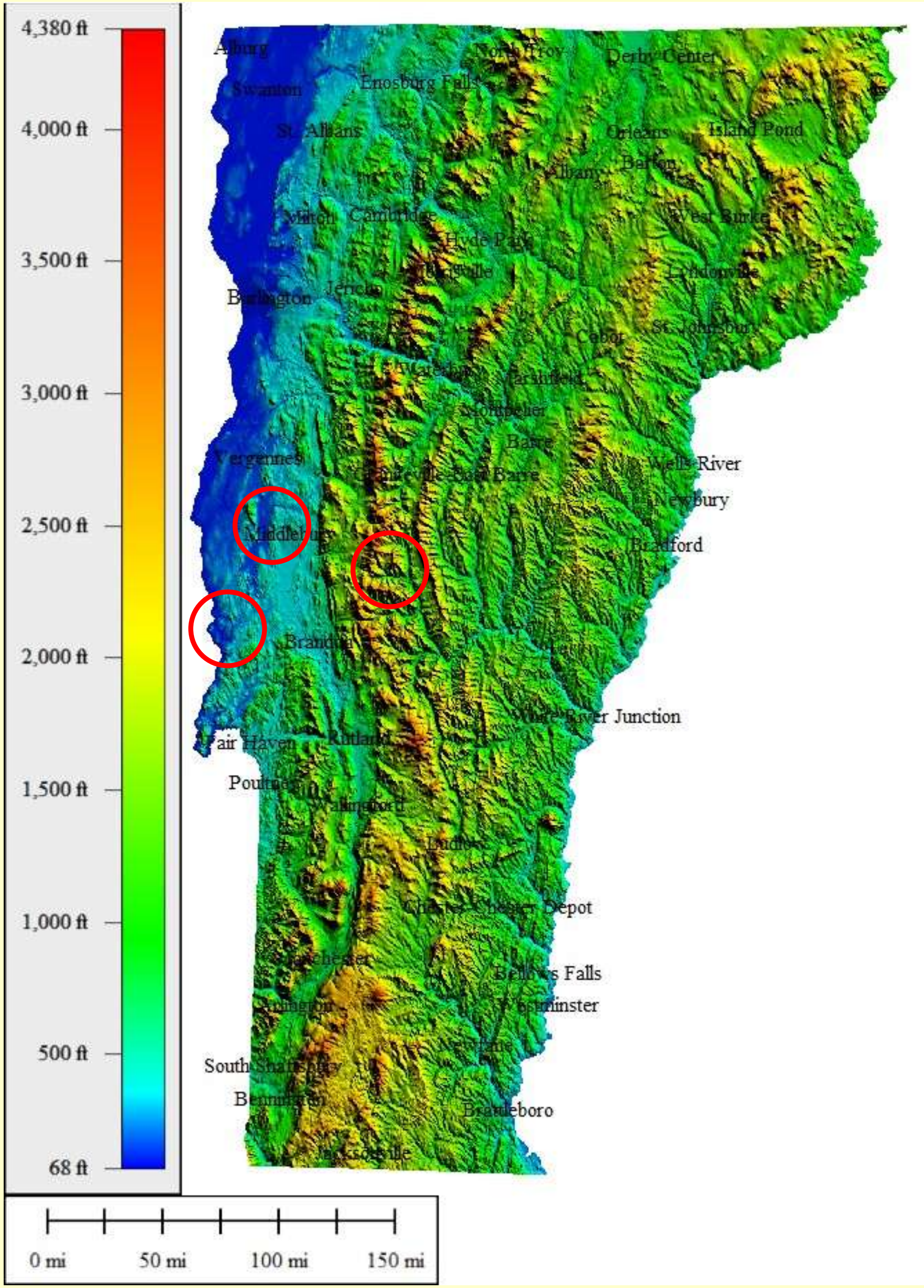
2011 Alumni College

Vermont Geology: From Mountain-Building to Ground Water Resources



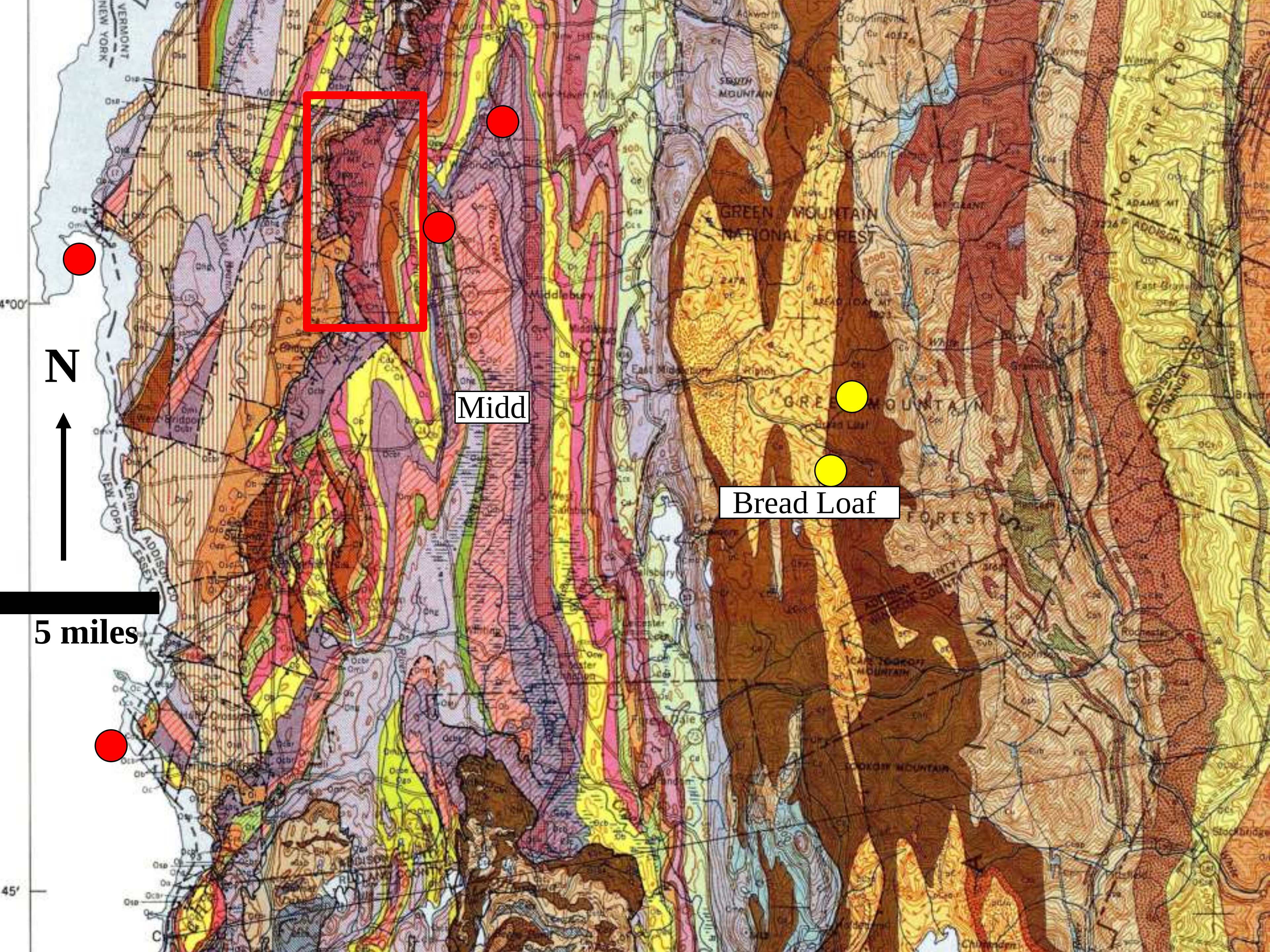
Schedule

Thursday 8/25: Plate tectonics, Vermont record of sedimentation and orogenesis.

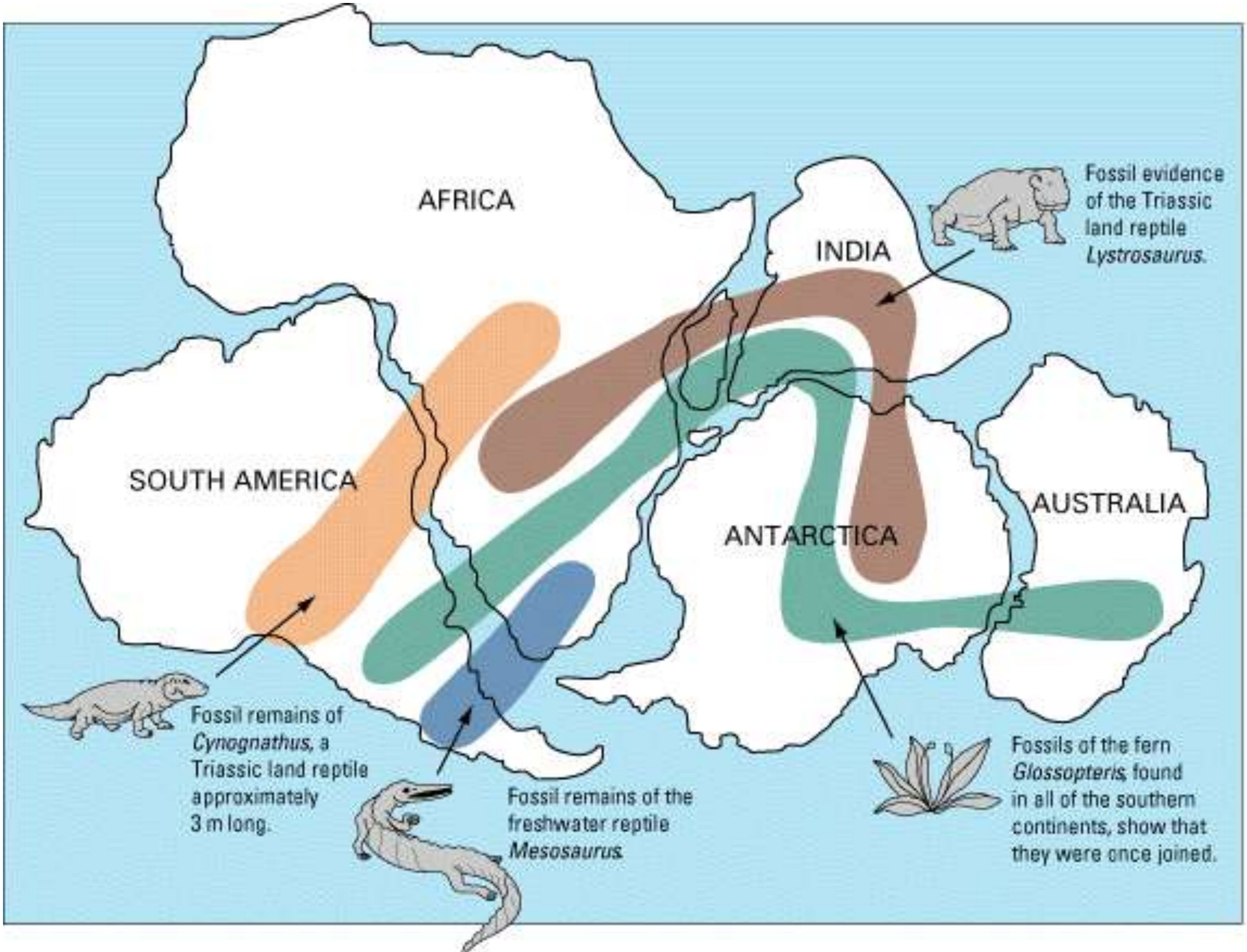
Friday 8/26: Field trip including (1) Precambrian (Grenville) record, (2) early Cambrian sedimentary record, (3) middle Ordovician sedimentary record, (4) middle-late Ordovician collision and mountain-building.

Saturday 8/27: Surficial geology including (1) stream geomorphology and surface water – ground water interactions and (2) glacial deposits and soils.

Sunday 8/28: Summary and discussion.


N
5 miles
Midd
Bread Loaf
GREEN MOUNTAIN
NATIONAL FOREST
SOUTH MOUNTAIN
Middlebury

1915– Alfred Wegener & “Origin of Continents And Oceans” …. Continental Drift


AFRICA
INDIA
SOUTH AMERICA
ANTARCTICA
AUSTRALIA
Fossil evidence of the Triassic land reptile *Lystrosaurus*.
Fossil remains of *Cynognathus*, a Triassic land reptile approximately 3 m long.
Fossil remains of the freshwater reptile *Mesosaurus*.
Fossils of the fern *Glossopteris*, found in all of the southern continents, show that they were once joined.

