Lesson 8 cont’d

Sedimentary rocks and processes

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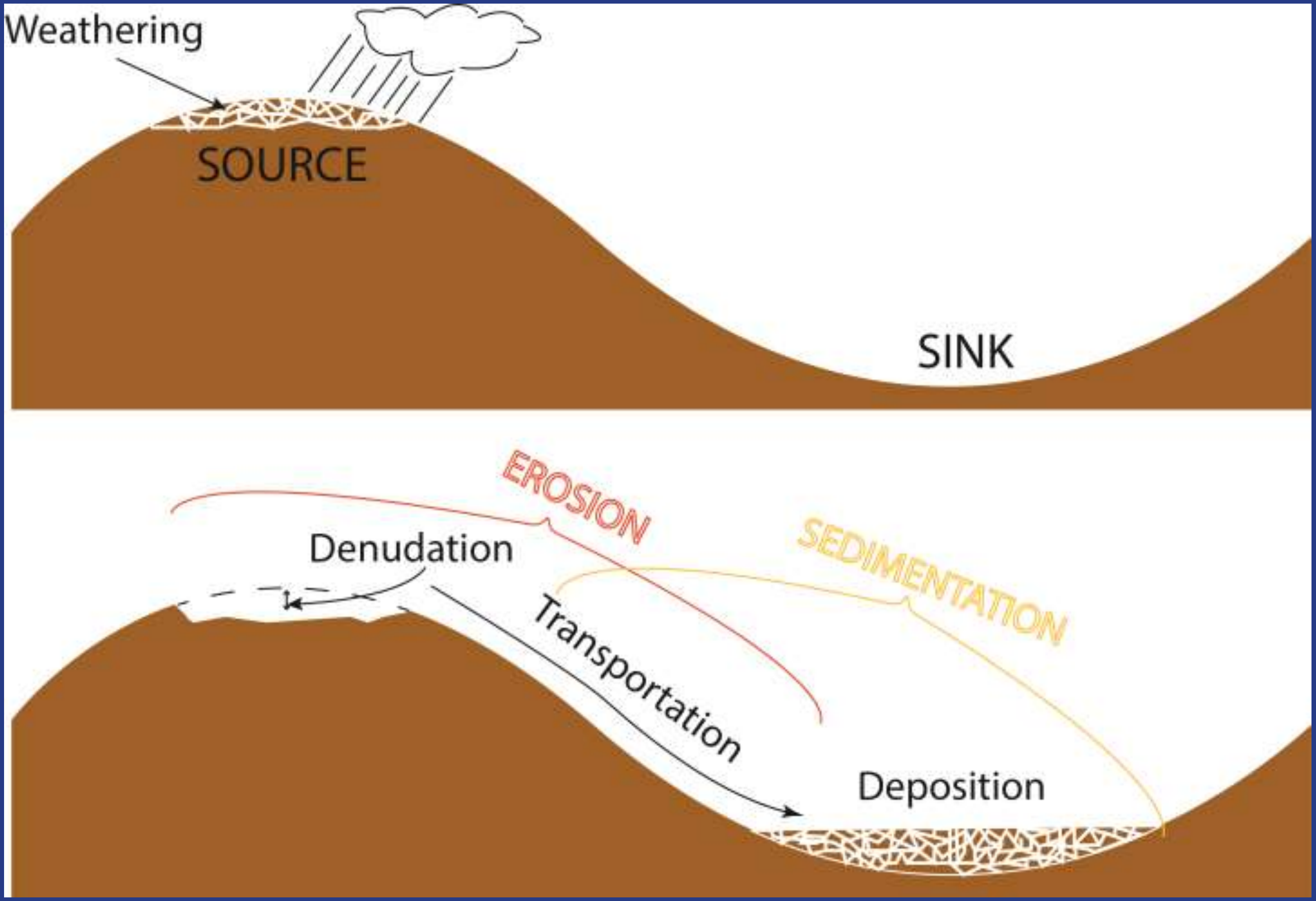
Earlier we had listed the sedimentary processes. They are what create the sedimentary rocks.

All sedimentary processes do two things: transportation of the material prepared by weathering away from source regions and its deposition in sink regions. All sedimentary rocks have a source and a sink.



Clastic sedimentary rocks

Conglomerates
Sandstones
Siltstones
Claystones and
Shales

Organic sedimentary rocks

Limestones
Dolomites
Other carbonate rocks
Cherts
Coals

Chemical sedimentary rocks

Banded iron deposits
Evaporites

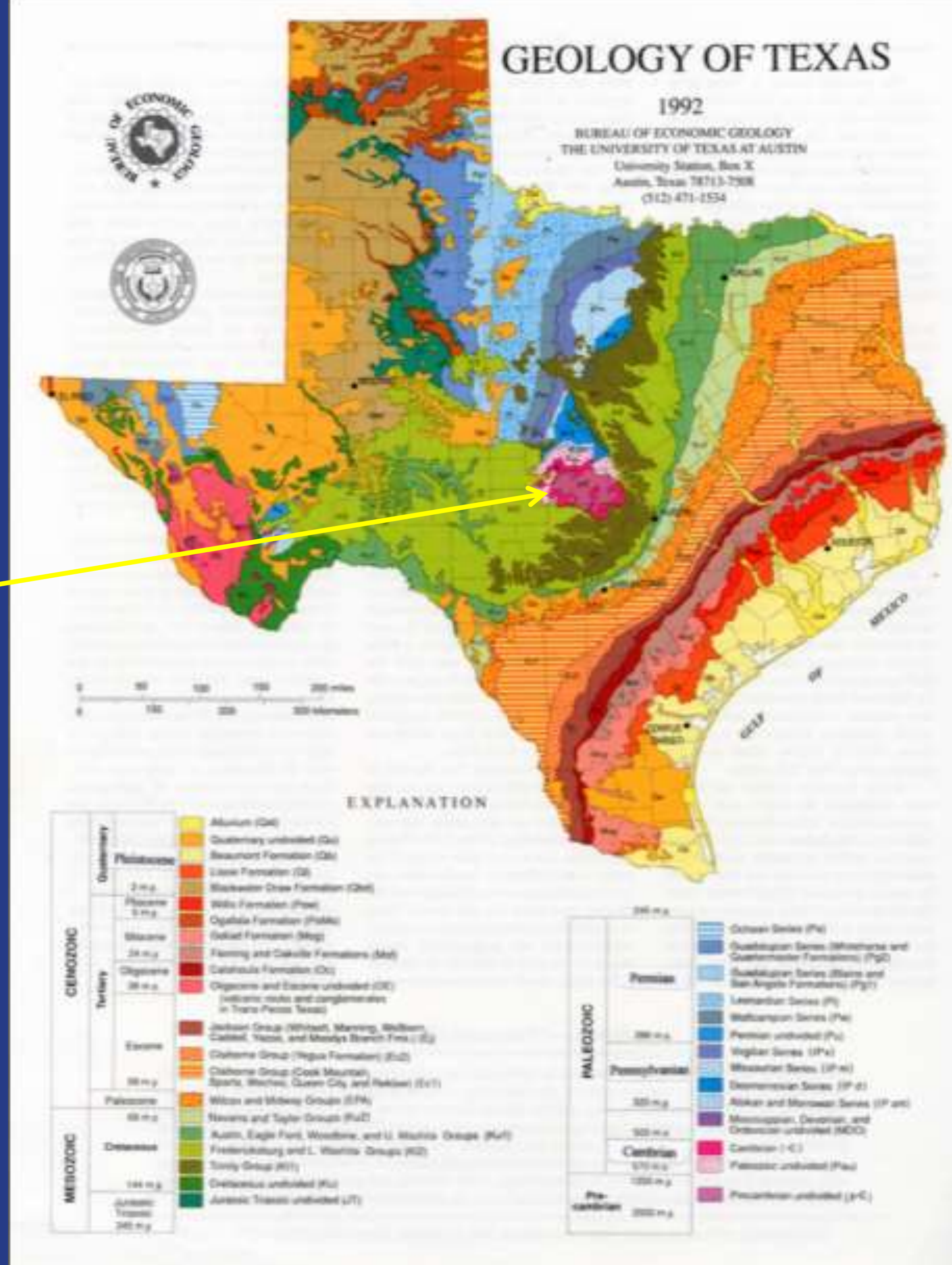
Notes:

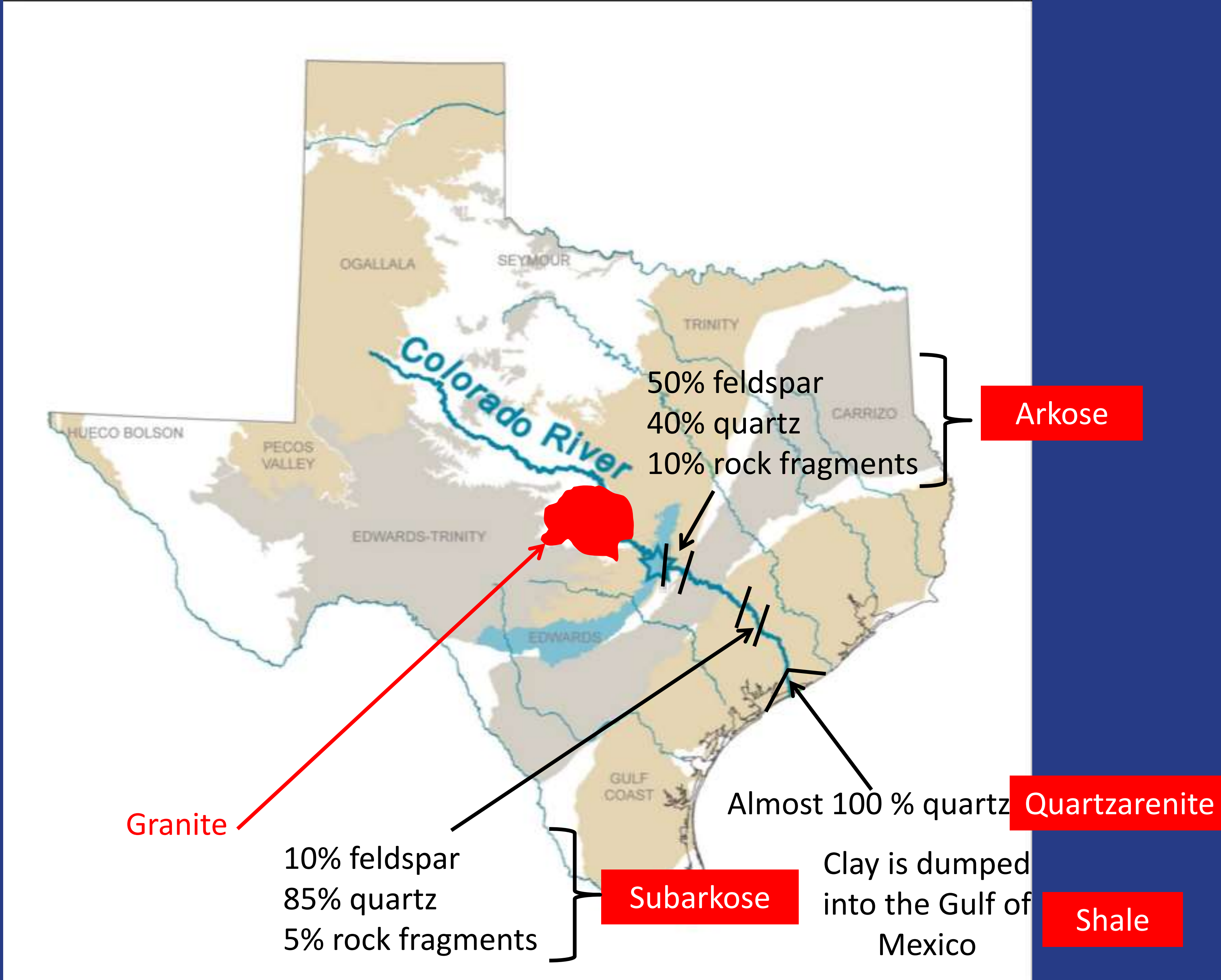
1. Some carbonate rocks form as organic sediments and then become granulated to turn into clastic sediments. Corals sands are examples.
2. Some chemical sediments form by the help of organisms. Banded iron formations are examples.

Let us begin with clastic sedimentary rocks which are the easiest to study among all sedimentary rocks.

Let us first consider what happens during transport. We take the Colorado River in Texas as an example.

Granites


GEOLOGY OF TEXAS
1992
BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
EXPLANATION
CENOZOIC
MESOZOIC
PALEOZOIC



Colorado River
OGALLALA
SEYMOUR
TRINITY
CARRIZO
HUECO BOLSON
PECOS VALLEY
EDWARDS-TRINITY
EDWARDS
GULF COAST
50% feldspar
40% quartz
10% rock fragments
Arkose
Granite
Almost 100 % quartz
Quartzarenite
10% feldspar
85% quartz
5% rock fragments
Subarkose
Clay is dumped into the Gulf of Mexico
Shale

How do these different clastic sedimentary rock types form along the course of the Colorado River of Texas?

There are two mechanisms which we are already familiar with from our consideration of weathering:

CHEMICAL

MECHANICAL

Water dissolves away the ferro-magnesian minerals that had been left over from weathering and turns the feldspars into clays. With the feldspars and the ferromagnesian minerals gone, the framework of the granite dissolves and the quartz crystals become free.

What happens to them?

All particles produced by the disintegration of the granite must obey Stoke's Law:

Density of mineral or rock grain

Density of water

$$V = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2$$

Fall velocity in water

Viscosity of water

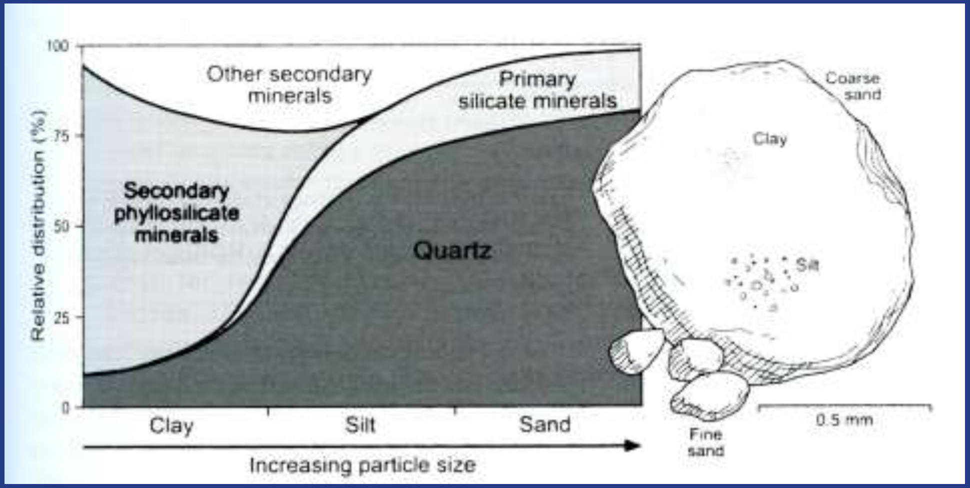
Gravity

Radius of rock or mineral grain

Basic message of Stoke’s equation: the larger and the denser a mineral or a rock fragment is, the faster it will fall to the bottom of the water.

Let us now remember the sizes and compositions of our grains:

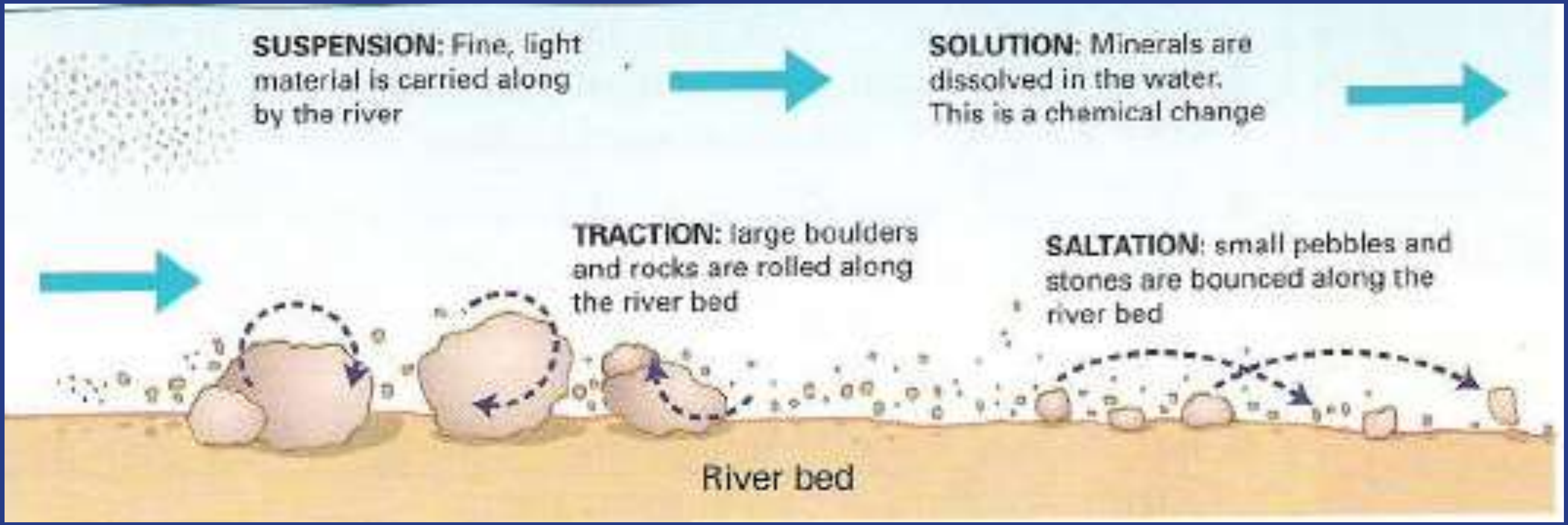
Soil fraction	Diameter	Description
Gravel	Larger than 2 mm	Coarse
Sand	0.05 - 2 mm	Gritty
Silt	0.002 - 0.05 mm	Floury
Clay	Smaller than 0.002 mm	Sticky when wet



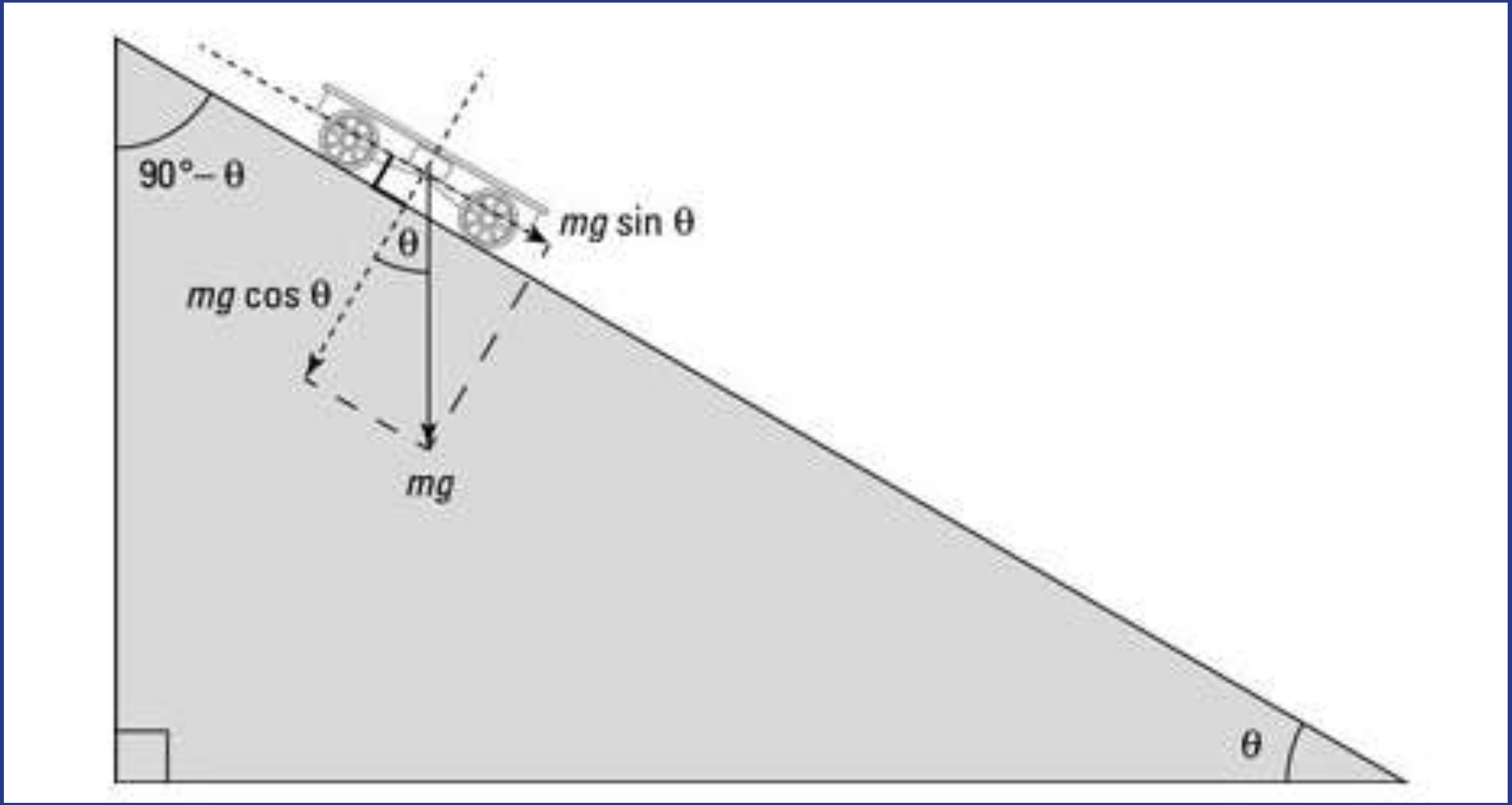
The densities of the clay minerals here produced are around 2.35 g/cm^3. By contrast quartz is 2.65 to 2.66. Similarly the rock fragments are closer to 2.65 to 2.7

Thus, the clay minerals are both small and light, so they will float away, but the rock fragments and quartz will sink to the bottom.

How do these mineral grains get carried by the flowing stream of the Colorado?

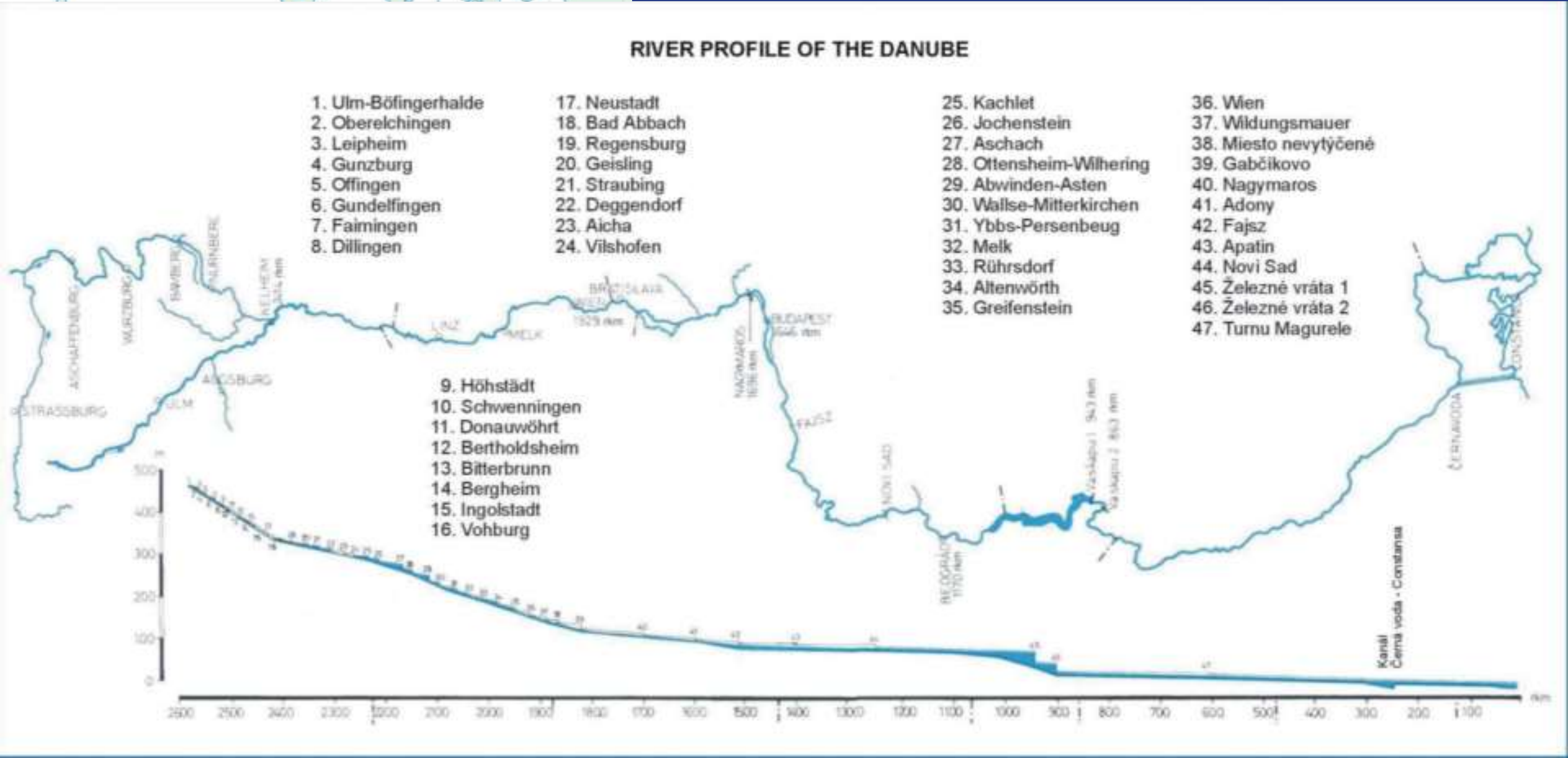


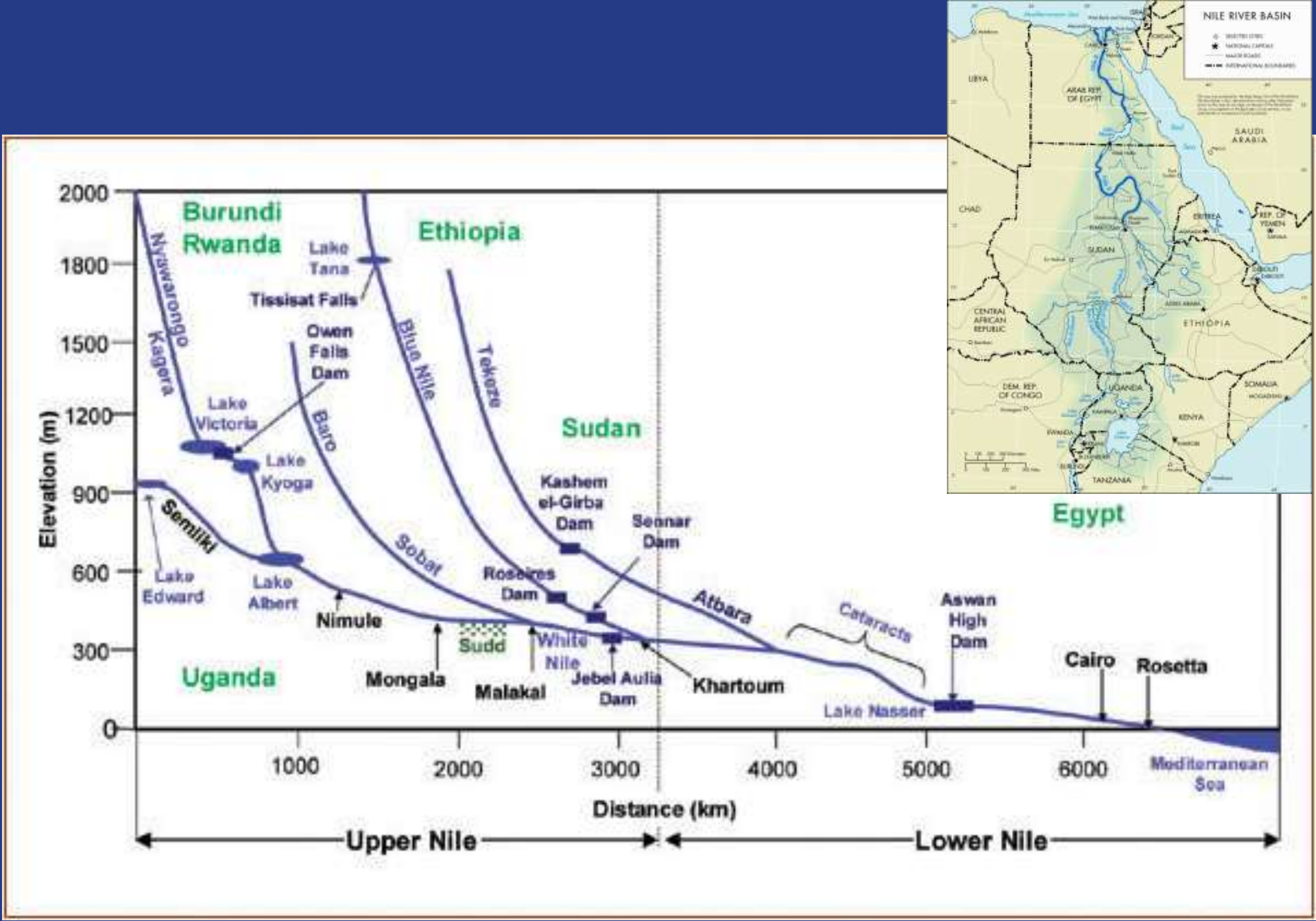
How flowing water will carry its load is dependent on its density, velocity and the weight of its load. Since force=mass X acceleration, for a fixed force, as the mass increases the acceleration must decrease.



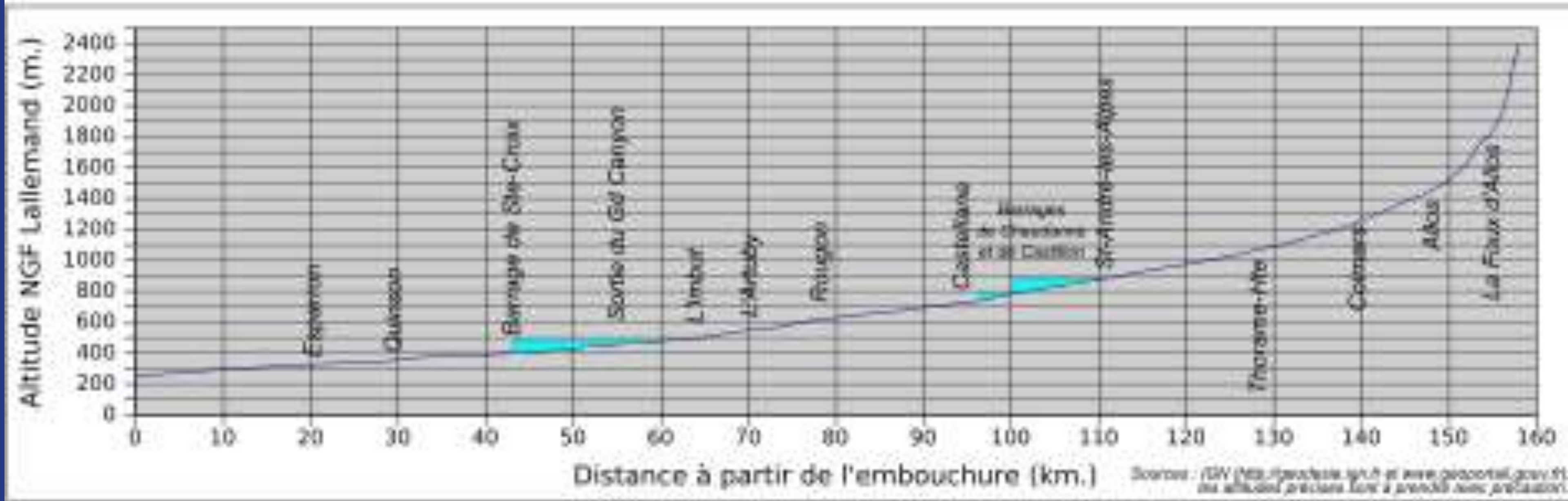
But the speed of the flow of the river is dependent entirely on its slope. As the slope decreases the velocity decreases. Rivers usually go from a high-slope upper course through a medium-slope middle course and a low-slope lower course. Let us look at some river profiles first.

The profile of the Danube

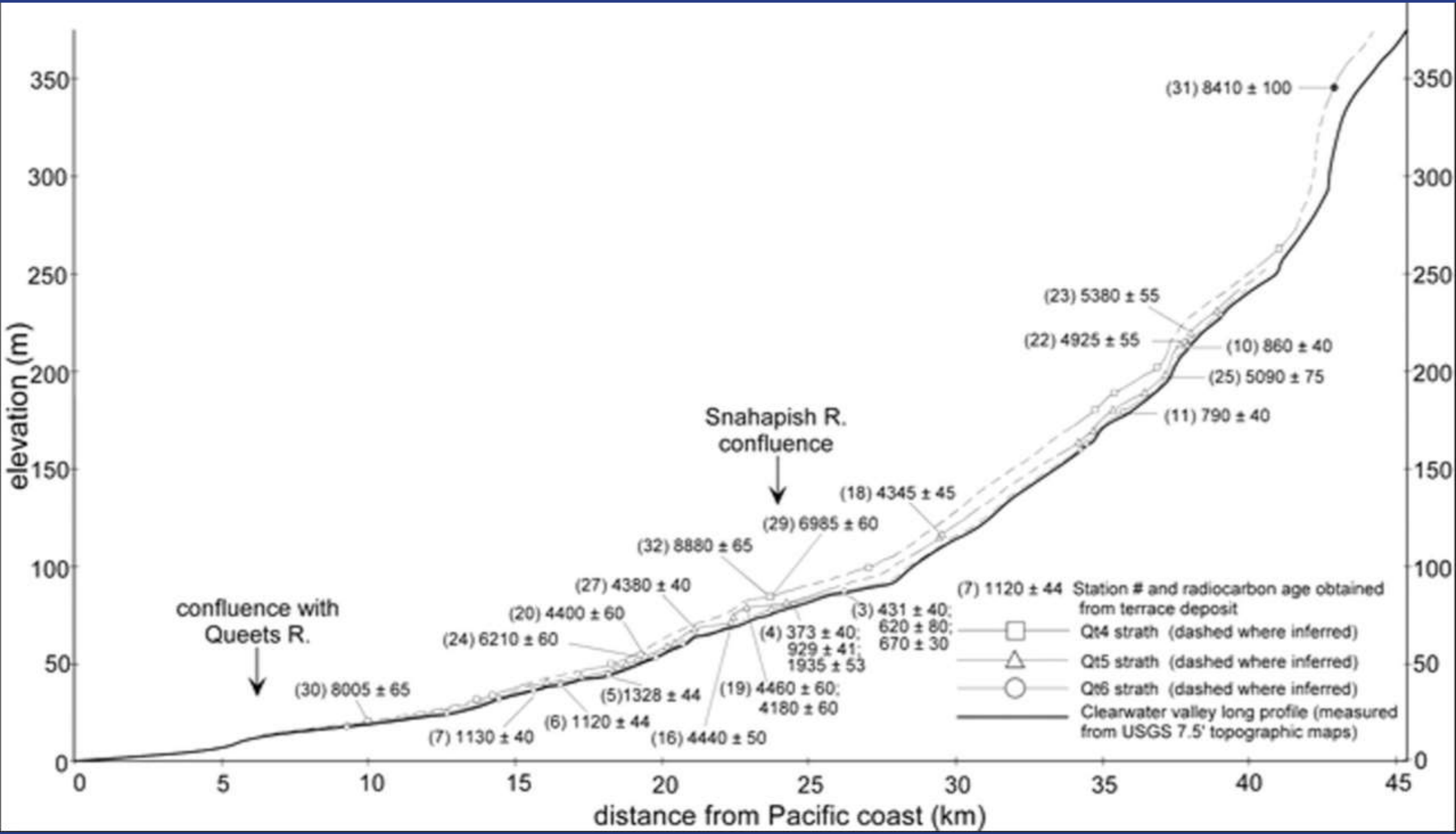




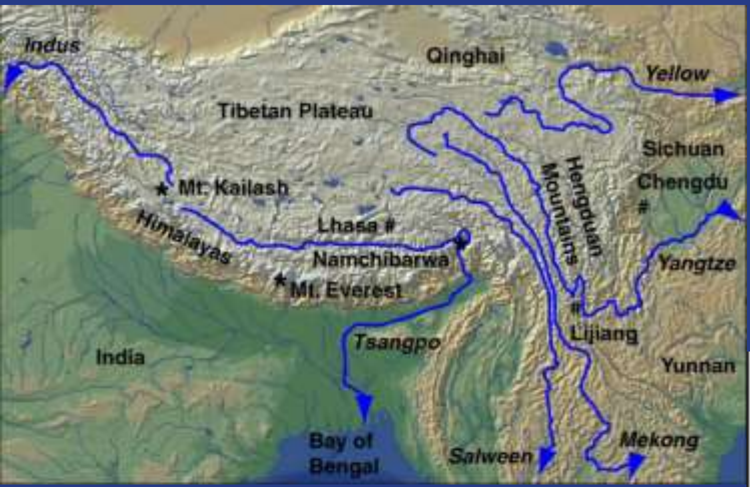
Longitudinal profile of the Nile

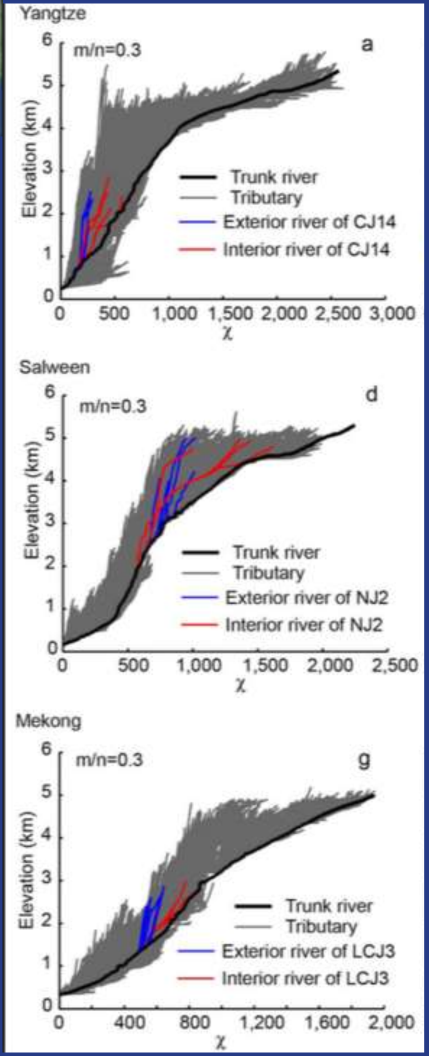


The longitudinal profile of the Verdon River, France.



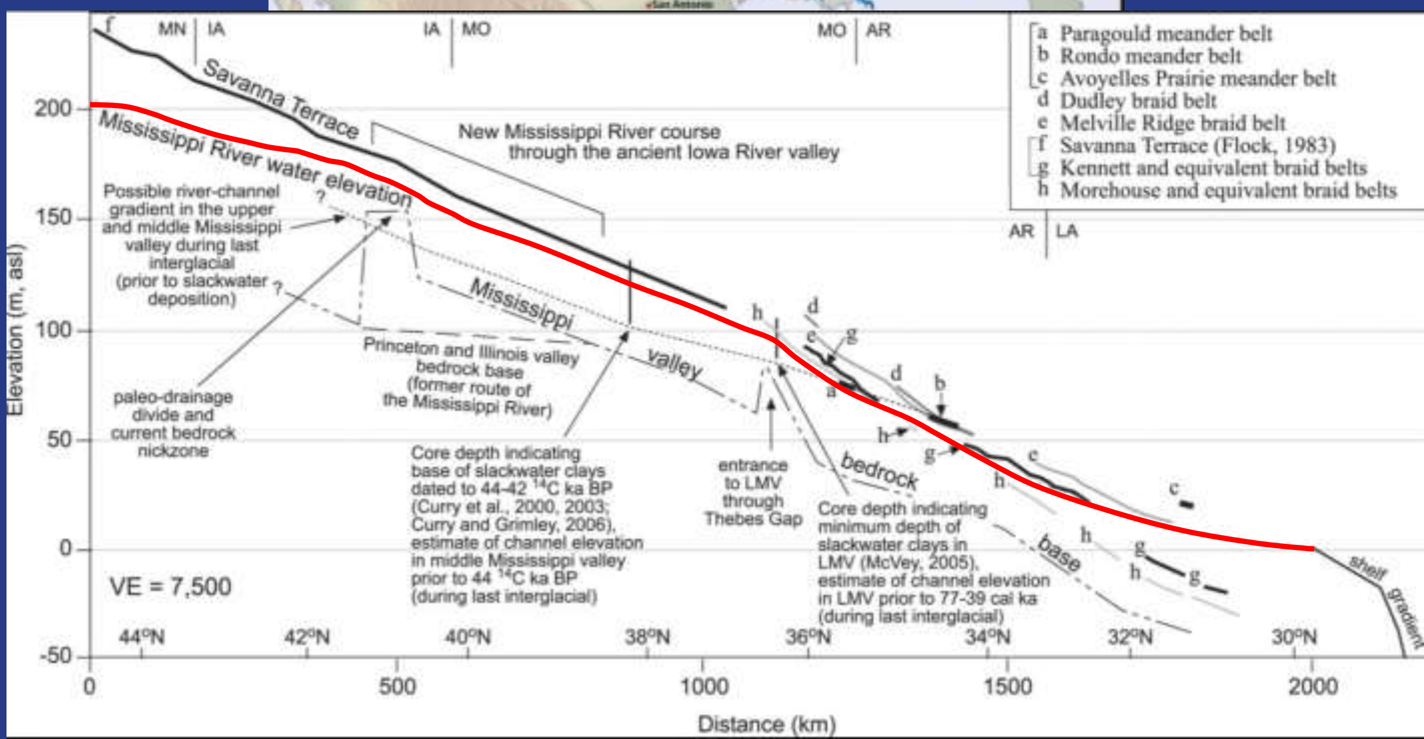
The longitudinal profile of the Clearwater River, Olympic Peninsula, Washington State, USA.

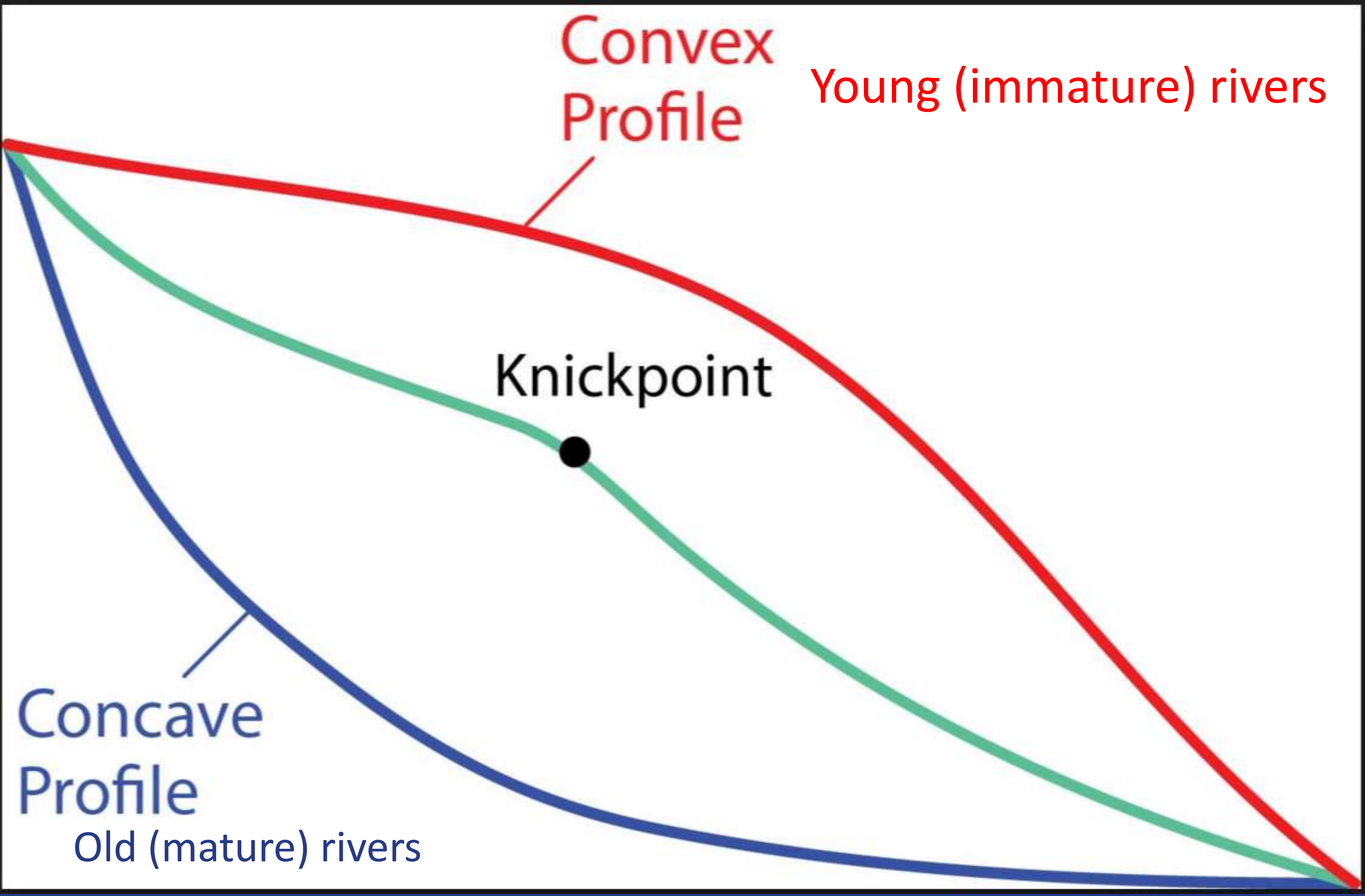




The profiles of three major rivers in a region of very young and rapid uplift.

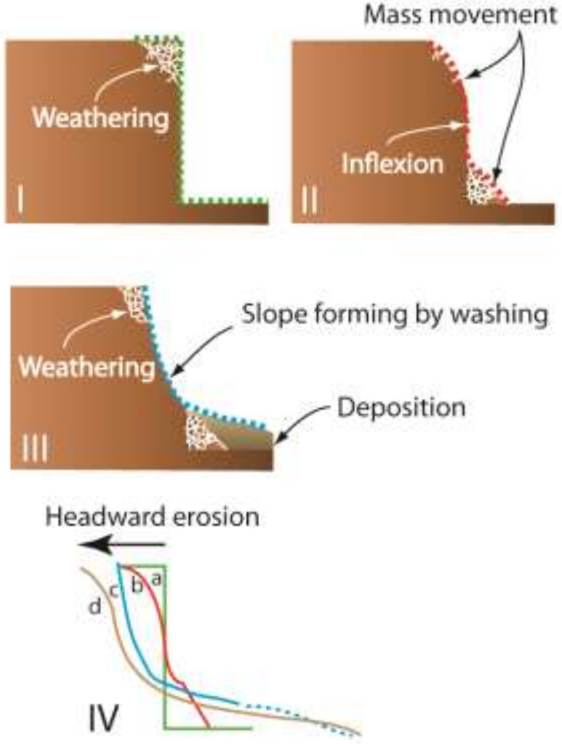

Calgary
Missouri
Yellowstone
Missouri
Mississippi
Platte
Kansas
Arkansas
Canadian
Ohio
Mississippi
Tennessee
Red
Chicago
Toronto
Phoenix
Dallas

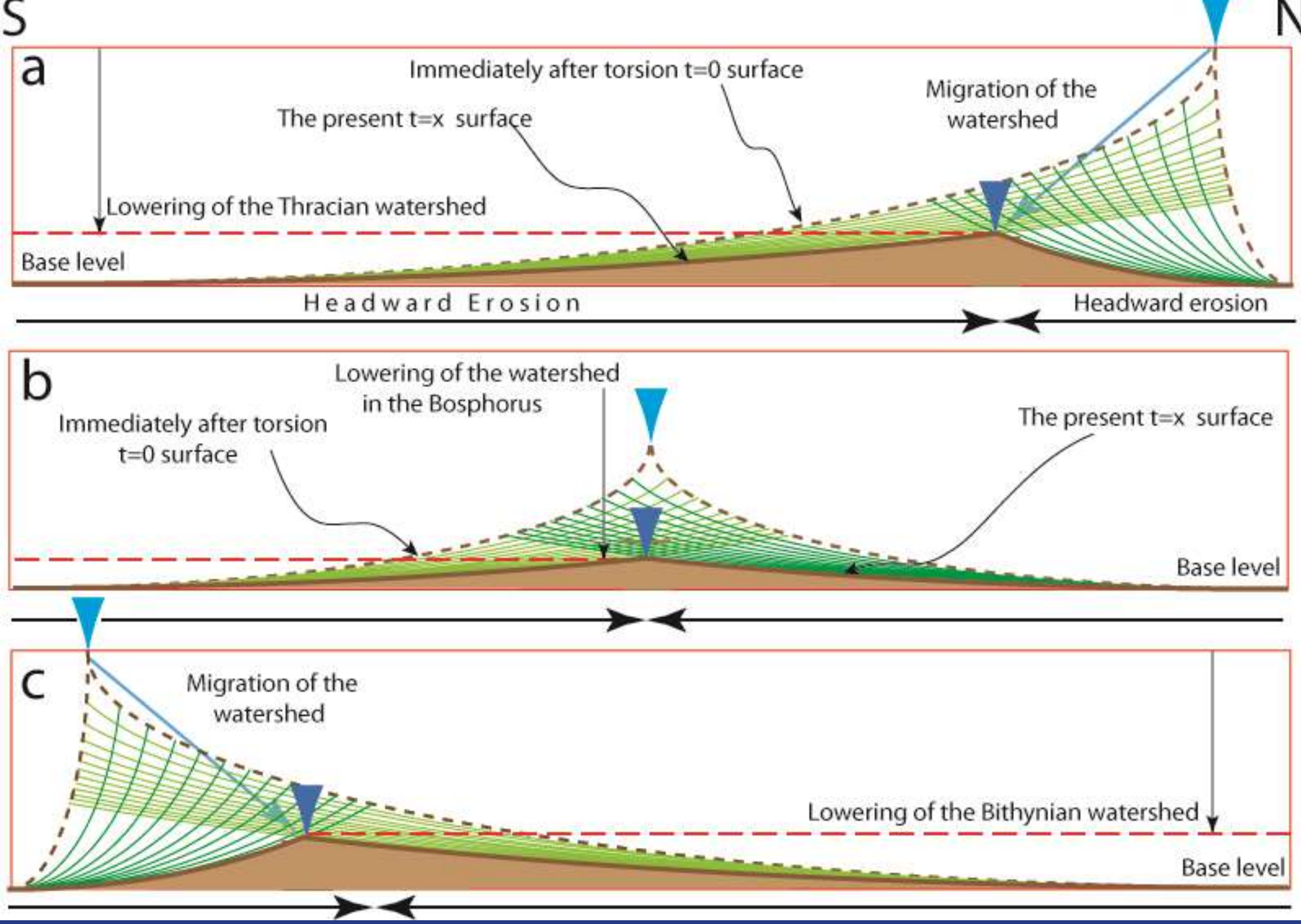

MN | IA
IA | MO
MO | AR
AR | LA
a Paragould meander belt
b Rondo meander belt
c Avoyelles Prairie meander belt
d Dudley braid belt
e Melville Ridge braid belt
f Savanna Terrace (Flock, 1983)
g Kennett and equivalent braid belts
h Morehouse and equivalent braid belts
Savanna Terrace
Mississippi River water elevation
New Mississippi River course through the ancient Iowa River valley
Possible river-channel gradient in the upper and middle Mississippi valley during last interglacial (prior to slackwater deposition)
Mississippi valley
Princeton and Illinois valley bedrock base (former route of the Mississippi River)
paleo-drainage divide and current bedrock nickzone
Core depth indicating base of slackwater clays dated to 44-42 ^{14}C ka BP (Curry et al., 2000, 2003; Curry and Grimley, 2006), estimate of channel elevation in middle Mississippi valley prior to 44 ^{14}C ka BP (during last interglacial)
entrance to LMV through Thebes Gap
Core depth indicating minimum depth of slackwater clays in LMV (McVey, 2005), estimate of channel elevation in LMV prior to 77-39 cal ka (during last interglacial)
bedrock base
shelf gradient
VE = 7,500
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
Elevation (m, asl)
Distance (km)
200
150
100
50
0
-50
0
500
1000
1500
2000



Evolution of river profiles

The origin of upwards convex and upwards concave slopes by weathering, mass wasting and fluvial erosion.





