Lesson 8

Surface processes and sedimentary rocks

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In lessons 1 through 7 we have looked at the structure of the earth, its minerals and the igneous rocks. Discussion of the igneous rocks gave us opportunity to talk about some internal processes and especially the structure of the continental crust. The topics covered included volcanism and the structure of volcanic edifices, intrusions, faulting and contact metamorphism that provided an introduction into metamorphism.

Igneous rocks are, so to say, the “primary material” of our planet. The materials predating them are not preserved. They were remelted and provided our earliest igneous rocks that date back to 4300 million years.

Igneous rocks generate the metamorphic rocks through such mechanisms as metamorphism and metasomatism. But metamorphic rocks can be made up of sedimentary rocks as well. So, before we talk about metamorphic rocks in detail, we need to consider the sedimentary rocks.

Rocks on earth and in other places in space form by means of three processes:

1. Agglomeration in space of space dust ("cosmic dust") that forms in stars and in supernovae. All stars and planets form through this mechanism that had begun with the Big Bang.

2. Internal processes of planets (on earth this is called internal geodynamics)

3. External processes of planets (on earth this is called external geodynamics)

The internal processes on any planet or any other space object such as a star are the procesess that derive their energy from the object itself without any outside contribution. On earth, internal processes drive plate tectonics and the mantle convection, including the mantle plumes and consist of the following phenomena seen at the surface:

1. Fast events (time scale from a few seconds to a few days; at most months)

A. Earthquakes

B. Volcanism (in English also vulcanism or vulcanicity)

2. Slow events (time scale from hundreds of years to millions of years)

WISON CYCLE OF OCEAN OPENING AND CLOSING

A. Plate boundary phenomena

I. Orogeny (mountain-building)

II. Taphrogeny (rift-building)

III. Thallasogeny (ocean-building)

IV. Keirogeny (horizontal shear-belt-building)

Mainly horizontal motions

B. Plate interior phenomena

I. Mantle plume-related events

II. Purely isostasy-related events

Mainly vertical motions

The external processes on any planet or any other space object such as a star are the procesess that derive their energy from outside the object itself without any inside contribution. On earth, external processes derive their energy from the Sun and are divided into erosion and deposition phenomena seen at the surface. The erosion and deposition occur through the following family of processes:

1. Weathering: Weathering is the mechanical and chemical disintegration of rocks producing regolith.

2. Fluvial processes: Fluvial processes are those caused by flowing water.

3. Groundwater processes: These are processes caused by groundwater. Their chief representatives are processes of rock dissolution, called karstic processes.

4. Glacial processes: These are processes caused by flowing ice (glaciers, inland ice caps)

5. Periglacial processes: These are processes that result from seasonal freezing and thawing of the ground.

6. Eolian processes: These are processes of erosion and deposition caused by wind.

7. Coastal processes: These are processes that take place along the interface between large water bodies such as lakes, internal seas and oceans and land. Stream margins are not a part of the coastal processes, but are studied under fluvial processes.

8. Subaqueous processes: These are caused by events taking place in large water bodies, such as sediment deposition by various processes such as precipitation, settling, and current flow. Erosion also takes place under water.

9. Mass movements of diverse types both subaerial and subaqueous.

According to the processes that create them, the rocks therefore are grouped under four major classes:

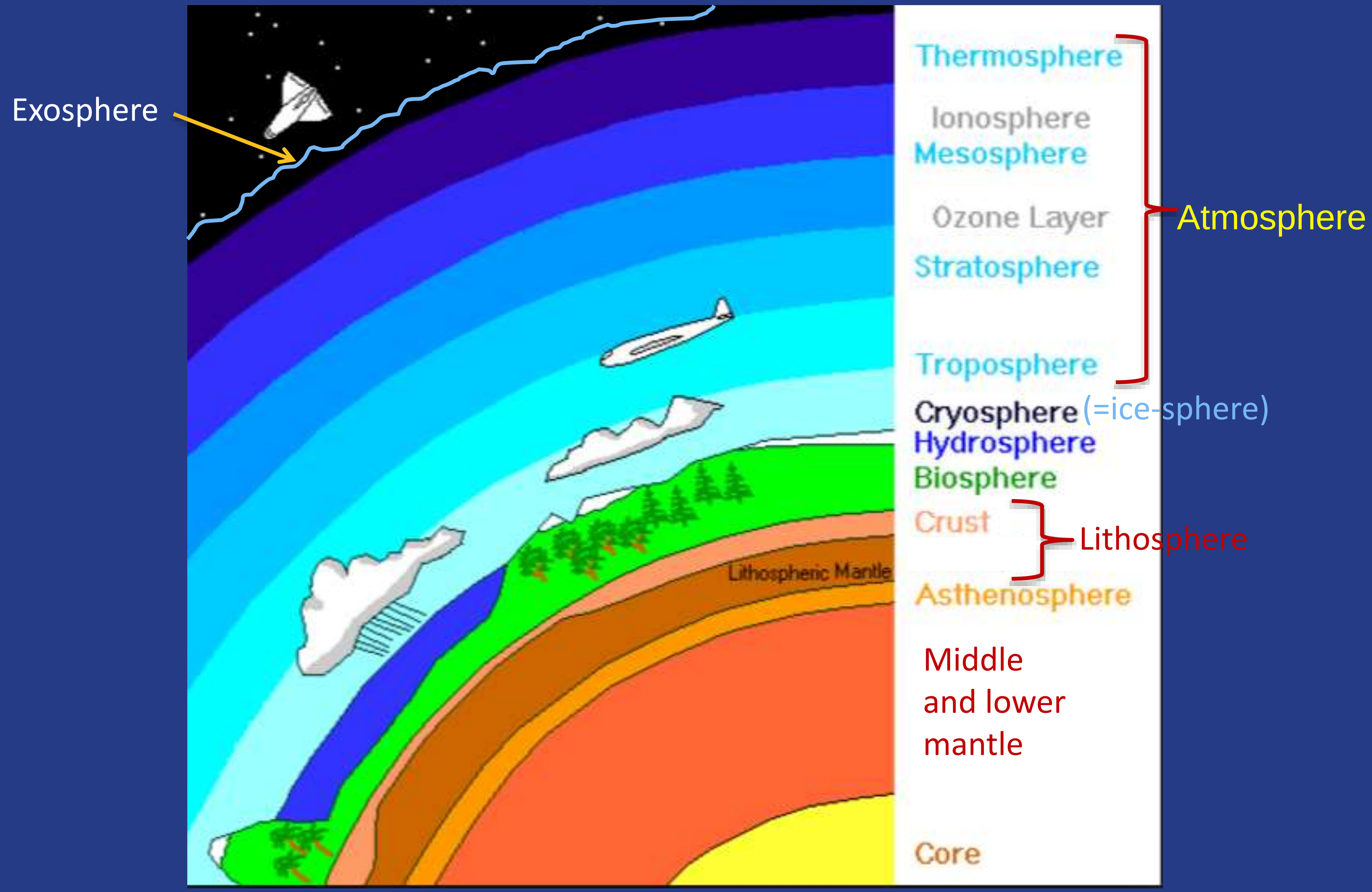
1. Magmatic rocks that slowly crystallise creating crystalline substances or are rapidly quenched to create glasses from magma.

2. Sedimentary rocks are formed from mechanical or chemical precipitation from a liquid or gaseous or fluid medium such as air or water or ice.

3. Metamorphic rocks are those that change their composition and/or their texture without any melting. Metamorphic rocks form through solid metamorphosis of other types of rocks.

4. Structural rocks are those rocks formed by structural processes such as faulting or in ductile shear zones. They form either by granulation or plastic flow processes.

Sedimentary rocks are created by external processes with some help from volcanism. In our list there is one item not mentioned among the external processes and that is life. Life has existed on this planet since 3800 million years ago and has always been a big player in rock making processes at the surface of the earth. In fact, in 1875, Eduard Suess considered life an independent earth-sphere and called it the biosphere located at the interface between the lithosphere and the atmosphere (and including the hydrosphere). Let us remember the earth-spheres:



Earth-spheres

THE ATMOSPHERE

From the Greek ἀτμός (atmos=vapour) and σφαῖρα (*sphera*= sphere)

The mass of the earth's atmosphere is about 5.15×10^{18} kg and dry air consists, by volume, of 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide and minute amounts of other gases. At sea-level, it usually contains 1% water vapour, but this is highly temperature dependent. Overall, the atmosphere contains 0.4 % water vapour. Because of the compressibilty of gases, three fourths of the earth's atmosphere is contained within the first 11 km above the surface of the planet.

The Kármán Line, about 100 km above the earth's surface is usually considered the boundary of the atmosphere against the outer space. Above this height

Ionosphere: This is the outermost layer of the atmosphere of the earth and contains the exosphere, the thermosphere and a part of the mesosphere. The ionosphere is a layer of electrically charged particles and also forms the lower part of what is called the magnetosphere (which is not a part of the atmosphere). It extends from about 50 km elevation to almost 10,000 km! But practically it ends at about 600 to 1000 km elevation depending on the solar activity.

Exosphere: This is the outermost layer of our atmosphere and, by thinning out, it merges with the outer space. Here the atmospheric molecules are gravitationally bound to the earth, but cannot behave like a gas by colliding with one another, because there are too few of them. Thus, this part cannot have any pressure. The earth loses volatiles (e.g. H_2O, C_2O, O_2 etc.) through the exosphere. The term comes from the Greek ἔξω (*exo*=outer, external, beyond) and σφαῖρα (*sphera*= sphere). The base of the exosphere (called “exobase”) ranges from 600 to 1000 km above the surface of the earth and is dependent on solar activity. The exosphere may extend up to 10,000 km above the earth’s surface.

Thermosphere: This is the layer that begins at about 85 km above the earth's surface and extends to the exobase. In it, temperatures increase with altitude because of absorption of highly energetic solar radiation and the temperatures here may rise up to 2000°C. The radiation ionizes the atmospheric atoms here and the radio waves bounce off it and thus go around the earth instead of being radiated into space. Although the gases in the thermosphere are so hot, the heat cannot be felt because of the extreme rarity of the gases. Above 160 km, the gas content is low that sound waves cannot be transmitted.

The name thermosphere is derived from the Greek θερμός (thermos=heat) and σφαῖρα (*sphera*= sphere)

Mesosphere: The mesosphere extends between 50 km and 85 km and is the coldest and the most poorly-known part of the atmosphere ("ignorosphere", i.e., sphere of ignorance), because it lies above the highest balloon range and below the lowest orbiting spacecraft. In its upper parts, temperature falls to -100 °C. The mesosphere is also the highest layer in which the atmosphere is uniform owing to turbulent flow.

Strong east-west winds dominate the weather in this layer. This is also the layer where noctilucent clouds form (furm the Latin *noctis* (=night) and *luceat* (=to shine). These are ice clouds.

The name comes from the Greek μέσος (mesos=middle) and σφαῖρα (*sphera*= sphere).

The lowest part of the thermosphere, the mesosphere and the stratosphere are collectively known as the middle atmosphere.

Noctilucent clouds seen over Estonia. These clouds form directly from water vapour from 75 to 85 km height.

Stratosphere: This is the layer that extends about 10 km to 50 km height in the atmosphere. It was discovered by the French meteorologist Léon Teisserenc de Bort in 1901. He derived the name from the Latin *stratum* = layer and the Greek σφαῖρα (*sphera*= sphere)

It is in the middle of this layer that the ozone cover of the earth forms. In the stratosphere the temperature increases from bottom to top forming a temperature inversion which results from the formation of the ozone.

The stratosphere has very little turbulence, but can influence terrestrial climate by generating strong easterly winds. The jet stream, strong, global westerly winds, form along the tropopause, i.e., the lower boundary of the stratosphere.

Troposphere: This is the lowest layer of the earth's atmosphere and, for geological phenomena, the most important, because most of the weather phenomena that profoundly affects how Sun's energy exercises influence on rocks on the earth's surface and to some depth into the rocky rind of the planet, take place in it.

It was delimited to the lowermost 10 to 17 km of the earth increasing to 20 km in the tropics and decreasing to some 7 km at the poles during the winter. Its delimitation became possible when the French meteorologist Léon Teisserenc de Bort discovered the stratosphere in 1901. It was also he who named the troposphere from the Greek τροπή (trope= a turn, turning) and σφαῖρα (*sphera*= sphere). As altitude increases in the troposphere the temperature decreases.

The American space shuttle *Endeavour* against a background of the earth’s atmosphere: the orange layer is the troposphere, the white is the stratosphere and the blue is the mesosphere.

Earth's climate largely happens in the troposphere and therefore, the troposphere is the geologically most relevant atmospheric layer. External processes are a function of three variables:

1. Climate

2. Structure

3. Time

These determine not only the atmospheric conditions and the duration of such conditions affecting rocks, but also the nature of life in any one given region. Let us look at these three variables plus life in turn:

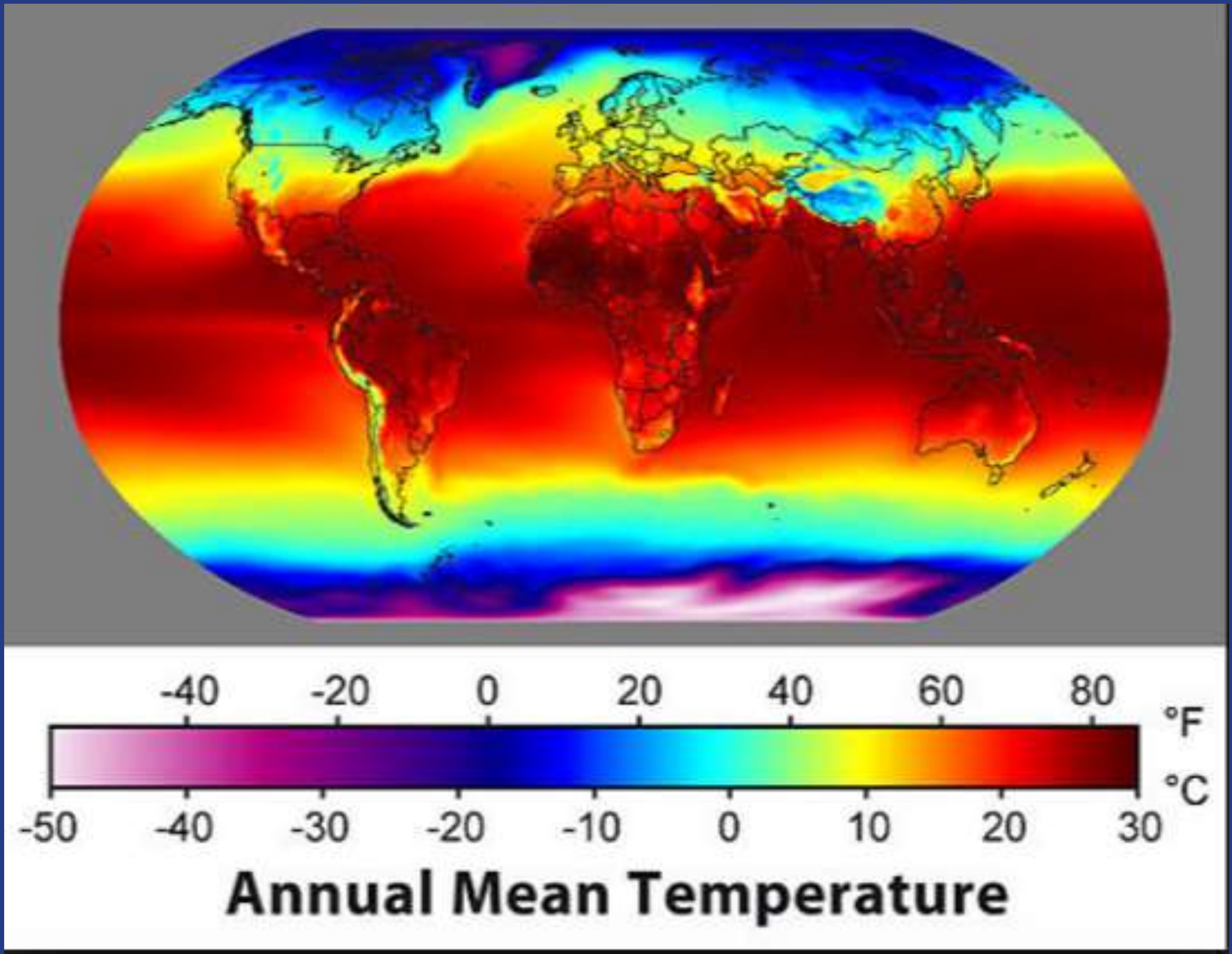
Climate

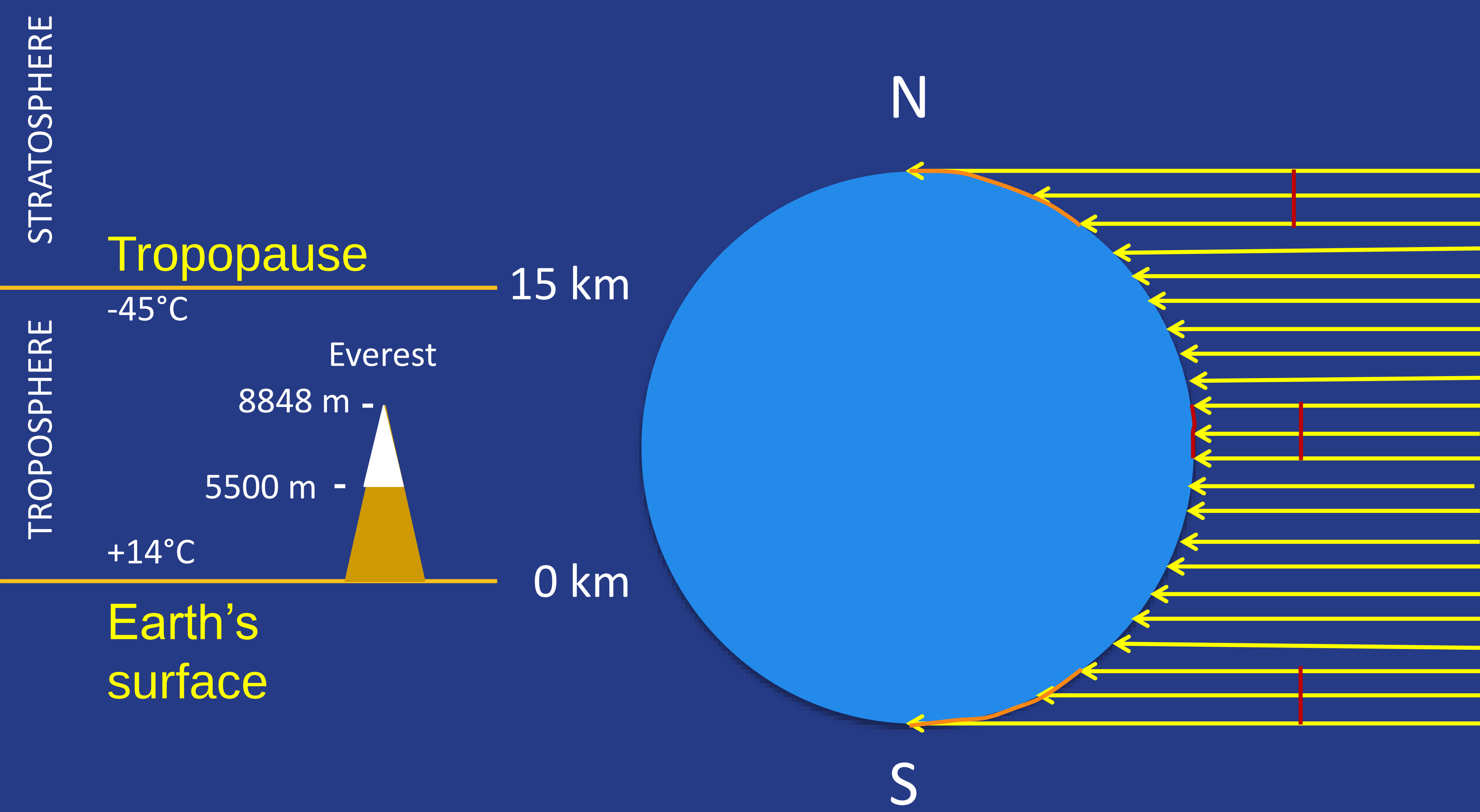
It is said popularly to define climate and weather that

“climate is what you expect, weather is what you get”.

Climate is defined to be the statistical average of the weather conditions usually over a time interval of 30 years. It detemines what kind of weather conditions will reign in any one region and at what time of the year.

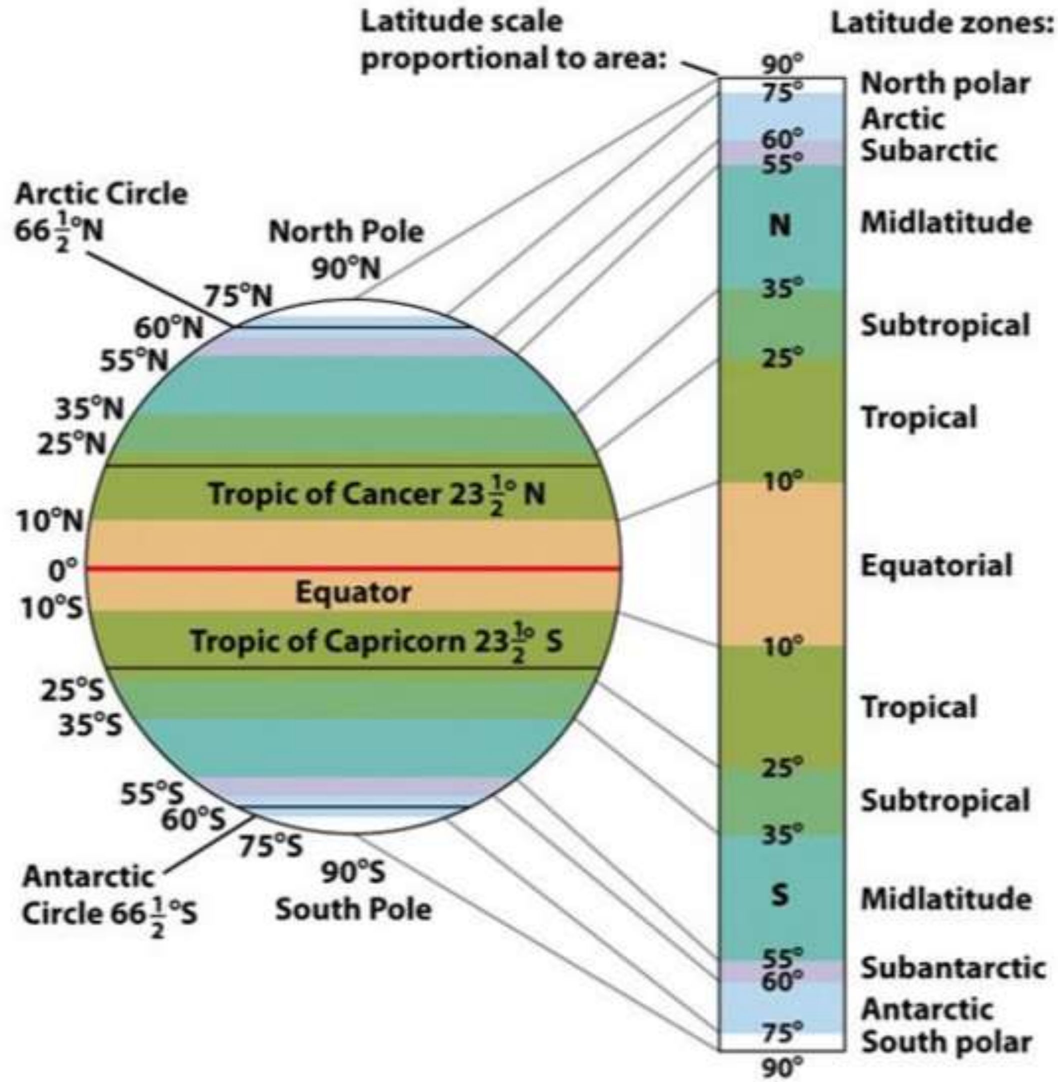
Climate is dependent on air temperature, air pressure (creating winds), humidity and precipitation. These variables change on the basis of latitude, altitude and the presence of water bodies. The French botanist Pitton de Tournefort observed on his journey from Trabzon to Ağrı Dağı during his expedition from 1700 to 1702 that as the elevation increases the climate changes in the same way as if one is going from the equator to the poles, an observation later corroborated and popularised by the great German geographer Baron Alexander von Humboldt in 1804. The reason for this is the temperature decrease as the altitude increases in the troposphere.

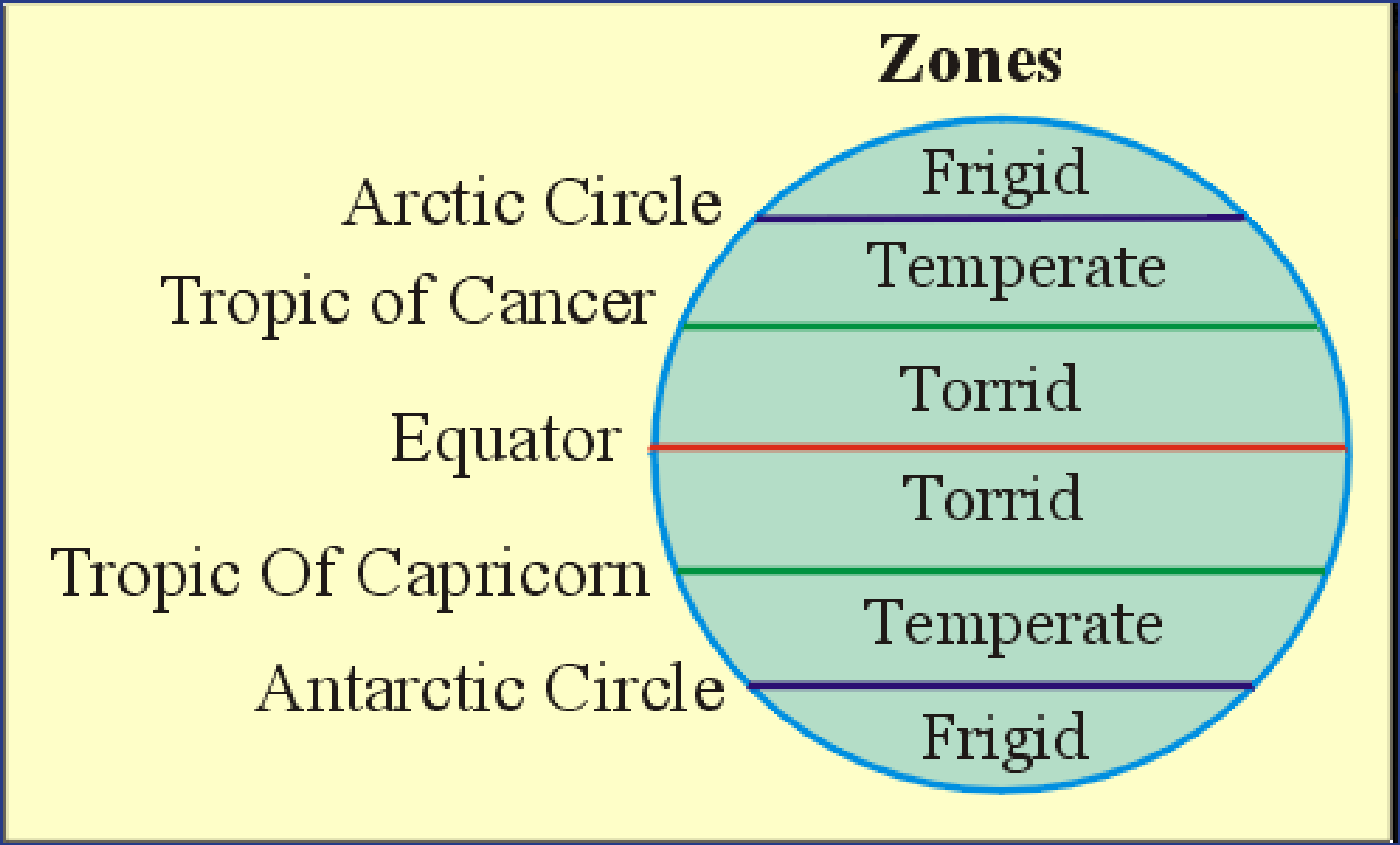

-40
-20
0
20
40
60
80
°F
°C
-50
-40
-30
-20
-10
0
10
20
30
Annual Mean Temperature


STRATOSPHERE
Tropopause
15 km
-45°C
TROPOSPHERE
Everest
8848 m
5500 m
+14°C
0 km
Earth's surface
N
S

World Latitude Zones

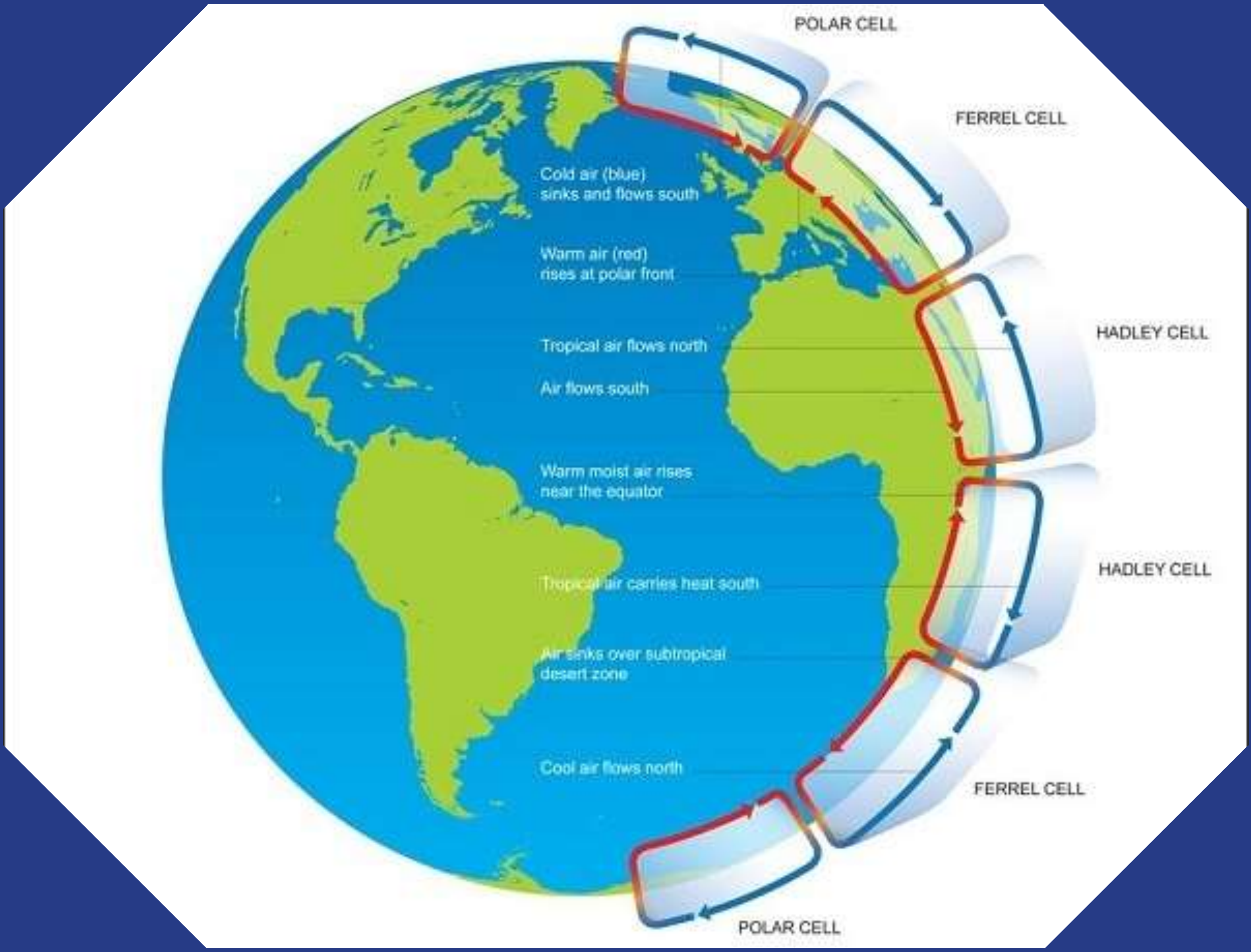
- **Terms used for latitude zones**
- **Generally greater seasonal change with greater distance from Equator**





If the earth were a perfect sphere with a single kind of surface (all water or all land) and no atmosphere, its ideal climatic zonation would have been as shown here. The present climate zonation roughly approximates this, but it is complicated by the atmosphere and the distribution of land and sea.