Pangaea ~ 200 Ma

A. Modern reconstruction of Pangaea

B. Wegener's Pangaea

Continental Drift

- **“Continental drift” hypothesis**
  - **Continents "drifted" to present positions**
  - **Continents plowed through the oceanic crust like boats through water**
- **Evidence used in support of the hypothesis**
  - **Fit of the continents**
  - **Fossil evidence**
  - **Rock type and structural similarities**
  - **Paleoclimatic evidence**

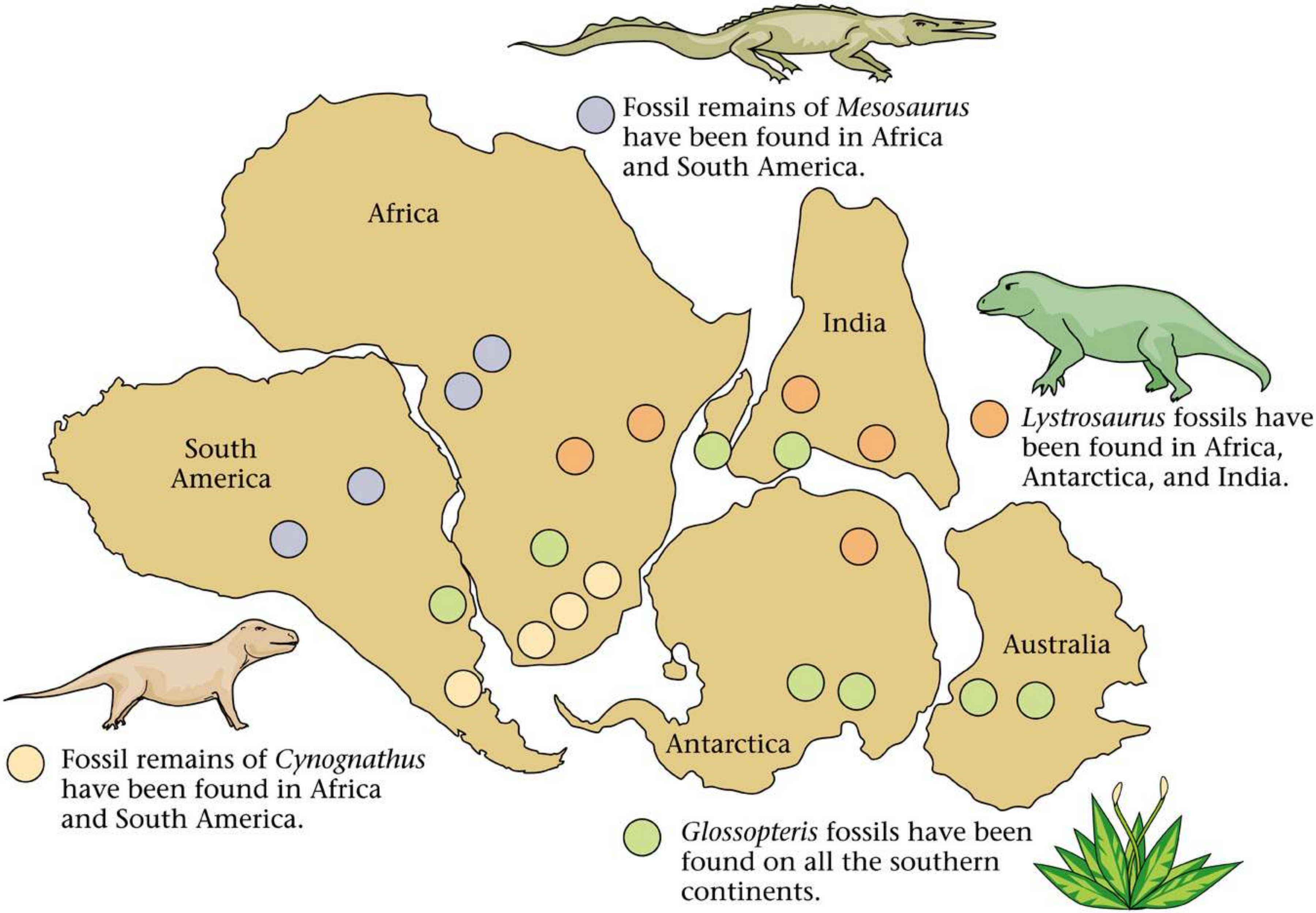
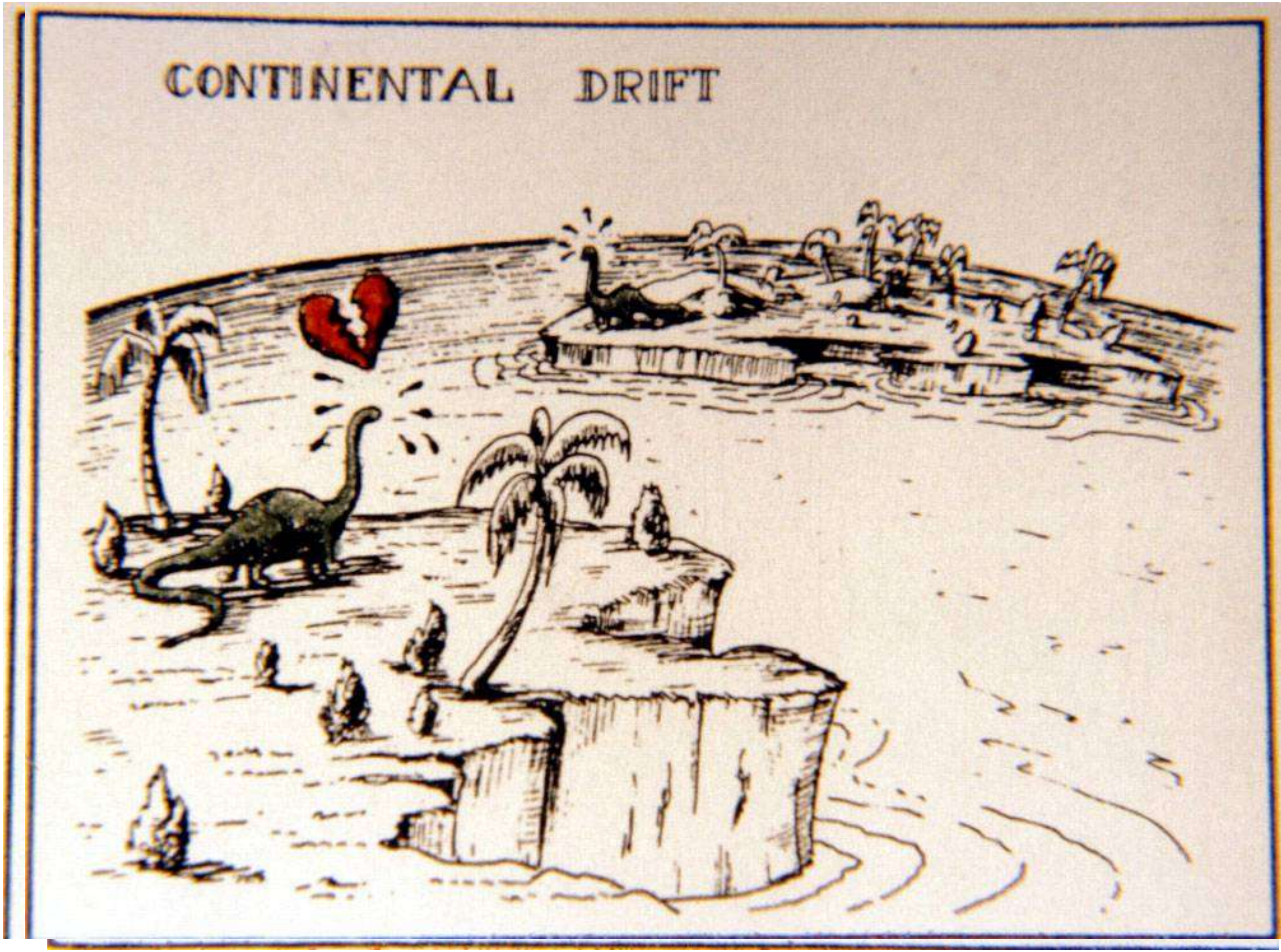
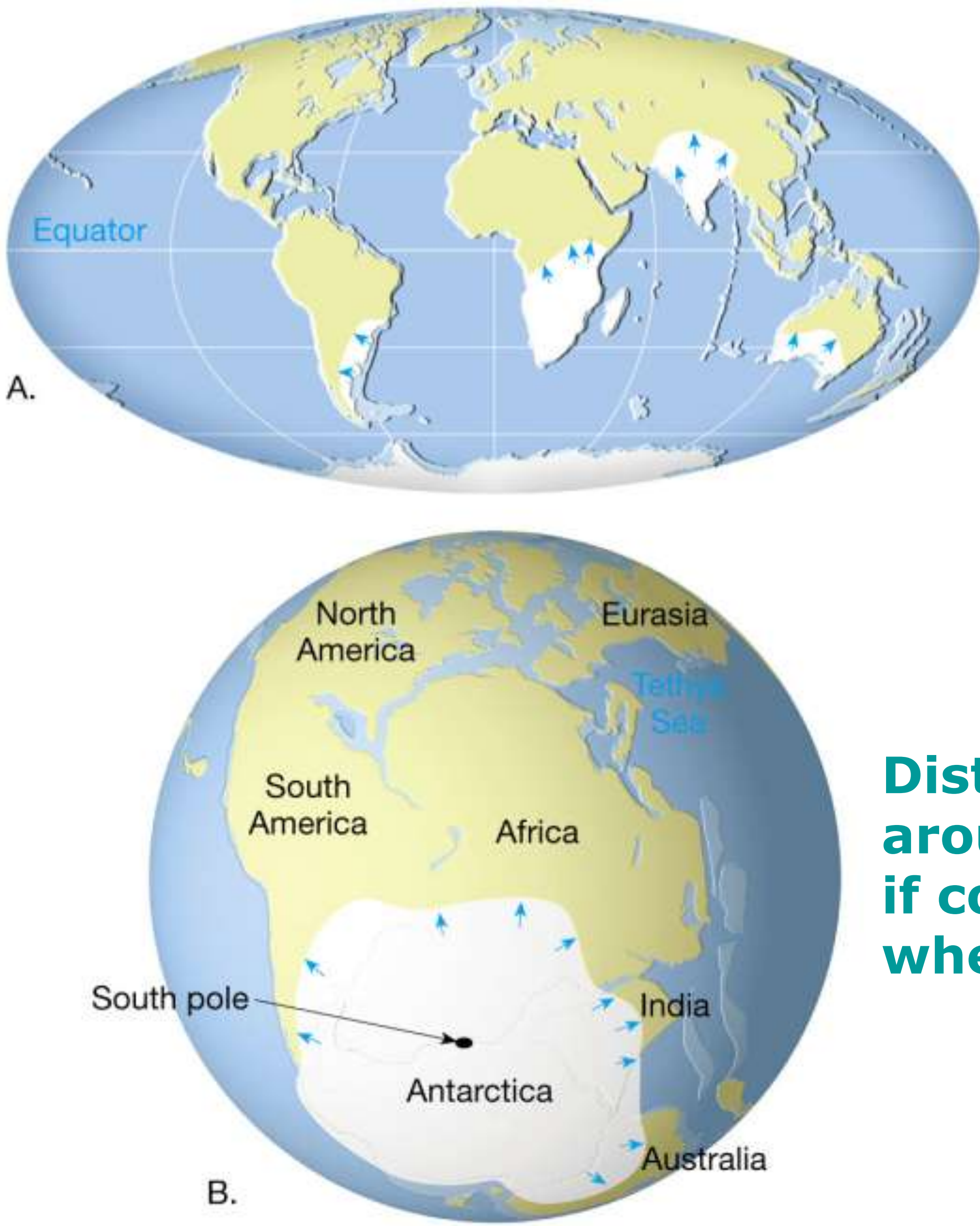

Fossil remains of *Mesosaurus* have been found in Africa and South America.
Africa
India
South America
Lystrosaurus fossils have been found in Africa, Antarctica, and India.
Australia
Antarctica
Fossil remains of *Cynognathus* have been found in Africa and South America.
Glossopteris fossils have been found on all the southern continents.

