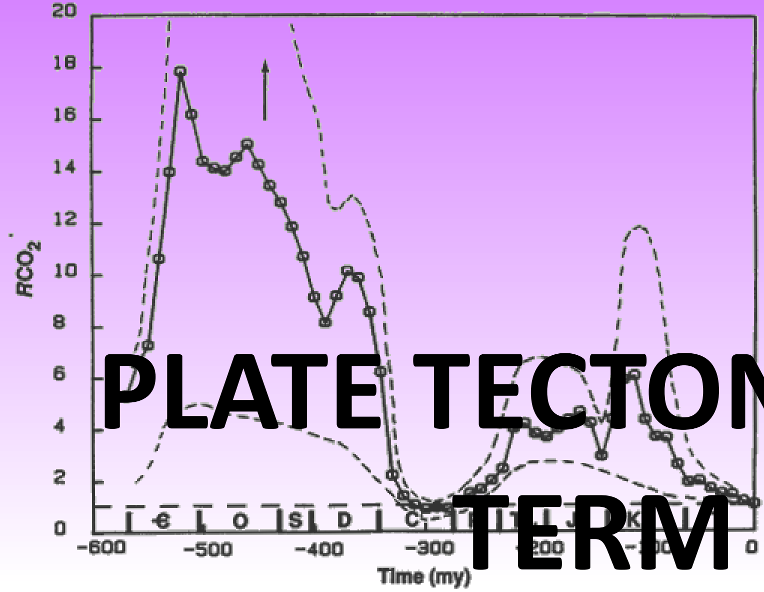
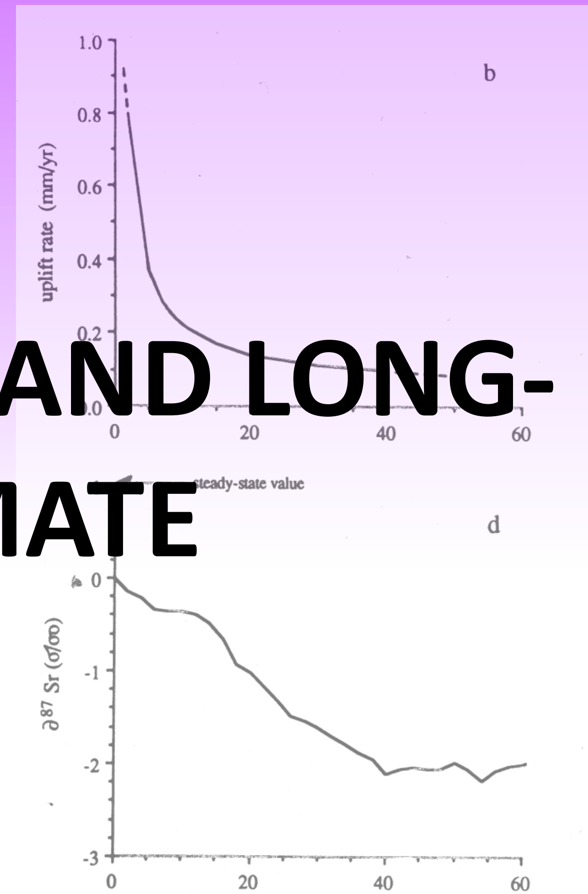
PLATE TECTONICS AND LONG-TERM CLIMATE





Source images: Ruddiman, 2007 (Chapter 4)

Introduction

•The past 550 million years are better documented than the initial 4 billion.

•More abundant sedimentary records enable more reliable reconstructions.

•This period shows a consistent cycle of icehouse and greenhouse intervals.

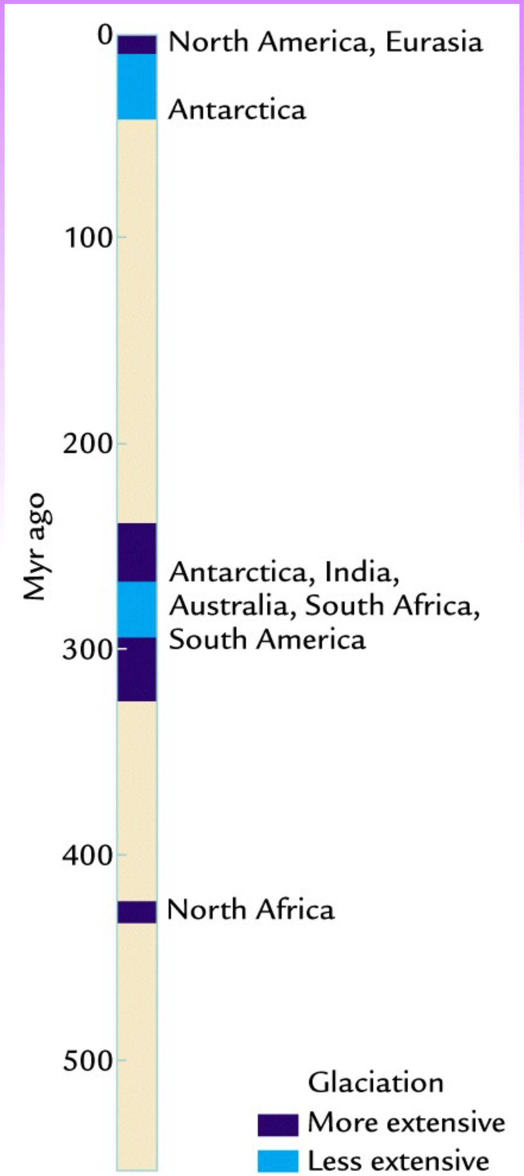
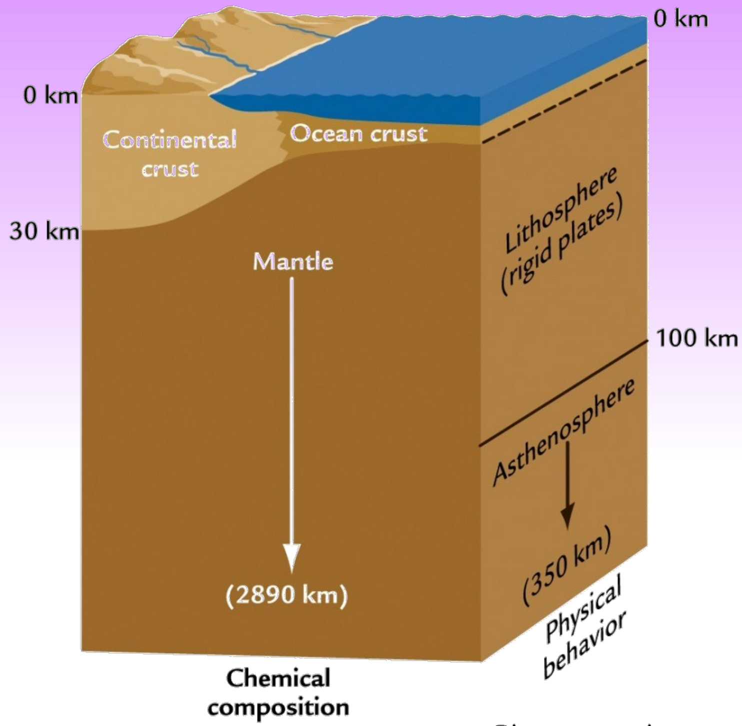
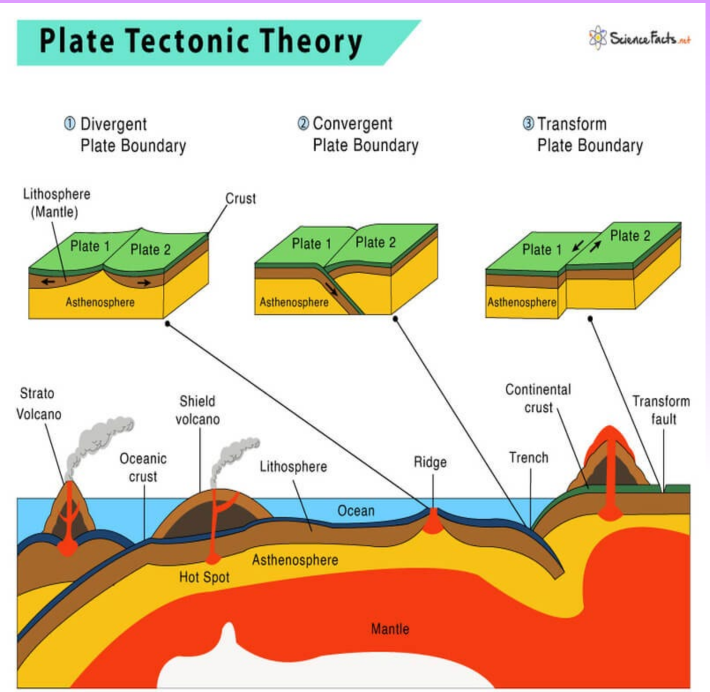


PLATE TECTONICS - 1





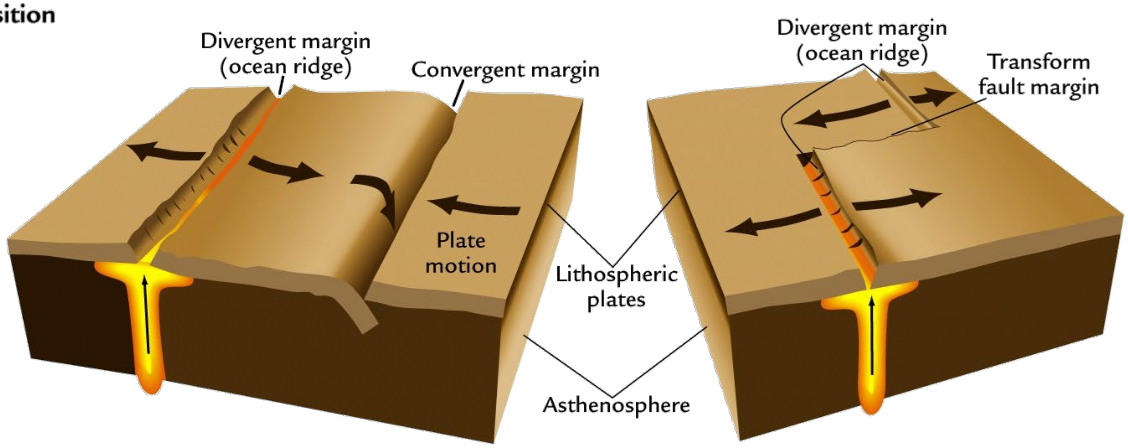
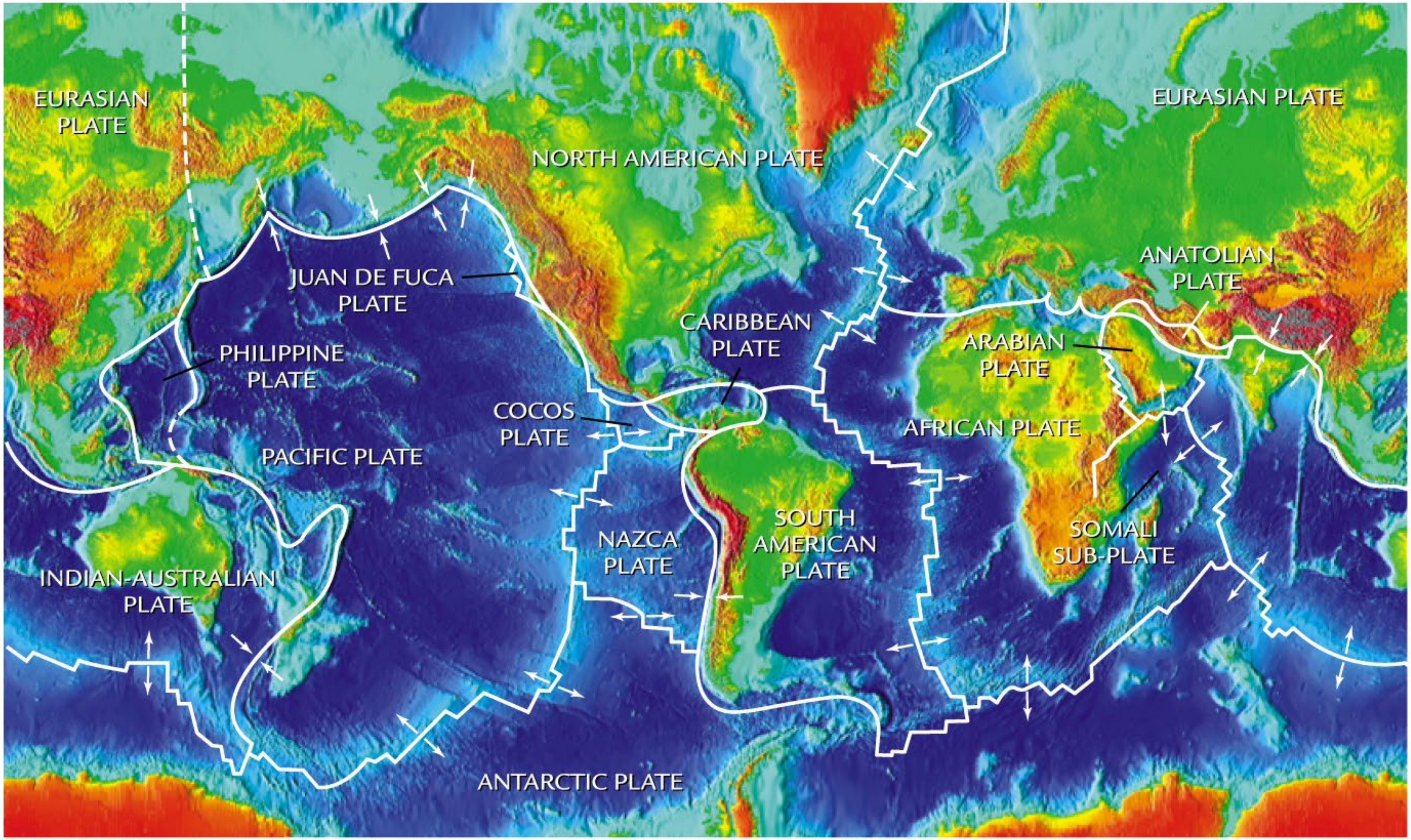