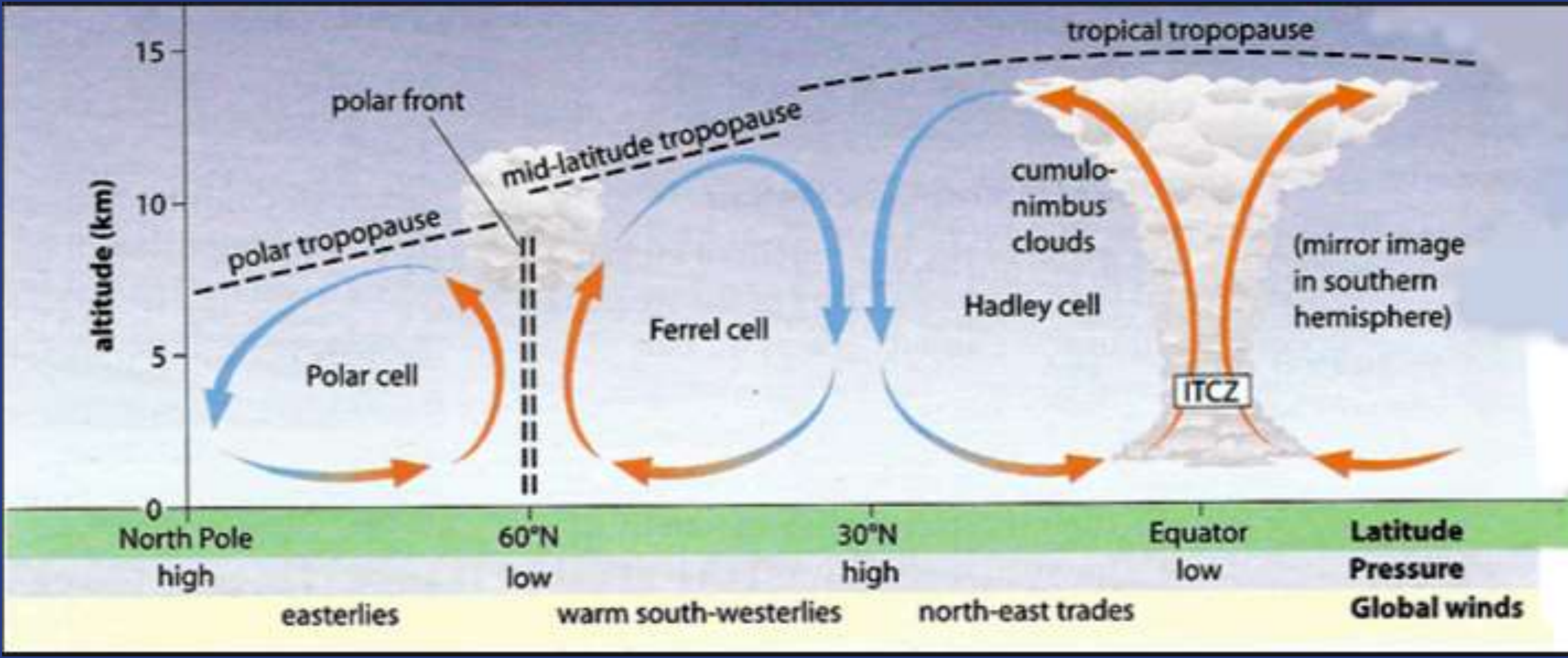
But let us first continue with this simple pattern: The earth's climate is dominated by six convective cells within the troposphere because of the differential heating of the earth's surface:



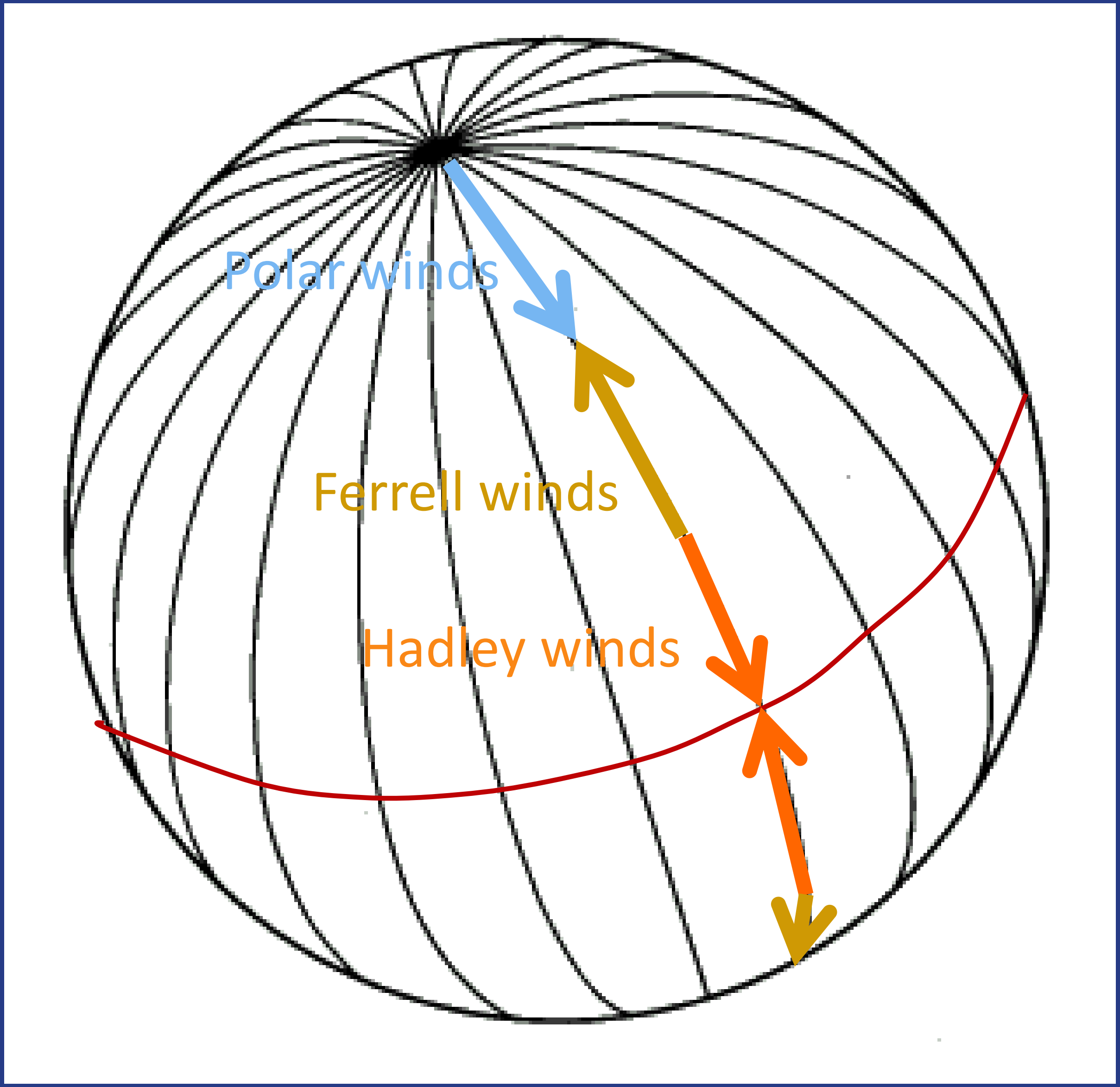
The Hadley Cell, also called the "primary cell", was discovered by the English amateur meteorologist of the early 18th century. Hadley published it in 1753.

His scheme was refined by William Ferrell, an American meteorologist in the nineteenth century. The Ferrell Cell is named after him.

Both the Ferrell and the Polar cells are also called the "secondary cells"

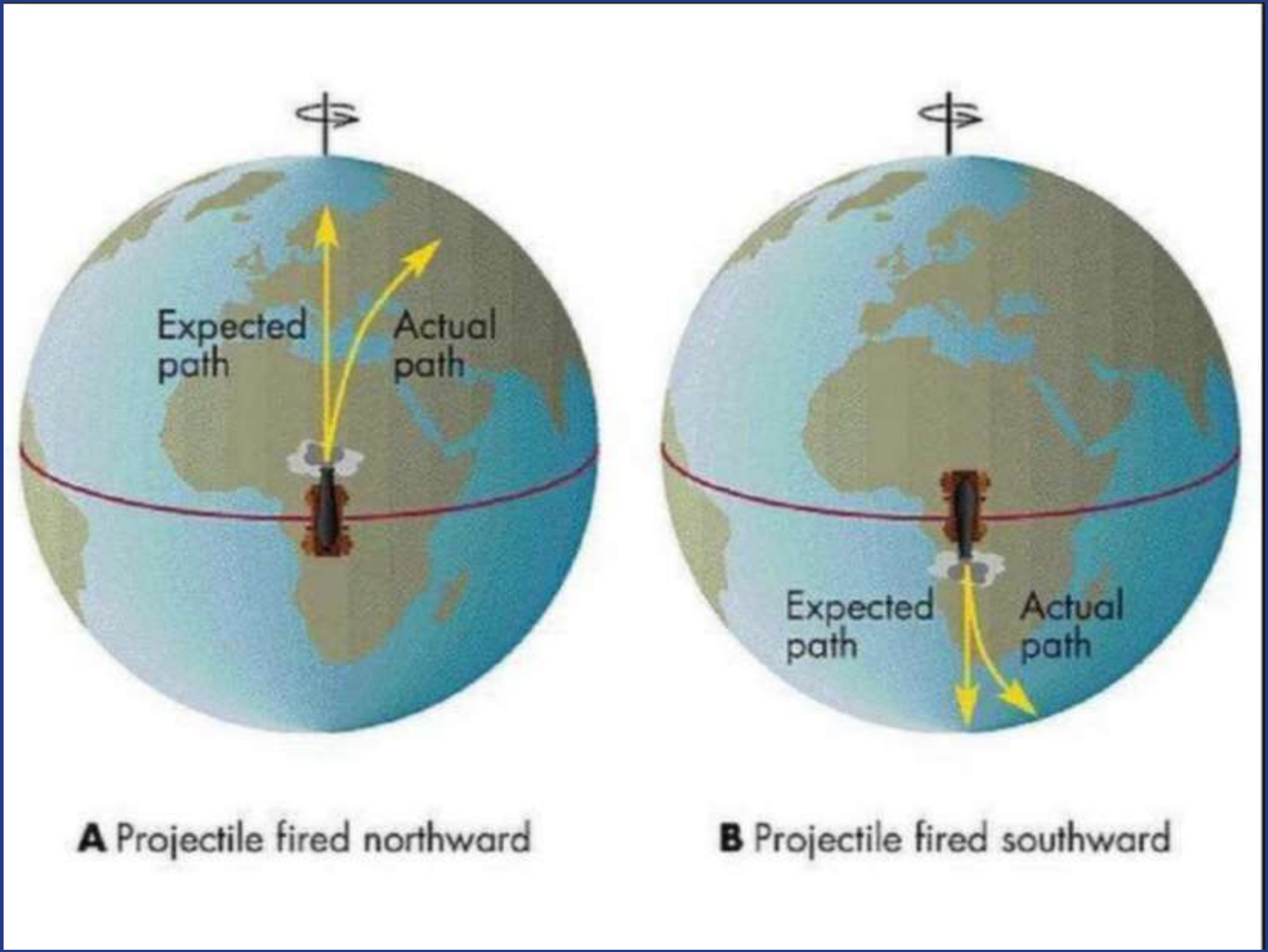


Because the troposphere is thinner over the poles than over the equator, the actual geometries of the three cells look like those shown here.

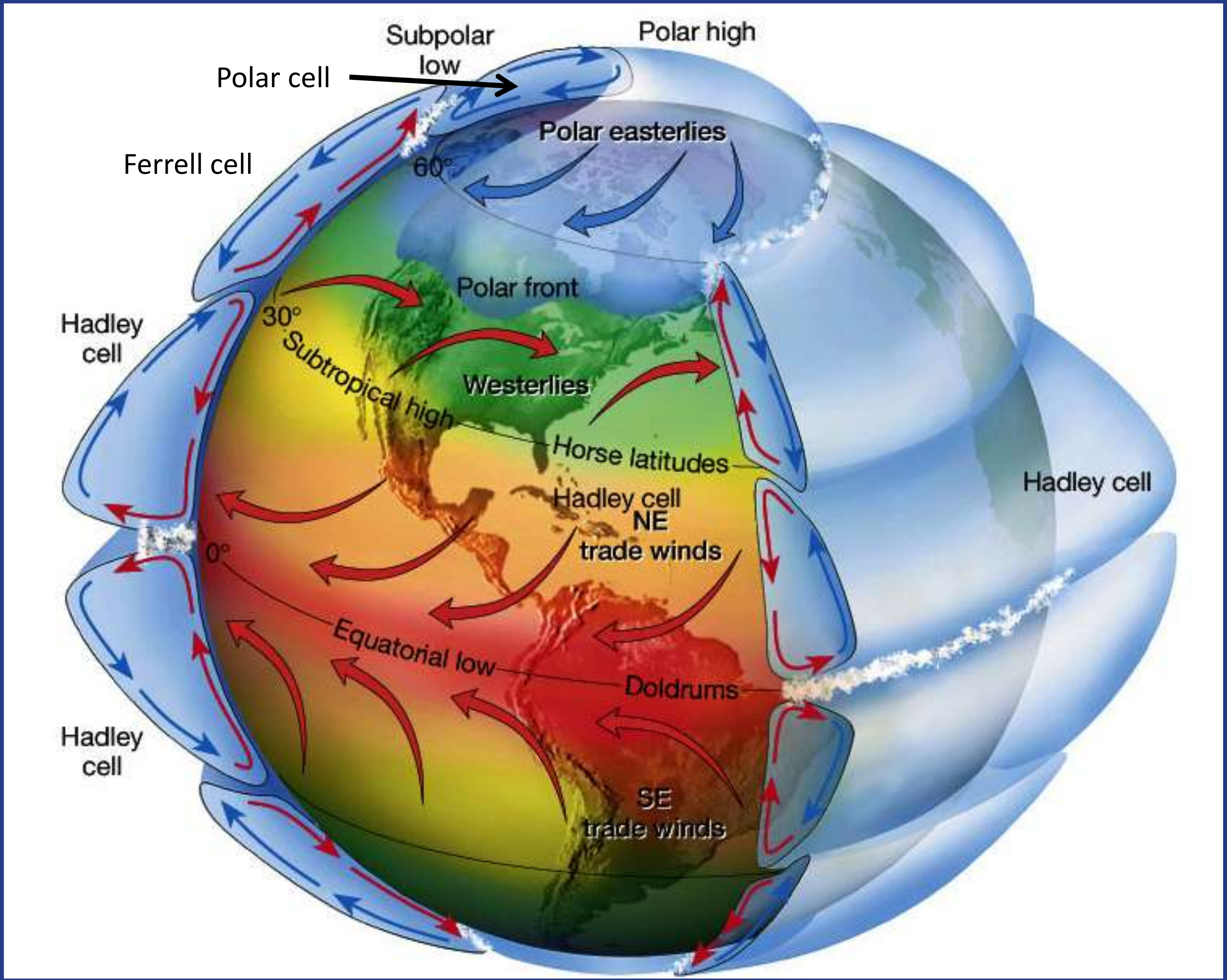


If our earth had not had a diurnal motion, this would have been the pattern of its winds.

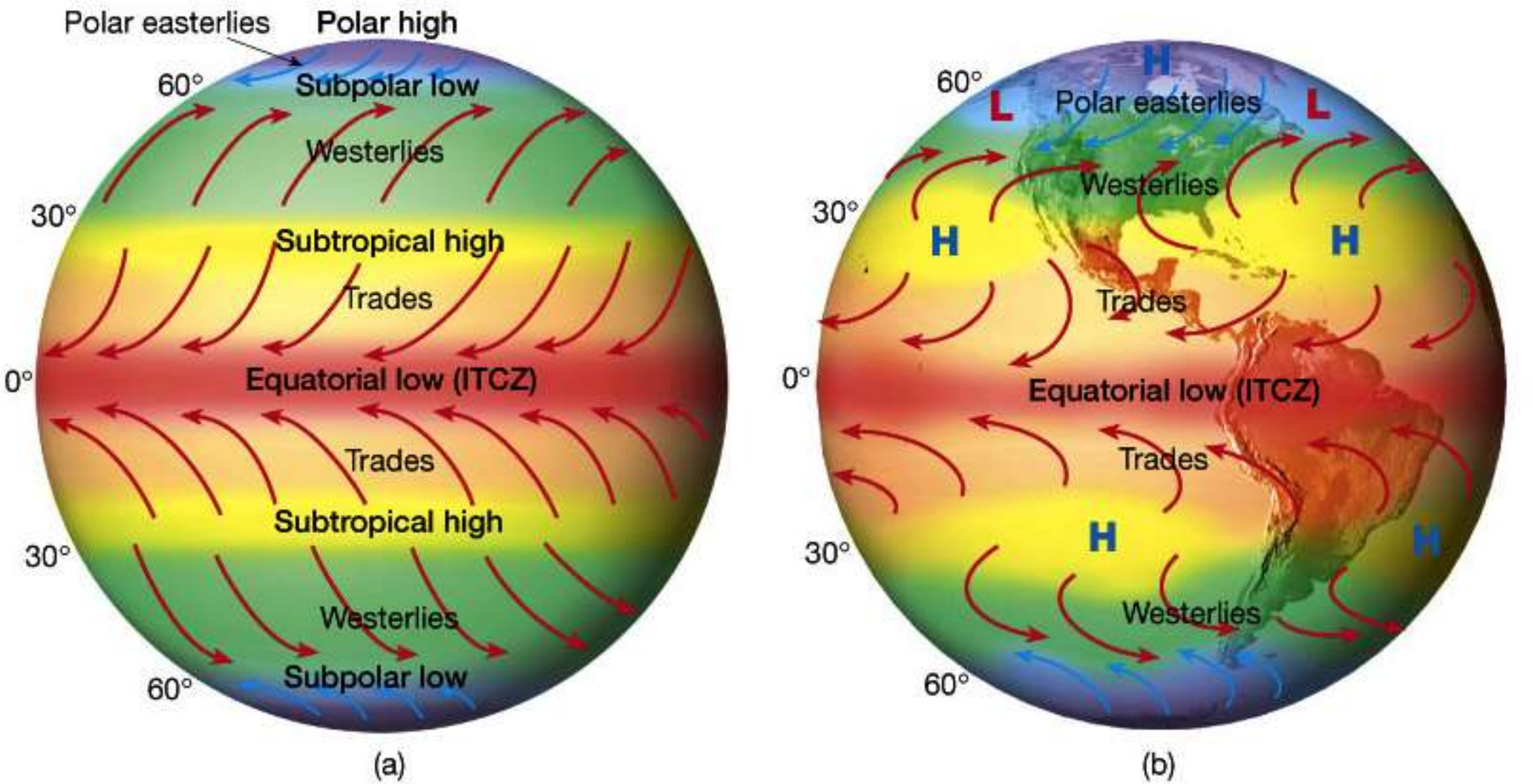
But, because the earth is a rotating sphere, the Coriolis force applies to these winds.



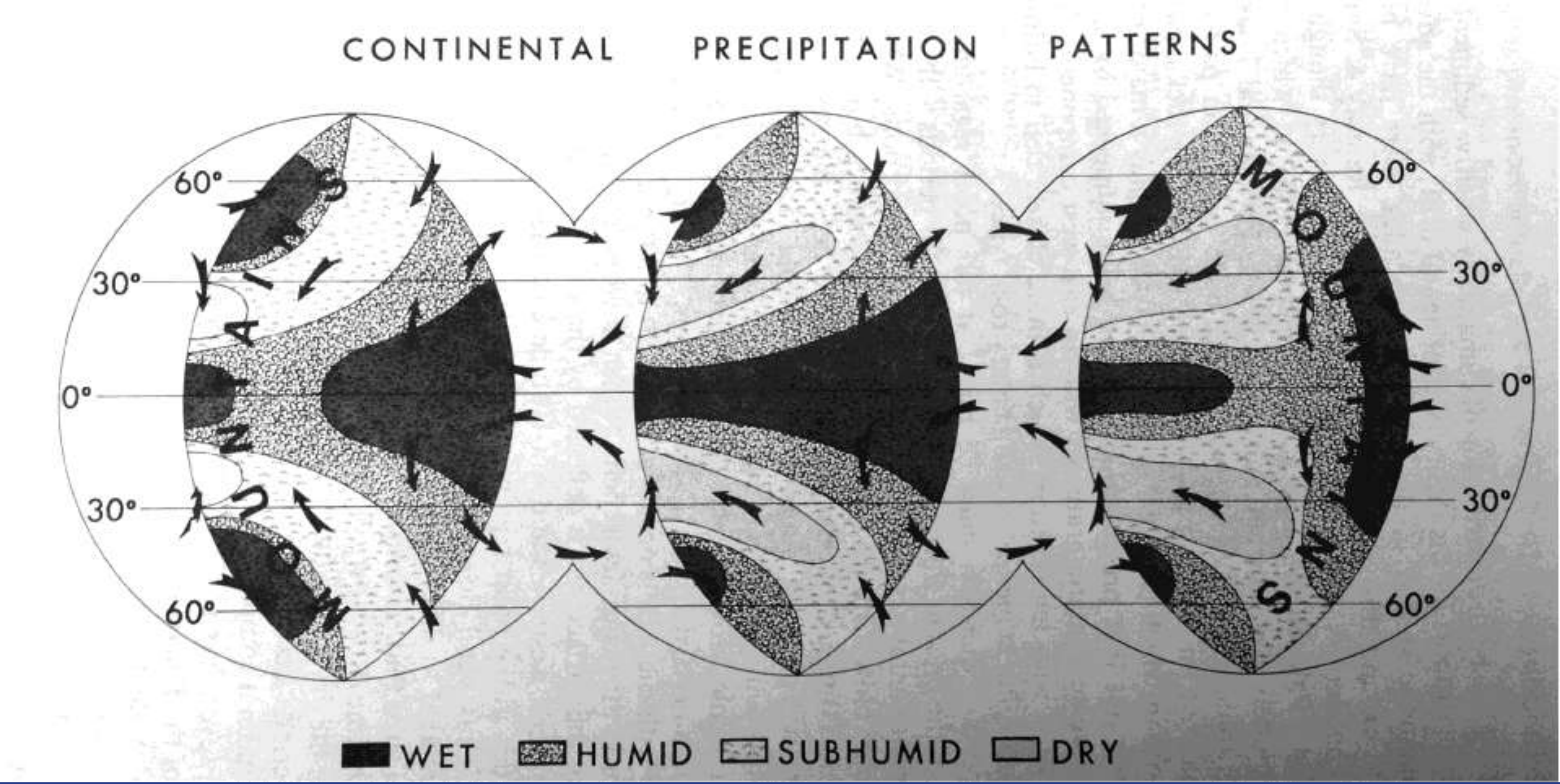
The Coriolis Force was named after the French mathematician and engineer Gustave Gaspard de Coriolis who first derived a mathematical formulation for it in 1835



Because of the earth's rotation and the resulting Coriolis force, the winds are deflected.



But even the Coriolis deflection cannot fully account for the actual directions of the principal winds. The map on the left shows the wind pattern if it were only governed by the convective circulation and the Coriolis force. The one on the right shows what happens when one introduces the present-day continents.



Idealised precipitation patterns of the present-day continents. Notice that here only the relationship of precipitation to the winds is shown. We shall see why that is so soon. From Ziegler et al., 1979.

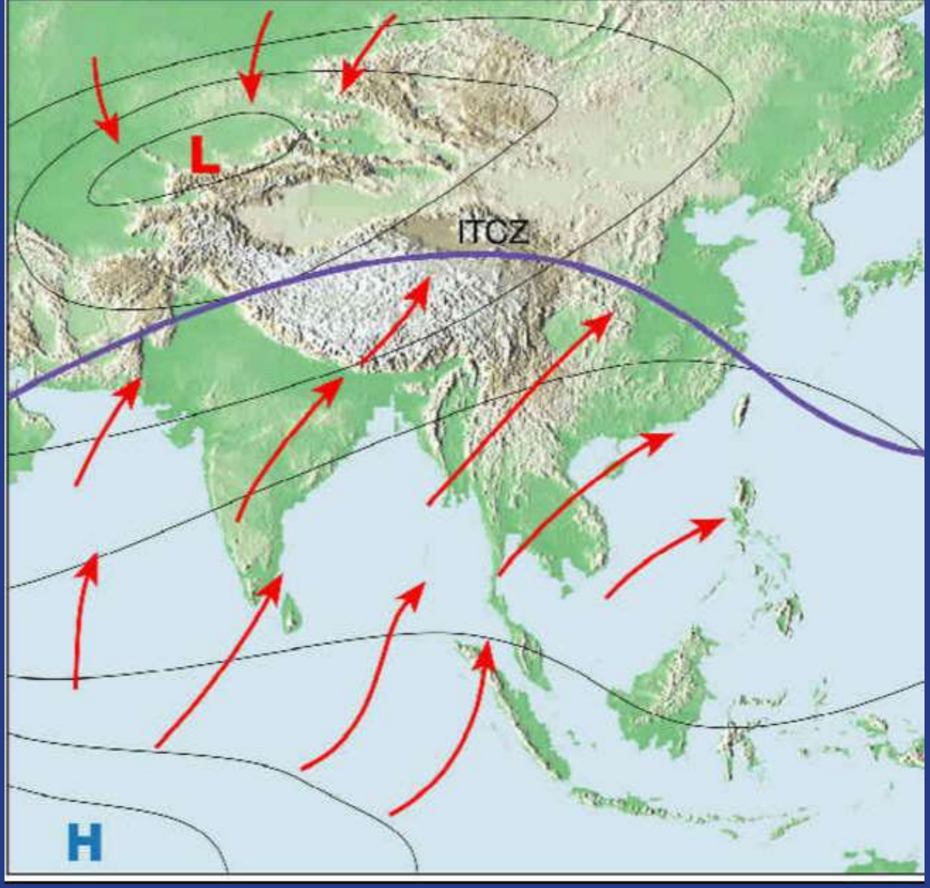
There are also other, local winds. The most important of these is the Asian monsoon.

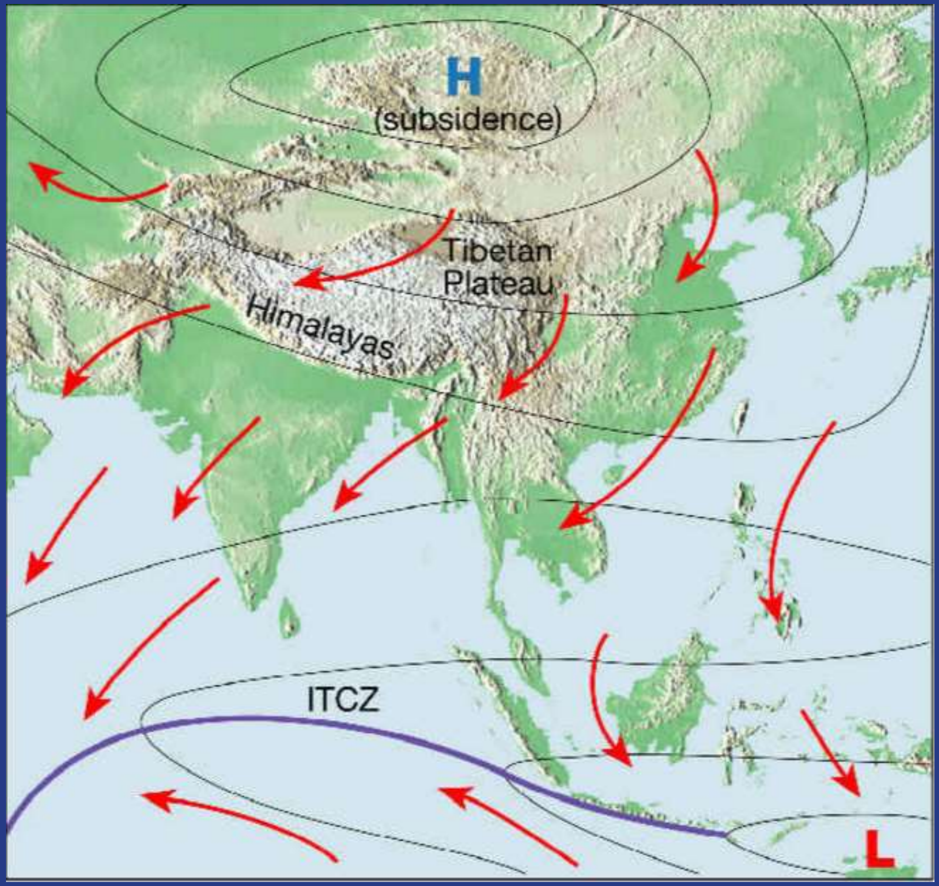
The Asian monsoon results from the fact that the heat capacity of rocks are much less than that of water.

Heat capacity may be defined as the ability of absorbing heat without actually getting hotter. Its rigorous definition is the ratio of the heat added to an object to the rise in its temperature and it is defined as energy/temperature. As one can see here, the objects with a high heat capacity are those that can absorb a lot of heat energy without greatly rising their temperature.

The Asian monsoon results from the fact that Central Asia becomes very hot during the summer and very cold during the winter. In summer it creates a huge area of low pressure sucking up the air masses from above the surrounding oceans (Indian and the Pacific). In winter, the reverse happens. Asia cools and creates an area of high pressure in its middle pushing the air masses above it towards the surrounding oceans.

The word monsoon comes from Arabic *al mawsim* (Turkish=mevsim).