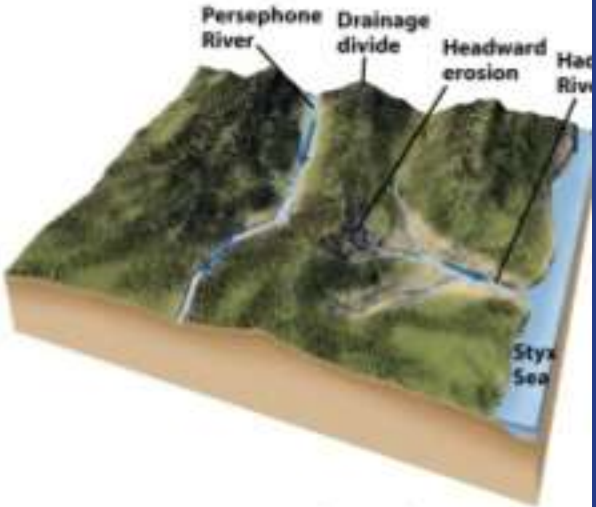
The evolution of valley profiles in the Thracian-Bithynian isthmus under the assumption of a dry climate in the late Pleistocene

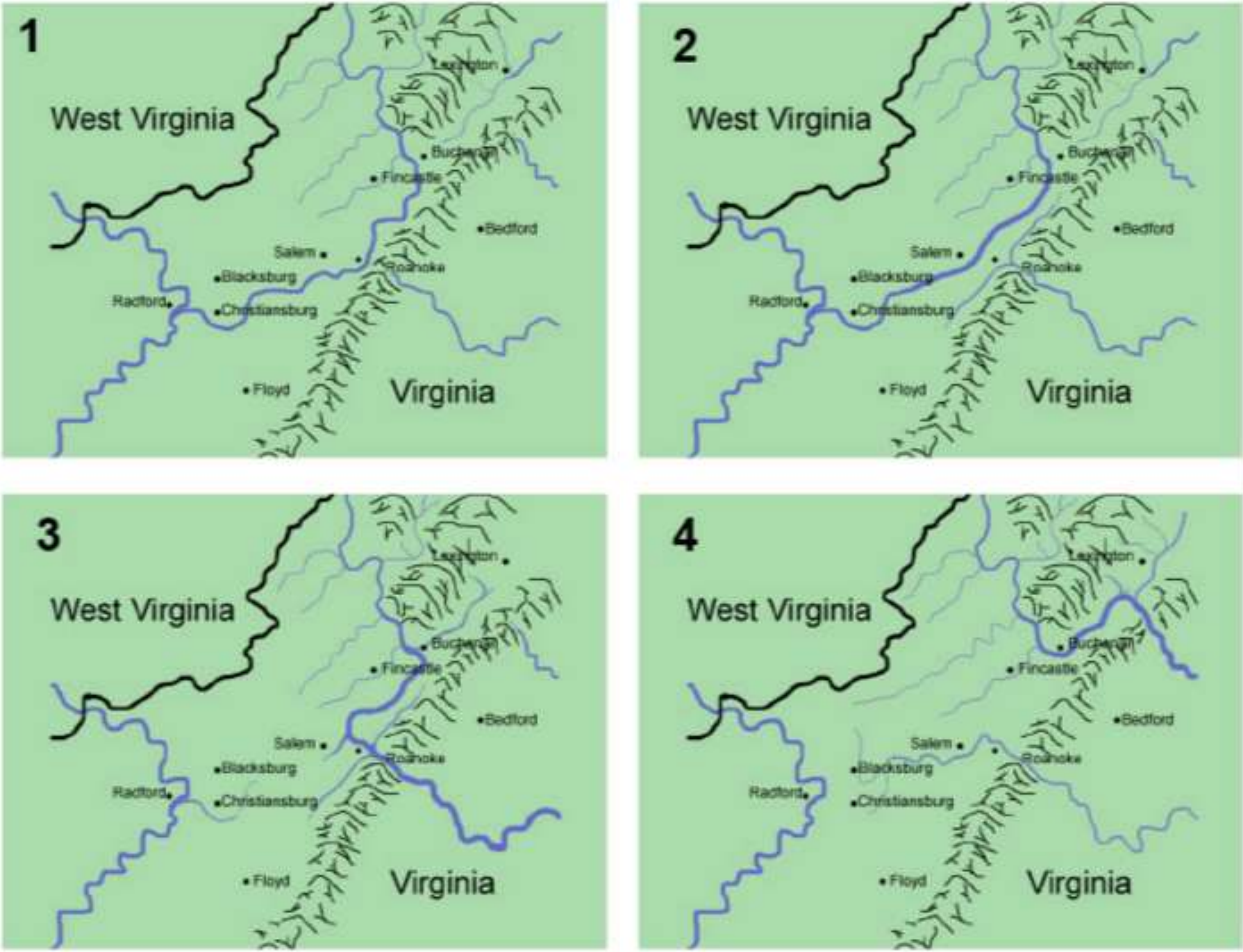
Headward erosion: Nemrut Caldera, eastern Turkey

Drainage Evolution

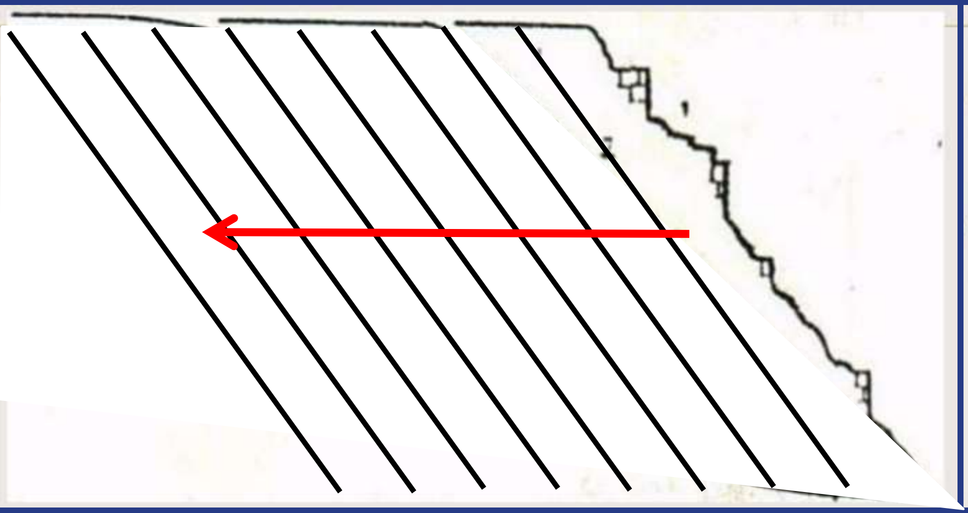
Stream piracy

- One stream captures flow from another
- Results from headward erosion
- A stream with more vigorous erosion (steeper gradient), intercepts another stream
- Captured stream flows into the new stream
- Below capture point, old stream dries up

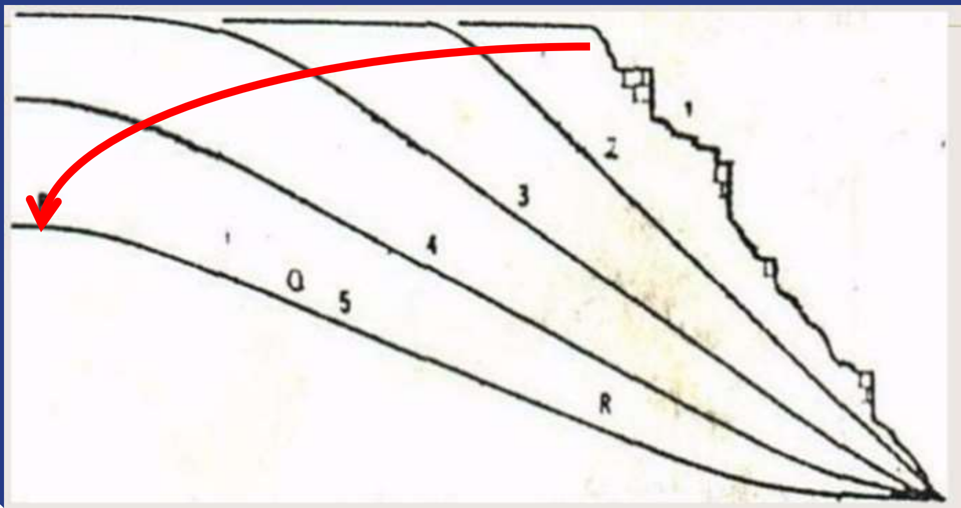



1
West Virginia
Lexington
Buchanan
Fincastle
Bedford
Salem
Roanoke
Blacksburg
Radford
Christiansburg
Floyd
Virginia
2
West Virginia
Lexington
Buchanan
Fincastle
Bedford
Salem
Roanoke
Blacksburg
Radford
Christiansburg
Floyd
Virginia
3
West Virginia
Lexington
Buchanan
Fincastle
Bedford
Salem
Roanoke
Blacksburg
Radford
Christiansburg
Floyd
Virginia
4
West Virginia
Lexington
Buchanan
Fincastle
Bedford
Salem
Roanoke
Blacksburg
Radford
Christiansburg
Floyd
Virginia

How do slopes evolve? How do we go from a highly dissected plateau to a fairly flat, low-lying plain? There have been two main ideas on this question, both of which are probably true depending on what climatic belt one is in.

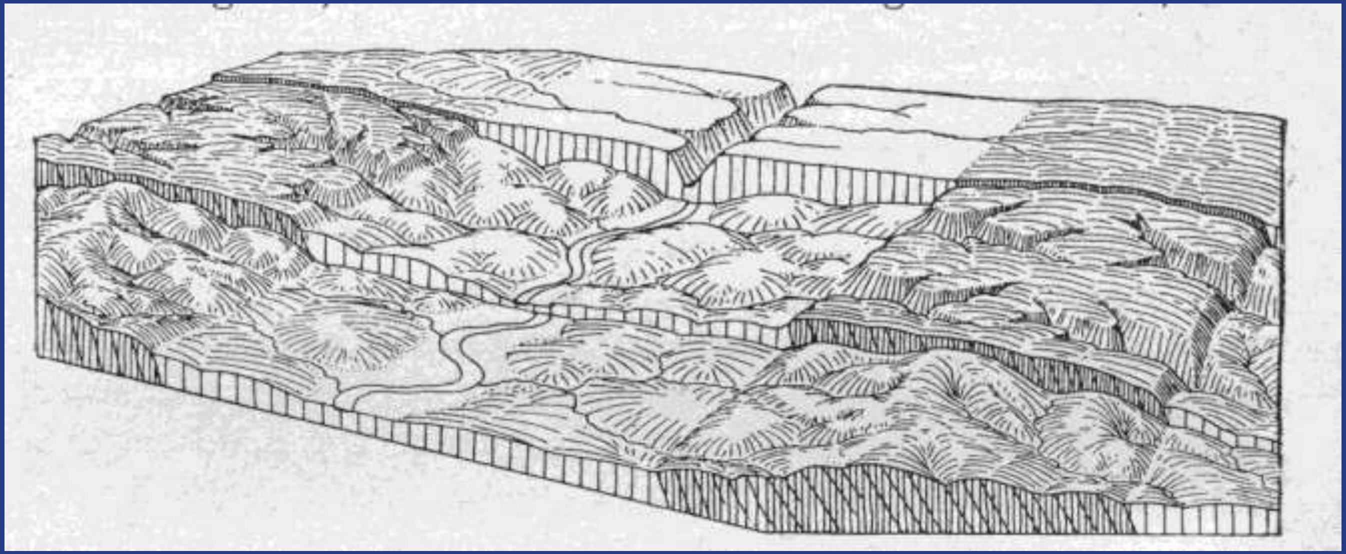


Slope retreat
(Walther Penck)
Arid morphology



Slope degradation
(William Morris Davis)
Humid morphology

This is a view of the central part of the North American continent from about 10,000 m height. Notice that not one topographic eminence disturbs the flatness of the area seen. This region is known to be underlain by large mountain belts created 1500 to 800 million years ago. What happened to them?



young

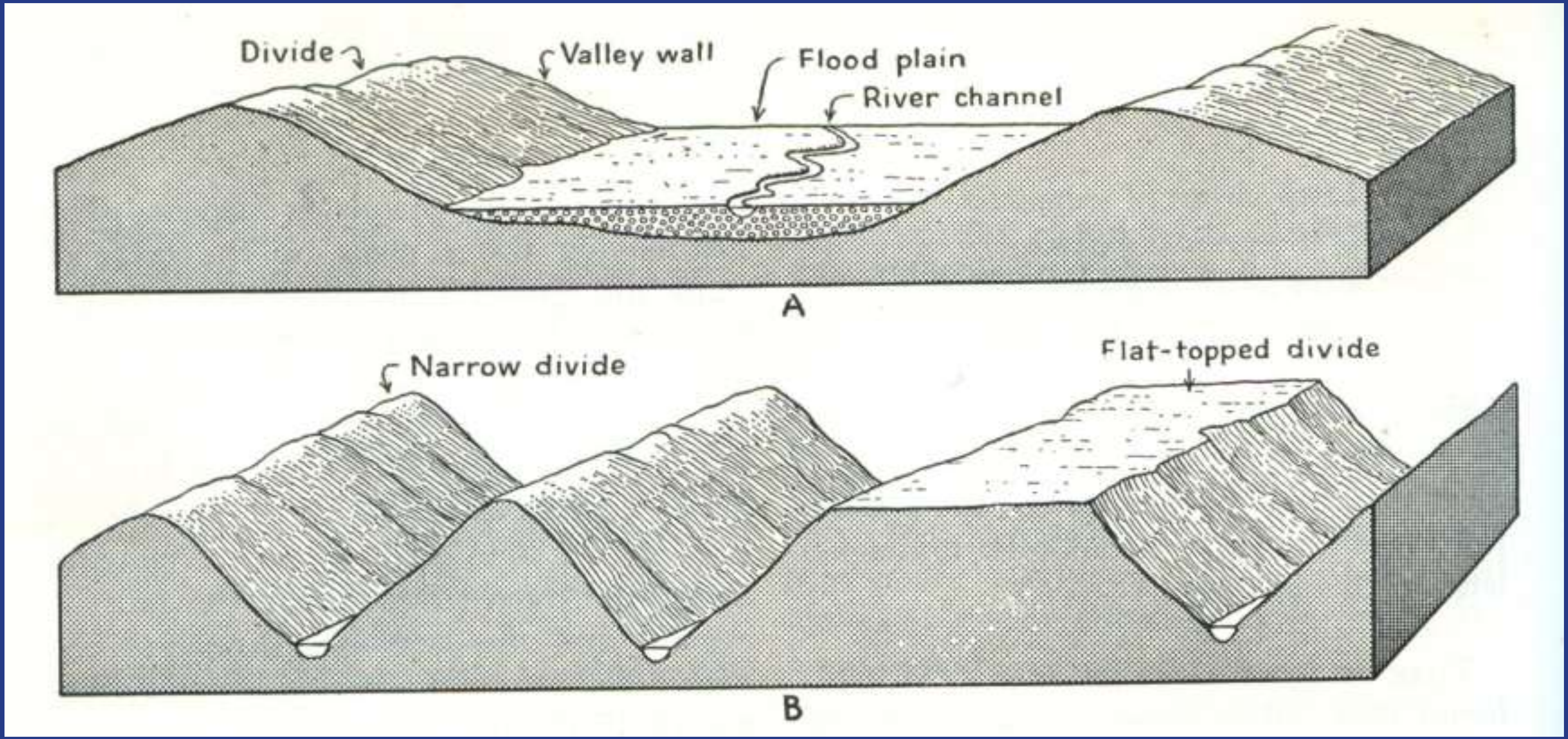
mature

old

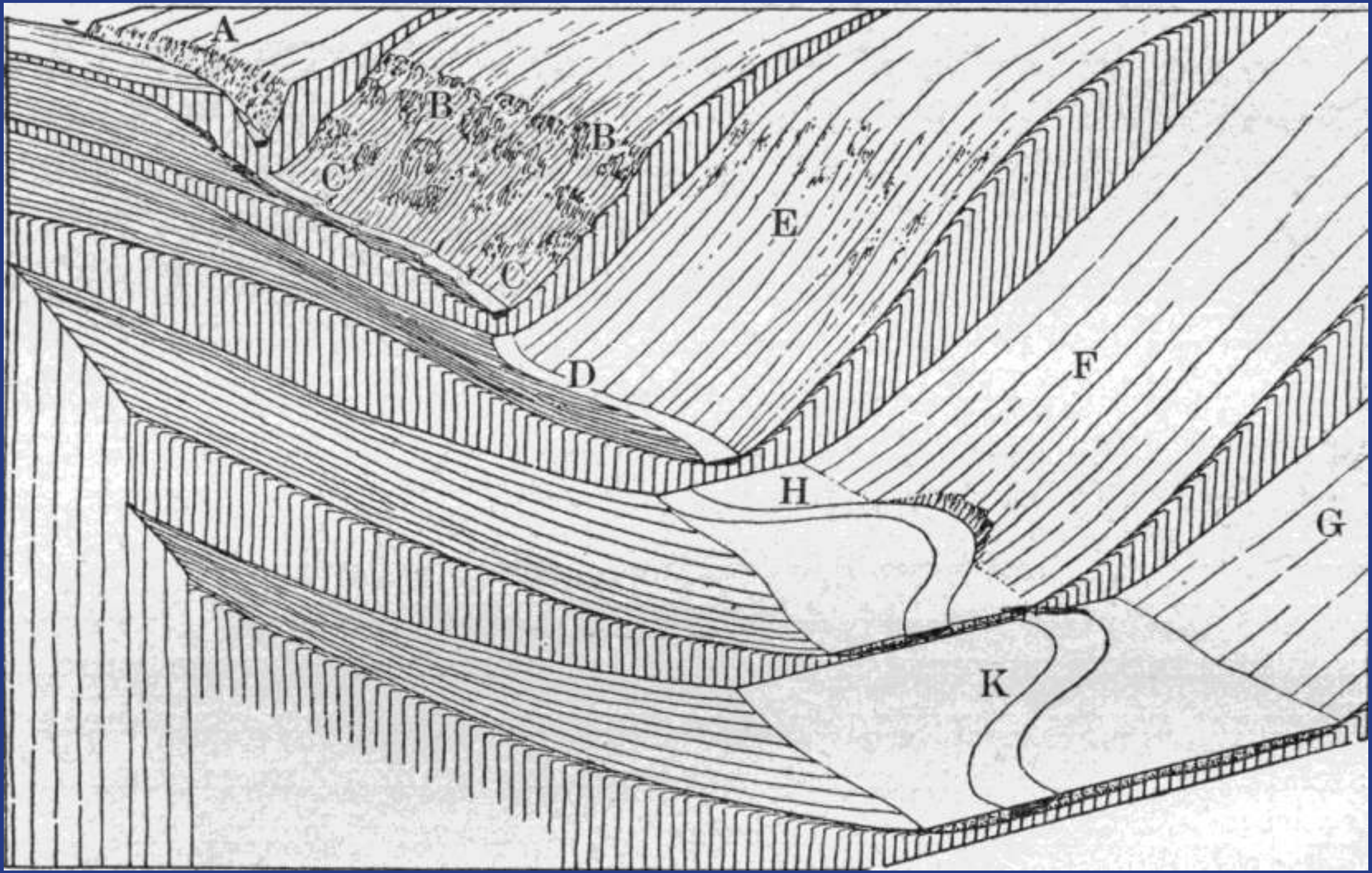
Stages of landscape development according to Davis. Notice the progressive flattening of the surface.

Dissection of a surface in a temperate climate (northern USA)

Dissection of a surface in a dry climate (western USA)

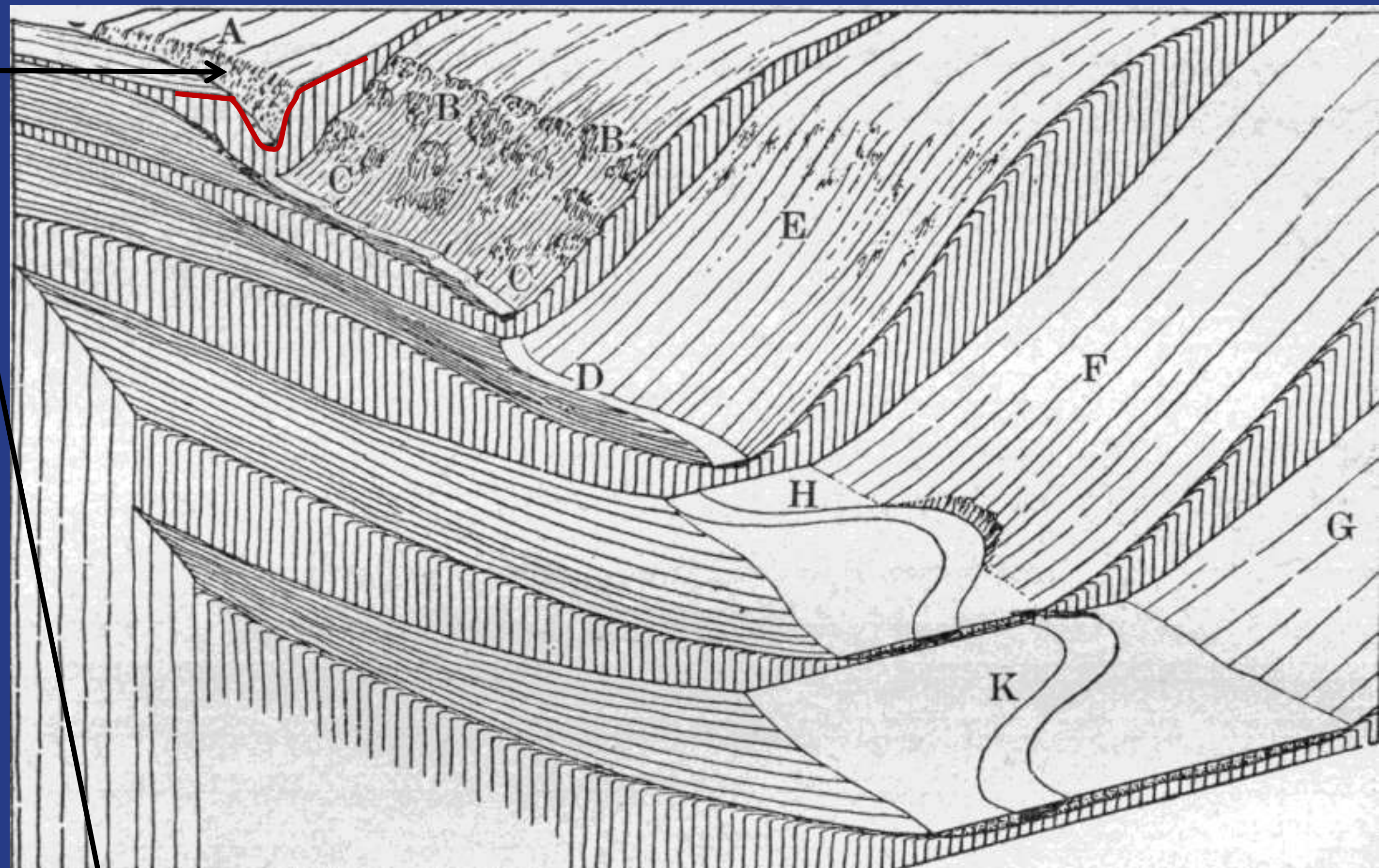


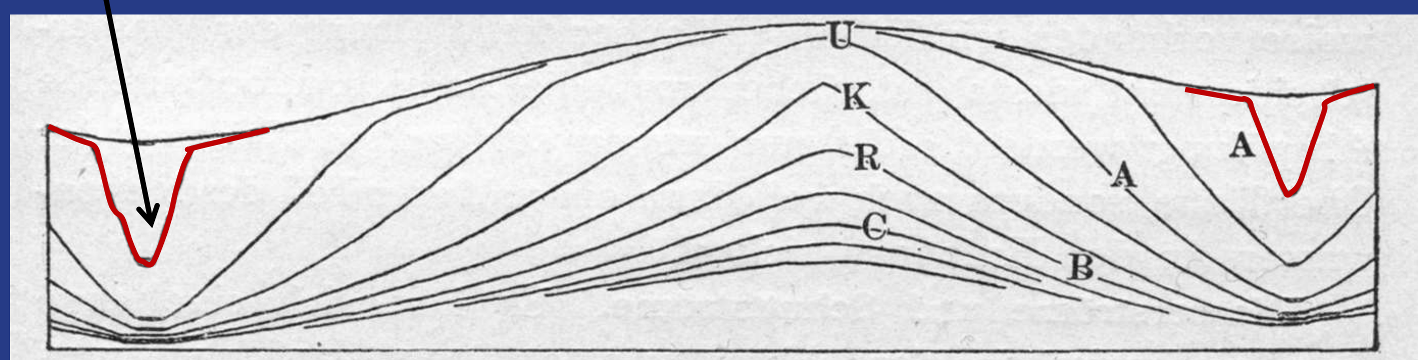
Basic geomorphological terminology of valleys



Development of a valley according to Davis.

Deep and narrow young valley cut into bedrock





Mediterranean climate (semi humid): the Gorge of Verdone, France

Arid climate: Grand Canyon of the Colorado River, Arizona, USA

In young valleys and in the upper courses of any valley the stream comes into contact with bedrock more frequently than in the old valleys or in the lower courses of any valley.

In young valleys and in the upper courses of any valley, the gradients are steeper and the erosive power of the river is greater. It is in these areas that we see most of the erosive features of the rivers, such as:

1. Water falls

2. Rapids

3. Potholes (=devil's cauldrons)

WATERFALLS

The Niagara Falls, USA and Canada, has the highest rate of flow of any waterfall in the world, with a vertical drop of some 50 m.

Lockport Dolomite

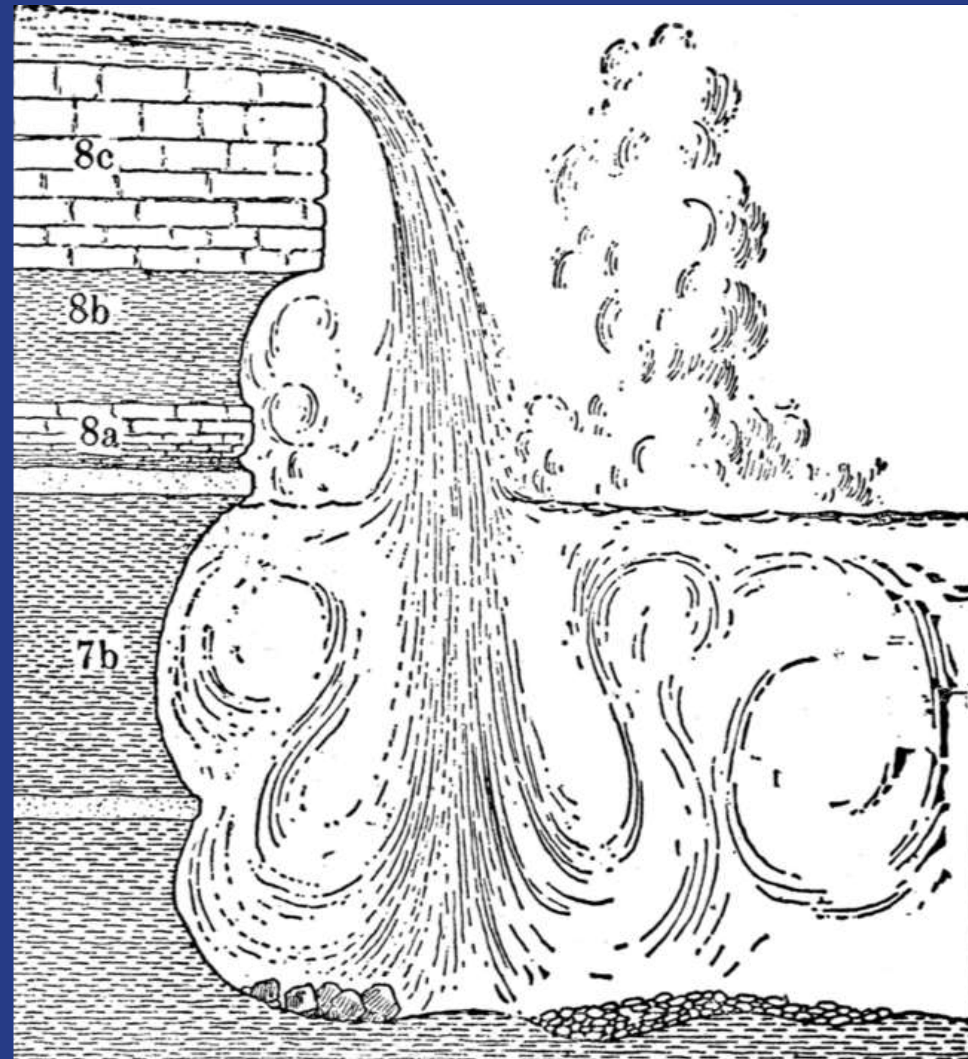
Rochester Shale

Clinton Limestone and Shale

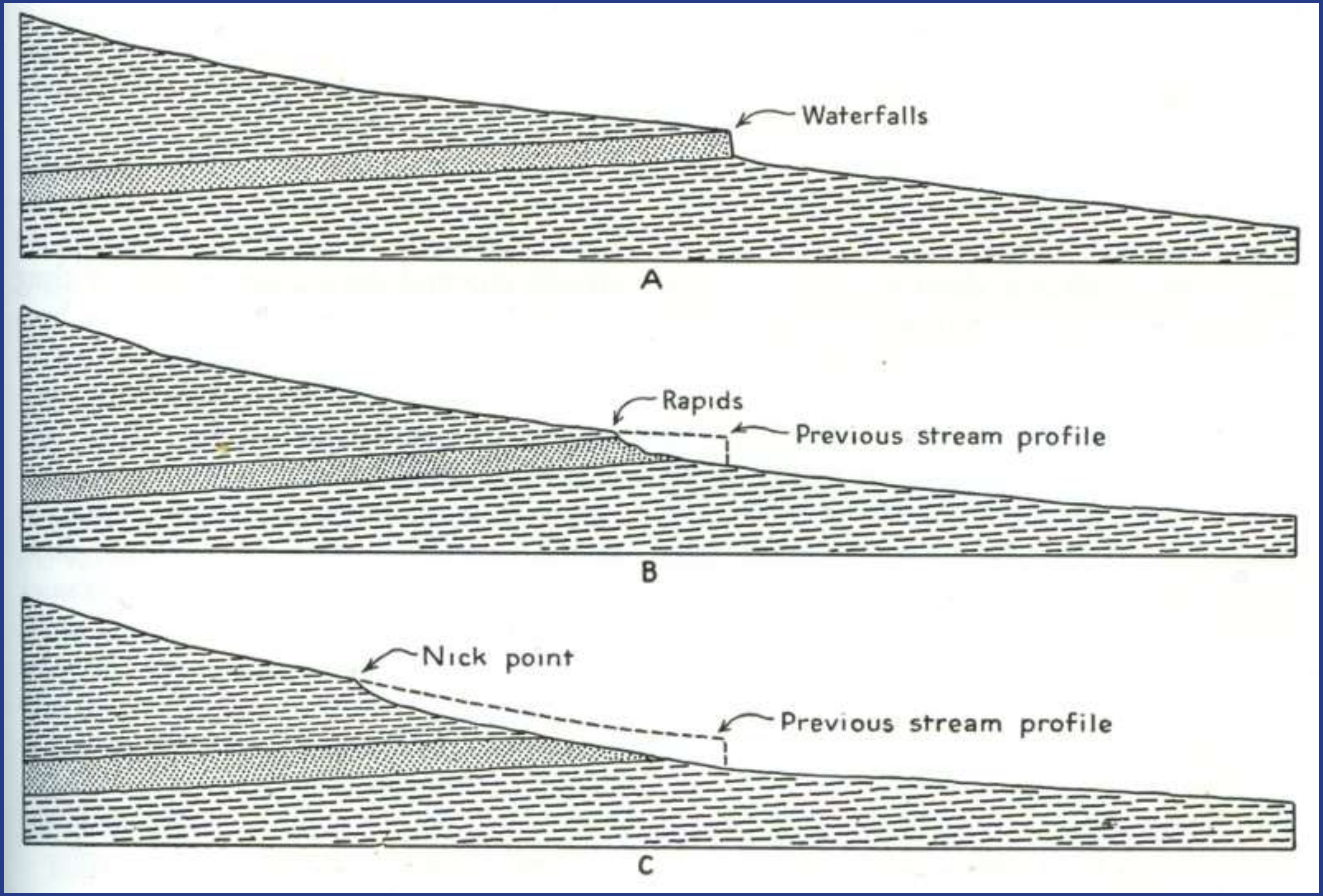
Medina Sandstone

Cataract Shale and Sandstone

Queenston Shale

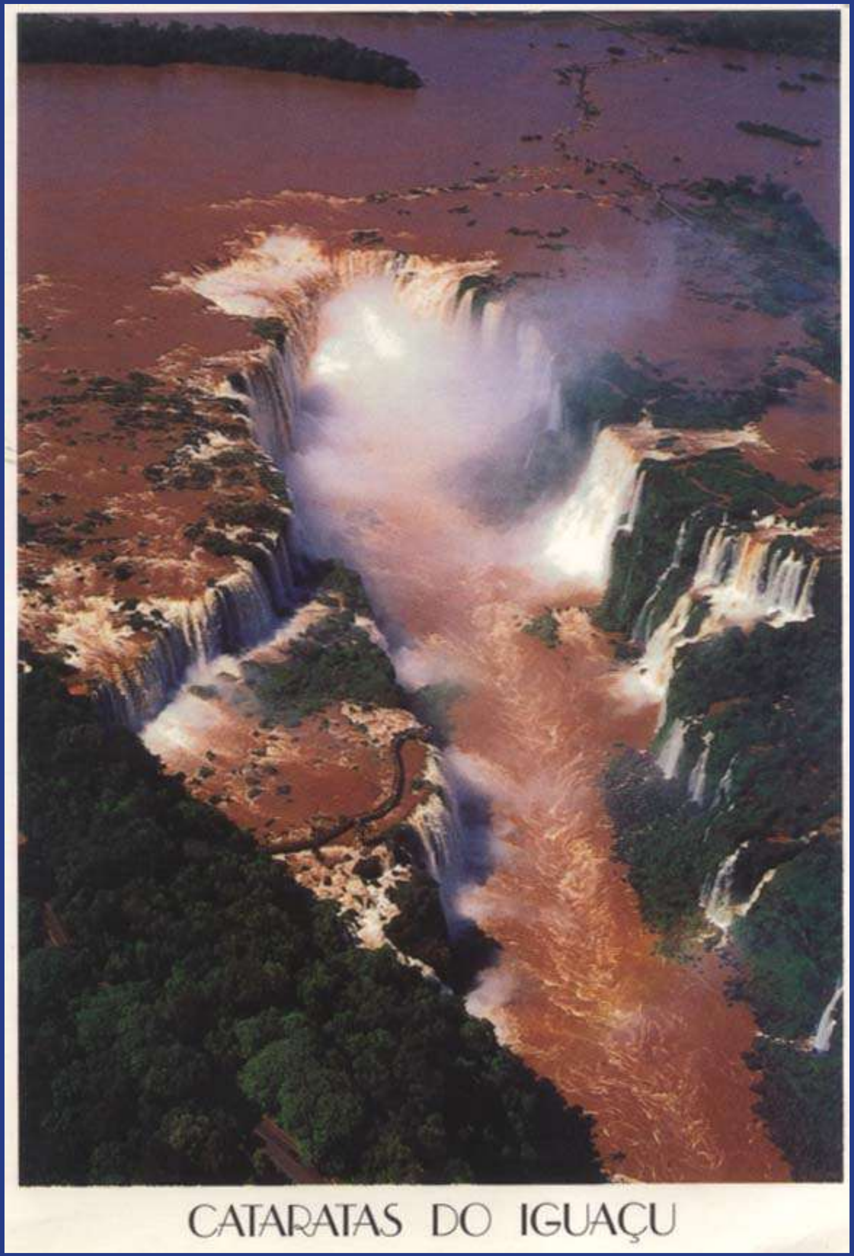


The geology of the Niagara Falls



Retreat and eventual destruction of a waterfall (inspired by the Niagara case)

J. P. Hackert’s painting of the Tivoli Falls near Rome, Italy (in the Belvedere Museum, Vi[illegible])

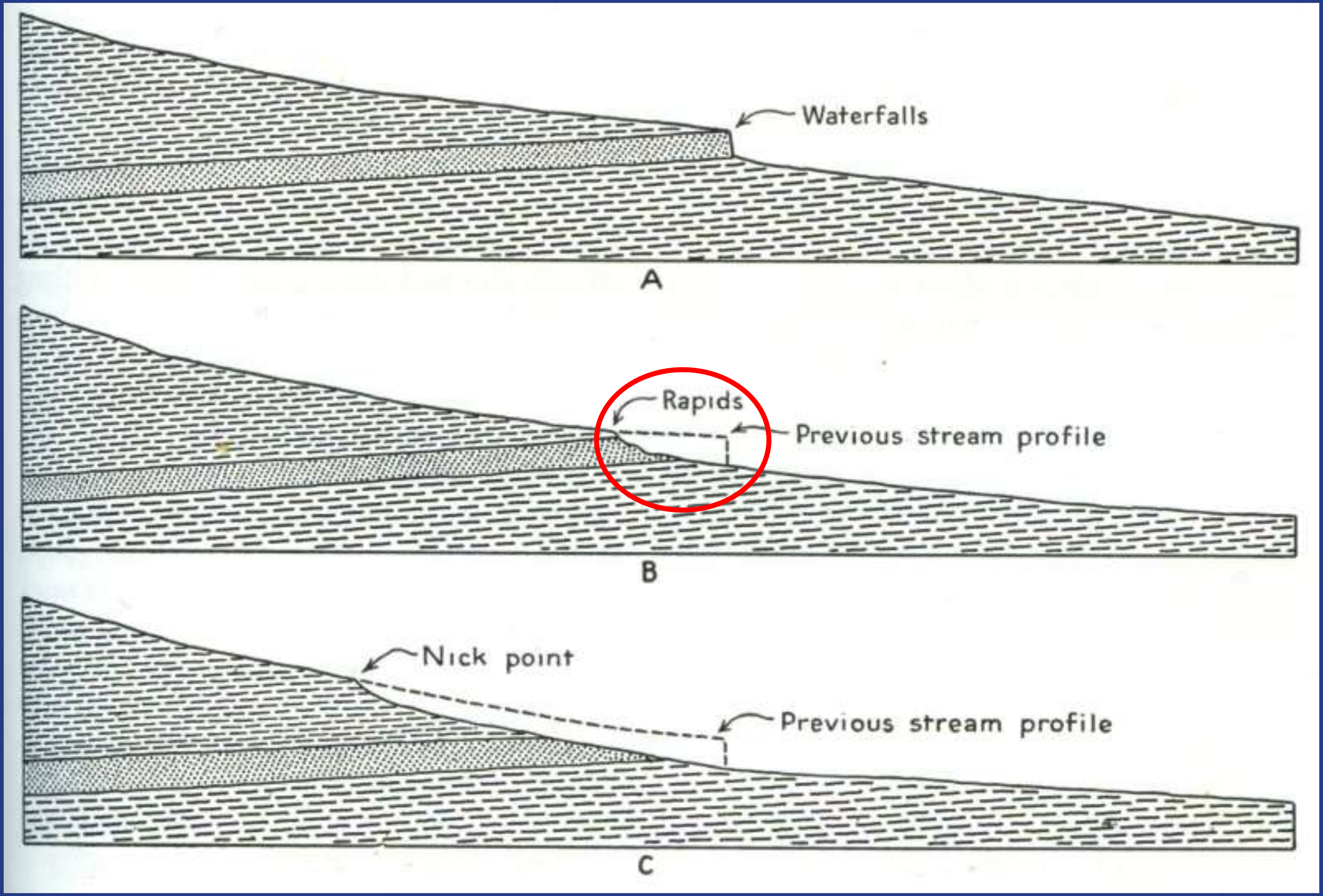


The Iguaçu Falls, Brazil

Angel Falls, Venezuela, on the Orinoco River, is the highest waterfall in the world. Its drop is 1000 metres and the waters reach the bottom only as vapour

The Victoria Falls (*Mosi oa Tunya*=smoke that thunders) on the Zambezi River at the border between Zambia and Zimbabwe, Africa. The Falls were discovered by the great Scottish geographer, missionary and humanist David Livingstone in 1855.

RAPIDS

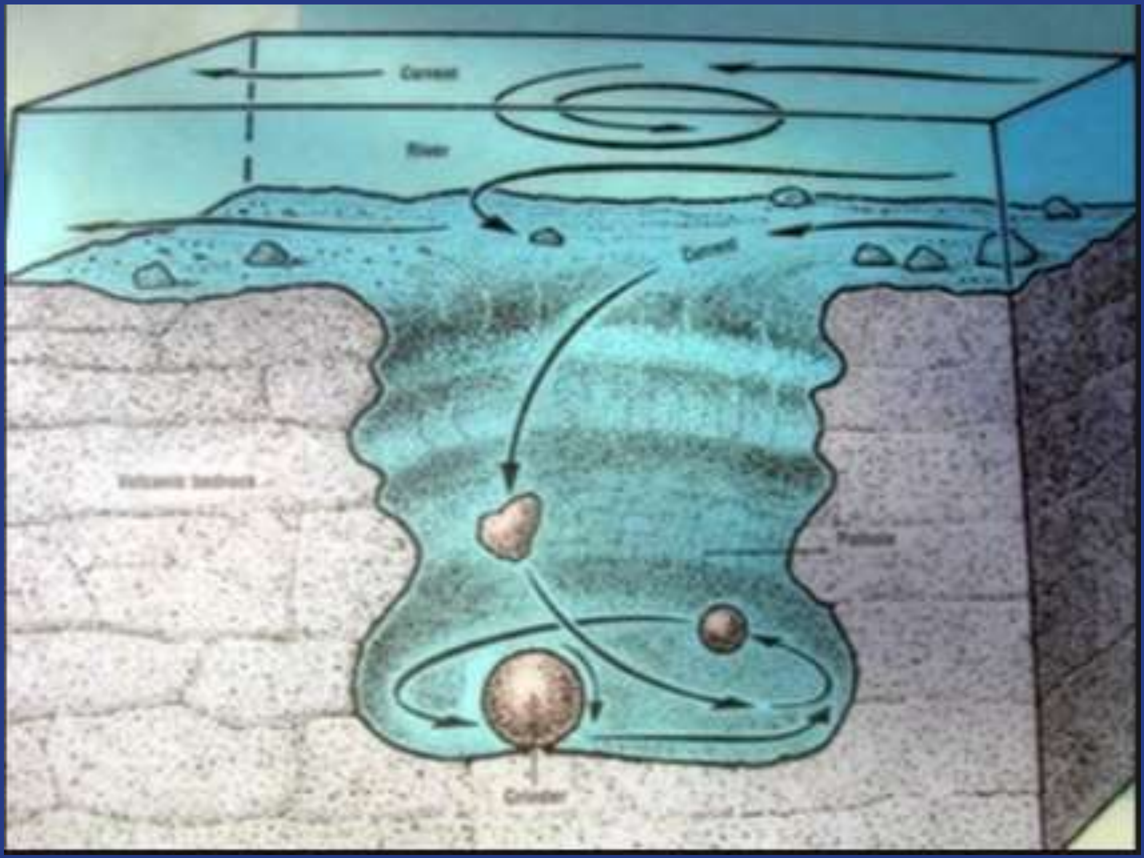

Waterfalls
A
Rapids
Previous stream profile
B
Nick point
Previous stream profile
C

The rapids of “Sweet’s Falls” in the upper Gauley River, West Virginia, USA

Blakeney Rapids, Mississippi River, Ontario, Canada

Rapids below the falls at Fonferek Glen, Wisconsin, USA

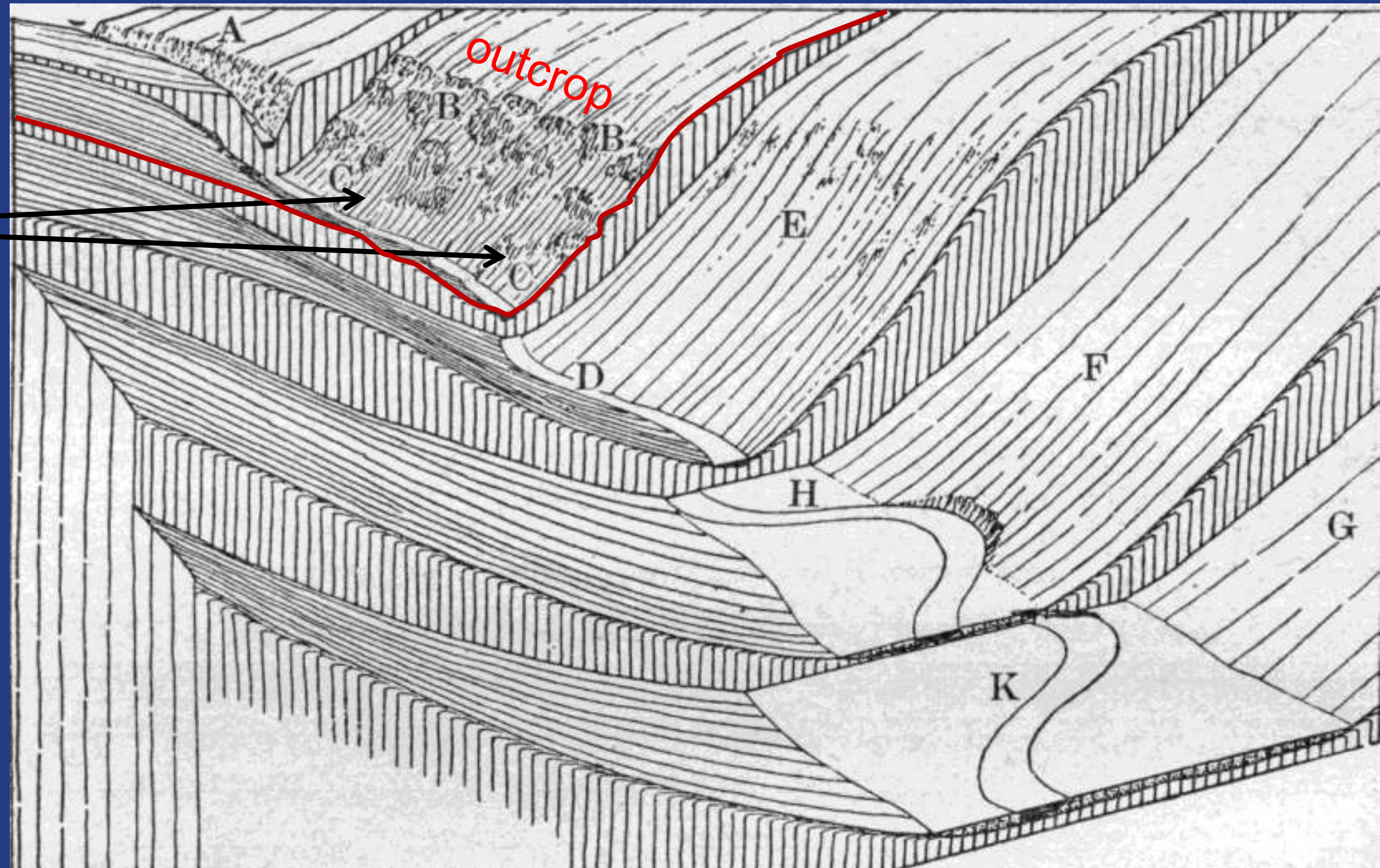
POTHOLES (=DEVIL'S CAULDRONS)

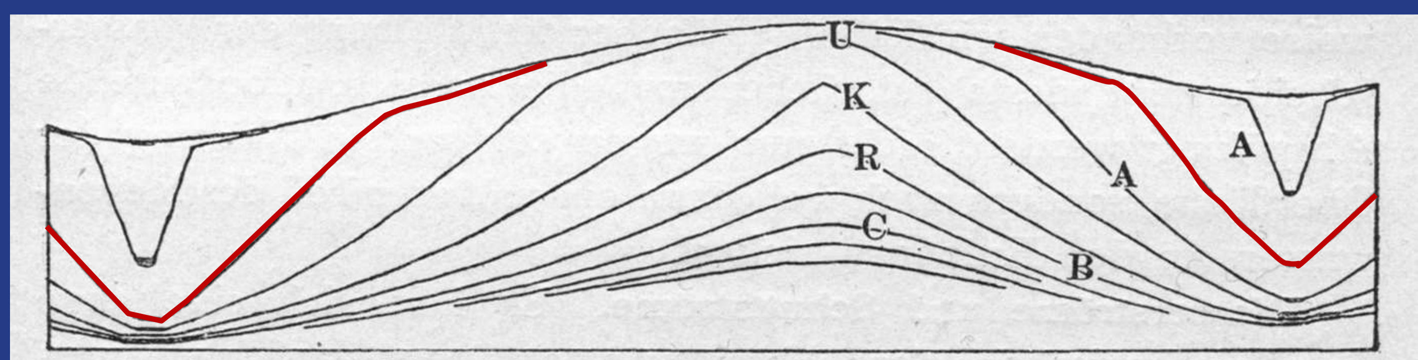


Potholes, location unknown

Bourke’s Luck Potholes, Blyde river Canyon, South Africa

Scree

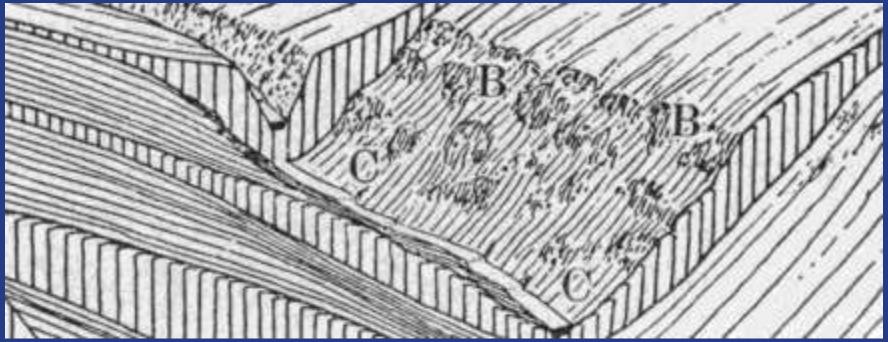


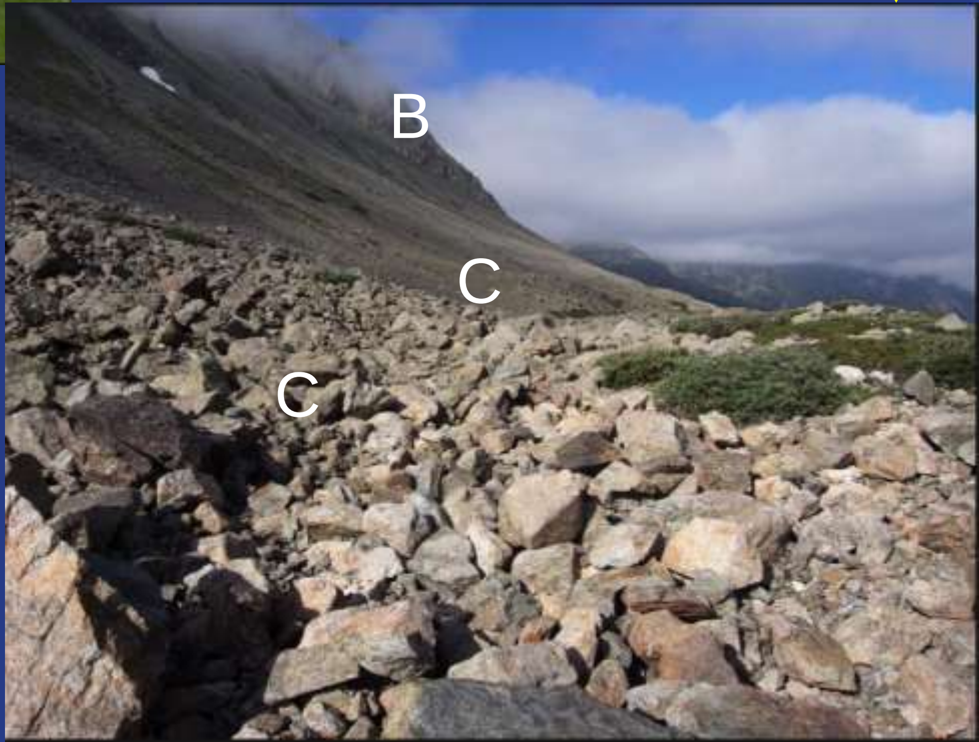


Mediterranean climate
(semi humid)

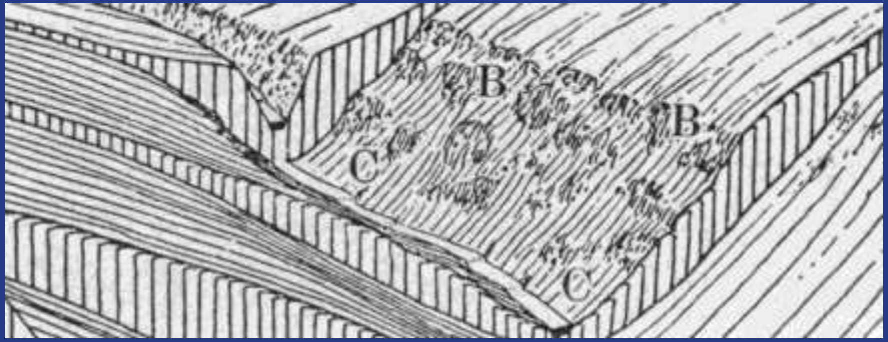
Scree in the Albula Pass

Albula Pass, Graubünden,
Switzerland



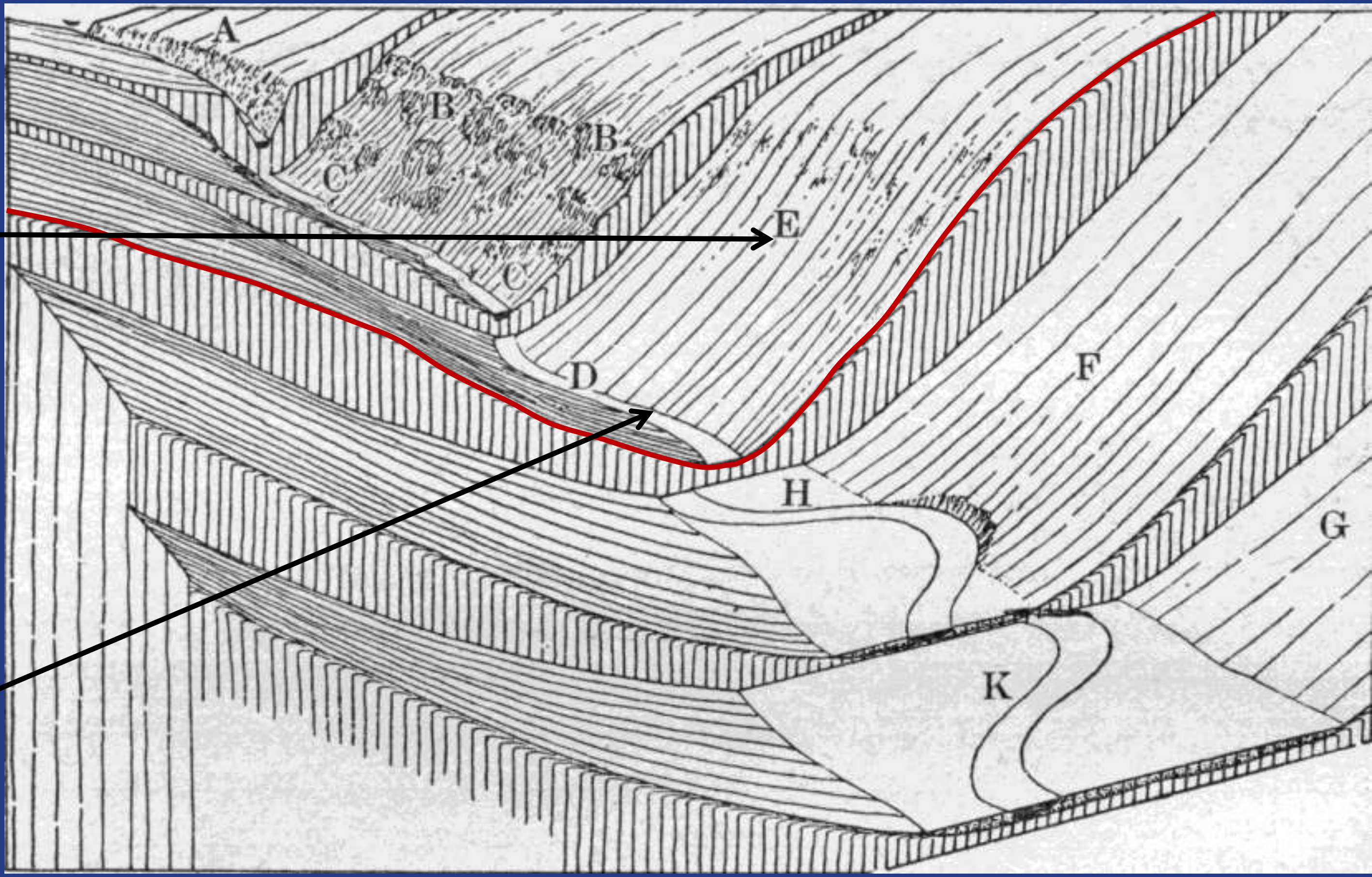


Arid climate

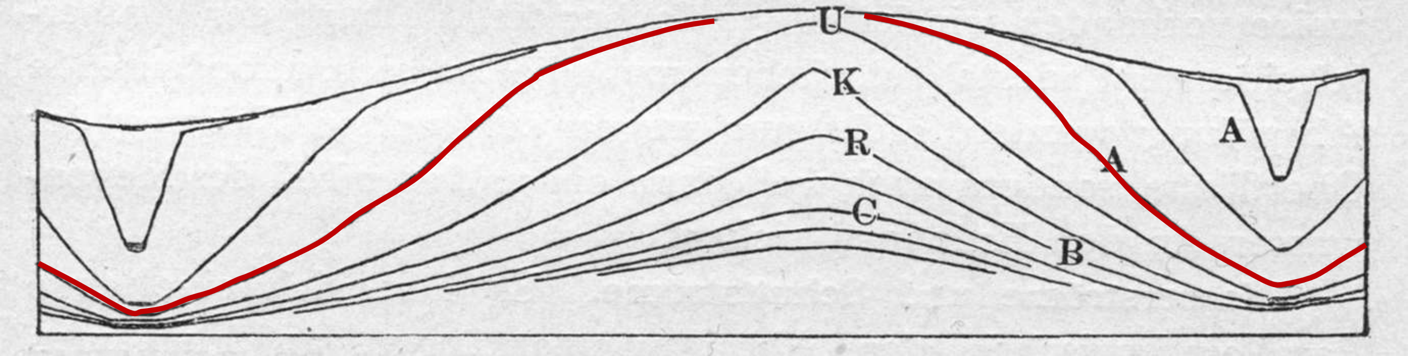


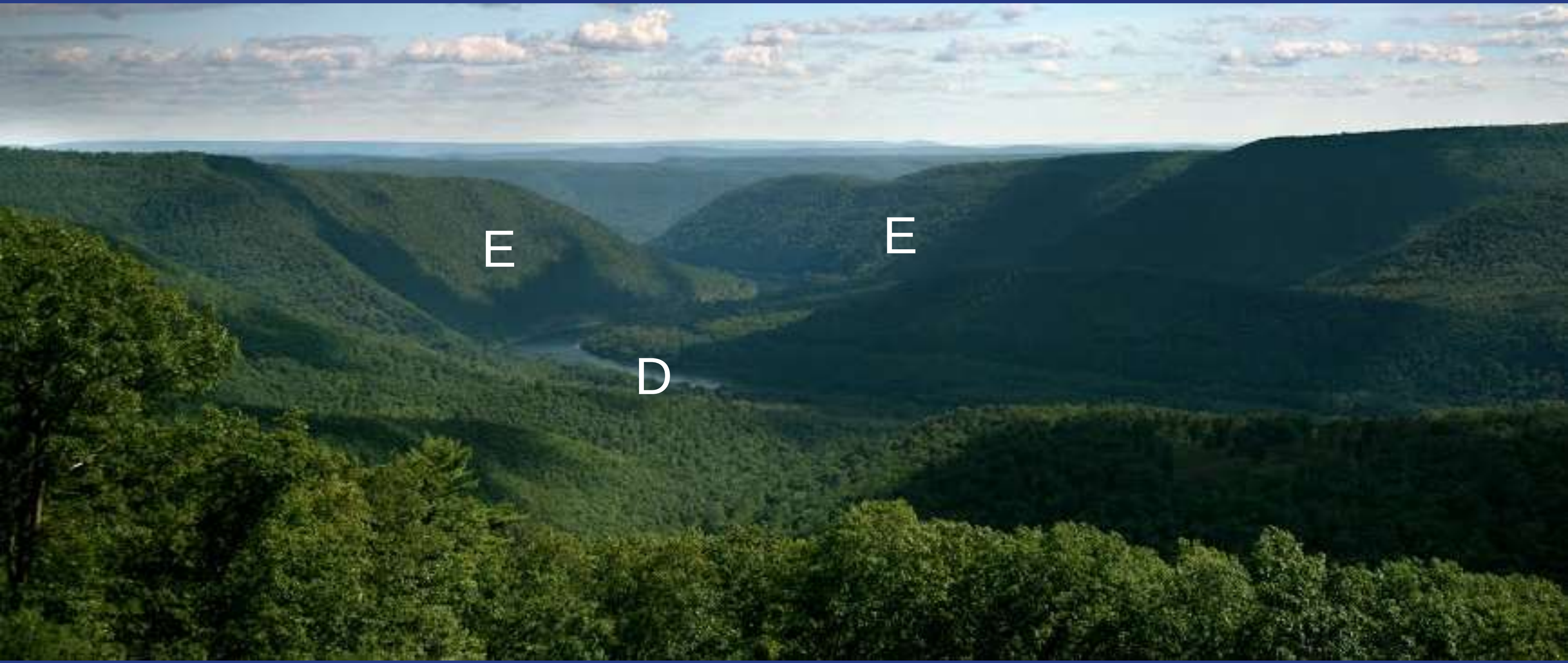
The valley of Ladakh, Transhimalaya, Xizang Autonomous Region (Tibet) , China.