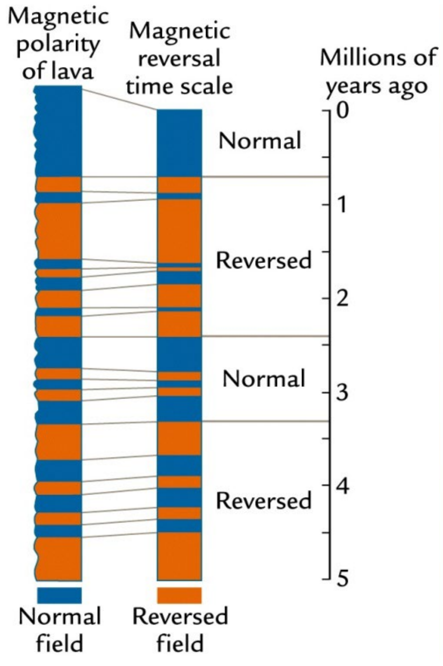
PLATE TECTONICS - 2

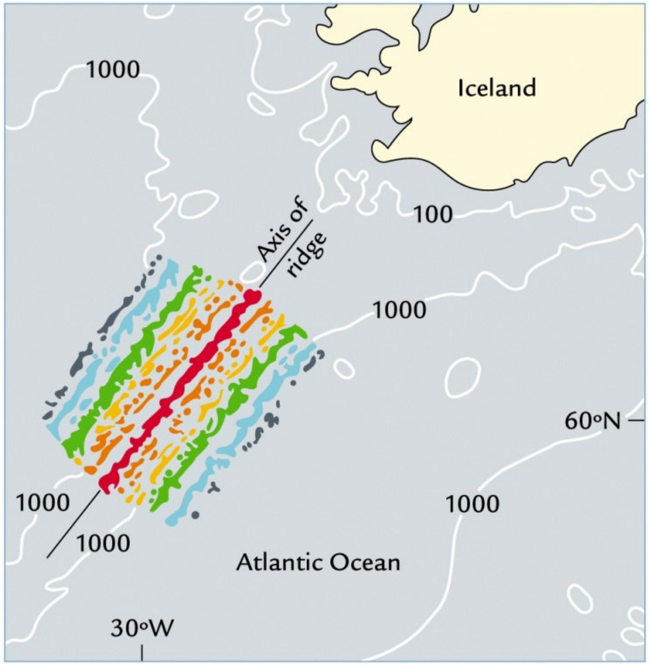


PALEOMAGNETISM AND PLATE TECTONICS

Paleomagnetism, the study of the Earth's ancient magnetic field recorded in rocks, uses declination measurements to determine the past positions of landmasses and ocean basins (paleolatitudes).

By recalibrating magnetic anomalies on the seafloor, past positions of tectonic plates can be reconstructed. These anomalies are essential for estimating ocean expansion rates.





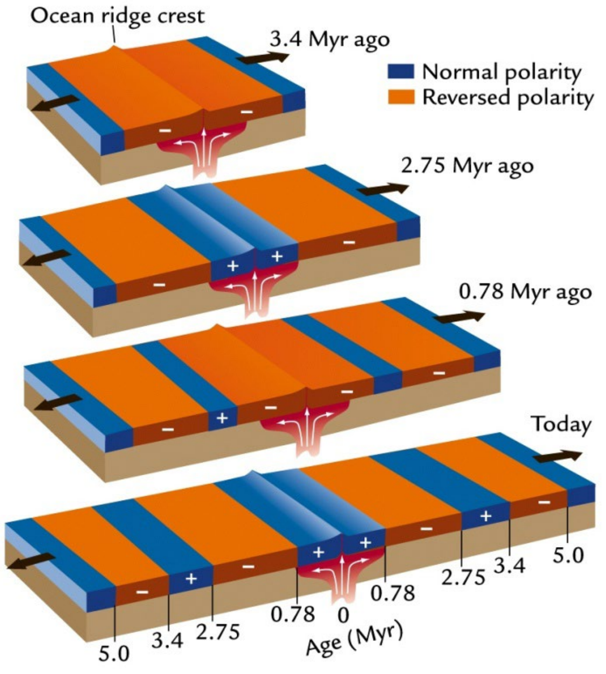


PLATE TECTONICS (540 MA-0 MA)

Scotese – Paleomap project https://www.youtube.com/watch?v=g_iEWvtKcuQ

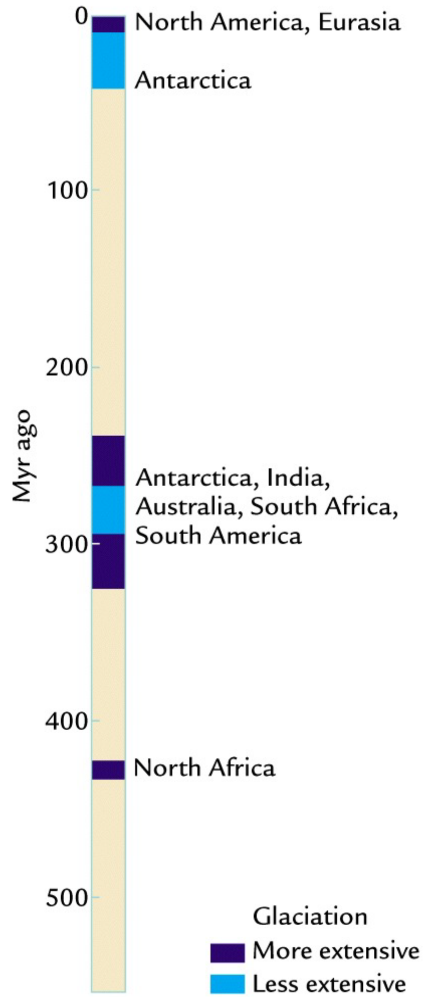
future https://www.youtube.com/watch?v=uLahVJNnoZ4

PLATE TECTONICS AND LONG-TERM CLIMATE CHANGES

GLACIATIONS

POLAR POSITION HYPOTHESIS -1

(1) Ice caps form on continents in polar or sub-polar latitudes.
(2) No ice should exist if continents are located outside polar regions.



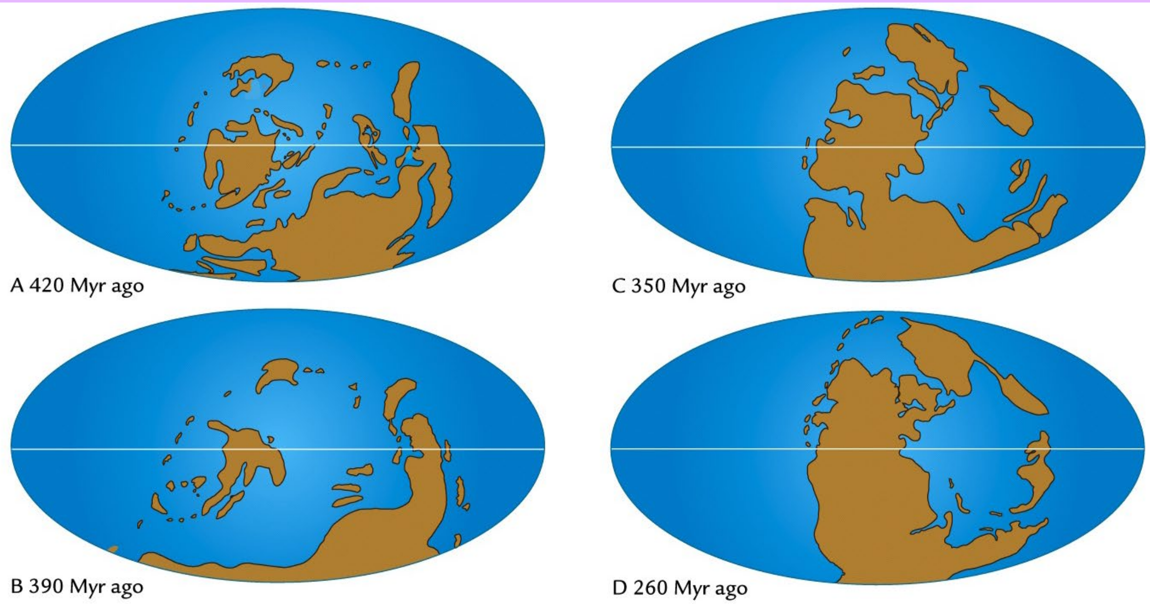


TABLE 5-1 Evaluation of the Polar Position Hypothesis of Glaciation

Time (Myr ago)	Ice sheets present?	Continents in polar position?	Hypothesis supported?
430	Yes	Yes	Yes
425–325	No	Yes	No
325–240	Yes	Yes	Yes
240–125	No	No	Yes
125–35	No	Yes	No
35–0	Yes	Yes	Yes