FIGURE 2.4


CONTINENTAL DRIFT

Matching Mountain Ranges



Paleoclimatic Evidence

Distribution of glacial deposits around world makes sense if continents were together when they formed

The Great Debate

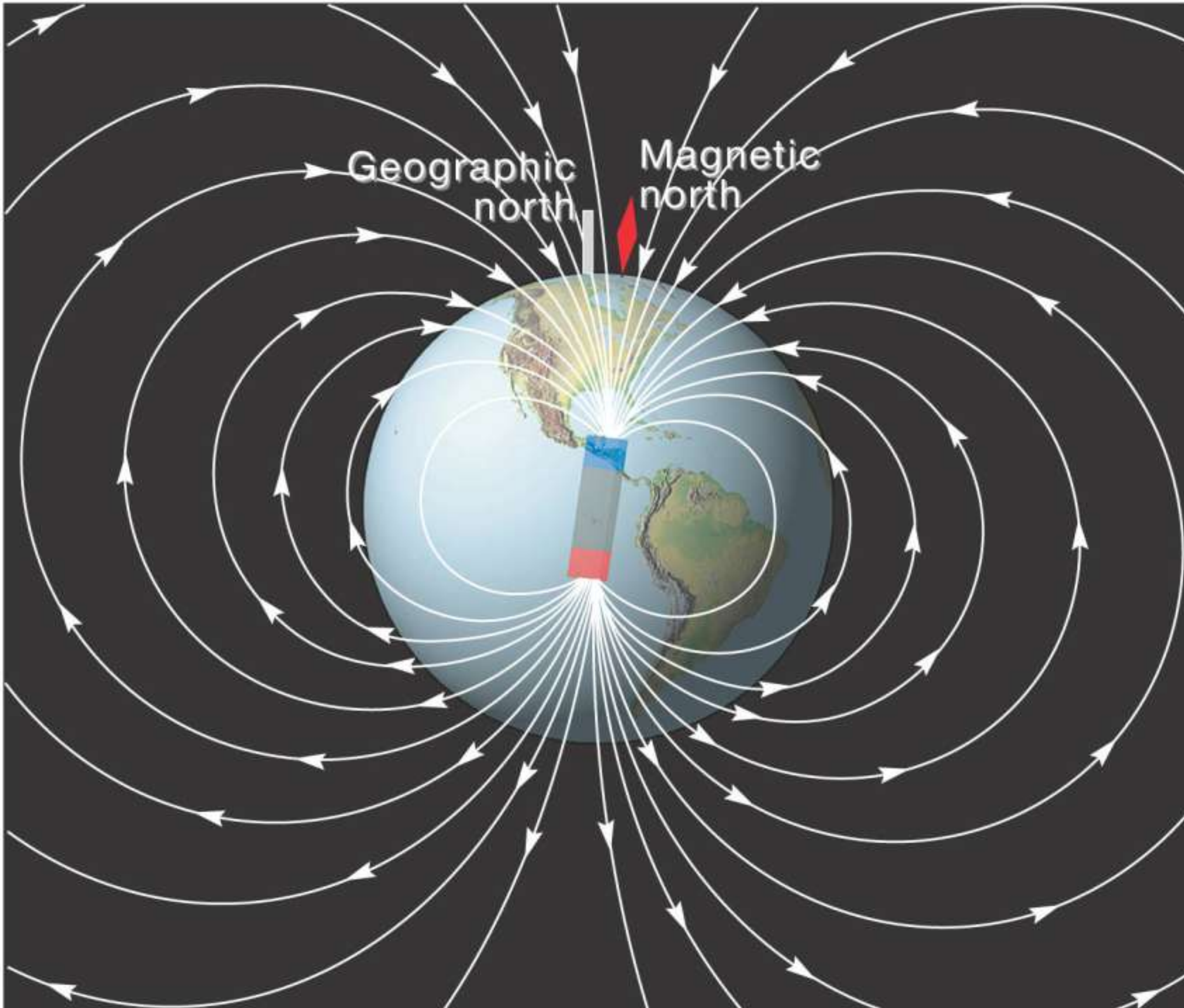
- **Objections to the continental drift hypothesis**
  - **Wegener's hypothesis lacked a mechanism capable of moving continents**
  - **He incorrectly suggested that continents broke through the ocean crust, much like ice breakers cut through ice – geophysicists proved this to be impossible.**
  - **Although ~ accepted by geologists in S. hemisphere (strong evidence there), CD faced strong opposition from geologists and physicists from US, Europe.**

The Great Debate

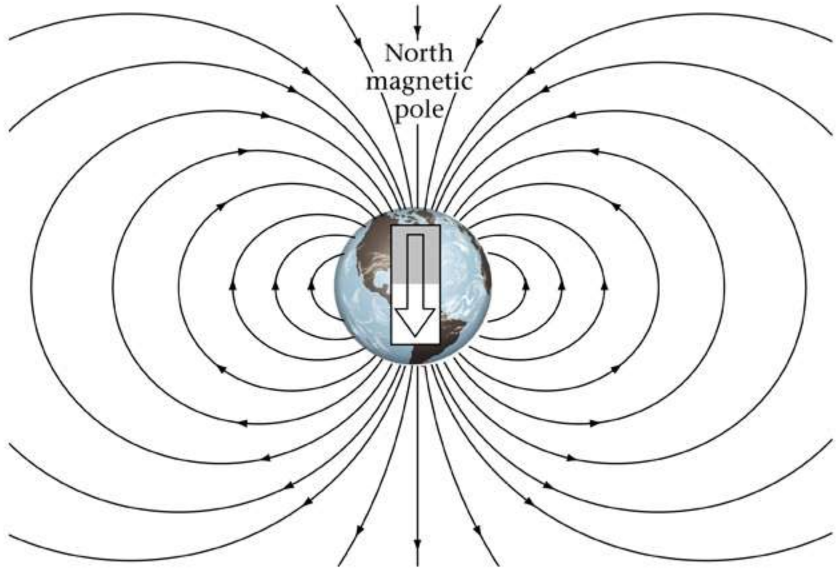
- **Continental drift and the scientific method**
  - **Wegener's hypothesis was testable and proved correct in principle, but contained incorrect details**
  - **A few scientists considered Wegener's ideas plausible and continued the search … but needed the types of scientific instrumentation that ultimately were developed in WWII.**

Reviving the Continental Drift Hypothesis

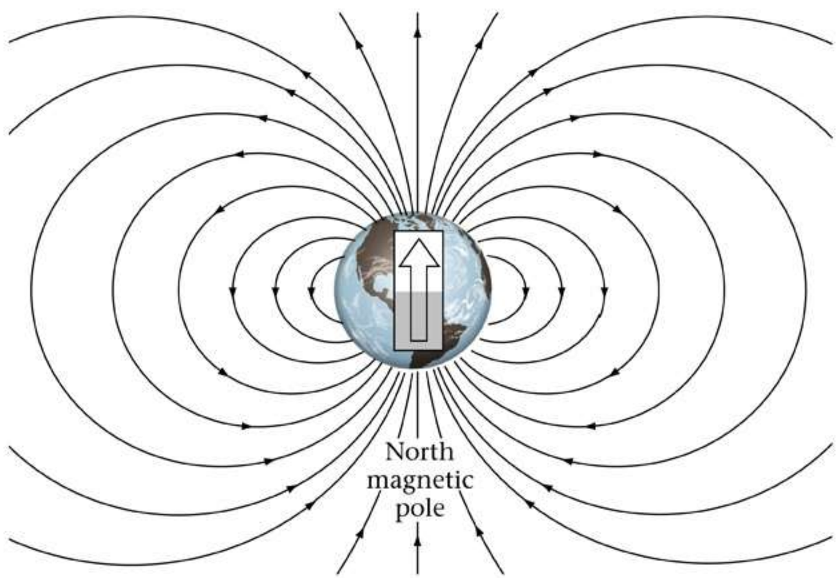
- **Paleomagnetism**
  - **Magnetic minerals (e.g. magnetite) in lavas record position of magnetic poles through geologic time**
  - **Used to support the idea that the continents drifted**
  - **How? … changing polarity of magnetic north.**



Geographic
north
Magnetic
north



(a)



(b)