SUMMER

WINTER

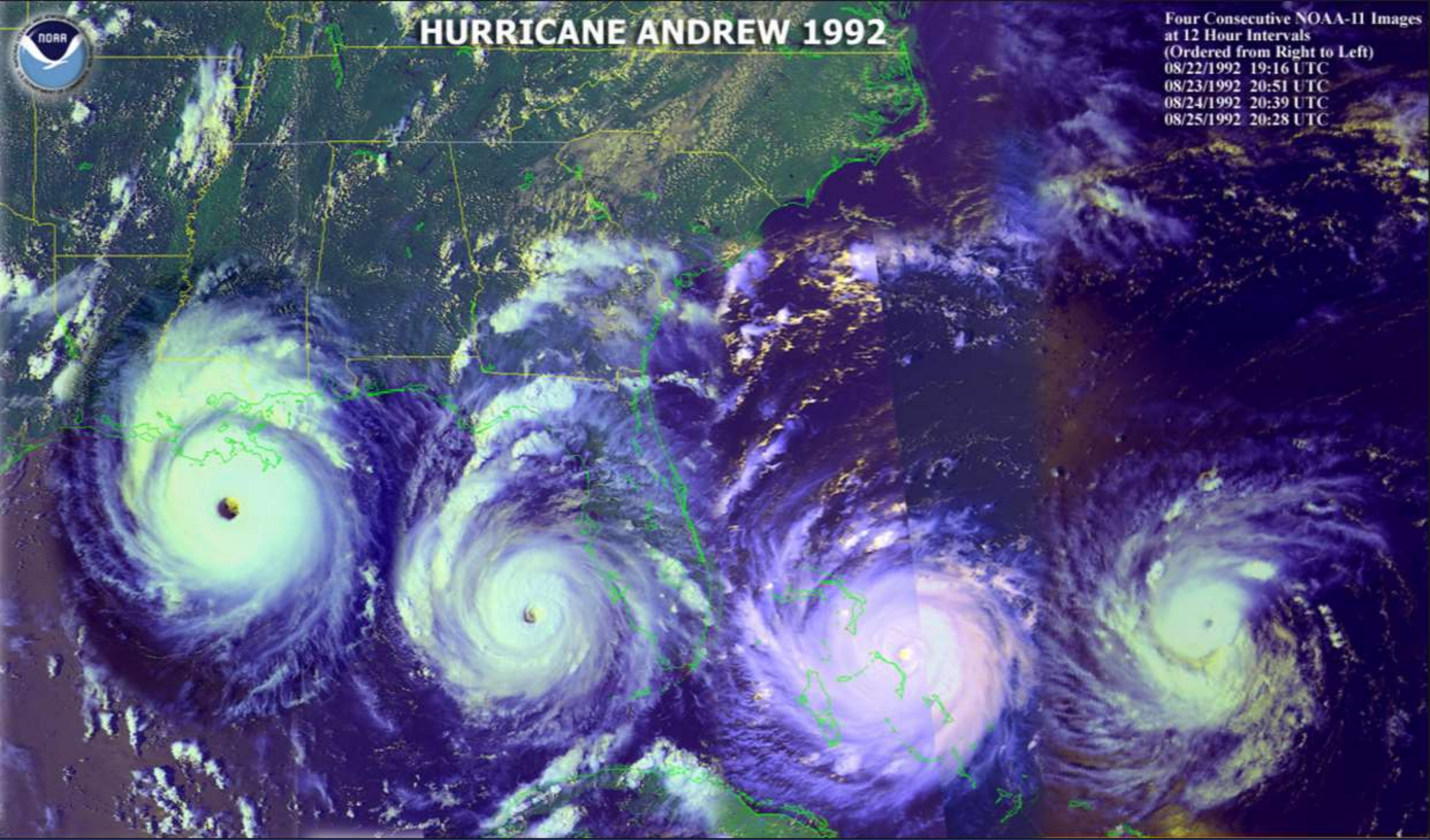
Wind patterns of the Asian monsoon

A view from the Takla Makan (=place of ruins) Desert, Central Asia, People's Republic of China

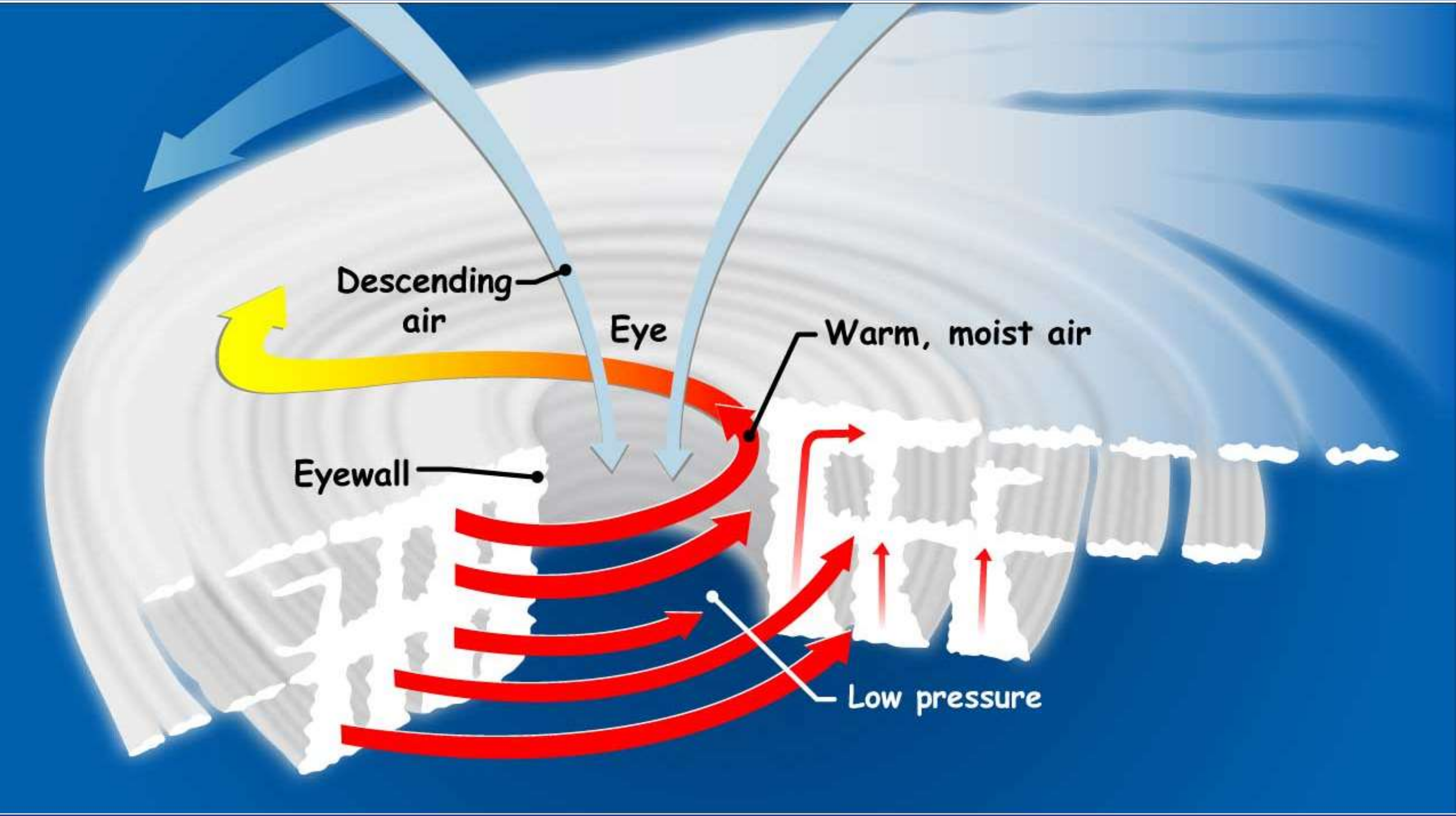
The ruins of the city of Lou-Lan, Takla Makan Desert, People's Republic of China

Cyclonic storms

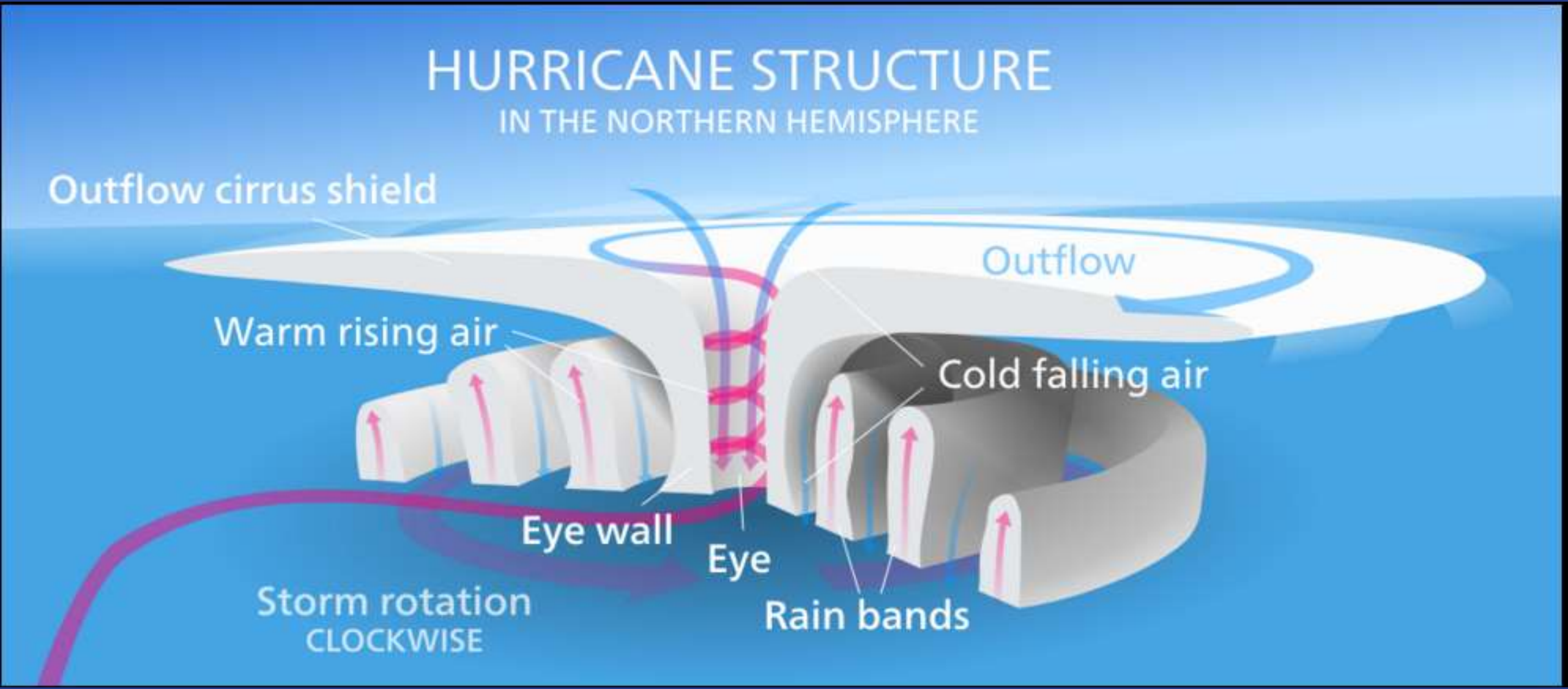
A cyclone is a large, rotating air mass around a centre of low pressure. Tropical cyclones create extremely powerful storms that are known under various names in various places on earth: in southern and eastern Asia they are known as typhoons, in north America they are known as hurricanes; they are also known under the designations of tropical storms, cyclonic storms, tropical depressions or simply as cyclones. But the most appropriate designations are the first two: typhoon and hurricane.



The track of the Hurricane Andrew in 1992. The images have been taken at 12 hour intervals. The rotation is because of the Coriolis force.



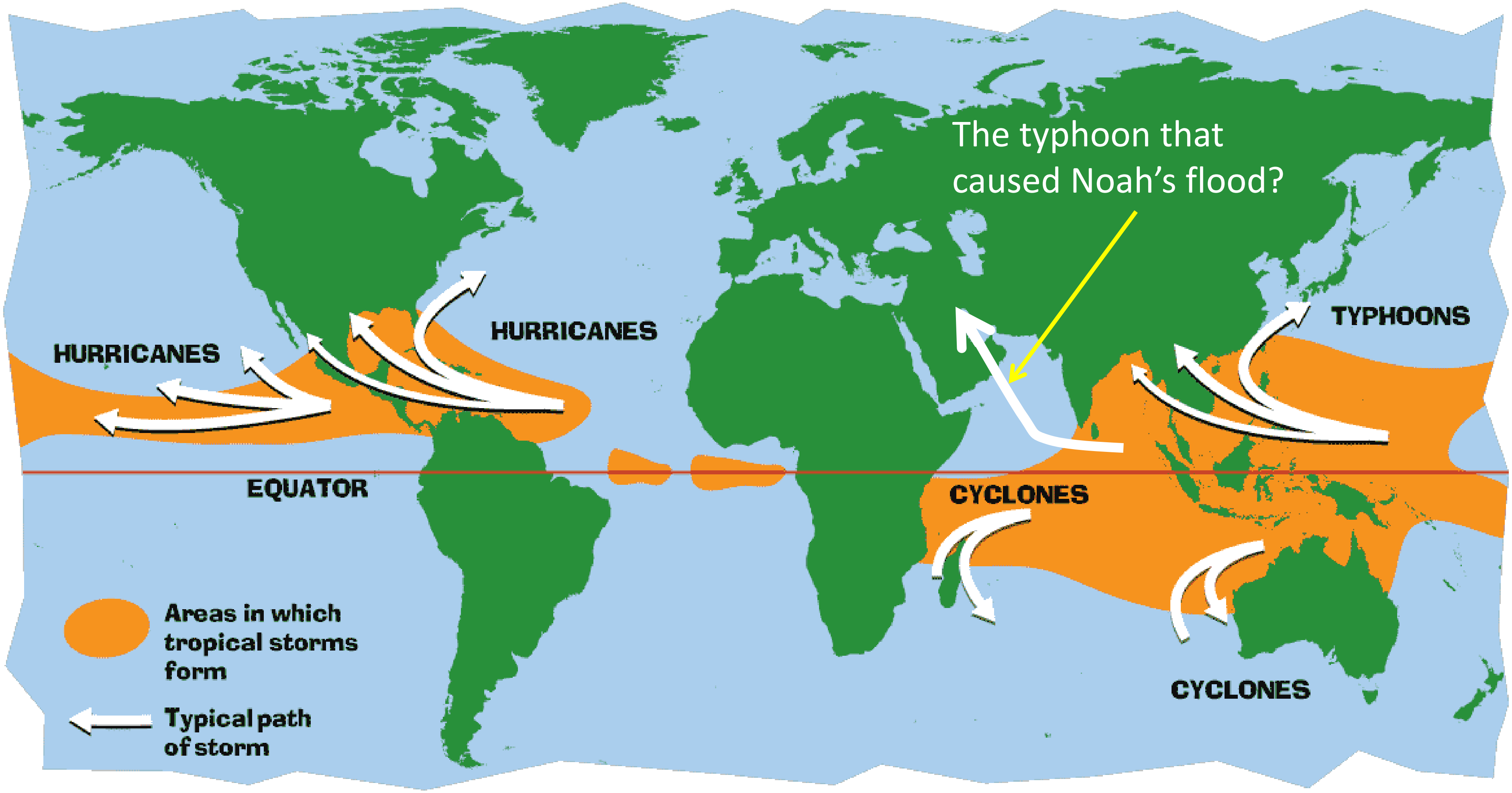
The mechanism of a typhoon or a hurricane. The hot air from the ocean surface rises (red arrows) and spreads outward (because of convection) and starts rotating (because of the Coriolis force). The storm is fed by heat and by the descending cold air in its eye.



Another depiction of the internal structure and mechanism of a tropical storm.

The Saffir-Simpson hurricane wind velocity scale.

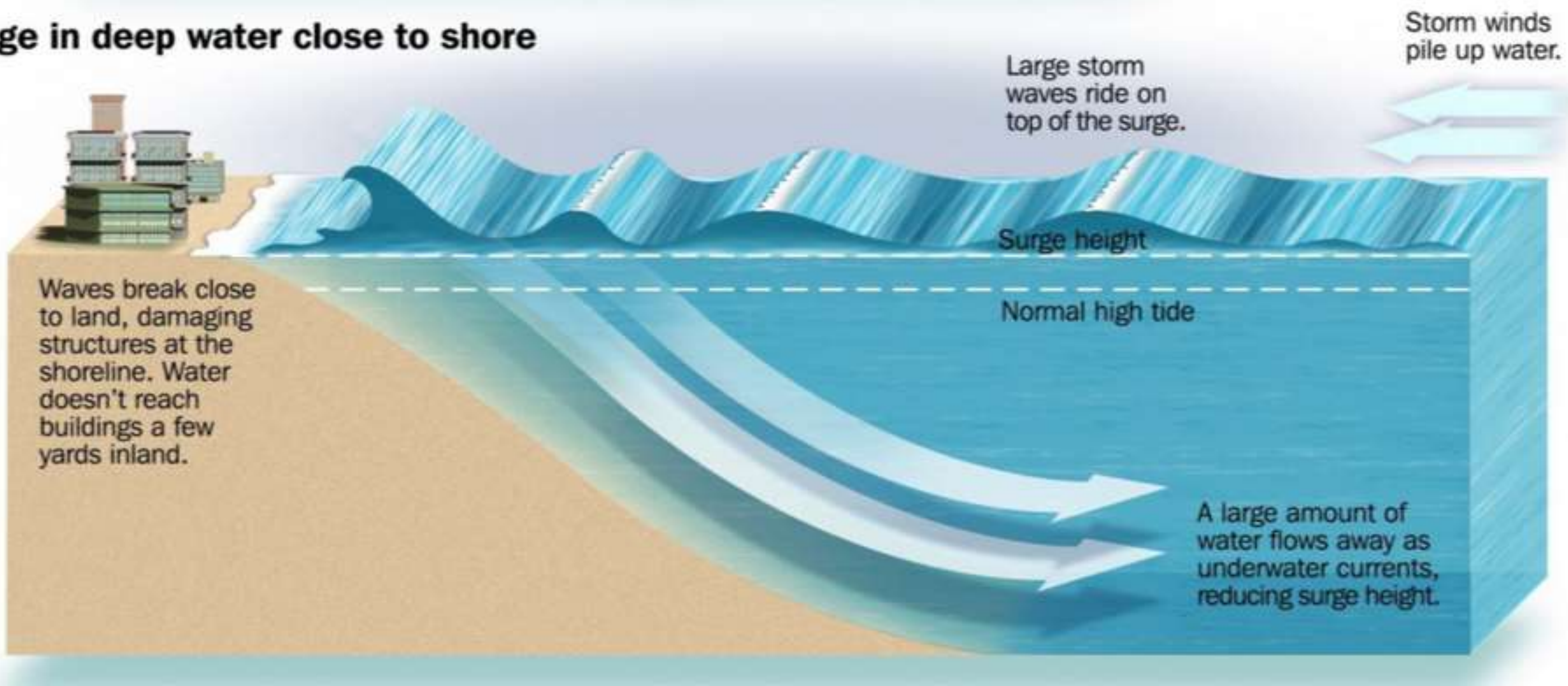
Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	74-95 mph 64-82 kt 119-153 km/h	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3 (major)	111-129 mph 96-112 kt 178-208 km/h	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	130-156 mph 113-136 kt 209-251 km/h	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5 (major)	157 mph or higher 137 kt or higher 252 km/h or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.



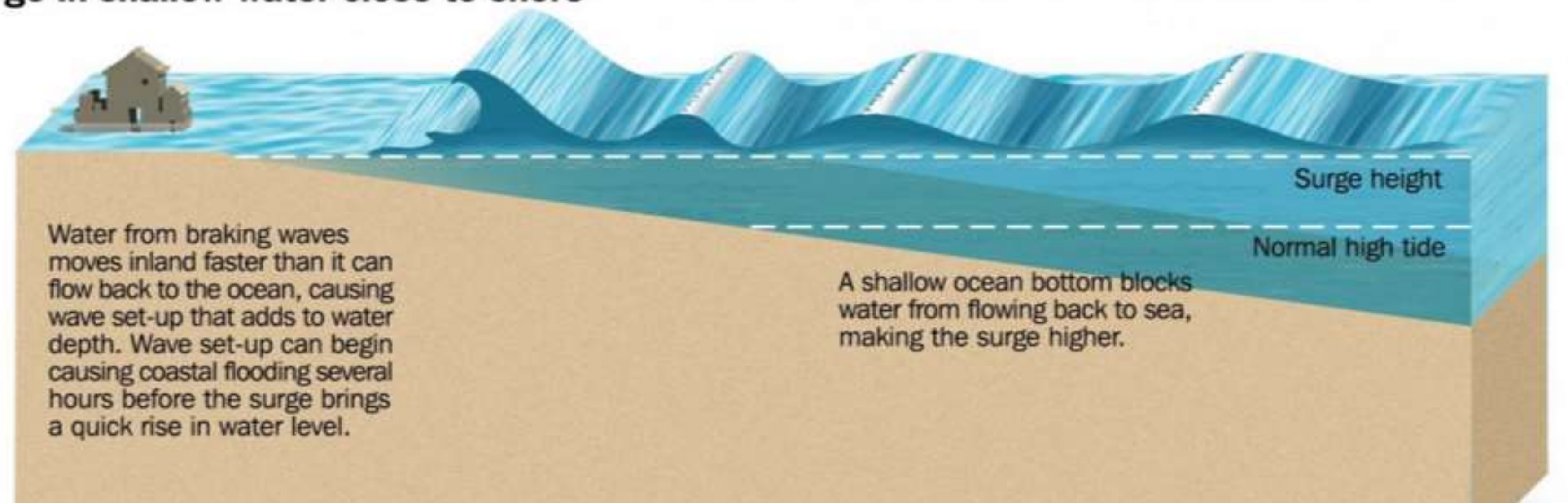
Areas in which tropical cyclones create violent tropical storms

The famous “Tufan-ı fil” that threw Seydi Ali Reis’ fleet from Arabia to Gujarat in India in 1554! The painting is by Naval Lieutenant Hüsnü Tengiz.

Surge in deep water close to shore



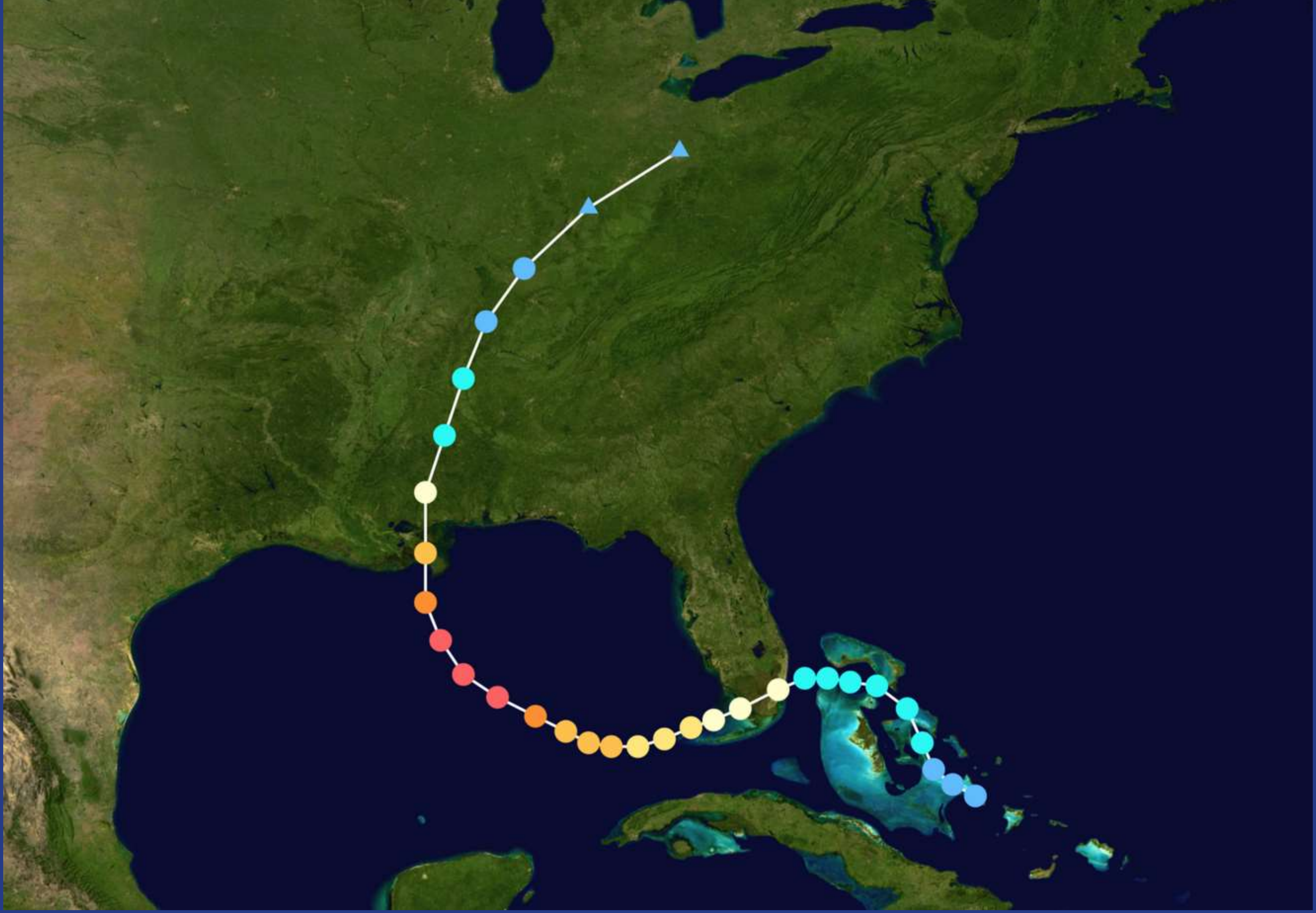
Surge in shallow water close to shore



Storm surge-related flooding caused by the Hurricane Irene near Centerport, New York, USA in 2011 (category 3, windspeeds around 160 km/h)

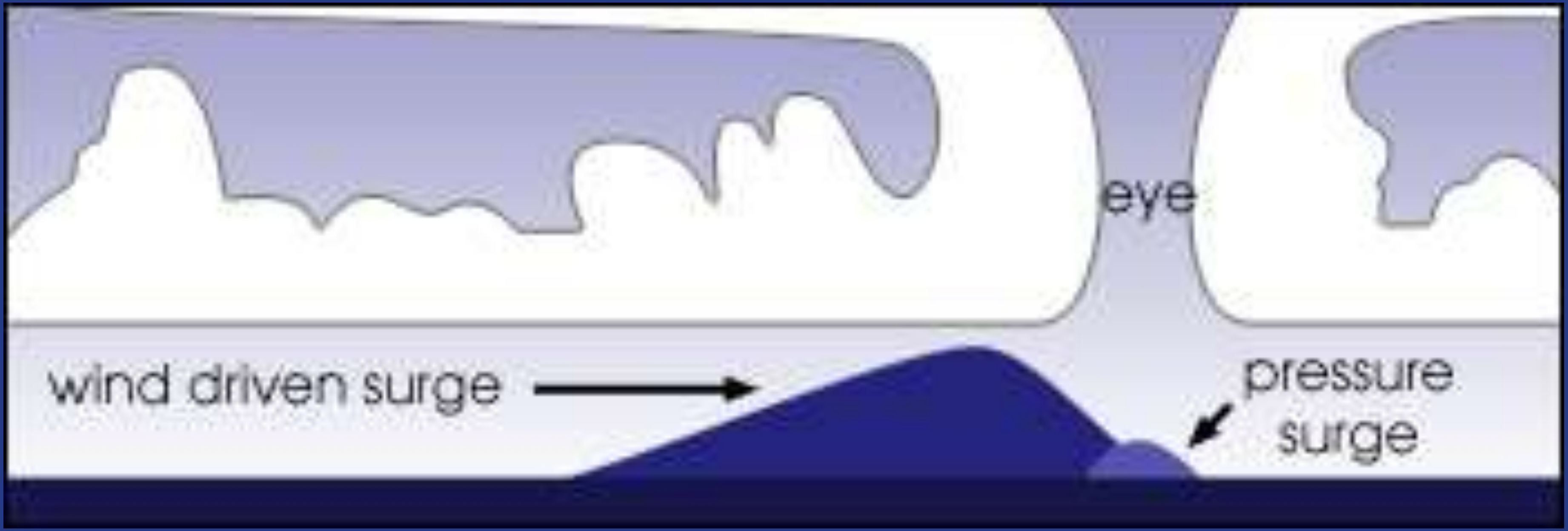
One of the worst storm surge disasters in recent years was the flooding of the city of New Orleans, Louisiana, USA, during the Katrina force 5 hurricane in 2005.

Katrina at peak strength on 28th August 2005



The track of Katrina

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



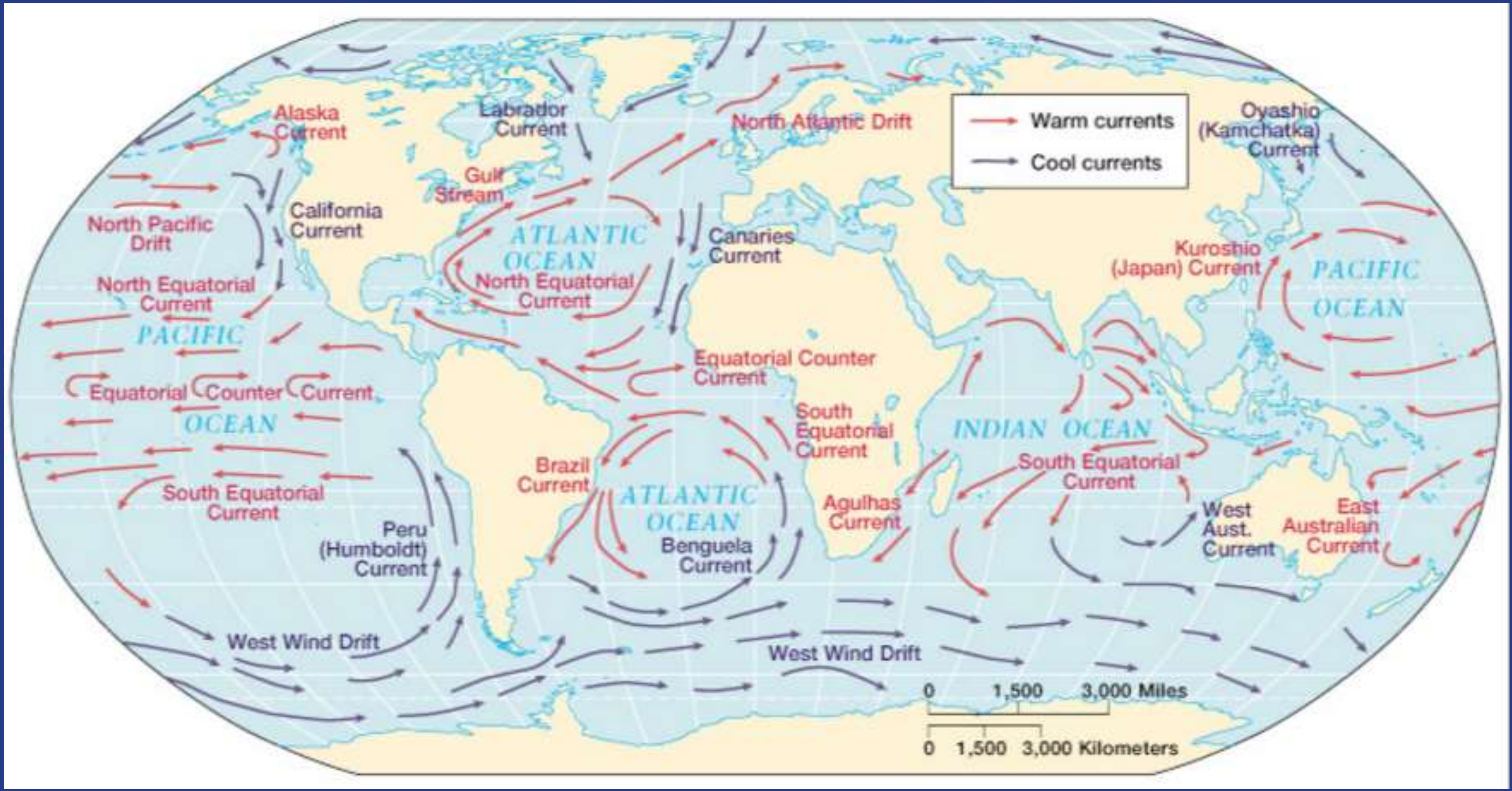
Two kinds of storm surges during the Hurricane Katrina

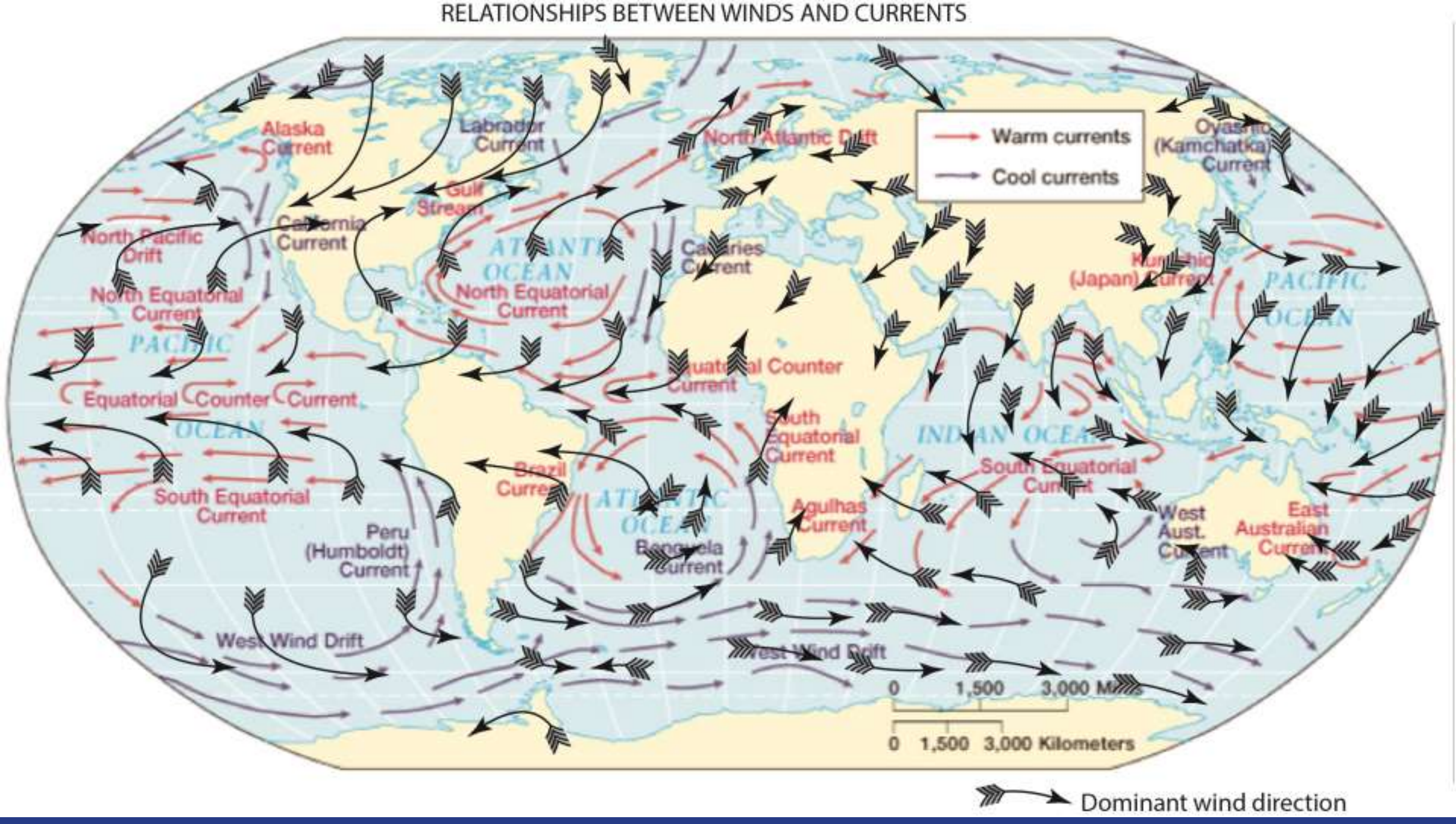
The city of New Orleans after the Katrina storm surge broke the levees

Storm surge resulting in rapidly flowing water into the city during Katrina. Does it have a geological record?