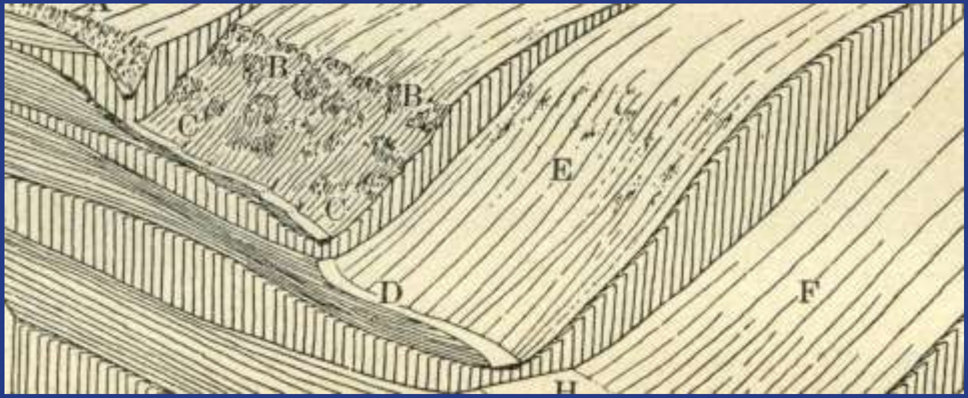
Scree covered slopes, small outcrops, if any



The stream approaches a point where it erodes very little

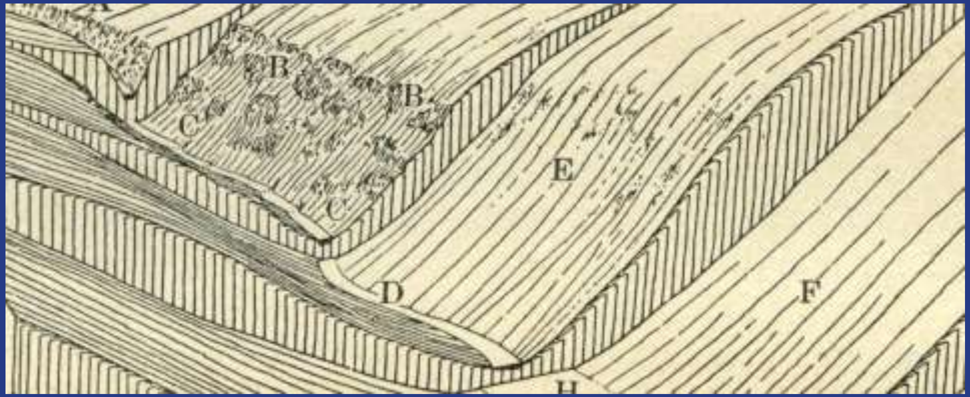




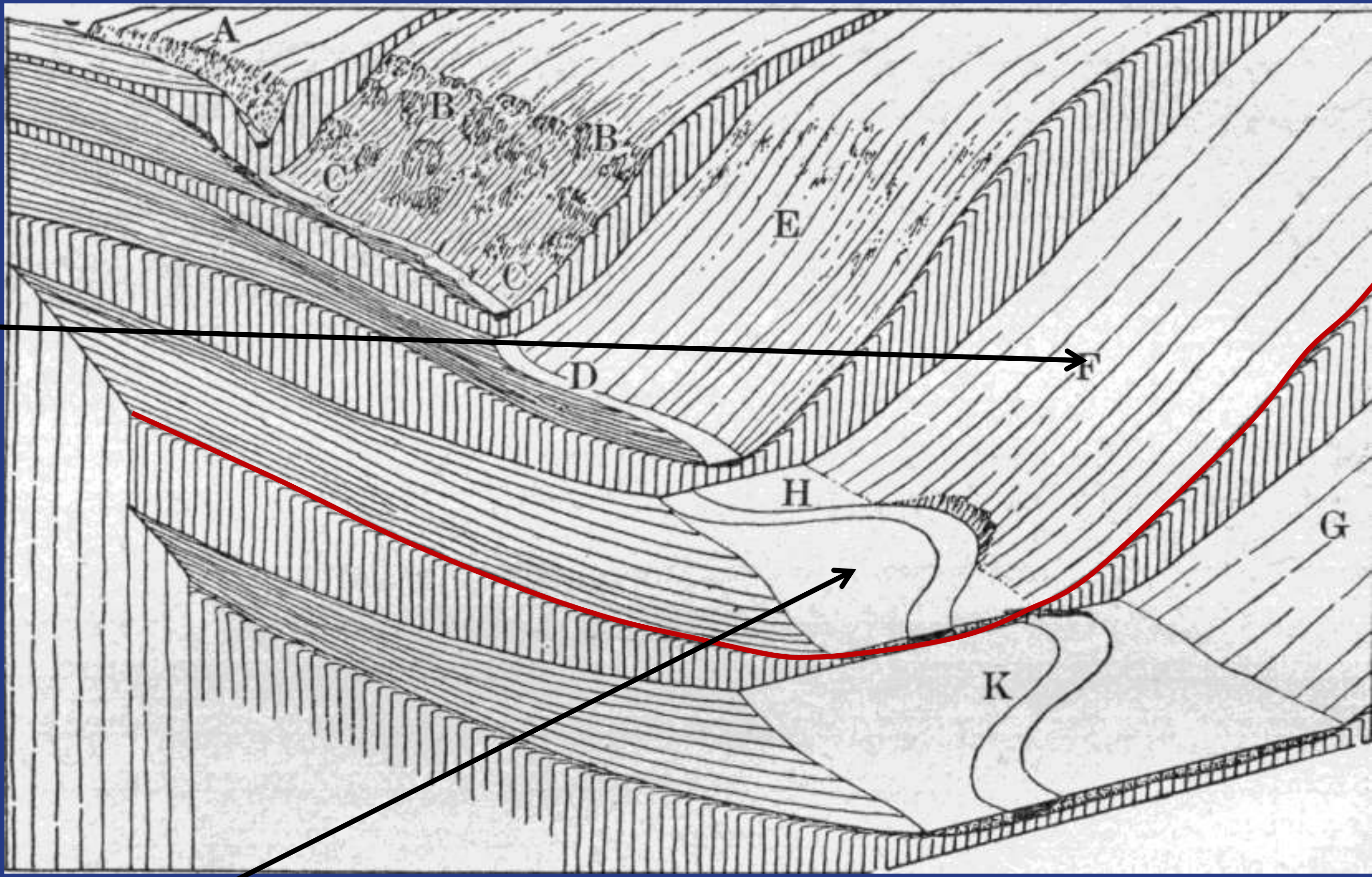


Hyner State Park in the Pennsylvanian Appalachians, USA, Sesquehanna River Valley

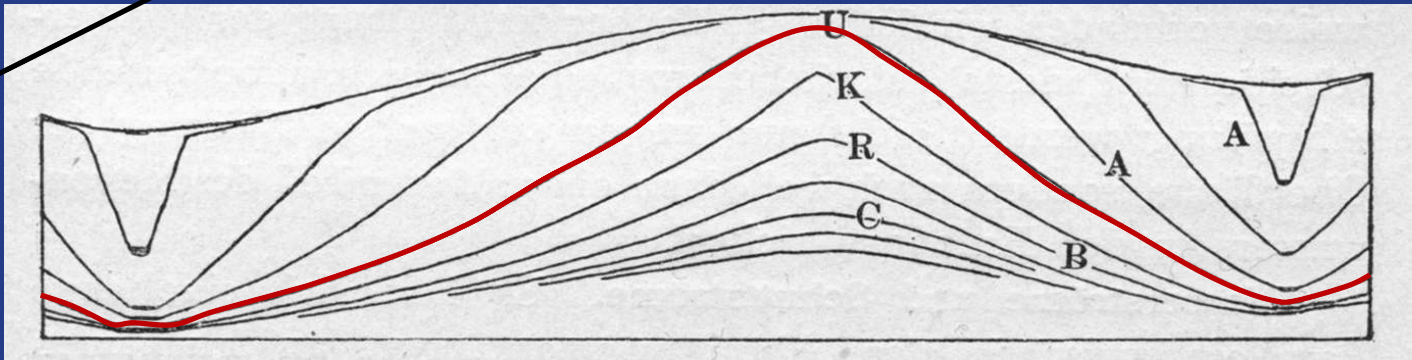

E
E
D (only in flood time)

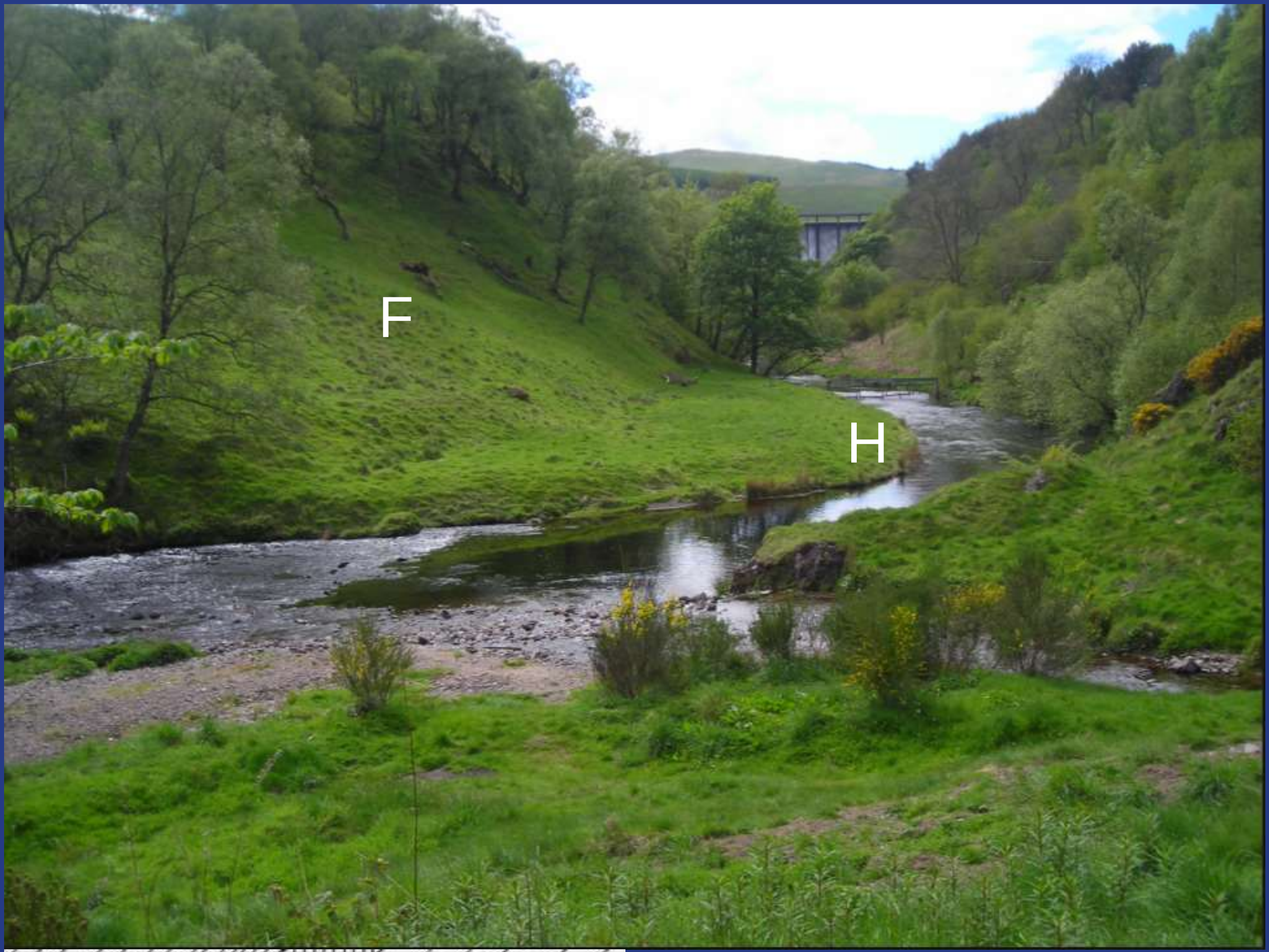

B
B
C
C
E
D
F

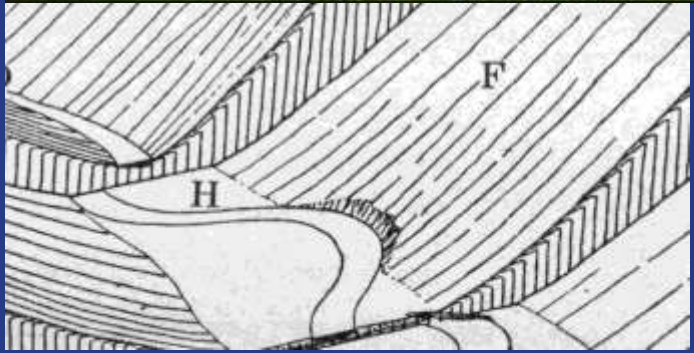
Valley slopes become gentler and the scree cover extends farther up



Valley bottom becomes wider and a flood plain appears.



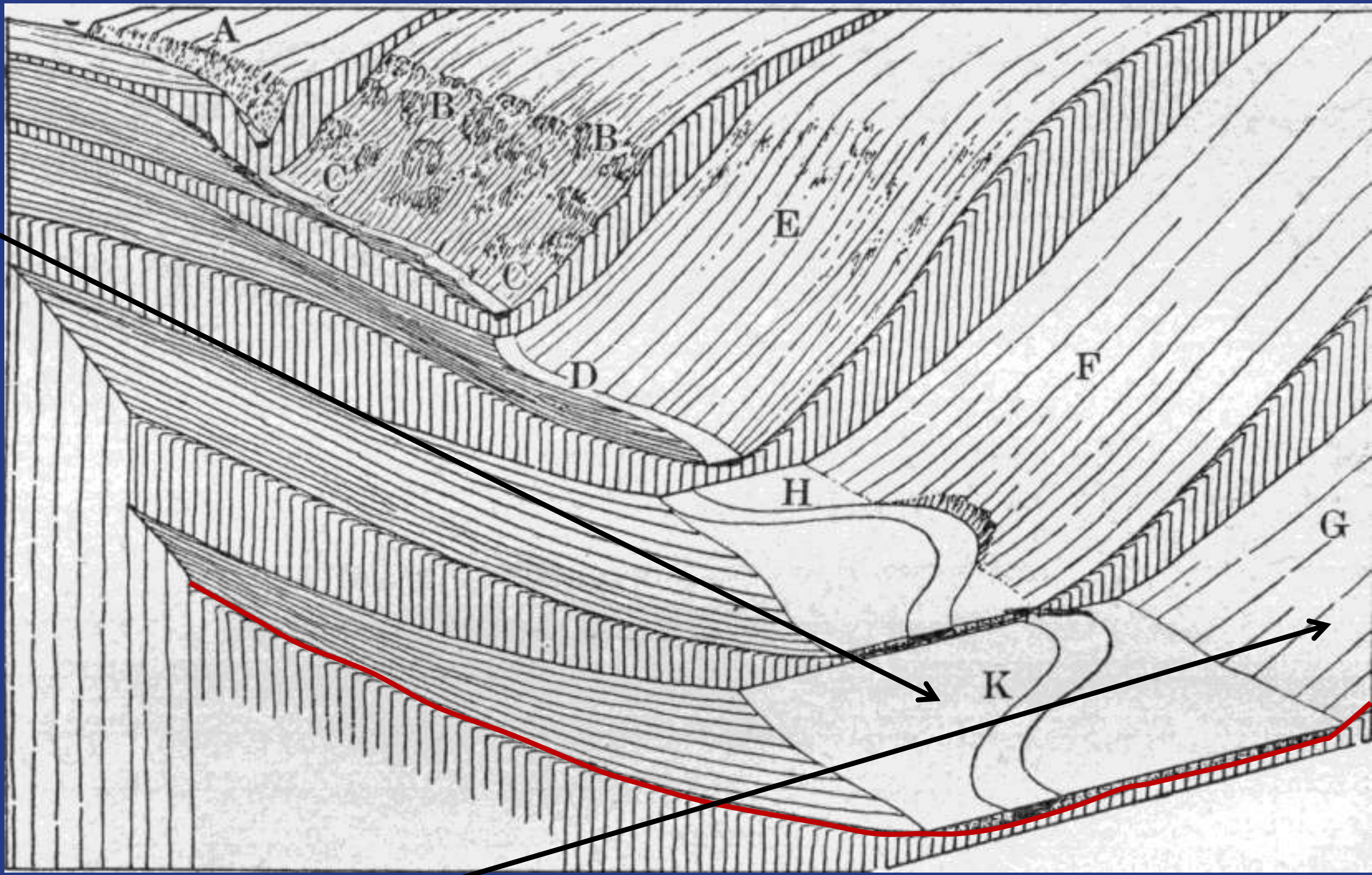


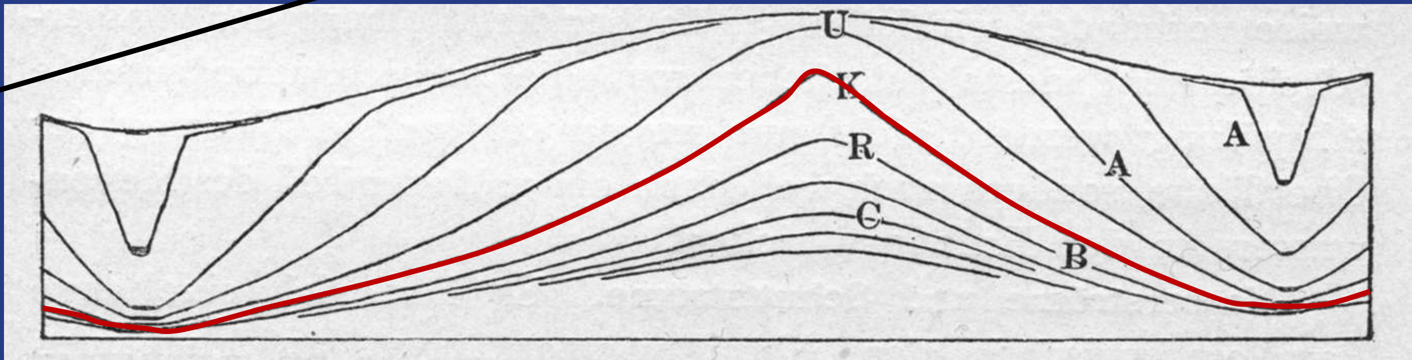


The mature river valley of the Dover River, England, with a newly-developing flood plain.

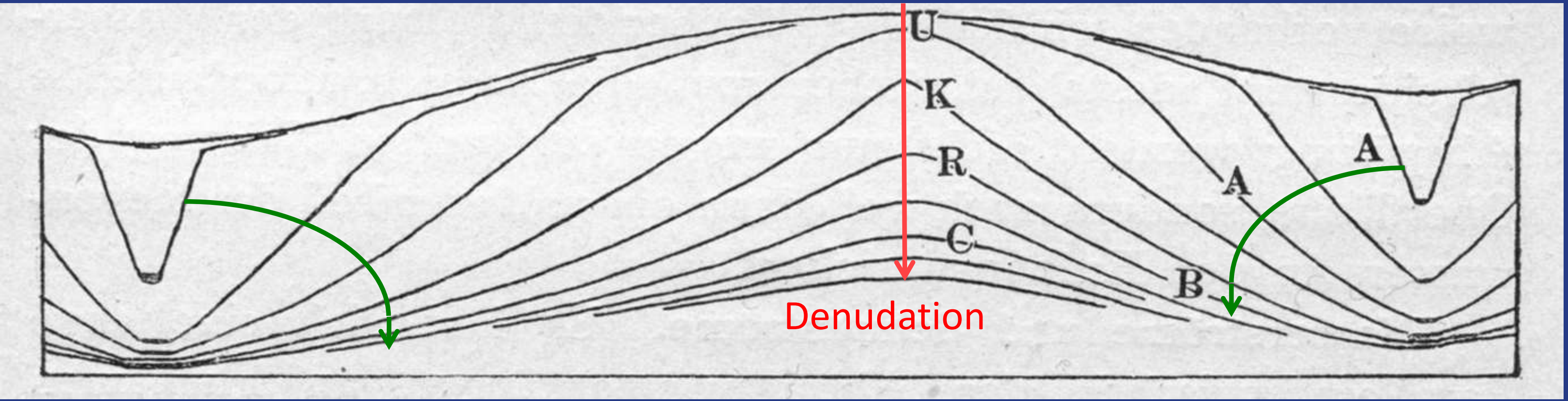
Flood plain becomes wider

The slope scree becomes finer grained as the valley slopes become ever gentler





A mature valley. Notice the far slopes. Do they present a problem for the Davisian model?



Slope flattening or slope degradation

Basic summary of Davis' model of valley evolution

Davis' model was dependent upon the assumption of RAPID UPLIFT and SLOW DENUDATION.

By contrast Walther Penck made no assumption of uplift rate. He simply pointed out that landforms would develop according to the rates of endogenous and exogenous processes that can be different in different tectonic and climatic provinces.

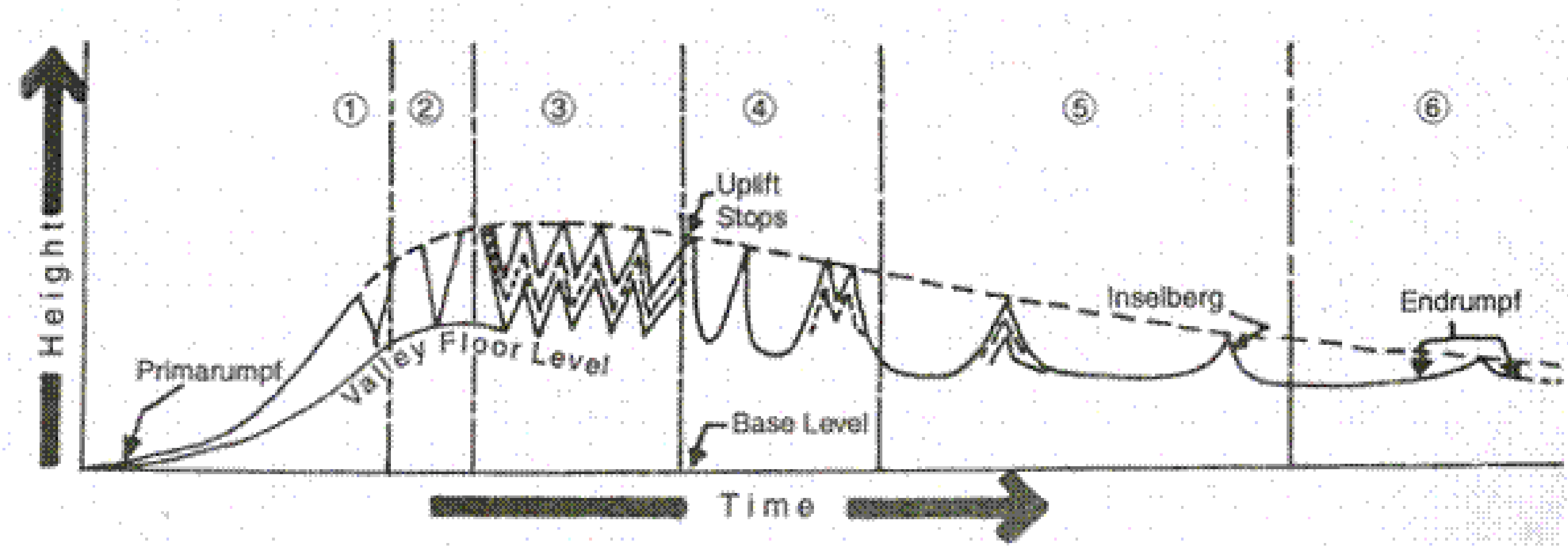


Fig. 1.46 A graphic presentation of Penck's geographical cycle.

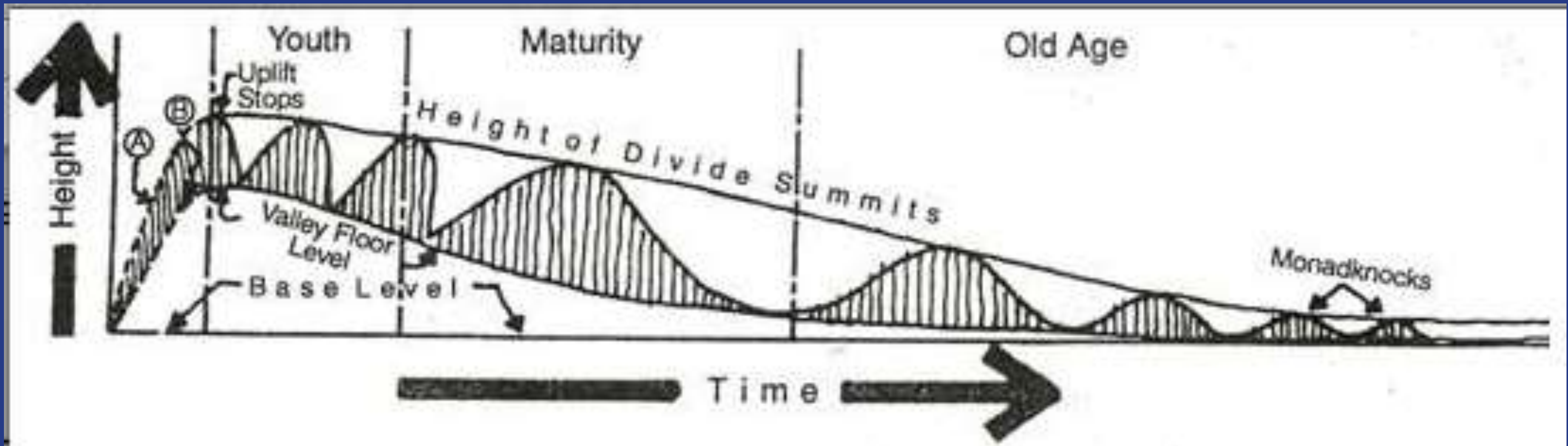
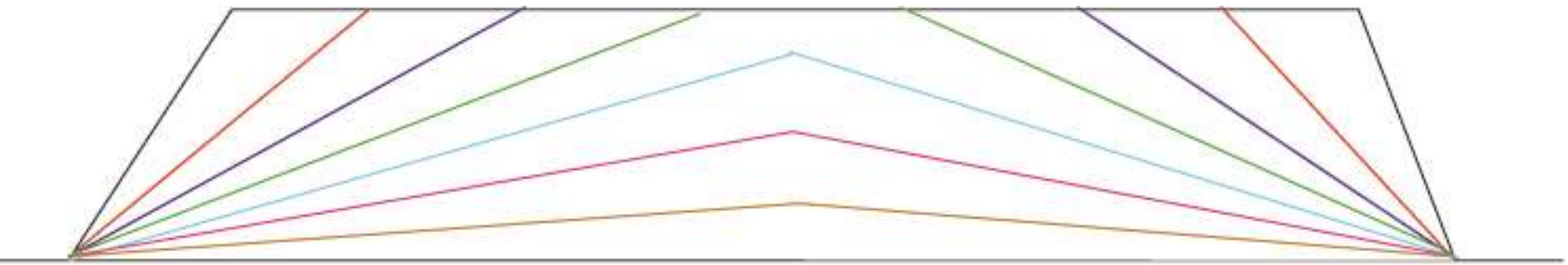
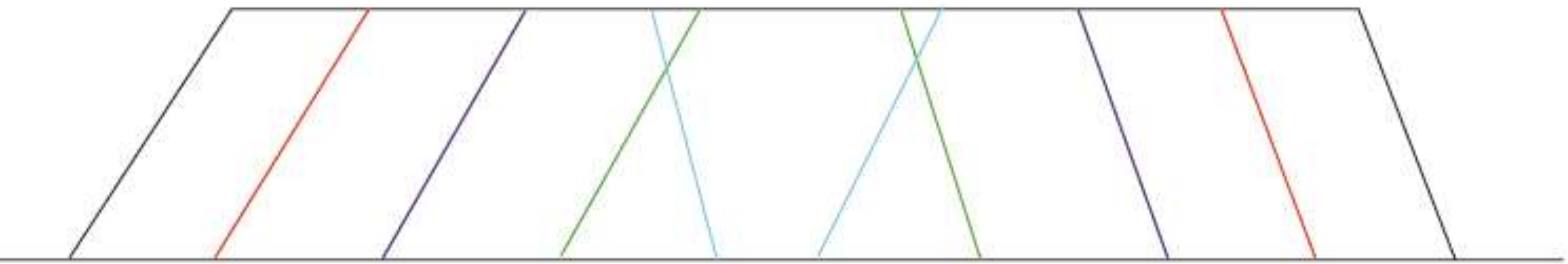


Fig. 1.44 A graphical presentation of geographical cycle proposed by W.M. Davis.



Slope evolution according to Davis' scheme. Edge erosion of the plateau is ignored for simplicity



Slope evolution according to Penck's scheme. Edge erosion of the plateau is ignored for simplicity

Slope evolution by parallel slope retreat: The Sahara Desert, Libya

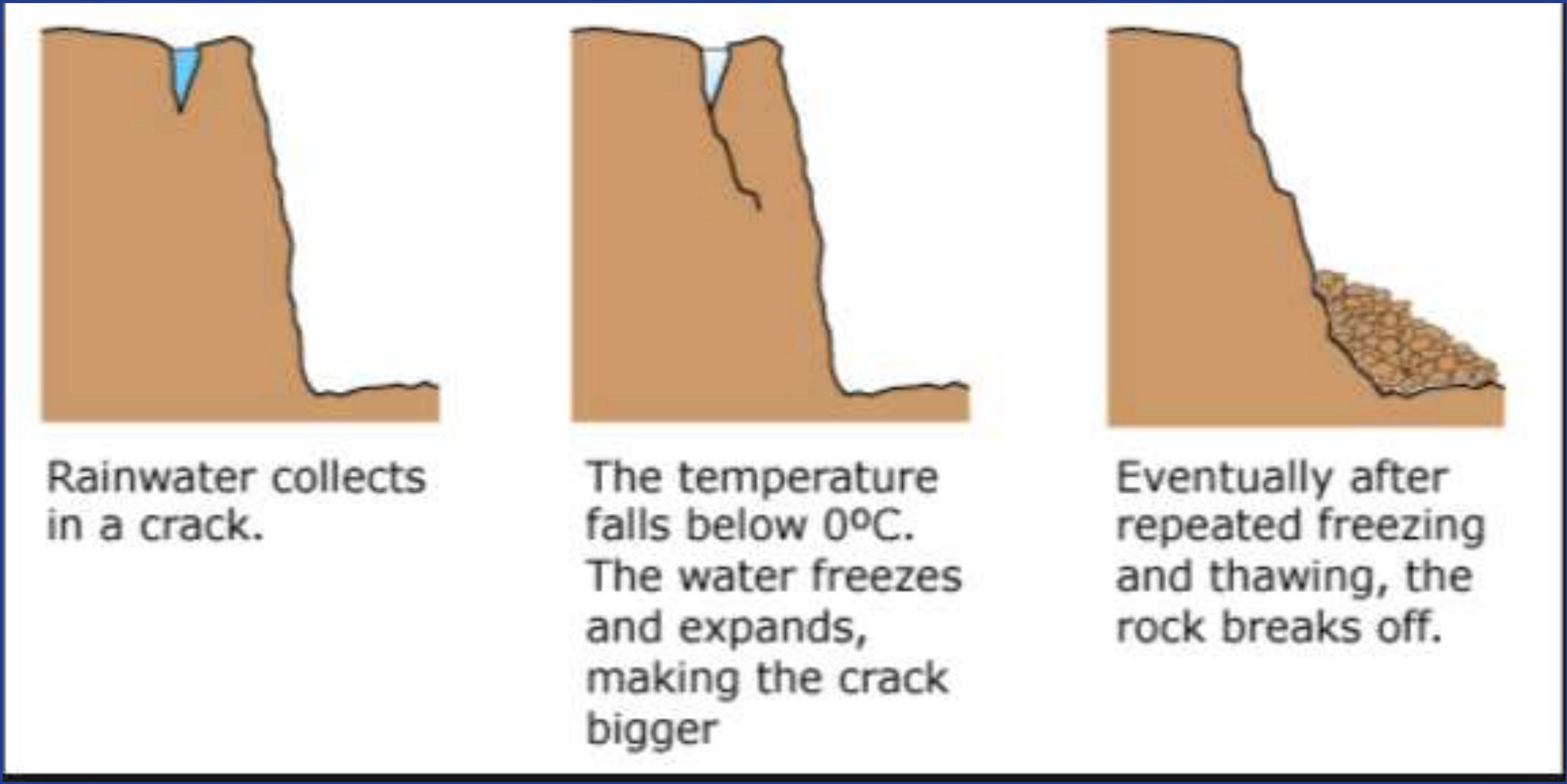
Slope evolution by parallel slope retreat: The Sahara Desert, Libya

Vertical to near-vertical slopes: the Sahara Desert, Libya

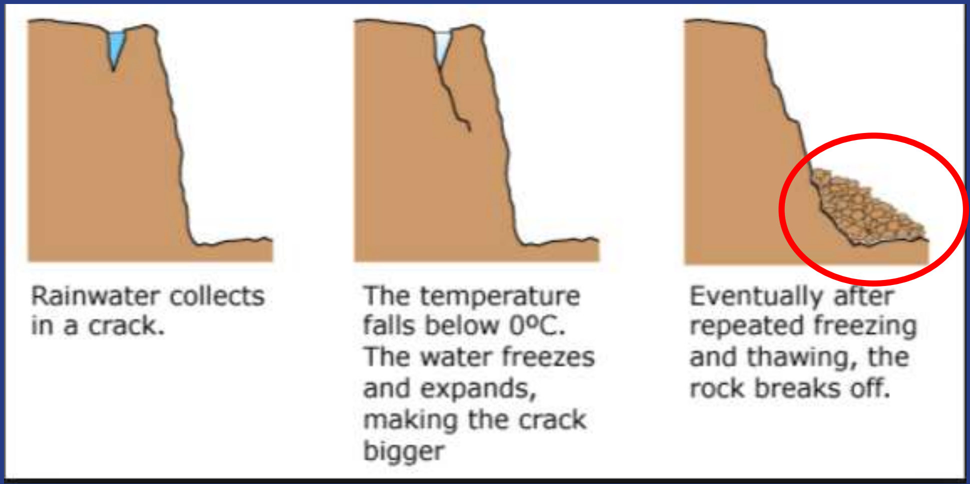
Various slopes, the Sahara Desert, Libya

Various slopes, the Sahara Desert, Libya

Vertical slopes, the Sahara Desert, Libya



If the separated rock is on a precipice, it would fall down the precipice and further disintegrate upon impact on the ground and thus further contribute to mechanical disintegration.


Rainwater collects in a crack.
The temperature falls below 0ºC. The water freezes and expands, making the crack bigger
Eventually after repeated freezing and thawing, the rock breaks off.

Vertical slopes, the Sahara Desert, Libya

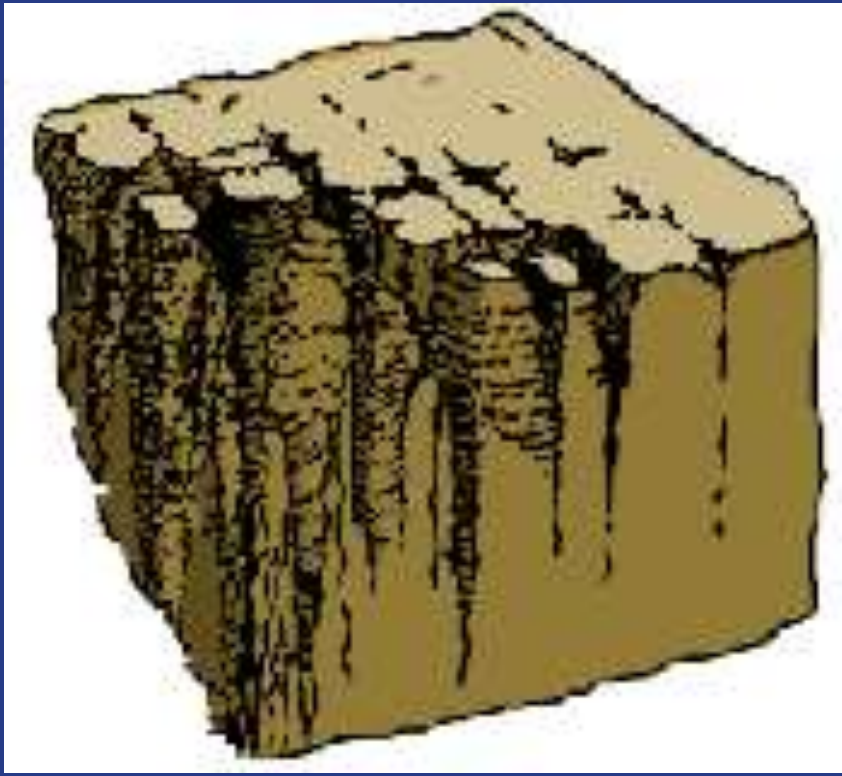
Vertical and reclining slopes, Monument Valley, Arizona-Utah border, USA

Monument Valley with the "Totem Pole" in Arizona, USA

The so-called “Saxon Switzerland”, the Czech Republic, showing vertical slopes in horizontal Cretaceous sandstones.

The so-called “Saxon Switzerland”, the Czech Republic, showing vertical slopes in horizontal Cretaceous sandstones.

The so-called “Saxon Switzerland”, the Czech Republic, showing vertical slopes in horizontal Cretaceous sandstones.



The vertical jointing in the horizontally-layered Cretaceous sandstones of the “Saxon Switzerland” and its role in the origin of the vertical slopes.

Differential erosion of thin beds *versus* thick beds:
Monument Valley, Utah/Arizona border, USA

Colorado River in the Grand Canyon, Arizona, USA: Why are the steps?

Stepped landscape in the horizontally-bedded terrain of the Grand Canyon, Arizona, USA: Why are the steps?

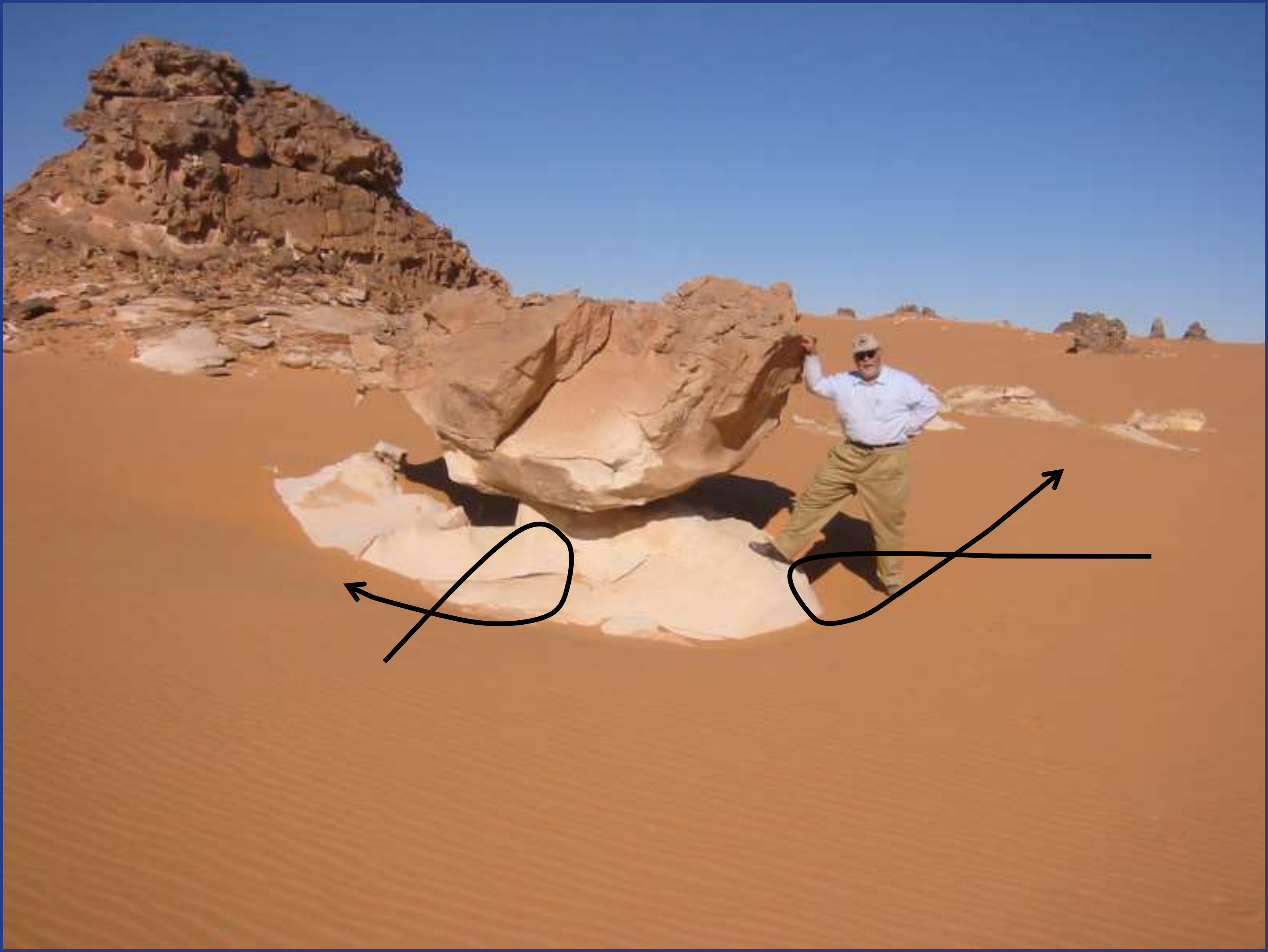
Erosion of bed heads, Grand Canyon, Arizona, USA

Palaeozoic sandstone layers, the Sahara Desert, Libya: anything strange?

The influence of the normal dip-slip fault on the erosion

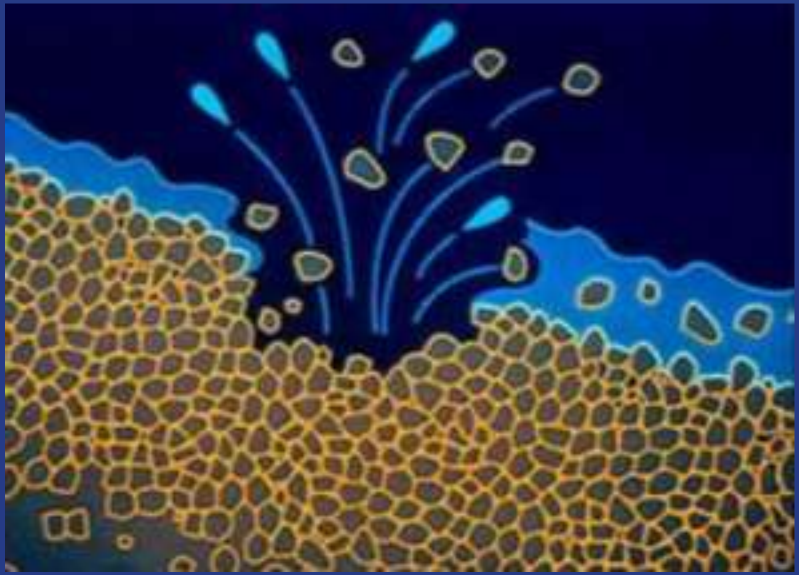
An “aerodynamic moat” at the foot of an “overhanging” cliff. The Sahara Desert, Libya. How did the overhang form?

Aerodynamic moat, the Sahara Desert, Libya



Formation of the aerodynamic moat by wind scouring

A simple lesson from the last two vignettes: while the theories by Davis and Penck are important to understand *landscape evolution on a large scale*, one needs to know the *details of the processes that shape the land surface*. It is to those details we now turn. We begin with processes associated with the work of flowing water.

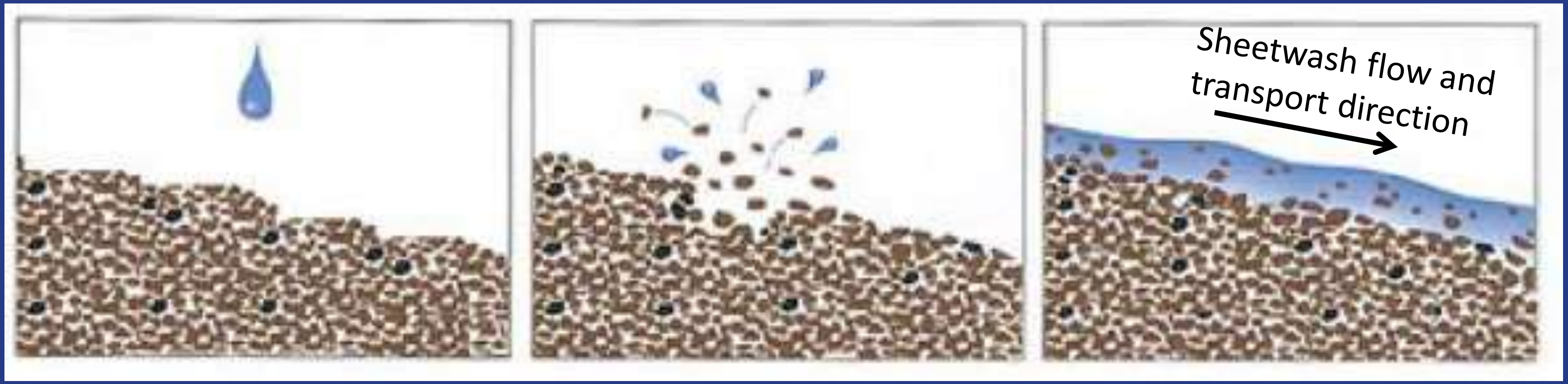


Raindrop erosion. Raindrops splash the soil and liberate particles that can then be carried by flowing surface waters (sheetwash, etc.)