FIGURE 2.24

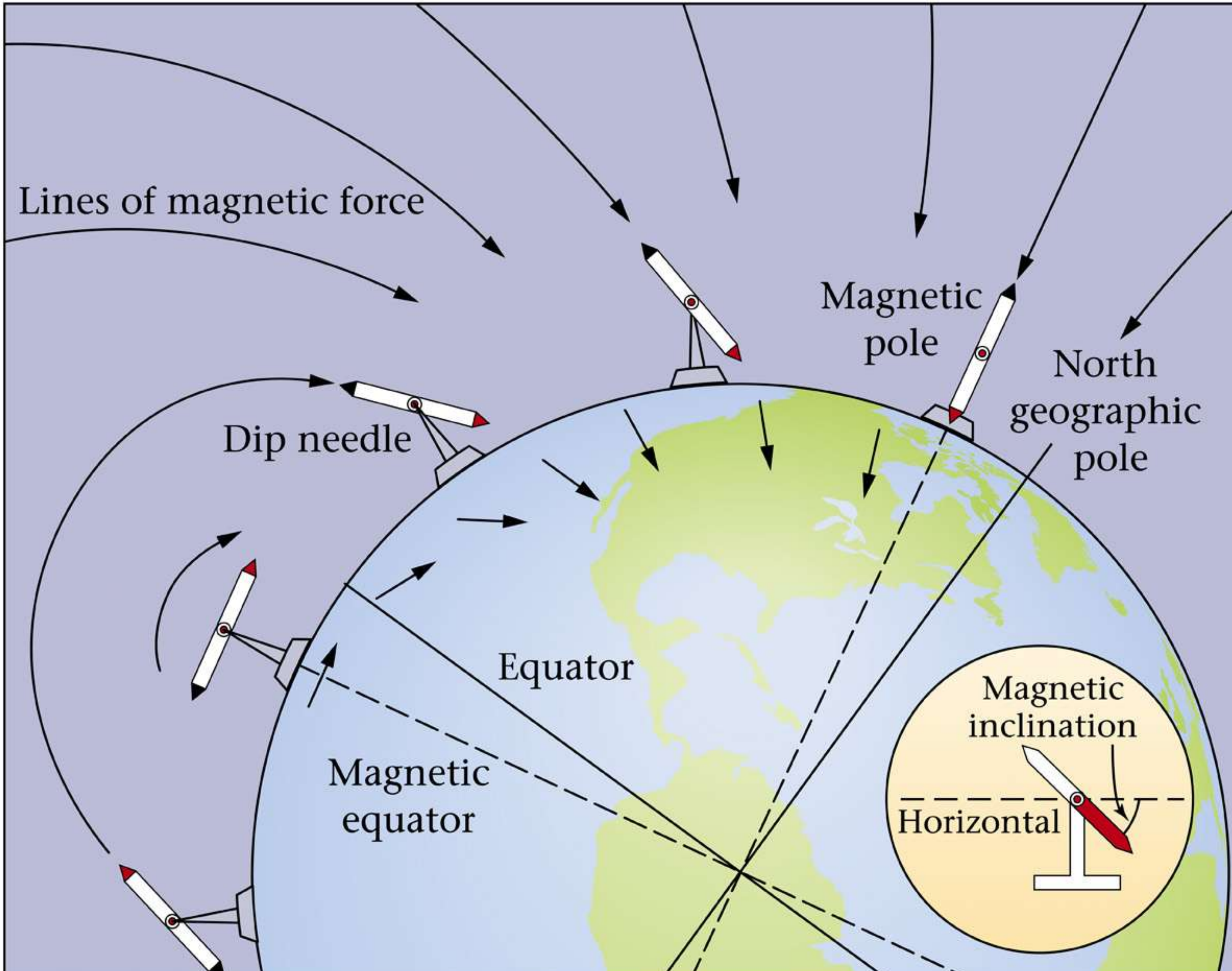


FIGURE 2.9

Essentials of Geology, 2nd Edition

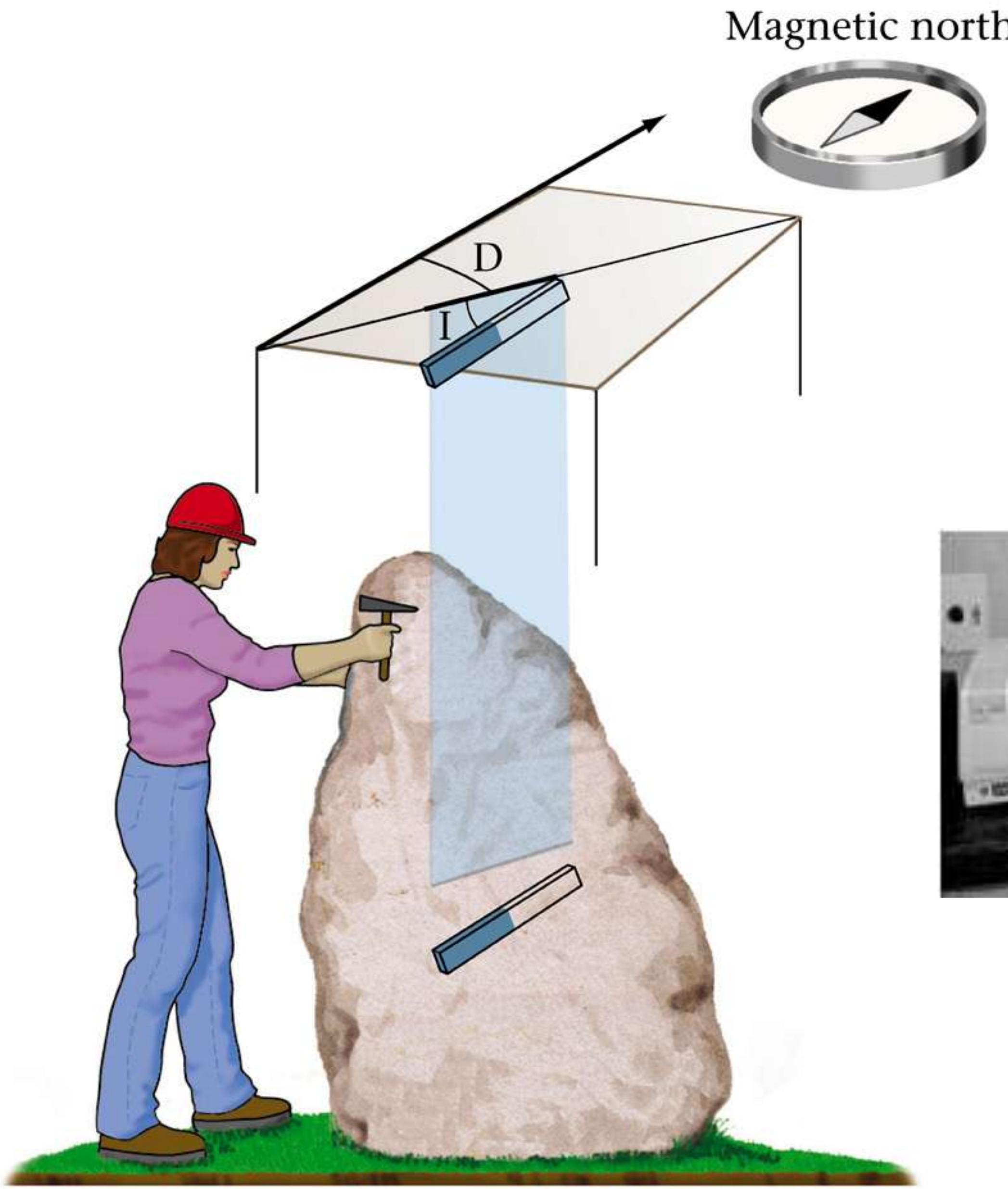
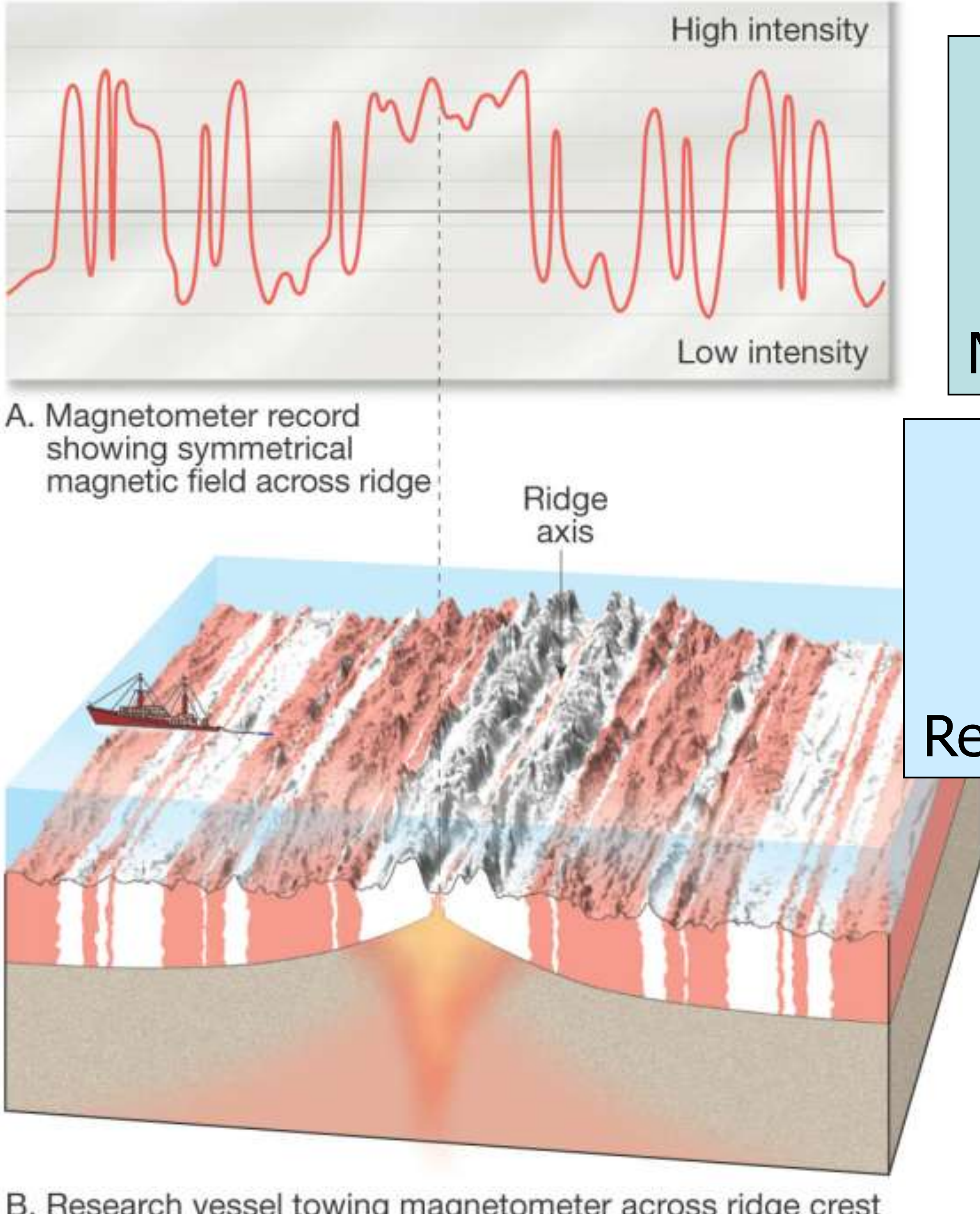


FIGURE 2.11

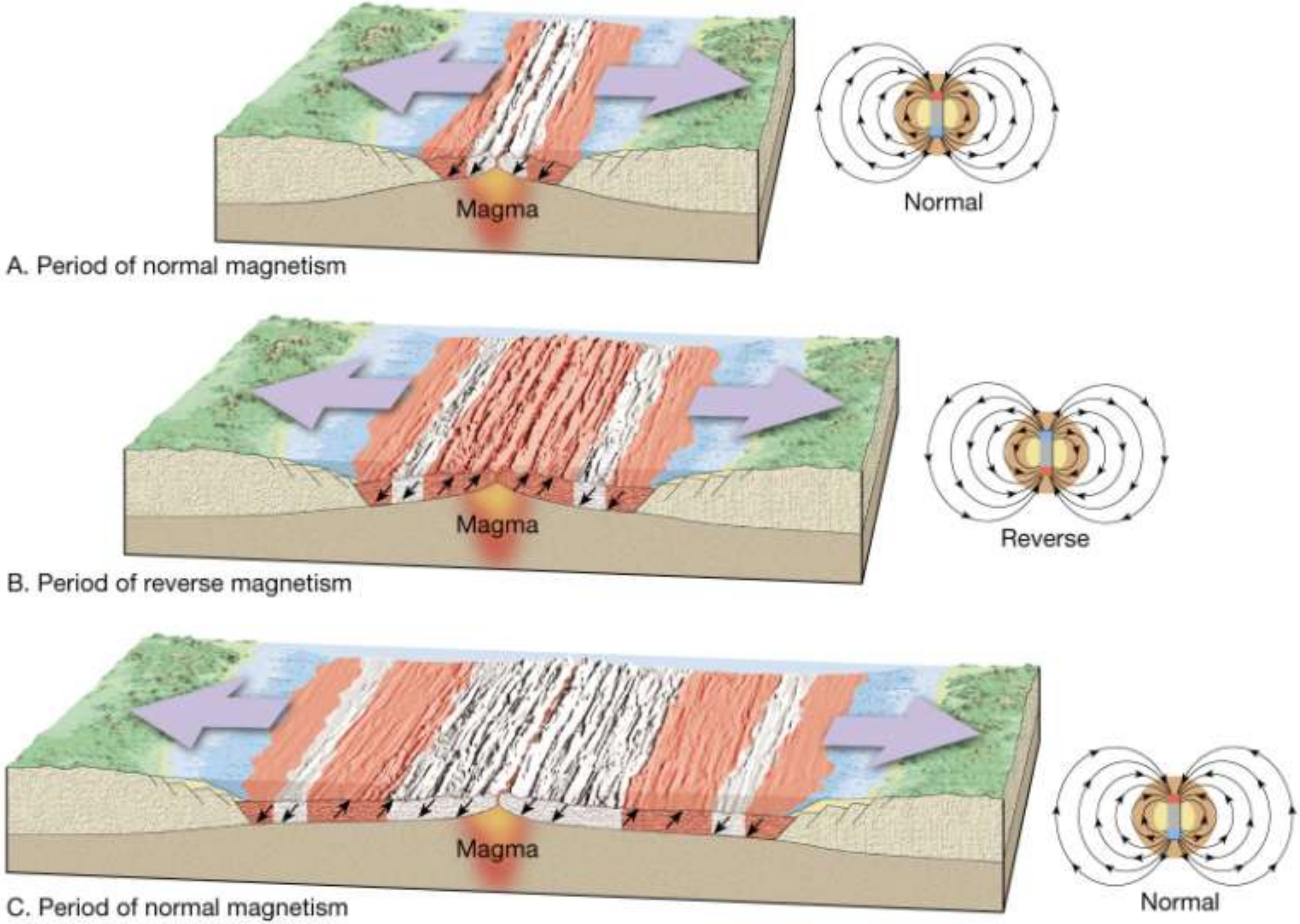
Essentials of Geology, 2nd Edition



High Intensity
=
Earth's Field
+
Normal field in rock

Low Intensity
=
Earth's Field
+
Reversed field in rock

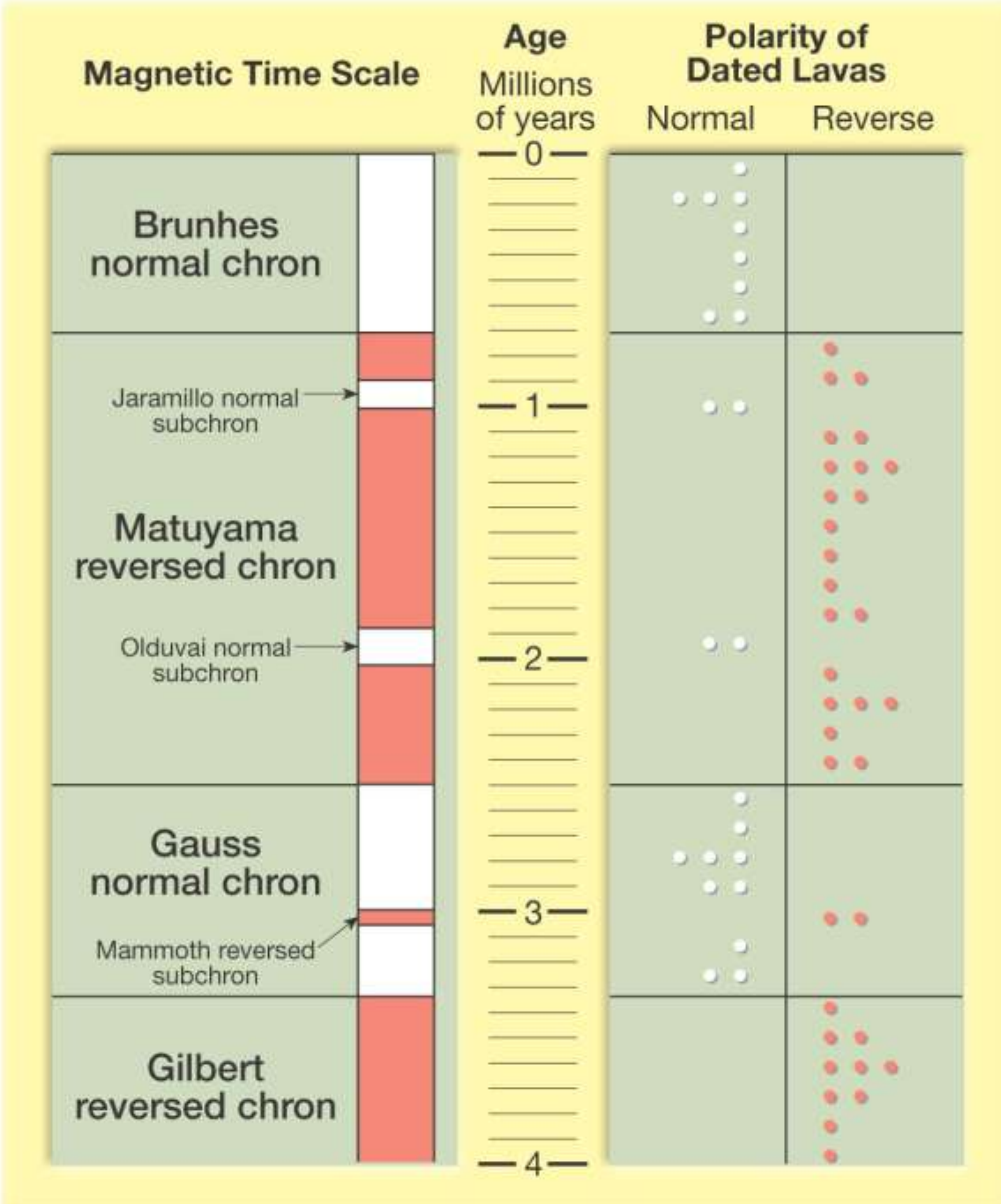
Paleomagnetic Reversals Recorded in Oceanic Crust



It is not easy to prove a theory in the sciences

The **Vine–Matthews–Morley hypothesis**, also known as the **Morley–Vine–Matthews hypothesis** was the first key scientific test of the seafloor spreading theory of continental drift and Plate tectonics. Geophysicist Frederick John Vine and the Canadian geologist Lawrence W. Morley independently realized that if the seafloor spreading theory was correct, then the rocks surrounding the mid-oceanic ridges should show symmetric patterns of magnetization reversals, a record of the Earth's geomagnetic reversals, captured in the cooling volcanic rocks. **Morley's letters to *Nature* (February 1963) and *Journal of Geophysical Research* (April 1963) were both rejected**, so Vine and his adviser Drummond Hoyle Matthews were first to publish in 1963. Later geomagnetic surveys found the patterns are in fact present, providing strong confirmation of the theory.
From wikipedia.

Yet the theory of seafloor spreading (and later, theory of plate tectonics) took many years to finally catch on.