Current-bedded sandstone burying
an automobile in New Orleans!

Winds drive the major ocean currents. Currents not only mix the ocean waters and ensure the proper aeration of the ocean, but they also control climate. Below is a map of the major ocean currents in the word classified as to whether they are warm water currents or cold water currents.





Study this map carefully: we said that winds drive currents. What other influence(s) do you discern here on the course of the major ocean currents?

Just like winds, deep ocean currents are driven by density differences in sea water in different parts of the ocean.

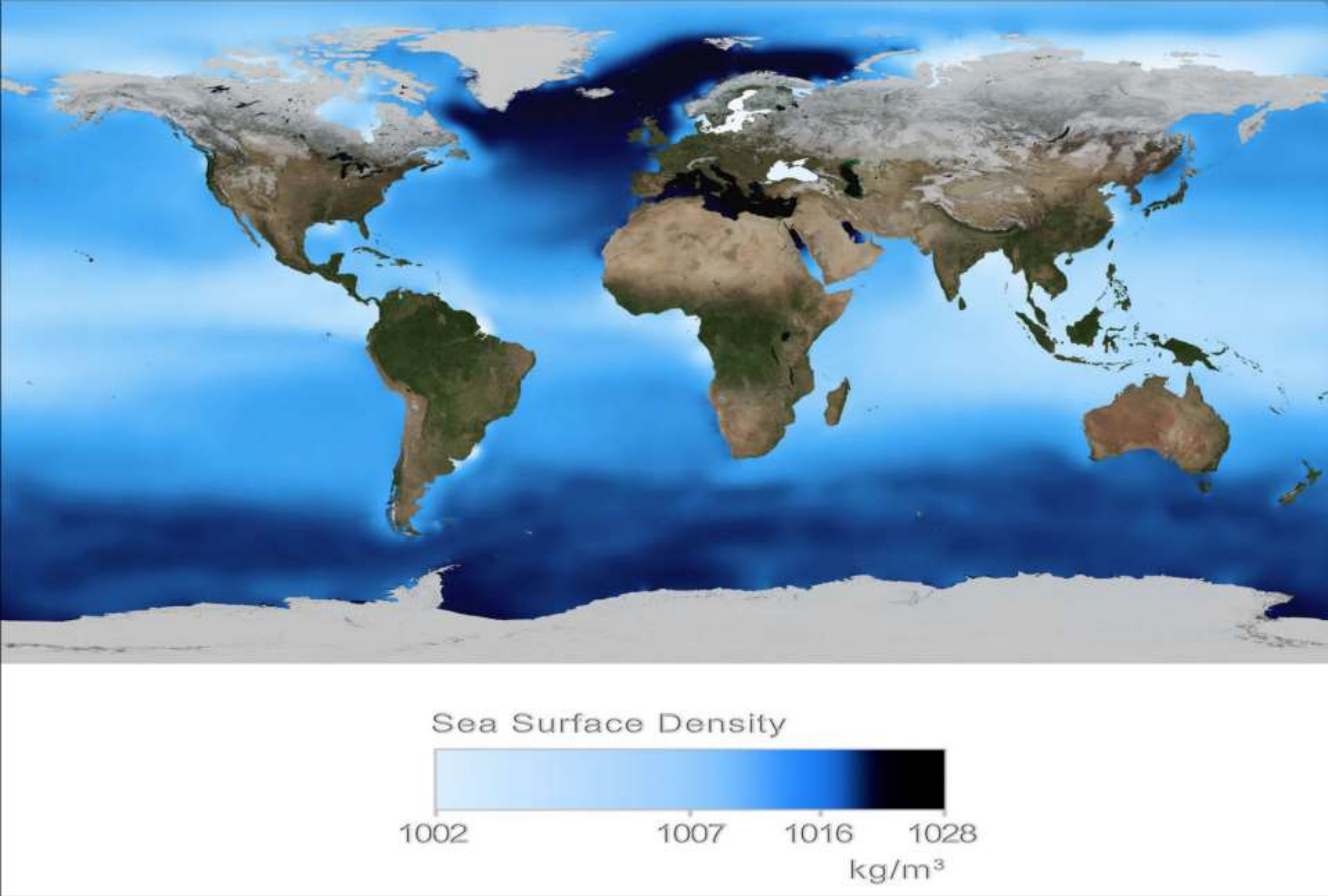
Seawater density is determined by mainly two things:

1. Temperature: the colder, the denser

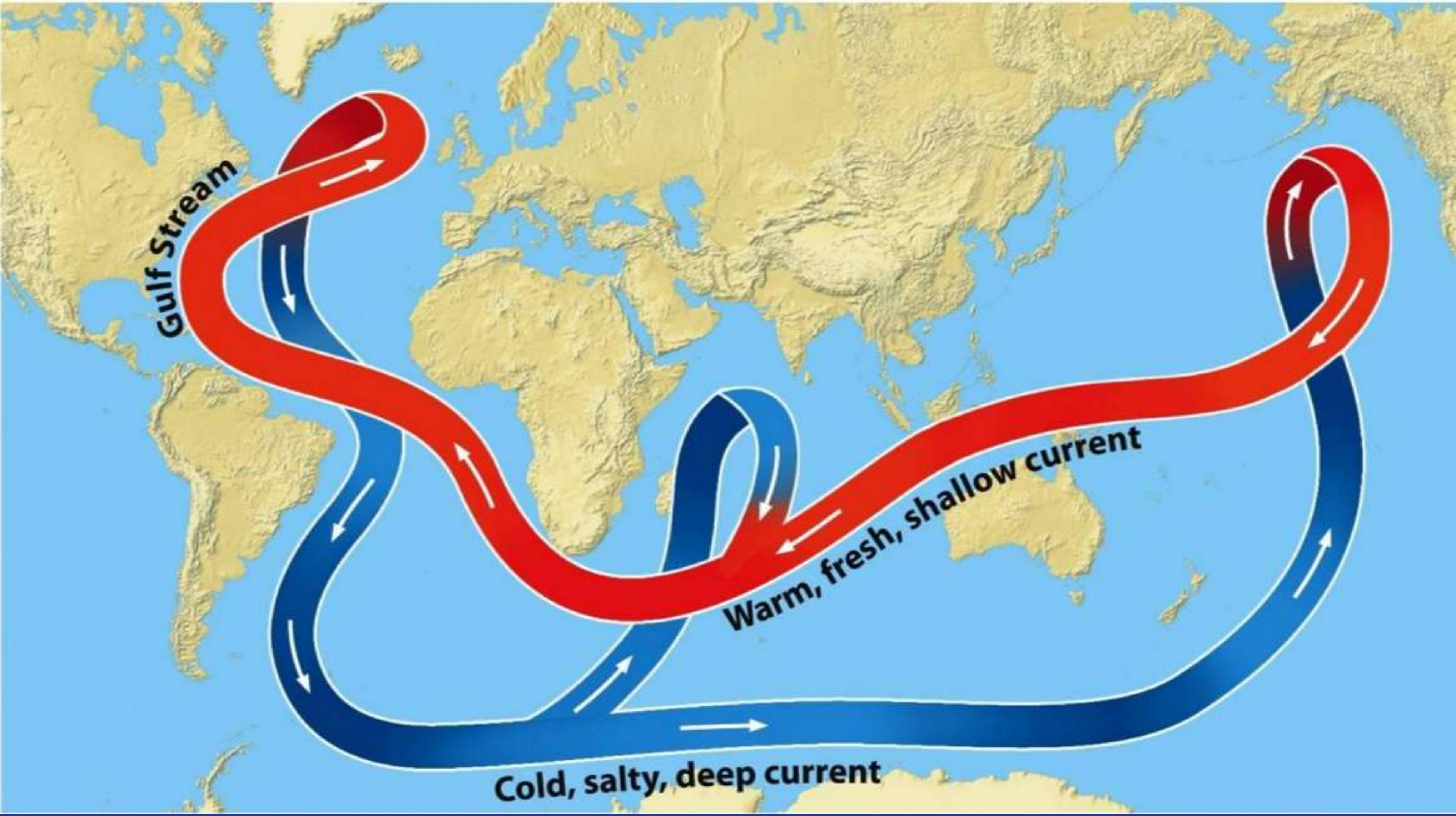
2. Salinity: the more saline, the denser.

In the polar regions, dense water forms because, when ice crystals form, salt accumulates into droplets called *brine*, which are usually returned into the ocean. This raises the salinity of the near-surface water. Some brine droplets become trapped in pockets between the ice crystals. These droplets are saline, whereas the ice around them is not. The brine remains in a liquid state because much cooler temperatures would be required for it to freeze. At this stage, the sea ice has a high salt content. Over time, the brine drains out, leaving air pockets, and the salinity of the sea ice decreases. Brine can move out of sea ice in different ways: Aided by gravity, the brine migrates downward through holes and channels in the ice, eventually emptying back into the ocean.

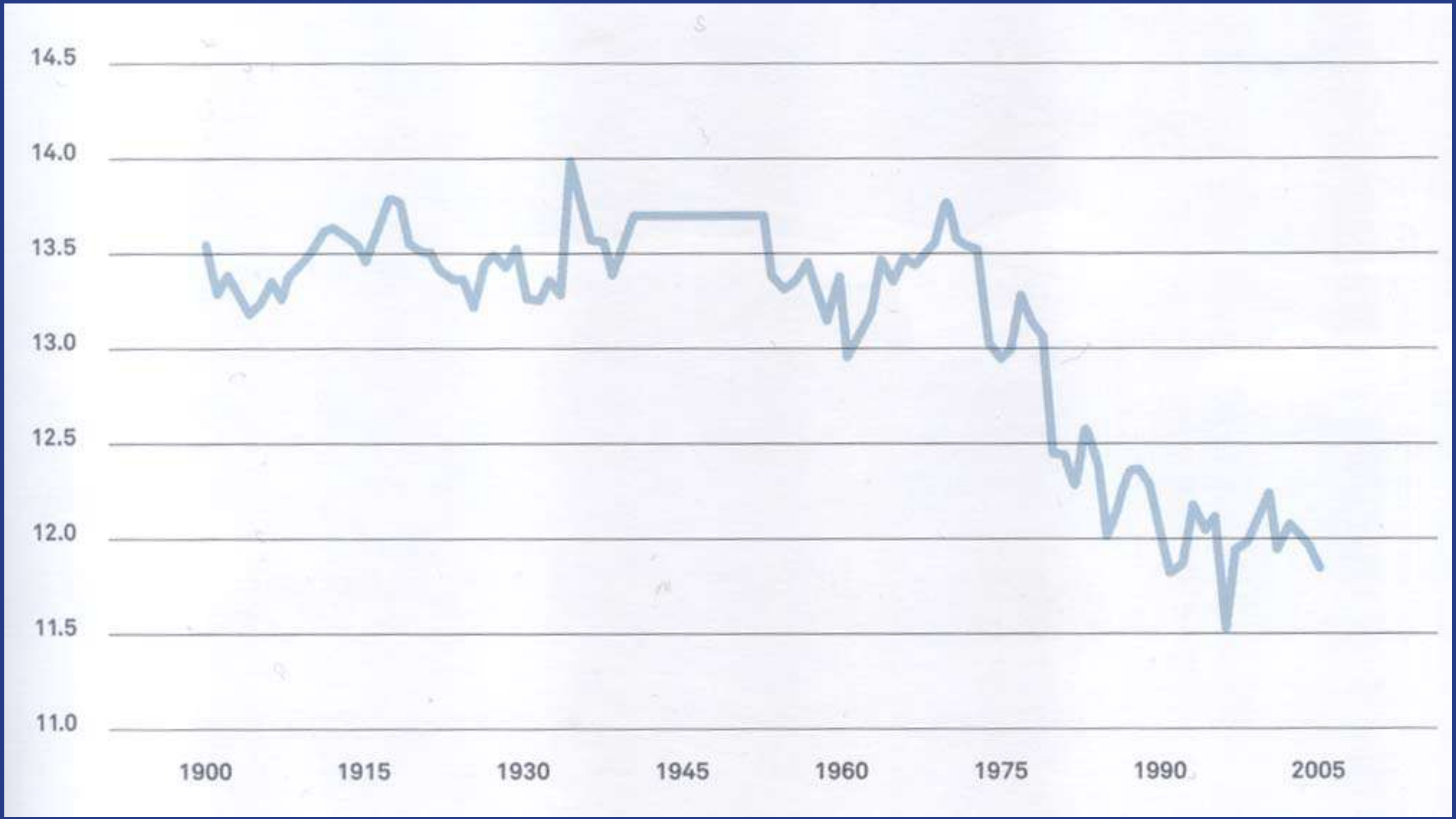
This raises the salinity of the surface waters and thus its density.



Map showing the distribution of density at and near the sea surface



Simplified course of the thermohaline circulation in the word ocean



Change in area of sea-ice cover in the northern hemisphere (in millions of km^2)

(from Al Gore, who forced the US Navy to release its data)

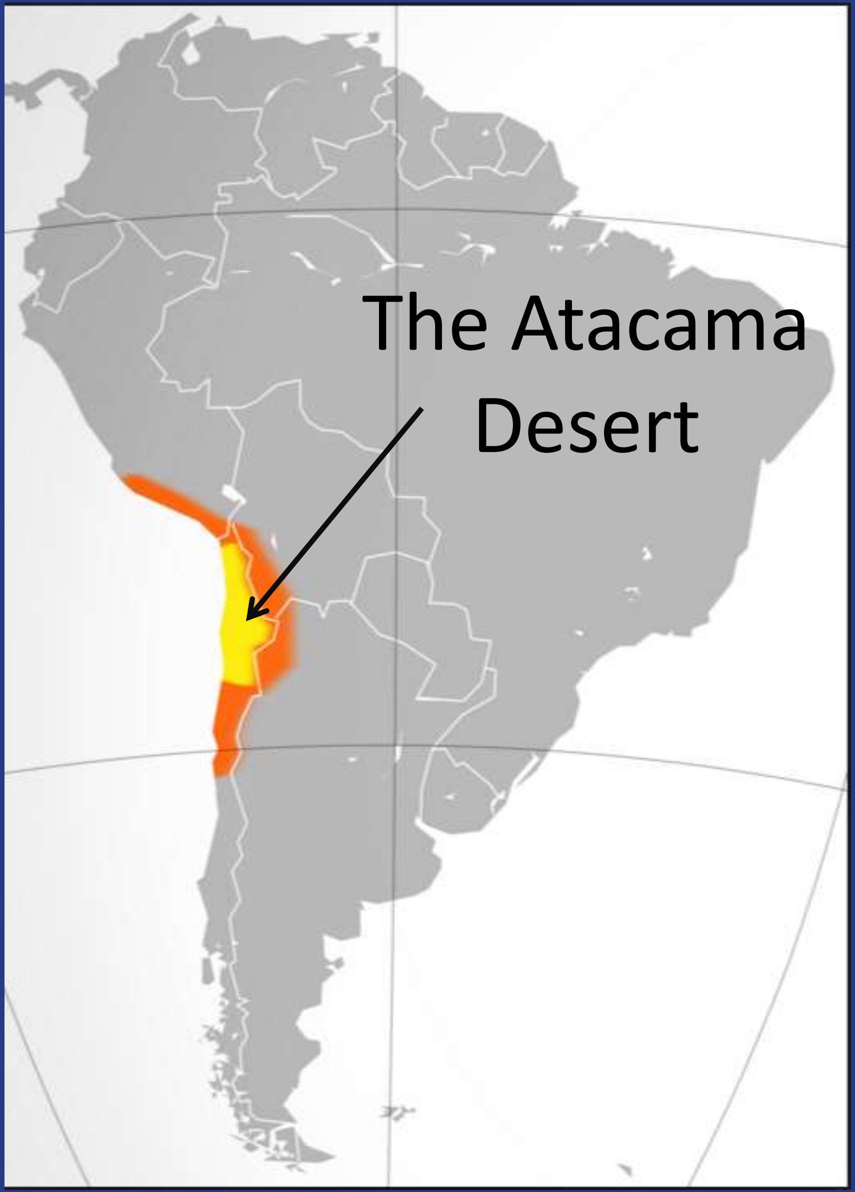
(Gore, 2006)

Glaciation in Europe with the northern Gulf Stream "switched off"
(from "The Gulf Stream and the Next Ice Age")

What happens if the Gulf Stream disappears?

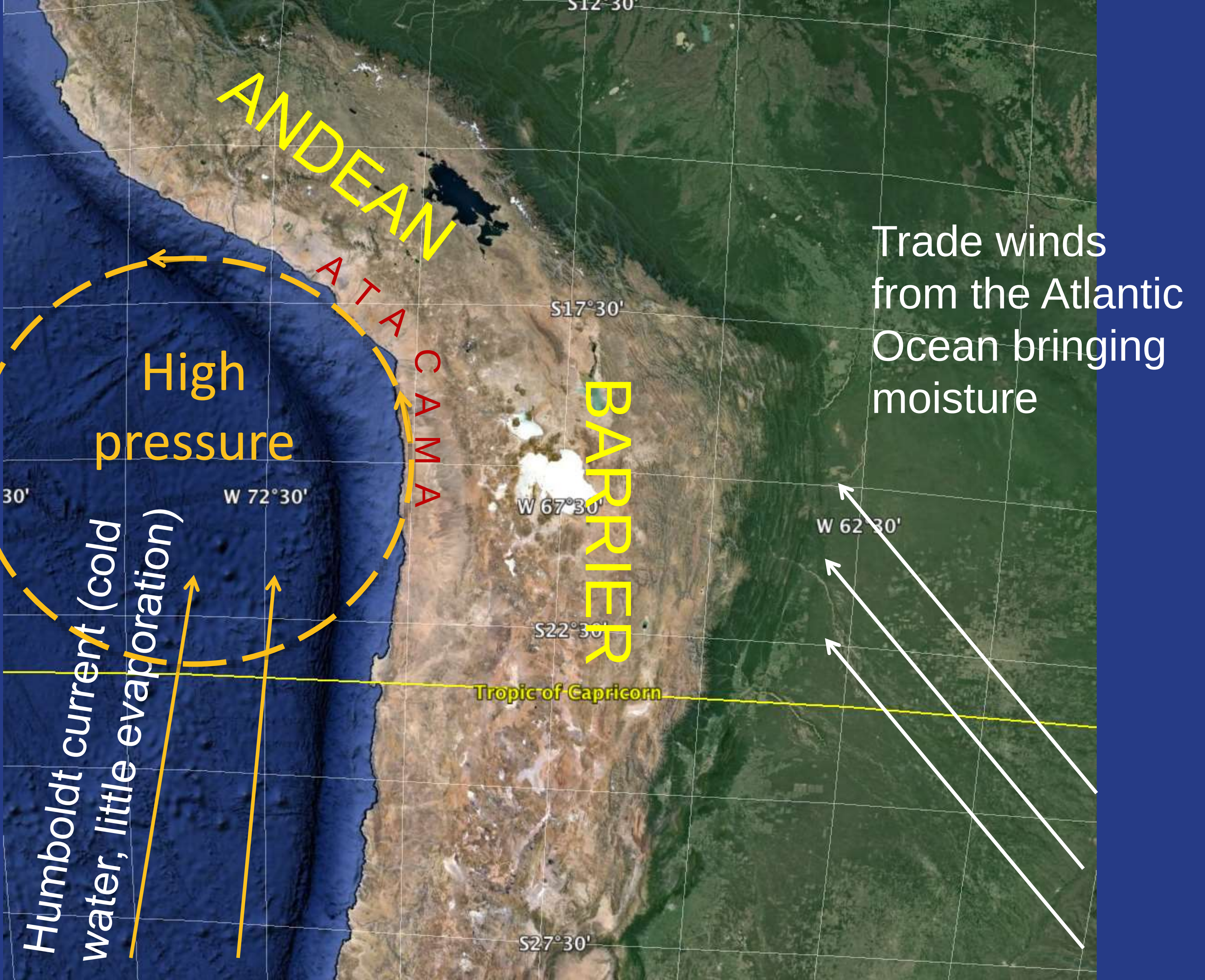
We said that climate is determined by temperature, pressure, humidity and precipitation. Let us see what kind of a role winds and currents play in this system and how this affects geology generally and sedimentation specifically.

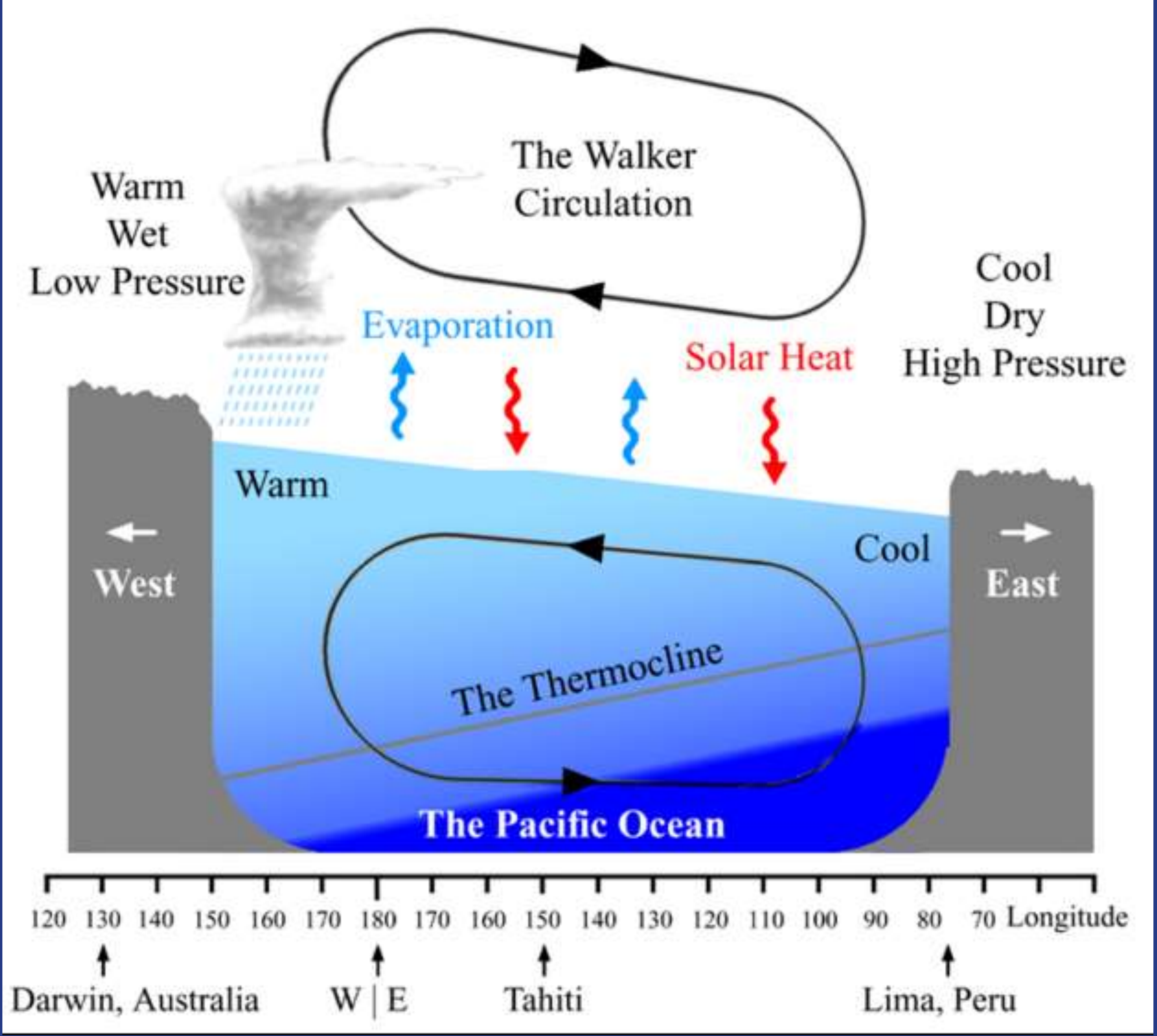
Example I: the driest place on earth, the Atacama Desert



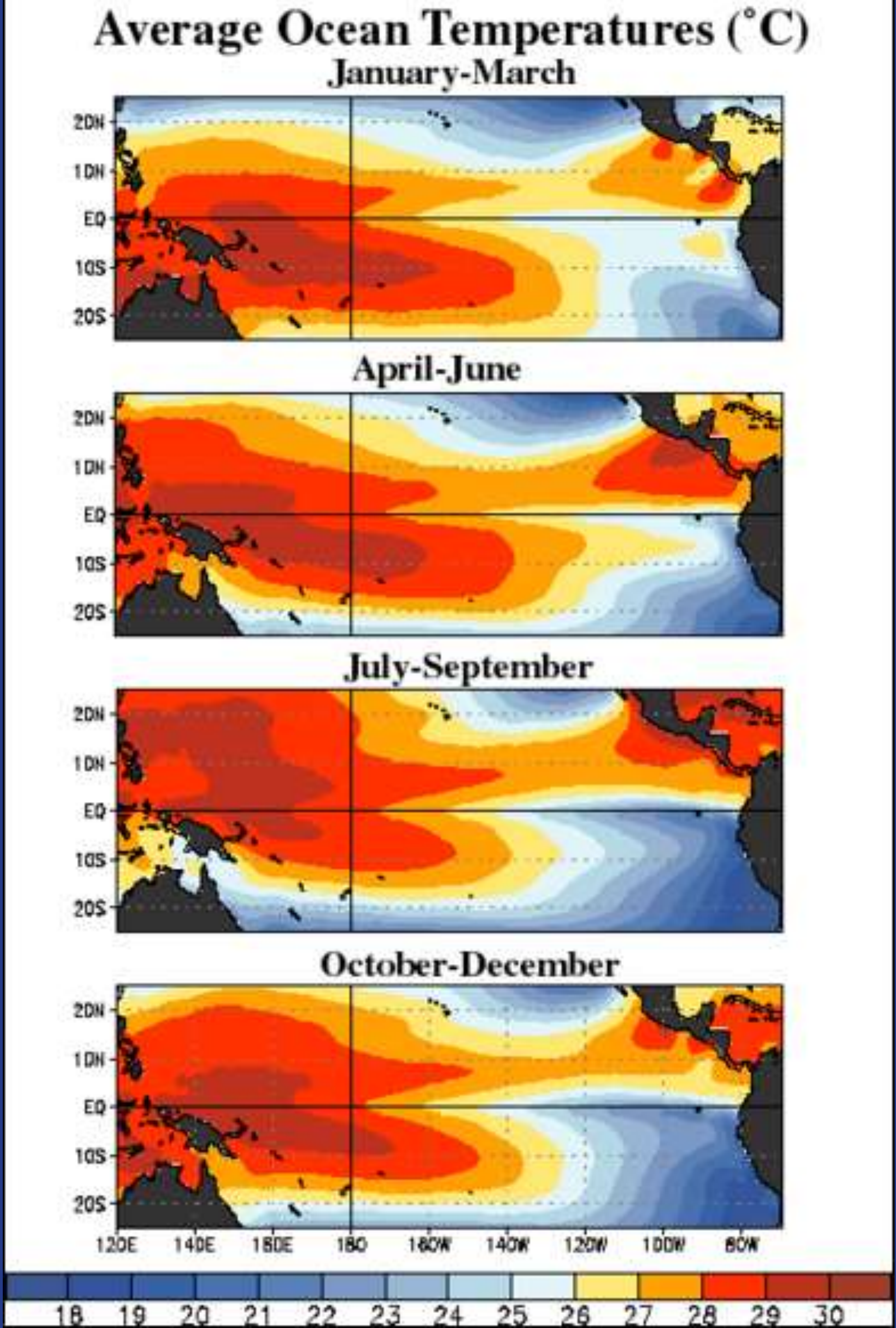
The Atacama desert seems not to have had any serious rainfall from 1570 to 1971, i.e. for 400 years!

Average annual rainfall is 15 mm/a. Some regions receive only 1 to 3 mm/a. Some weather stations in the area have never recorded any rain.