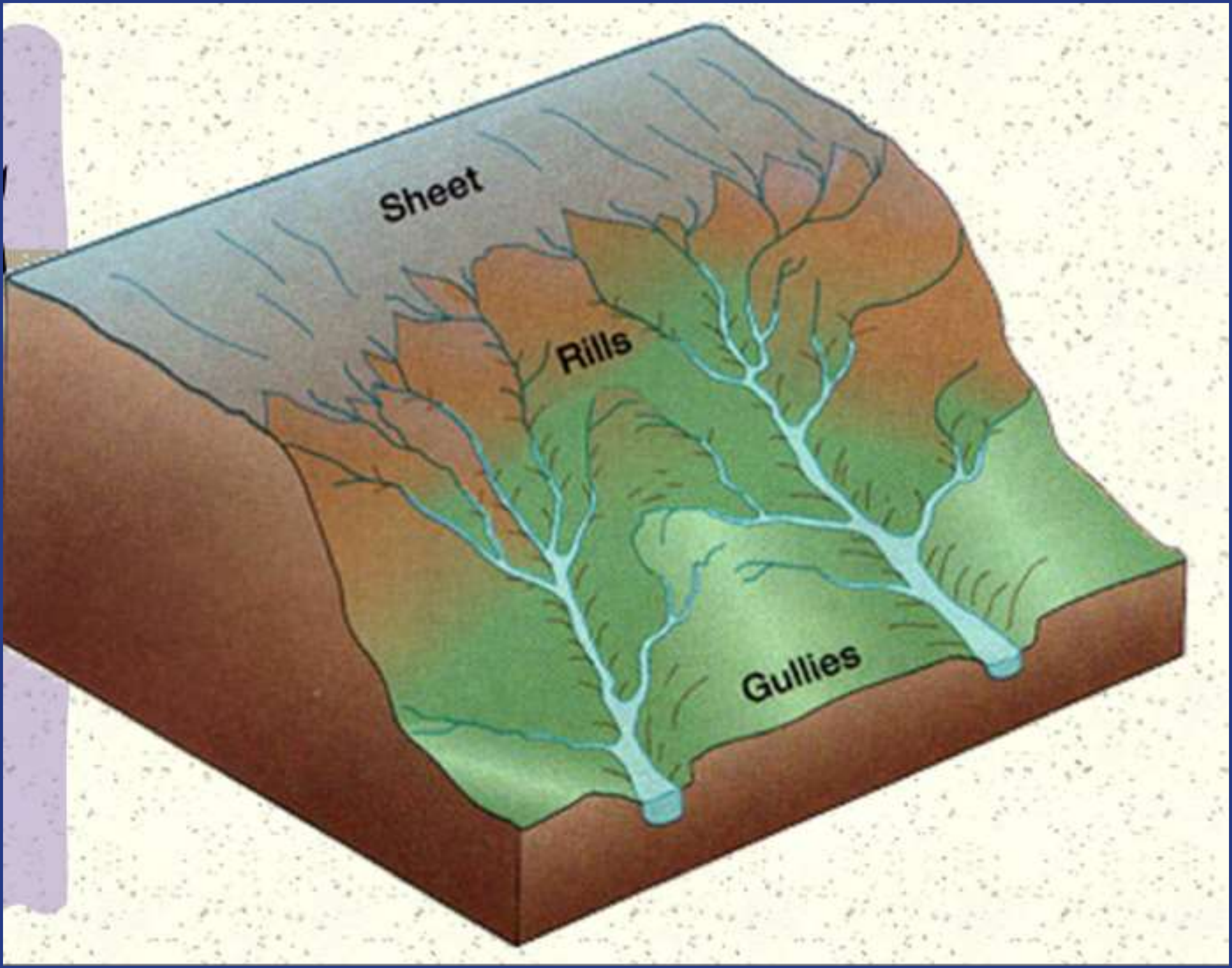
Sand surface eroded by raindrops (locality unknown)

Sheetwash:

Sheetwash is surface water flowing without being confined to a channel. Sheetwash usually occurs after strong rains and rapid snow melting



Raindrops release particles and then sheetwash carries them away. Their presence in the sheetwash gives the latter heightened powers of abrasion, which leads to the creation of rills and gullies in the landscape.



Downslope, sheetwash gives way to rills and gullies

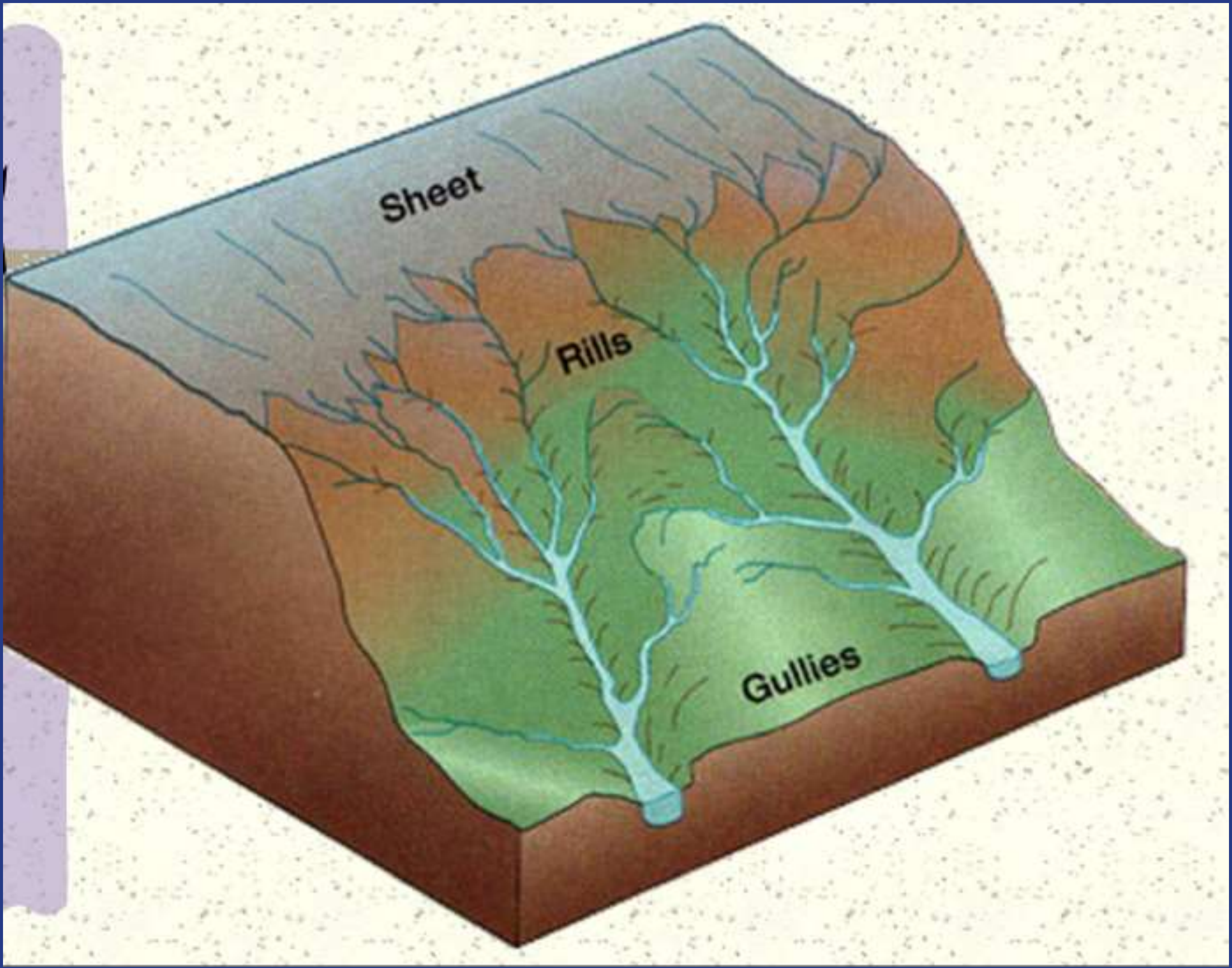
Rill is a is a small stream with a narrow (at most a metre wide) and shallow channel (no more than a few tens of centimetres deep) cut into soil or regolith by the erosive action of temporary flowing water. Also called a runnel or a rivulet.

Rills incising a slope

A transitional landfrom: sheetwash to rill: County Tyrone, Northern Ireland

Initiation of a rill on a raindrop-beaten surface

Soil erosion caused by rills



Downslope, sheetwash gives way to rills and gullies

A gully (also spelled gulley) is an erosive landform formed by running water, eroding sharply into soil or regolith or sedimentary rock, typically on a hillside. Gullies resemble large ditches or small valleys, but are metres to tens of metres in depth and width. When the gully formation is in process, the water flow rate can be substantial, causing a significant deep cutting action into its bed.

Typical gullies

Sheetwash, rills and gullies form landforms generated by temporary flowing water bodies. They come together to form larger streams and rivers formed by permanent flowing water bodies.

River valley slopes are formed not only by flowing water but also by solid mass movements called mass-wasting. Mass wasting may be of four types:

1. Soil creep

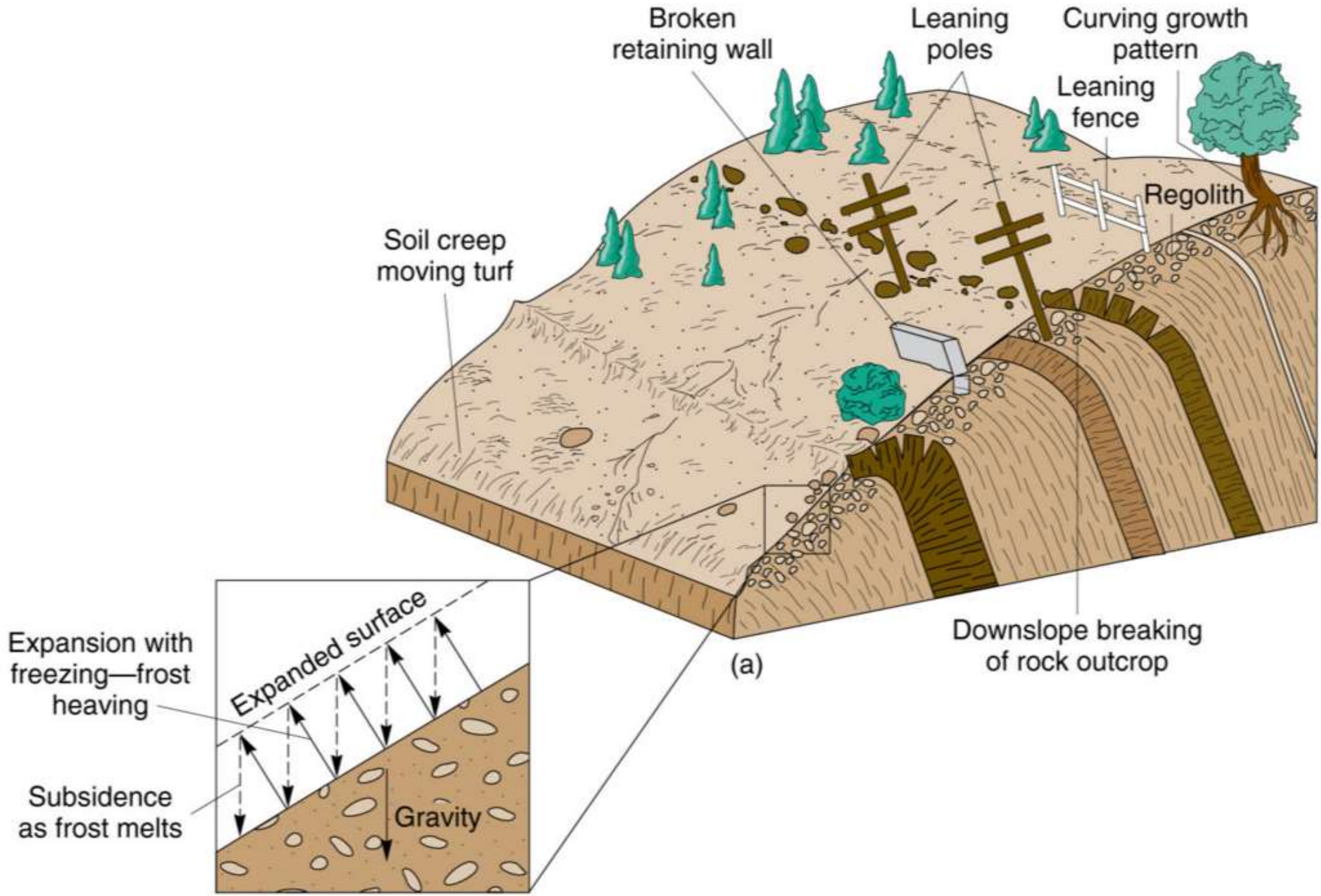
2. Mudflow

3. Rock fall

4. Landslide (including slump)

Soil creep

Soil creep or downhill creep refers to the *en masse* motion surficial rock material and soil down a slope under the influence of gravity. Soil creep depends on 1) steepness of the slope (i.e., on its gradient), 2) water absorption and content of the creeping material and 3) presence and type of vegetation in the creeping material. Steeper slope, richer water content and sparsity or absence of vegetation contribute to soil creep.

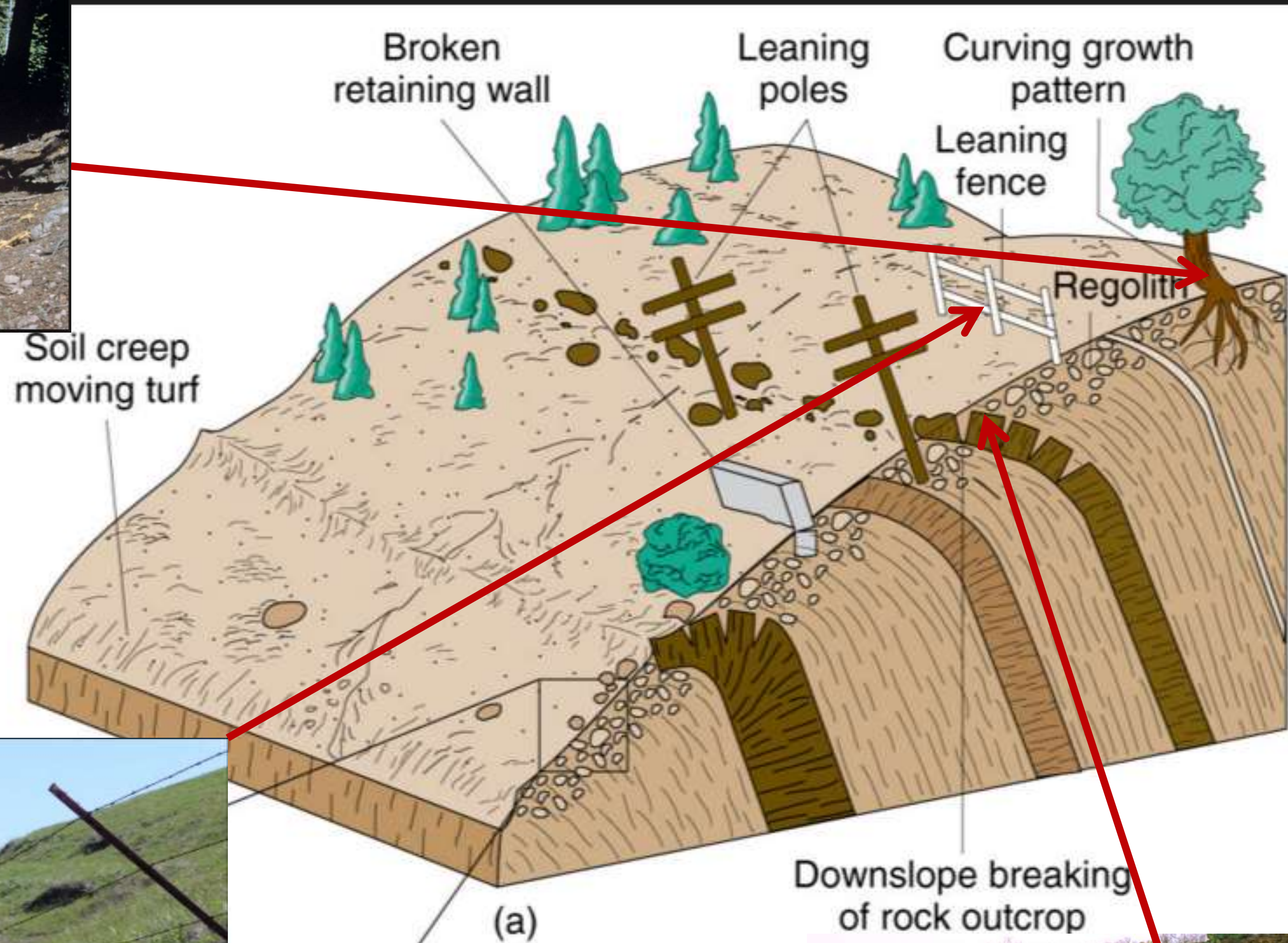

Broken
retaining wall
Leaning
poles
Curving growth
pattern
Leaning
fence
Regolith
Soil creep
moving turf
Downslope breaking
of rock outcrop
(a)
Expansion with
freezing—frost
heaving
Expanded surface
Subsidence
as frost melts
Gravity

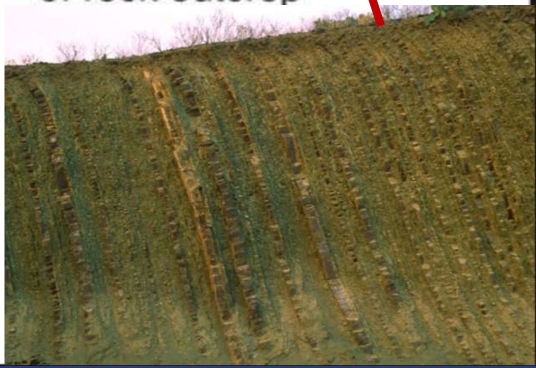
Soil creep as indicated by the curving of layer tops

Soil creep indicated by curving tree trunks

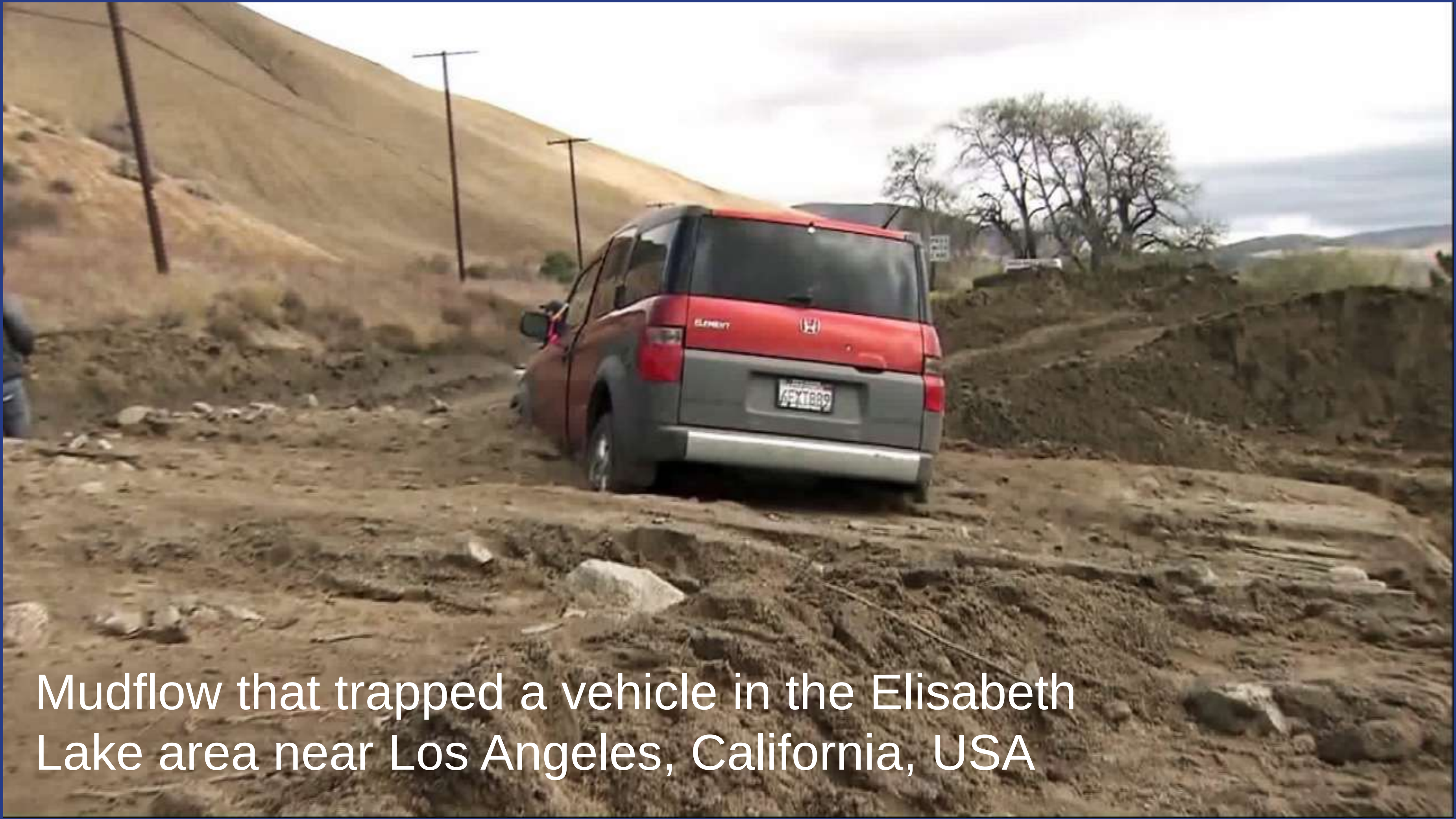
Soil creep indicated by reclining fence poles

SOME MANIFESTATIONS OF SOIL CREEP





Mudflow is water-saturated soil or regolith moving downslope under the influence of gravity. Its viscosity depends on the amount of water content and its grain size.



Mudflow that trapped a vehicle in the Elisabeth Lake area near Los Angeles, California, USA

Another mudflow from California, USA

Rock fall

Rock fall is the falling of a large quantity of rock freely from a cliff face or down a steep slope under the influence of gravity.

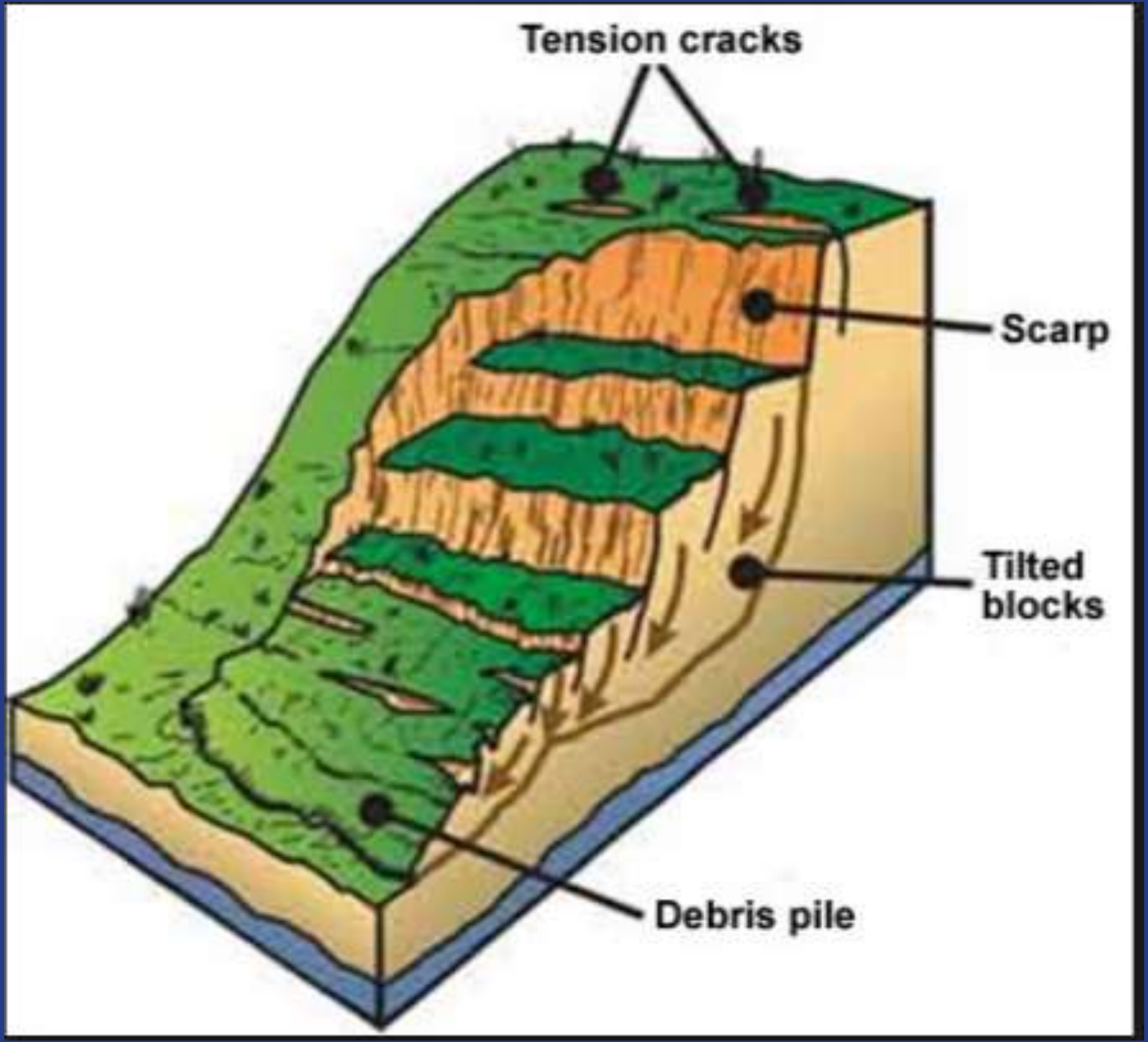
Rockfall blocking a road

Landslide

A landslide is a form of mass movement that transports a considerable amount of solid rock matter over a surface of detachment down a slope under the effect of gravity.

Landslides may move coherently or they may flow. Where they flow, their behaviour approaches that of mudflows. Debris flows are intermediate masses between landslides and mud flows.

Landslides are generally facilitated by the presence of water, impermeable rock bodies and appropriate structure.



Anatomy of a landslide

The landslide of 23rd August 2005 in Entlebuch, central Switzerland.

2010 Tekirdağ Landslide, Turkey

The Hanyuan Landslide, Sichuan, People's Republic of China, 28th January 2010

A human-induced landslide: Bingham Canyon Mine in Utah, 10th April 2013; Utah, USA

A part of the Bingham Canyon Mine landslide

So far we have looked at valley slopes and considered their evolution and the processes controlling that evolution. It is time we look at the geology of the valley bottoms. To that end, we distinguish two kinds of streams:

1. Braided streams

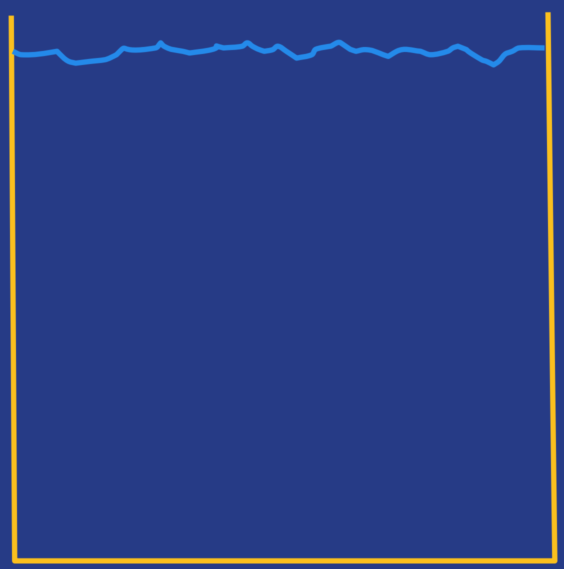
2. Meandering streams

The term braided comes from the ordinary braid, but the term meander comes from the river Meandros (=Menderes in Turkish) in Turkey.

In both these kinds of streams the water is discharged along channels. The discharge is calculated according to the following formula:

Discharge = channel width X channel depth X velocity of water flow

Now imagine what happens when discharge increases. One, or two or all of these parameters must increase. For instance, if the channel width cannot be increased, then the depth must increase, which would lead to flooding. Therefore, when planning canals, one must construct canal beds with sloping walls to allow the width also to enlarge so as not to allow the waters to overtop the channel.



WRONG DESIGN OF CHANNEL

In case of a discharge increase, only depth and velocity can change

CORRECT DESIGN OF CHANNEL

In case of a discharge increase, all three variables can change

Let us go back to our two kinds of streams

1. Braided streams

2. Meandering streams

The term braided comes from the ordinary braid, but the term meander comes from the river Meandros (=Menderes in Turkish) in Turkey.

A braid

A typical braided river: the Taku River, Alaska, USA

The type meanders: a part of the Büyük Menderes River, Turkey

Braided Rivers

Braided rivers is one of the two main channel types of streams. They consist of a braid-like network of commonly temporary channels separated by equally temporary islands of sediment called bars (in America) and aits (in the UK). Such channels form wherever there is a high sediment load and/or a dramatic decrease of channel depth as on alluvial fans and river deltas.

If the slope of a river increases above 0.016 for a 0.0042 m^3/s with poorly-sorted coarse sand, then the river channel will be braided. The following conditions increase the probability of building braided channels in rivers:

1. Rich sediment supply

2. High channel slopes

3. Rapid and frequent changes in water discharge

4. Easily erodible banks

A braided stream in the Tien Shan Mountains, Kyrgyzstan

A typical braided river: the Taku River, Alaska, USA

The bed of a braided river: Tagliamento River, northern Italy

The braided channels of the Rakaia River, New Zealand

What do the sediments of braided rivers look like?

In any cross-section of the deposits of a braided river, one sees lenses of sands, conglomerates and silts and muds representing active channels, abandoned channels and sand and/or conglomerate aits.

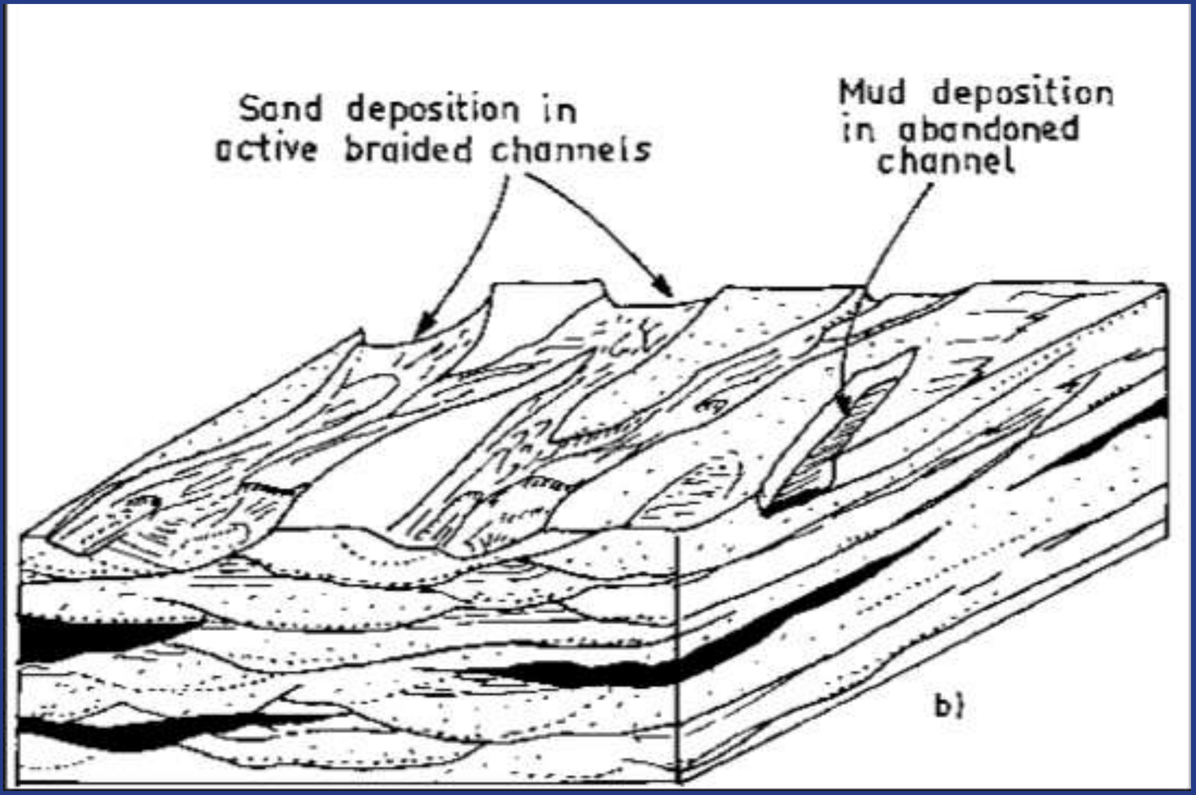
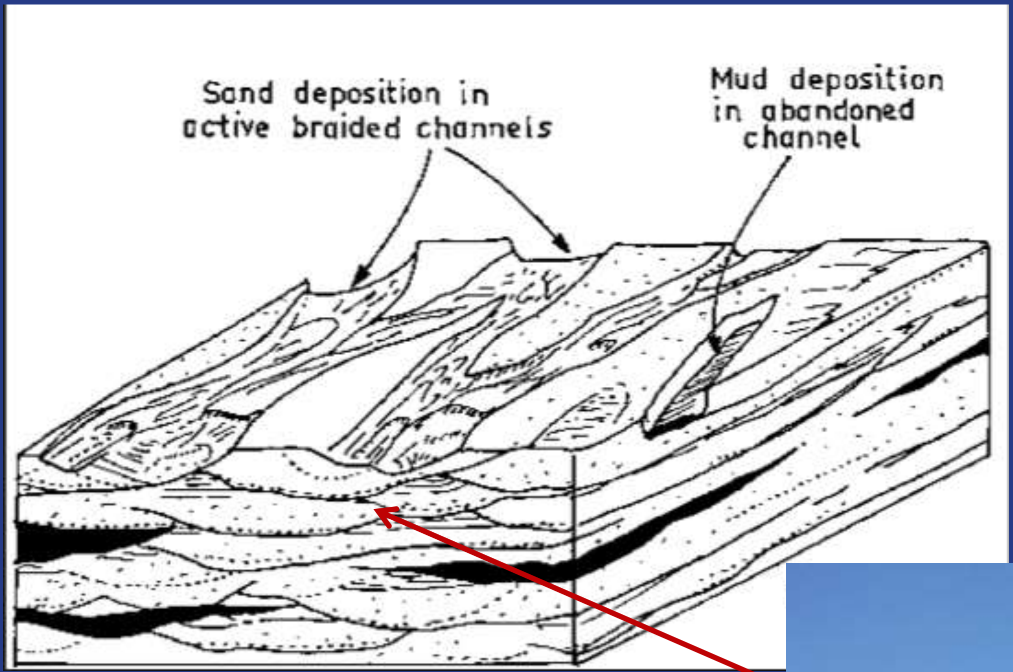


Figure 6. Quarry exposure of analogous coarse, braided-stream deposits showing disconnected sand lenses (S) and a variety of cobble-dominated facies ranging from poorly-sorted massive units (Gm), to moderately-sorted horizontally-bedded units (Gh) and trough crossbedded units (Gt). Heavy lines identify bounding surfaces between depositional sequences. Prime Earth quarry northwest of Boise, Idaho. For scale, quarry face is approximately 12 m high.

A Quaternary-age braided river deposit in Patagonia
(photo by Karen at https://landscapes-revealed.net/2012/01/)



Note the lenticular aspect of the individual deposits corresponding to the shapes of their depositional environments

Meandering Rivers

Meandering rivers are those with a well-defined channel that has a markedly sinuous course.

The River Inn meandering around the town of Wasserburg, Bavaria, south Germany

Why do meanders form?

First of all, to form a stable channel one needs those conditions that are the opposite of those leading to the formation of braided channels:

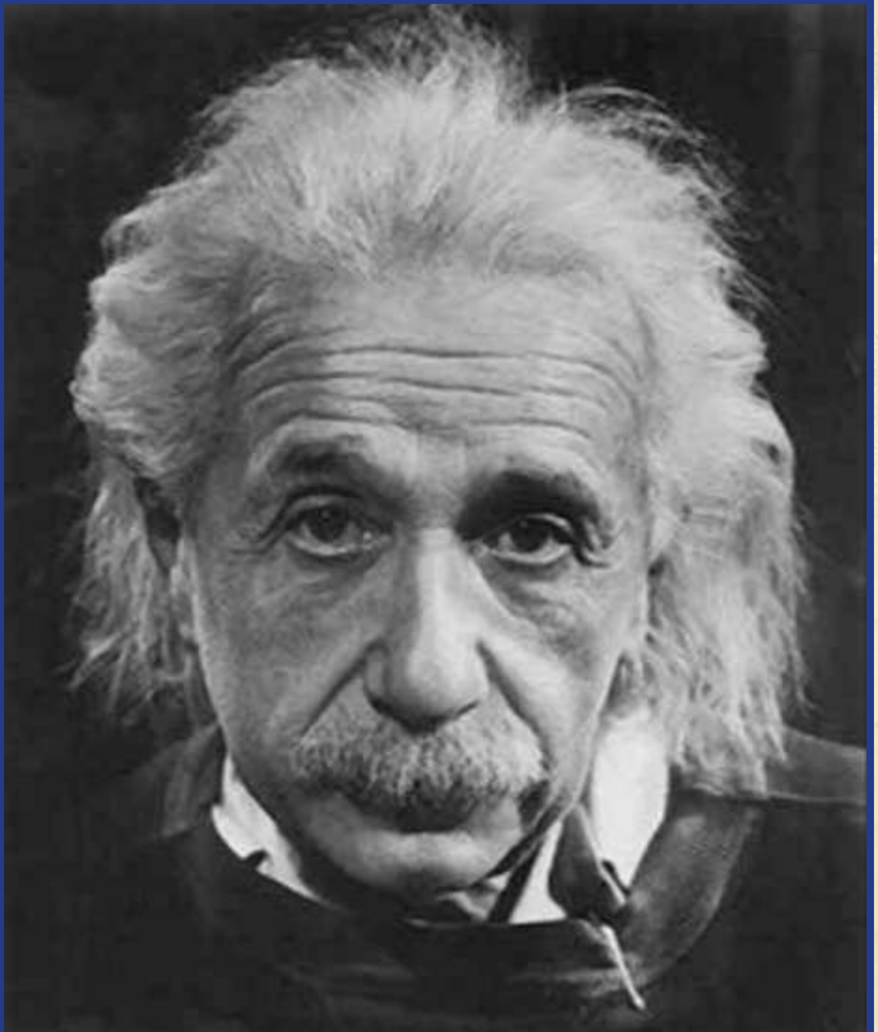
1. Very gentle slopes (lower than 0.016!)

2. Little sediment load (and mainly fine-grained)

3. Regular flow (no rapid and large discharge fluctuations)

4. Resistant channel borders

These conditions are usually met with in the middle to lower courses of rivers.



Albert Einstein (1879-1955), the man who solved the problem of the origin of meanders

nen gefunden werden, normale ε-Werte gefunden werden, wenn stark verdampfende Teilchen genommen werden. Da wohl kaum behauptet werden kann, daß der Ladungswert der Teilchen in Wirklichkeit vom Verdampfungsprozeß beeinflußt werde, so können natürlich diese Messungen auch als ein erneuter Beweis für die Nichtexistenz des Subelektrons herangezogen werden.

Die Ursache der Mäanderbildung der Flußläufe und des sogenannten Baerschen Gesetzes.

Von A. EINSTEIN, Berlin.

Es ist allgemein bekannt, daß Wasserläufe die Tendenz haben, sich in Schlangenlinien zu krümmen, statt der Richtung des größten Gefälles des Geländes zu folgen. Ferner ist den Geographen wohlbekannt, daß die Flüsse der nördlichen Erdhälfte die Tendenz haben, vorwiegend auf der rechten Seite zu erodieren; Flüsse auf der Südhälfte verhalten sich umgekehrt (BAERsches Gesetz). Versuche zur Erklärung dieser Erscheinungen liegen in großer Zahl vor, und ich bin nicht sicher, ob dem Fachmann irgend etwas, was ich hierüber im folgenden sage, neu ist; Teile der darzulegenden Überlegungen sind jedenfalls bekannt. Da ich jedoch niemand gefunden habe, der die in Betracht kommenden ursächlichen Zusammenhänge vollständig gekannt hätte, halte ich es doch für richtig, dieselben im folgenden kurz qualitativ darzulegen.

Zunächst ist es klar, daß die Erosion desto stärker sein muß, je größer die Strömungsgeschwindigkeit unmittelbar an dem betreffenden Ufer ist, bzw. je steiler der Abfall der Strömungsgeschwindigkeit zu Null hin an einer ins Auge gefaßten Stelle der Flußwandung ist. Dies gilt unter allen Umständen, gleichgültig ob die Erosion auf mechanischer Wirkung oder auf physikalisch-chemischen Faktoren (Auflösung von Bodenbestandteilen) beruht. Wir haben daher unser Augenmerk auf diejenigen Umstände zu richten, welche die Steilheit des Geschwindigkeits-Abfalles an der Wandung beeinflussen.

In beiden Fällen beruht die Asymmetrie bezüglich des ins Auge zu fassenden Geschwindigkeitsgefälles indirekt auf der Ausbildung eines Zirkulationsvorganges, auf den wir zunächst unser Augenmerk richten wollen. Ich beginne mit einem kleinen Experiment, das jeder leicht wiederholen kann.

Es liege eine mit Tee gefüllte Tasse mit flachem Boden vor. Am Boden sollen sich einige Teeblättchen befinden, die dadurch am Boden festgehalten sind, daß sie etwas schwerer sind als die von ihnen verdrängte Flüssigkeit. Versetzt man die Flüssigkeit mit einem Löffel in Rotation, so sammeln sich die Teeblättchen alsbald in der Mitte des Bodens der Tasse. Der Grund dieser Erscheinung ist folgender: Durch die Drehung der Flüssigkeit wirkt auf diese eine Zentrifugalkraft. Diese würde an sich zu keiner Modifikation der Strömung der Flüssigkeit Veranlassung geben, wenn diese rotierte wie ein starrer Körper. Aber in der Nähe der Wandung der Tasse wird die Flüssigkeit durch die Reibung zurückgehalten, so daß sie dort mit geringerer Winkelgeschwindigkeit umläuft als an anderen, mehr im Innern gelegenen Stellen. Im besonderen wird die Winkelgeschwindigkeit des Umlaufens und damit die Zentrifugalkraft in der Nähe des Bodens geringer sein als in größerer Höhe. Dies wird zur Folge haben, daß sich eine Zirkulation der Flüssigkeit von dem in Fig. 1 dargestellten Typus ausbildet, die so lange anwächst, bis sie unter der Wirkung der Bodenreibung stationär geworden ist. Die Teeblättchen werden durch diese Zirkulationsbewegung nach der Mitte der Tasse mitgenommen und dienen zu deren Nachweis.

Fig. 1.

Analog ist es bei einem Flusse, der eine Krümmung erleidet (Fig. 2). In allen Querschnitten des Flußlaufes wirkt, wo dieser gebogen ist, eine nach der Außenseite der Biegung (von A nach B) gerichtete Zentrifugalkraft. Diese ist aber in der Nähe des Bodens, wo die Strömungsgeschwindigkeit des Wassers durch Reibung reduziert ist, kleiner als in größerer Höhe über dem Boden. Dadurch bildet sich eine Zirkulation aus von der in der Figur angedeuteten Art. Aber auch da, wo keine Flußbiegung vorhanden ist, wird sich eine Zirkulation von der in Fig. 2 dargestellten Art ausbilden, wenn auch nur in schwachem Betrage, und zwar unter dem Einfluß der Erddrehung. Diese bewirkt nämlich eine quer zur Strömungsrichtung gerichtete Corioliskraft, deren nach rechts gerichtete Horizontalkomponente pro Masseneinheit der Flüssigkeit $2 v \Omega \sin \varphi$ beträgt, wenn v die Strömungsgeschwindigkeit, Ω die Umdrehungsgeschwindigkeit der Erde und φ die geographische Breite bedeutet. Da die Bodenreibung eine Abnahme dieser Kraft nach dem Boden hin bewirkt, so veranlaßt auch diese Kraft eine Zirkulationsbewegung von der in Fig. 2 angedeuteten Art.

Nach dieser vorbereitenden Überlegung kommen wir zurück auf die Frage der Geschwindigkeitsverteilung im Flußquerschnitt, welche ja für die Erosion maßgebend ist. Zu diesem Zweck müssen wir uns zuerst vergegenwärtigen, wie die (turbulente) Geschwindigkeitsverteilung in einem Flusse zustande kommt und aufrecht erhalten wird. Würde das vorher ruhende Wasser eines Flußlaufes durch Anbringen eines gleichmäßig verteilten beschleunigenden Kraftimpulses plötzlich in Bewegung gesetzt, so würde die Verteilung der Geschwindigkeit über den Querdurchschnitt zunächst eine gleichmäßige sein. Erst allmählich würde sich durch den Einfluß der Wandreibung eine Geschwindigkeitsverteilung herstellen, bei welcher die Geschwindigkeit von den Wandungen aus nach dem Innern des Strömungsquerschnittes hin allmählich zunimmt. Eine Störung dieser (im groben Mittel) stationären Geschwindigkeitsverteilung über den Querschnitt würde sich (unter dem Einfluß der Flüssigkeitsreibung) nur langsam wieder ausgleichen. Die Hydrodynamik veranschaulicht den Vorgang der Einstellung jener

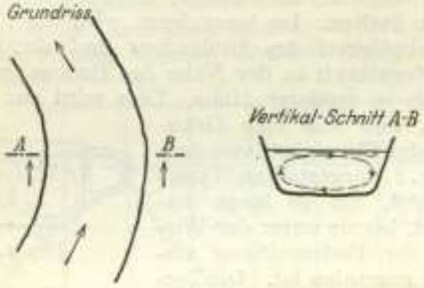


Fig. 2.

stationären Geschwindigkeitsverteilung in folgender Weise. Bei gleichmäßiger Strömungsverteilung (Potential-Strömung) sind alle Wirbelfäden an der Wandung konzentriert. Sie lösen sich los und bewegen sich langsam gegen das Innere des Flüssigkeitsquerschnittes vor, indem sie sich auf eine Schicht wachsender Dicke verteilen. Dabei nimmt das Geschwindigkeitsgefälle an der Wandung langsam ab. Unter der Wirkung der inneren Reibung der Flüssigkeit werden die Wirbelfäden im Innern des Flüssigkeitsquerschnittes langsam aufgezehrt und durch solche ersetzt, welche sich an der Wand neu bilden. So entsteht eine quasistationäre Geschwindigkeitsverteilung. Wesentlich für uns ist es, daß der Ausgleich der Geschwindigkeitsverteilung zur stationären Geschwindigkeitsverteilung hin ein langsamer Prozeß ist. Hierauf beruht es, daß bereits relativ geringfügige, stetig wirkende Ursachen die Verteilung der Geschwindigkeit über den Querschnitt erheblich zu beeinflussen vermögen.

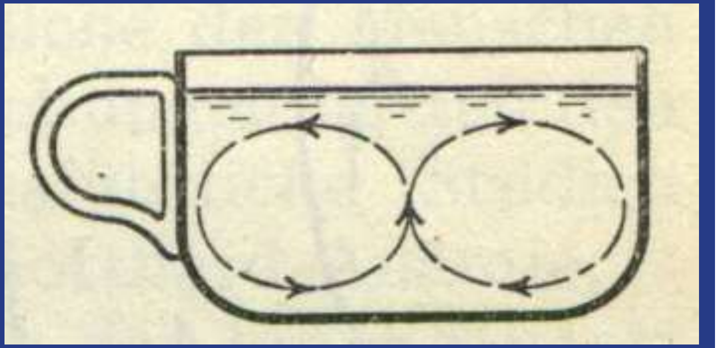
Nun überlegen wir, was für einen Einfluß die durch eine Flußbiegung oder durch die Corioliskraft bewirkte, in Fig. 2 dargestellte Zirkulationsbewegung, auf die Geschwindigkeitsverteilung über den Flußquerschnitt haben muß. Die am raschesten bewegten Flüssigkeitsteilchen werden am weitesten von den Wandungen entfernt sein, also sich im oberen Teile über der Bodenmitte befinden. Diese raschesten Teile der Flüssigkeit werden durch die Zirkulation zur rechten Seitenwandung getrieben, während umgekehrt die linke Seitenwandung Wasser erhält, welches aus der Gegend nahe dem Boden stammt und eine besonders kleine Geschwindigkeit hat. Deshalb muß auf der rechten Seite (im Falle der Fig. 2) die Erosion stärker sein als auf der linken Seite. Man beachte, daß diese Erklärung wesentlich darauf beruht, daß die langsame Zirkulationsbewegung des Wassers darum einen erheblichen Einfluß auf die Geschwindigkeitsverteilung hat, weil auch der dieser Folge der Zirkulationsbewegung entgegenwirkende Ausgleichsvorgang der Geschwindigkeiten durch innere Reibung ein langsamer Vorgang ist.

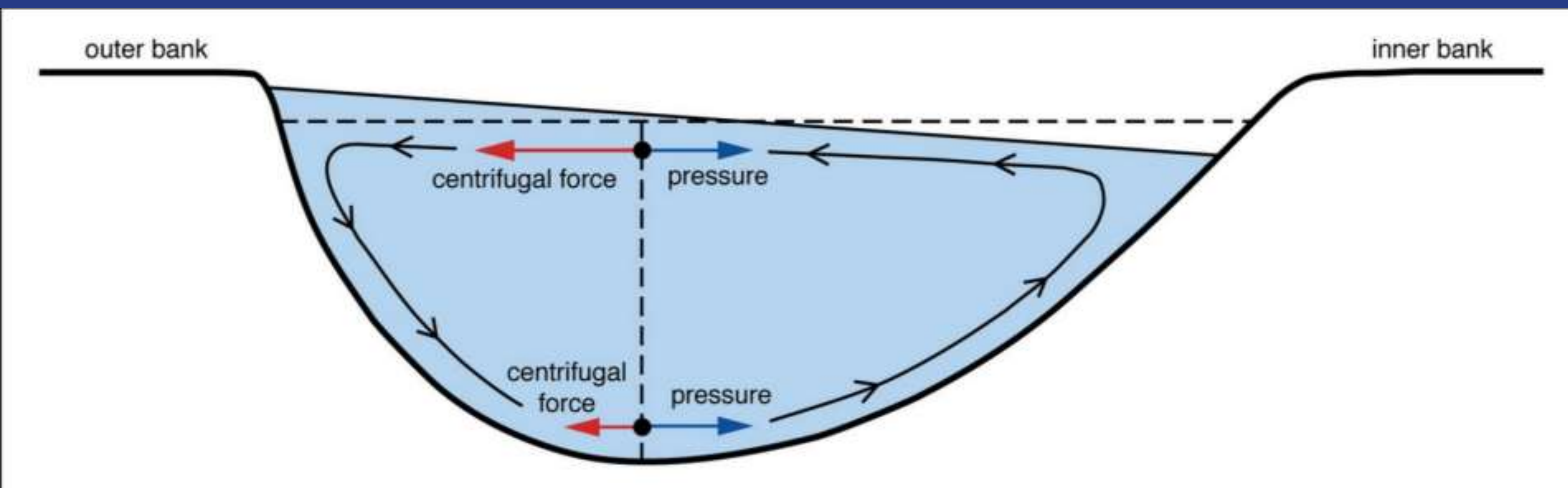
Damit haben wir die Ursache der Mäanderbildung aufgeklärt. Aber auch gewisse Einzelheiten lassen sich ohne Mühe folgern. Die Erosion wird nicht nur an der rechten Seitenwand, sondern auch noch auf dem rechten Teil des Bodens verhältnismäßig groß sein müssen, so daß die Neigung bestehen wird, ein Profil von der in Fig. 3 angegebenen Gestalt zu bilden. Ferner wird das Wasser an die Oberfläche von der linken Seitenwand geliefert werden, also (besonders auf der linken Seite) an der Oberfläche weniger rasch bewegt sein als das Wasser in

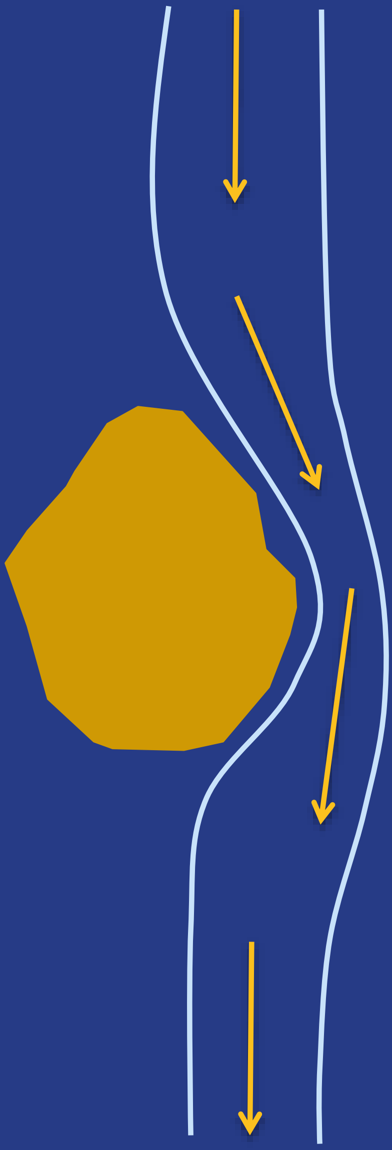
Fig. 3.

etwas größerer Tiefe; dies hat man tatsächlich beobachtet. Ferner ist zu beachten, daß die Zirkulationsbewegung Trägheit besitzt. Die Zirkulation wird also erst hinter der Stelle der größten Biegung ihren maximalen Betrag erlangen, ebenso natürlich die Asymmetrie der Erosion. Dadurch wird im Verlaufe der Erosionsbildung ein Vorschreiten der Wellenlinien der Mäanderbildung im Sinne der Strömung stattfinden müssen. Endlich wird die Zirkulationsbewegung desto langsamer durch Reibung aufgezehrt werden, je größer der Flußquerschnitt ist; es wird also die Wellenlänge der Mäanderbildung mit dem Flußquerschnitt wachsen.

For an English translation of this paper go to http://people.ucalgary.ca/~kmuldrew/river.html




outer bank
inner bank
centrifugal force
pressure
centrifugal
force
pressure



Any obstacle on the course of a stream may deflect it and cause a bend. Then, Einstein’s mechanism will accentuate that bend.

Einstein pointed out that even without any obstruction on its course a river would begin meandering because of Baer’s law.