Magnetic Time Scale
Age
Millions of years
Polarity of Dated Lavas
Normal
Reverse
0
1
2
3
4
Brunhes normal chron
Jaramillo normal subchron
Matuyama reversed chron
Olduvai normal subchron
Gauss normal chron
Mammoth reversed subchron
Gilbert reversed chron

More testing of the Sea Floor Spreading hypothesis was conducted and all data supported the hypothesis

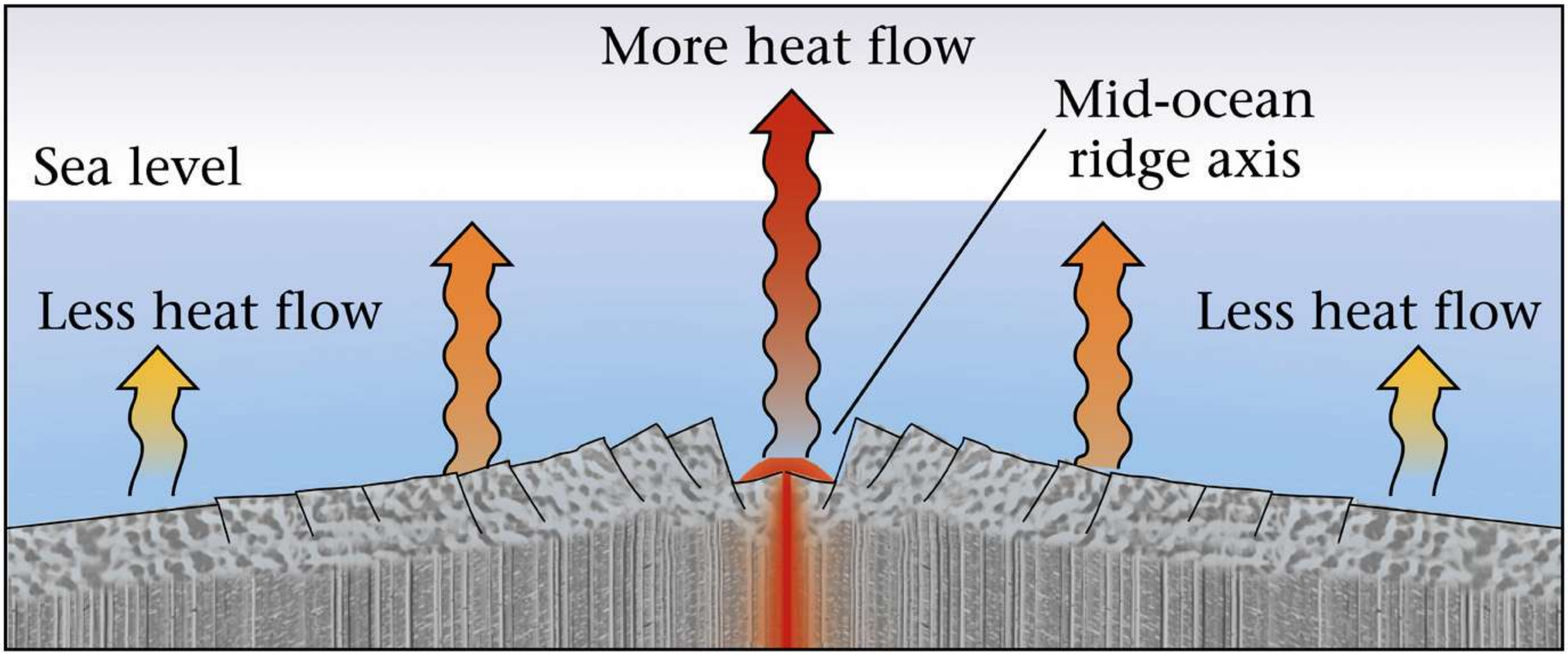
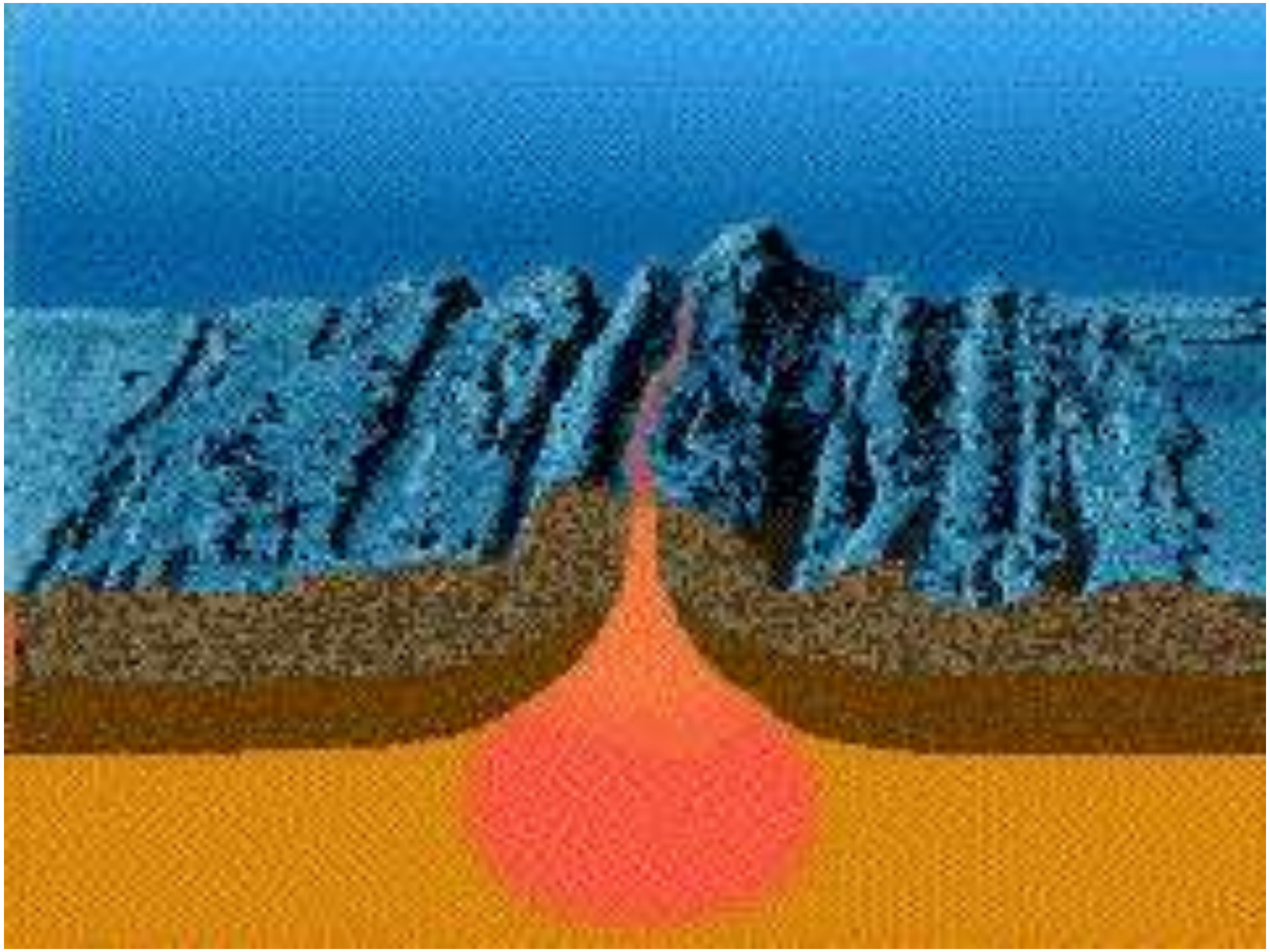
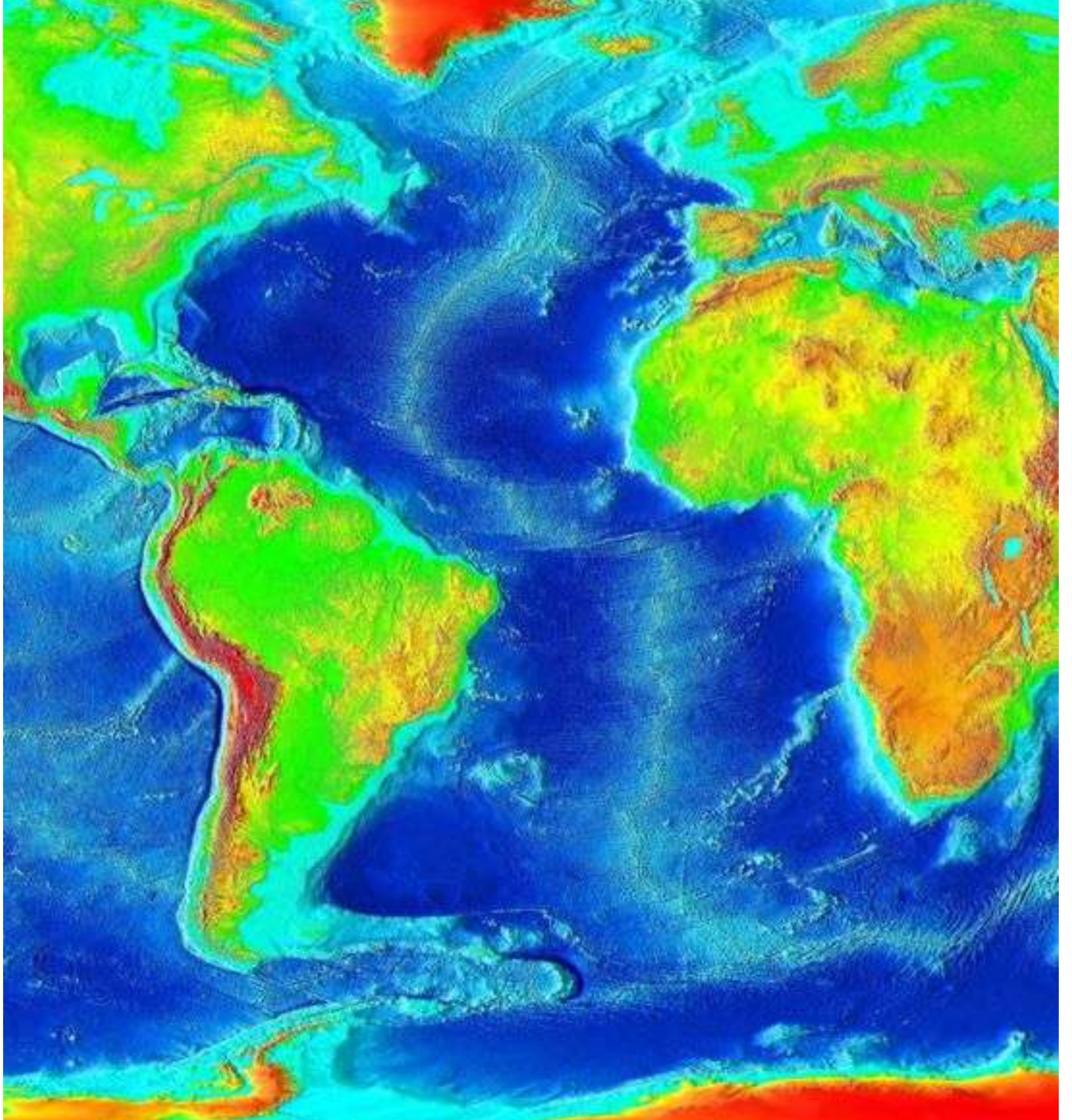