POLAR POSITION HYPOTHESIS - 2

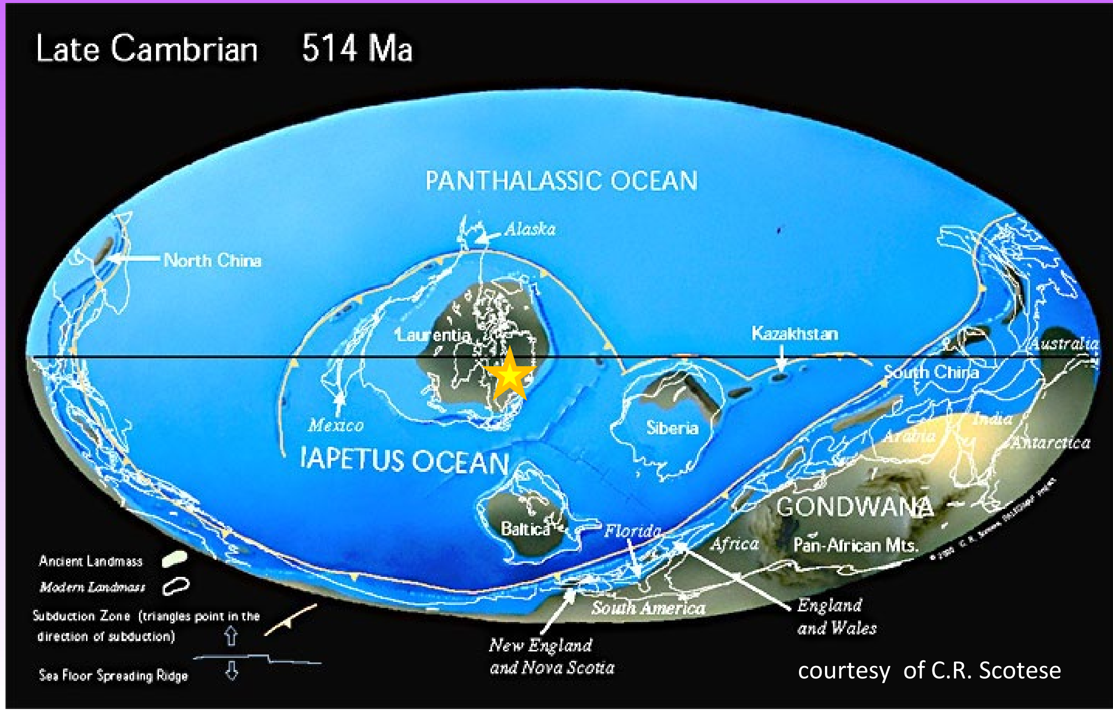
NEW POLAR POSITION HYPOTHESIS

Necessary but insufficient condition:
Ice caps form when emerged lands predominate in polar or sub-polar regions.

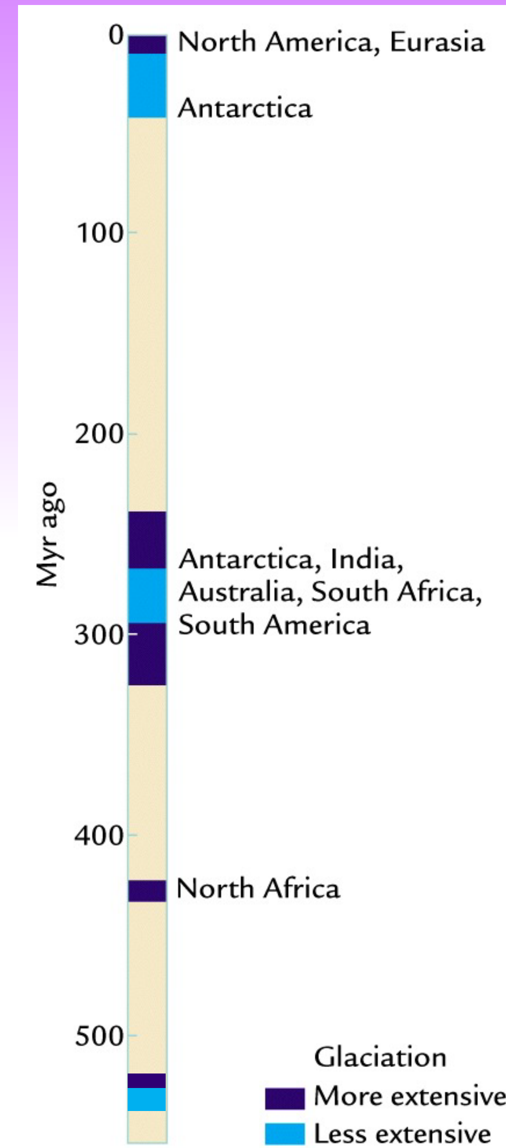
However:
The presence of continents in polar zones alone does not ensure ice cap formation.

Therefore:
Additional factors, such as the influence of greenhouse gases, must control the climate to promote or inhibit ice cap formation at the poles.

PALEOZOIC GLACIATIONS



INFRA-CAMBRIAN GLACIATION



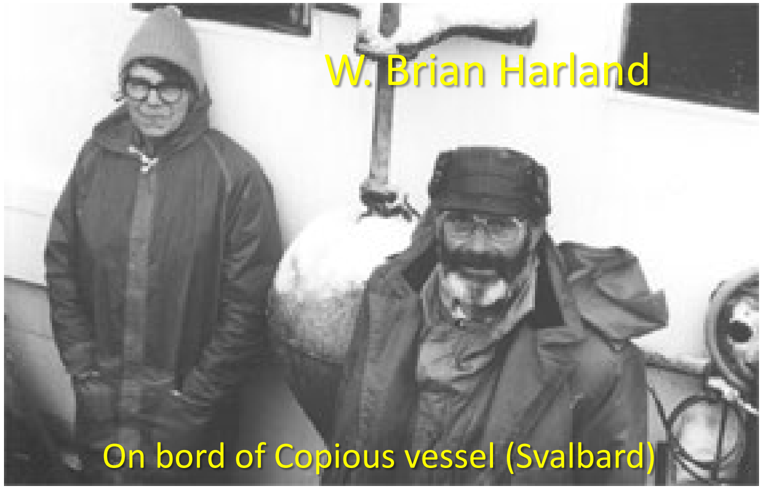
infra-Cambrian glaciation?

LOW LATITUDE GLACIAL SEDIMENTS

In 1964, W. Brian Harland (Harland and Rudwick) presented paleomagnetic data showing that tillites in Greenland and Svalbard had formed in tropical latitudes.

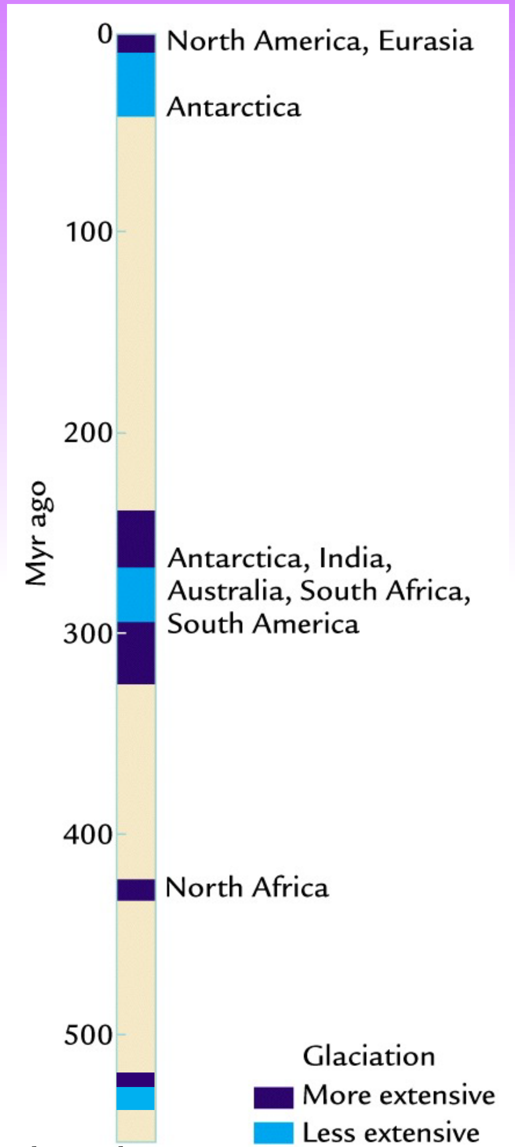
Sedimentological evidence also confirmed that glacial sediments interrupted sequences in tropical regions.

Harland thus proposed these sediments documented a major infra-Cambrian glaciation, around 550-540 million years ago, affecting low latitudes.



Diamictite is a poorly sorted conglomerate or breccia with at least 25% of the clasts> 2mm. They consist of sedimentary, igneous or metamorphic clastic fragments supported by a clayey matrix

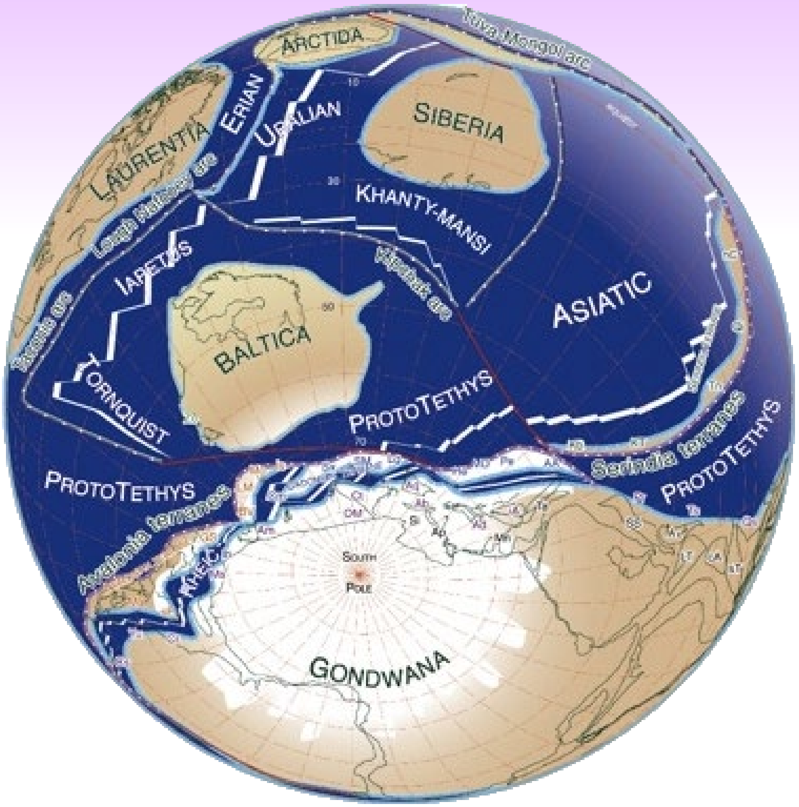
LATE ORDOVICIAN GLACIATION (ca.450-440 Ma)

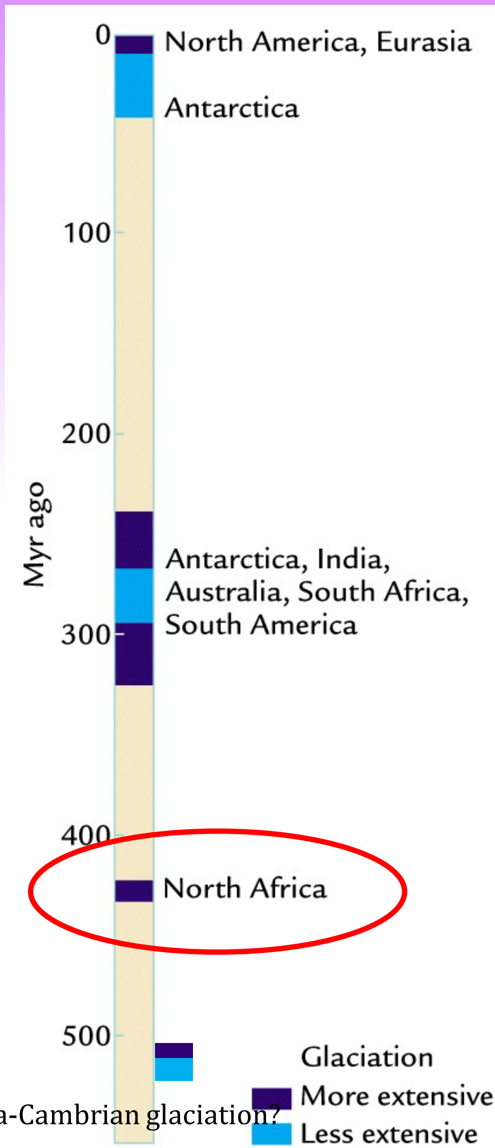


infra-Cambrian glaciation?

LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 1

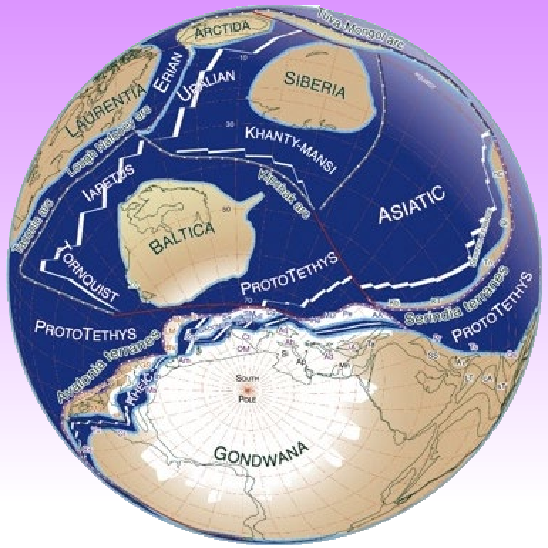
An ice cap, similar in size to today's, existed at the South Pole, covering the North African part of Gondwana.





infra-Cambrian glaciation?

LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 1



POSSIBLE CAUSES

(1) LAND MASSES AT HIGH LATITUDES

(2) LESS INTENSE INCOMING SOLAR RADIATION
ISR was -4% compared to today.

(3) LOW LEVELS OF GREENHOUSE GASES
- slower input of CO_2[decrease in volcanic activity]
- efficient weathering [post *Taconic orogeny* or *Katian large igneous province* => continental basalts located at tropics]

(4) VASCULAR VEGETATION FIRST ENTRY => weathering increase (Lenton et al. 2012 – Nature)

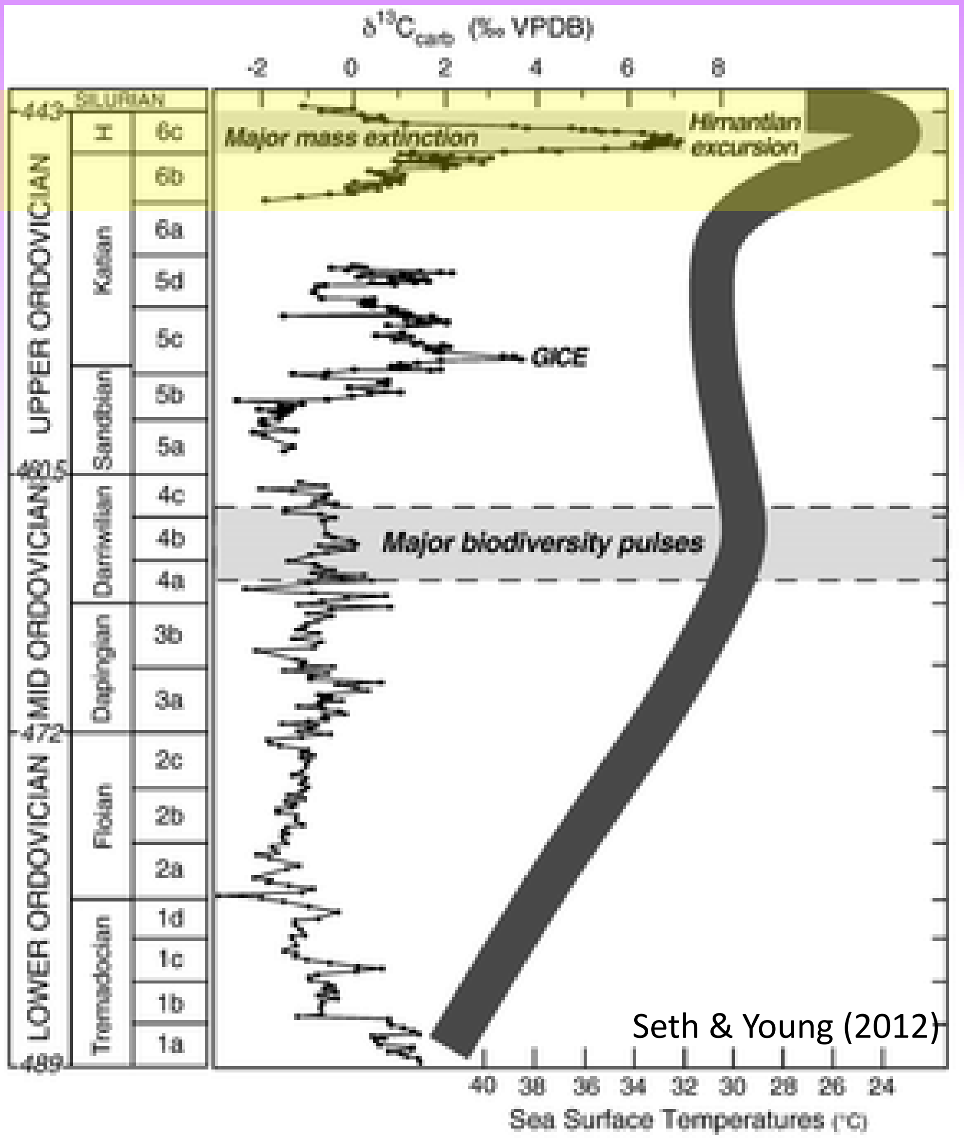
(5) INCREASE IN C_{ORG} BURIAL

LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 2

The Upper Ordovician glaciation is the only one associated with one of the "big five" extinctions, leading to the loss of around 60% of marine species.

A positive $\delta^{13}C$ excursion is linked to this extinction. Typically, increased $\delta^{13}C$ indicates higher productivity. During extinctions, a decrease is expected.

Why does this decrease not appear?
$\delta^{13}C$ is governed by factors other than productivity.



Seth & Young (2012)

LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 2

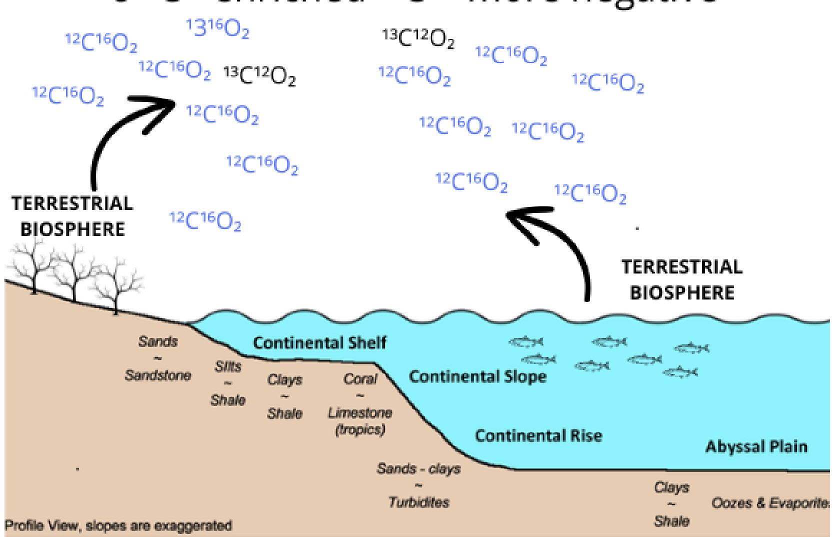
MASS EXTINCTION

⇒ lithosphere ^{12}C enriched (Corg) = $\delta^{13}C$ more positive

⇒ Ocean-atmosphere $\delta^{13}C$ more negative

OCEAN-ATMOSPHERE

$\delta^{13}C$= enriched ^{12}C = more negative



LITHOSPHERE (ROCK-SEDIMENTS)

$\delta^{13}C$= depleted ^{12}C = more positive

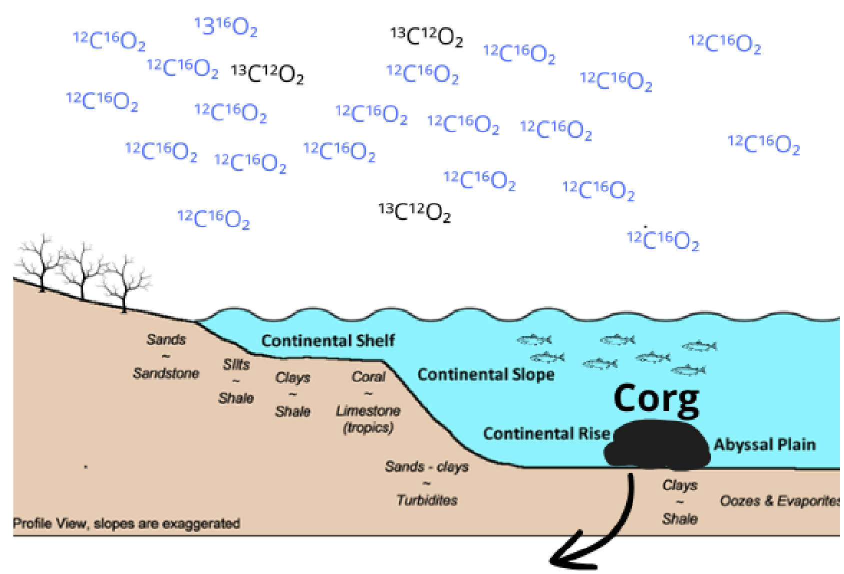
C_{ORG} BURIAL

⇒ lithosphere ^{12}C enriched (Corg) = $\delta^{13}C$ more negative

⇒ Ocean-atmosphere $\delta^{13}C$ more positive

OCEAN-ATMOSPHERE

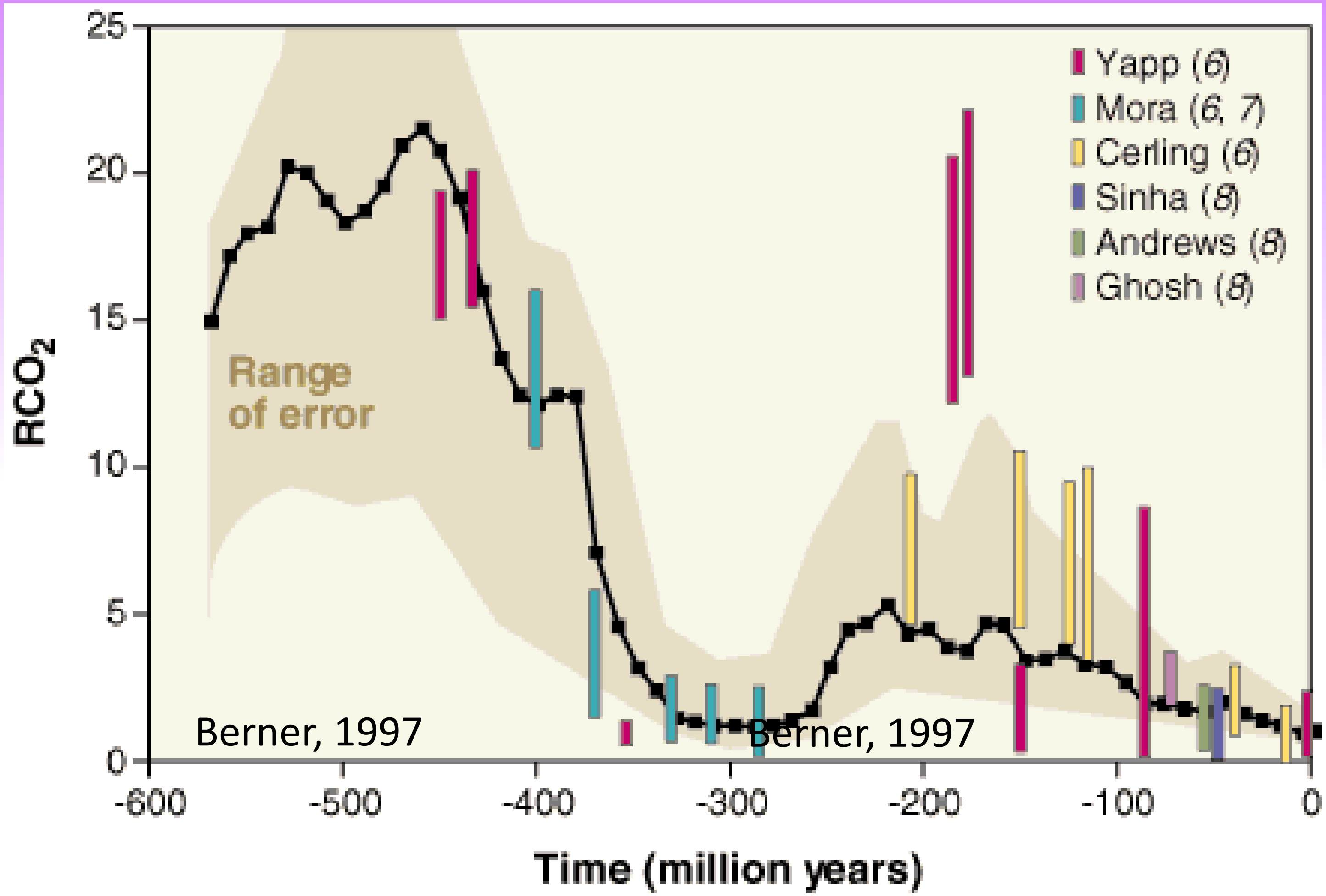
$\delta^{13}C$= depleted ^{12}C = more positive