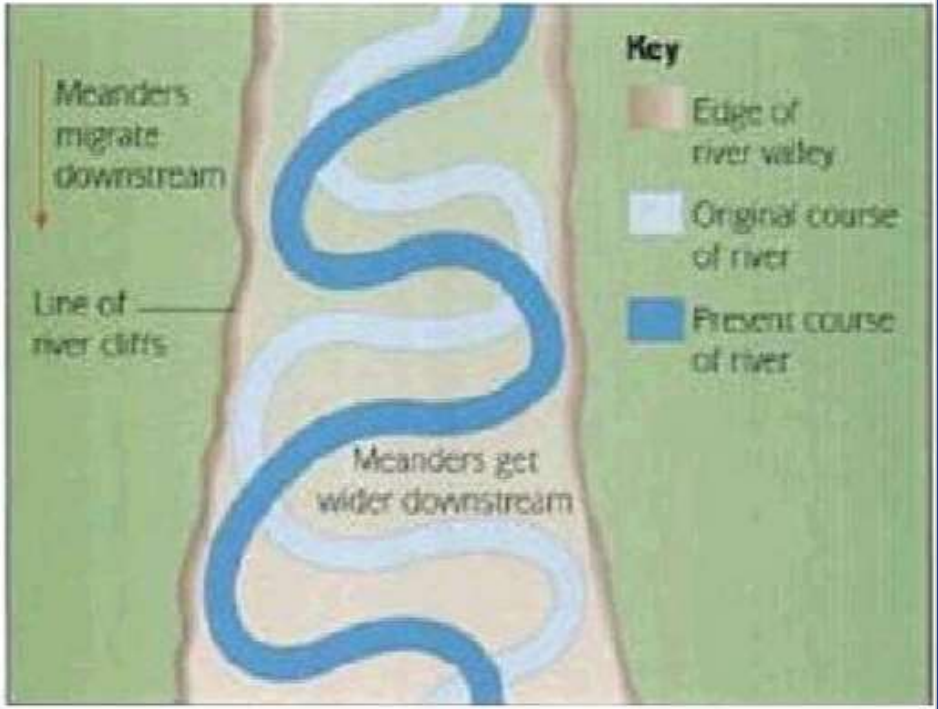
Karl Ernst von Baer’s law states that rivers flowing north in the northern hemisphere will erode their right banks more than their left banks because of the Coriolis force. For the rivers flowing south in the southern hemisphere , the opposite will be true.

Meander Migration

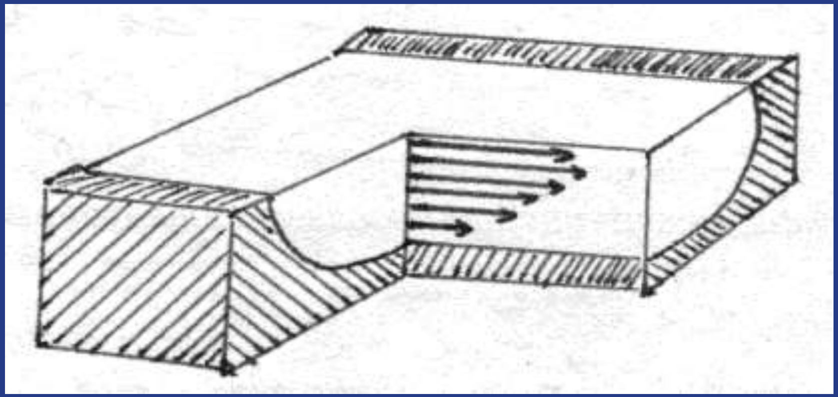
- River flows downstream becoming deeper and wider

- Deposition builds up the deposits of alluvium to create a valley floor

- This creates a line of river cliffs along the edge of the valley floor.

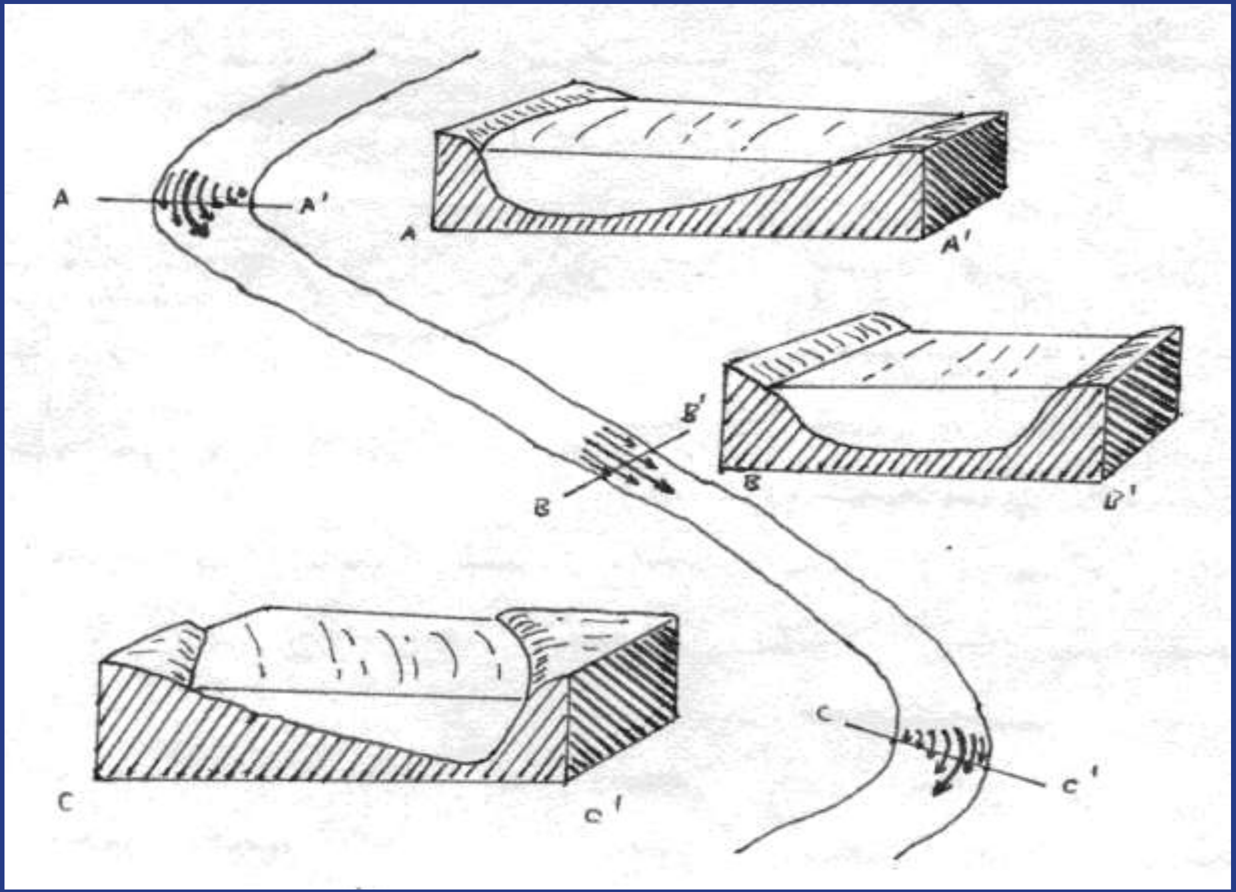


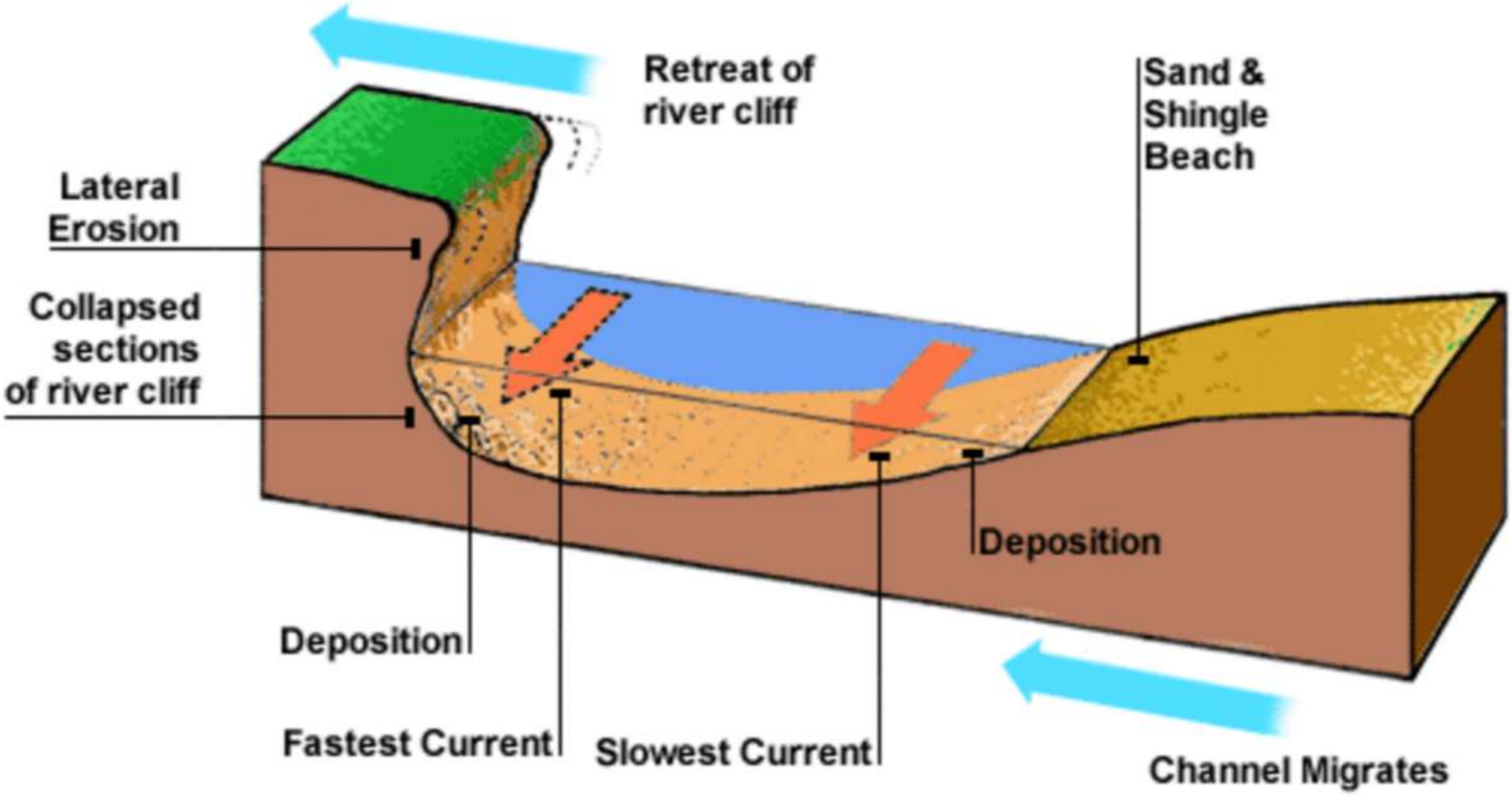
Einstein also pointed out that because of the inertia of the flowing water, the maximum erosion around a bend will always be just beyond the maximum bend downstream. That will cause the meanders to migrate downstream.



Velocity distribution in a river channel. Velocites drop near the walls and the bottom because of friction. Some tiny drop in velocity also occurs at the very top because of friction with air.

At bends, velocities are always higher at the concave side than at the convex side. That leads to erosion of the concave side and deposition at the convex side.

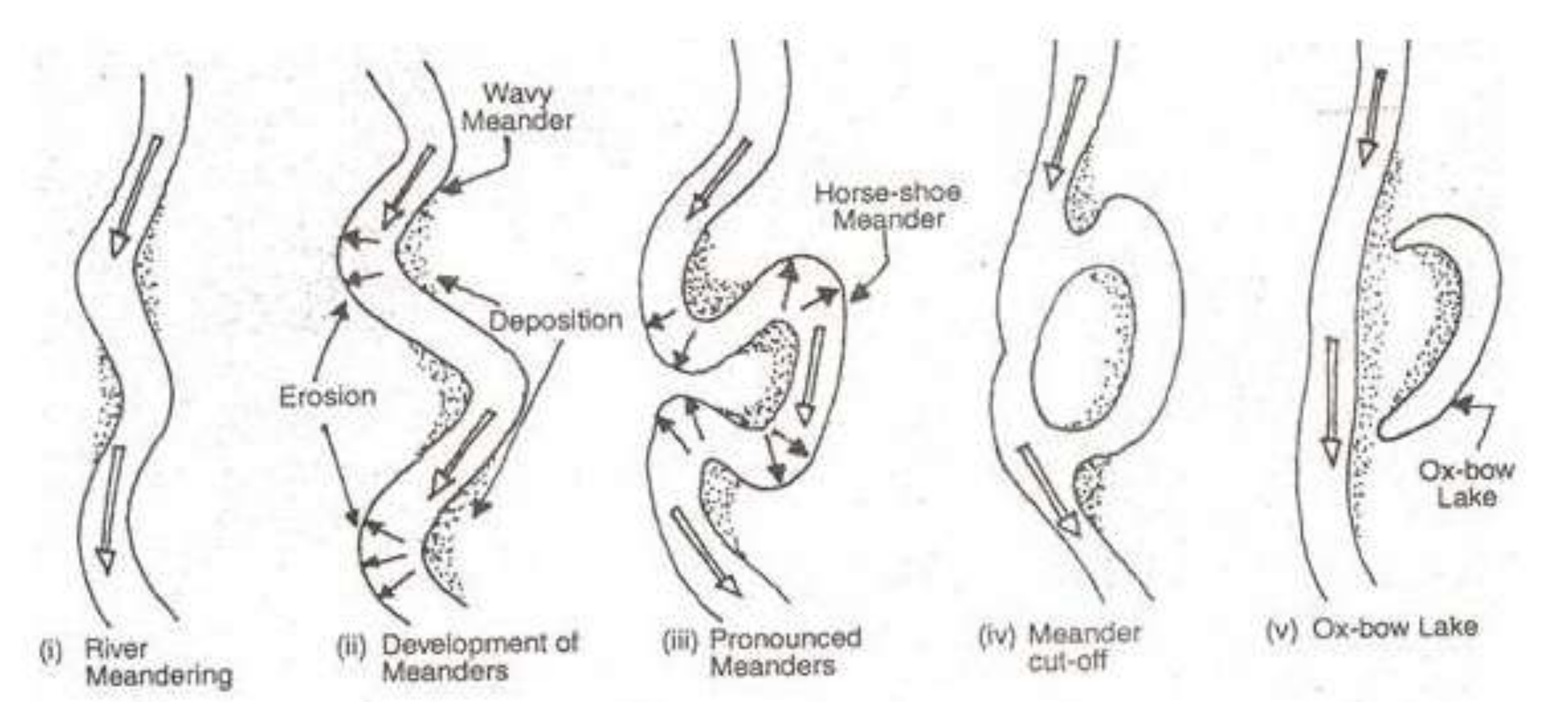




CONCAVE SIDE

CONVEX SIDE

Erosion and deposition in river meanders



One result of erosion of the concave sides and deposition at convex sides in meanders is the formation of ox-bow lakes as shown above.

A meandering river with abandoned channels and ox-bow lakes, Western Siberia, Russia

Erosion, deposition and channel migration in a meandering river, Western Siberia, Russia

Meandering river with ox-bow lakes, Western Siberia, Russia.

Meandering river, Bulgaria

Meandering river in a dry climate: western Mongolia

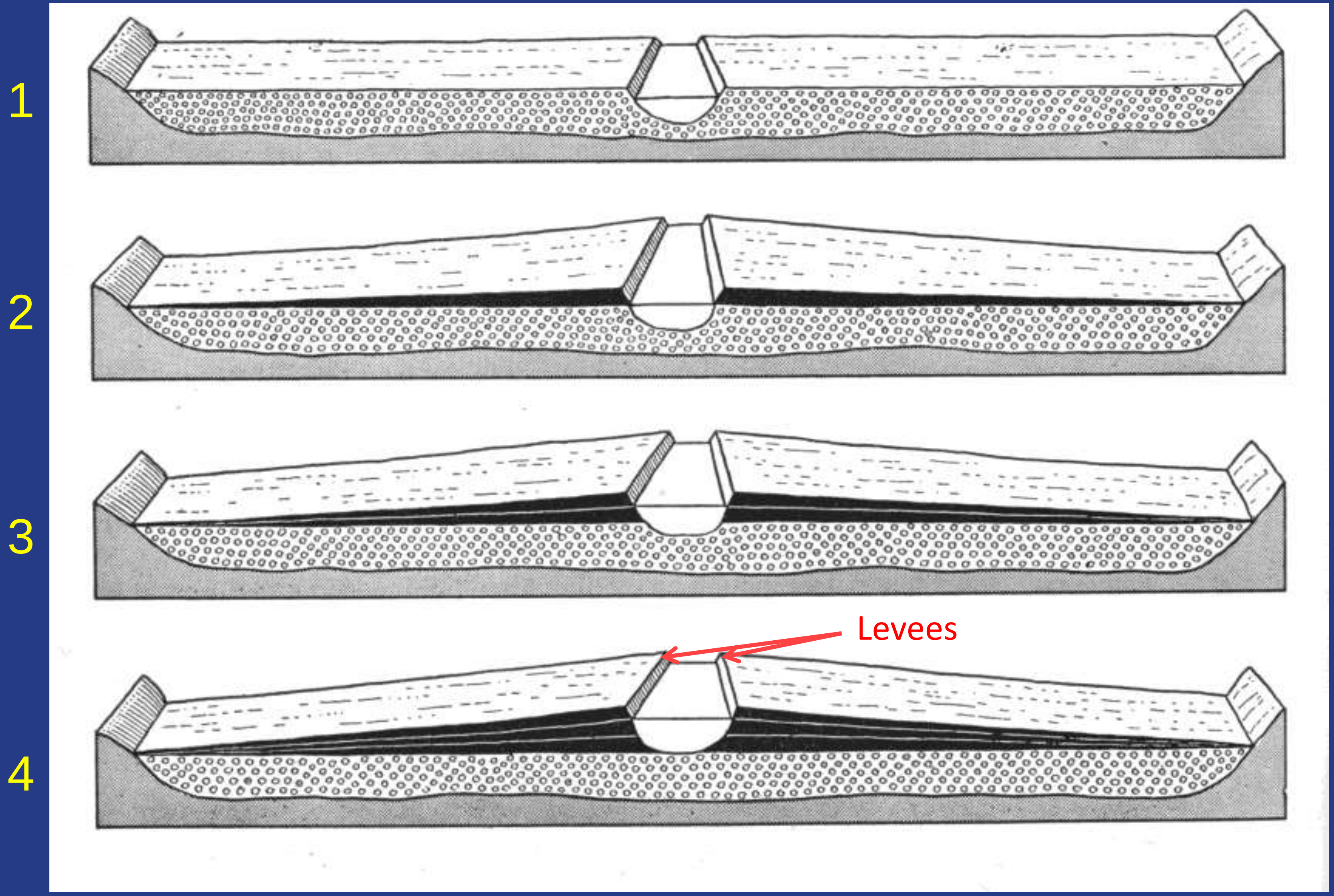
Meandering river, western Mongolia

A close-up of the last view

Channel migration in evolving meanders: western Mongolia

Flood plain of a meandering river in western Mongolia

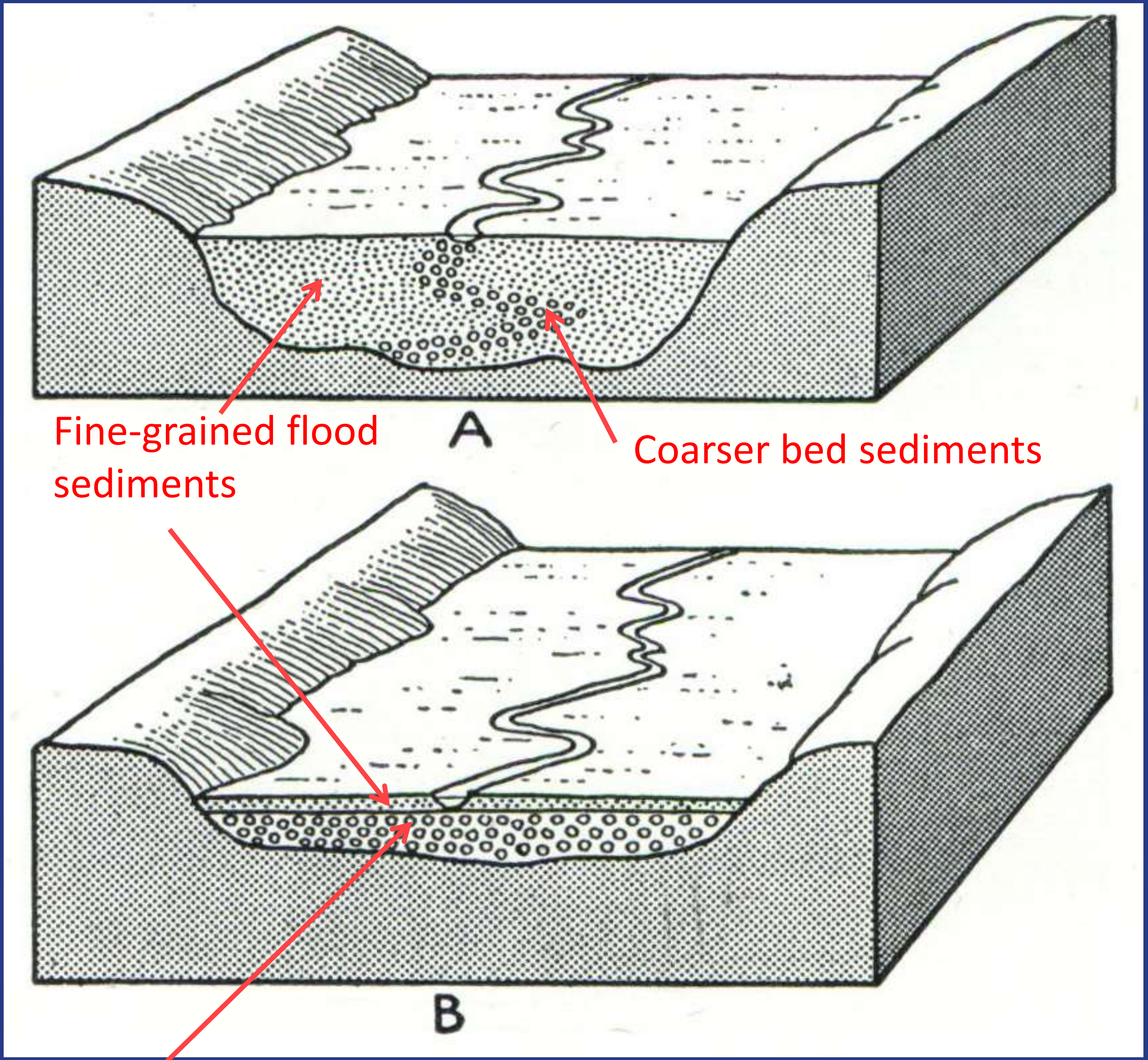
Flood plain of a meandering river in Germany



Aggradation of a flood plain and the origin of natural levees

Fast aggrading flood plain

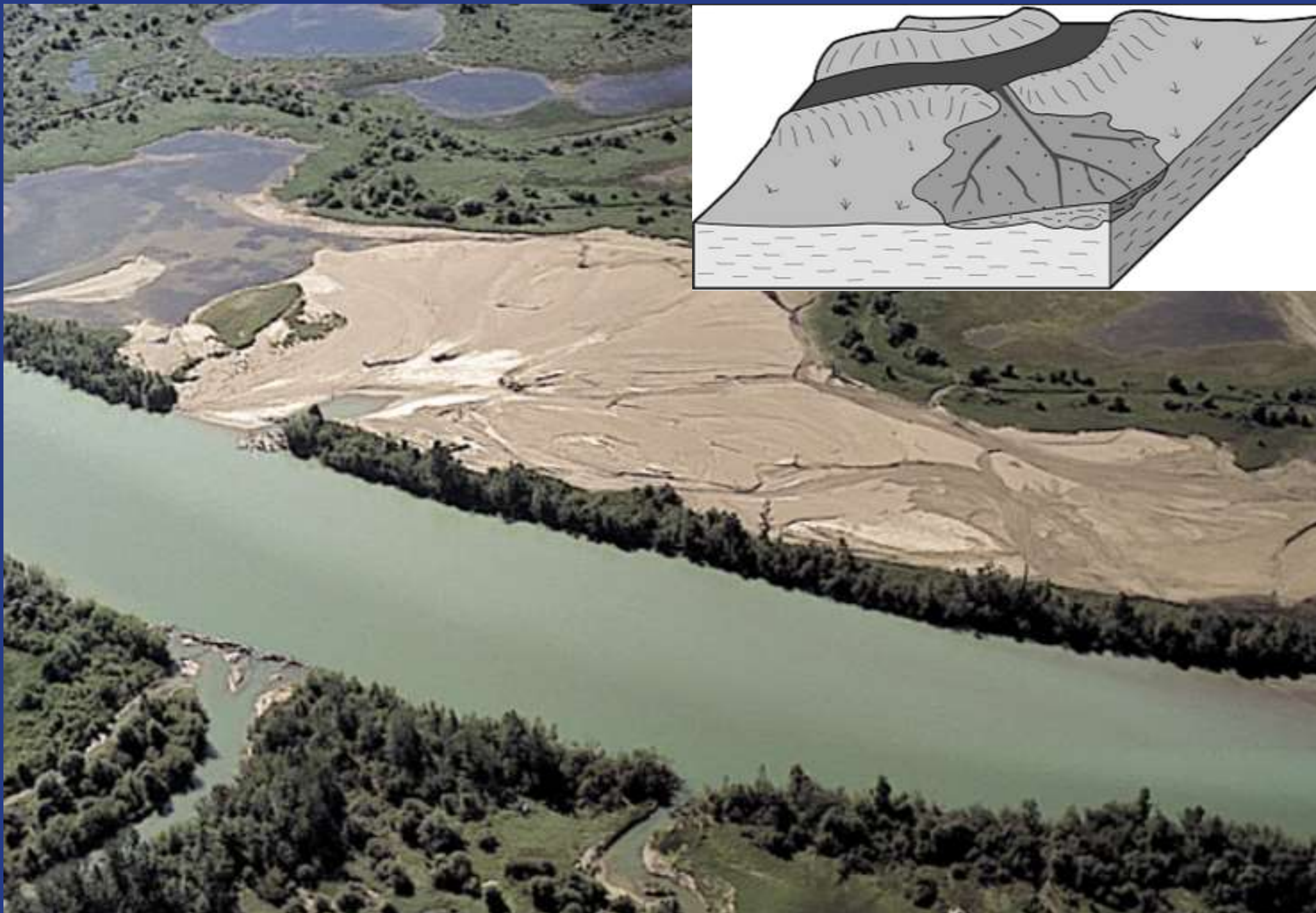
Slowly aggrading or erosional flood plain



Coarser bed sediments distributed across the entire flood plain (because the river has more time to wander)

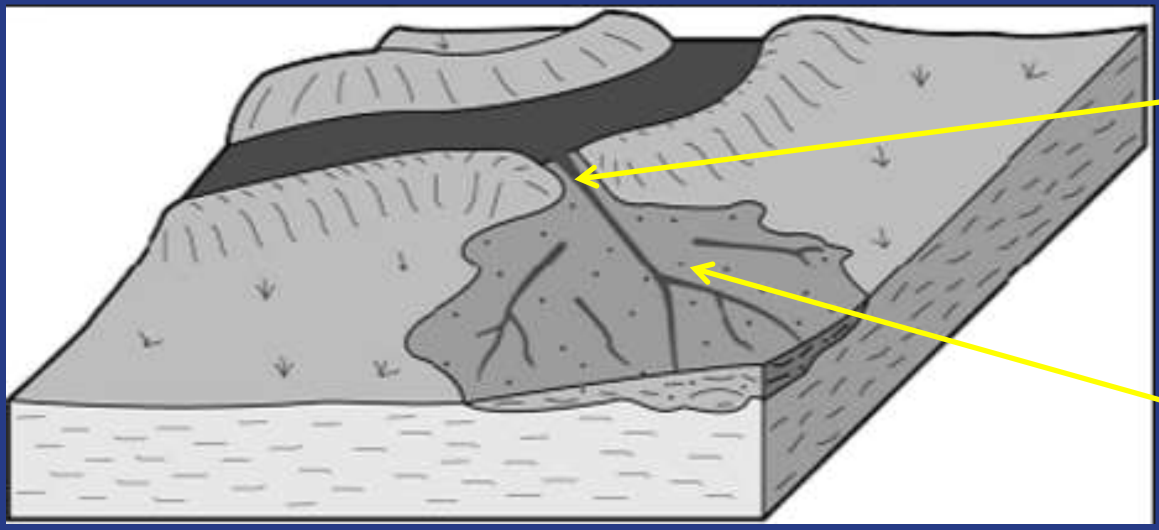
From Leet and Judson 1958

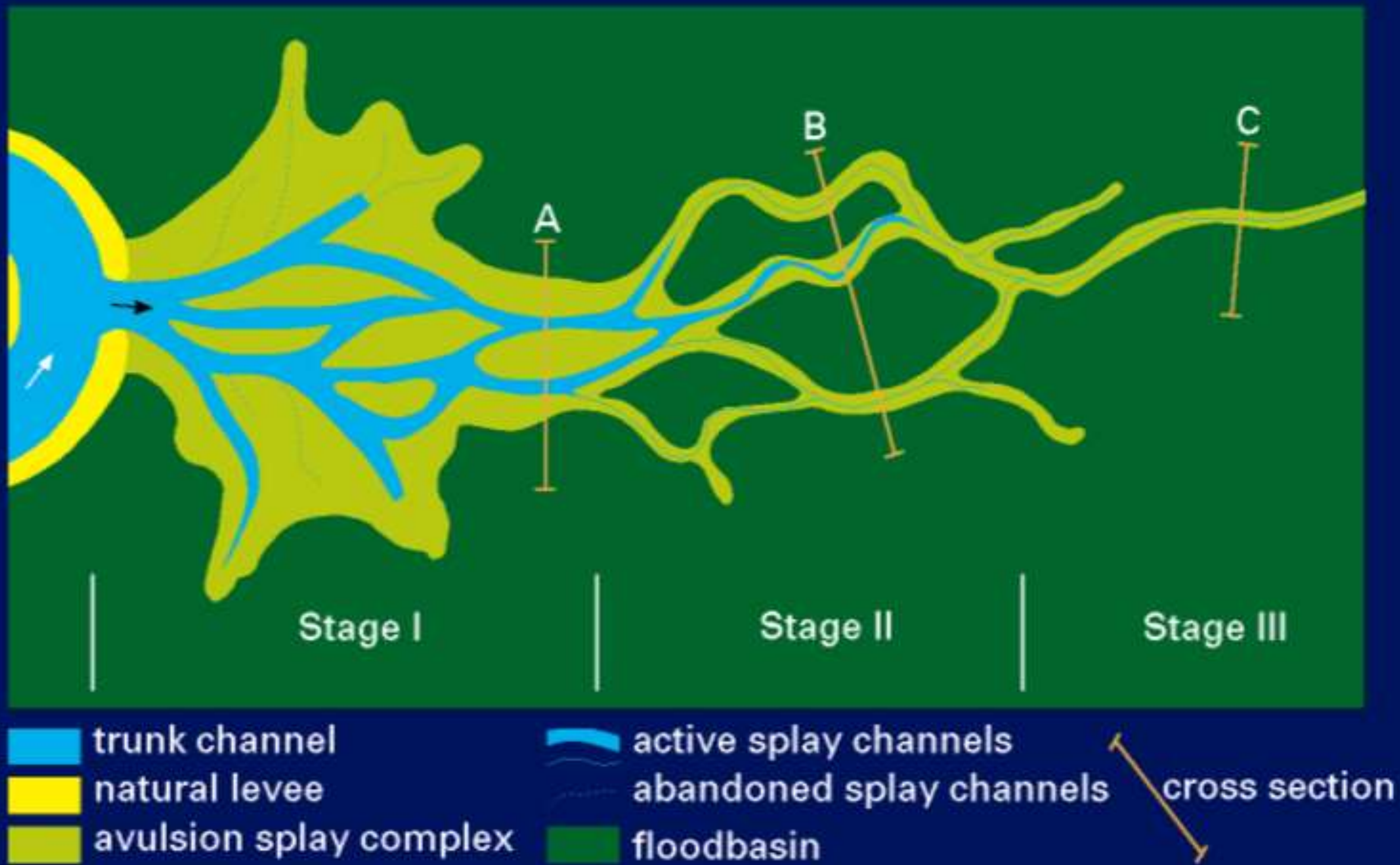
What happens when the stream breaks a levee?



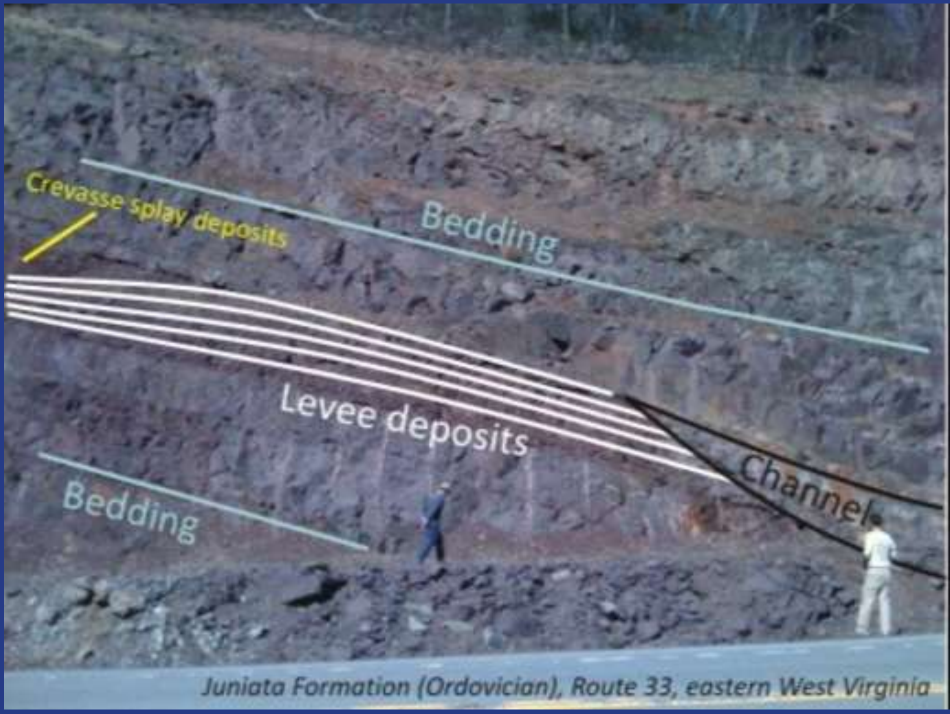
When a levee breaks or is overtopped, splay deposits form. Splay in English means thrust or spread (like spreading one's fingers). If the levee is broken one speaks of crevasse splay deposits. Splay deposits resemble other river deposits and can create graded sequences.

When a break ("crevasse") in a levee causes the entire river to change its course it is called an "avulsion". Avulsion in English simply means pulling or tearing away.

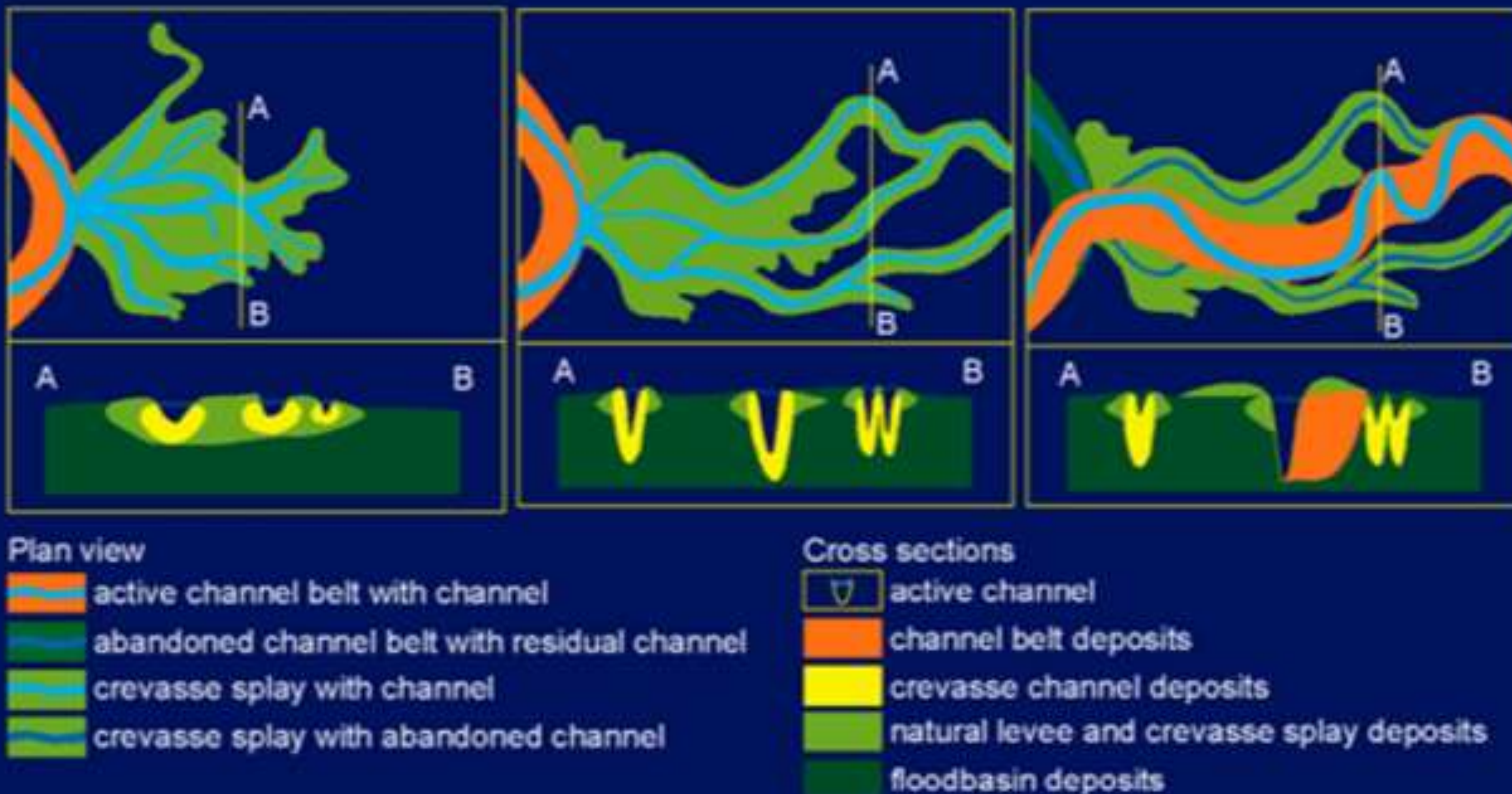




Formation of a crevasse complex and an avulsion belt (after Smith 1989 and Makaske 1998)



This is what an overtopped levee and the splay deposits look like in the geological record



Proximal deposits associated with full avulsion

Map showing where the levees protecting the city broke under the pressure of the storm surge

Current-bedded sandstone forming splay deposits and burying an automobile in New Orleans! This gives us an idea how quickly splay deposits may form

In extreme floods, the entire flood plain can get flooded. Here only the levees are sticking out of the flood level!

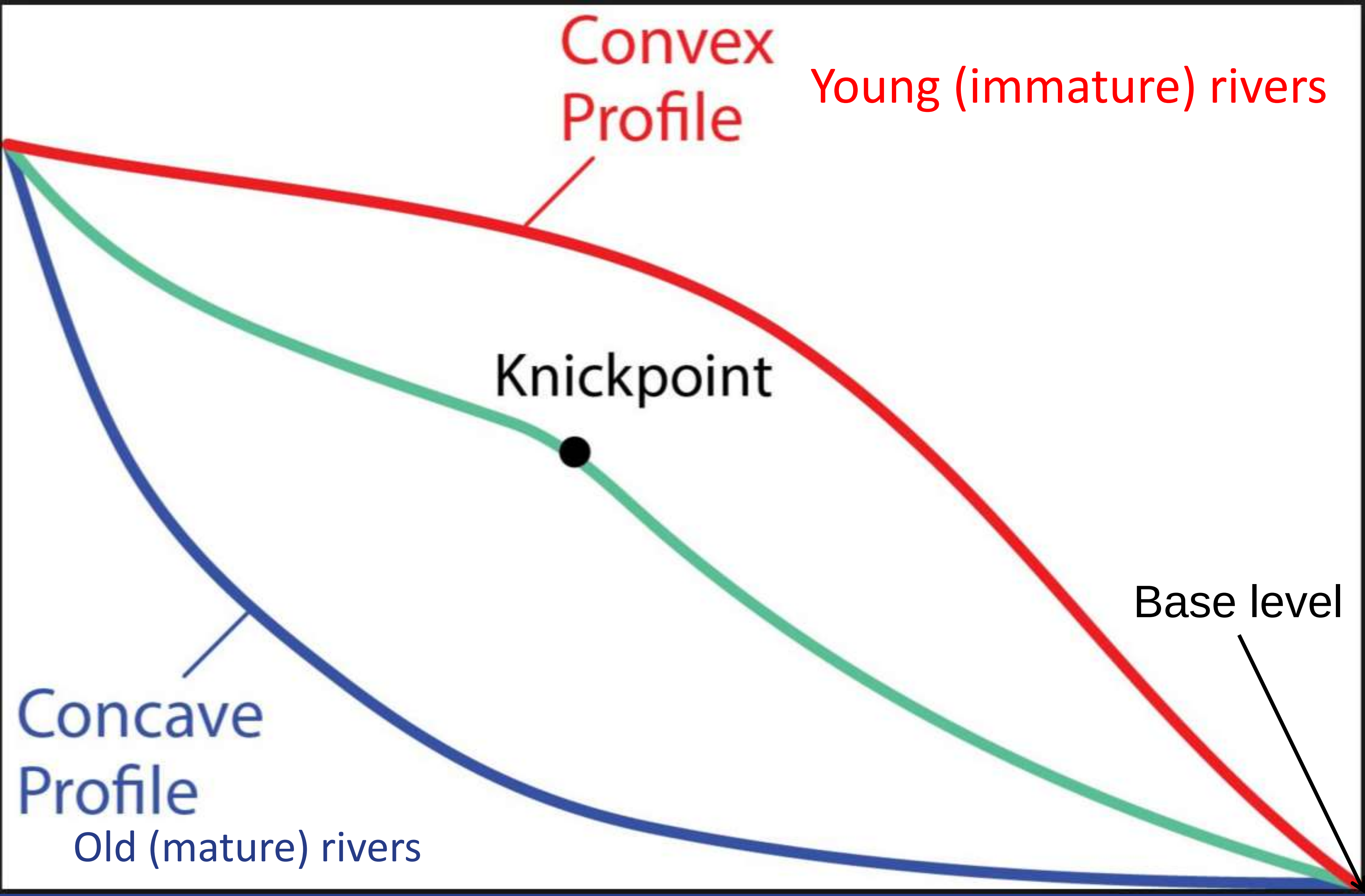
All rivers eventually reach a base level and disappear. Base levels may be

1. Temporary

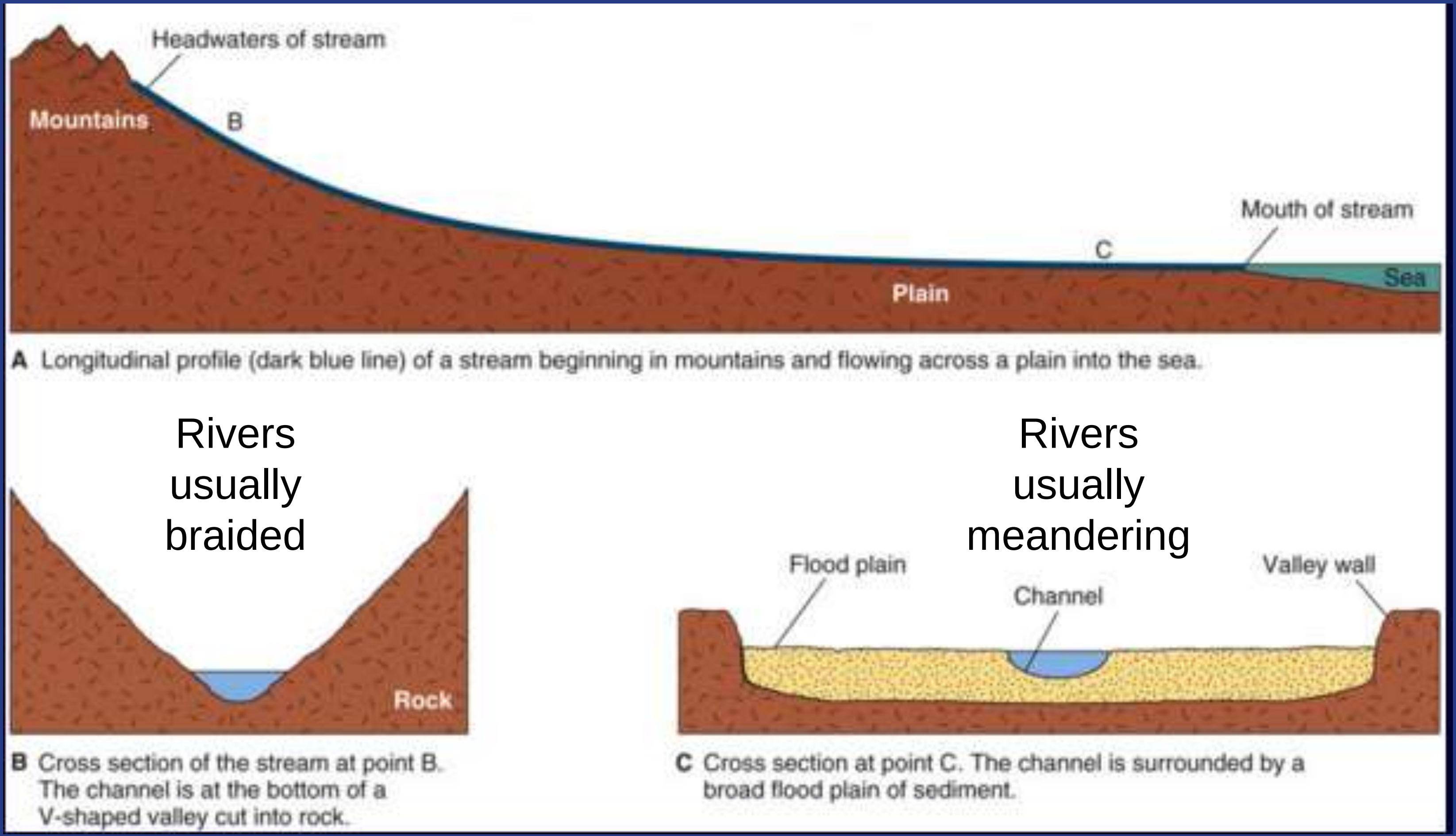
2. Permanent (or "ultimate")

Temporary base levels may be another river into which the river in question empties, or it may be a lake, or a place where the river simply evaporates away (in deserts).

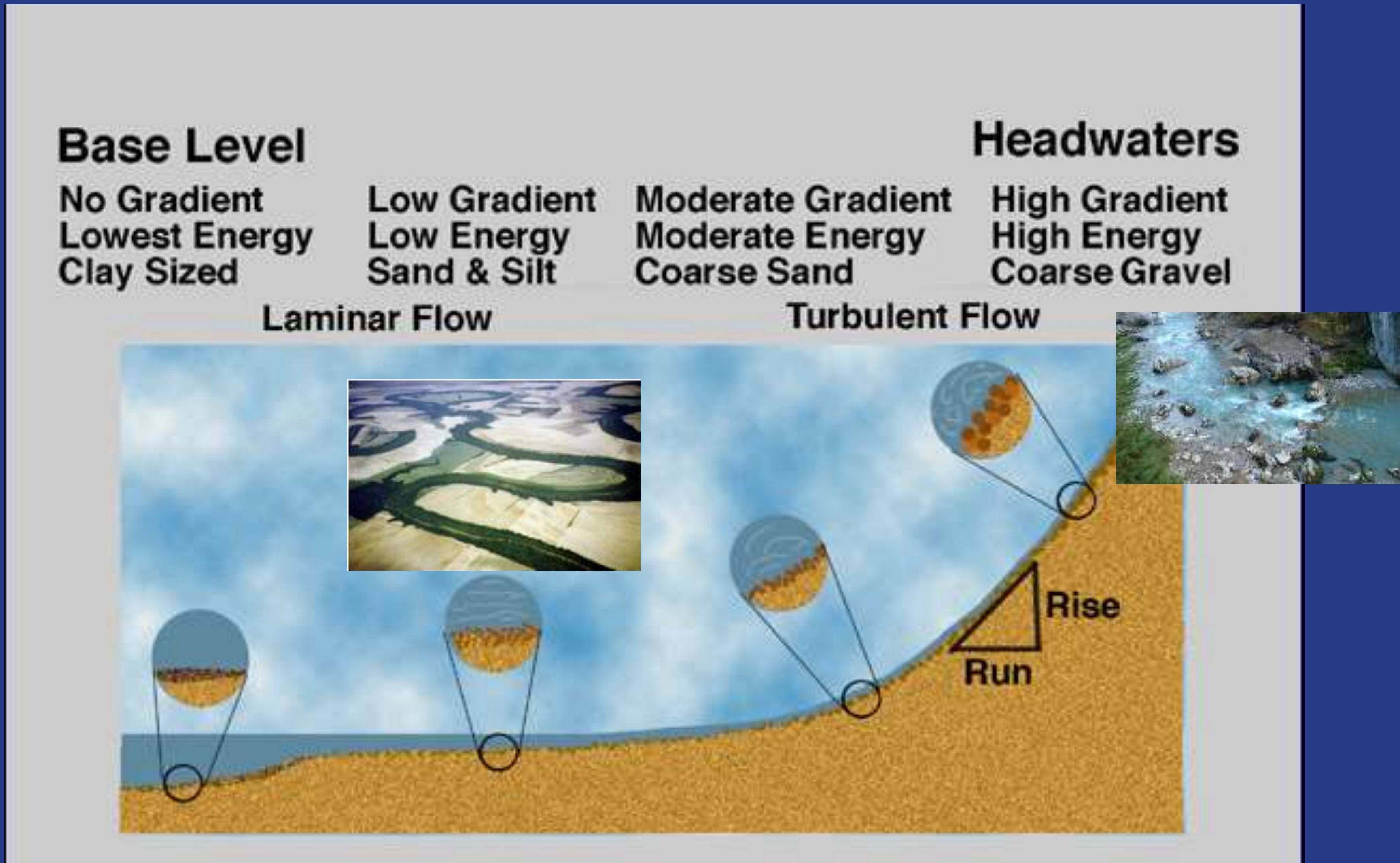
The permanent (or "ultimate") base level is the sea-level.