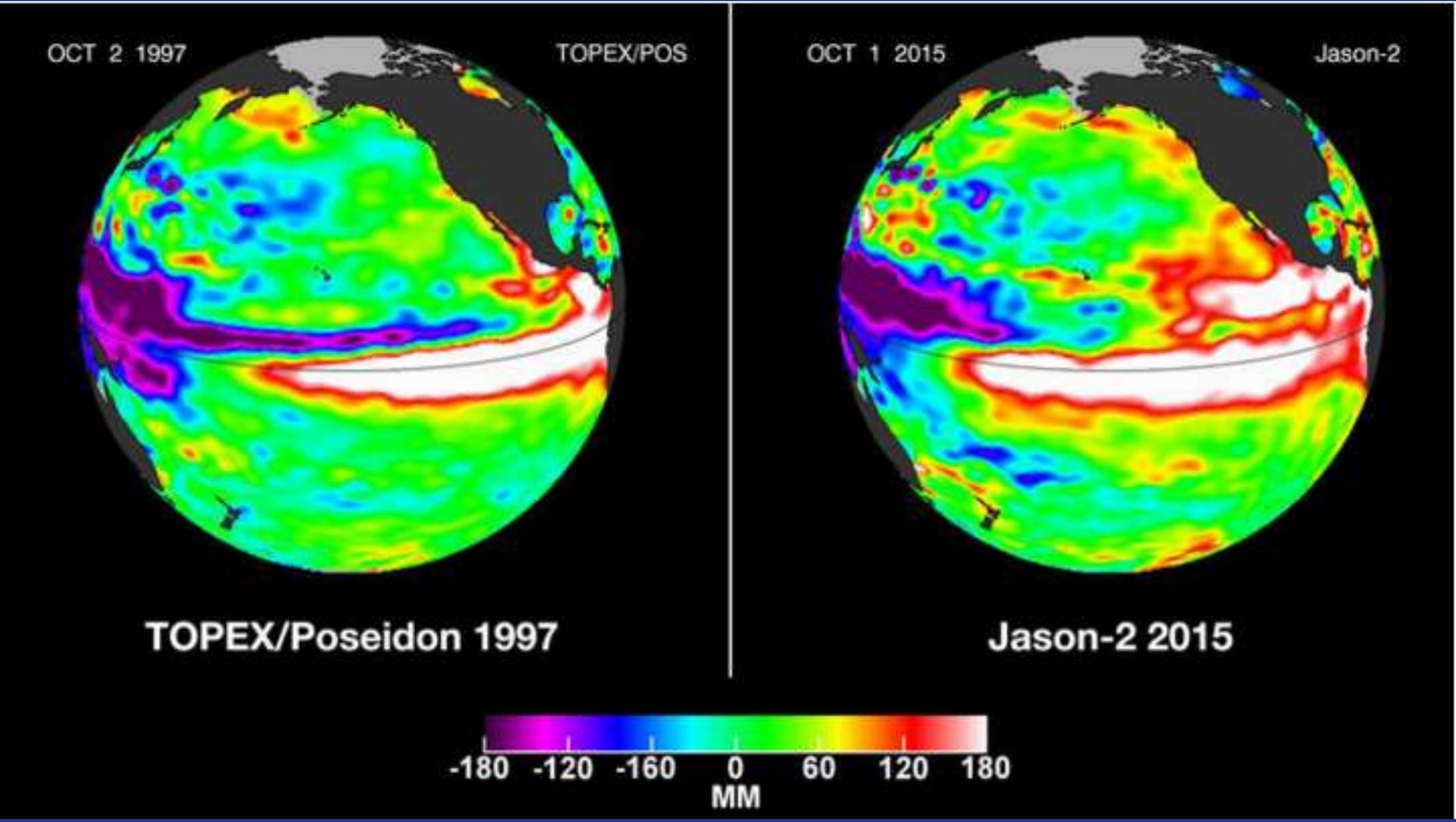

ANDEAN
ATACAMA
High pressure
BARRIER
Trade winds from the Atlantic Ocean bringing moisture
Humboldt current (cold water, little evaporation)
S12°30'
S17°30'
S22°30'
S27°30'
W 72°30'
W 67°30'
W 62°30'
Tropic of Capricorn



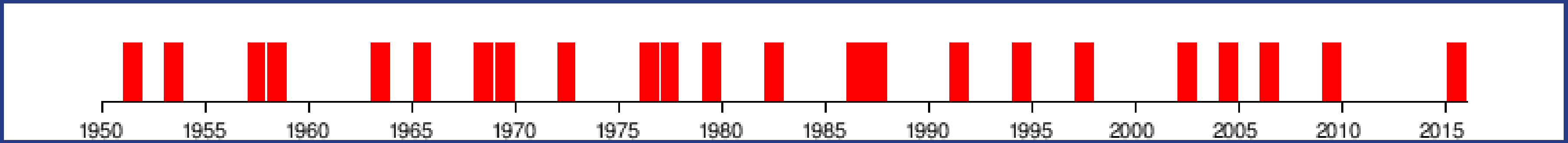
The Humboldt and the equatorial currents cause the Walker circulation (discovered by the English mathematician Gilbert Walker in 1904)


Average Ocean Temperatures (˚C)
January-March
April-June
July-September
October-December
20N
10N
EQ
10S
20S
120E
140E
160E
180
160W
140W
120W
100W
80W
18
19
20
21
22
23
24
25
26
27
28
29
30

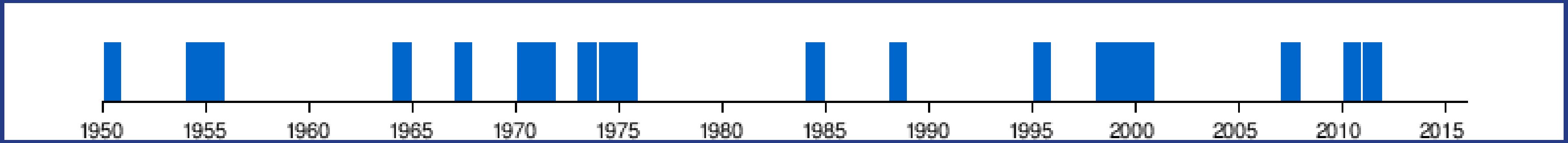
But in some years the Walker circulation weakens and the Hadley circulation dominates. Then the ocean temperatures change and bring warm waters to the western coast of South America. This condition is known as El Niño (the boy baby). The term comes from the usage of the Peruvian sailors, because the warm, north flowing current appeared around the Christmas and thus was called El Niño (the baby, referring to the baby Jesus). This was reported by Captain Camillo Ciarrillo in 1892 to the Geographical Society congress in Lima. Gilbert called El Niño "the southern oscillation". So now this phenomenon is known as the El Niño Southern Oscillation or ENSO for short. The opposite of El Niño is called La Niña, i.e. the baby girl.



Warm water distribution during the 1997 El Niño and 2015 El Niño (as inferred from sea surface elevation)



The El Niño years since 1950. Note the non-periodicity. Can you compare this with the non-periodicity of the Lorenz Wheel?



The La Niña years since 1950. Note the non-periodicity. Can you compare this with the non-periodicity of the Lorenz Wheel?

This year’s El Niño caused unusual rainfall in the Atacama Desert and led to catastrophic flooding.

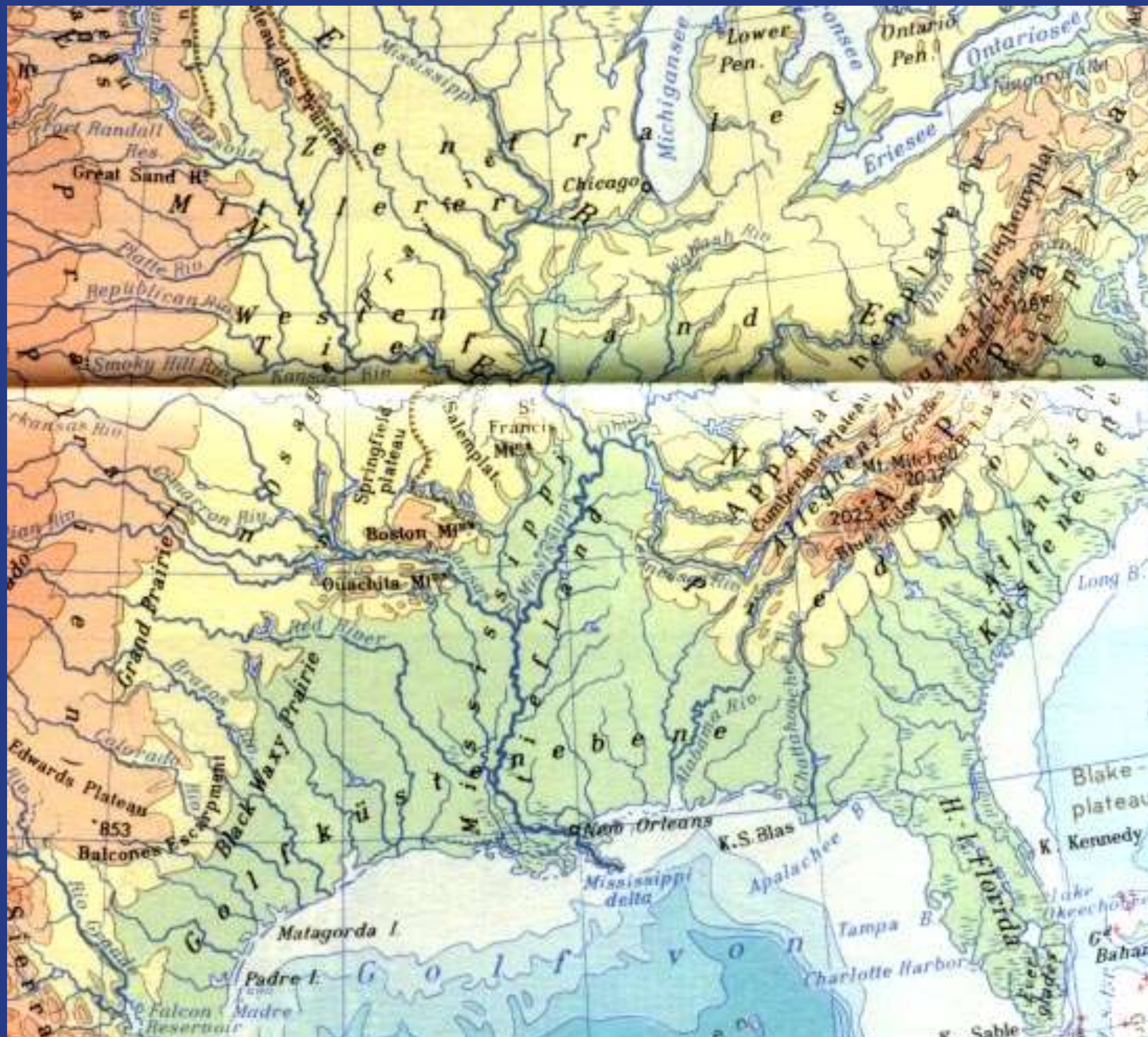
What does such catastrophic flooding do?

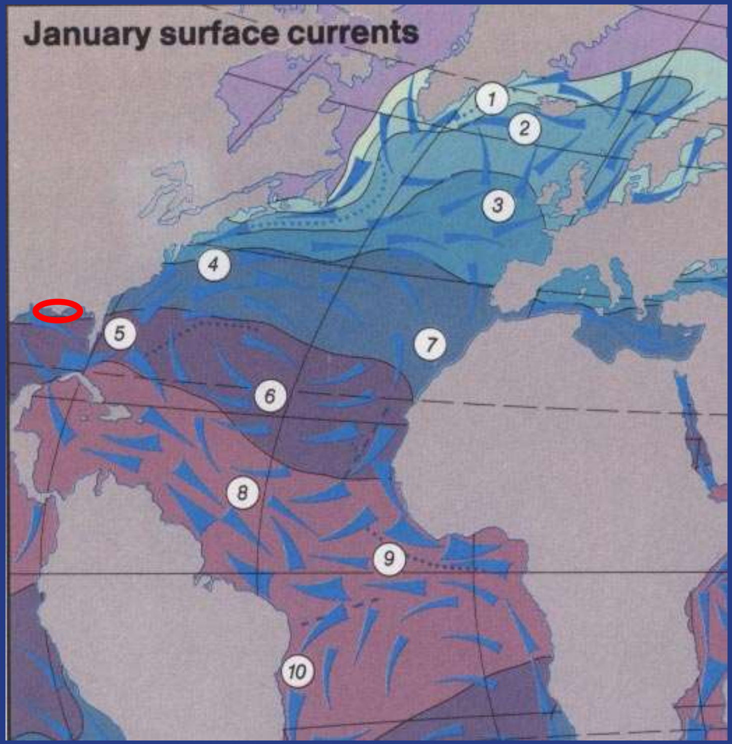
1. It erodes:

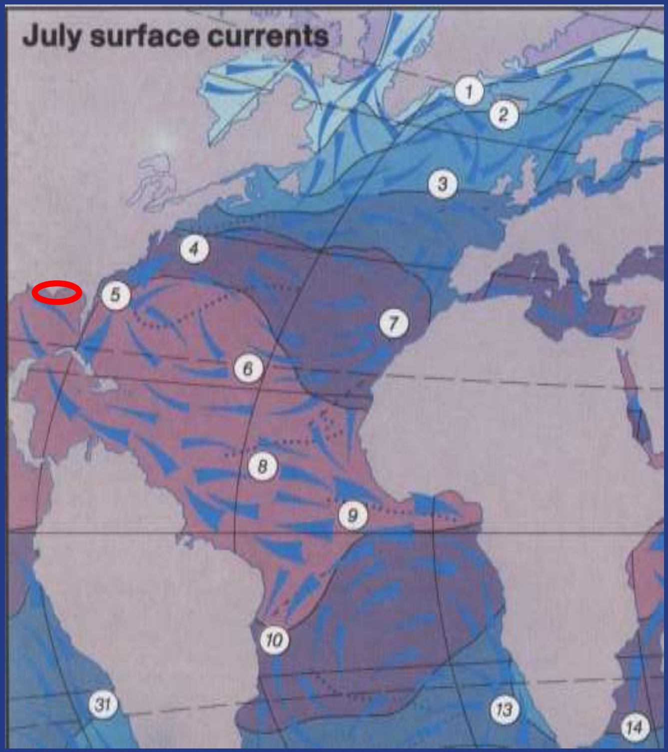
2. It deposits:

For sedimentation, this brief consideration of climate has already taught us something: many of the clastic sedimentary processes accomplish almost 90 % of their work during short-lived episodes of intense activity caused by climatic incidents. We have already seen the splay deposits on cars in New Orleans. In the Atacama region we now see vast deposits forming and erosional events taking place in a span of a few days, where for centuries very little had happened. What does that say about the geological record? Let us note this and come back to it later.

Example II: The Mississippi river carries some 15 million km^3 sediment, but its delta is growing only by 7.2 million km^3 per year. Where does the 7.8 km^3 sediment go?





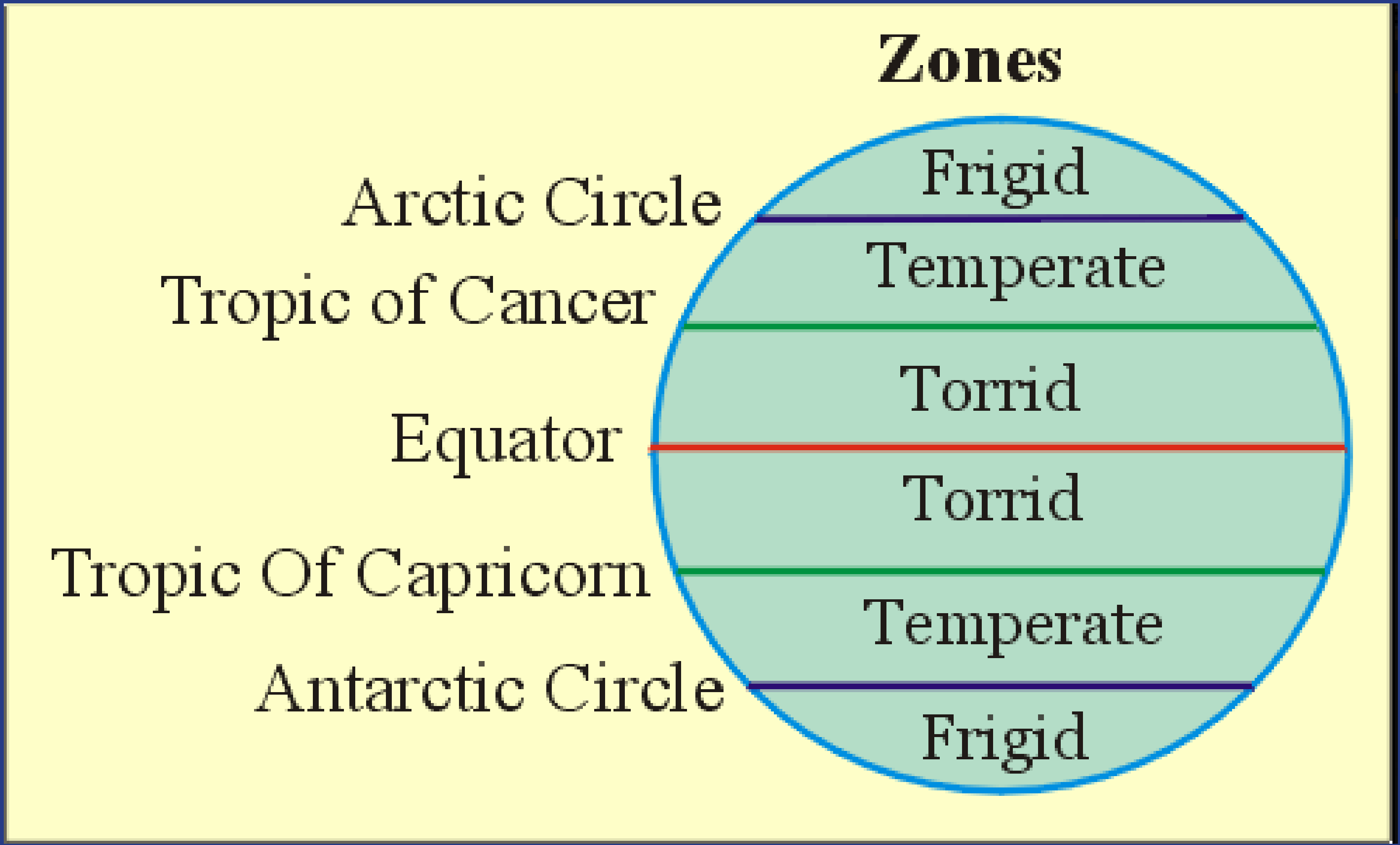


Gulf of Mexico

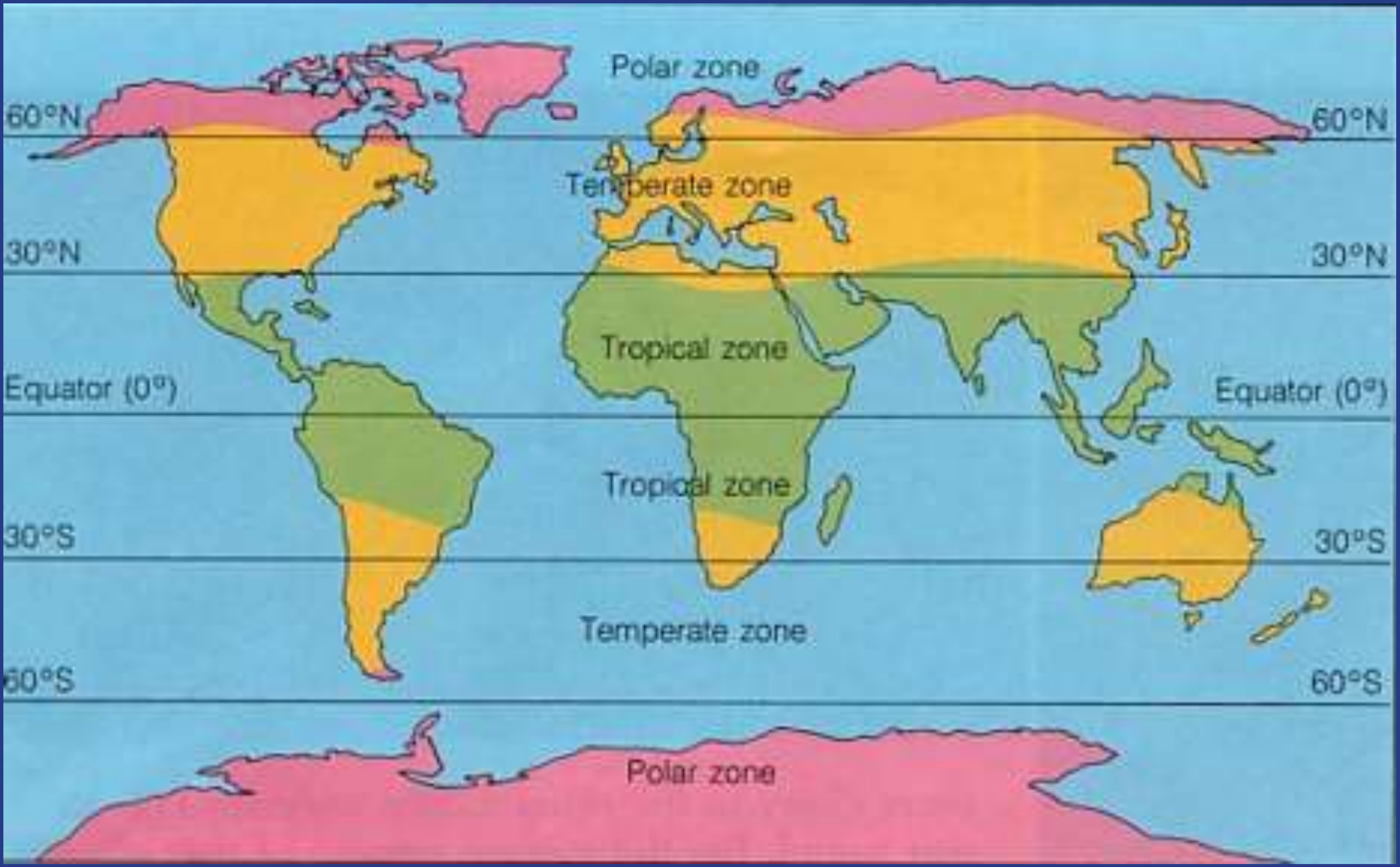
January surface currents   July surface currents

The Gulf Stream carries away half the sediment of the Mississippi River

From the example of the Mississippi we learnt another lesson: where the climate is
not subject to wild fluctuations, the sedimentary processes may be more steady.



If the earth were a perfect sphere with a single kind of surface (all water or all land) and no atmosphere, its ideal climatic zonation would have been as shown here. The present climate zonation roughly approximates this, but it is complicated by the atmosphere and the distribution of land and sea.



Although this is a very crude distribution schema of global climates, it clearly does not reflect the real climate distribution. For that we need more detail than just latitude!

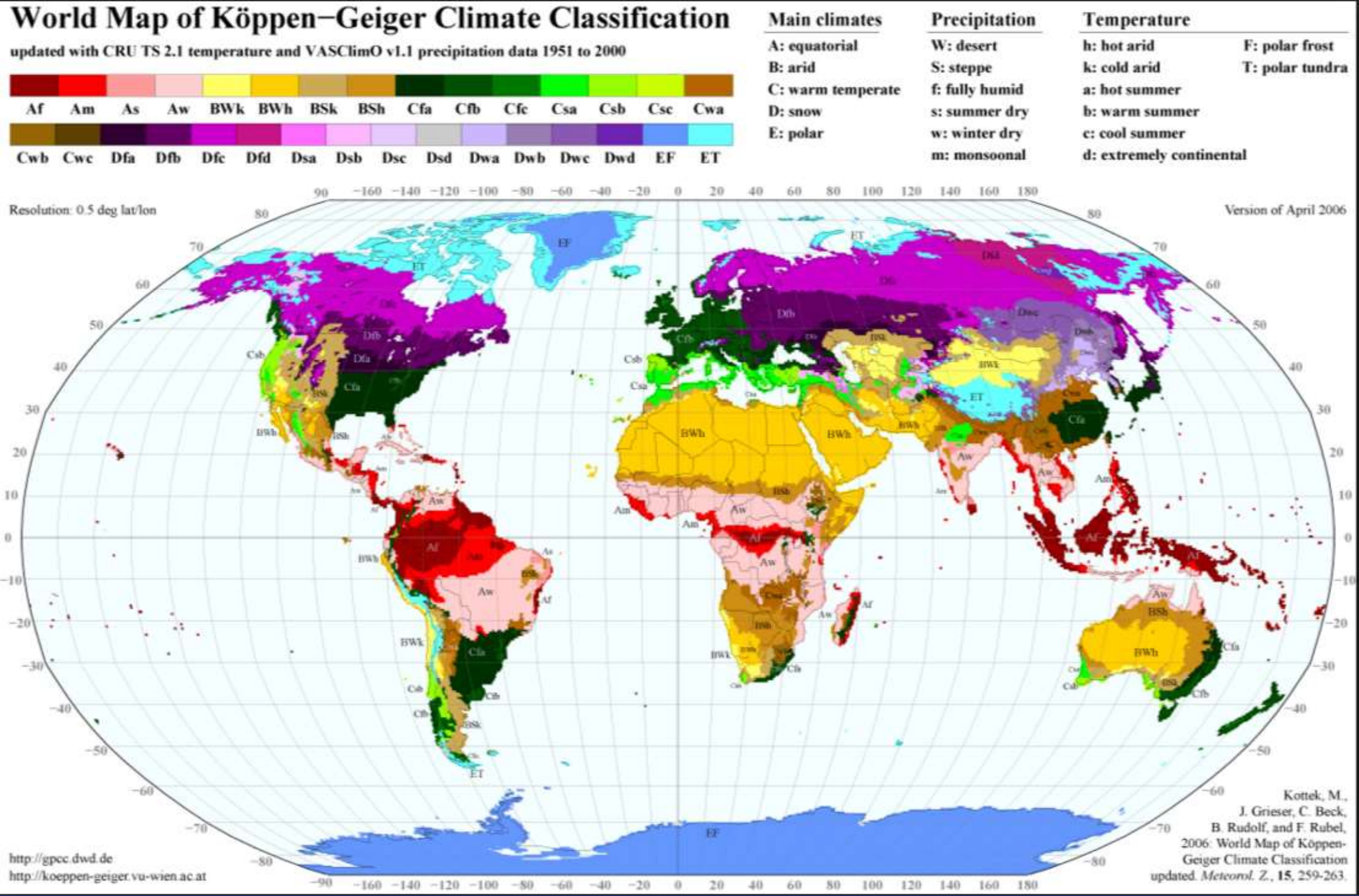
Let us go back to the distribution of climate types on the surface of the earth:

To study this distribution we need to define what a climate type is. There are a number of schemes of doing this, but the most popular belongs to the German meteorologist Wladimir Köppen who was the father-in-law of Alfred Wegener, the man who discovered continental drift. Köppen first published it in 1884. Later in 1918 and 1936 another German meteorologist Rudolf Geiger cooperated with Köppen and the presently used scheme is called the Köppen-Geiger classification of climates.

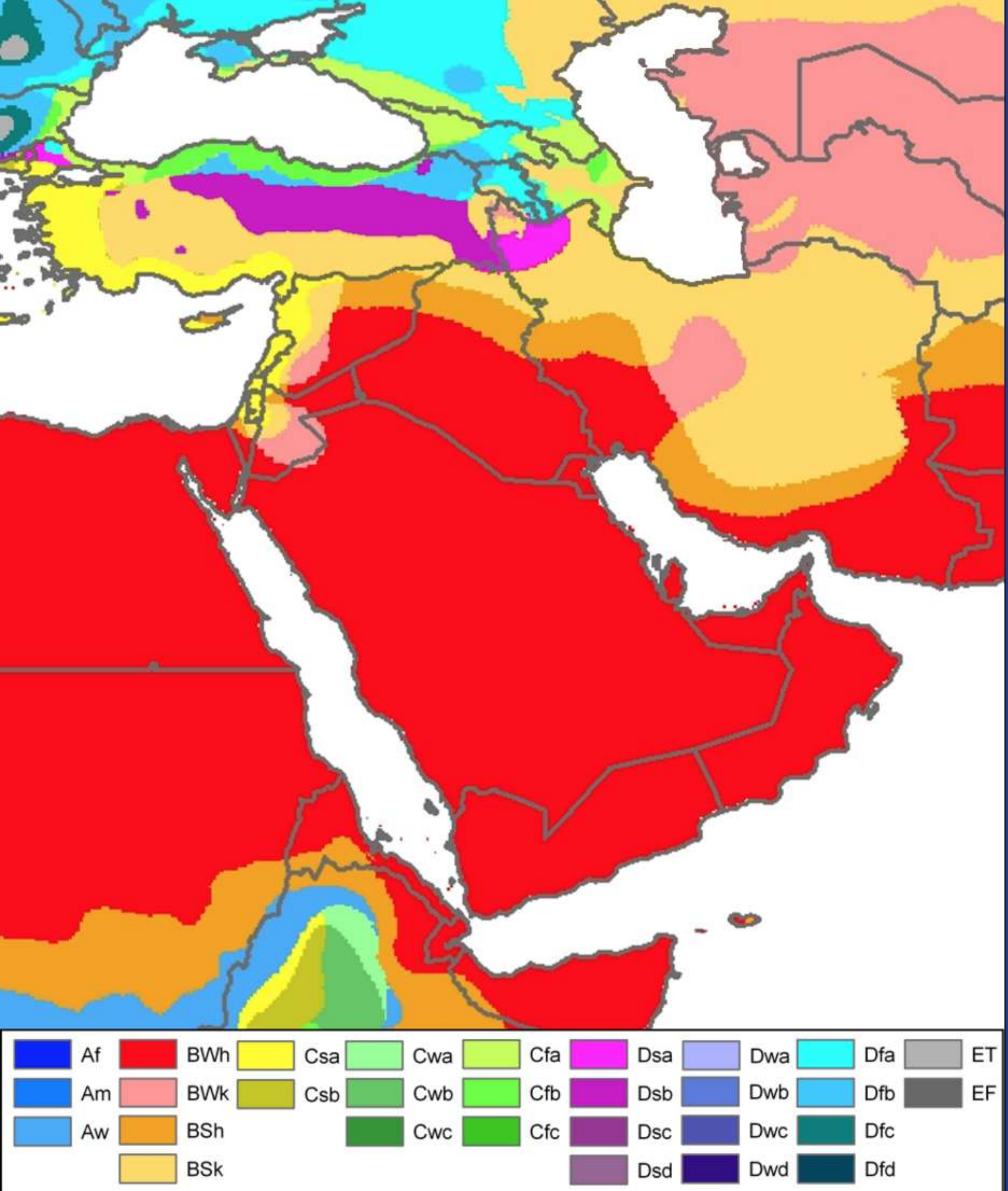
This classification scheme assumes that the vegetation is the best expression of climate, but is not based on the observation of vegetation, but rather on temperature and precipitation.

It divides the climates as follows:

Climate Zone:	A	B	C	D	E
Climate type:	f, m, w, s	W, S	f, w, s		T, F
Climate sub-type:		h, k	a, b, c, d		



The updated version of the Köpper-Geiger classification of climates on earth



Distribution of climate types according to the updated Köppen-Geiger classification in the Middle East, southwestern Europe and southeastern Asia

We considered climate to have a better understanding of geological processes leading to the generation of sedimentary rocks. All sedimentary-rock-generating processes are under the heavy influence of climate.

Let us begin studying this relationship by considering the kinds of sedimentary rocks and the processes producing them:

SEDIMENTARY ROCKS

- Clastic sedimentary rocks
- Organic sedimentary rocks
- Chemical sedimentary rocks

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.

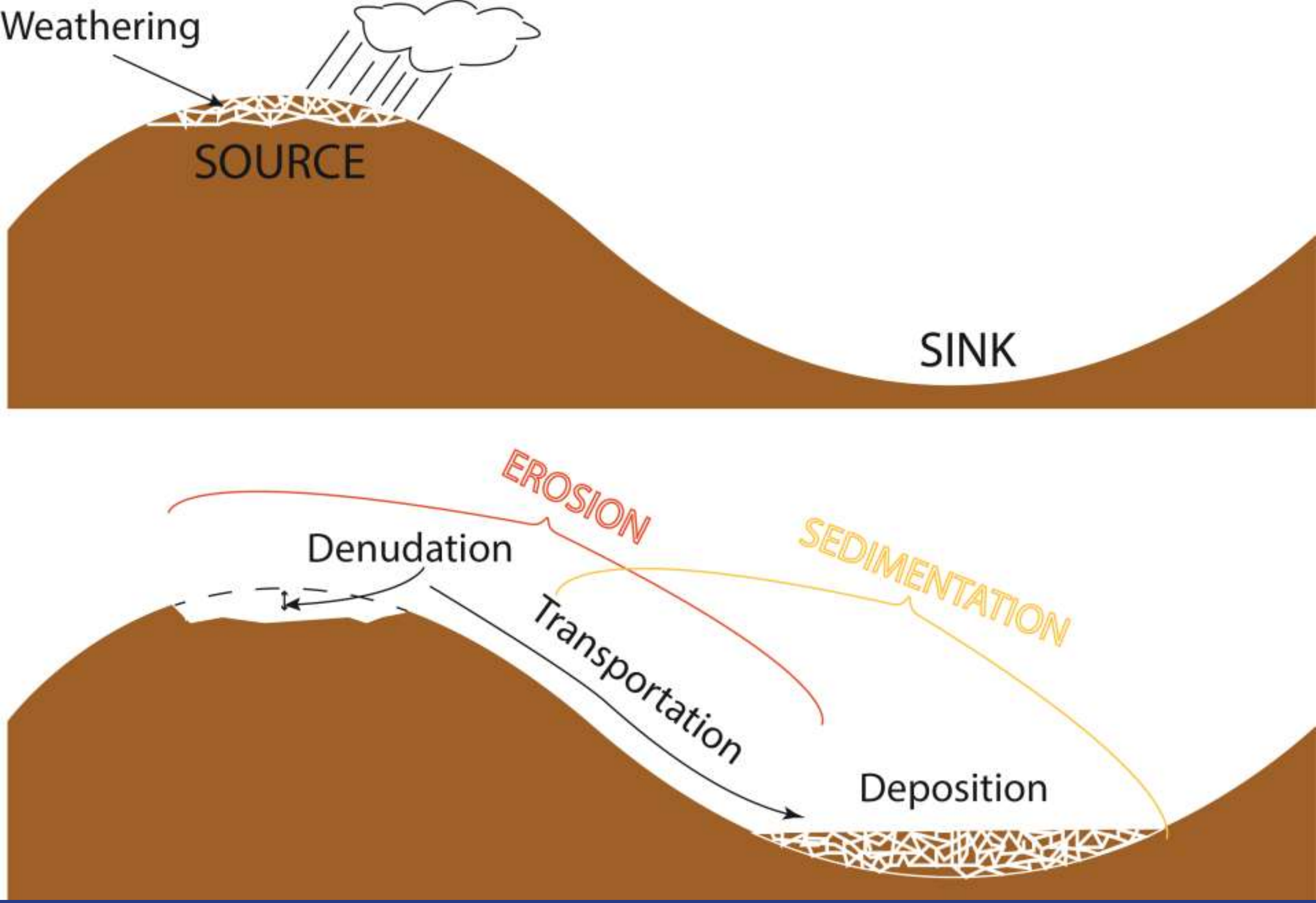
Let us begin with the study of clastic sedimentary rocks. We have learnt while considering the pyroclastic rocks that the word clastic means broken and comes from the Greek word κλάσις (*klasis*= a breaking).