LITHOSPHERE (ROCK-SEDIMENTS)

$\delta^{13}C$= enriched ^{12}C = more negative

LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 2



Atmospheric CO_2 versus time for the Phanerozoic (past 550 million years). The parameter RCO_2 is defined as the ratio of the mass of CO_2 in the atmosphere at some time in the past to that at present (with a pre-industrial value of 300 parts per million). The heavier line joining small squares represents the best estimate from GEOCARB II modeling (10), updated to have the effect of land plants on weathering introduced 380 to 350 million years ago. The shaded area encloses the approximate range of error of the modeling based on sensitivity analysis (10). Vertical bars represent independent estimates of CO_2 level based on the study of paleosols.

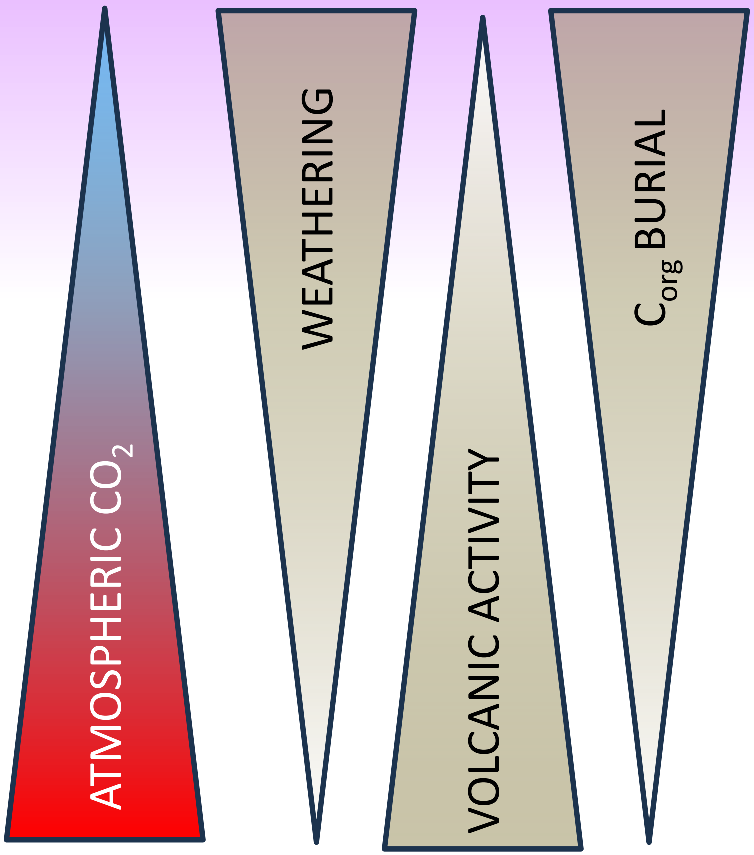
LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 3

Estimated Duration: Ranges from 10 million to 1 million years. A mechanism is needed to explain greenhouse gas decline and/or CO_2 sequestration.

Comments:

•**Enhanced weathering or reduced volcanic activity** (post-orogenesis/ volcanism) are relatively slow processes.

•**Increased burial of organic carbon(C_{org})**, which accounts for about 20% of exchanges in shallow reservoirs, occurs rapidly and raises $\delta^{13}C$ in ocean waters (short-term carbon cycle).

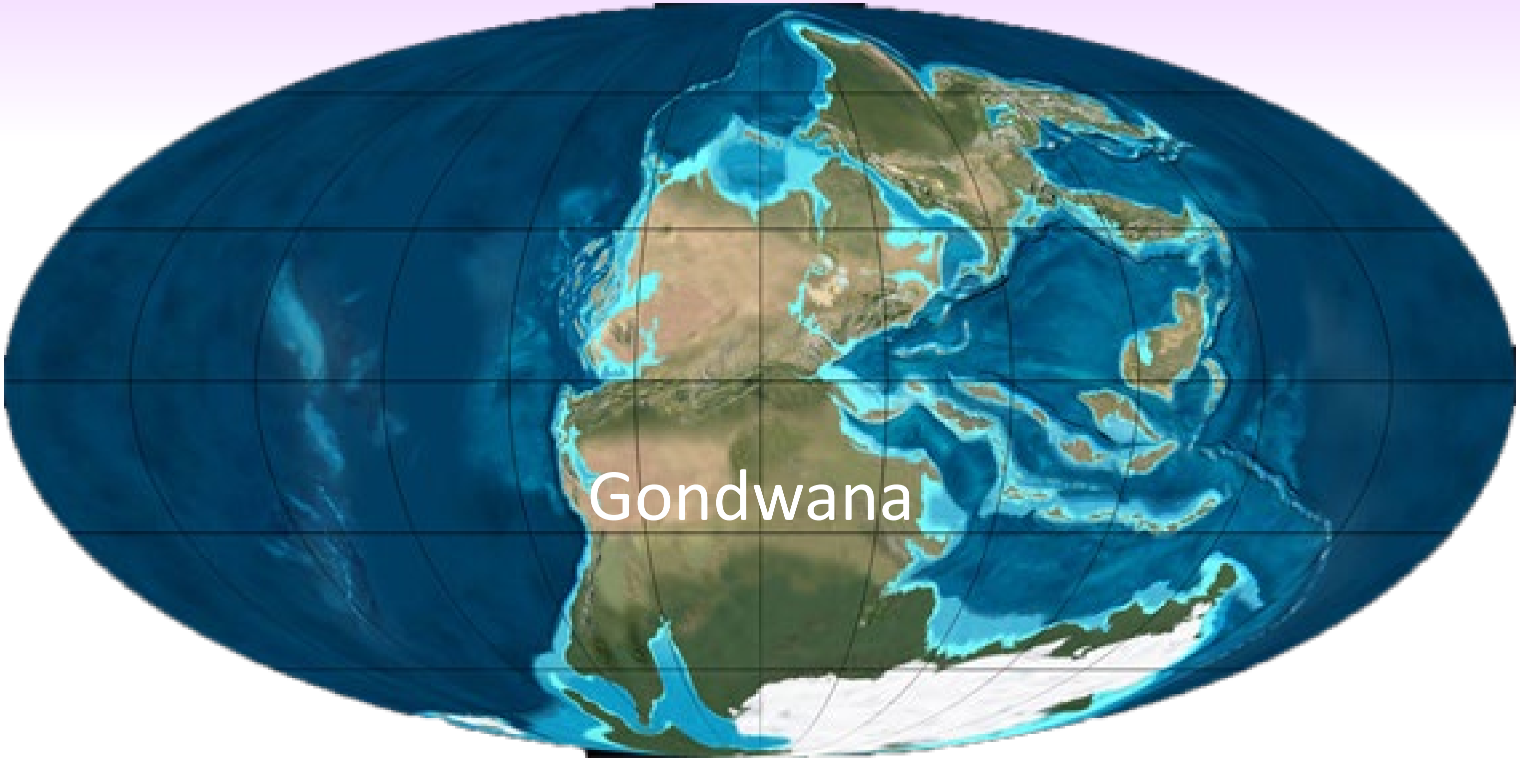


LATE ORDOVICIAN GLACIATION (ca.450-440 Ma) - 3

CAUSES TO EXPLAIN THE INCREASE OF BURIAL OF C_{org}

- Change in wind direction → increase in upwelling in coastal areas
- Increase in C_{org} and nutrients released into the ocean
- Wetter climates on the continental margins
- Isolation of small ocean basins in regions of high rainfall → C_{org}-rich washout
- ETC

LATE PALEOZOIC GLACIATIONS
(ca. 360-300 Ma)
Carboniferous-Permian

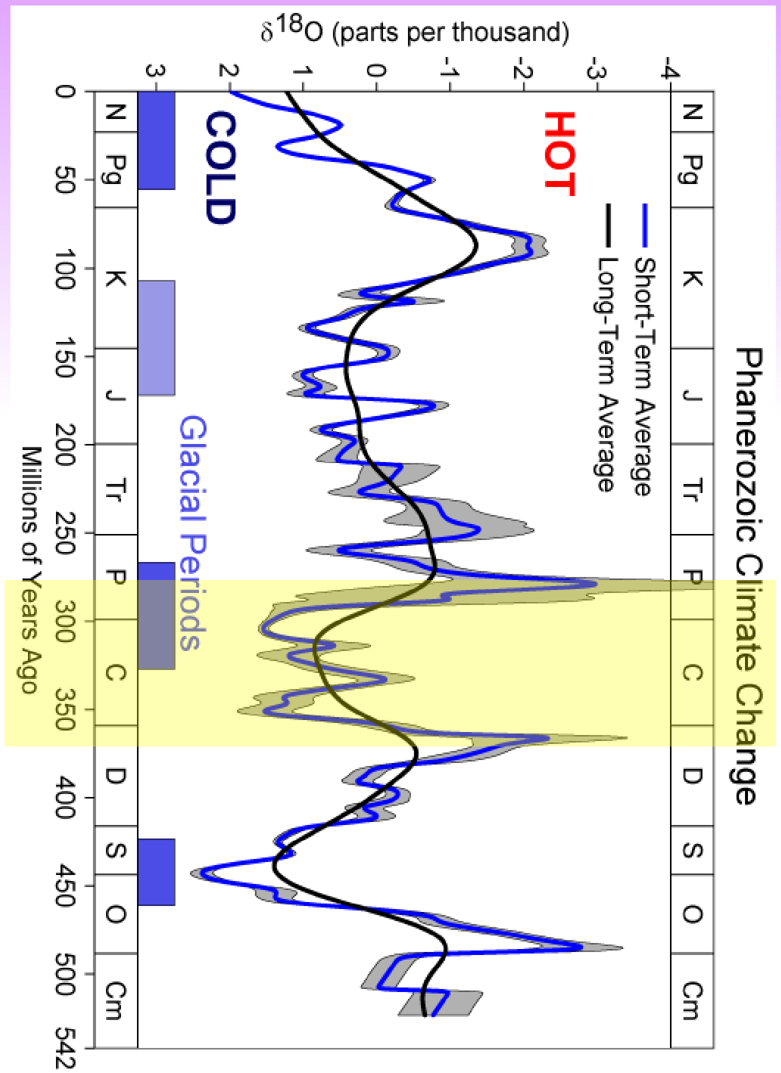


LATE PALEOZOIC GLACIATION - 1

The stratigraphic record shows episodic glaciations at various intervals (Crowell, 1982, 1999).

One notable phase involved the supercontinent **Gondwana**, formed after Pannotia's breakup, during the Upper Paleozoic.

This phase marks the longest and most continuous glaciation in the Phanerozoic (Eyles, 1993).