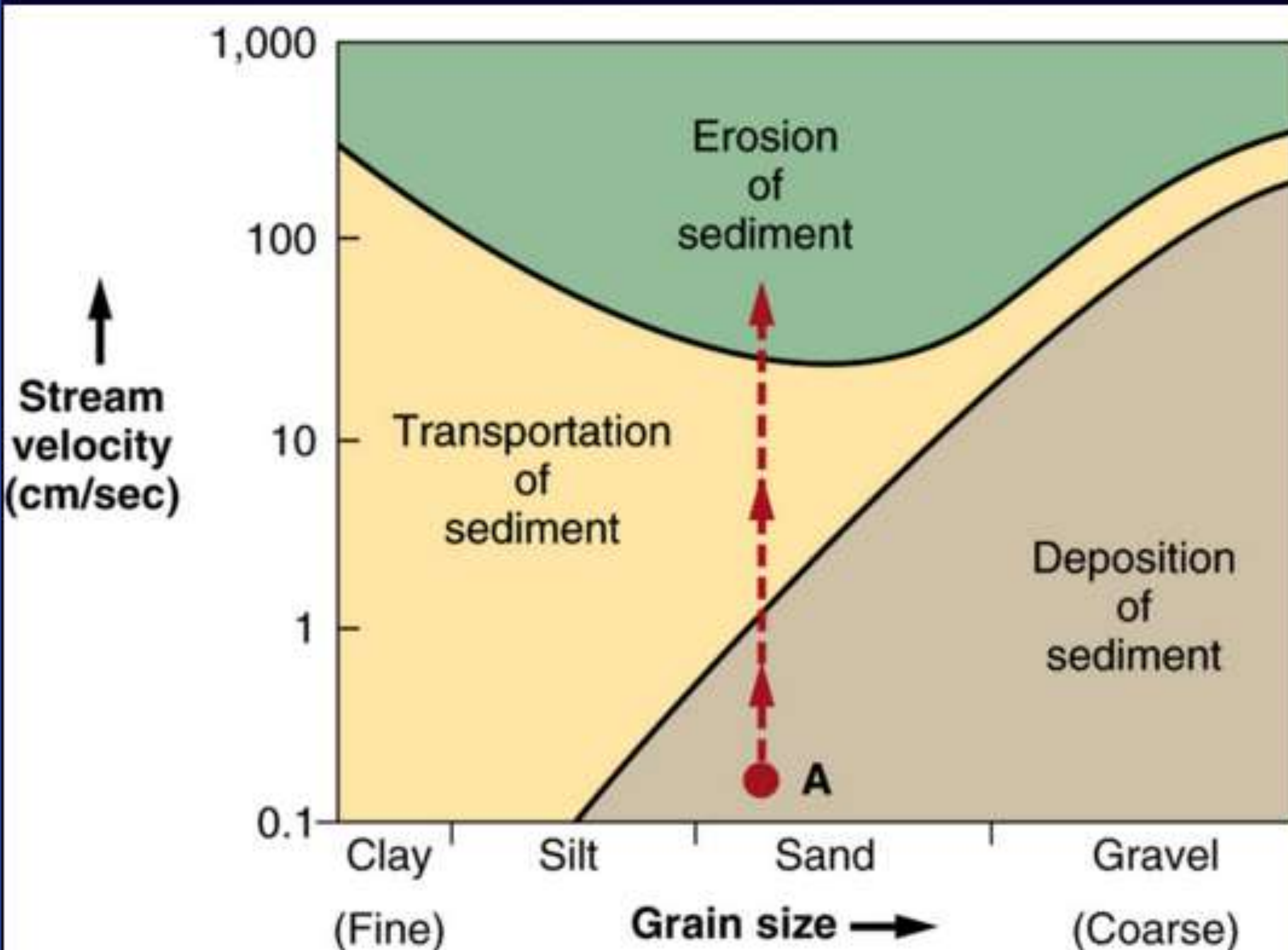
Evolution of river profiles

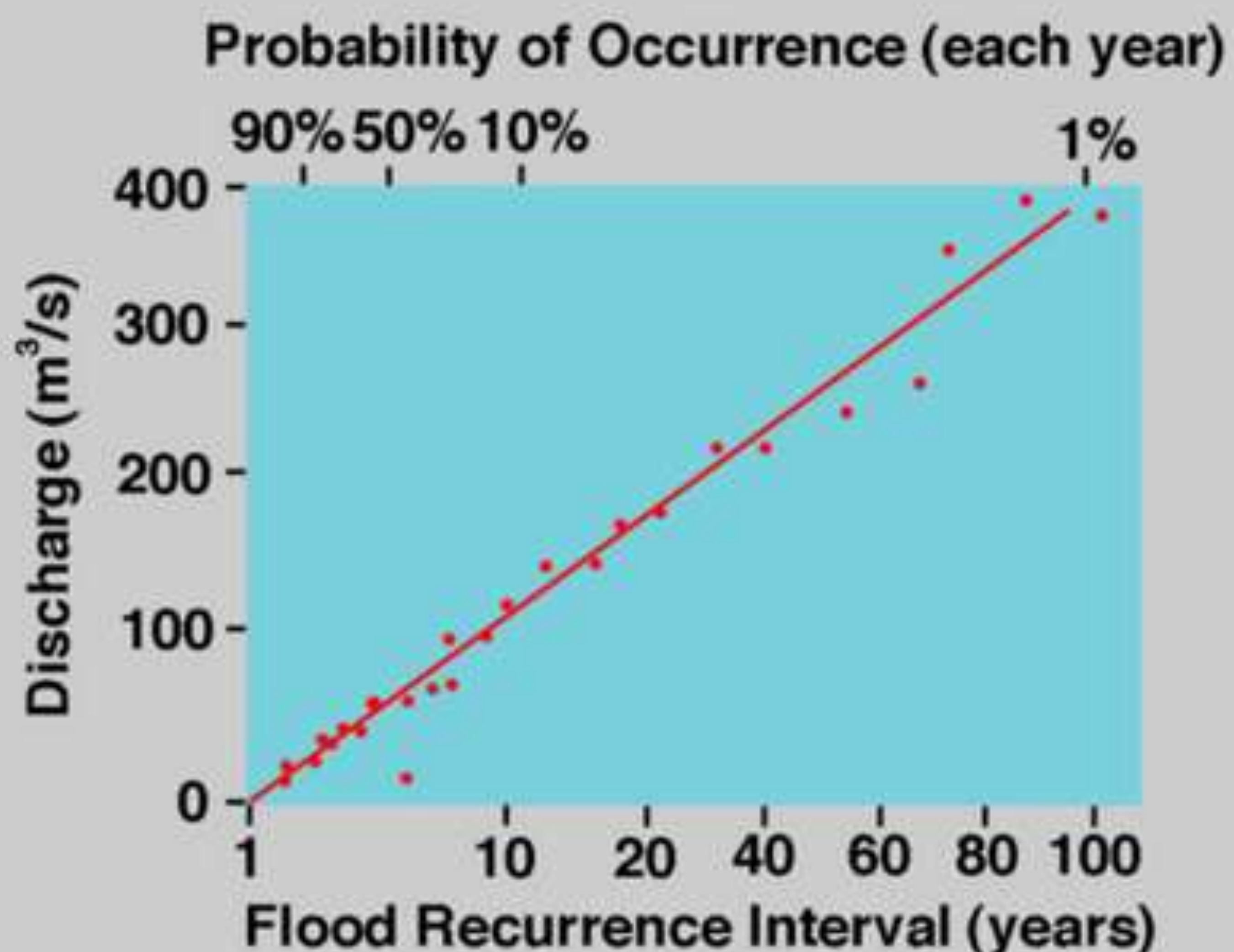


Equilibrium profile of a river and the corresponding valley shapes



Gravel	Larger than 2 mm	Coarse
Sand	0.05 - 2 mm	Gritty
Silt	0.002 - 0.05 mm	Floury
Clay	Smaller than 0.002 mm	Sticky when wet


1,000
100
10
1
0.1
Stream velocity (cm/sec)
Erosion of sediment
Transportation of sediment
Deposition of sediment
A
Clay
Silt
Sand
Gravel
(Fine)
Grain size
(Coarse)


Probability of Occurrence (each year)
90% 50% 10% 1%
Discharge (m^3/s)
400
300
200
100
0
1 10 20 40 60 80 100
Flood Recurrence Interval (years)

What happens if the base level changes?

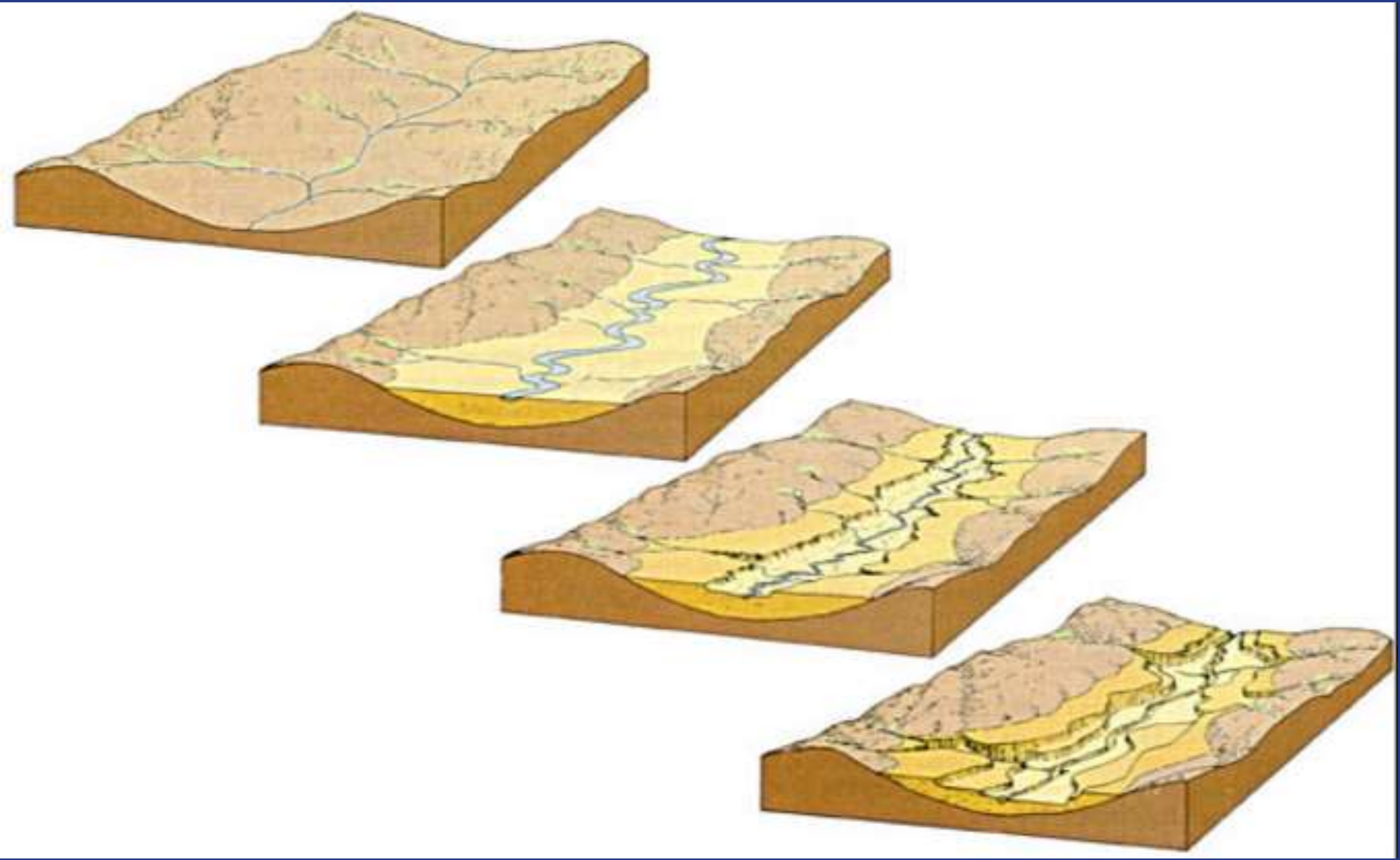
1. Temporary base levels may change because:

a. The river forming the base level may cut its channel deeper and its surface elevation changes or its meandering may cause the tributary to change its base

b. The lake forming the base level may evaporate or shift

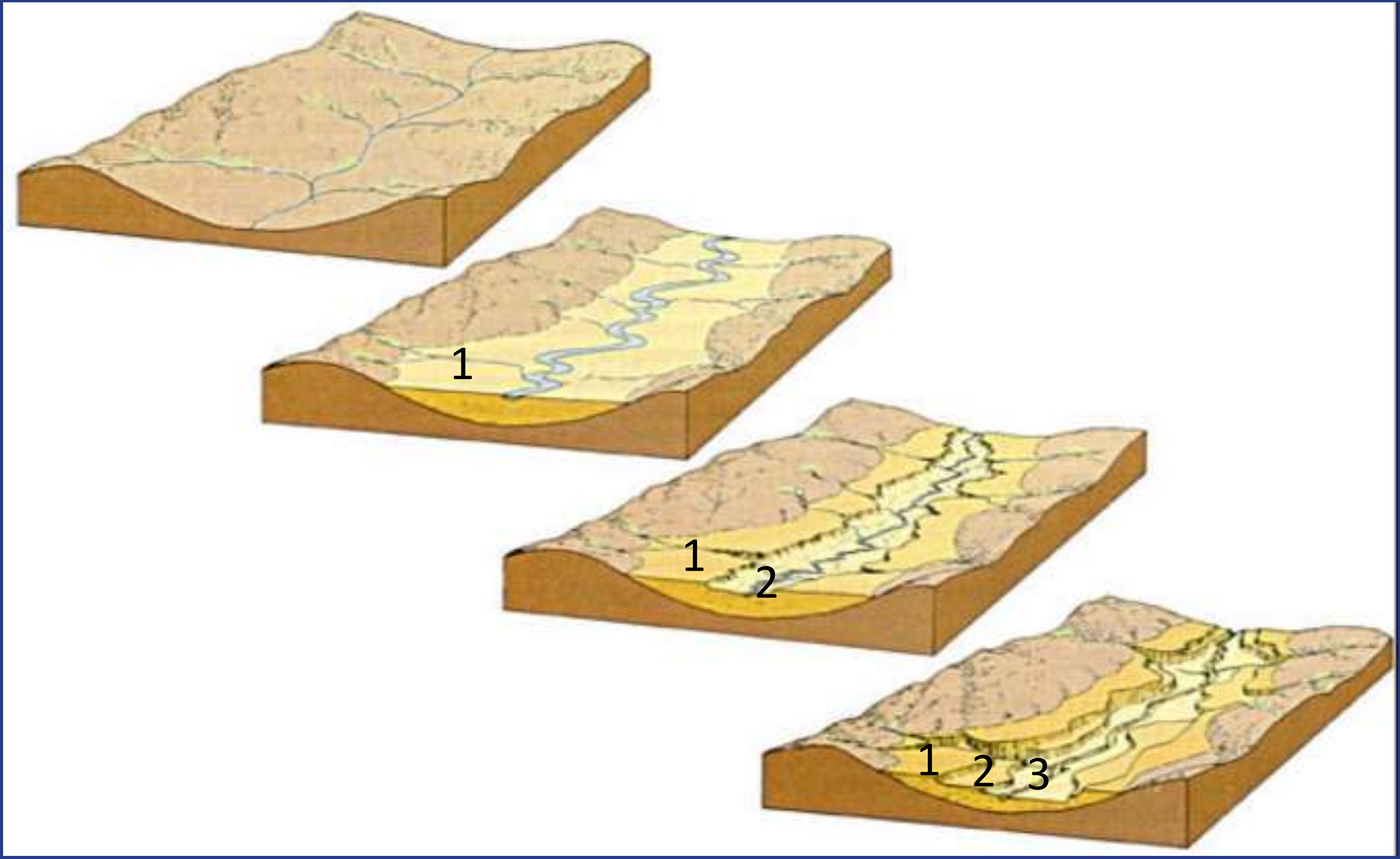
c. The ground forming the base level may be faulted down or up

2. Permanent base level may change because of sea-level changes caused by eustatic changes or by upheavals or depressions of land.

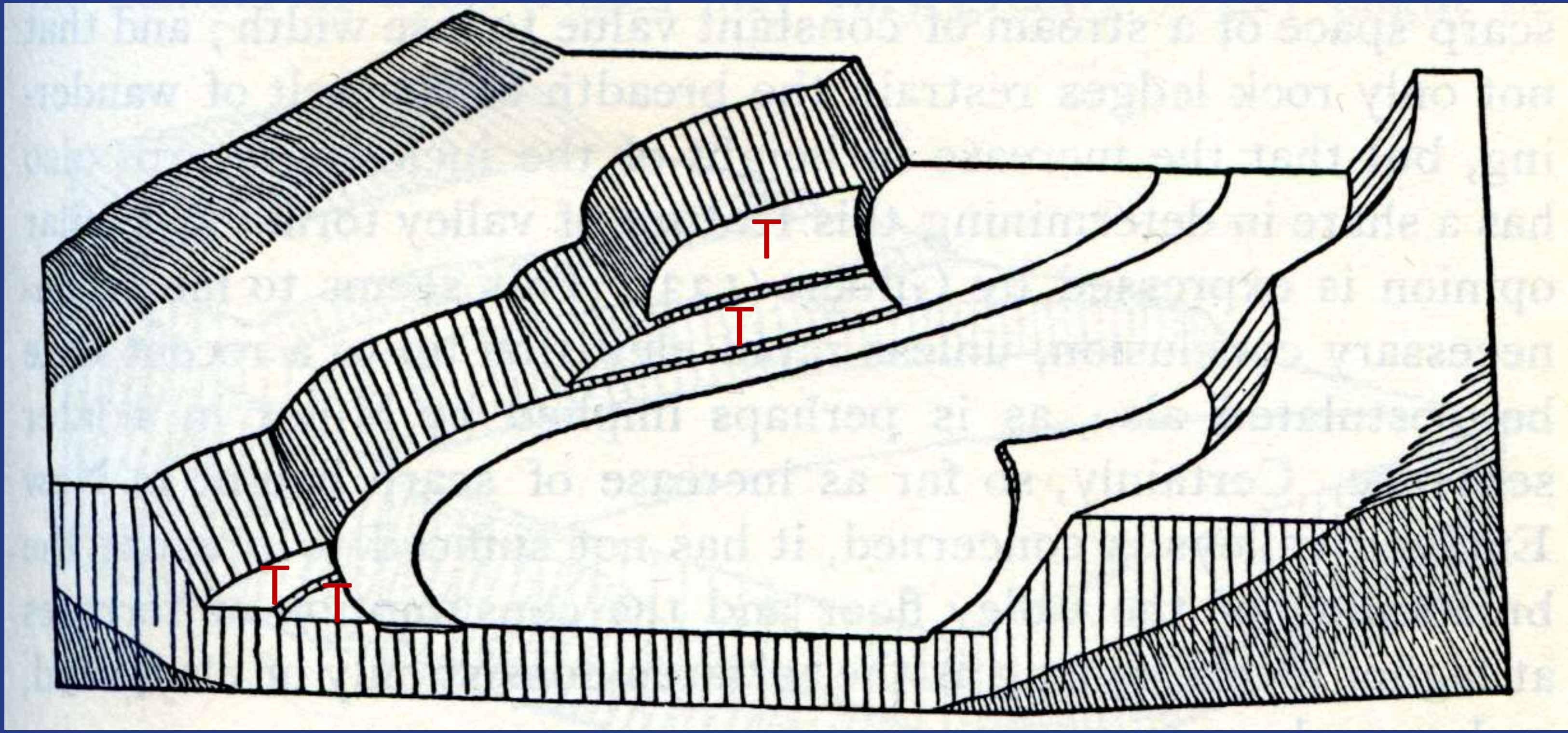


As the temporary (or “local”) base level deepens because of the downcuttinhg of the main river, the tributary base levels drop.

Four former levels of flood plains. They now appear in the form of "river terraces"

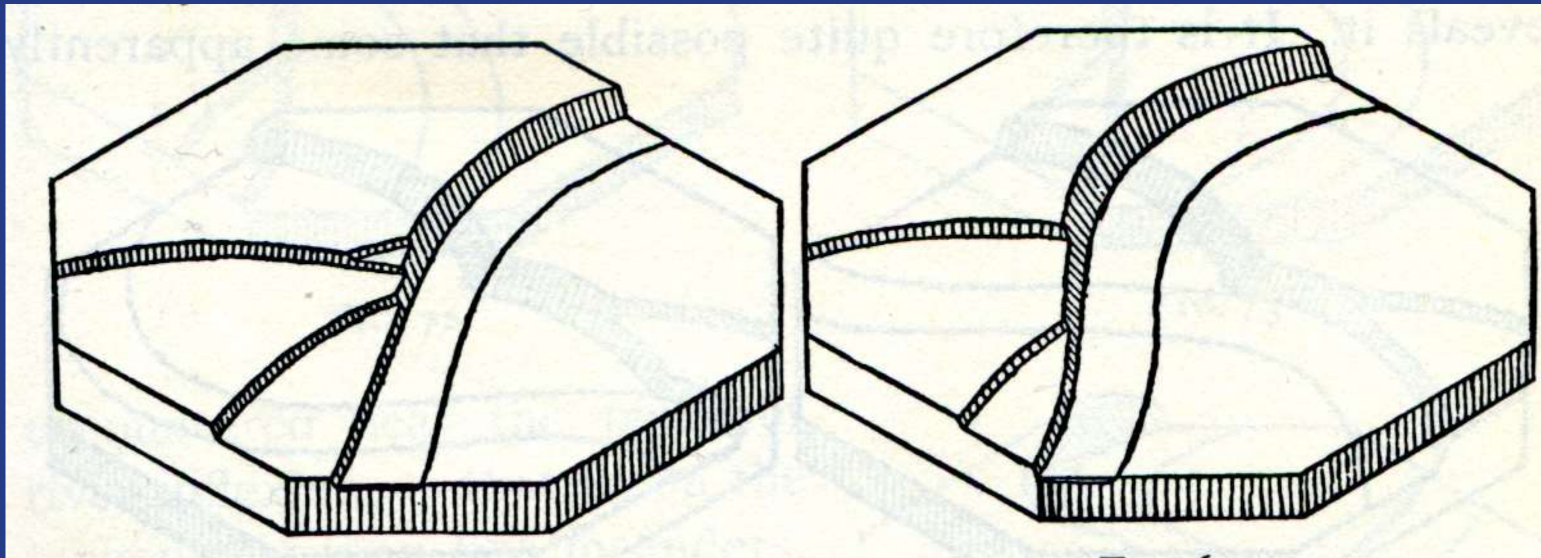


Relative ages of terraces: the higher a terrace, the older it is.

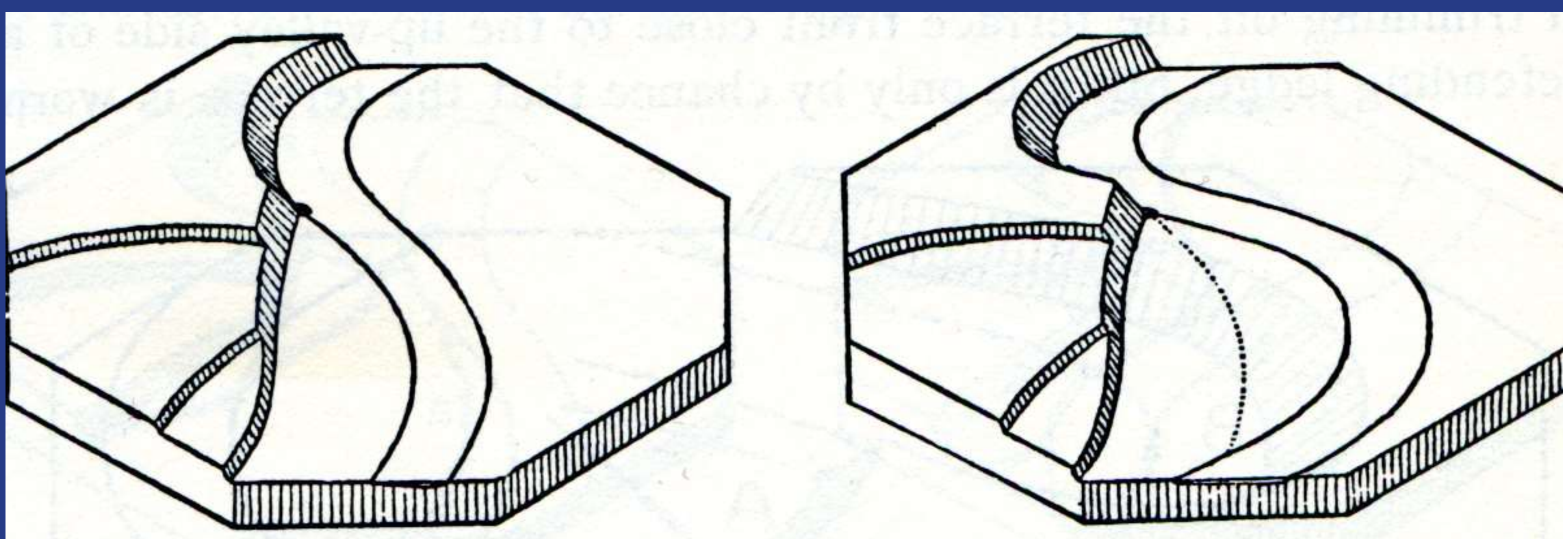


Terraces (T) caused by meandering of the main river

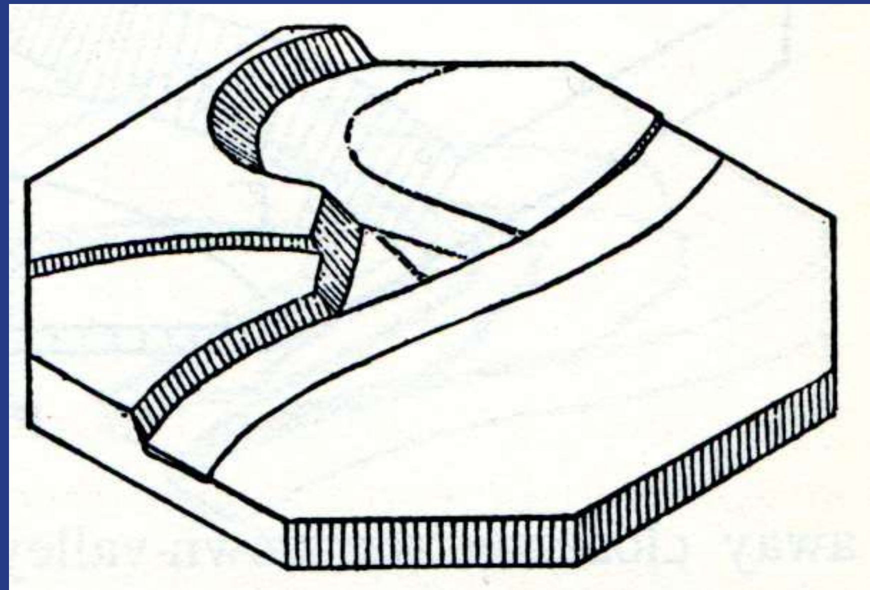
1



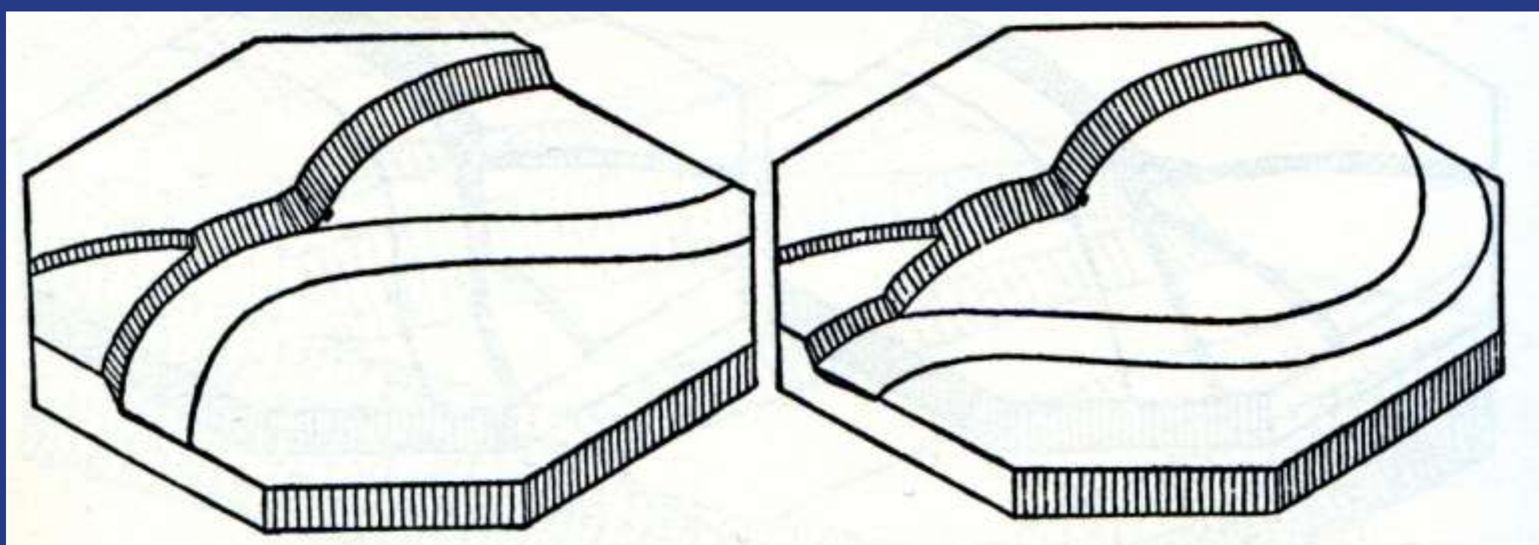
2

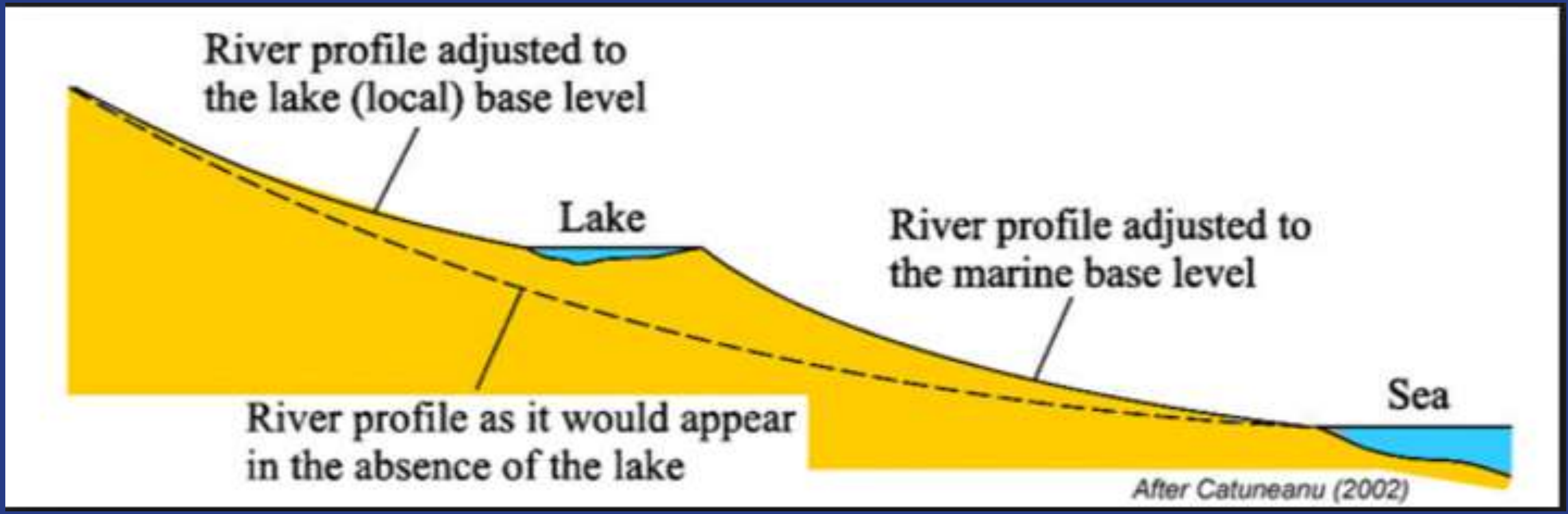


3



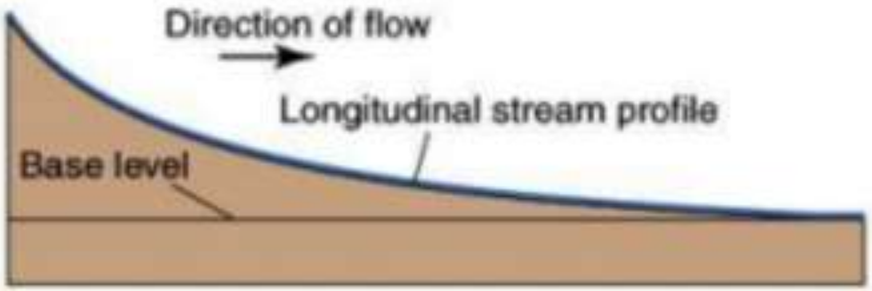
4



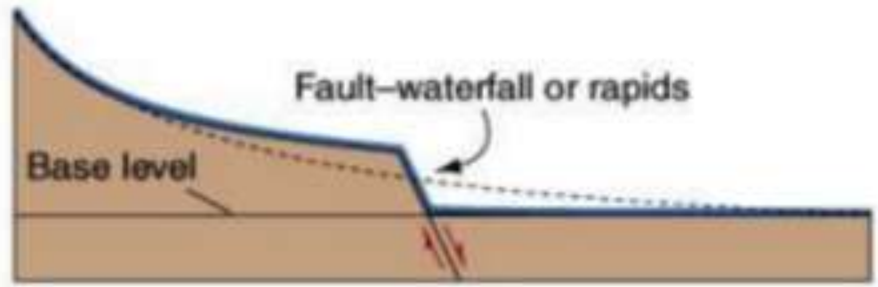


The lake here forms a temporary or a local base level. If it disappears, the river will resume its job of seeking a new equilibrium profile according to the ultimate base level.

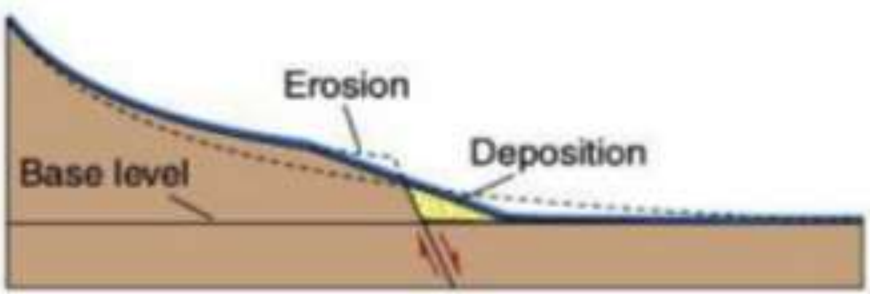
Graded Profile Changes



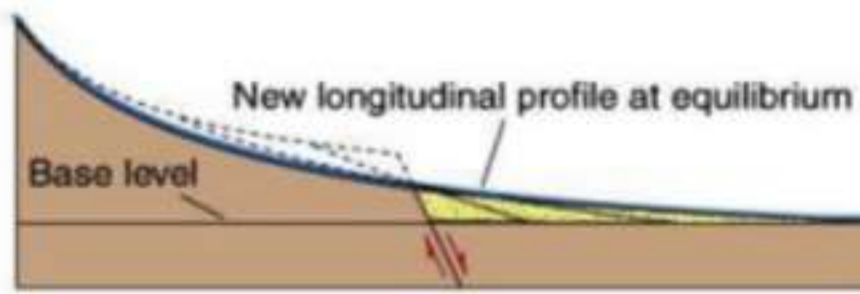
(A) Initially, when the stream profile is at equilibrium, the velocity, load, gradient, and volume of water are in balance. Neither erosion nor deposition occurs.



(B) Faulting disrupts equilibrium by decreasing the gradient downstream and increasing the gradient at the fault line.

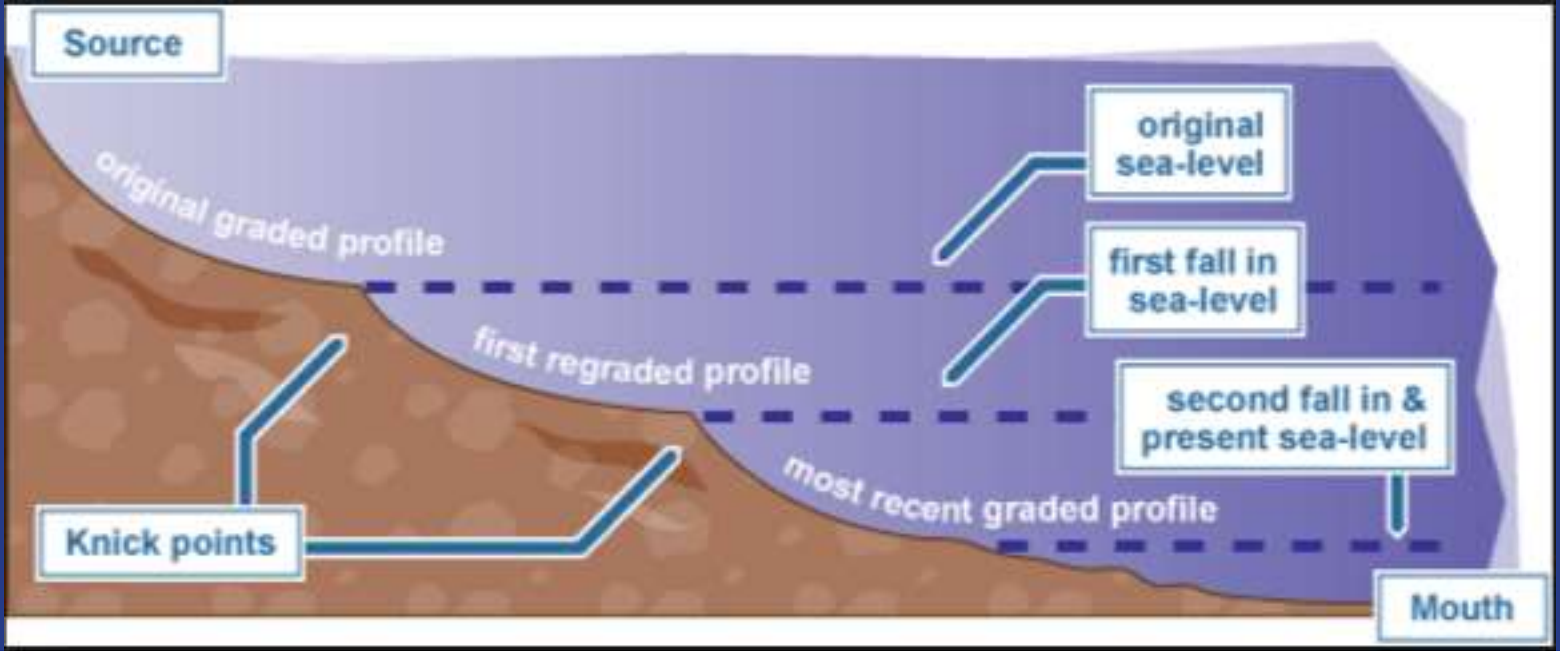


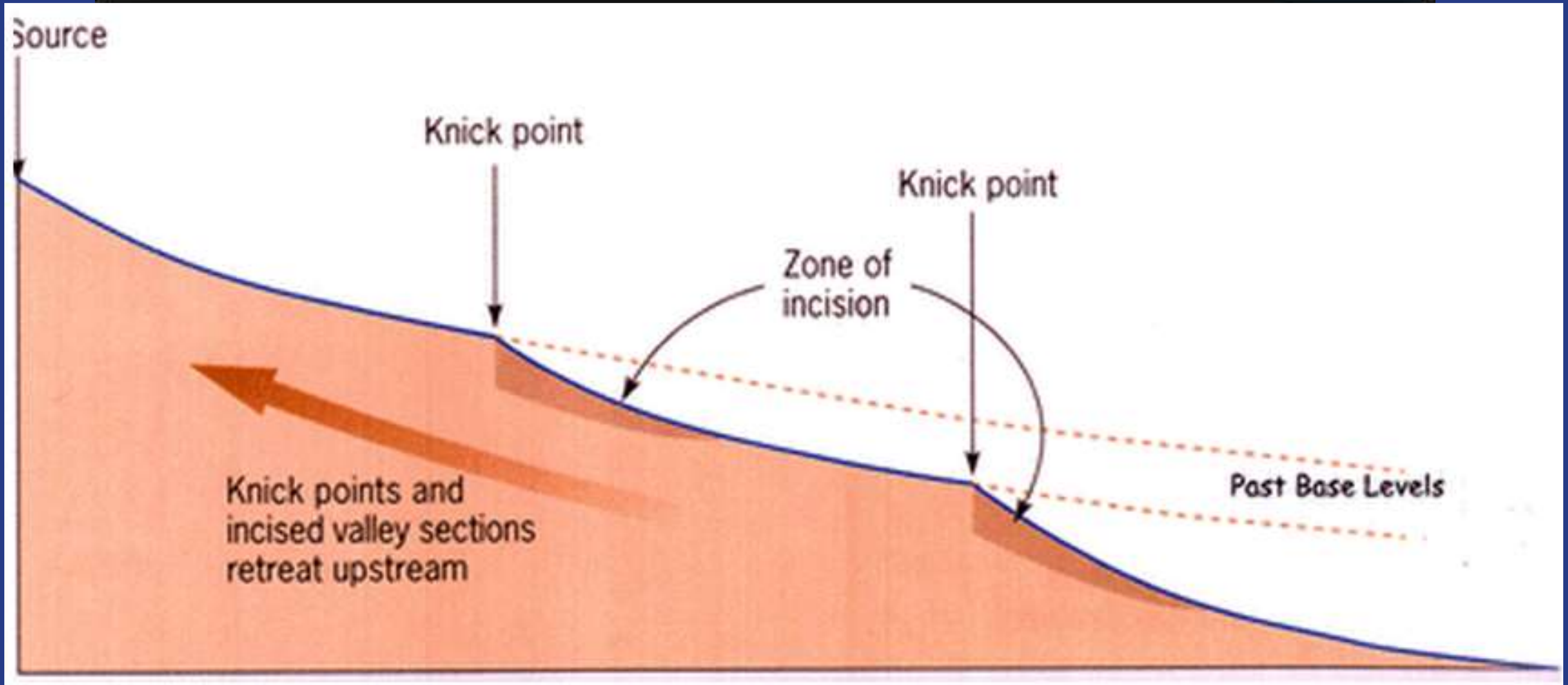
(C) Erosion proceeds upstream from the fault, and deposition occurs downstream and a new stream profile starts to develop.



(D) Erosion and deposition eventually develop a new stream profile at which the velocity, load, gradient, and volume of water will be in balance so that neither erosion nor deposition occurs.

Any change to a graded profile eliminates earlier conditions of equilibrium, and a new profile is developed. Changes are related mostly to tectonic movements or fluctuations in base level.

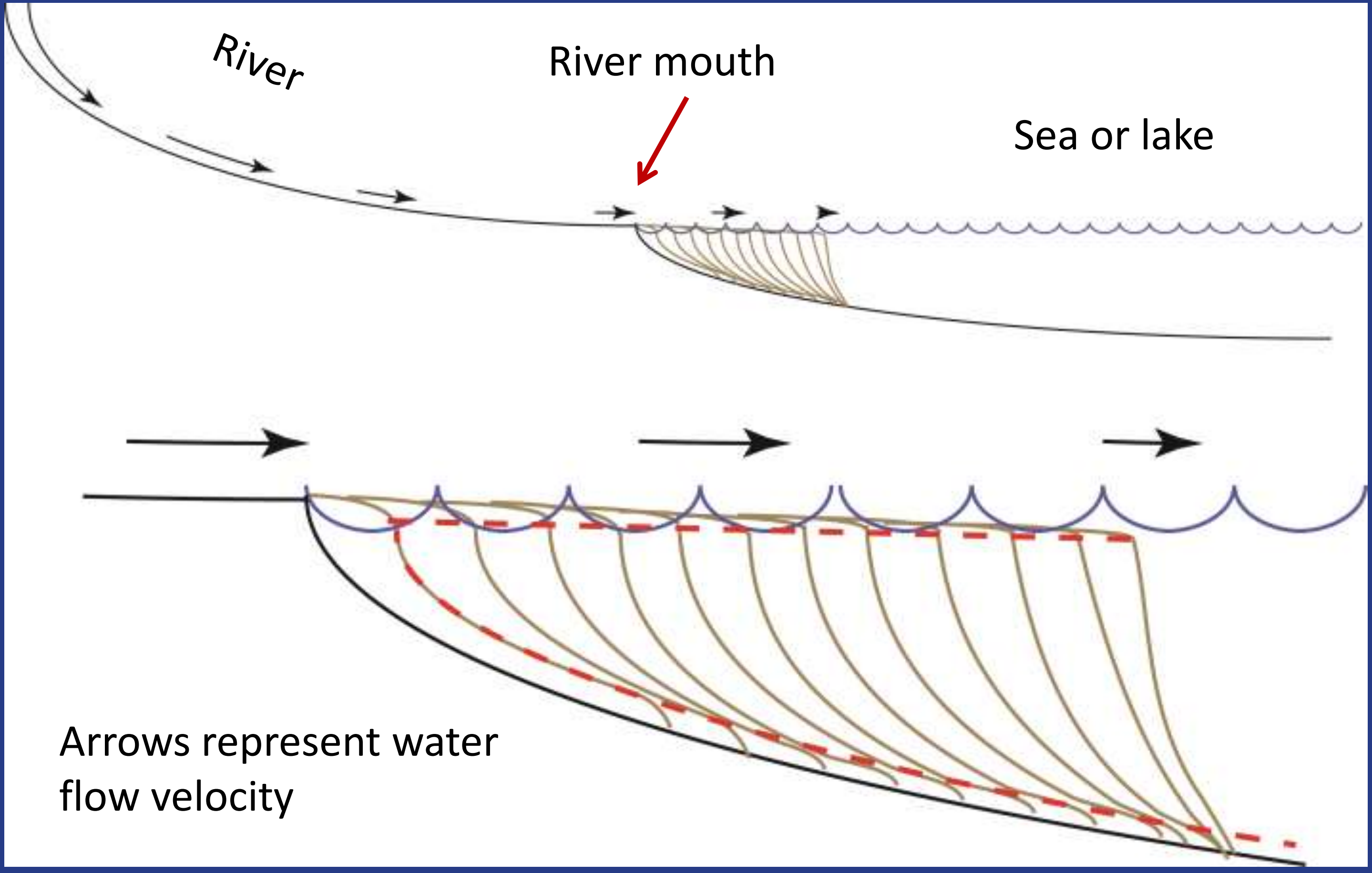

Source
original graded profile
original sea-level
first fall in sea-level
first regraded profile
second fall in & present sea-level
most recent graded profile
Knick points
Mouth


Source
Knick point
Knick point
Zone of incision
Past Base Levels
Knick points and incised valley sections retreat upstream

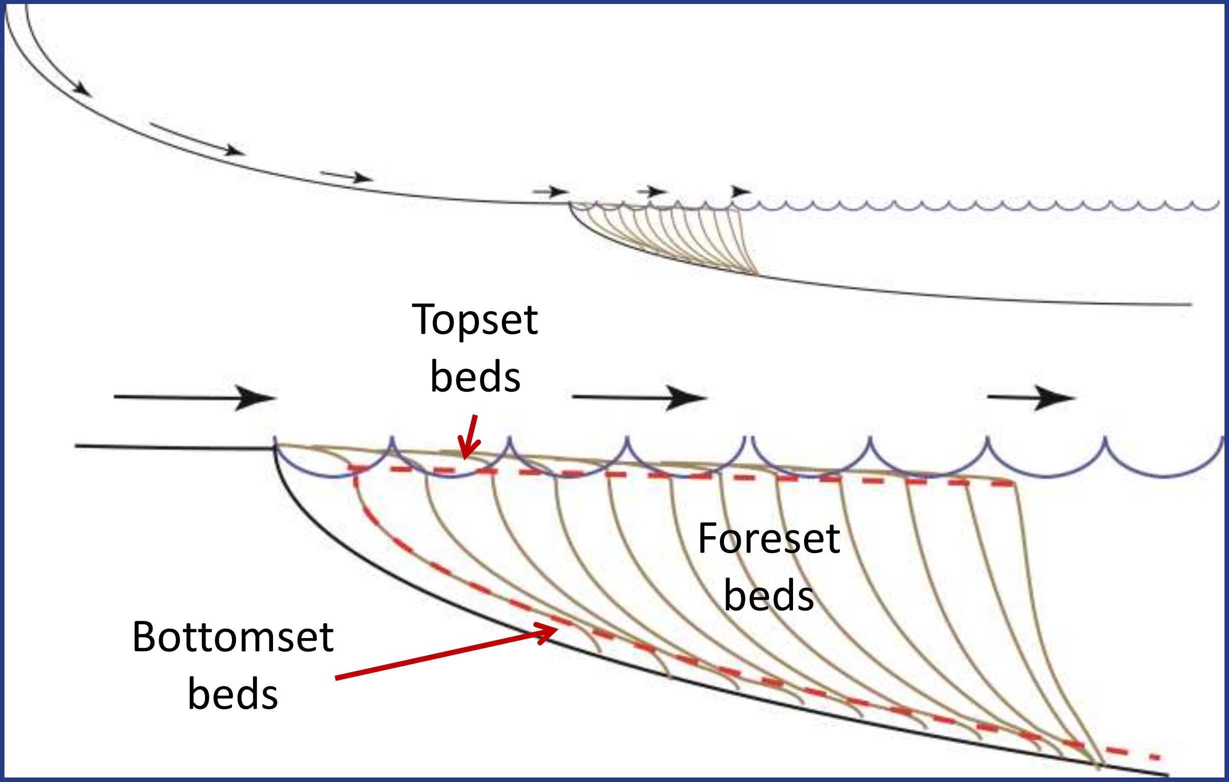
What happens when a river reaches the sea or a lake?

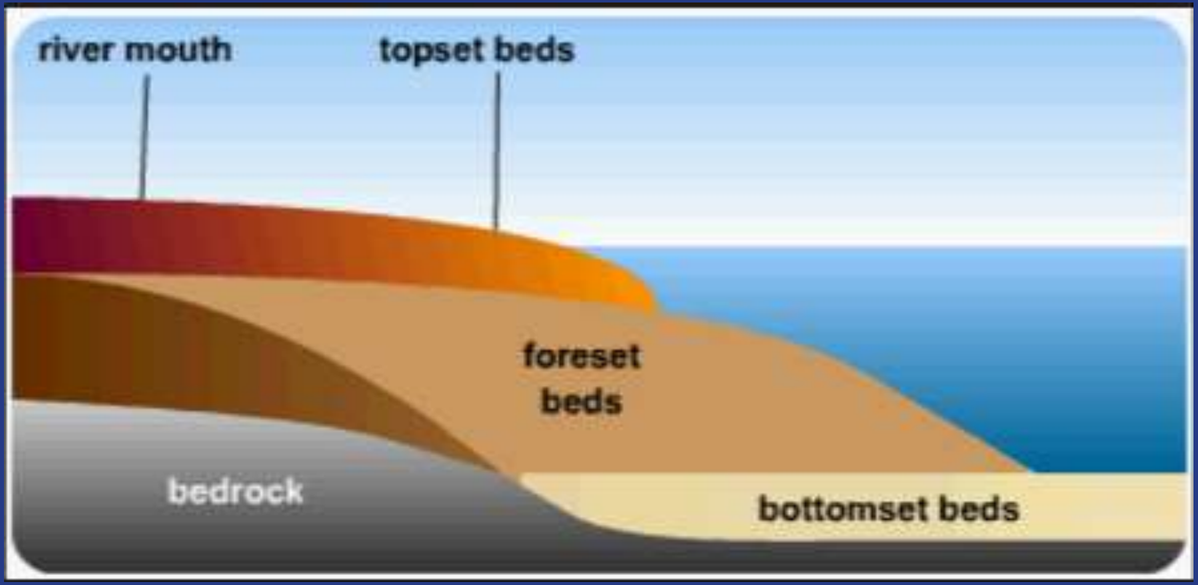
Elwha River dam removal project, Washington State, USA

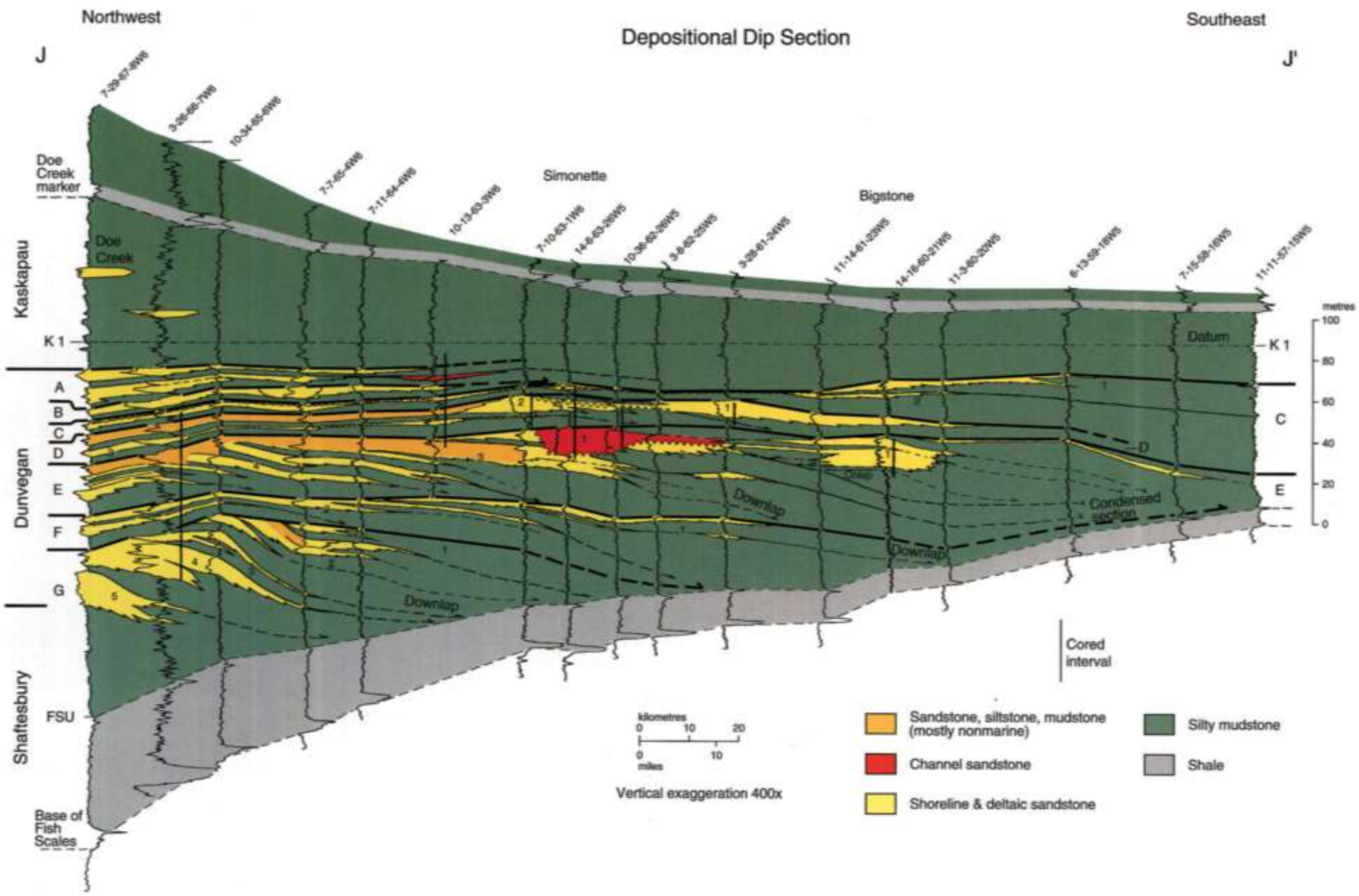
When a river reaches a stagnant body of water, the flow velocity of its waters eventually reaches zero and the river drops whatever sediment load it may be carrying at some distance from its mouth. Thus a sediment accumulation takes place at the river mouth and beyond up to the point where water velocity becomes zero.