All clastic sedimentary rocks form by the attrition and disintegration, i.e. breaking up of preexisting rocks. This attrition and disintegration are collectively called weathering. There are two kinds of weathering:

WEATHERING

- Corrasion (mechanical weathering, disintegration)
- Corrosion (chemical weathering, dissolution)

Erosion, the carrying away of weathered materials, denudes the surface on which it acts. The weathered material is transported by various fluid and/or organic agents on the surface of the earth or within the upper part of the lithosphere where water, air and organisms may freely circulate causing denudation. Finally the carried material comes to rest in a receptacle. This receptacle may be any surface, but is usually a basin. This processes coming to rest within a receptacle is called deposition. Transportation and deposition are collectively referred to as sedimentation in a geological context. The following schema explains the origin of clastic sedimentary rocks:



The origin of clastic sedimentary rocks and associated landforms

Some examples of rates of denudation from the major drinage basins in the world

River	Drainag are(10^6 km^2)	Denudation rate(mm/a)
1. Amazon	6,15	0,070
2. Kongo	3,82	0,007
3. Mississippi	3,27	0,044
4. Nile	2,96	0,015
5. Paraná	2,83	0,019
6.Yenisey	2,58	0,009
7. Ob	2,50	0,007
8. Lena	2,43	0,011
9. Yangtze	1,94	0,133
10. Amur	1,85	0,013
11. Mackenzie	1,81	0,030
12. Volga	1,35	0,020
13.Niger	1,21	0,024
14. Zambezi	1,20	0,031
15.Nelson	1,15	0,031
16. St. Lawrence	1,03	0,013
17. Orange	1,02	0,058
18. Orinoco	0,99	0,091
19. Ganges	0,98	0,271
20. İndus	0,97	0,124
21. Chari	0,88	0,003
22.Yukon	0,84	0,037
23. Danube	0,81	0,047
24. Mekong	0,79	0,095
25. Huang Ho	0,77	0,579
26. Şatt-al Arab	0,75	0,104
27. Rio Grande	0,67	0,009
28. Columbia	0,67	0,029
29. Kolyma	0.64	0,005
30. Colorado	0,64	0,084
31. Brahmaputra	0,58	0,677
32. Dnyepr	0,50	0,006

Let us start with corrasion, i.e., mechanical disintegration of rocks

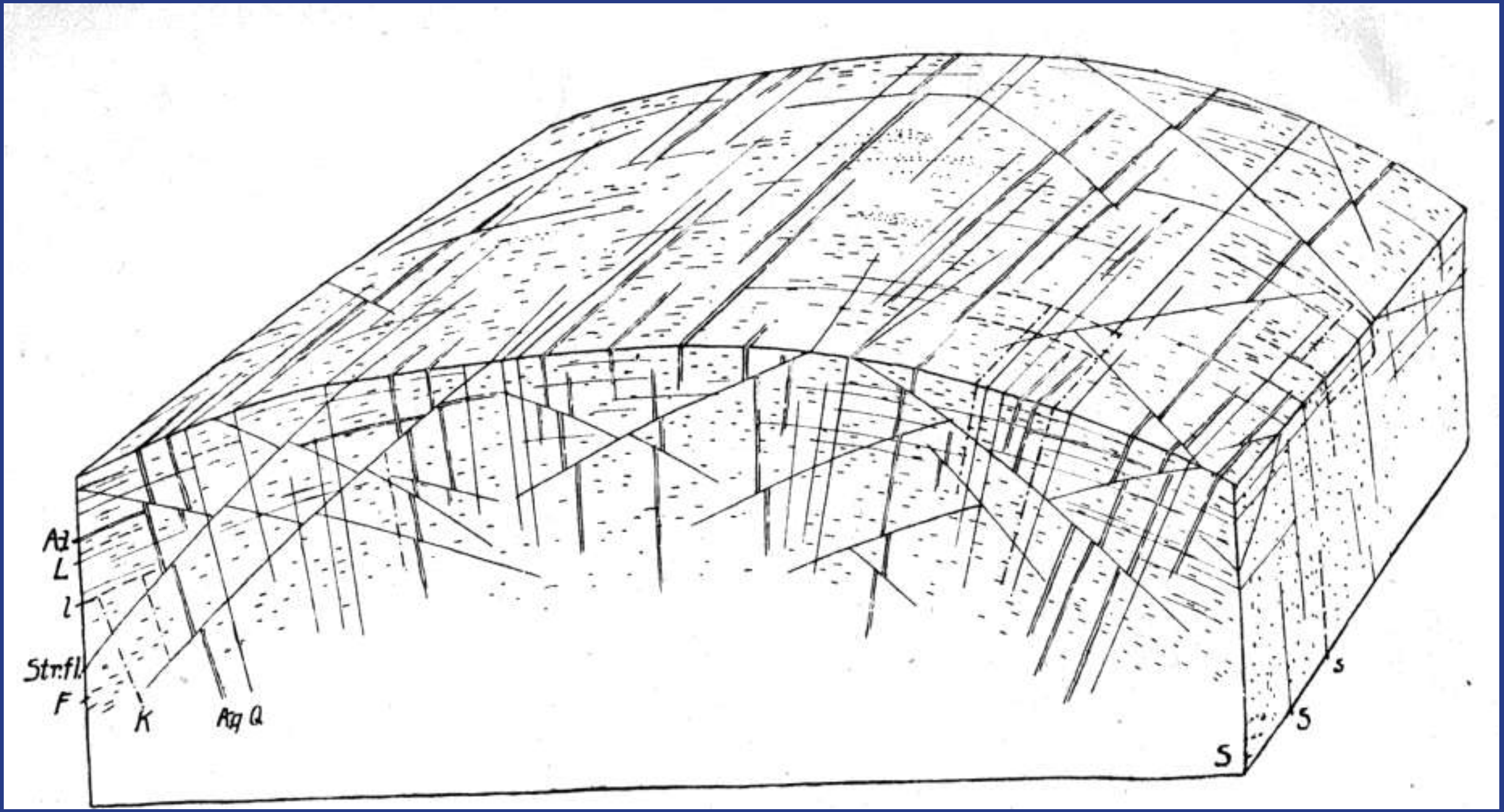
Rocks are corraded by a variety of means including water, ice, wind, earthquakes, animals and plants ad even thunderbolt.

Split apple rock, Abel Tasman National Park, New Zealand South Island

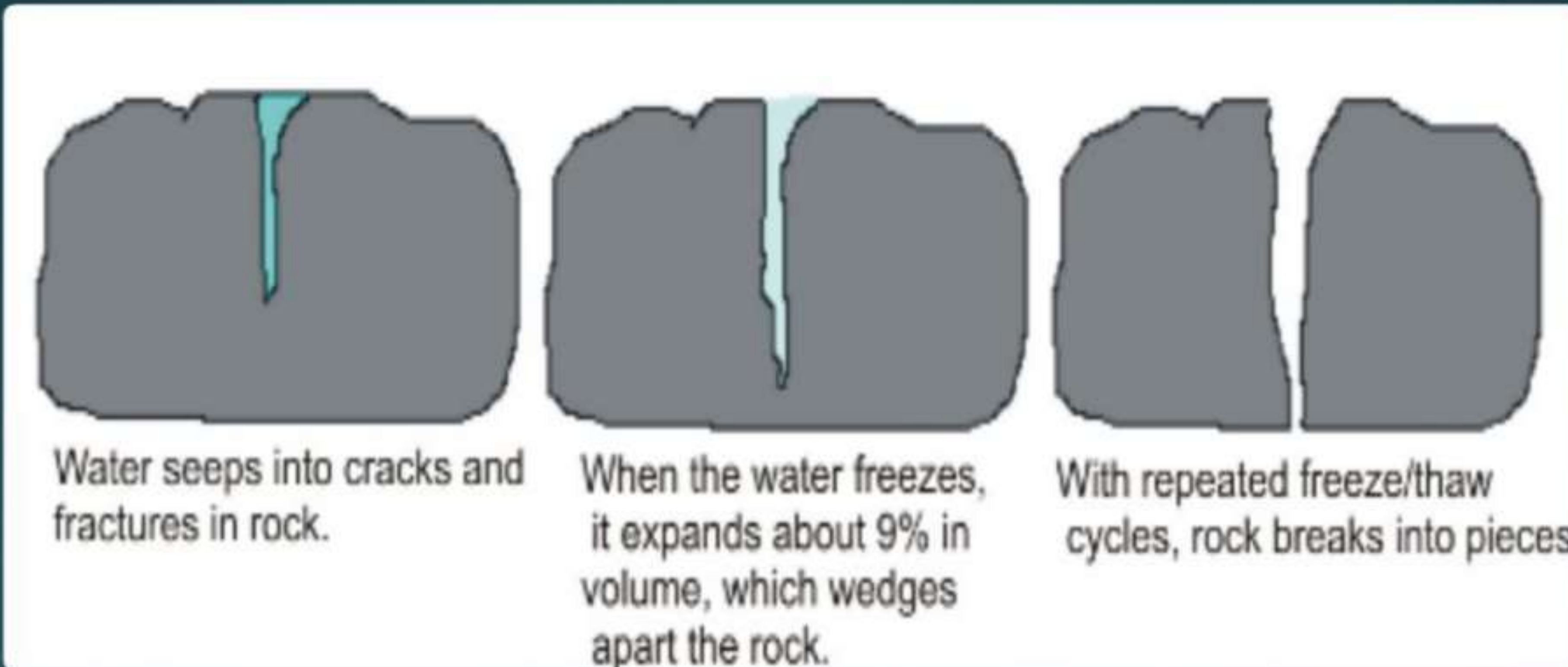
Split granite boulder in a semi-desert environment

Cracked granite boulder with aplite dykes and xenoliths.
How does it crack?

One way to crack a granite is ice wedging. What is ice wedging? Remember that a granite at the surface is traversed by numerous fractures, joints and other brittle discontinuities. These allow water access to the interior of the outcrop.

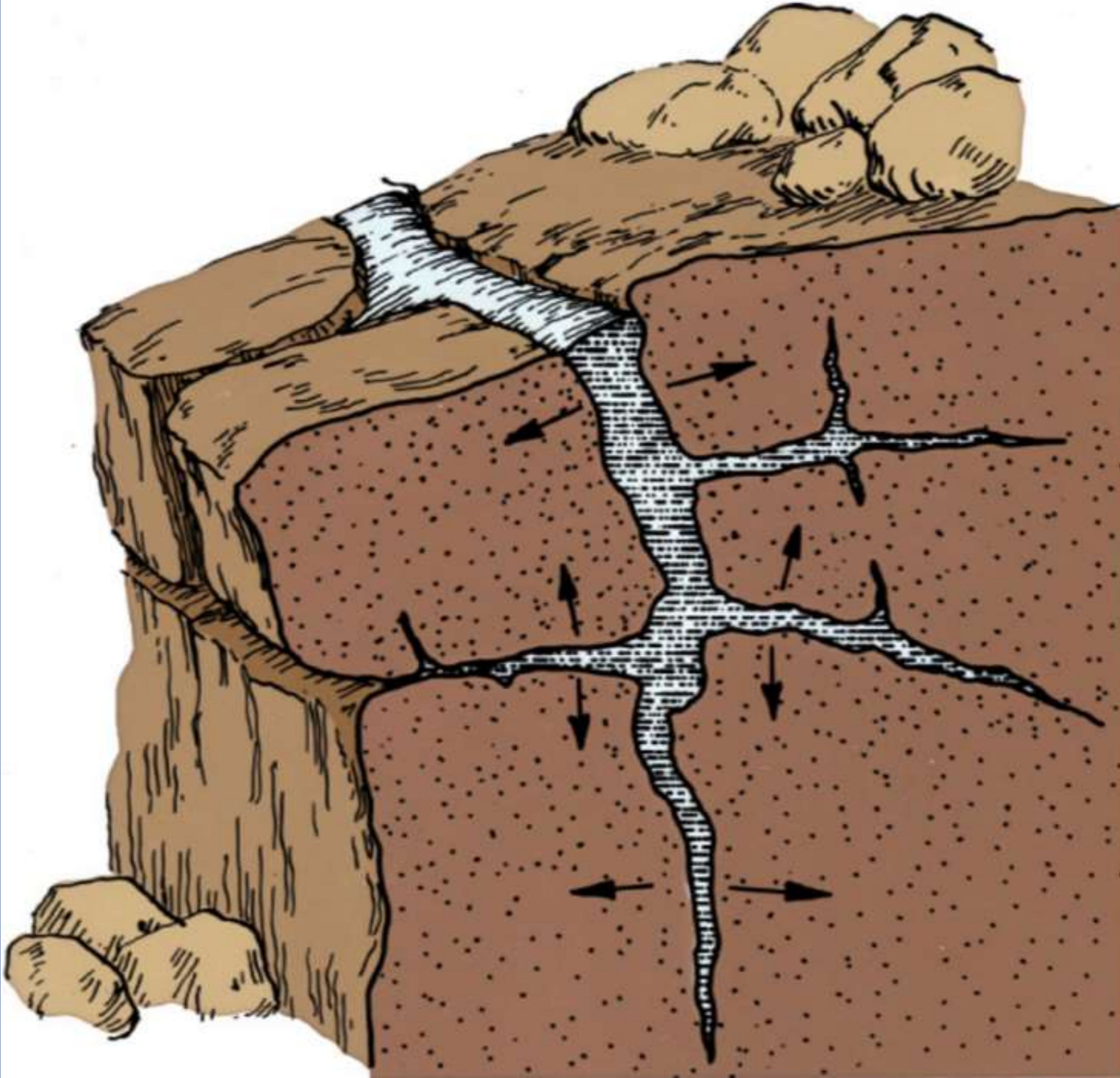


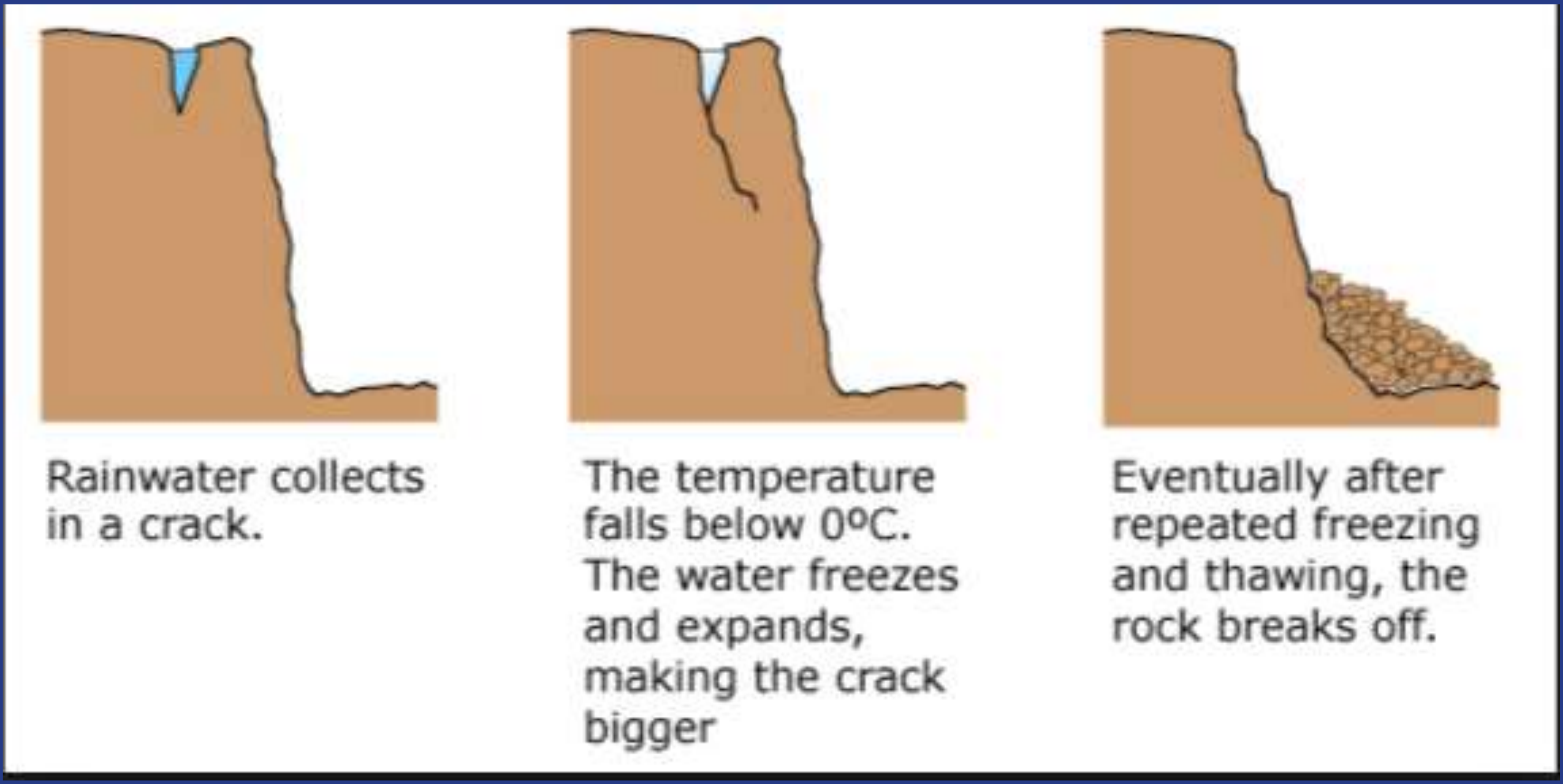
Internal structure of a batholith as seen at the surface (from Cloos, 1922)



Ice Wedging

The process of mechanical weathering in which water seeps into a crack in a rock during warm weather and then freezes during cold weather; when it expands, the ice pushes against the sides of the crack and forces it open wider.

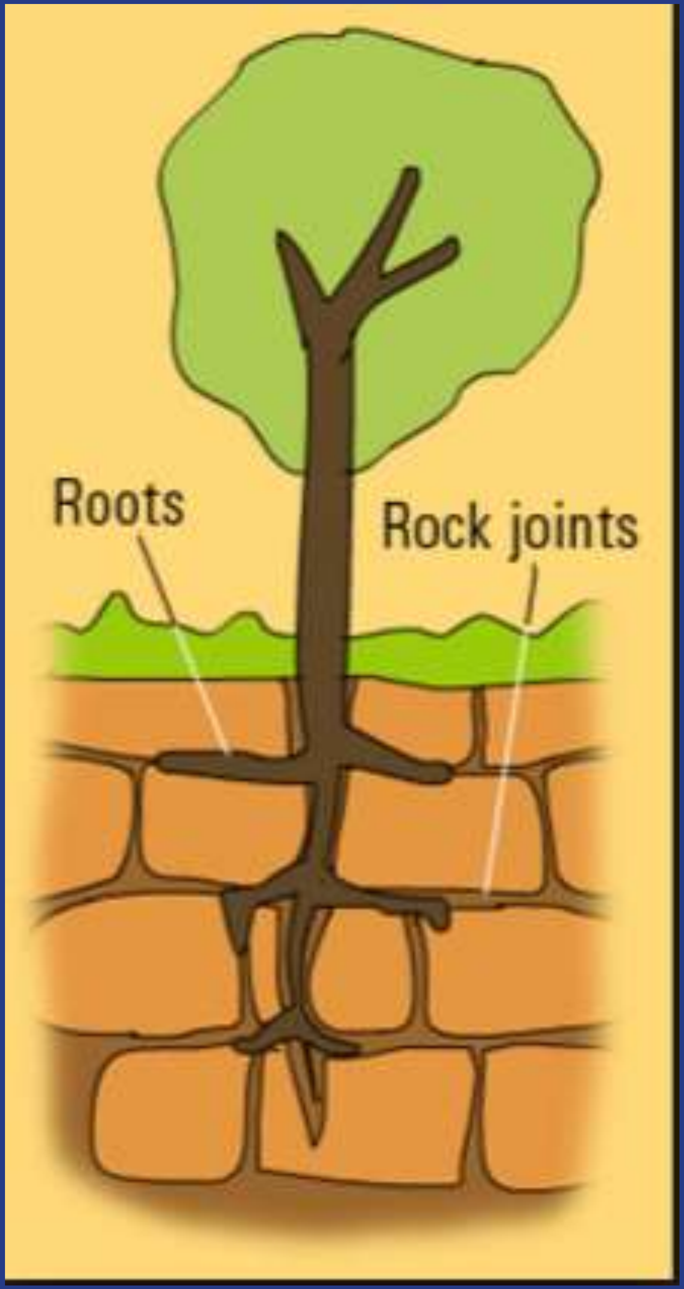




If the separated rock is on a precipice, it would fall down the precipice and further disintegrate upon impact on the ground and thus further contribute to mechanical disintegration.

Trees also help disintegrate rocks. Here is a granite boulder being split by a tree growing in a crack.

Here is a tree splitting what is probably a sedimentary rock.



Weathering.

You are surely familiar with everyday examples from your surroundings as to how trees split rocks.

During a forest fire, an average surface fire on the forest floor might have flames reaching 1 metre in height with temperatures of 800°C or more (melting temperature of dry granite!). Under extreme conditions, a forest fire can give off 10.000 kilowatts or more per metre of fire front. This would mean flame heights of 50 metres or more and flame temperatures exceeding 1200°C (i.e., the temperature of basaltic lava flows). This is surely enough to split any rock by differential expansion and contraction of its constituent minerals.

A granite splitting along its joints

But jointing and other kinds of fracturing is not unique to granites or even to igneous rocks. Sedimentary rocks and metamorphic rocks and structural rocks may also be jointed.

But what is a joint?

A joint is a brittle fracture of rock that consists of significant planar surfaces.

Joints may be extensional or shear. What distinguishes a shear joint from a fault is that the movement along a shear joint is usually measured in millimetres.

A set of joints: X-shaped joints are shear joints. The ones that cut them are probably extensional joints

Shear joints in Hatay, Turkey

“X-shears” after an earthquake in Simav, Turkey!

Joints in folded Eocene turbiditic sandstones, Korudağ, Thrace, Turkey

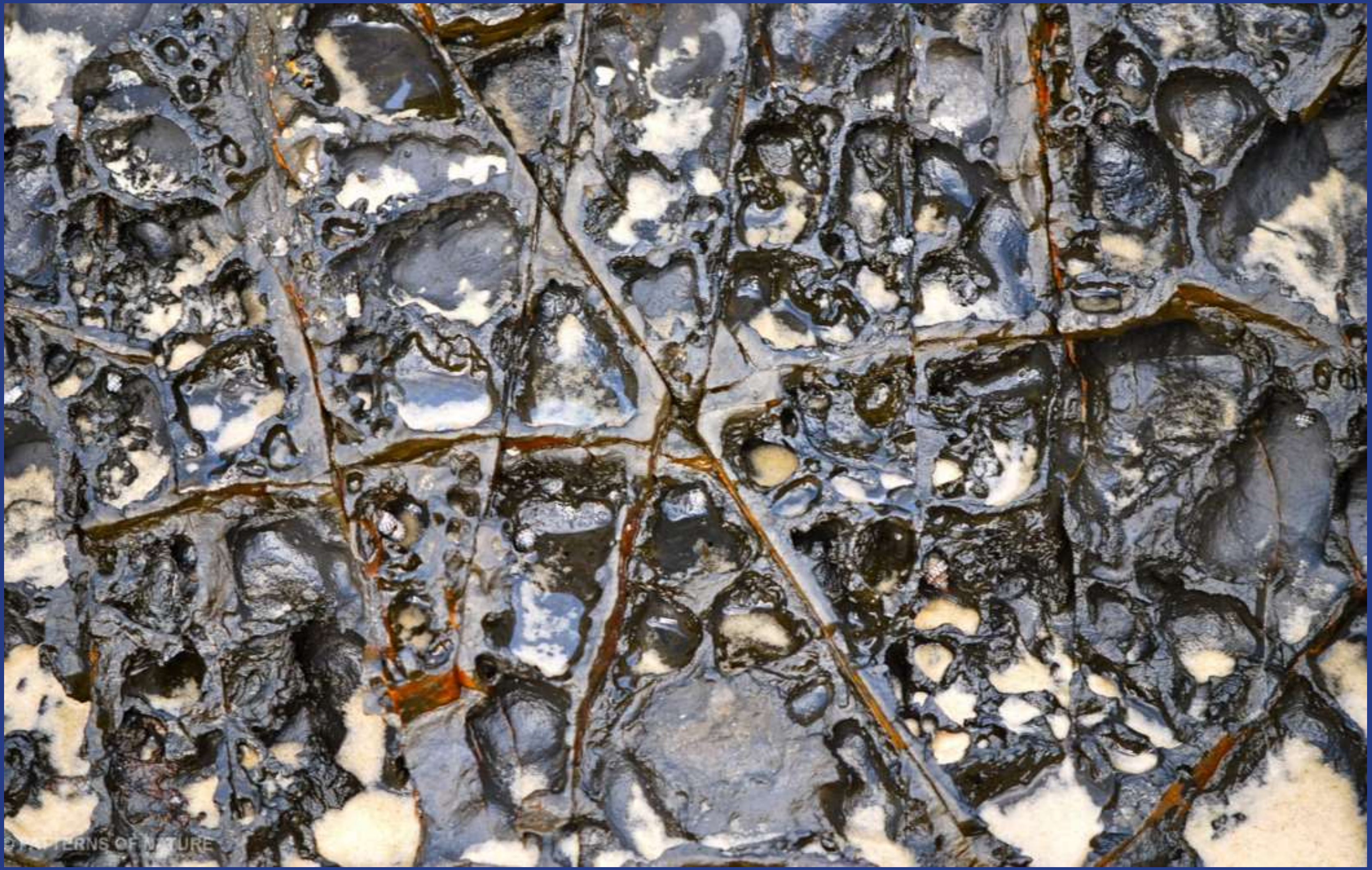
Same place - detail

Same kind of jointing in the Palaeozoic sandstones of the Sahara, Libya

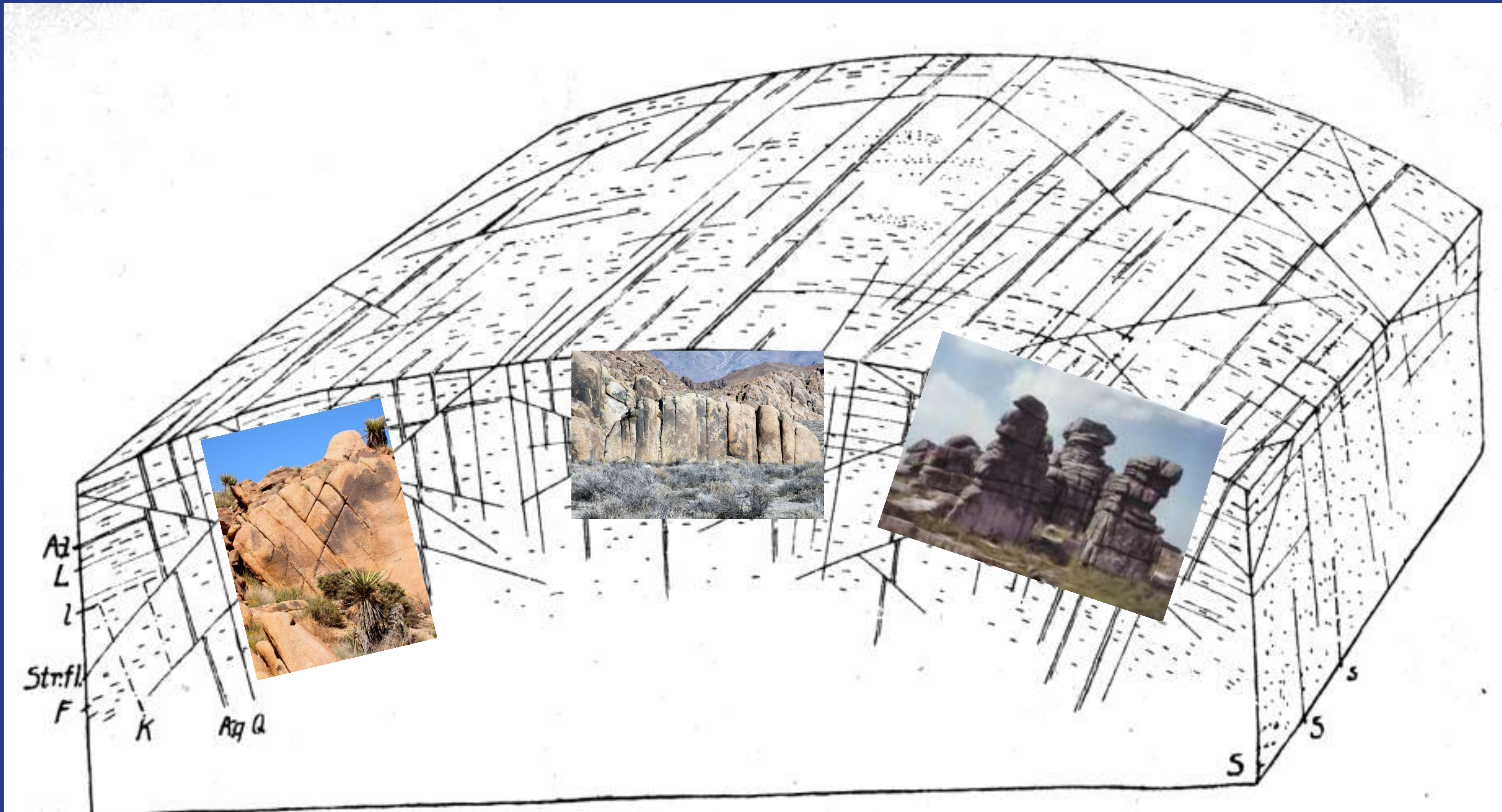
Joints in 20-million-year andesitic volcanics at Assos, Turkey

Vertical joints in granite: unknown locality.

Shear joints in granite in a desert environment.