LATE PALEOZOIC GLACIATION - 3

This glacial phase divides into three distinct episodes (López-Gamundí, 1997):

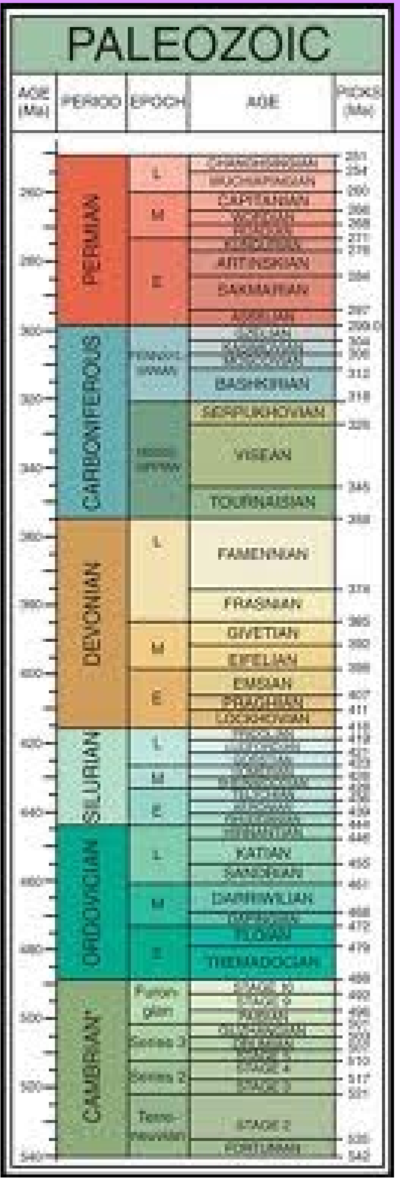
Episode I (ca. 360 Ma) occurred at the Devonian-Carboniferous transition in South America (Veevers and Powell, 1987).

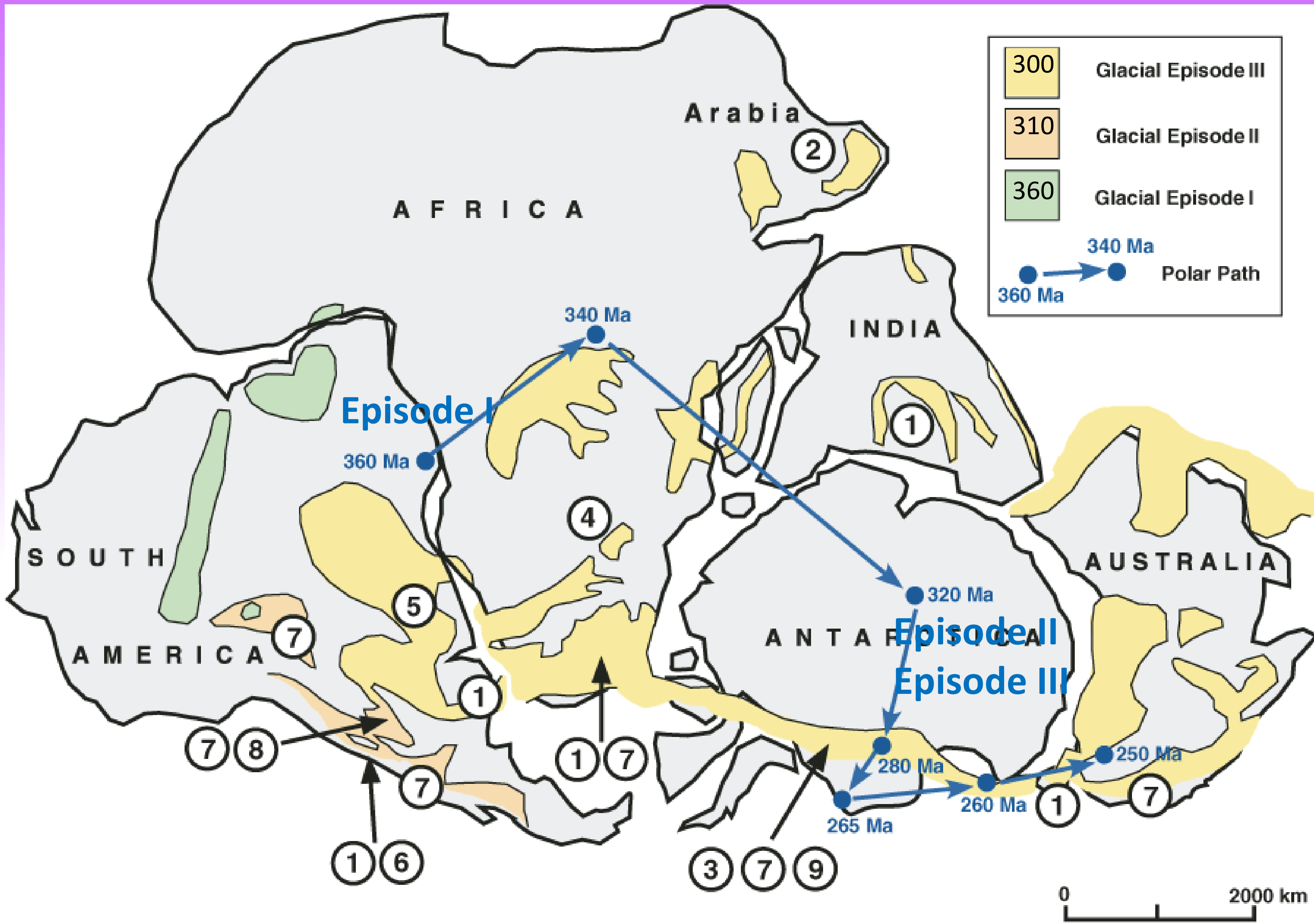
Episodes II and III happened during the Upper Carboniferous and Carboniferous-Permian transition (ca. 300 Ma).

The ice cover gradually shifted across Gondwana from South America to Australia (Crowell, 1999).

Polar wander within Gondwana enables paleolatitude checks, confirming the diachronous nature of Episodes I, II, and III.

Local processes (basin dynamics, topographical barriers, glaciation styles) also influenced melting and ice formation timing.





Carboniferous/lower Permian glacial successions are well known in all the subcontinents of Gondwana (South America, Africa, India, Australia, Antarctica, ...)

PLATE TECTONICS (540 MA-0 MA)

Scotese – Paleomap project https://www.youtube.com/watch?v=g_iEWvtKcuQ

future https://www.youtube.com/watch?v=uLahVJNnoZ4

WHAT CONTROLS THE PASSAGE FROM GREENHOUSE TO ICEHOUSE PHASES?

POLAR POSITION HYPOTHESIS

CHANGES IN pCO_2

CAUSES FOR CO_2 VARIATION

Land distribution alone can't fully explain the shift from greenhouse to icehouse phases; it's a prerequisite. The key factor appears to be changes in CO_2 levels.

But what controls atmospheric pCO_2?

TECTONIC CONTROL:

BLAG SPREADING RATE HYPOTHESIS (Berner, Lasaga & Garrels, 1983): Climate change over hundreds of millions of years is driven by **the rate of CO_2 release through tectonic processes** into the ocean-atmosphere system.

UPLIFT-WEATHERING HYPOTHESIS (Raymo, Ruddiman & Froelich, 1988): Chemical **weathering**, beyond triggering negative feedbacks, **actively regulates climate change.**

BLAG SPREADING RATE HYPOTHESIS -1

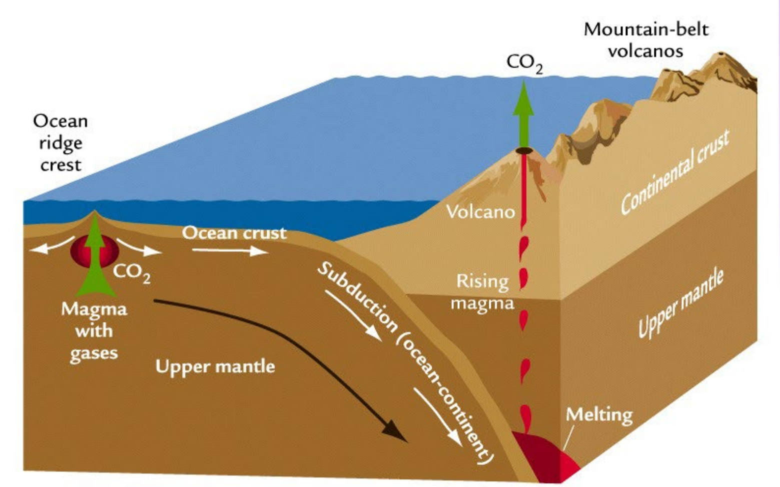
Variations in ocean crust expansion rates control the amount of CO_2 released into the atmosphere, impacting Earth's climate.

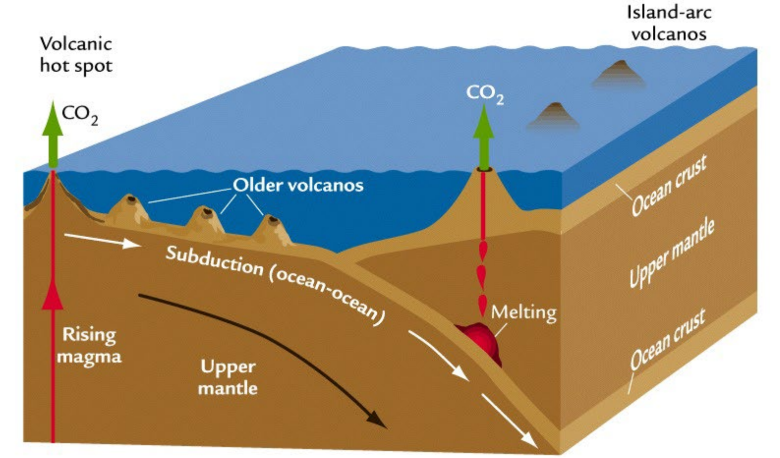
When tectonic activity is high, more CO_2 is emitted through volcanic processes:

Convergent Margins: Subducting plates melt, producing CO_2-rich magmas that reach the surface (mountain belts, island-arc volcanoes).

Divergent Margins (Ocean Ridges): Magma and CO_2 erupt directly at these sites.

Hot Spots: Volcanic regions fueled by unusually hot mantle areas.

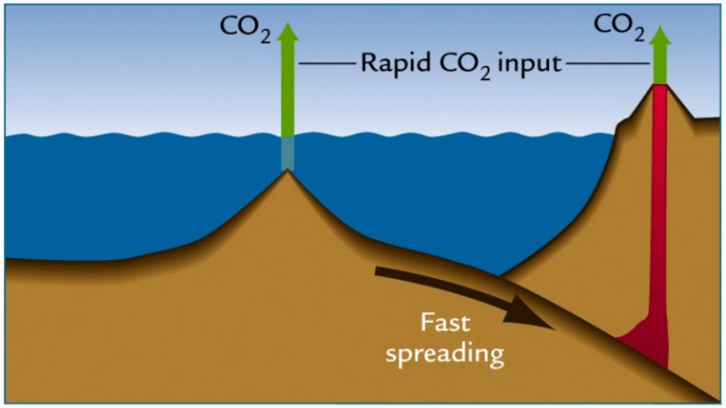




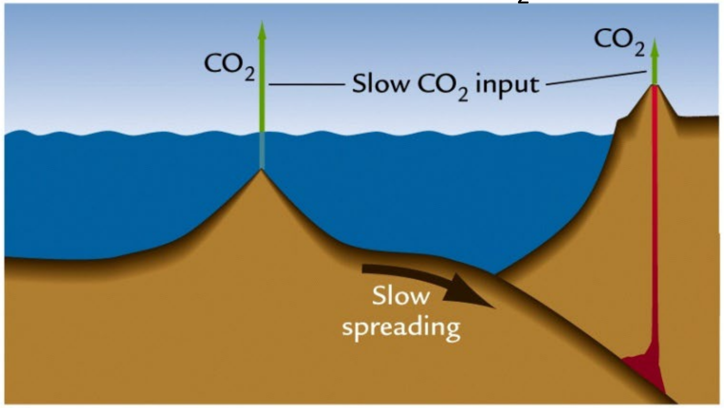
BLAG SPREADING RATE HYPOTHESIS -2

The BLAG spreading rate hypothesis acknowledges the essential role of weathering as a mitigator (negative feedback) in the early stages of climate change.