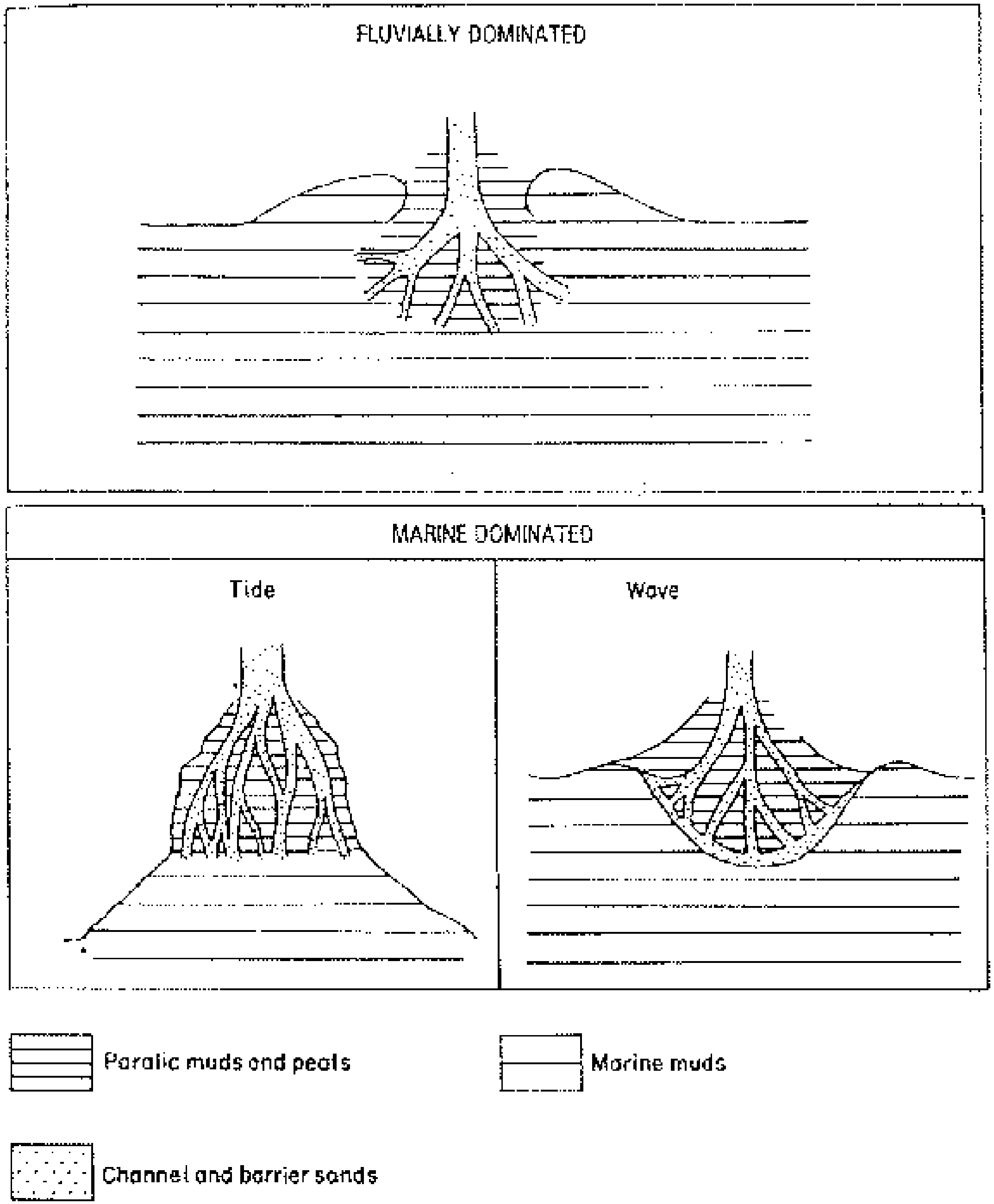
Such accumulations have received the name “delta” from the Greek letter delta (Δ) , because the first recognised such accumulation was the Nile delta that really resembles an upside-down Δ. The term seems to have been used in antiquity as a proper name for the Nile delta. The earliest reference I know is in Herodotus. Samuel Johnson may have been the first to use is as a technical term in the 18th century.


Topset
beds
Foreset
beds
Bottomset
beds

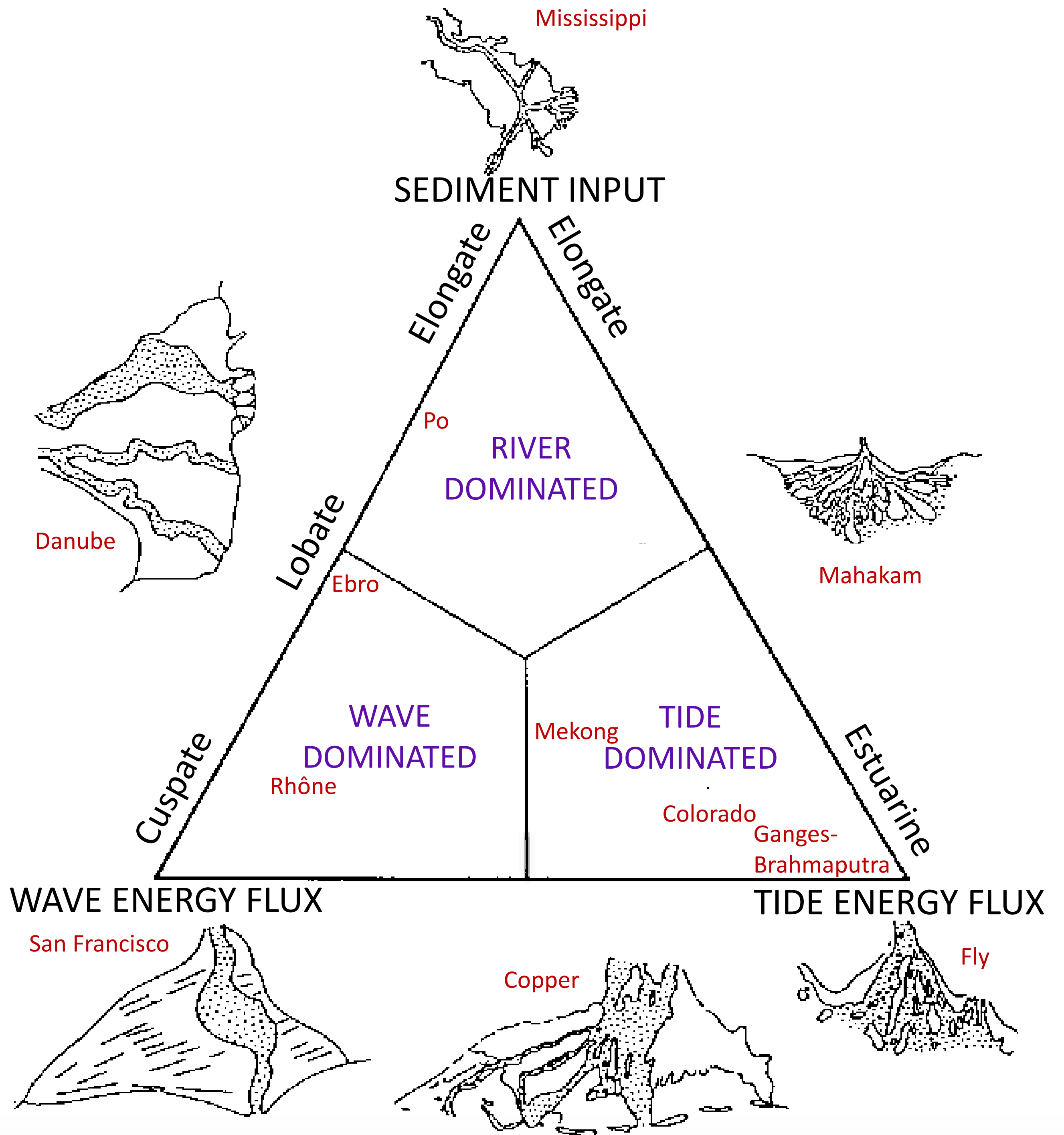

river mouth
topset beds
foreset
beds
bedrock
bottomset beds

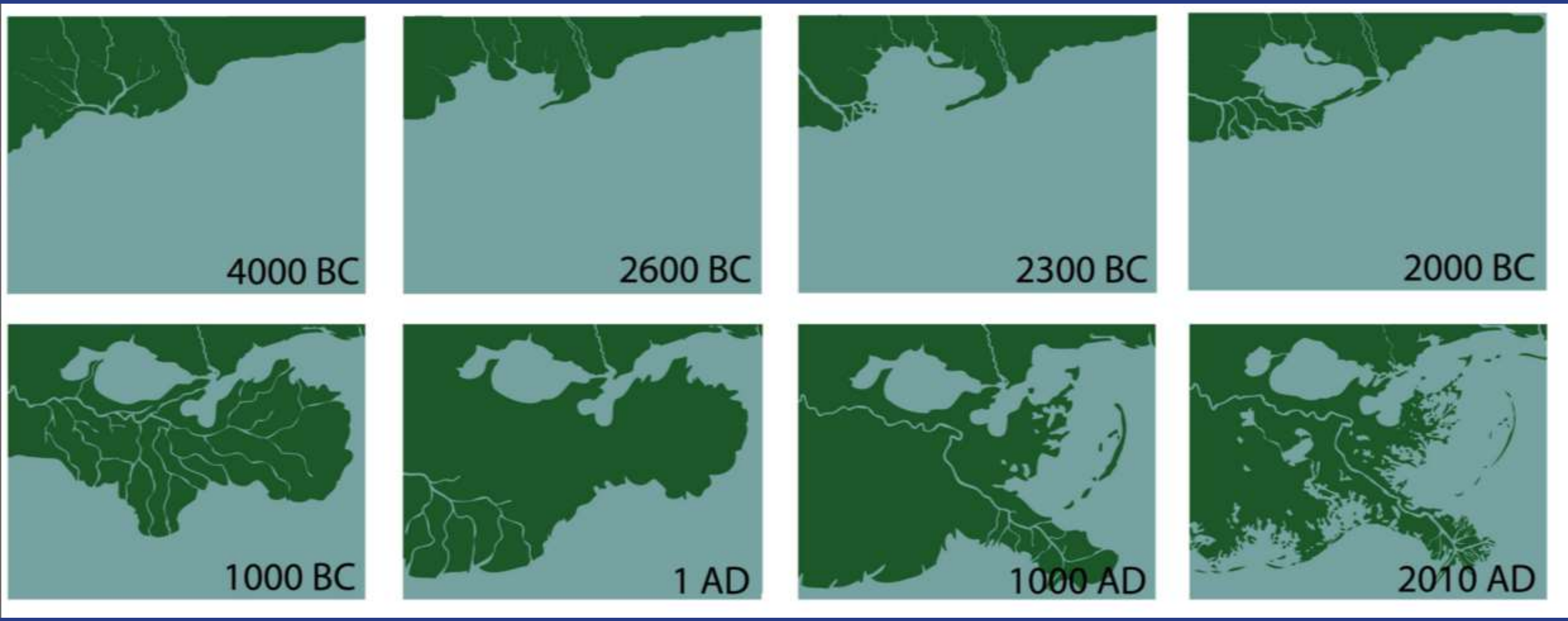


A detailed cross-section across the Cretaceous-age Dunvegan formation, which is a delta deposit, western Canada.



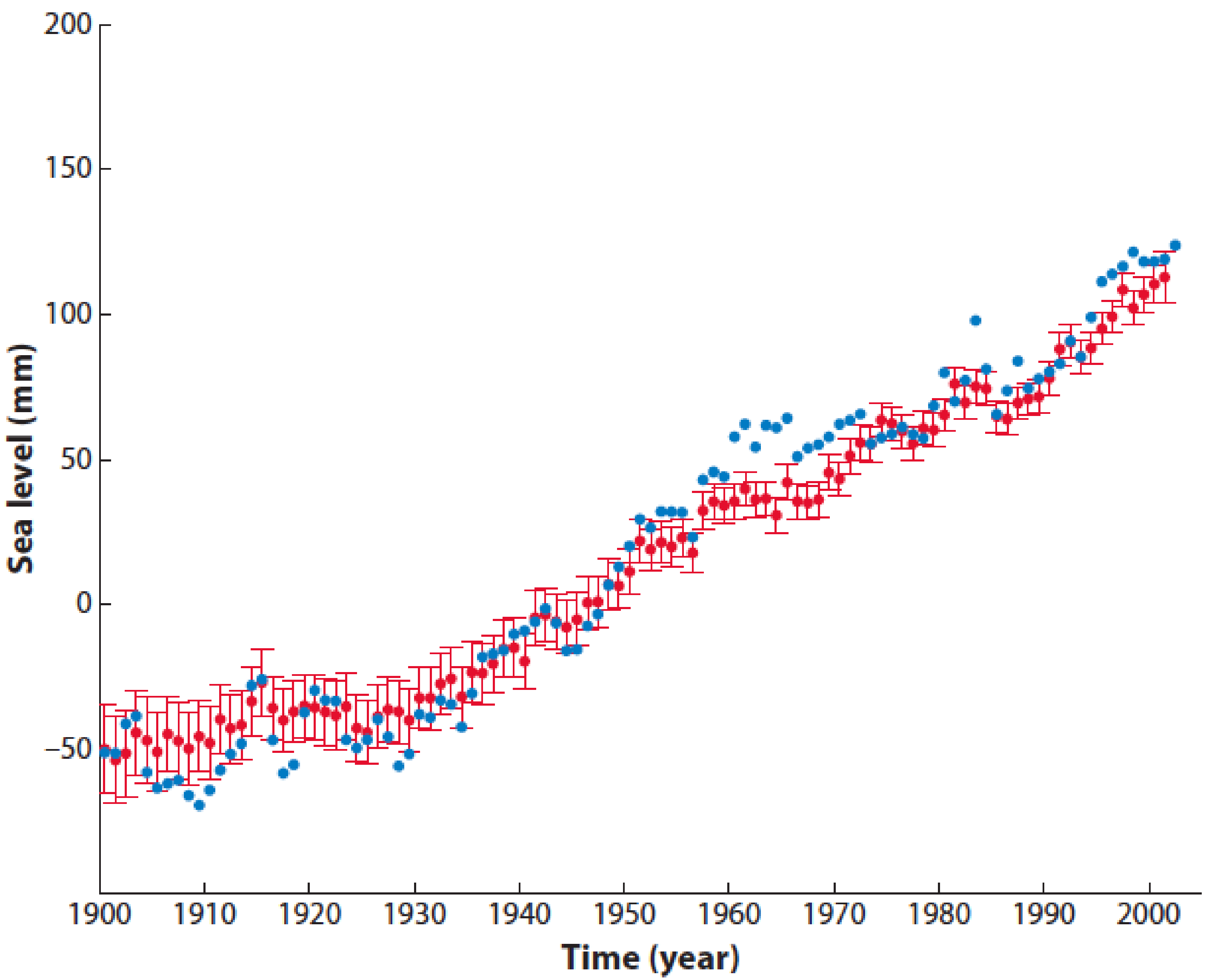
ure 3.10 - The basic types of delta: birdfoot type (fluvially dominated); lobate (wave-dominated and tide-dominated)


Mississippi
SEDIMENT INPUT
Elongate
Elongate
Po
RIVER
DOMINATED
Danube
Lobate
Ebro
Mahakam
WAVE
DOMINATED
Mekong
TIDE
DOMINATED
Cuspate
Estuarine
Rhône
Colorado
Ganges-
Brahmaputra
WAVE ENERGY FLUX
TIDE ENERGY FLUX
San Francisco
Copper
Fly



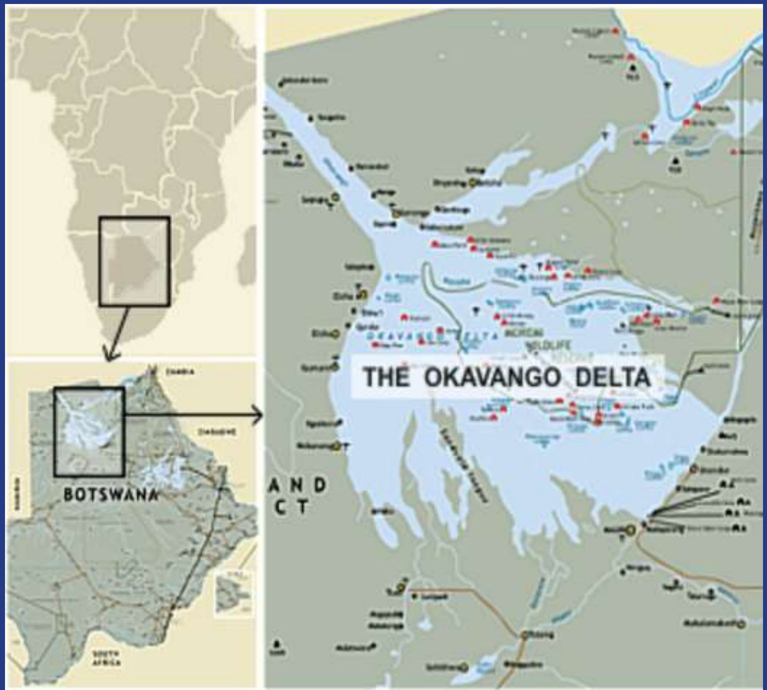
Why is the delta getting smaller here?

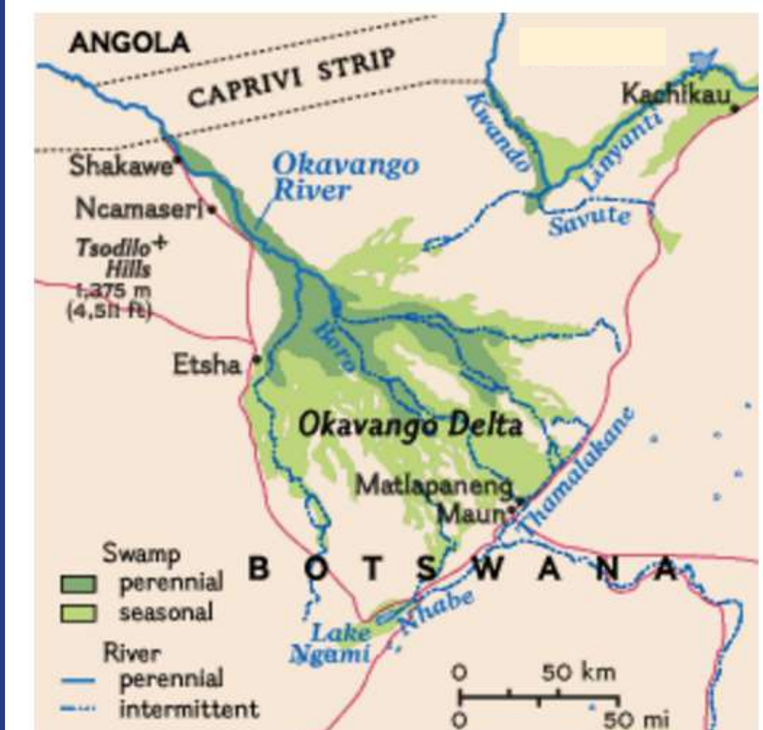
The growth of the Mississippi Delta since 4000 BC. Let us remember that the coastline was established after the last ice age, i.e. after some 10,000 years ago.



Observed mean sea-level from tide gauges (from Cazenave and Llovel, 2010)

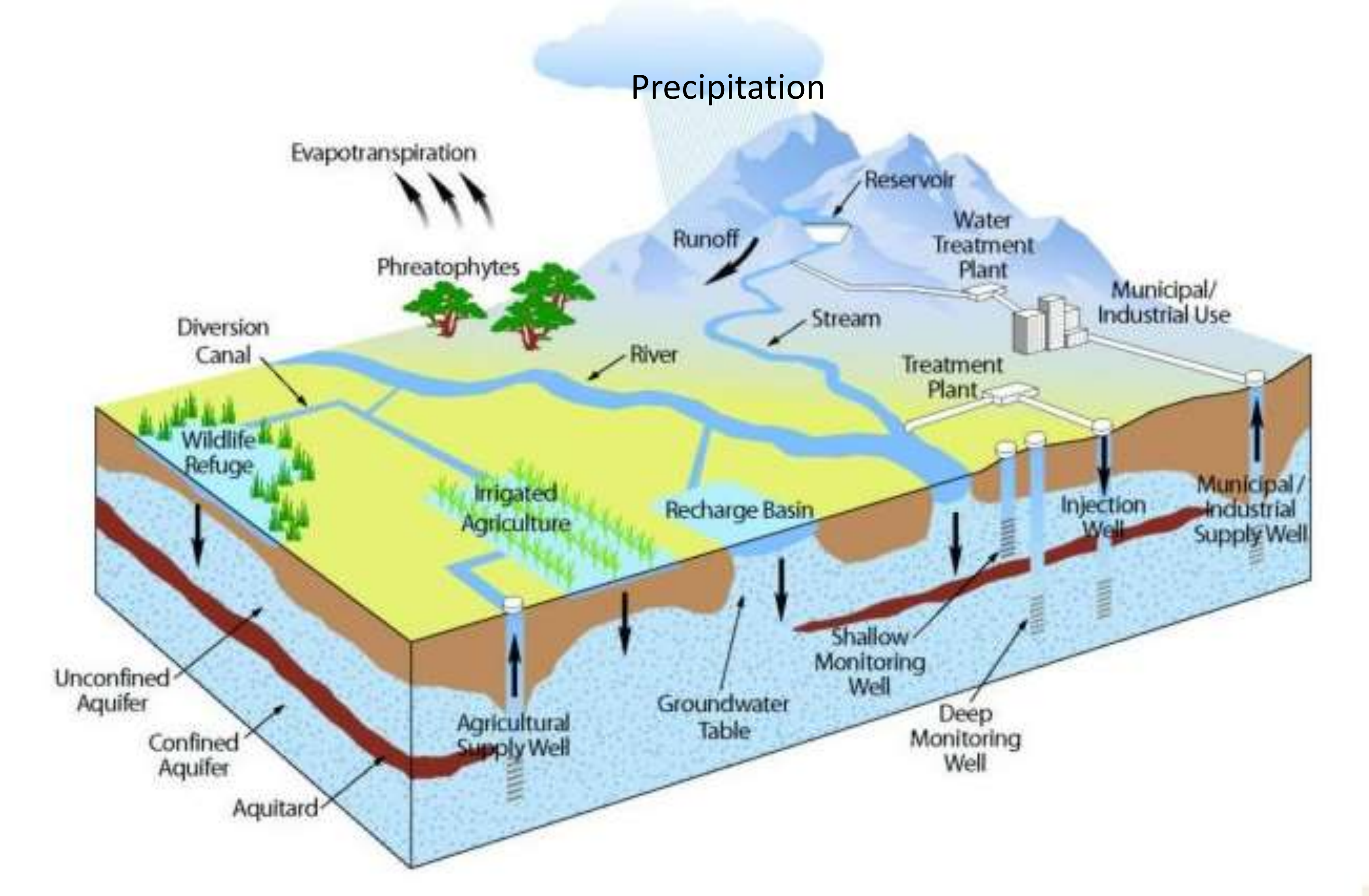
There is another group of deltas that most delta researchers seem to ignore: inland deltas that do not form in the sea or in lakes, but on open land which periodically they turn into swamps. The Okavango Delta in Botswana (Africa) is perhaps the most famous example.





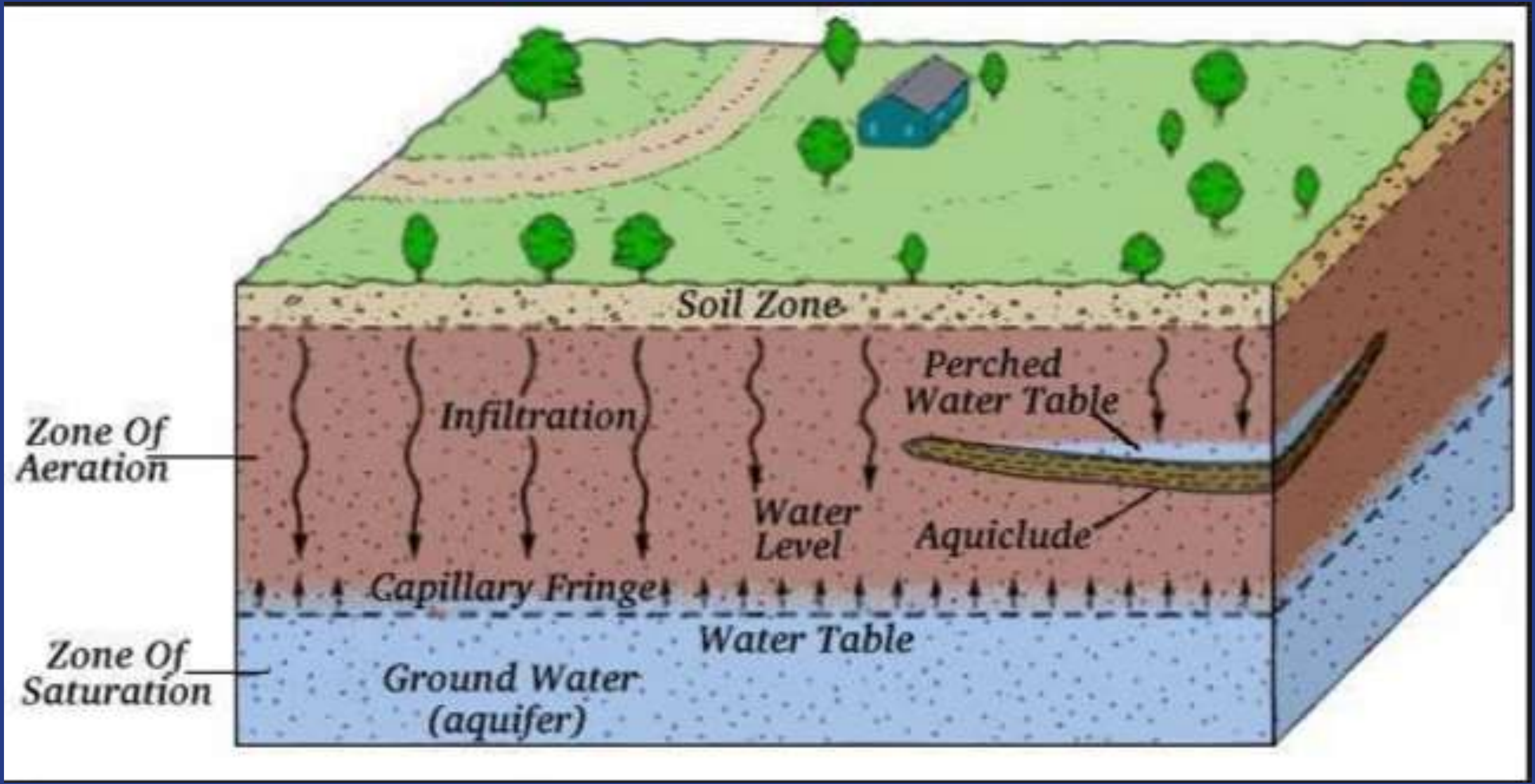
The surface of the Okavango Delta during the wet season

Deltas are places where fluvial (riverine) and marine (sea) or limnic (lake) or paludal (swamp) processes interfere with one another. Therefore naturally we should have been going after a consideration of deltas to shoreline processes. But, before doing that we need to consider one other aspect of inland waters, namely the ground water. Associated with ground water is an entire group of landforms that come into being in soluble rocks such as carbonates, gypsum and halite salts. That group of landforms are known under the name of Karst topography.

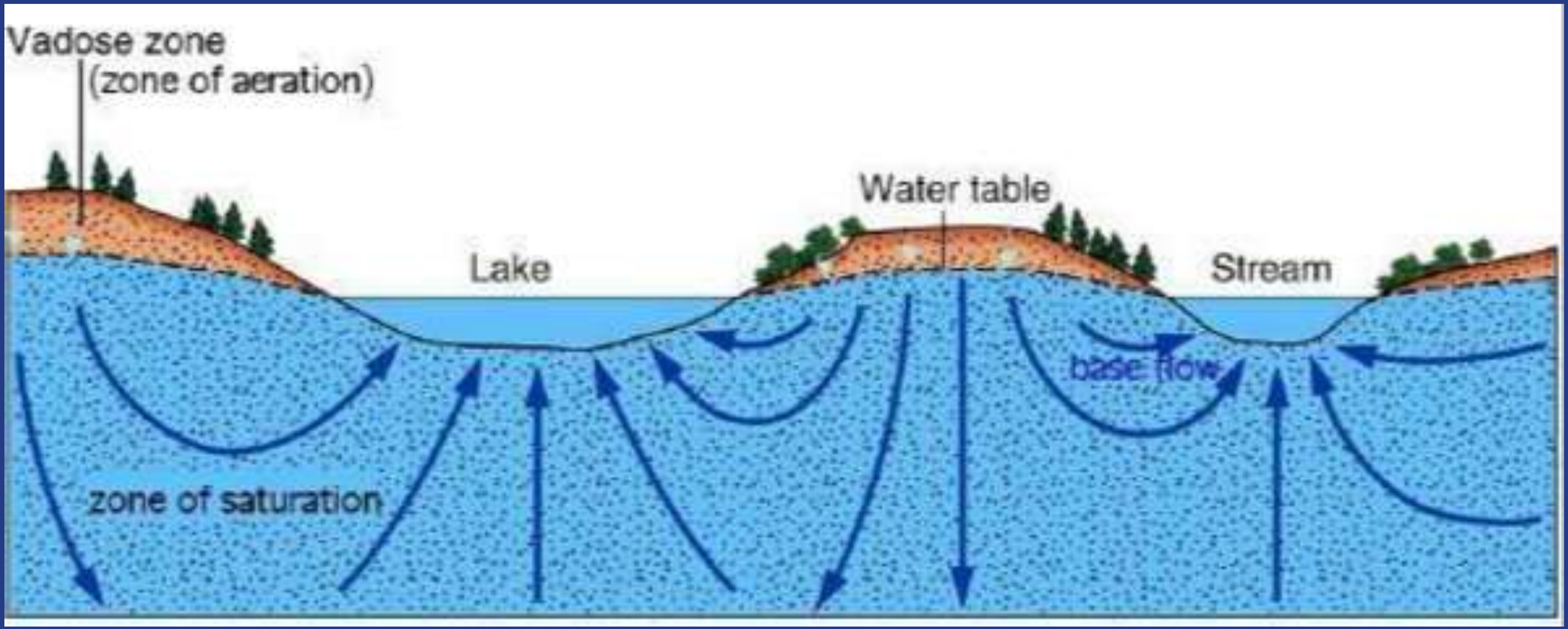

Precipitation
Evapotranspiration
Reservoir
Water Treatment Plant
Runoff
Phreatophytes
Municipal/ Industrial Use
Stream
Diversion Canal
River
Treatment Plant
Wildlife Refuge
Irrigated Agriculture
Recharge Basin
Injection Well
Municipal / Industrial Supply Well
Shallow Monitoring Well
Unconfined Aquifer
Groundwater Table
Deep Monitoring Well
Agricultural Supply Well
Confined Aquifer
Aquitard

There are Two Zones Under the Ground---

1. **ZONE OF AERATION** – the area in the soil where most of the spaces are filled with air.
2. **ZONE OF SATURATION** – the area in the soil where most of the spaces are filled with water…it is saturated.



A highly schematised view of the groundwater in areas of non-soluble rocks.



Water table is the upper surface of the zone of saturation. It mimicks the topography is a subdued manner. Where it intersects the surface, we might have lakes, streams or springs

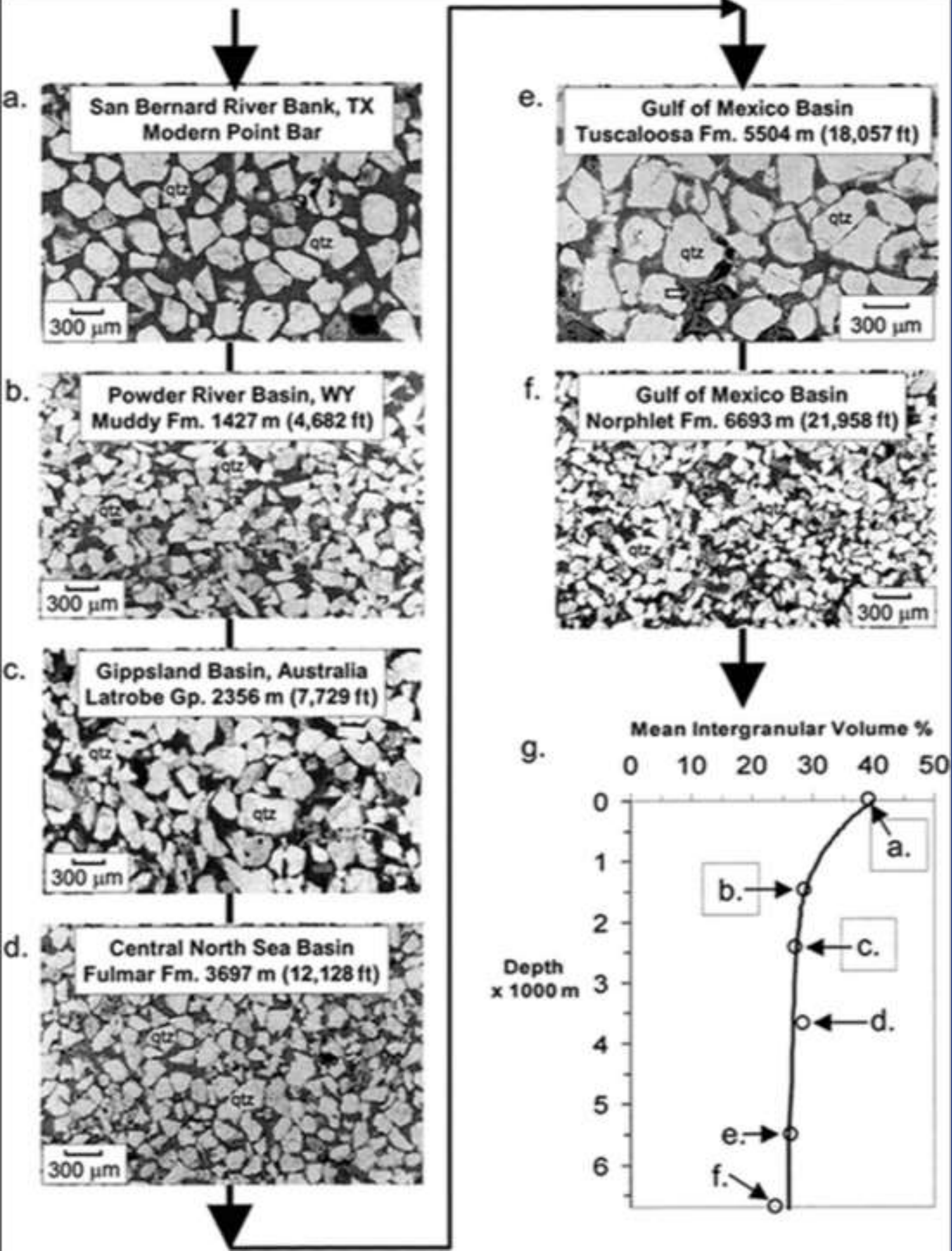
Groundwater is housed in the pores of the rocks, but it can only get there using the rocks' permeability. Water that is trapped in sedimentary rocks while the rock is forming is called connate water.

Pores in rocks are simply open spaces that can be occupied by such fluids as water or oil or gas. Porosity (Φ) or void fraction in a rock is the ratio of the void spaces (V_V) to the total volume of the rock (V_T):

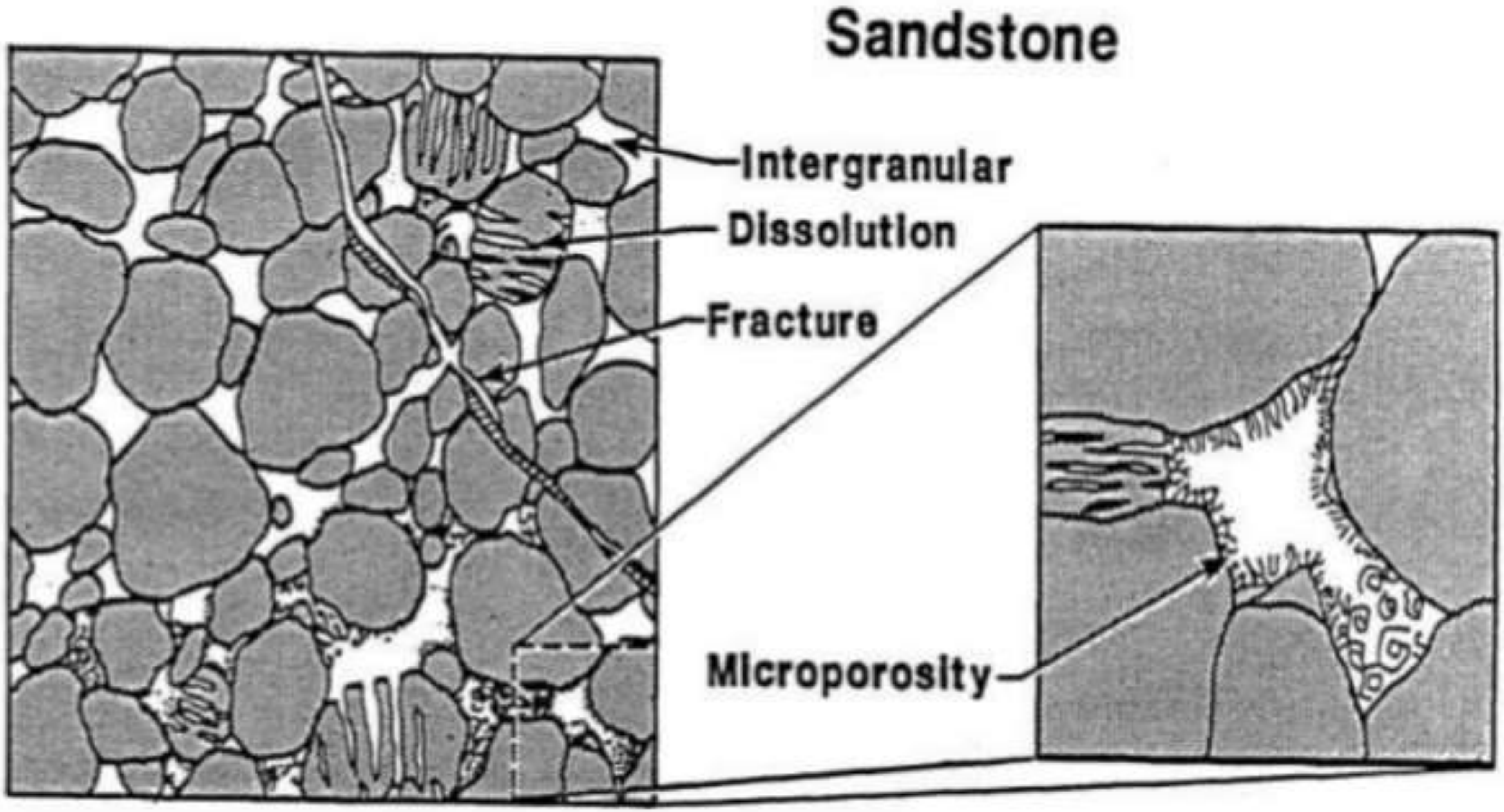
$$\Phi = V_V/V_T$$

and it changes between 0 and 1. Porosity may also be expressed as a percentage and then changes between 0% (no pore spaces) and 100% (no rock)

Examples of porosities in various clastic rocks



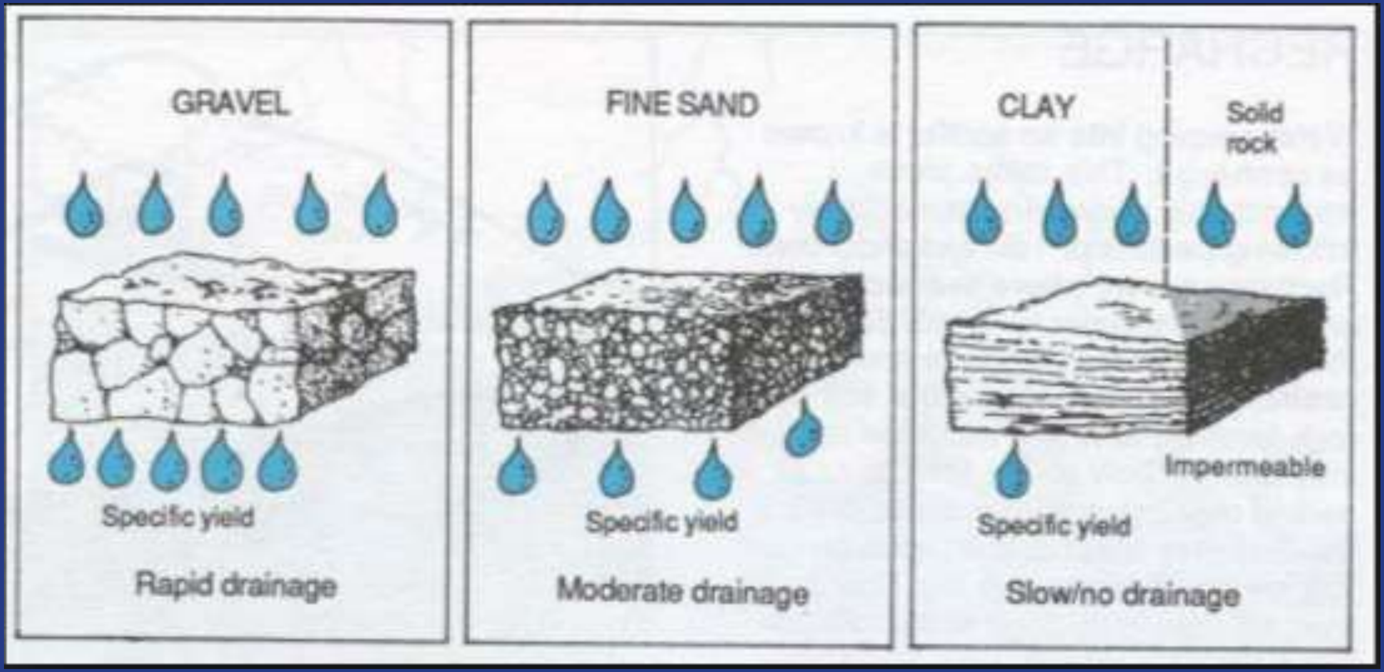
Basic Porosity Types



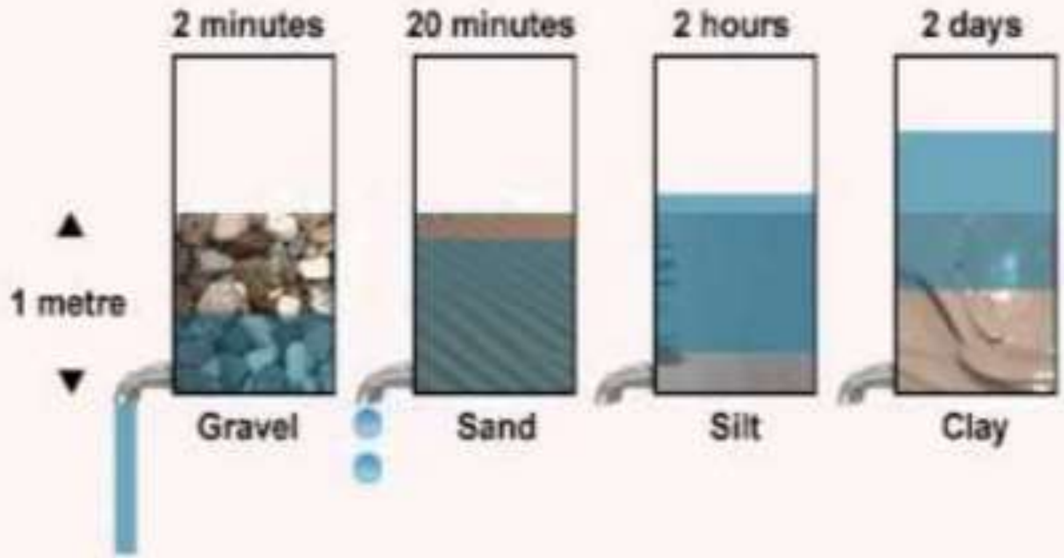
But ground water can neither form nor move if it were not for the permeability of the rocks.

Permeability of a rock is defined as as the rock's ability to let a liquid pass through it.

A rock may be highly porous, but if its pores are not interconnected it would have zero permeability. For example, claystones and shale are extremely porous, but not permeable at all.

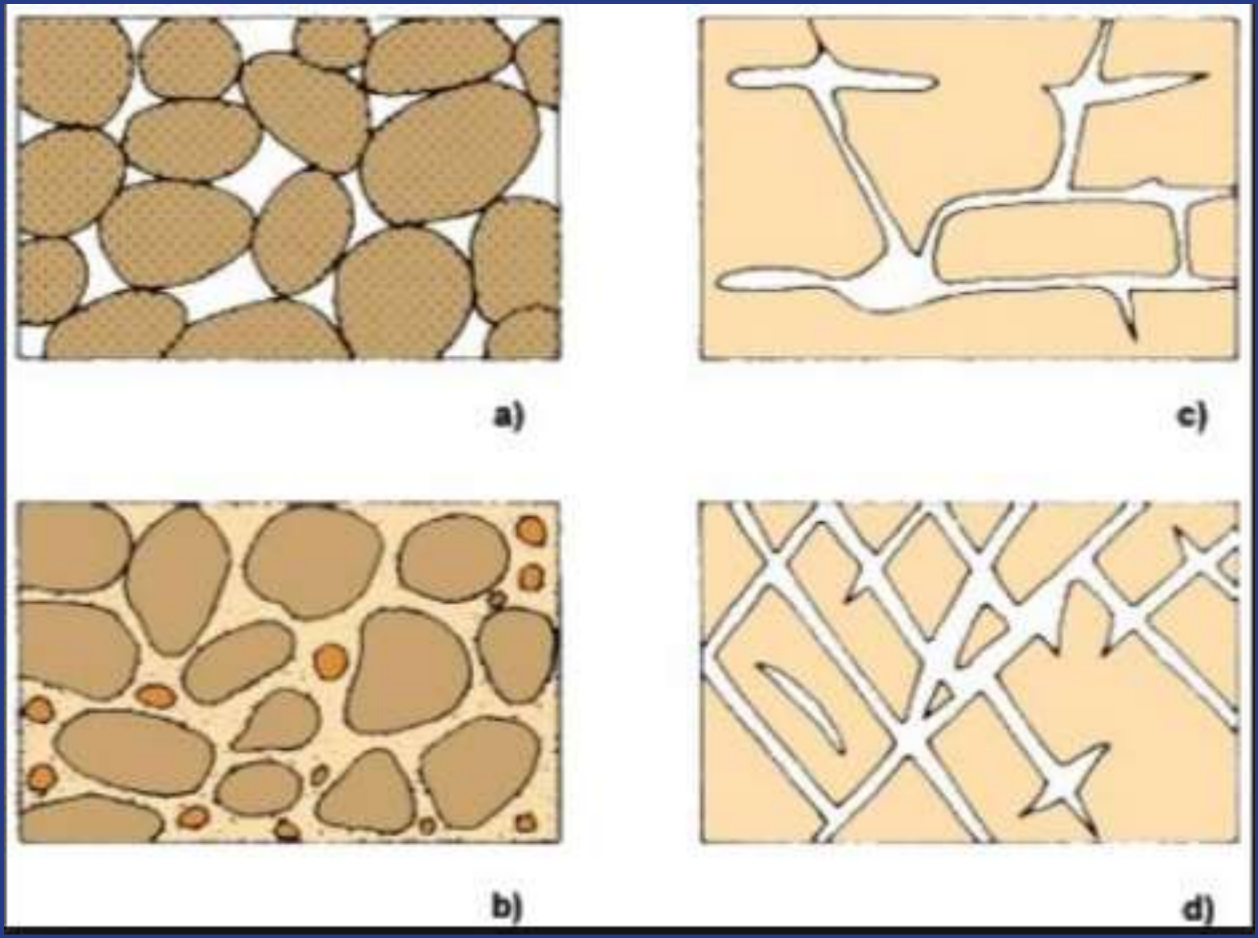


Permeability



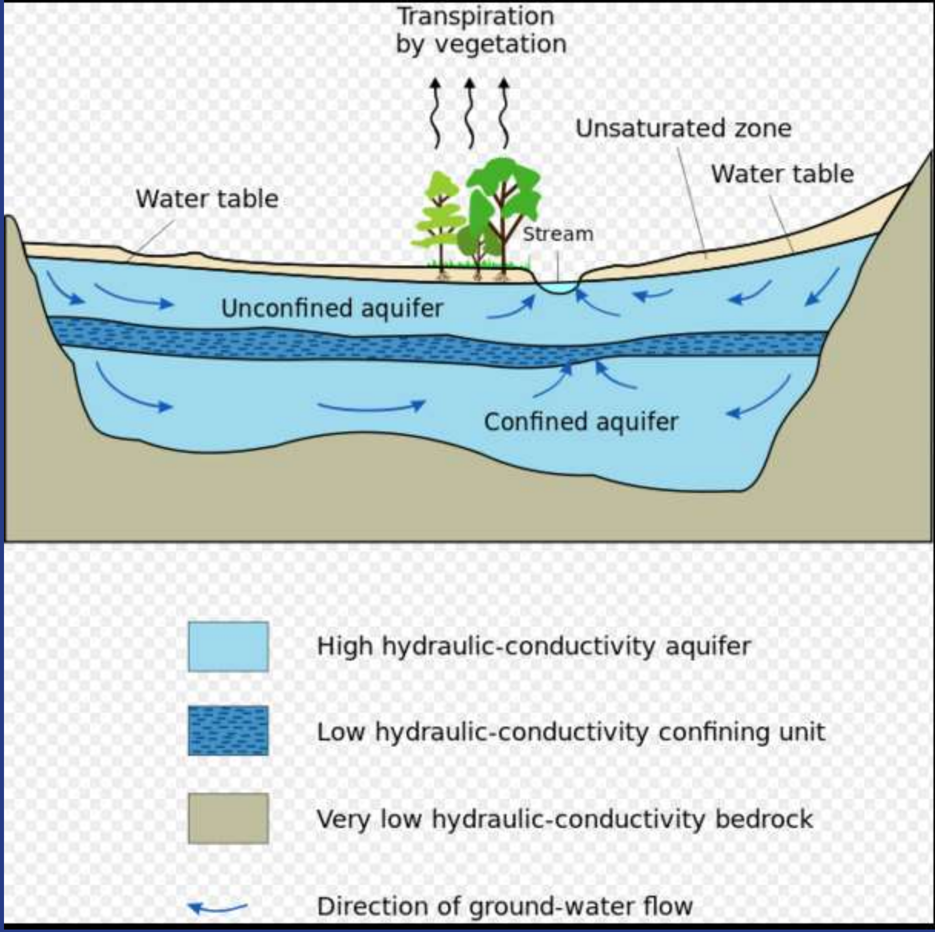
Porous *but not* permeable

Porous *and* permeable



Some additional definitions:

Aquifer: Aquifer is the water-bearing permeable rock body underground. The term comes from the French *aquifère* meaning water-carrying. It could be any rock and its permeability may be of any type (intergranular, fracture-caused, etc). Aquifers may be confined or unconfined.



Aquitard: A layer of low permeability within an aquifer

Aquiclude: An impermeable layer underlying an aquifer. From the Latin *aqua*= water and *cludere*= to close

Phreatic zone: Another name for the saturated zone. The term is derived from the Greek φρεᾱτία (*freatia*=a tank or a reservoir)

Water table: The upper surface of the saturated zone where the pressure head (=pressure of water/density of water X gravitational acceleration) equals 1 atmosphere.

The origin of groundwater:

Groundwater has two origins one very minor, called juvenile, and the other, the main, called vadose.

Juvenile water, so named by Eduard Suess in 1909 from the Latin word *juvenile* meaning youthful, is the water released from the interior of the earth by volcanic or hydrothermal processes. It is also called magmatic or mantle water, but the latter need not be true. I recommend we stick to the usage by Suess.

Vadose water includes all water that comes down to the earth by precipitation. The term vadose was first proposed by the Czech geologist František Pošepny in 1894. The term comes from the Latin word *vadose* meaning “shallowly”.

Although the rôle of juvenile waters is extremely important in volcanic phenomena, their contribution to groundwater is very minor. Therefore in the following discussion I shall ignore them.

Places where groundwater naturally comes to the surface are known as springs. There are numerous kinds of springs and they can be classified from various viewpoints:

1. Classification according to the hydrostatic pressure of the groundwater coming out of the spring

2. Classification according to the temporal behaviour of the spring

3. Classification according to the temperature of the groundwater coming out of the spring

4. Classification according to the chemical composition of the groundwater coming out of the spring

5. Classification according to the geological structure of the spring

6. Classification according to the morphology of the spring area

Classification according to the hydrostatic pressure of the groundwater coming out of the spring:

1. Freely flowing springs in which the water pressure is the same as the ambient atmospheric pressure.

2. Artesian springs in which the pressure of the groundwater is greater than the ambient atmospheric pressure. The term artesian comes from the French region of Artois where artesian wells were first drilled by the Carthusian monks of the Abbey of Lillers in 1126.