FIGURE 2.19

New Oceanic Lithosphere is created during Sea-floor spreading

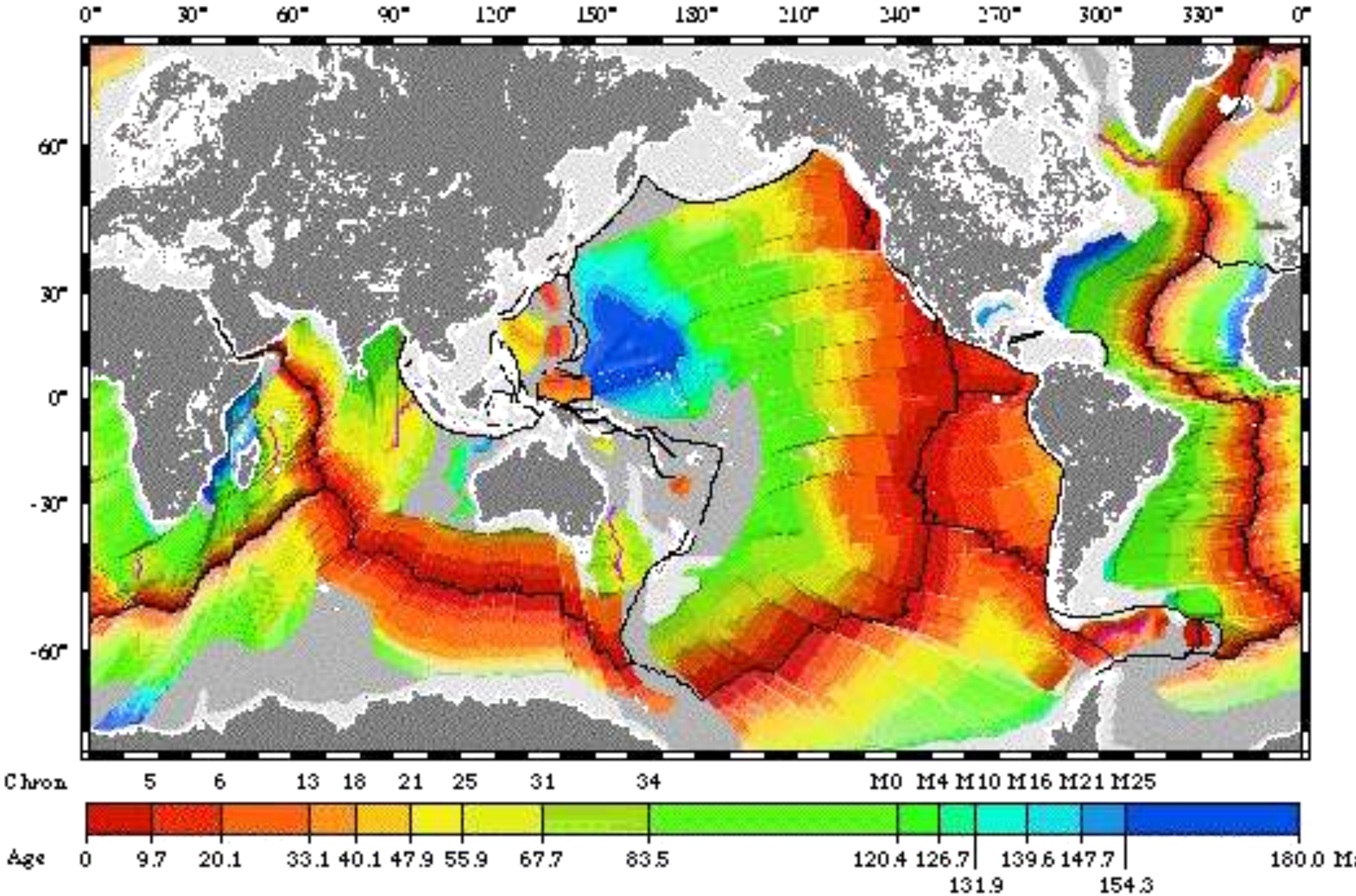


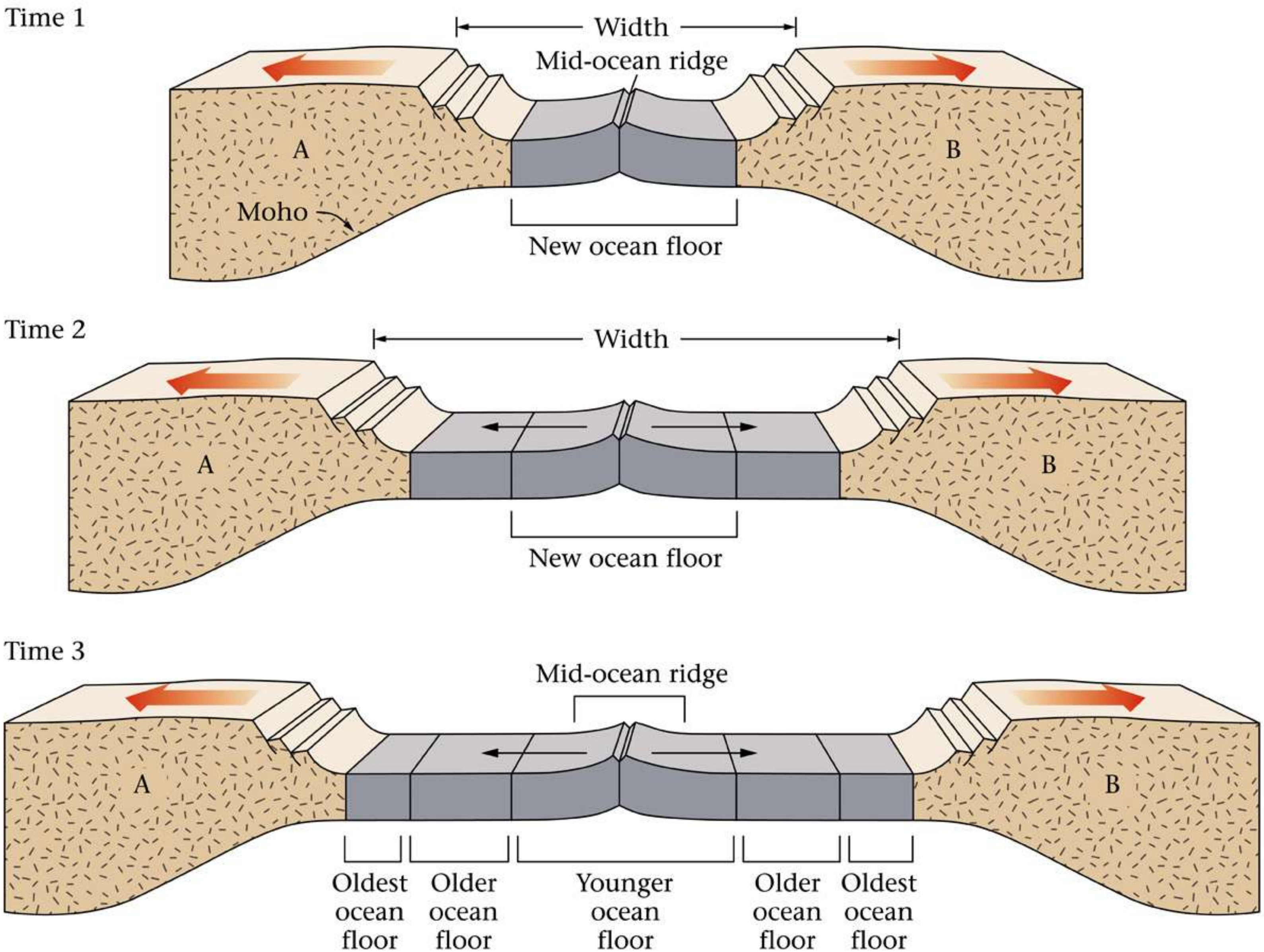


Age of basaltic rocks on the seafloor?

Digital Isochrons of the Ocean Floor

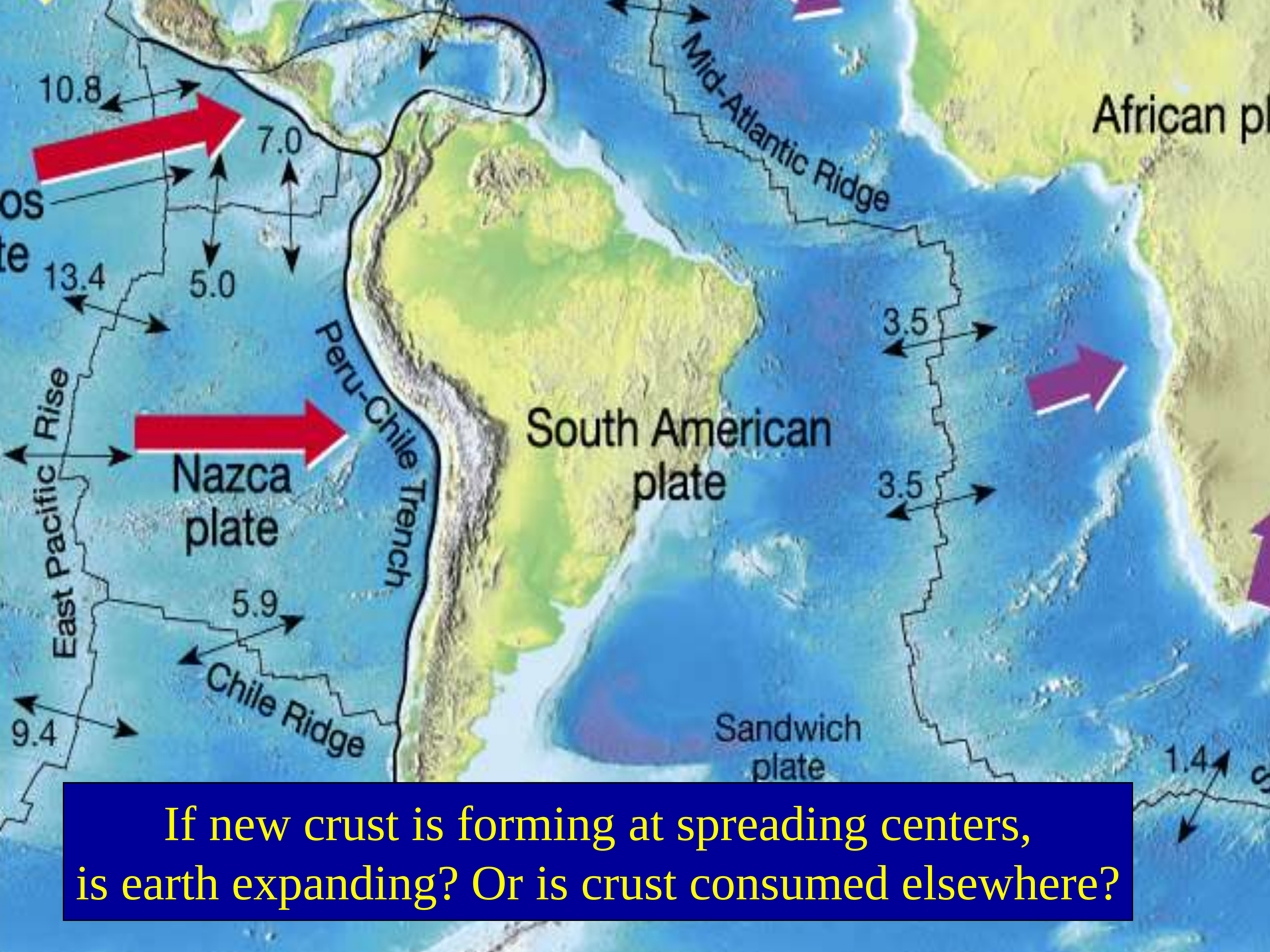
R.D. Müller, W.R. Roest, J.-Y. Royer, L.M. Gahagan, J.G. Sclater