SPREADING RATE =>CO_2 EMISSION

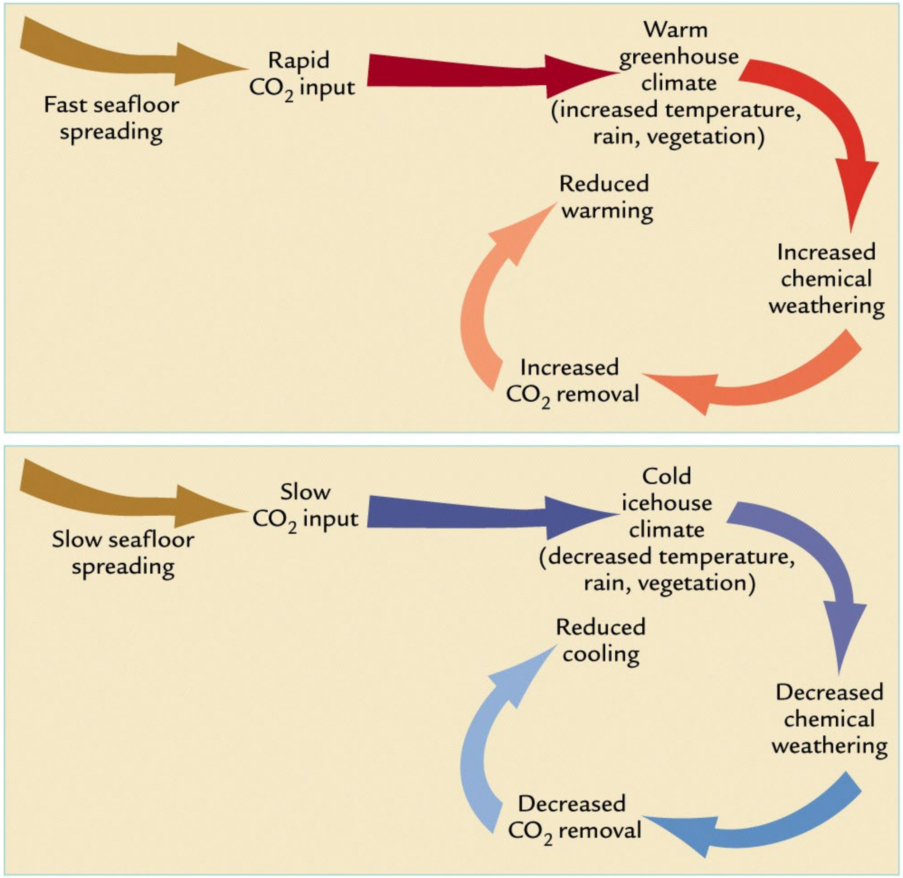


A FAST SPREADING => HIGH CO_2 EMISSION



B SLOW SPREADING => LOW CO_2 EMISSION

CLIMATE CHANGES => FEEDBACKS



BLAG SPREADING RATE HYPOTHESIS -3

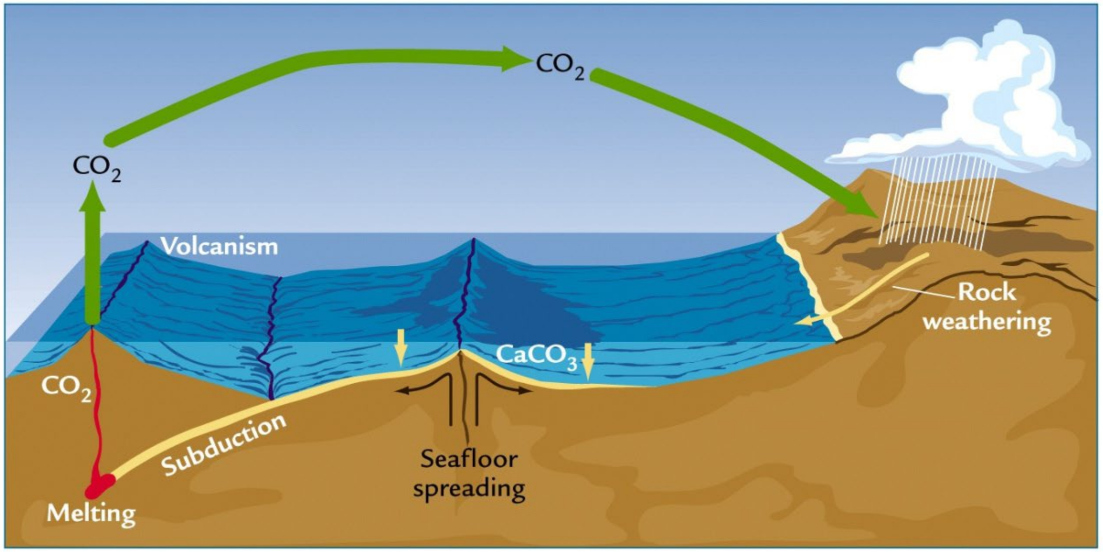
The BLAG spreading rate hypothesis assumes a closed carbon cycle between the deep earth and the atmosphere.

MELTING AND TRASFORMATION IN SUBDUCTION ZONES

$CaCO_3$	+	SiO_2	→	$CaSiO_3$	+	CO_2
Ocean sediments				Silicate rock		Atmosphere

CHEMICAL WEATHERING ON LAND/OCEAN

$CaSiO_3$	+	CO_2	→	$CaCO_3$	+	SiO_2
Silicate rock		Atmosphere		Plankton		Plankton



BLAG SPREADING RATE HYPOTHESIS -4

Does the BLAG hypothesis align well with the geological record?

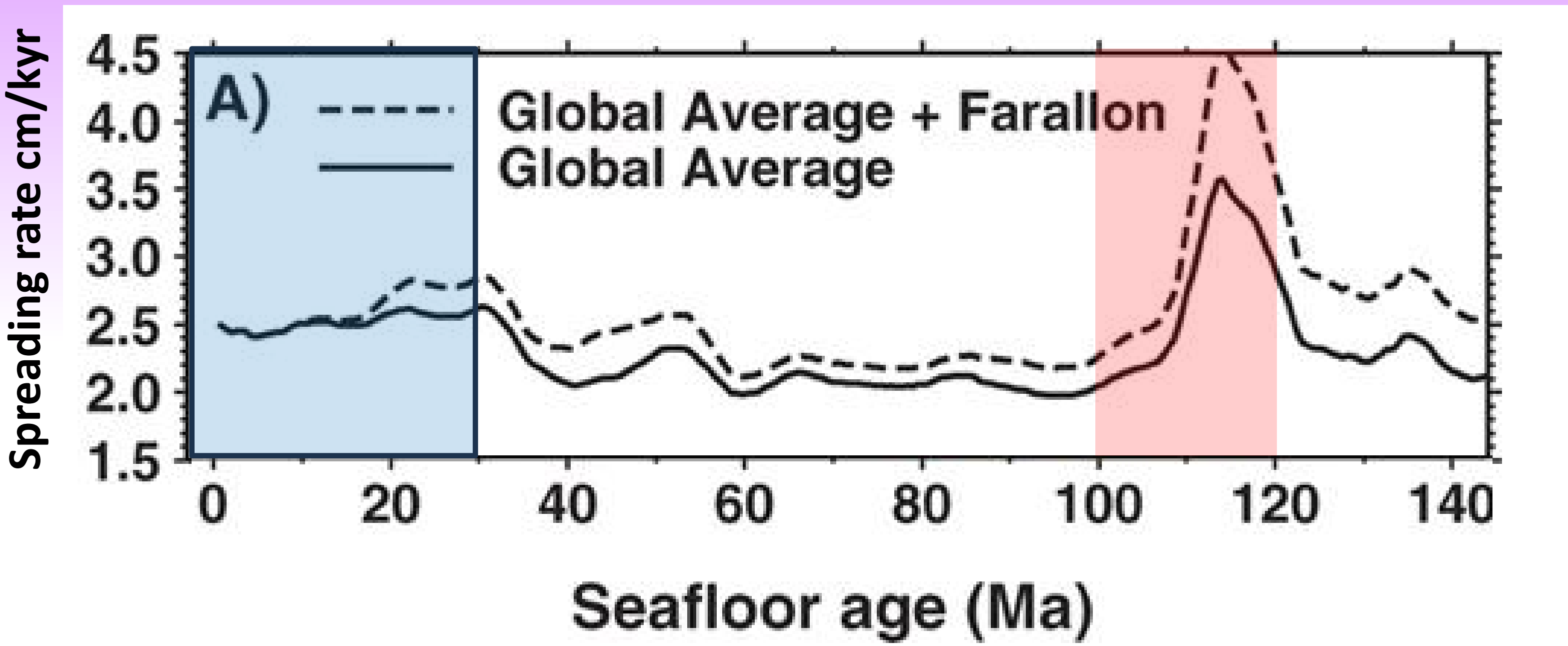
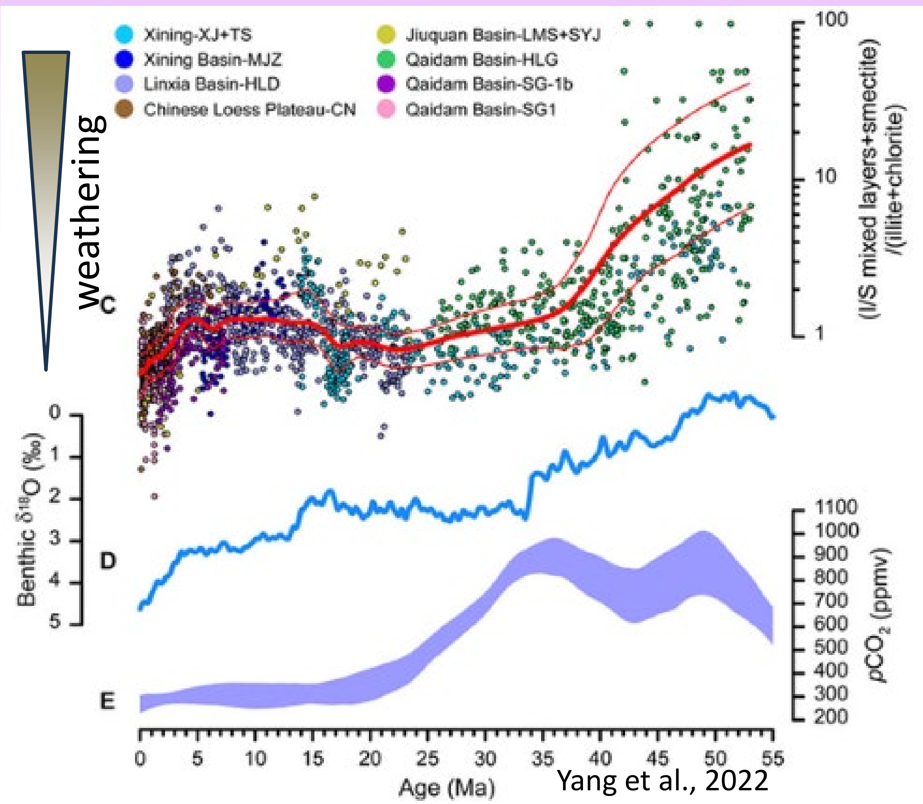


TABLE 5-2 Evaluation of the BLAG Spreading Rate (CO_2 Input) Hypothesis

Time (Myr ago)	Ice sheets present?	Spreading rates	Hypothesis supported?
100	No	Fast	Yes (high CO_2)
0	Yes	Slow	Yes (low CO_2)

UPLIFT-WEATHERING HYPOTHESIS-1

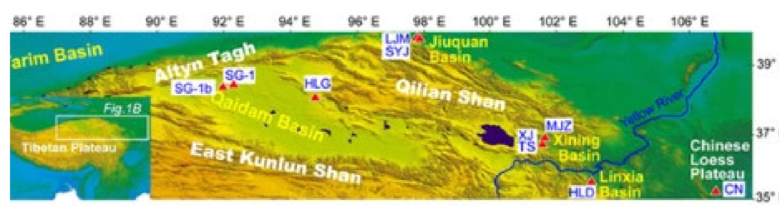
The scientific theory by Raymo, Ruddiman & Froelich (1988) proposes that chemical weathering triggers climate change rather than merely acting as a negative feedback to counter it.