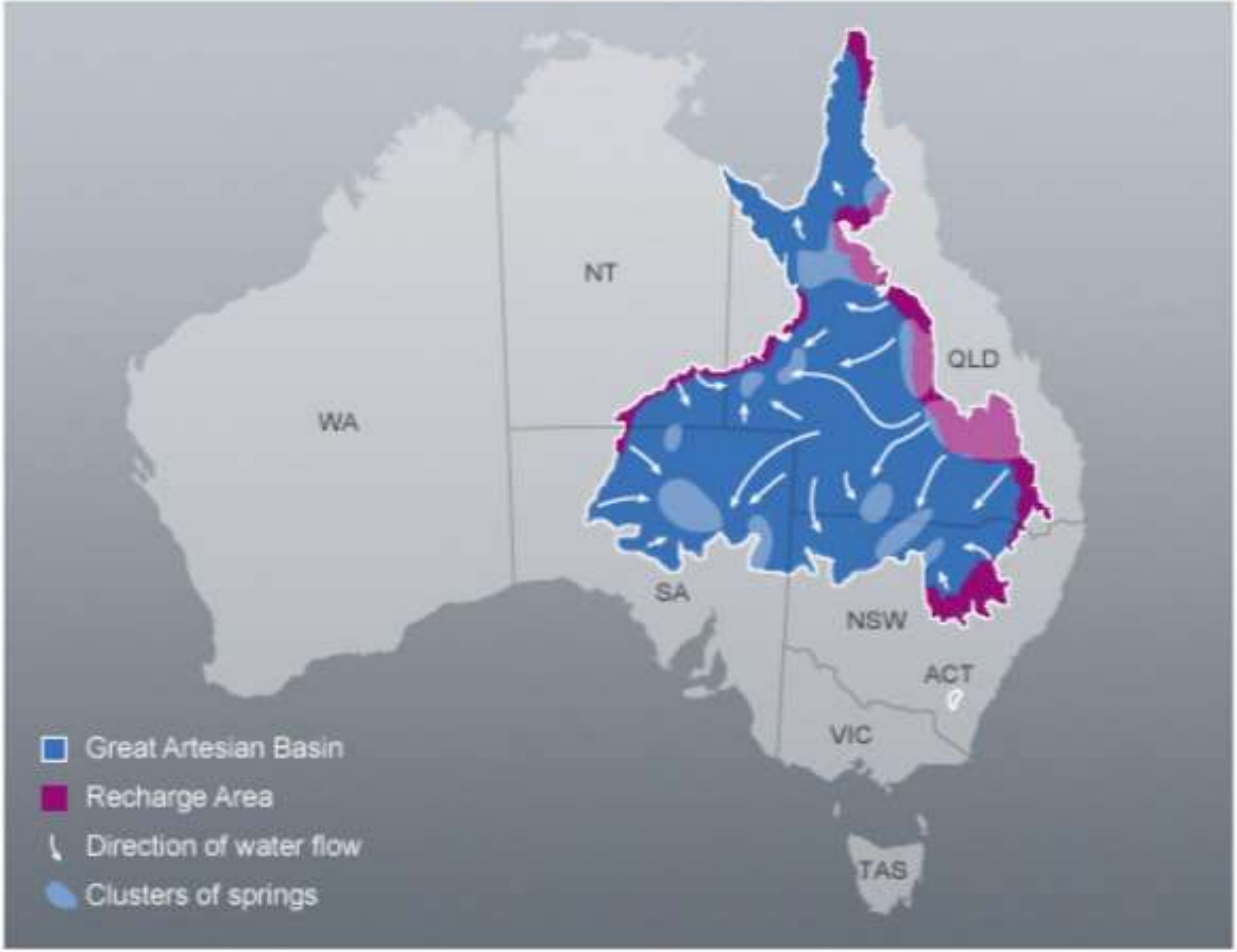
1. Freely flowing springs in which the water pressure is the same as the ambient atmospheric pressure.

A freely-flowing spring.

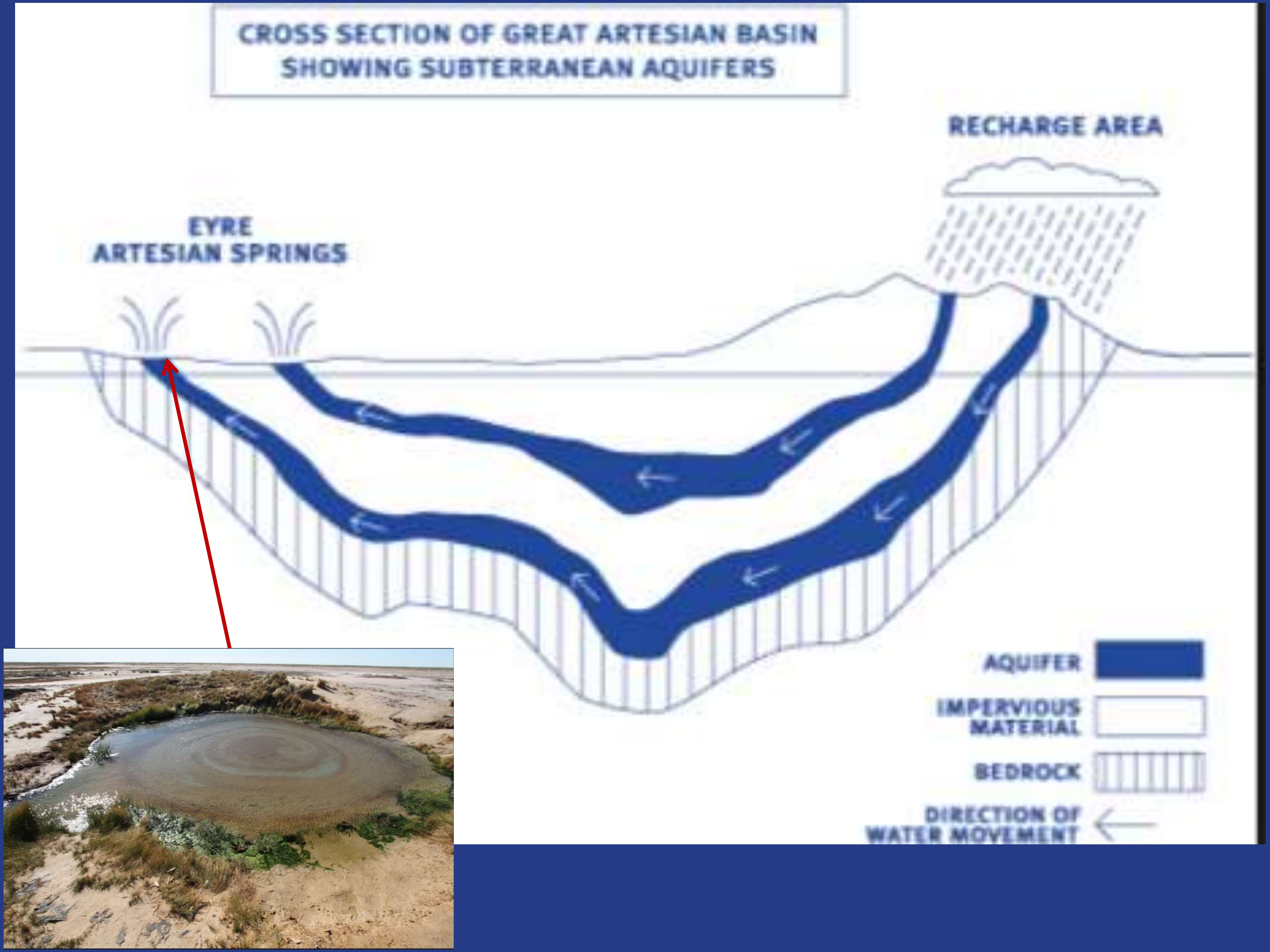
2. Artesian springs in which the pressure of the groundwater is greater than the ambient atmospheric pressure.

An artesian spring near Lake Eyre Australia

Great Artesian Basin



In the classic model of the Great Artesian Basin, the aquifer is mainly recharged by rainfall and streamflow along the eastern border of the Basin, and is discharged in a series of springs that lie mainly in the south of the Basin.


CROSS SECTION OF GREAT ARTESIAN BASIN
SHOWING SUBTERRANEAN AQUIFERS
RECHARGE AREA
EYRE
ARTESIAN SPRINGS
AQUIFER
IMPERVIOUS
MATERIAL
BEDROCK
DIRECTION OF
WATER MOVEMENT

Classification according to the temporal behaviour of the spring

1. Perennial springs flow the year round without regard to seasons or any other factor

2. Intermittent springs stop flowing at intervals. They can be periodic or episodic in their behaviour. In Germany, such intermittent springs in karstic areas are also known as hunger springs (*Hungerbrunnen*), because folk beliefs consider their stopping a bad omen for the coming of hard times.

The intermittent karstic spring Kirschensoog, Germany.

Classification according to the temperature of the groundwater coming out of the spring

1. Springs in which the temperature of the water corresponds to the annual average atmospheric temperature of the region

2. Hot springs: These are springs in which the water temperature lies higher than the annual average atmospheric temperature. There seems to be no agreed temperature limit for the definition of a hot spring.

Hot spring at Tuzla, Çanakkale, Turkey

The world-famous hot springs of Hierapolis (Pamukkale), Turkey (water temperature is about 40°C)

Classification according to the chemical composition of the groundwater coming out of the spring

1. Salt springs
2. Sulphurous springs
3. Acid springs
4. Alkaline springs
5. Bitter springs
6. Iron springs
7. Radioactive springs

These springs are also known as “mineral springs”

The Dallol salt springs in the Afar depression, Ethiopia, Africa

The famous sulphurous springs of Karlsbad (now Karlovy Vary in the Czech Republic), one of the most famous mineral spring localities in the world

Acid springs in the Rotokawa Geothermal area, New Zealand

Beverly natural alkaline hot springs in Los Angeles, California, USA

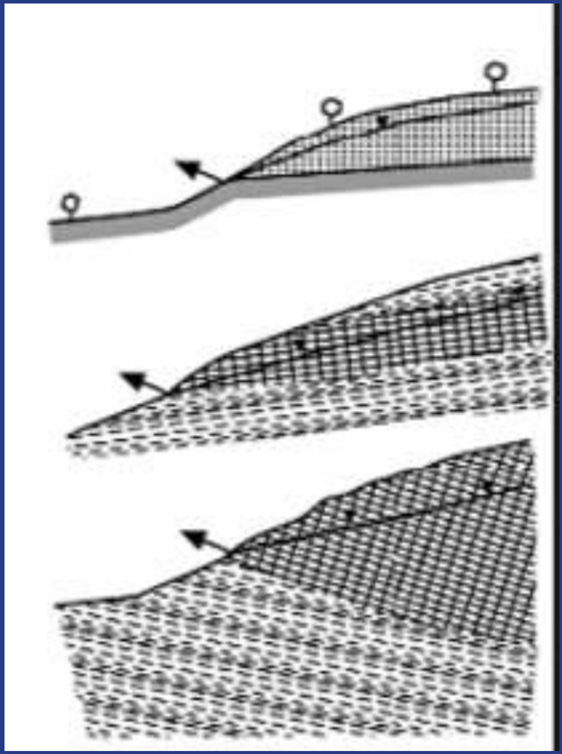
Tha Karagöl bitter spring in the gypsum karst of Sivas, near Canova village.

Iron-bearing waters of the famous Marie-Henriette spring at Spa, Belgium

Radioactive spring resulting from the presence of radon gas in the water: Radium Hot Springs, British Columbia, Canada

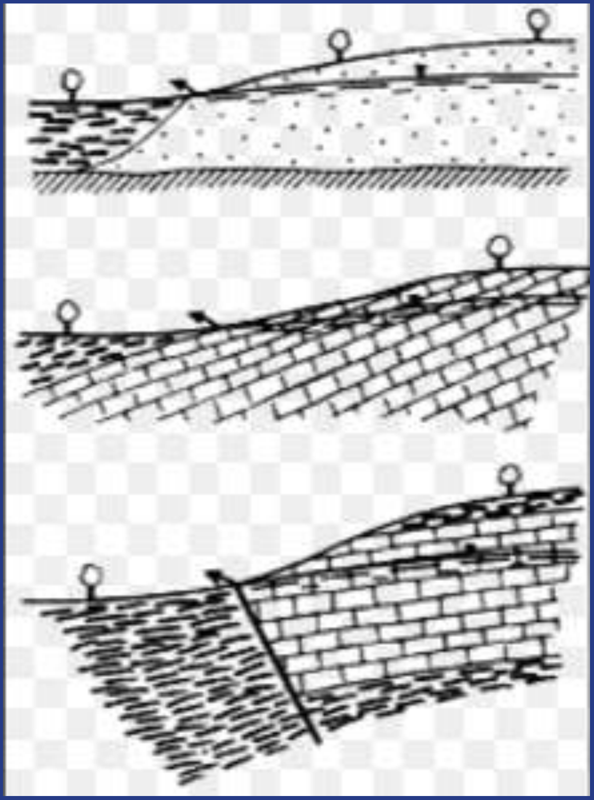
Classification according to the geological structure of the spring

1. Layer or stratigraphic springs: These form when an aquifer is underlain by an aquiclude and is intersected by the topography for a variety of reasons such as erosion or faulting.



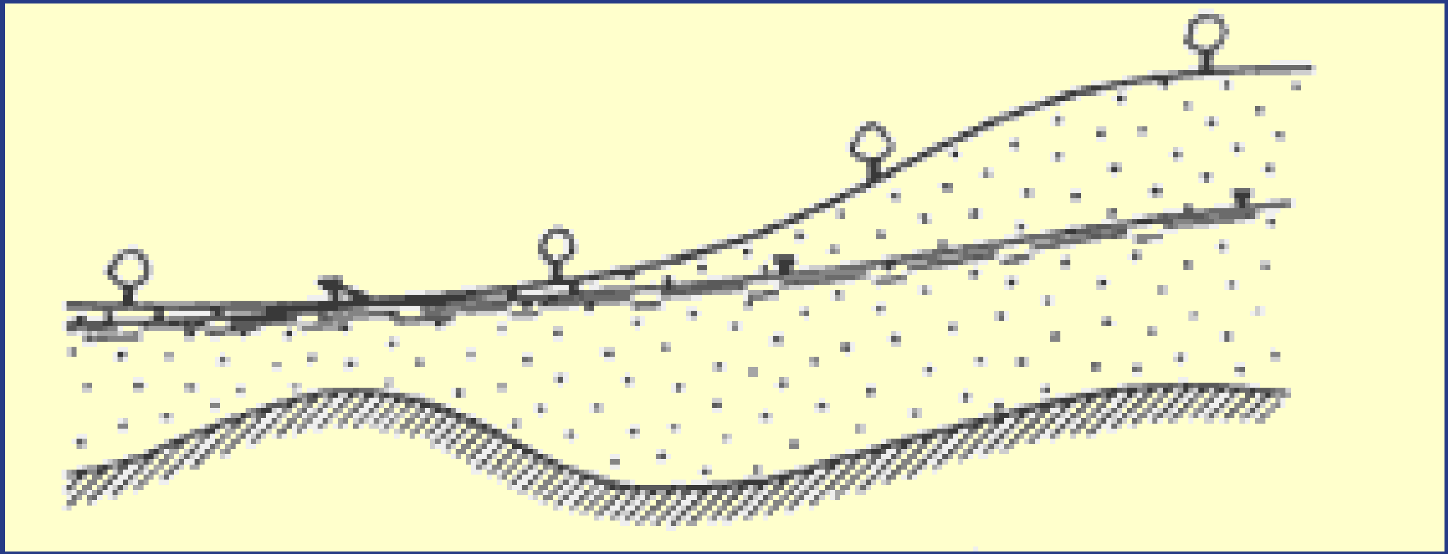
Various situations in which a stratigraphic spring may form

2. Overflow springs: These form when an aquifer has the shape of a basin or a tank and the waters overflow it.

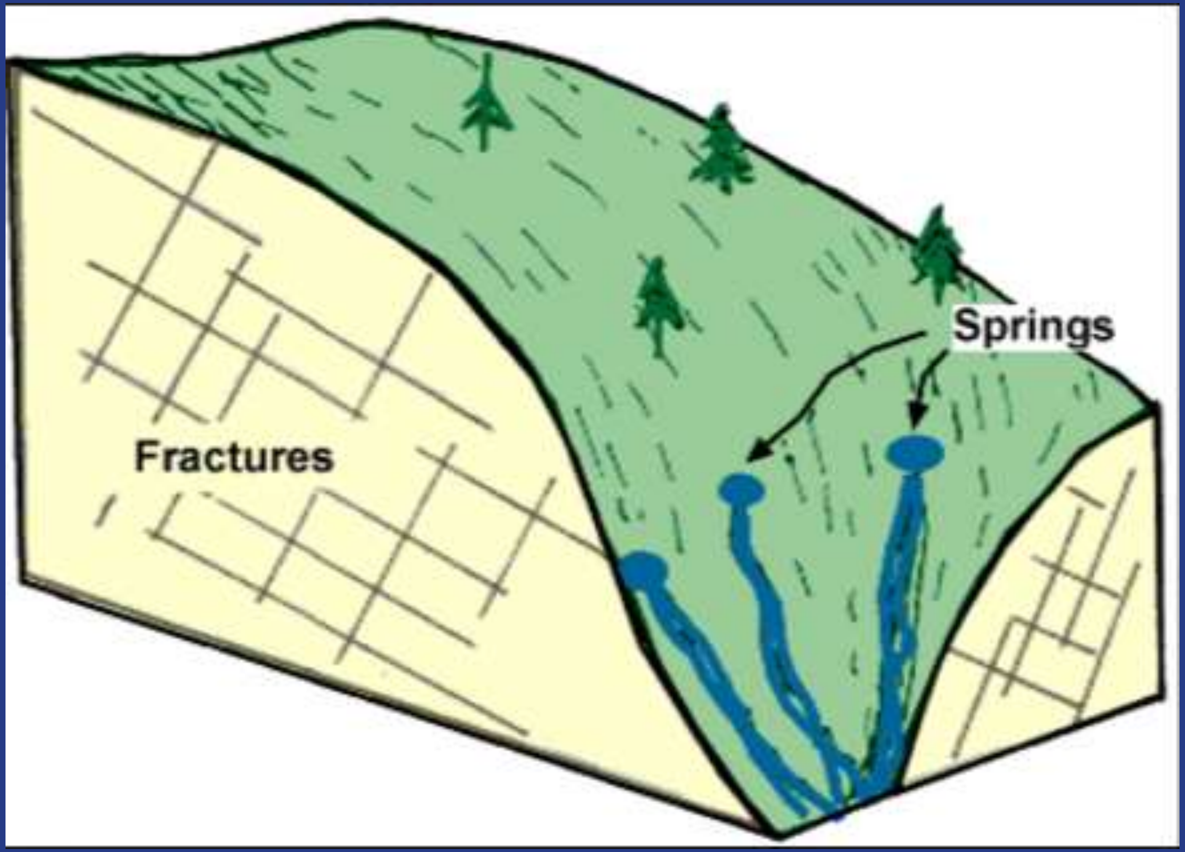


Possible ways in which overflow springs may originate

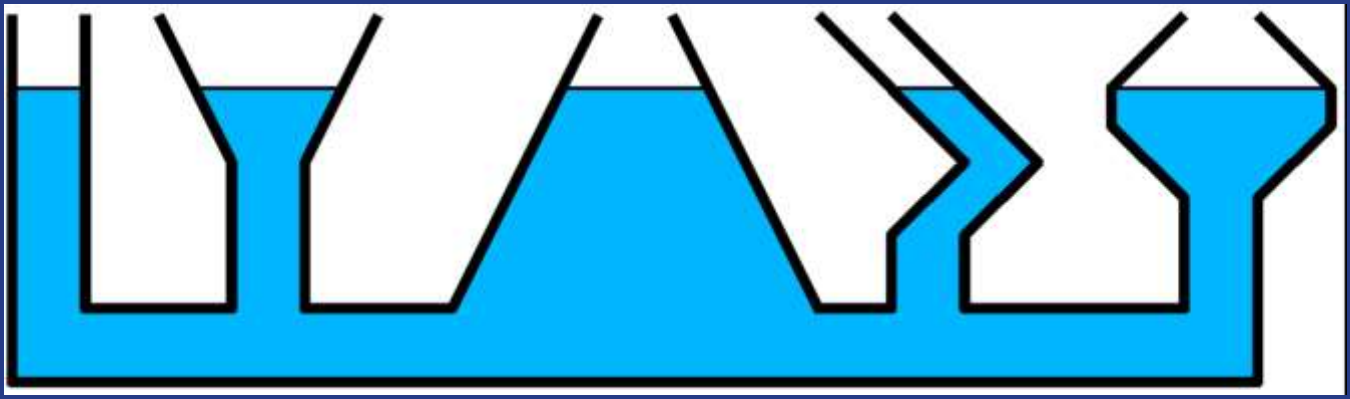
3. Bottleneck springs: These springs originate when an aquifer is narrowed and thus the water pressure is increased. In such cases the water may rise and in place may intersect the surface.



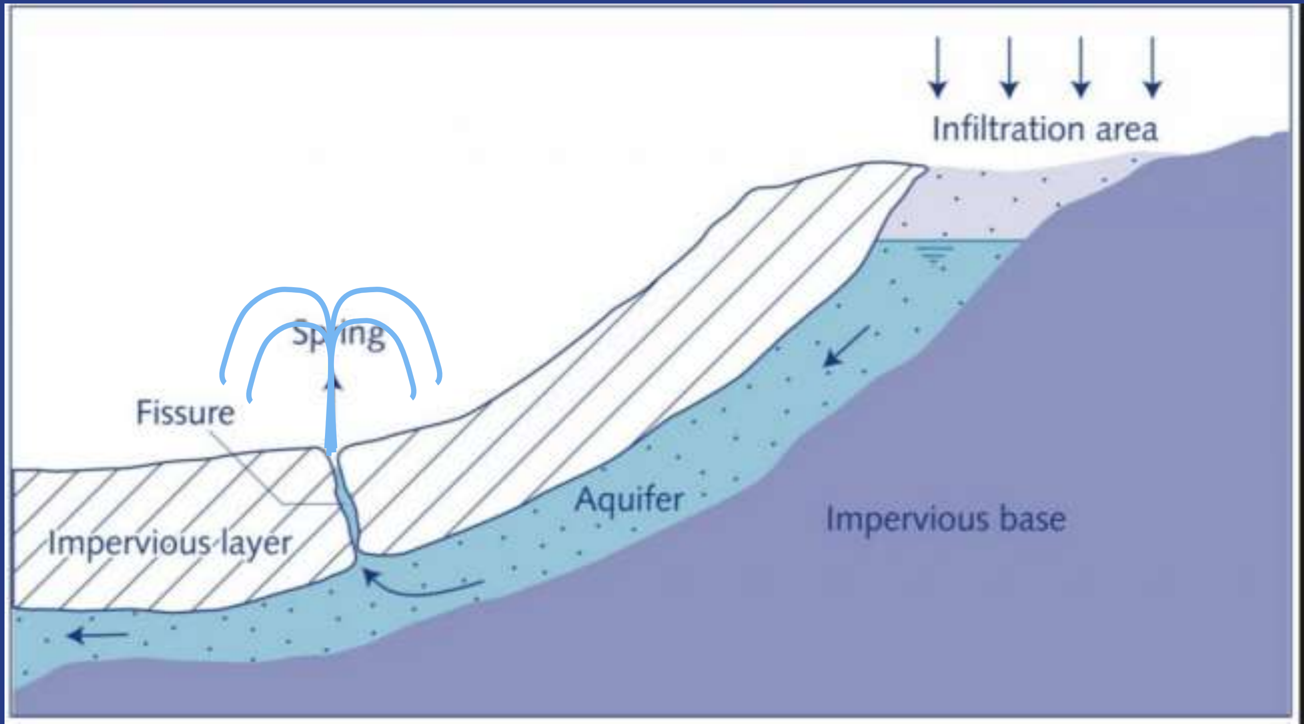
4. Fracture springs: Fracture springs form where the aquifer consists of fractured rock and the water table intersects the topography because of one or more of the fractures forming the aquifer.



5. Artesian springs: As pointed out earlier, these operate under the principle of communicating vessels



Communicating vessels (remember Pascal's principle)

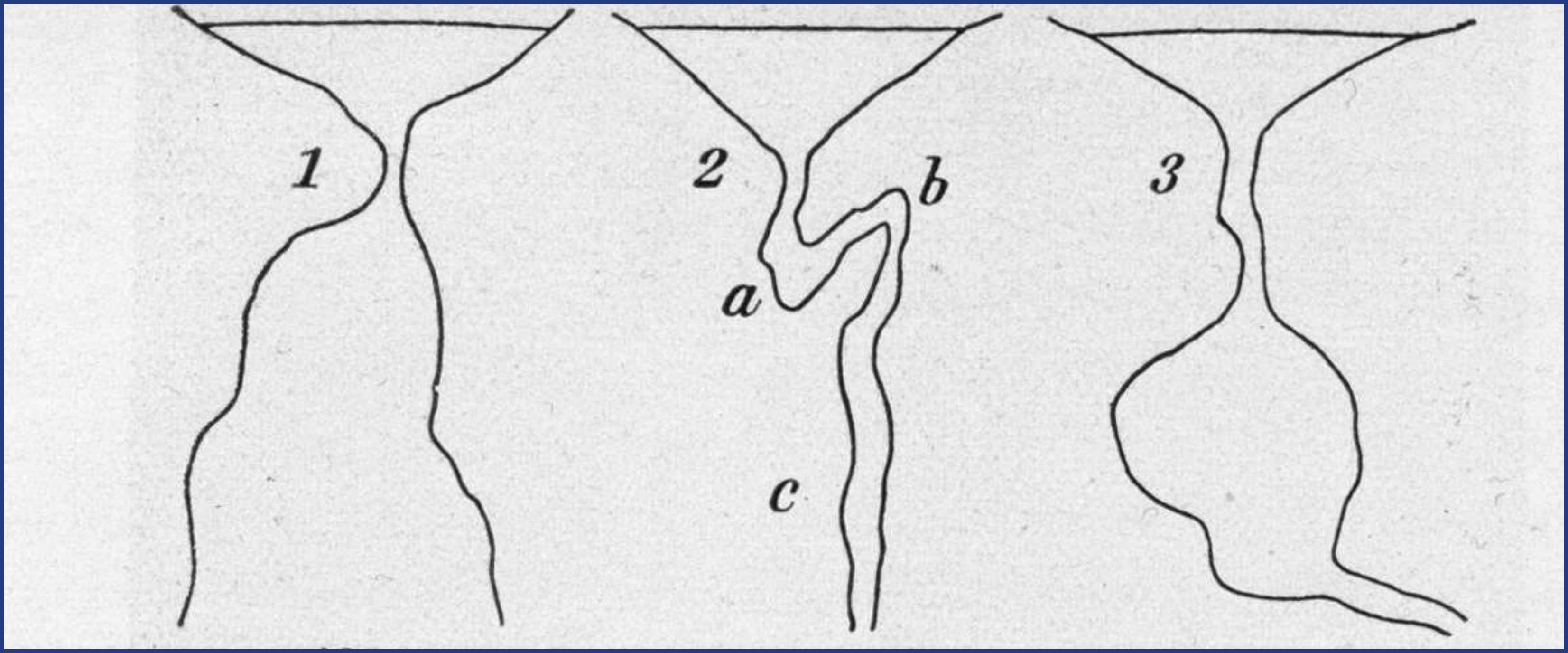


6. Fountaining springs or gushers: These are springs of that gush out either because of high-rate or CO_2-laden waters erupting or because of geyser making the spring erupt into fountains.

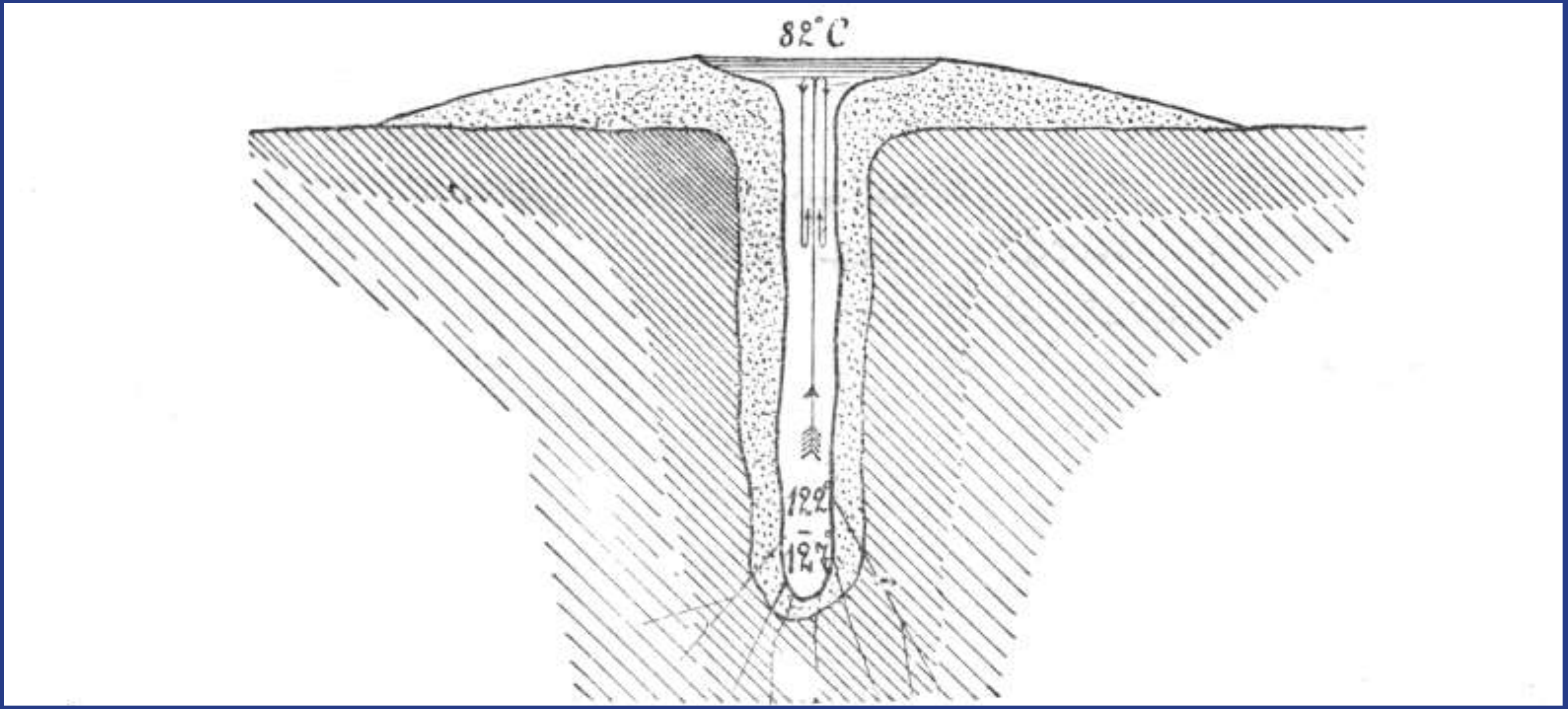
The gushing spring of Deildartunguhver in Iceland.

The “Old Faithful” geyser in the Yellowstone National Park, Wyoming, USA

The “Great Geysir” or “Stori Geysir” in Iceland. The technical term geyser comes from the name of this great gusher. Unfortunately the Great Geysir stopped erupting in 1916. The only other eruption known occurred in 1935. Its greatest eruption occurred in 1845, when it erupted a water column 170 metres high.



Internal structure of geysers (from Kayser, 1923). What causes the eruptions is the inhibition of convection in the entire water column because of irregularities in the geyser chamber. This leads to the accumulation of overheated water under pressure in the lower parts of the chamber. When finally some bubbles are built, they push a bit of the water out of the geyser basin above reducing the pressure over the overheated chamber, leading to catastrophic boiling and eruption.



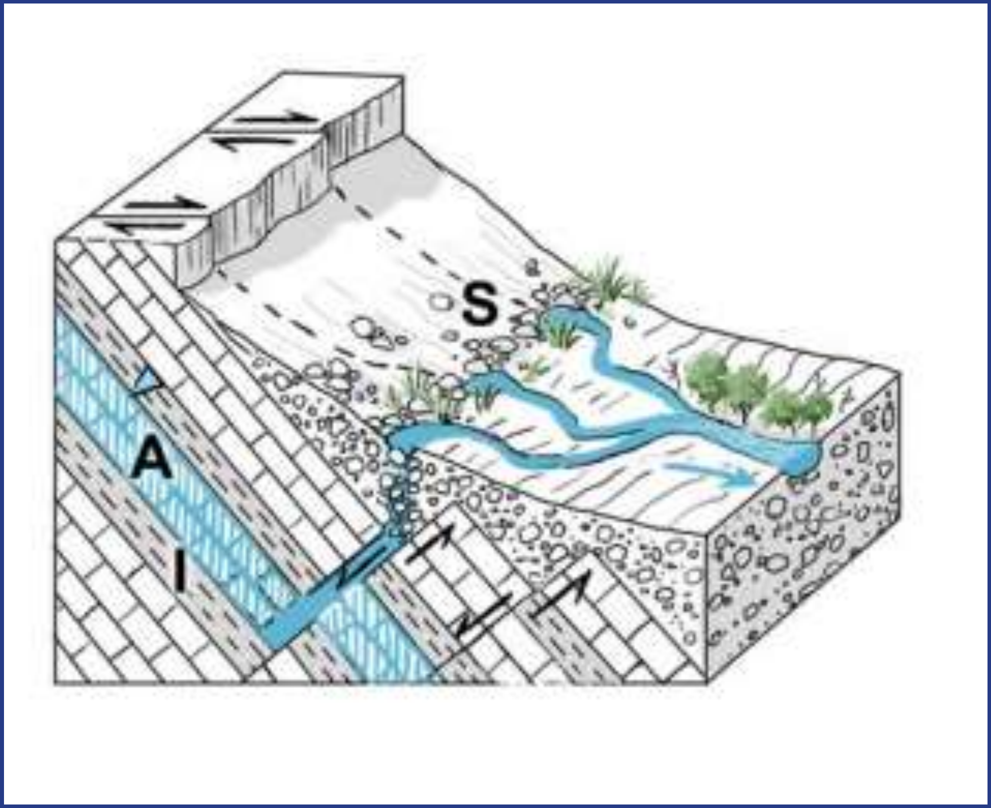
An impossible geyser geometry.
This geyser can never erupt.
Can you tell why?

The eruption of the "Old Faithful" dying down

The upper geyser basin in the Yellowstone National Park, Wyoming, USA

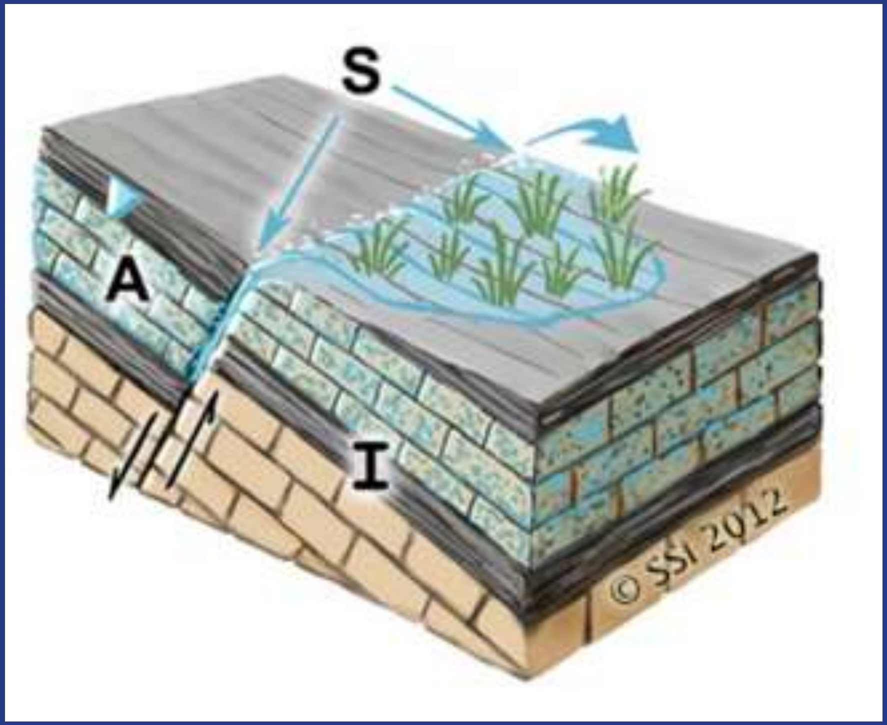
Classification according to the morphology of the spring area

1. Rheocrene springs: those that emerge into one or more streams. They can be flowing springs or gushers



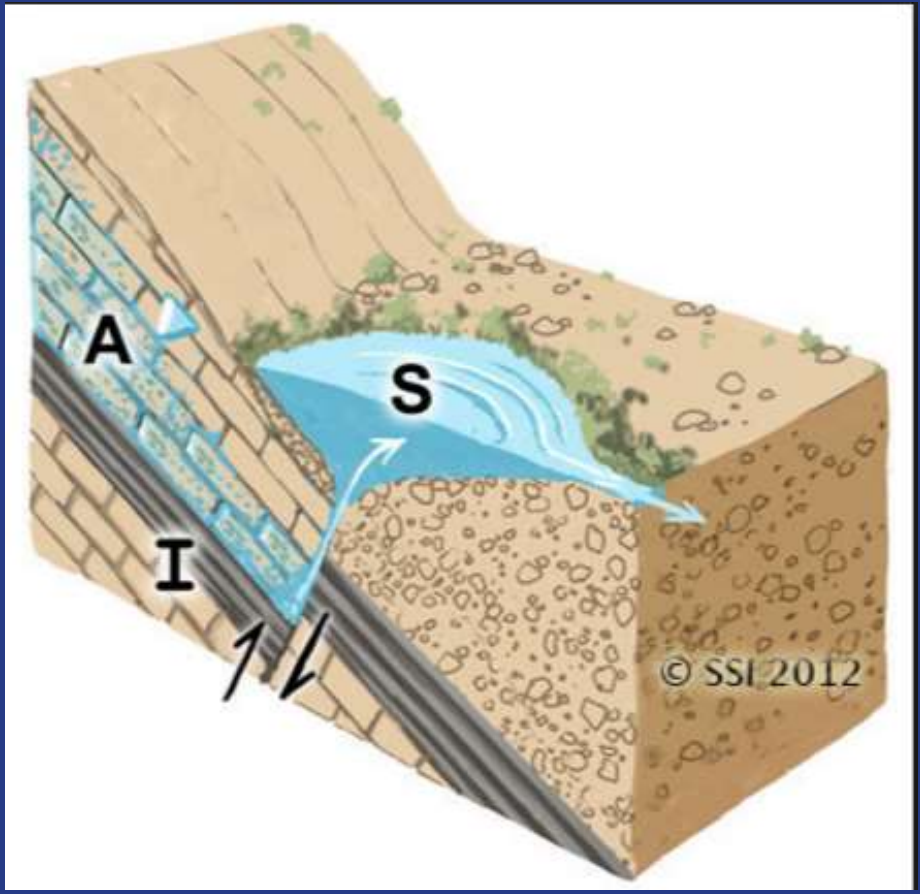
The term rheocrene is derived from the Greek ‘ρέο (*reo*=to flow) and κρήν (*kren*=fountain) and was introduced by the German scientist K. Bornhauser in 1913.

2. Helocrene springs: those emerging into swamps, marshlands and bogs. They emerge in low gradient wetlands and are commonly indistinct or multiple sources seeping from shallow, unconfined aquifers. The term was also introduced by Bornhauser and was derived from the Greek έλος (elos=marsh) and κρήν (*kren*=fountain).



Pinto hot spring in Black Rock Conservation Area, Nevada, USA. A helocrene spring

3. Limnocrene springs: those that emerge in pools and small lakes. The term was introduced by Bornhauser and is derived from the Greek λίμνη (*limne*= pool of standing water) and κρήν (*kren*=fountain).

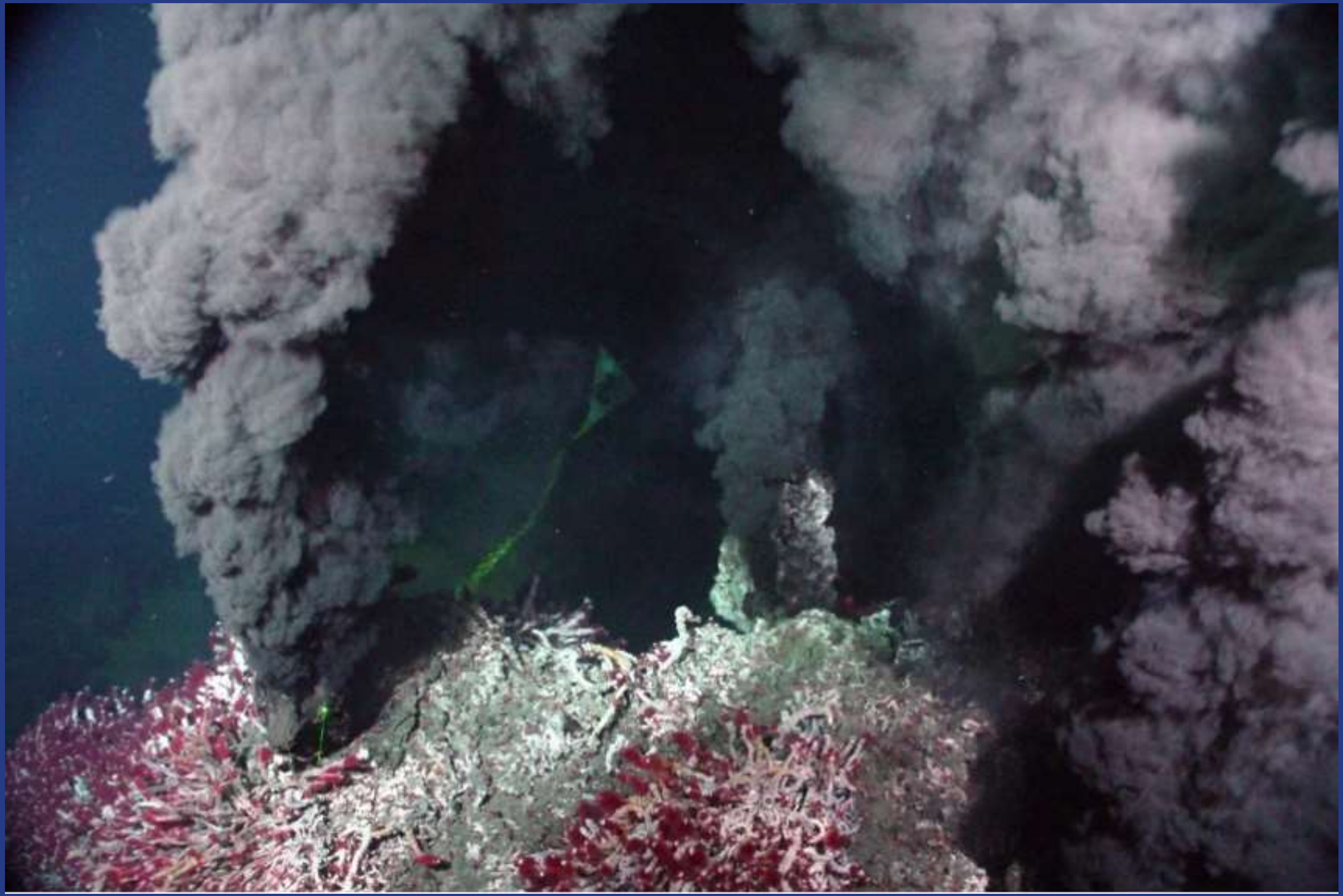


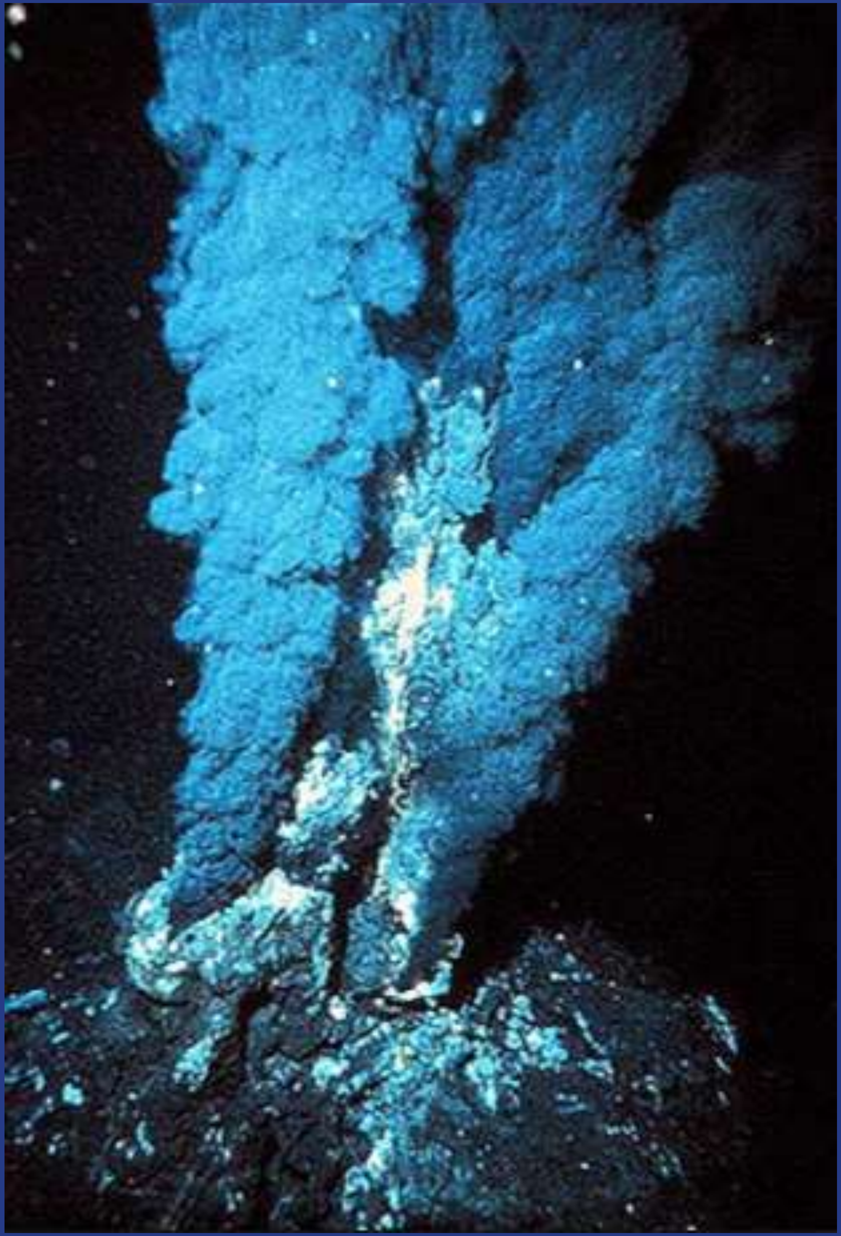
The Montezuma Well, central Arizona, USA. A limnocrene spring.

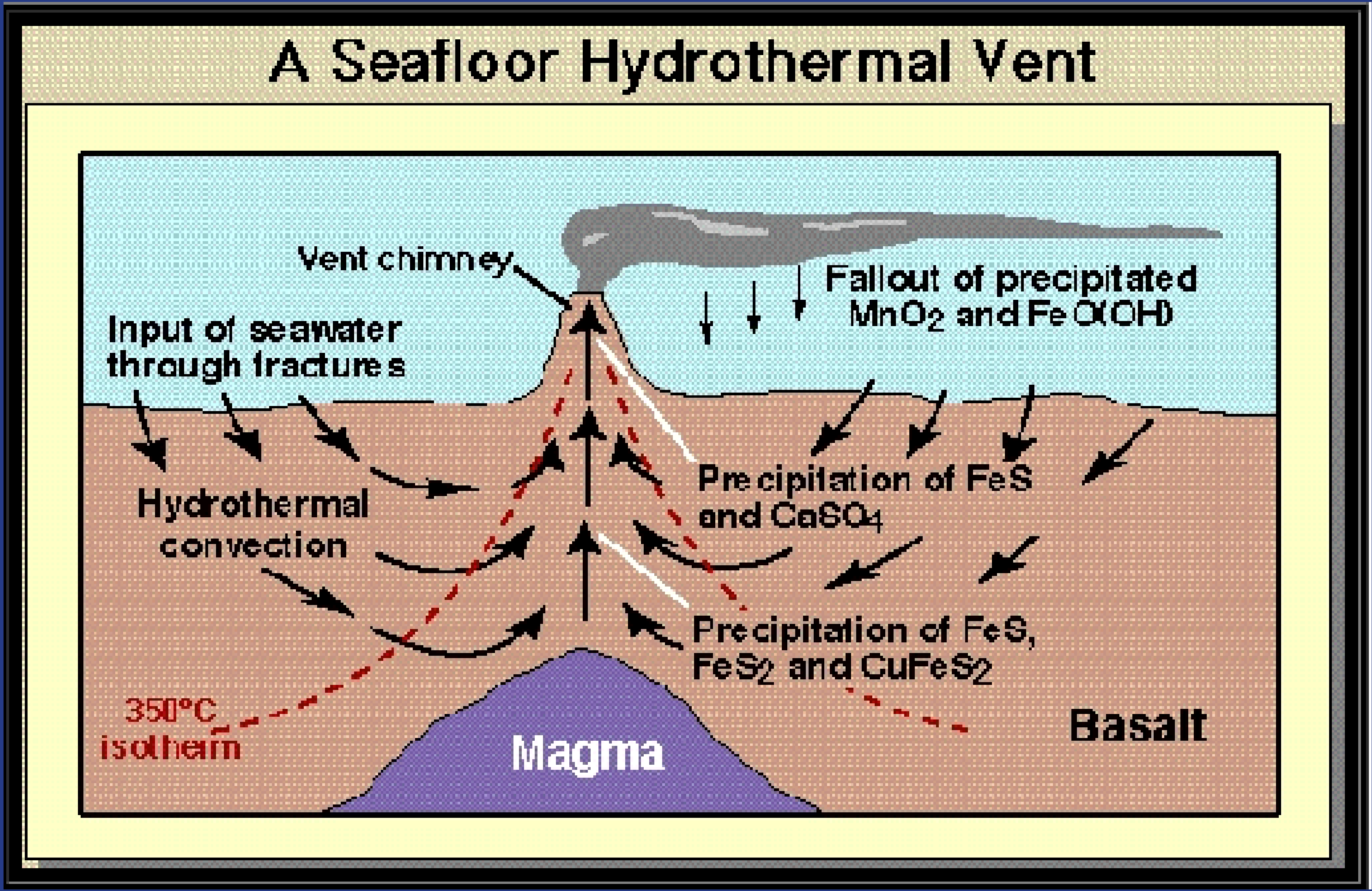
4. Hypocrene springs: these are springs whose waters do not reach the surface for a variety of resons (high evaporation, subterranean pools etc.). The term seems to be introduced by Springer et al. in 2008 and comes from the Greek ὑπό (*uepo*= from under, deep) and κρήν (*kren*=fountain).

A hypocrene spring (how does it differ from an aquifer?)

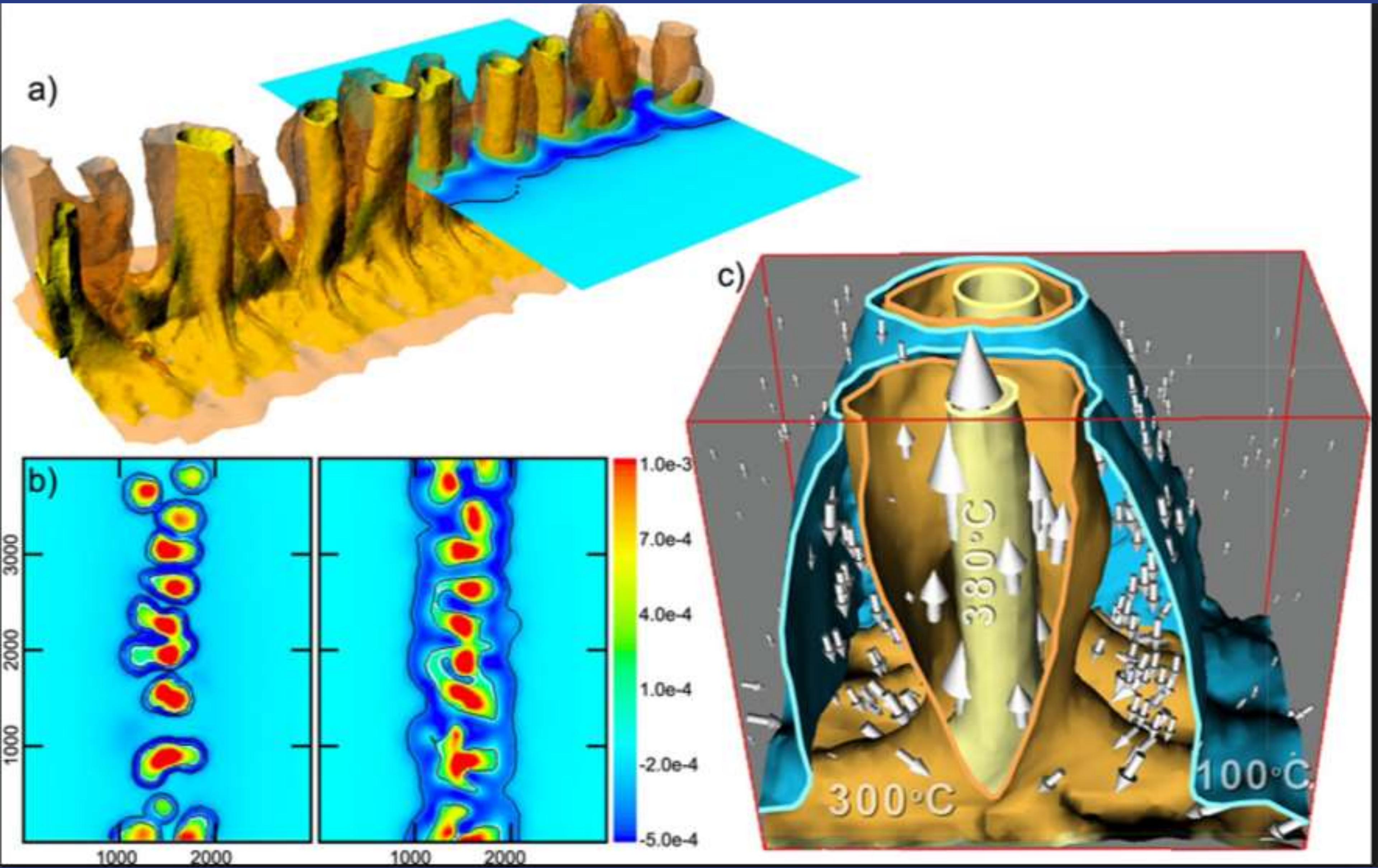
5. Submarine springs: These are springs that are active on the sea-floor. The most famous of these are the hot springs along the mid-oceanic ridges. Their temperature can go up to 400°C.







The origin of the “Black Smokers”



Internal structure of black smokers

A submarine spring in the Sea of Marmara, along the northern branch of the North Anatolian Fault