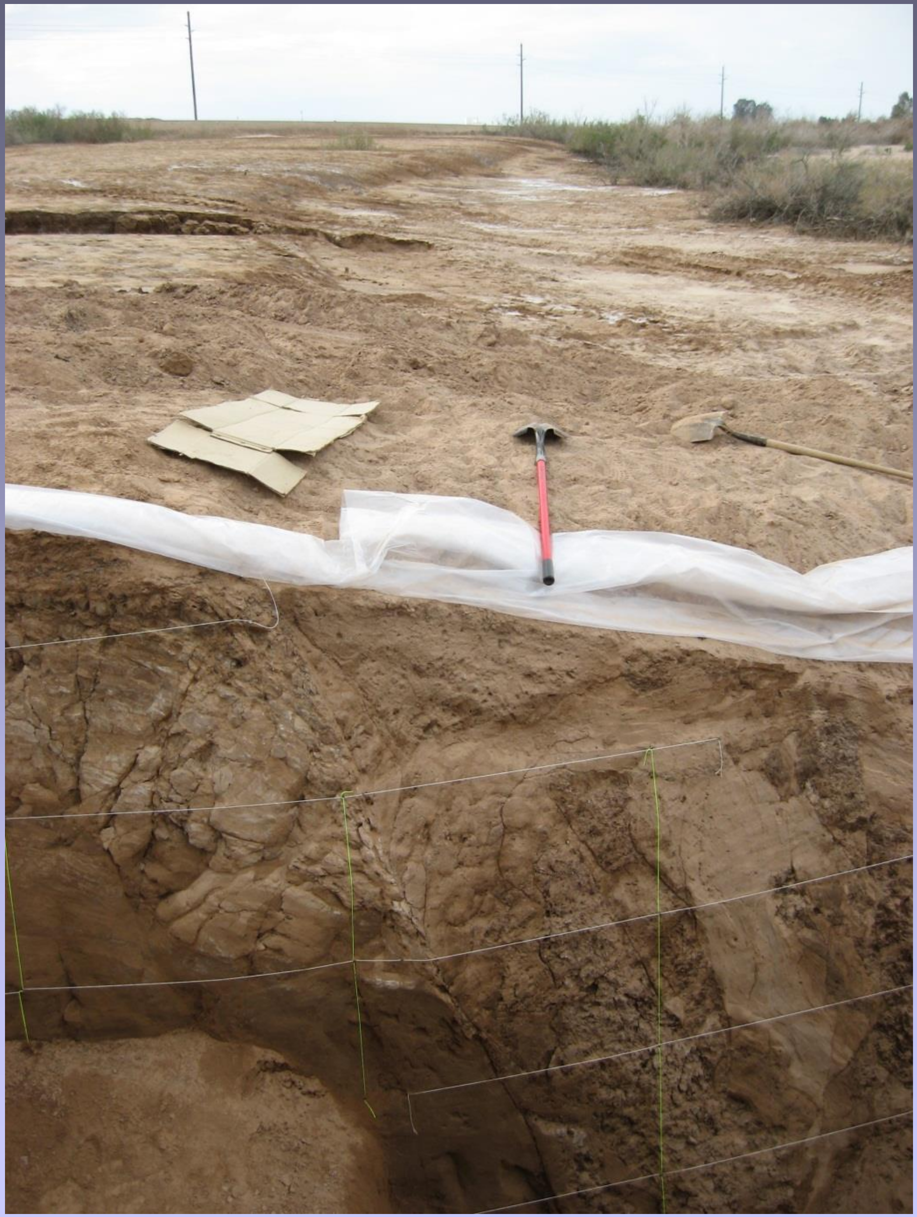
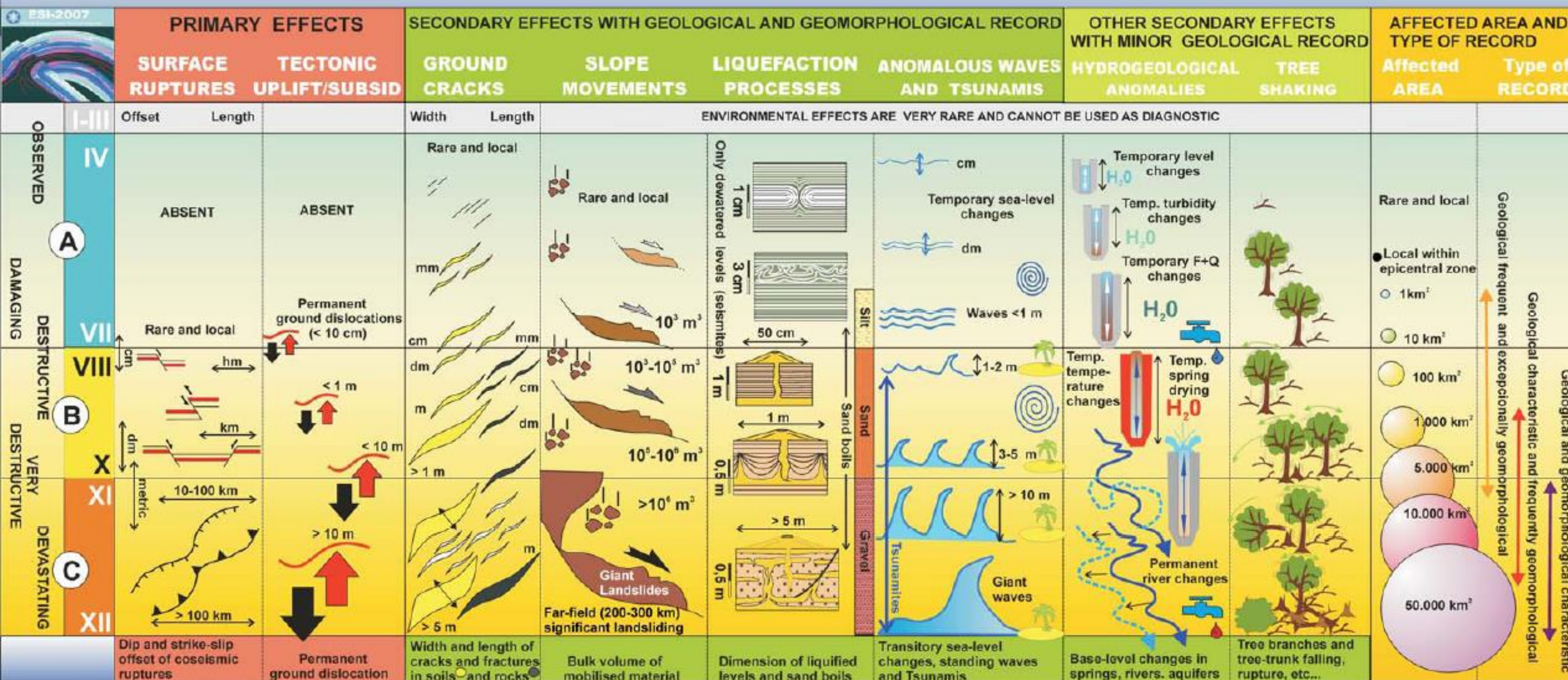


CHART OF THE INQUA ENVIRONMENTAL SEISMIC INTENSITY SCALE 2007 - ESI 07



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