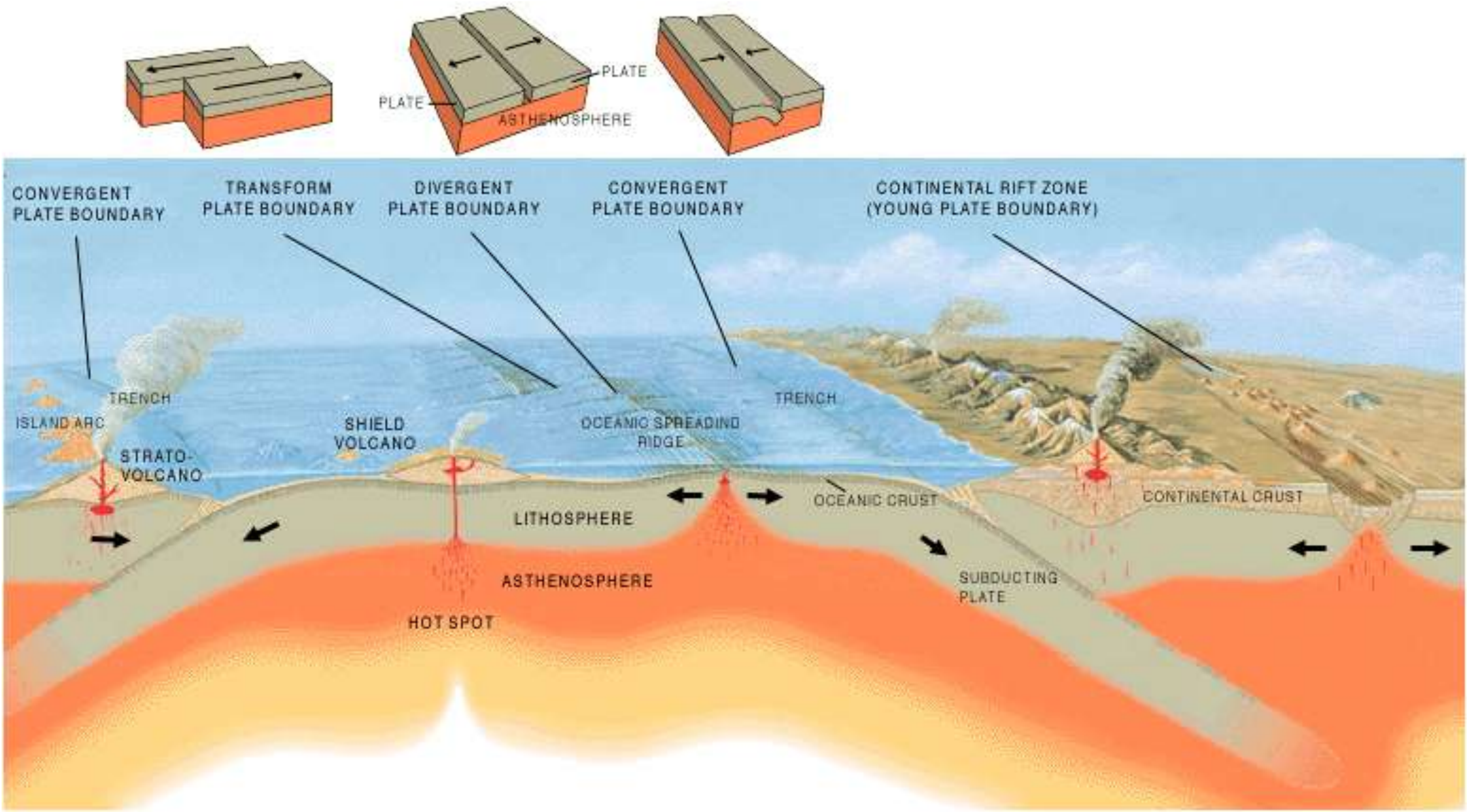
Essentials of Geology, 2nd Edition

FIGURE 2.33



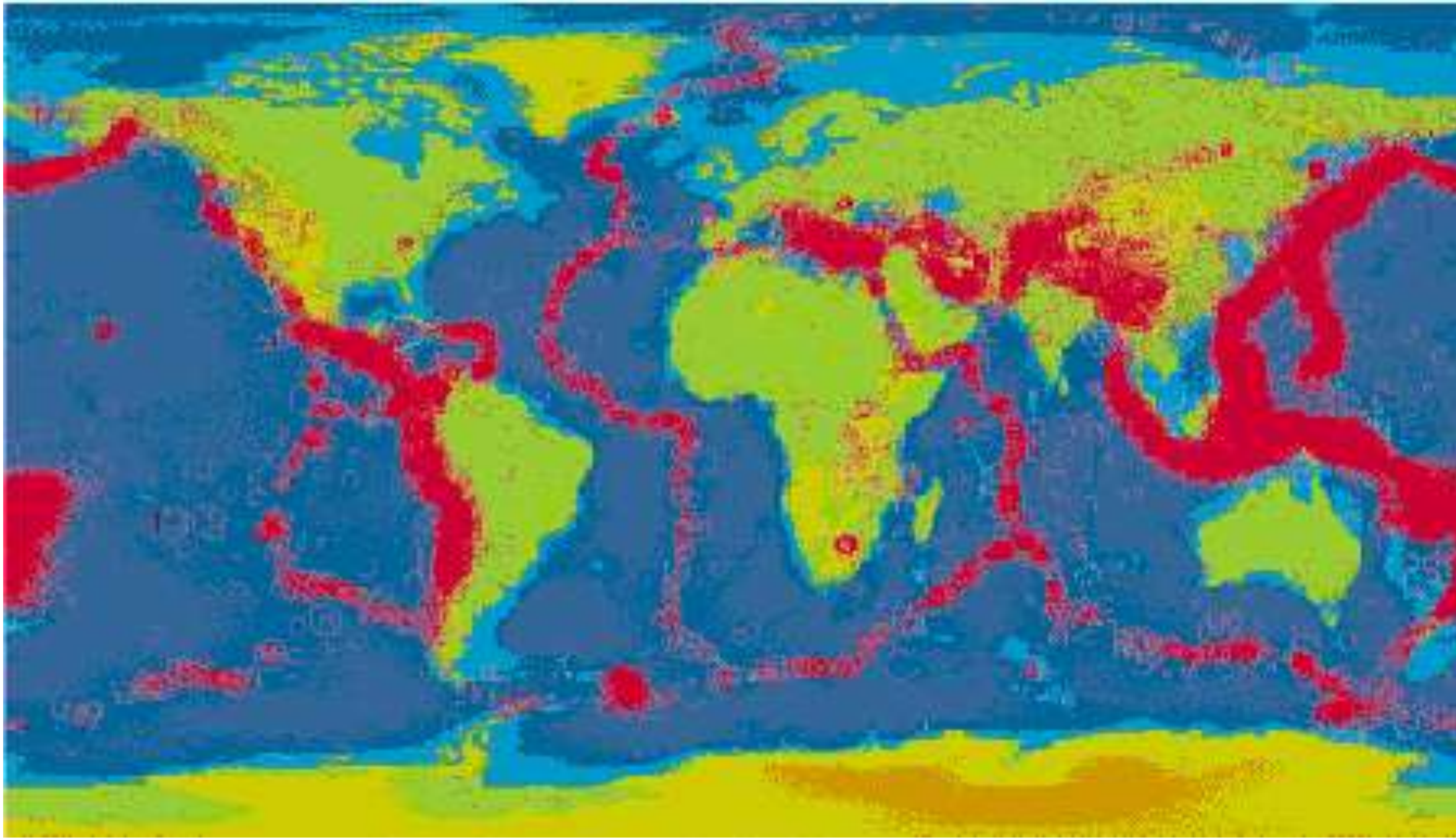
If new crust is forming at spreading centers,
is earth expanding? Or is crust consumed elsewhere?

Earth's lithosphere consists of rigid plates that move over plastic-like asthenosphere … driven by flow and convection in the upper mantle (asthenosphere). Oceanic plates are consumed at subduction zones …. → Theory of Plate Tectonics

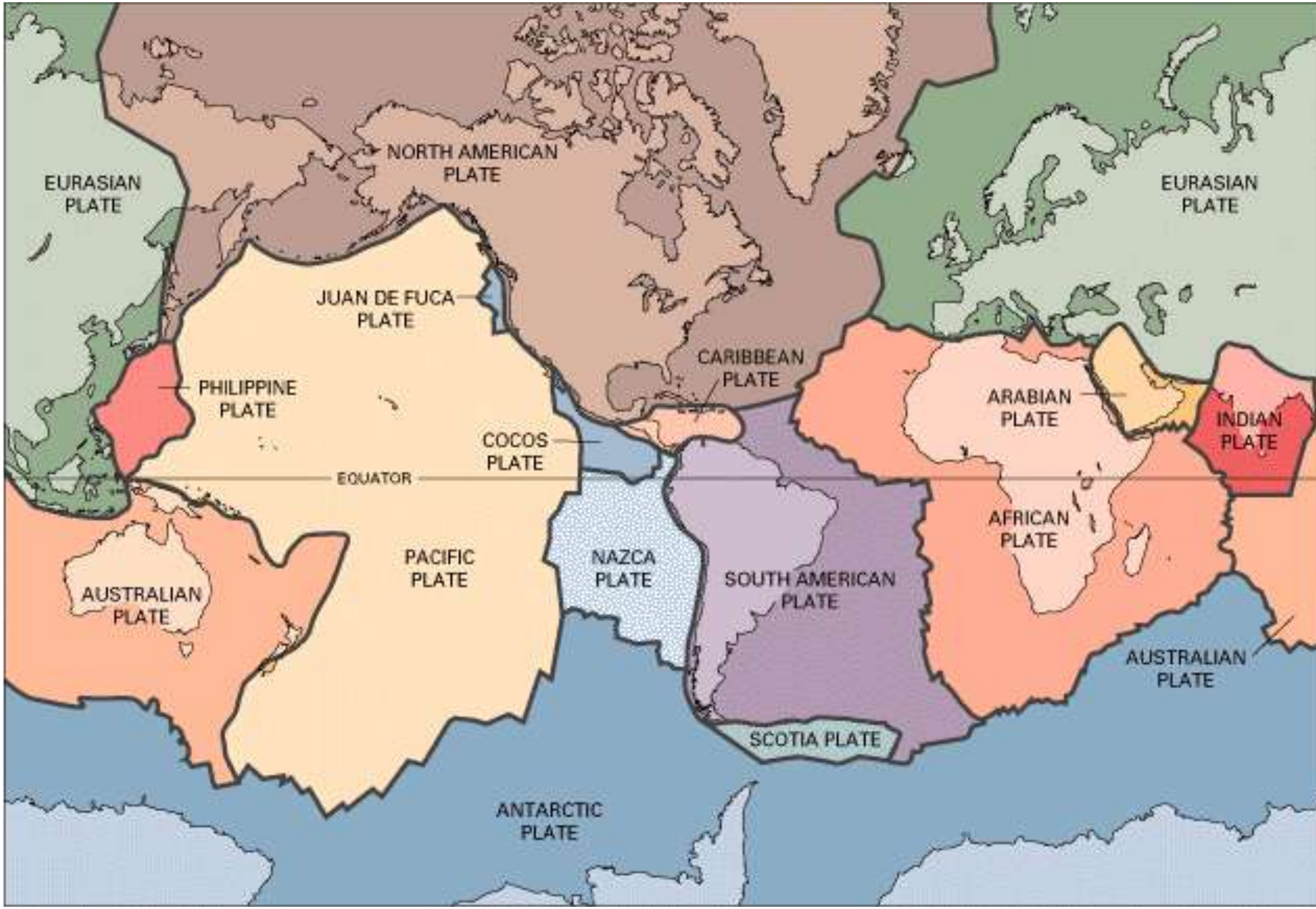


Interactions at the borders of plates causes results in major geologic activity such as earthquakes and volcanic eruptions.

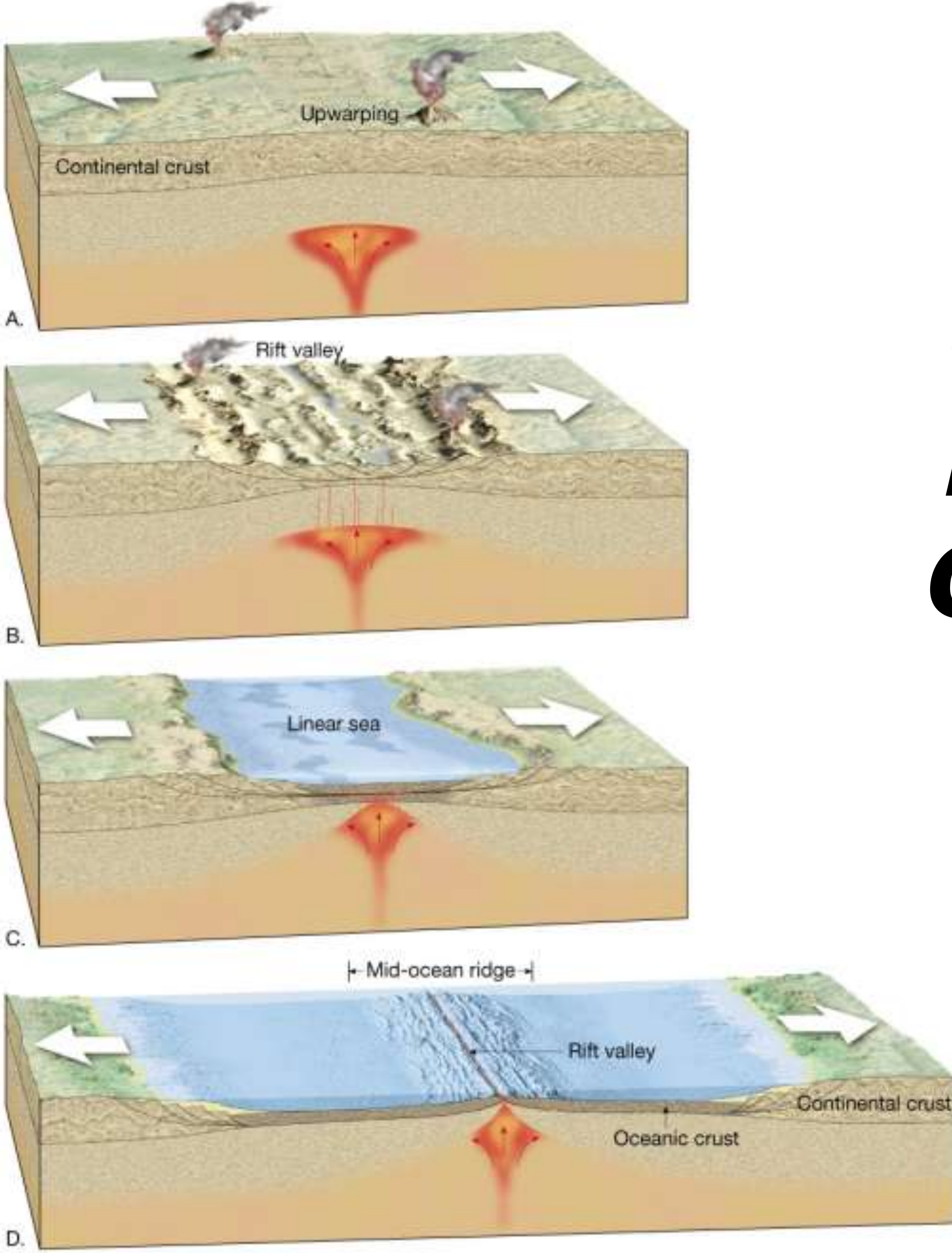
Spatial distribution of earthquakes helps to map plate boundaries