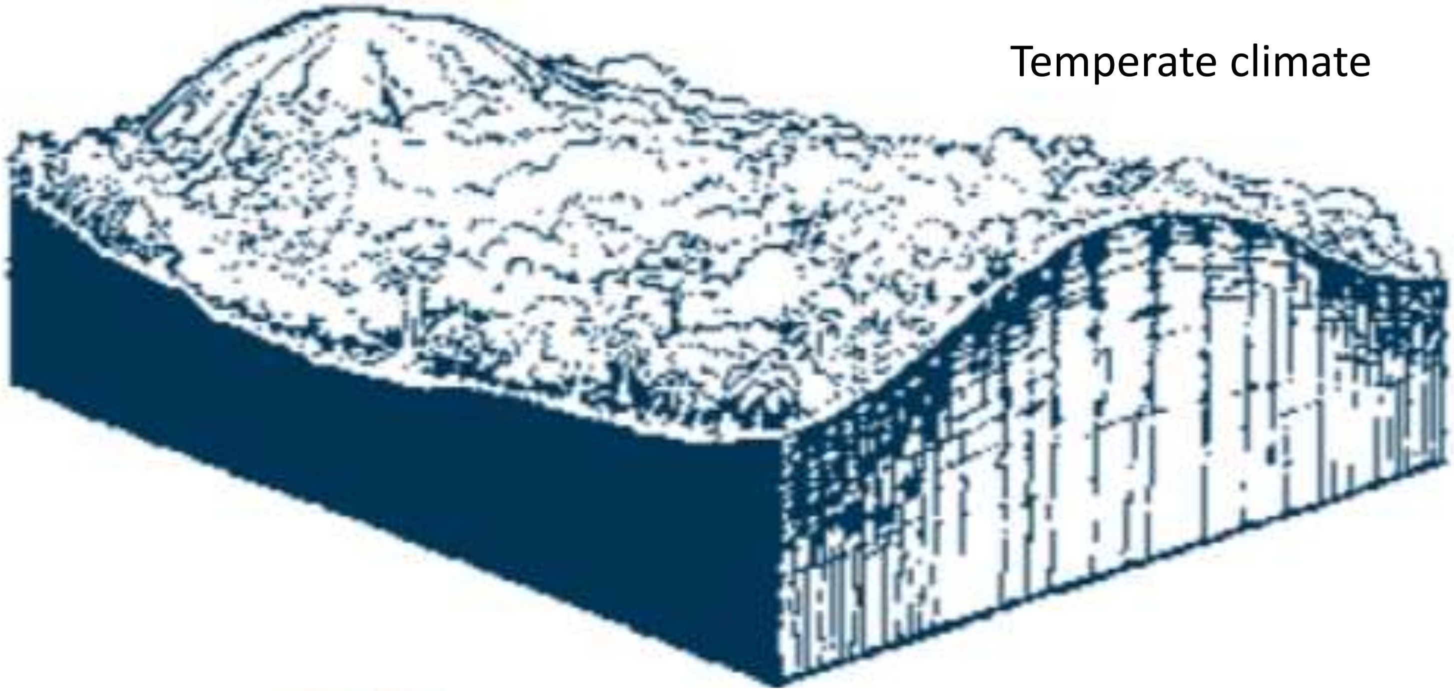


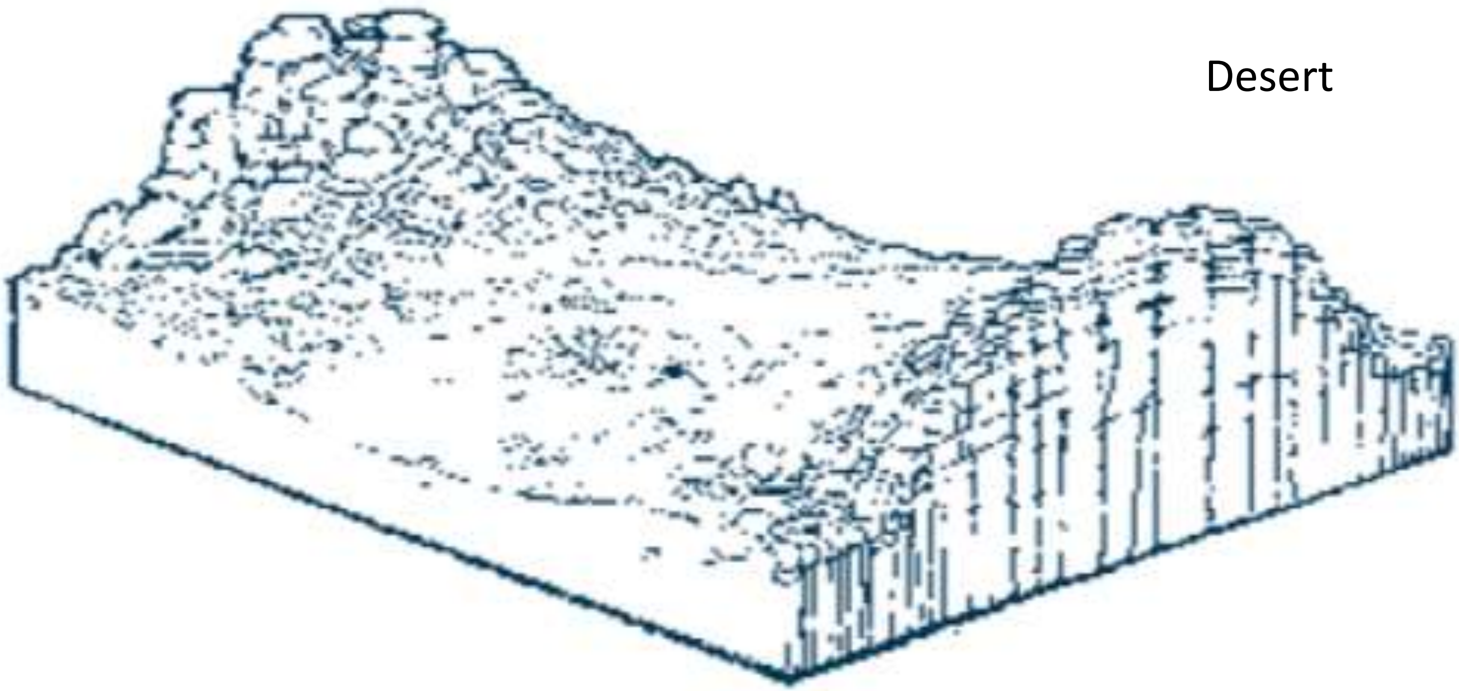
Shear and extensional joints in basalt (?) showing offset. Unknown locality



Joint systems in a granite batholith

This is a sedimentary equivalent of what you have just seen. Notice how erosion attacks the rocks along the vertical joints here also.


Temperate climate


Desert

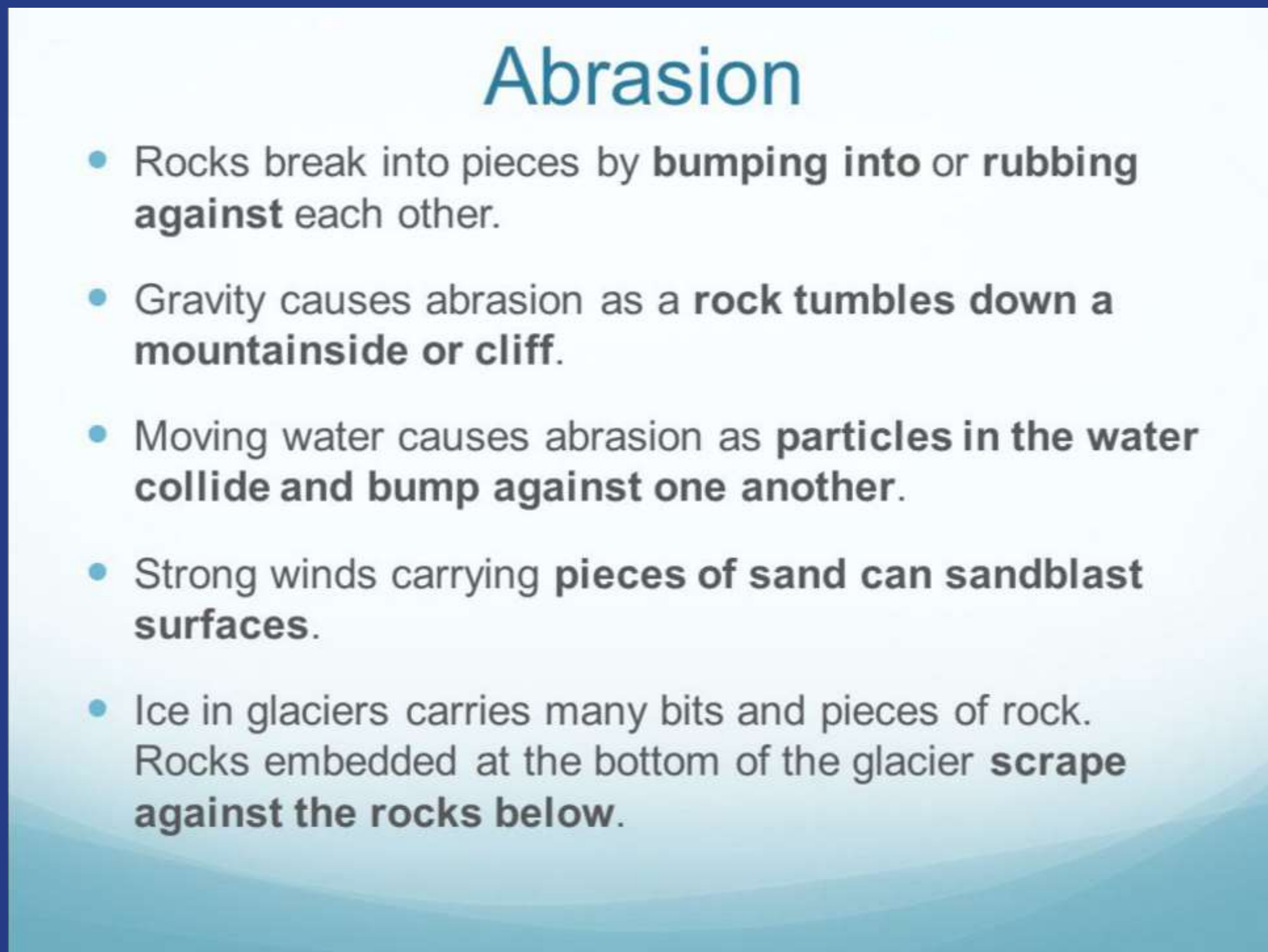
Erosion along vertical joints isolating individual pillars: Sahara, Libya

Disintegrating rocks: Sahara, Libya

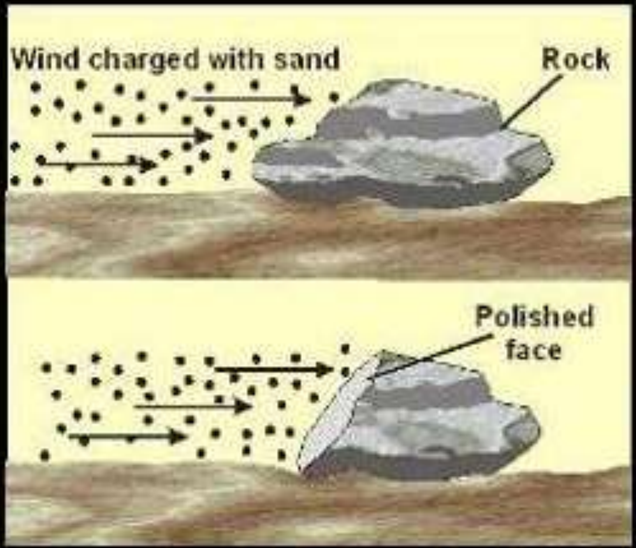
Granite disintegrating mechanically to become a coarse sand: Sahara, Libya

Formation of quartz sandstone (orthoquartzite) from granite in a desert environment, Sahara, Libya

Abrasion is another powerful mechanism of weathering and erosion. It is defined as the grinding and wearing away by friction of other rock particles of a rock surface. It is a sort of “filing of rock surfaces by other rocks”.




(1)



(3)


(5)


(2)


(4)

We now turn to corrosion, the chemical weathering of rocks.

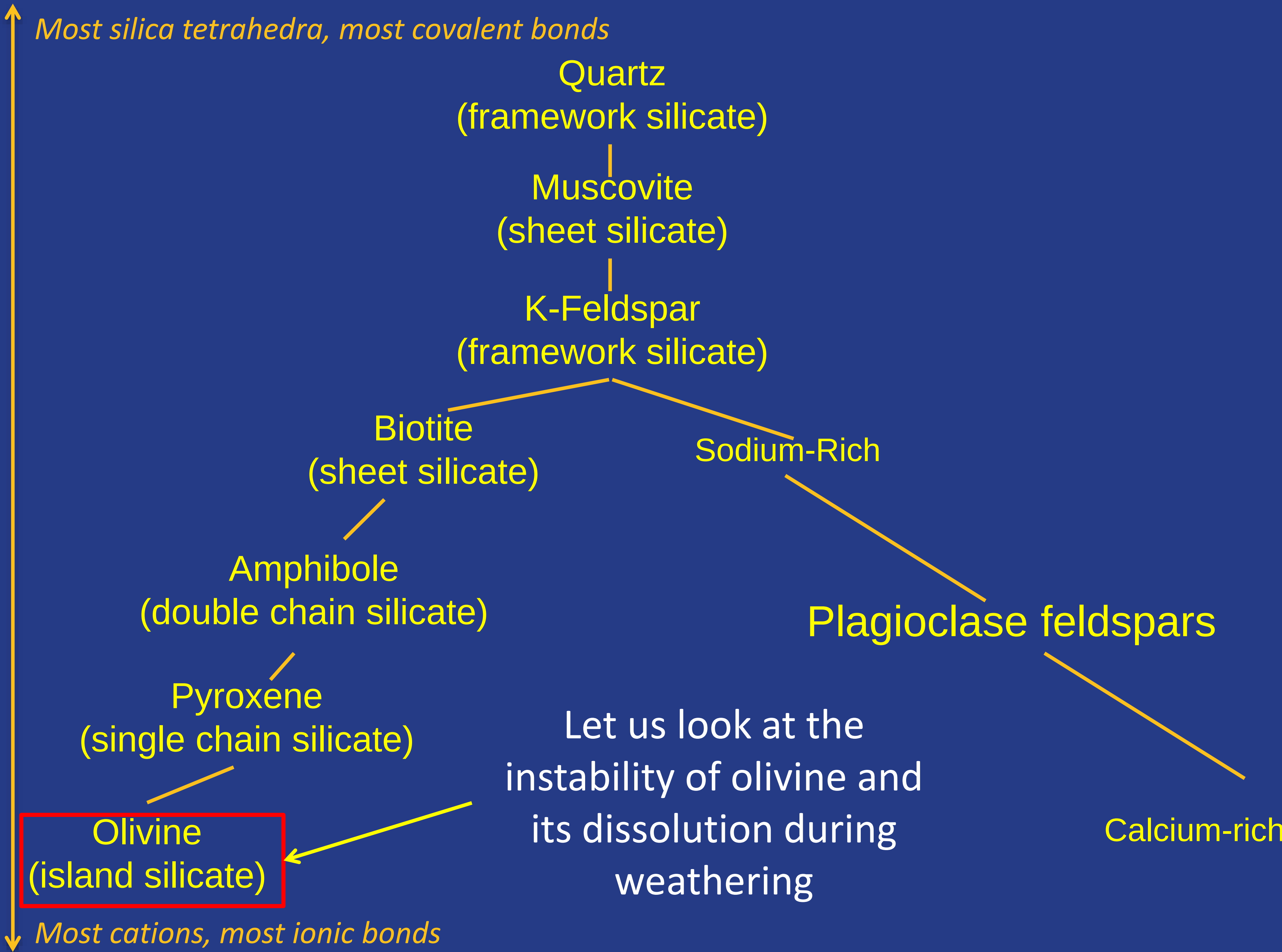
Chemical weathering acts through dissolution, hydration, hydrolisis, and oxidation.

We have already seen an example of dissolution when we discussed the dissolution of $CaCO_3$ by acidic rain water creating karst topography.

Let us remember what that was:

Carbondioxide + water = carbonic acid

Carbonic acid + calcium carbonate = calcium bicarbonate in solution



Let us look at the instability of olivine and its dissolution during weathering

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \leftrightharpoons 2Mg_2 + 4\ HCO^{3-} + H_4SiO_4$$

With enough water, NOTHING remains of the magnesium olivine (forsterite) in the rock. The entire mineral is dissolved and carried away in solution.

Most silica tetrahedra, most covalent bonds

Quartz
(framework silicate)

Muscovite
(sheet silicate)

K-Feldspar
(framework silicate)

Biotite
(sheet silicate)

Amphibole
(double chain silicate)

Pyroxene
(single chain silicate)

Olivine
(island silicate)

Sodium-Rich

Plagioclase feldspars

Calcium-rich

Most cations, most ionic bonds

Let us look at the instability of the K-feldspars and their hydrolisis during weathering

$$2\ KAlSi_3O_8 + 2\ H_2CO_3 + 9\ H_2O \rightleftharpoons Al_2Si_2O_5(OH)_4 + 4\ H_4SiO_4 + 2\ K^+ + 2\ HCO_3^-$$

Notice that in this case, the feldspar is dissolved, but kaolinite has formed in its stead. Therefore, unlike the olivine weathering, the K-feldspar weathering resulted in the formation of a mineral that is the product of weathering itself.

All clay minerals form in the presence of water and on the earth and Mars they seem to be the result of weathering in the presence of water.

Remember what we said about the great importance of clay minerals in nature and in our lives. Without clays there can be hardly any continents as we know them! So continents are a result of hydrous weathering.

Another important means of chemical weathering is oxydation, i.e. the “rusting of rocks”.

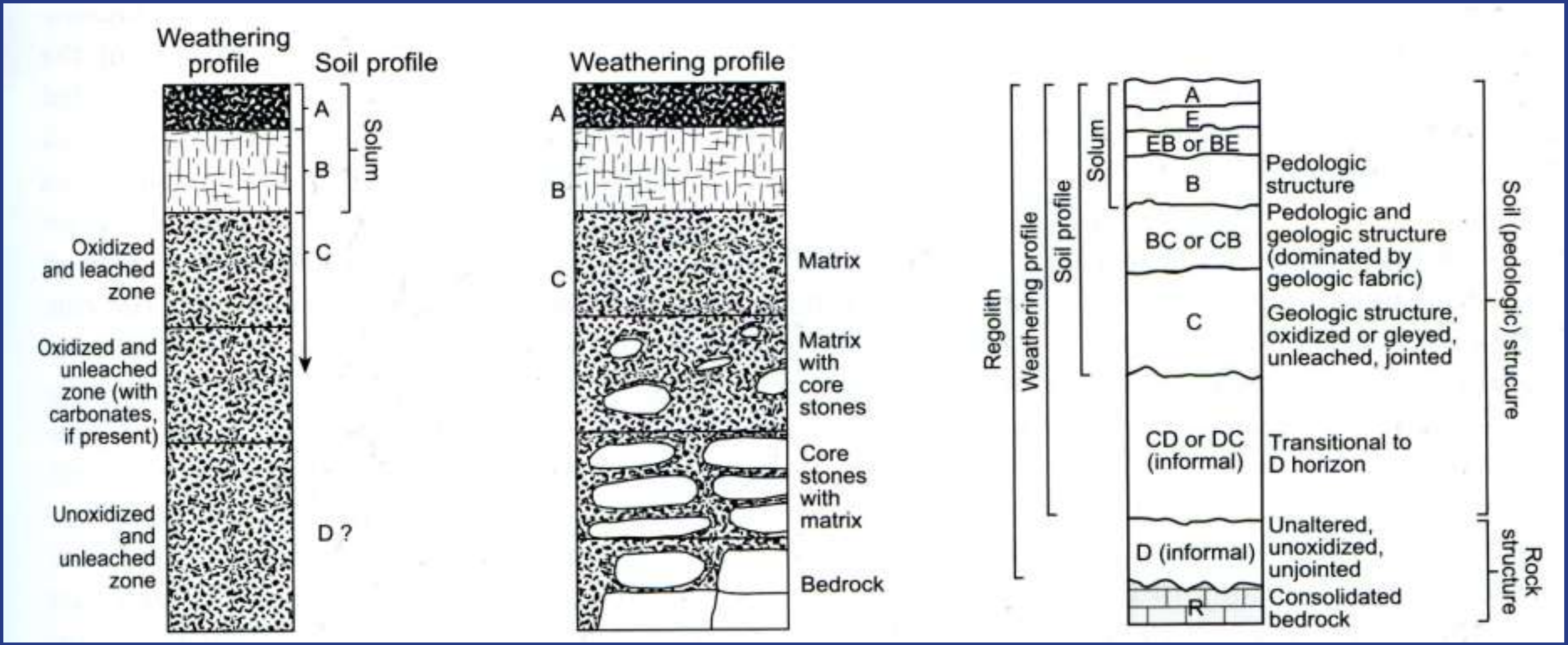
The most widespread variety is the formation of Fe^{3+} from the oxidation of Fe^{2+} to form such minerals as goethite, ilmenite and hematite. Again in these case we create new minerals from the chemical reactions of existing ones with the hydrosphere and the atmosphere.

Corrasion and corrosion almost always go hand in hand on earth (and evidently also on Mars). The only place where this is not the case, is the surface of the Moon. There only corrasion happens because there is hardly any water. There the corrasive agent is the meteorite bombardment, including micrometeorites. The incessant bombardment from space pulverizes the Moon rocks at the surface and creates an extremely fine grained Lunar regolith.

The regolith on earth is the product of all the processes we just reviewed. It is therefore time we define the term regolith:

Regolith is the residual covering of loose earth produced by weathering. It was first introduced into geology as a concept and a term by the American geologist George Perkins Merrill in 1897. It comes from the Greek ῥῆγος (*rhegos*=rug, blanket) and λίθος (*lithos*=stone).

Regolith is the product of weathering and constitutes the weathering profile on a weathered rock.



The weathering profile is defined as a vertical assemblage of different weathering zones from the surface to the unaltered bedrock. Here the weathering profile according to Hallberg et al. (1978) based on their work in the state of Iowa, USA, which is shown on the left.

The weathering profile shoud not be confused with soil profile.

The regolith leads us to the consideration of the origin and evolution of soils. The branch of geology and geography that studies soils is known as pedology.

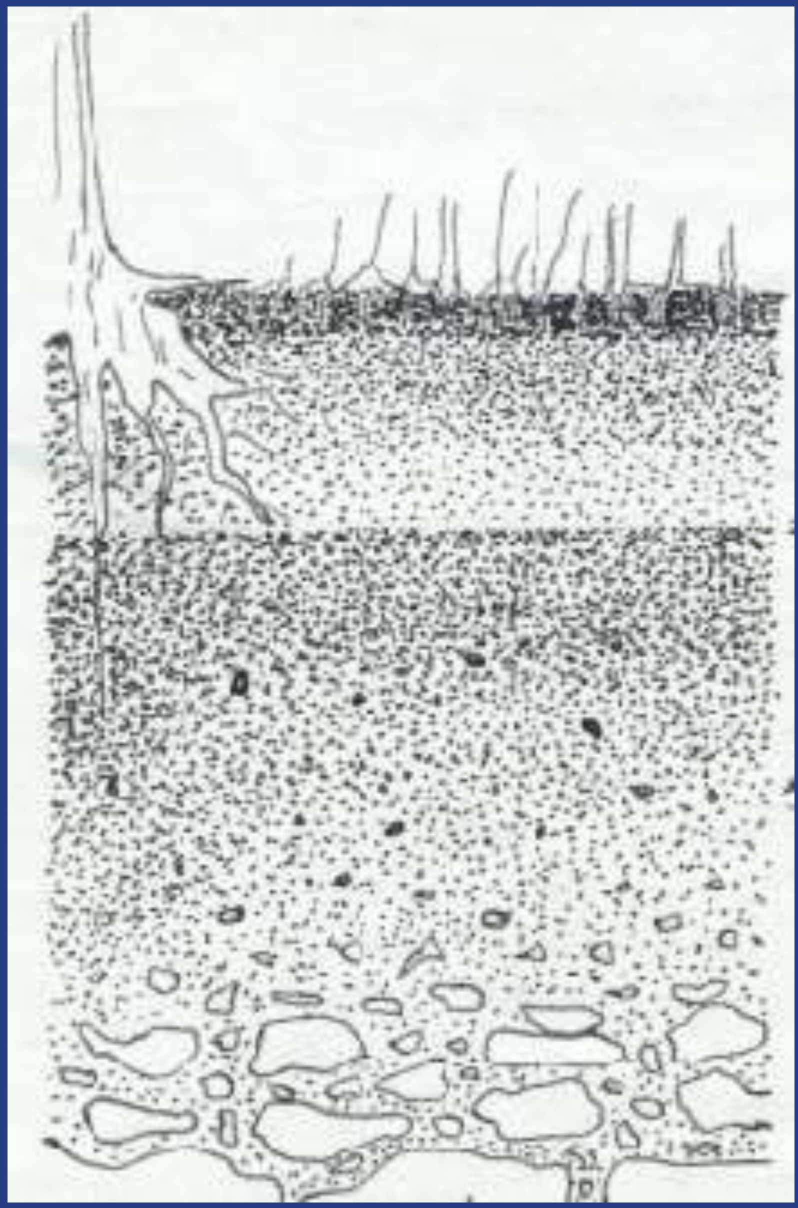
The two definitions of soil given by Schaetzl and Anderson (2005) are the following:

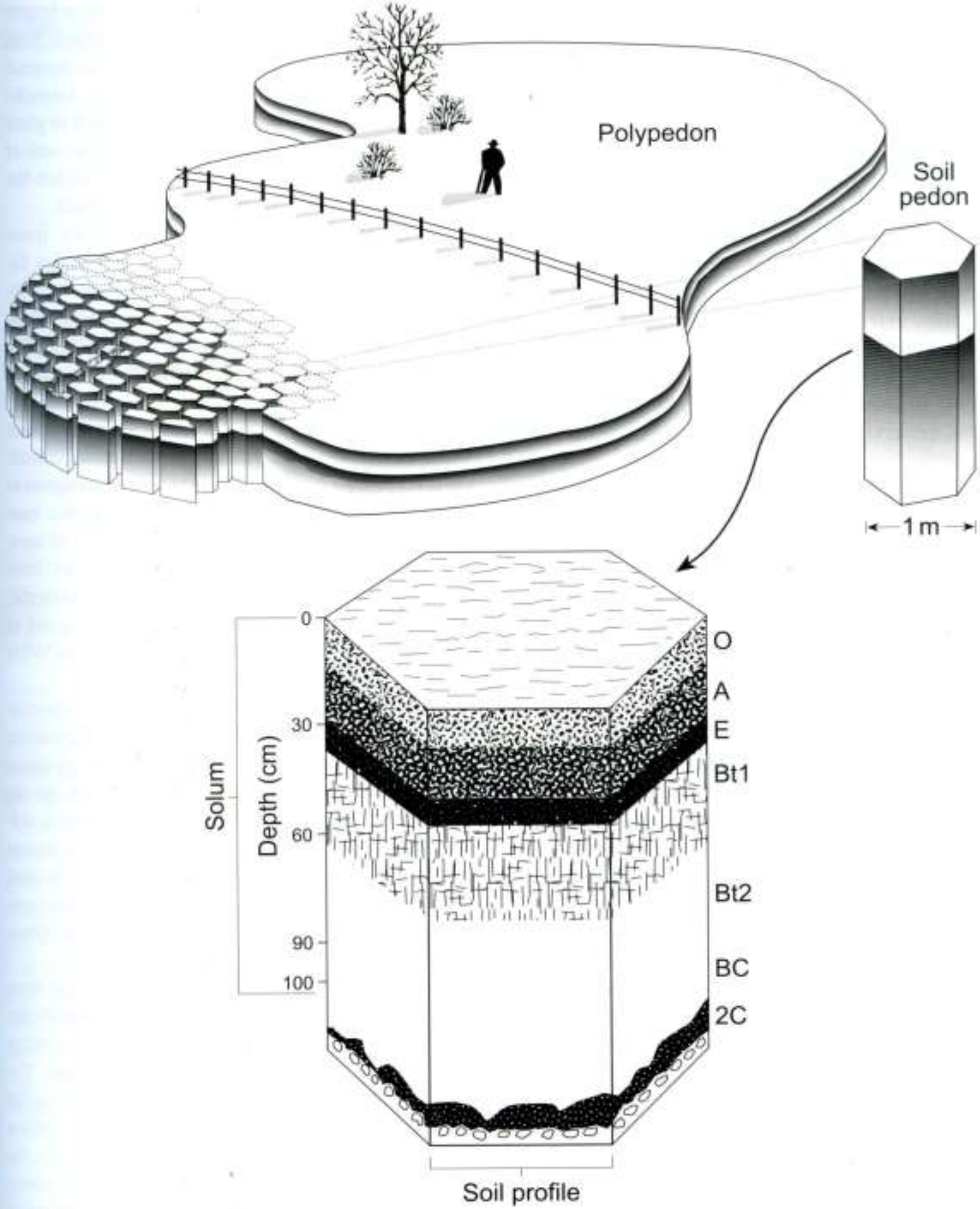
1. Soil is the unconsolidated mineral and organic material on the surface that serves as a natural medium for the growth of land plants, or that responds to diurnal and seasonal climatic and microclimatic conditions in the absence of plants (as in parts of Antarctica)

2. Soil is the unconsolidated mineral and organic matter on the surface that has been subjected to and influenced by genetic and environmental factors of parent material, climate (including moisture and temperature effects), macro- and microorganisms, topography, all acting over a period of time and producing a product — soil — that differs from the material from which it is derived in many physical and chemical, biological and morphological properties and characteristics.

The word pedology comes from the Greek πέδον (*pedon* =soil) and λόγος (*logos*=to talk about, to discourse, to reason) and was invented by the Italian geologist Paolo Eugenio Vinassa de Regny in 1904.

A typical simplified soil profile





Solum: The upper and most weathered part of the soil profile comprising the A, E and B horizons. This is the actual soil on which life depends.
The word comes from the Latin *solum* meaning soil.

Podum: The smallest unit which shows all the characteristics of a given soil type.

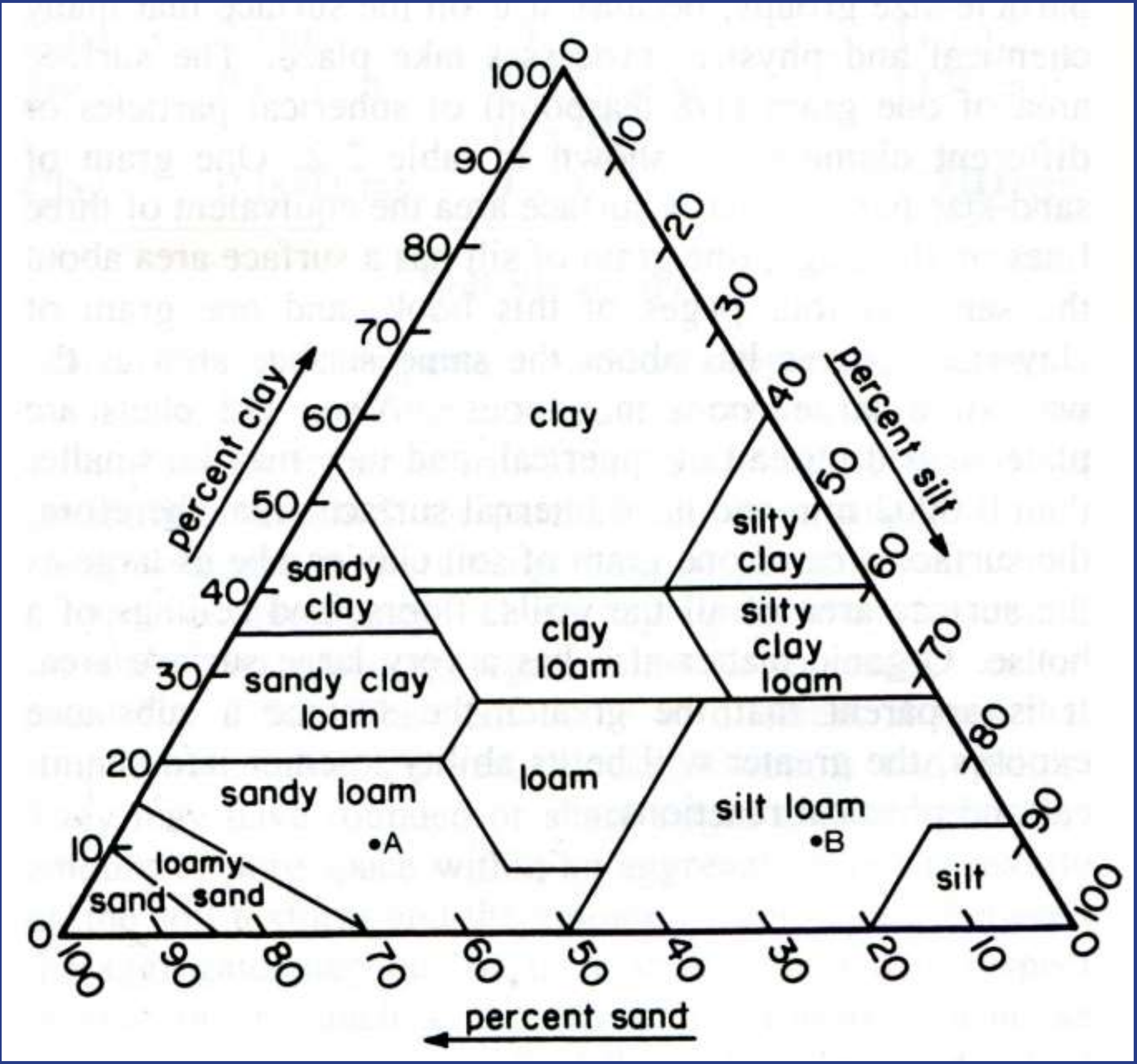
Polypedon: The area in which a certain podum is dominant.