Yang et al., 2022

weathering => storing CO_2 + clay minerals

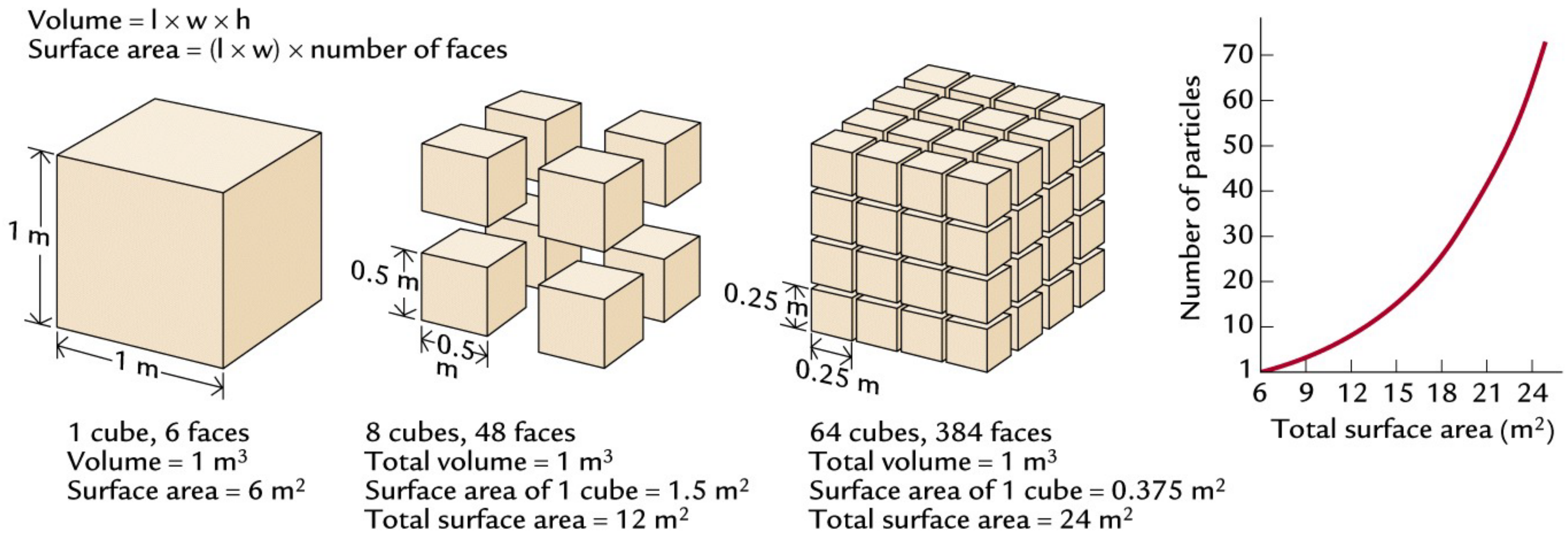
Global cooling over the last millions of years may be linked to **decreased atmospheric CO_2** due to **enhanced continental weathering in tectonically active regions**, like the Himalayas.



UPLIFT-WEATHERING HYPOTHESIS-2

How can the efficiency of weathering be increased globally?
To increase weathering efficiency, enhancing the exposure of "fresh" rocks for alteration is key. This factor can have a greater impact than temperature, precipitation, or vegetation on local and global scales.

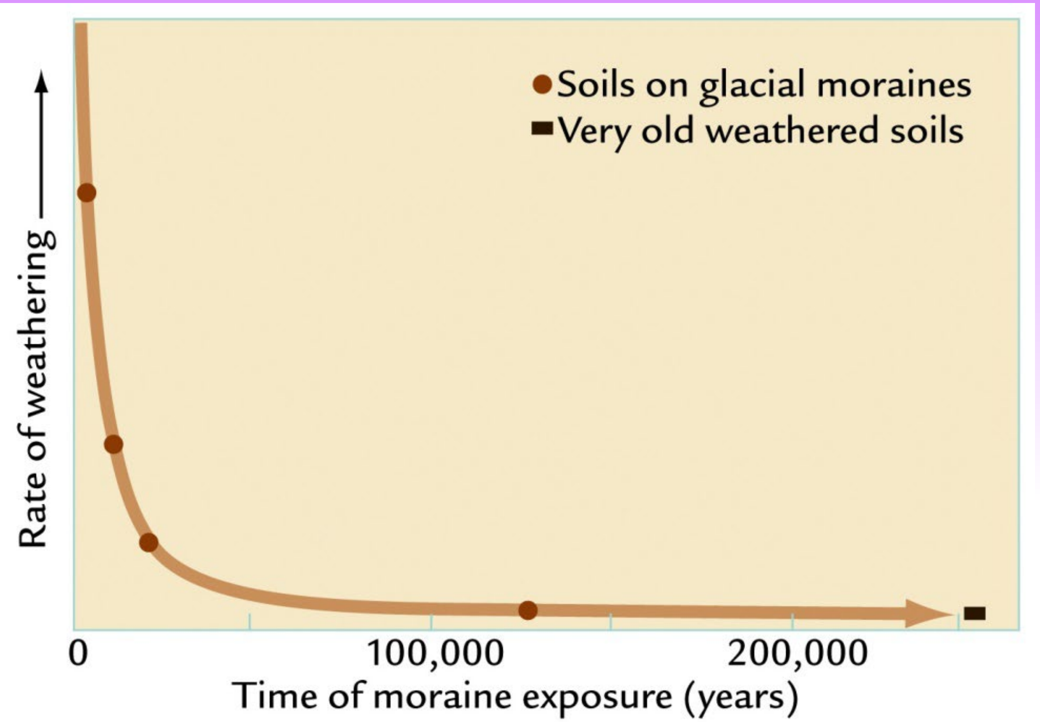
Dimensions of cube faces (m)	Number of cubes	Total surface area of cubes (m^2)	Total volume of cubes (m^3)
1.0	1	6	1
0.5	8	12	1
0.25	64	24	1
0.125	512	48	1
0.062	4096	96	1
0.031	32,768	192	1
0.016	262,144	384	1
0.008	2,100,000	768	1
0.004	16,800,000	1536	1
0.002	134,000,000	3072	1
0.001	1,100,000,000	6144	1



THE WIND RIVER BASIN OF WYOMING

In this catchment, all source rocks are granite, representing the response of continental rocks to weathering.

An undeformed moraine ridge is present, dating to the last 200 kyr.



Weathering is described by an asymptotic curve: the rate is initially high, then quickly decreases

The degree of weathering is assessed by analyzing soils formed after weathering, which gradually lose cations (Mg^{2+}, Na^{+}, K^{+}, Ca^{2+}).
Younger moraine deposits, with more alterable minerals and fine sediments, show higher weathering rates than older ones.

FACTORS AFFECTING FRESH ROCK EXPOSURE (weathering efficiency) IN UPLIFT AREAS

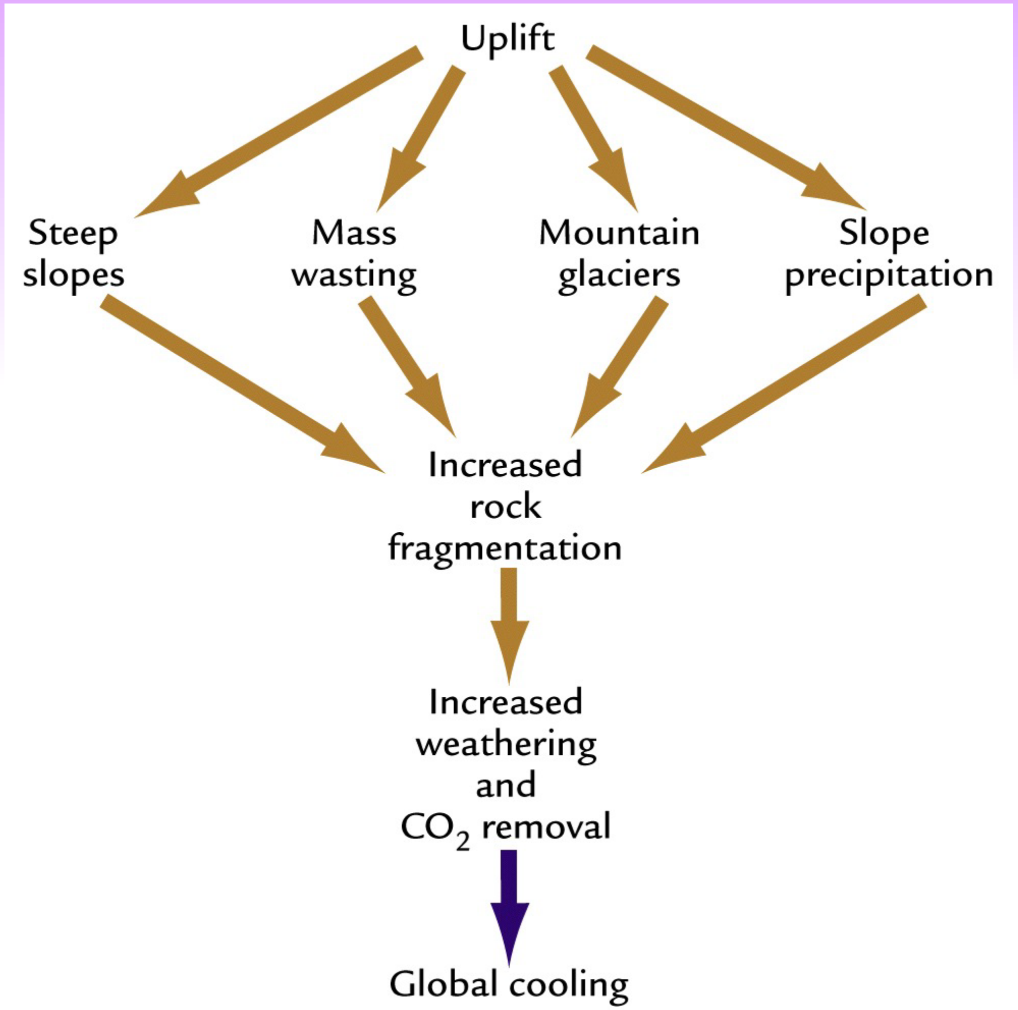
Factors Affecting Fresh Rock Exposure in Uplift Areas:

•**Steep slopes and Mass wasting** (erosion, landslides, debris)

•**Mountain glaciers** (glacial abrasion)

•**Earthquakes** (rock destabilization)

•**Rainfall** (increased weathering from condensation on mountain tops)



WEATHERING IN THE AMAZON BASIN

Precipitation occurs essentially:

(1) In the plain

(2) In the Andes

EVIDENCE

(1) In the Amazonian plains there are extensive deposits of altered clays

(2) There is no clear evidence of weathering (no clay) in the Andes

WHERE IS THE MOST VIGOROUS WEATHERING CURRENTLY TAKING PLACE?

https://app.wooclap.com/events/PCCC24/0

WEATHERING IN THE AMAZON BASIN

Explanation:

Current Chemical Weathering:

- 20% occurs in the plains.
- 80% occurs in the Andes.

•**Low Weathering**: Red clays in the Amazonian plain indicate significant past weathering. Currently, few fresh rocks are exposed, and most erodible rocks are well-covered.

•**High Weathering**: In the Andes, weathering products (clays) are continually removed by coarser, erodible material and transported to the Atlantic.