Master horizon	Characteristics
O	Layers dominated by organic material (litter and humus) in various stages of decomposition.
A	Mineral horizons that formed at the surface or below an O horizon and (1) are characterized by an accumulation of humified organic matter intimately mixed with the mineral fraction, or (2) have properties resulting from cultivation, pasturing or similar kinds of disturbance.
E	Light-colored mineral horizons in which the main feature is loss of weatherable minerals, silicate clay, iron, aluminum, humus, or some combination, leaving a concentration of mostly uncoated quartz grains or other resistant materials.
B	Subsurface mineral horizons dominated by (1) illuvial accumulations of clay, iron, aluminum, humus, etc., (2) removal of primary carbonates, (3) residual concentrations of sesquioxides, (4) distinctive, non-geologic structure and/or (5) brittleness.
C	Mineral horizons, excluding hard bedrock, that have been little affected by pedogenic processes and lack properties of O, A, E or B horizons. Most C horizons are mineral soil layers and retain some rock structure (if developed in residuum) or sedimentary structure (if developed in transported regolith). Included as C horizons are deeply weathered, soft saprolite (see Chapter 8).
D	Deep horizons that show virtually no evidence of pedogenic alteration, such as leaching of carbonates or oxidation. D horizons retain geologic structure and are often dense and slowly permeable. Like C horizons, D horizons are formed in unconsolidated sediments.
R	Hard, continuous bedrock that is sufficiently coherent to make digging by hand impractical.

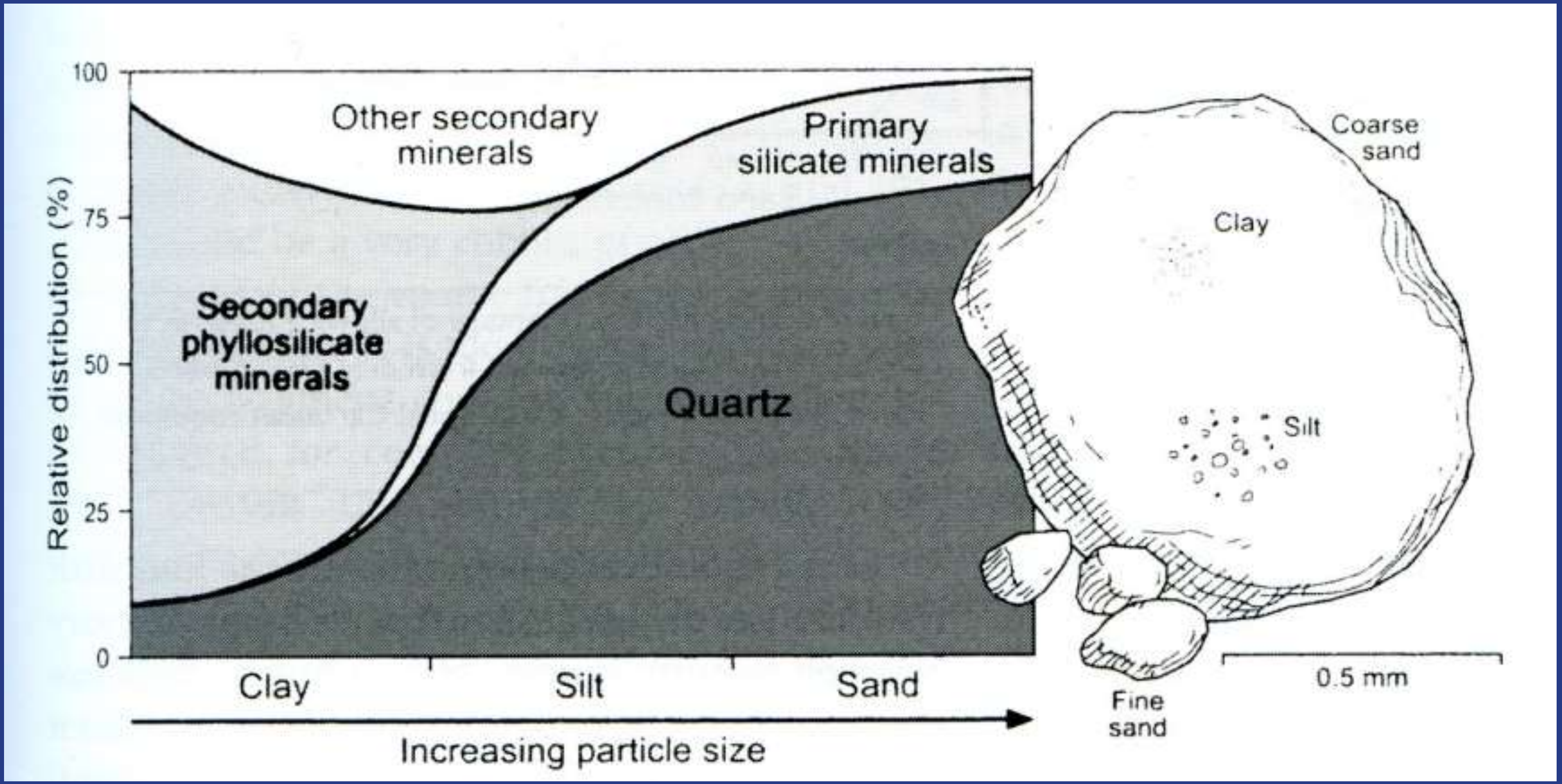
Characteristics of the main soil horizons
(from Schaetzl and Anderson, 2005)

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

Kind of particle	Diameter of particle	Number of particles in 1 gram	Surface area of one gram
Sand	2 mm	90	11 cm^2
Silt	0.02 mm	90,000,000 (9×10^7)	1130 cm^2
Clay	0.0002 mm	9×10^{13}	113,000 cm^2



Terminology of the size-based regolith classes



Distribution of mineral types in various size classes of grains in soils and sedimentary rocks (from Schaetzl and Anderson, 2005)

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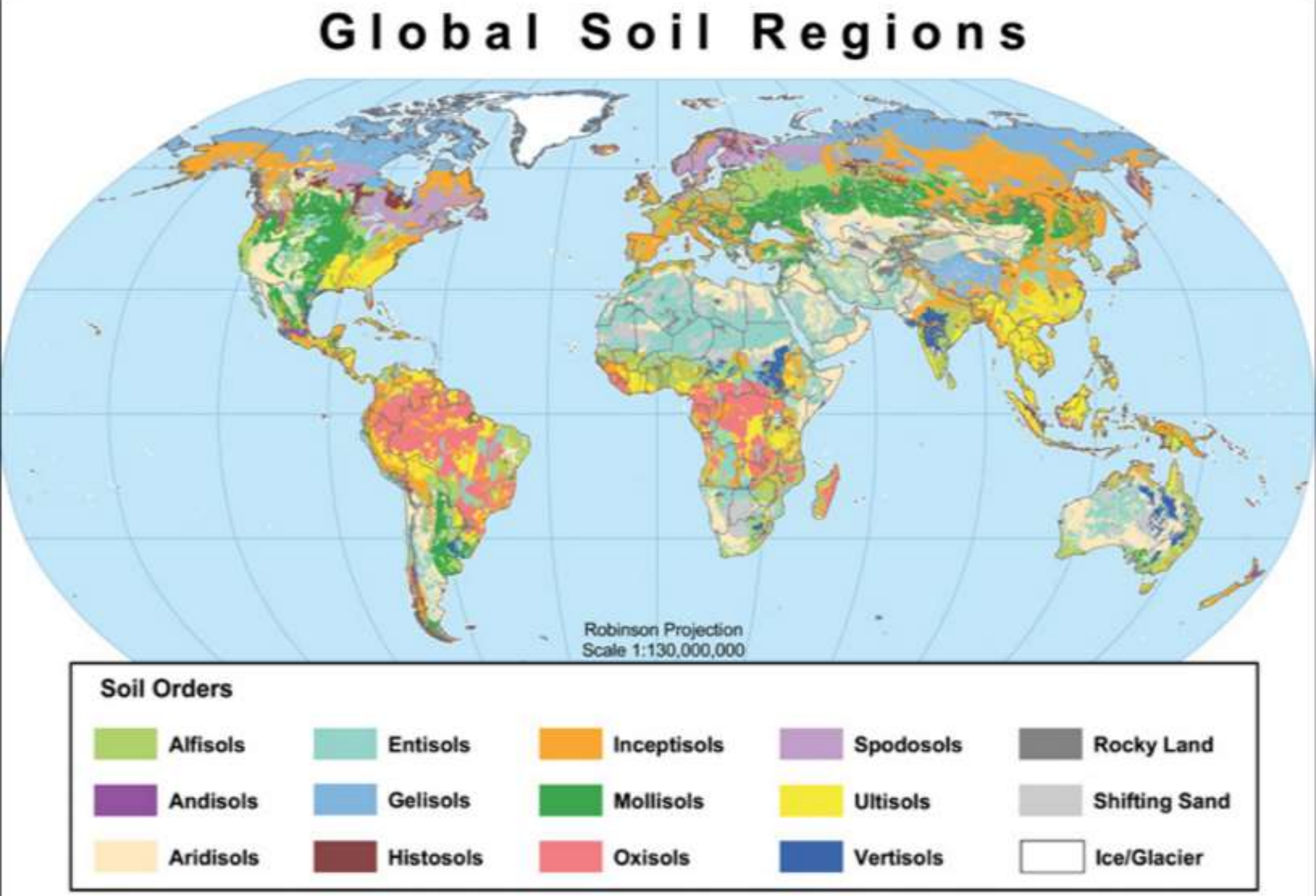
Different types of soils are classified into orders, suborders, great groups, subgroups, families and series. There are only 12 soil orders but more than 15,000 soil series (this number is still growing!!)

This subdivision system is based on the presence of absence of certain soil horizons.

The following list of the 12 orders gives their main characteristics:

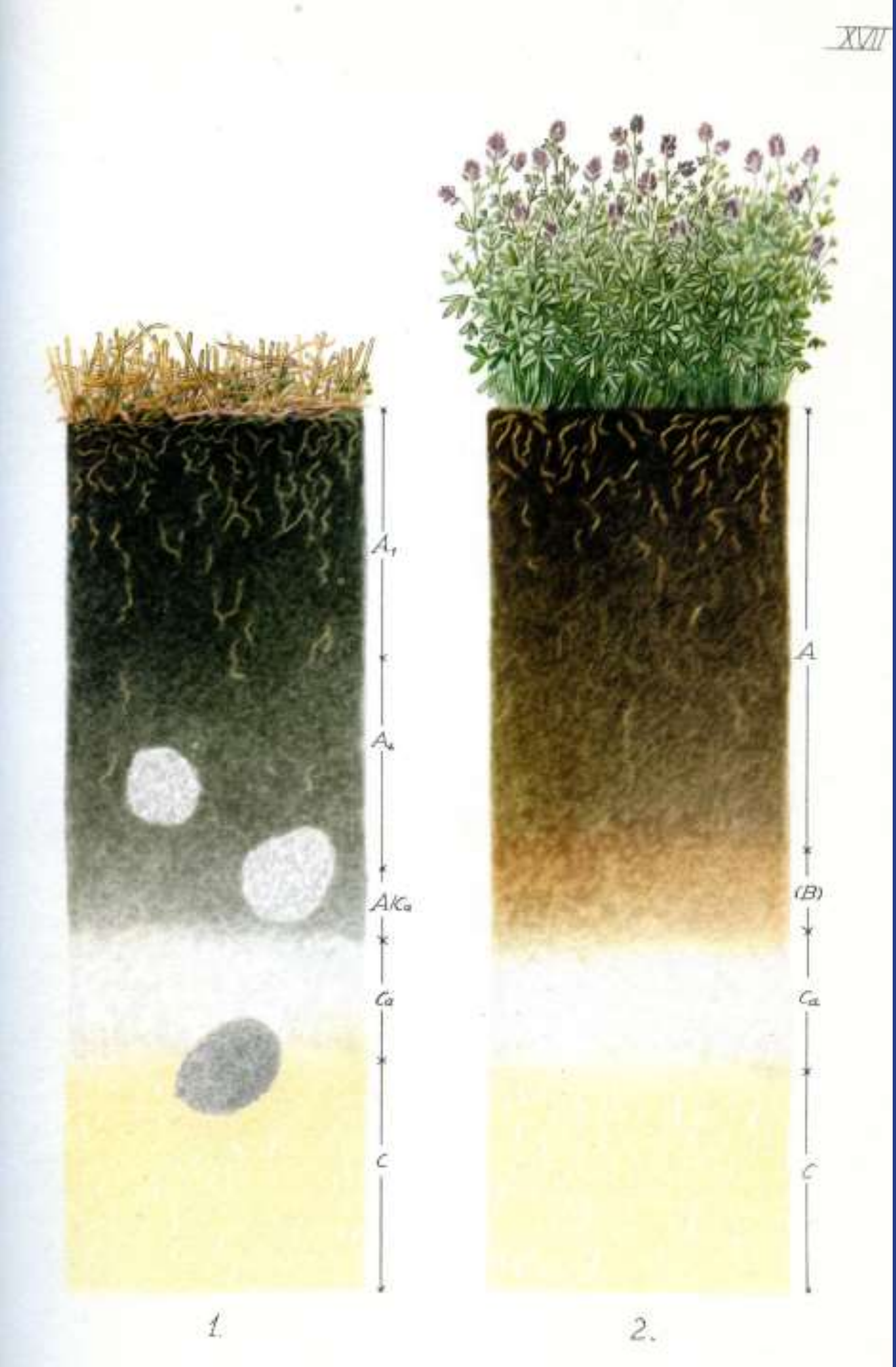
Order	Formative element	Derivation[a] of formative element	Pronunciation	General characteristics and descriptors[b]
Gelisol	-el	L. *gelare*, to freeze	Gel	Soils with permafrost within 100 cm of the surface
Histosol	-ist	Gr. *histos*, tissue	Histology	Organic soils without shallow permafrost, dominated by decomposing organic matter; most are saturated at times
Spodosol	-od	Gr. *spodos*, wood ash	Odd	Soils in which translocation of compounds of Fe, humus and Al is dominant
Andisol	-and	Modified from *ando*	And	Soils that have often formed in parent materials with a large component of volcanic ash
Oxisol	-ox	F. *oxide*, oxide	Oxides	Highly weathered, relatively infertile soils dominated by oxide, low-activity clays
Vertisol	-ert	L. *verto*, turn, mix	Invert	Dark soils of semi-arid grasslands and savannas which develop deep cracks in the dry season; cracks swell shut in wet season as the shrink–swell clays rehydrate and expand
Aridisol	-id	L. *aridus*, dry	Arid	Soils of dry climates with some development in the B horizon, often as precipitated compounds of calcium or other salts
Ultisol	-ult	L. *ultimus*, last	Ultimate	Acid, leached soils of warm, humid climates that have a B horizon enriched in clay, usually 1:1 and oxide clays
Mollisol	-oll	L. *mollis*, soft	Mollify	Base-rich soils that have a thick, dark A horizon, often formed under grasslands or savanna
Alfisol	-alf	Aluminum (Al) and iron (Fe)	Ralph	Soils that are less acidic than Ultisols, and which have a B horizon enriched in silicate clays
Inceptisol	-ept	L. *inceptum*, beginning	Inception	Soils with weak B horizon development
Entisol	-ent	Meaningless syllable from "recent"	Recent	All other soils, usually very weakly developed, on young surfaces or eroded/disturbed sites or forming on difficultly weatherable materials



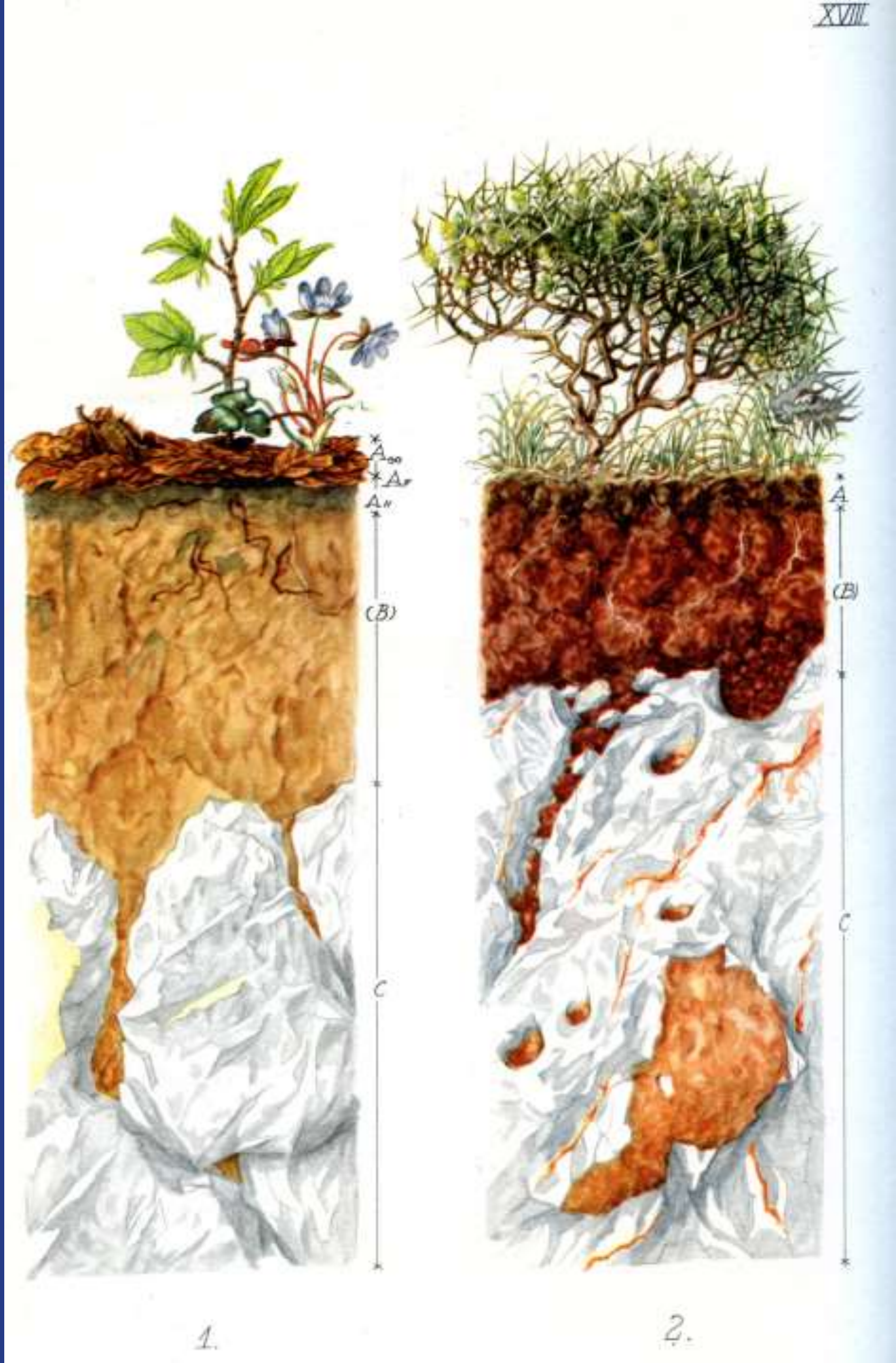
Global distribution of soil orders

Category VI (Order)	Category V (Suborder)	Category IV (Great soil groups)
Zonal Soils: Pedocals	Soils of the cold zone	Tundra soils
	Light-colored soils of arid regions	Desert soils
		Red Desert soils
		Sierozem
		Brown soils
		Reddish Brown soils
	Dark-colored soils of the semi-arid, subhumid and humid grasslands	Chestnut soils
		Reddish Chestnut soils
		Chernozem soils
		Prairie soils
		Reddish Prairie soils
Zonal soils: Pedalfers	Soils of the forest–grassland transition	Degraded Chernozem soils
		Noncalcic Brown or Shantung Brown soils
	Light-colored podzolized soils of the timbered regions	Podzol soils
		Brown Podzolic soils
		Gray-Brown Podzolic soils
	Lateritic soils of forested warm-temperate and tropical regions	Yellow Podzolic soils
		Red Podzolic soils (and Terra Rossa)
		Yellowish Brown Lateritic soils
		Reddish Brown Lateritic soils
		Laterite soils
Intrazonal soils	Halomorphic (saline and alkali soils)	Solonchak or saline soils
		Solonetz soils
		Soloth soils
	Hydromorphic soils of marshes, swamps and seep areas	Wiesenböden (meadow soils)
		Alpine Meadow soils
		Bog soils
		Half Bog soils
		Planosols
		Groundwater Podzol soils
		Groundwater Laterite soils
	Calcomorphic	Brown Forest soils (Braunerde)
		Rendzina soils
Azonal soils		Lithosols
		Alluvial soils
		Dry sands

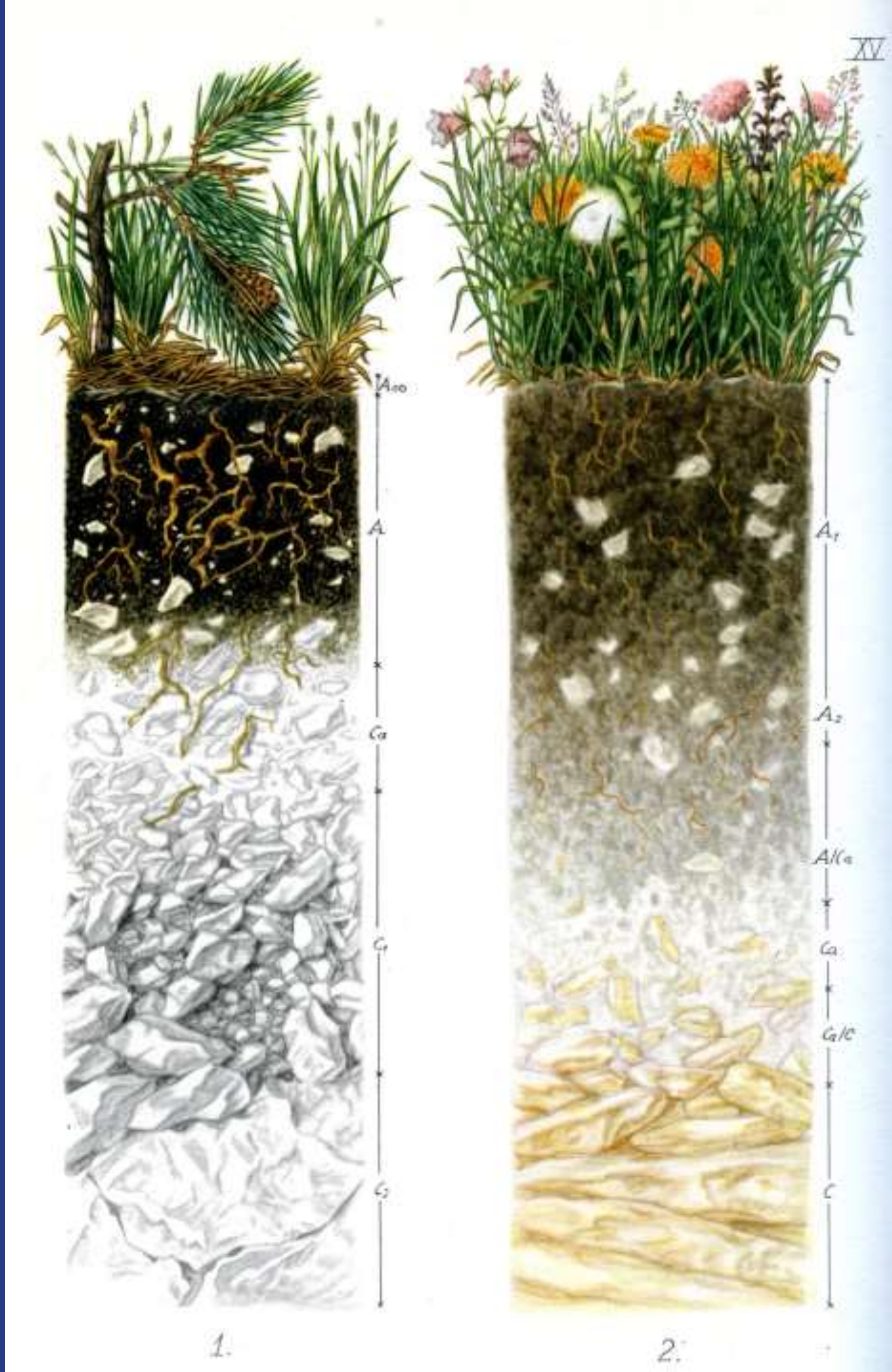
Classical, but now abandoned soil classification (dating from 1938; taken from (from Schaetzl and Anderson, 2005)



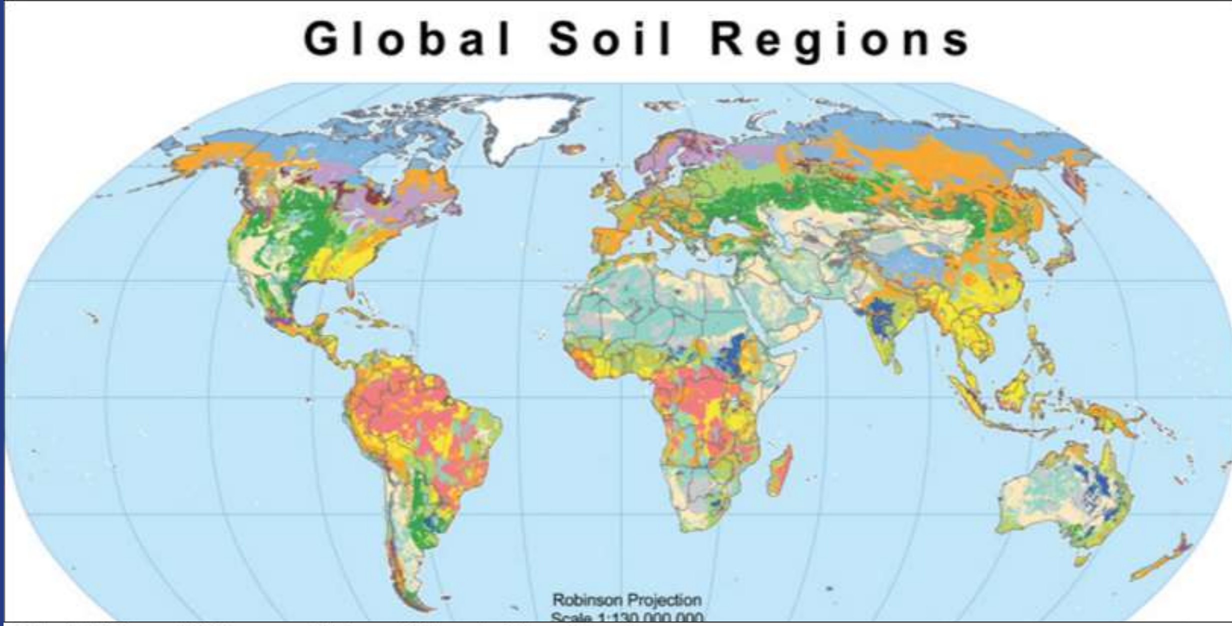
The famous *Chernozyom* (black soils) of the Rusisan steppes. A typical mollisol. From Kubiena, 1953.

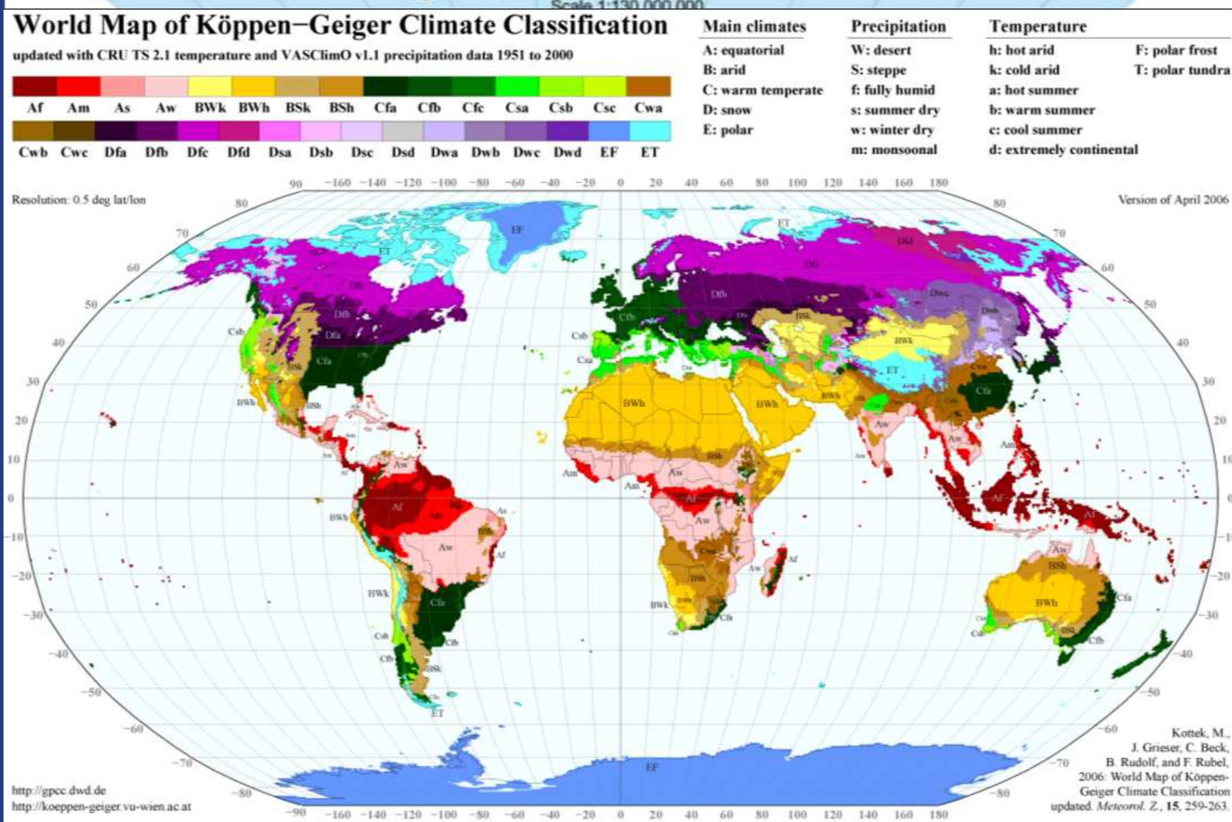


Terra Rossa (meaning red soil in Italian) soil forming in karstic regions above dissolving limestones. An inceptisol.



Rendzina soils. These are the typical soils of west of İstanbul, for example. The word rendzina comes from the Polish “rzędzić” meaning “to chat”. This name was given to the soil, because of the high number of gravels it contains. Because of that it creaks and screeches when polughed and thus “chats” with the farmer! Rendzinas are also considered inceptisols.





A comparison showing the dependence of soil orders on climate types.