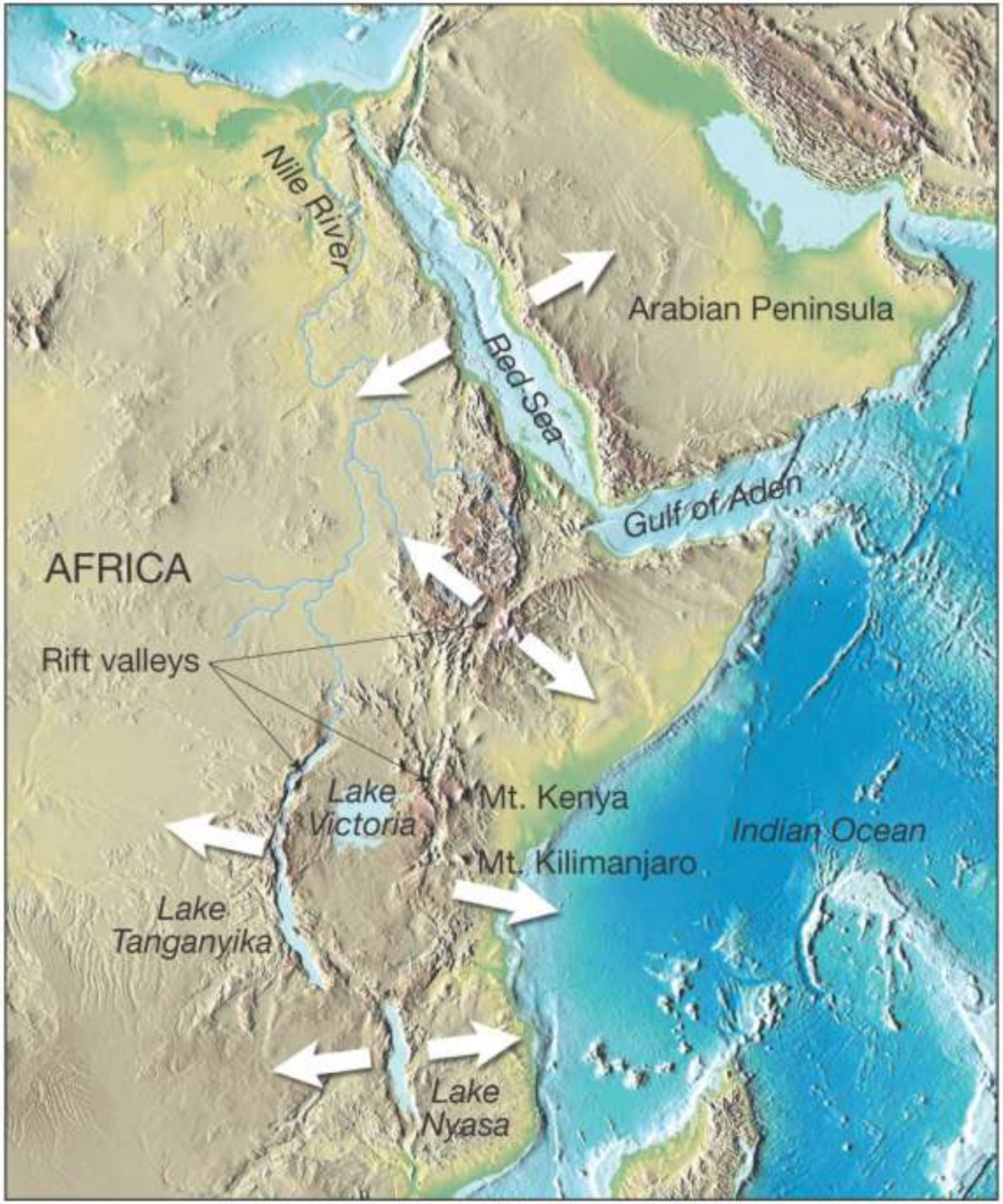


Earth’s Lithospheric Plates



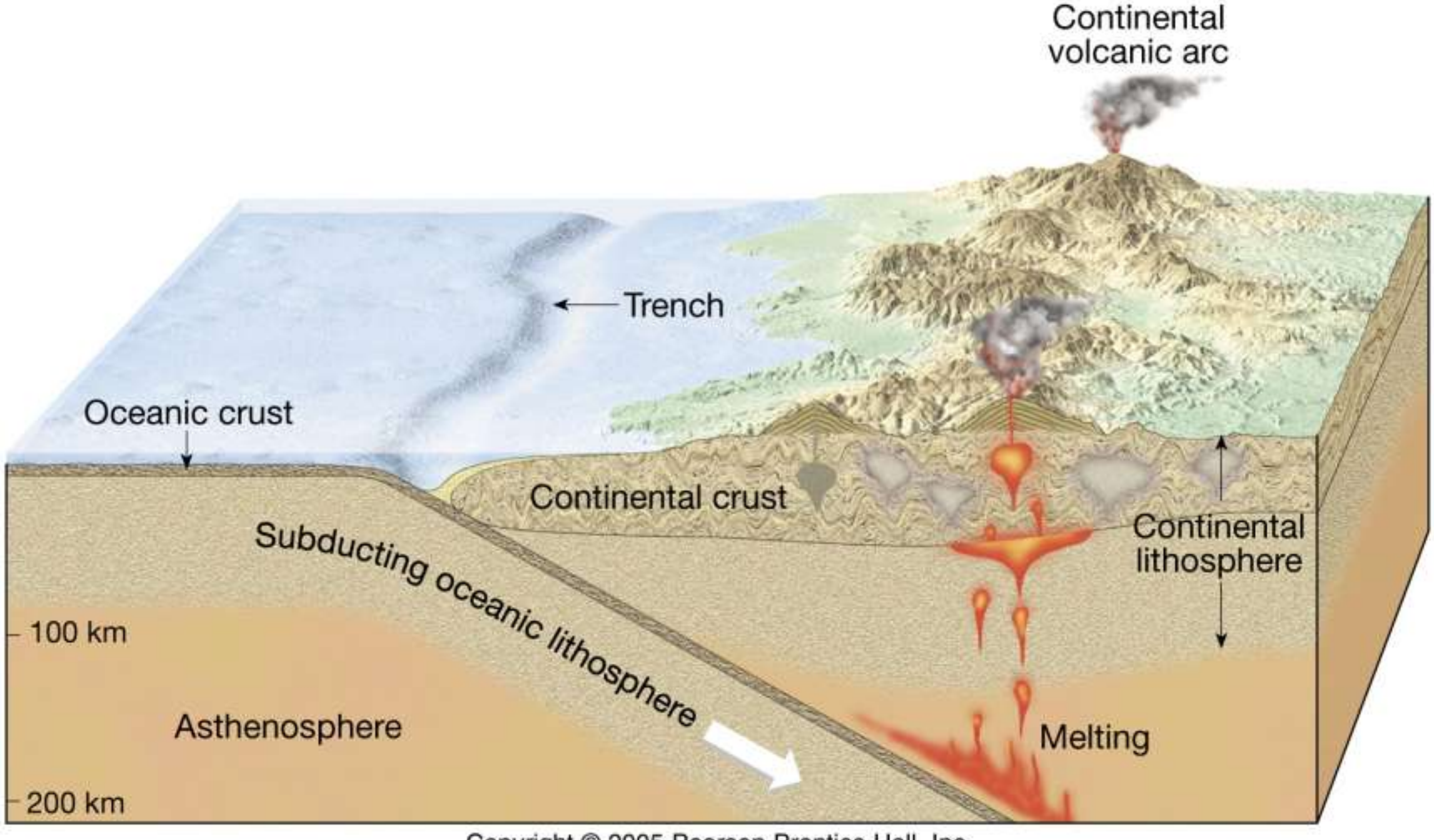
Continental Rifting, and Ocean Basin Formation



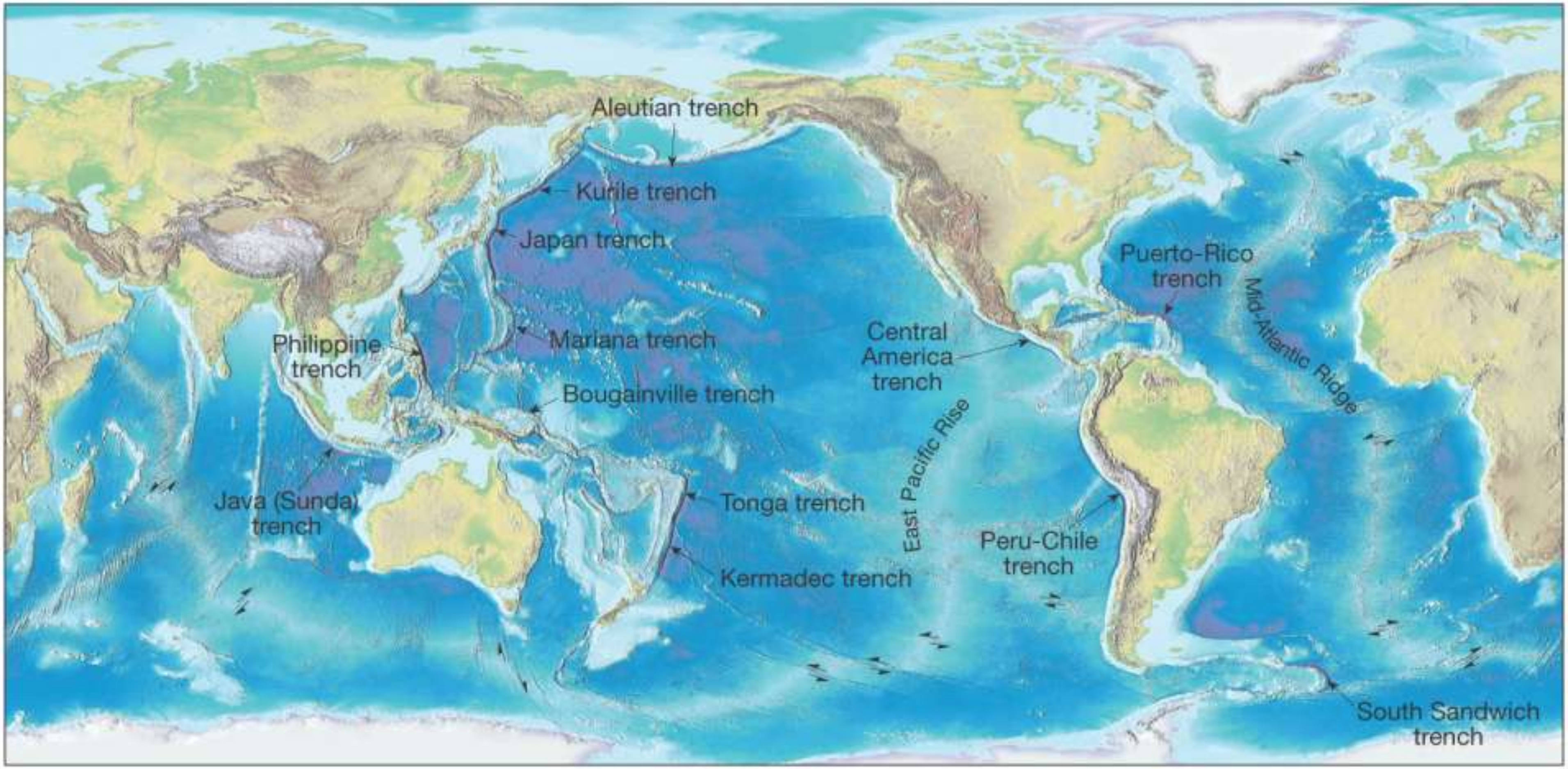


Continental Rifting

Oceanic-Continental Convergence



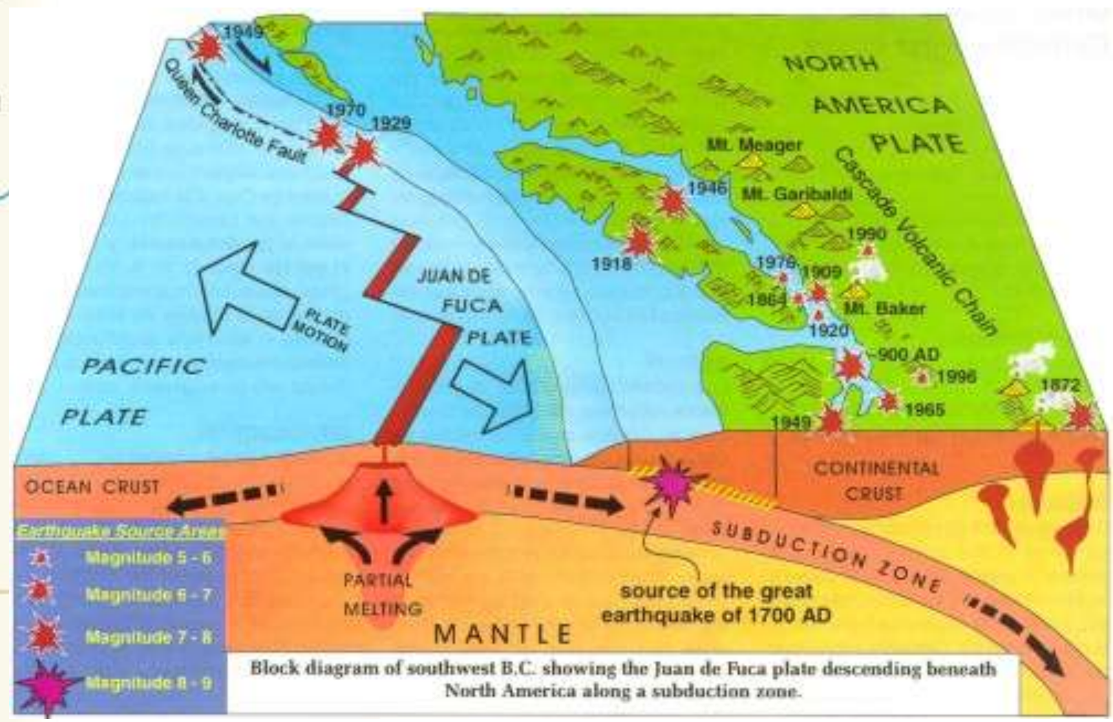
Convergent Plate Boundaries



Cascadia Subduction Zone

1100 km long subduction of the Juan de Fuca plate beneath the Pacific Northwest

Young, bouyant ocean lithosphere is being subducted – **Stress!**



Block diagram of southwest B.C. showing the Juan de Fuca plate descending beneath North America along a subduction zone.

Continental-Continental Convergence & Collision

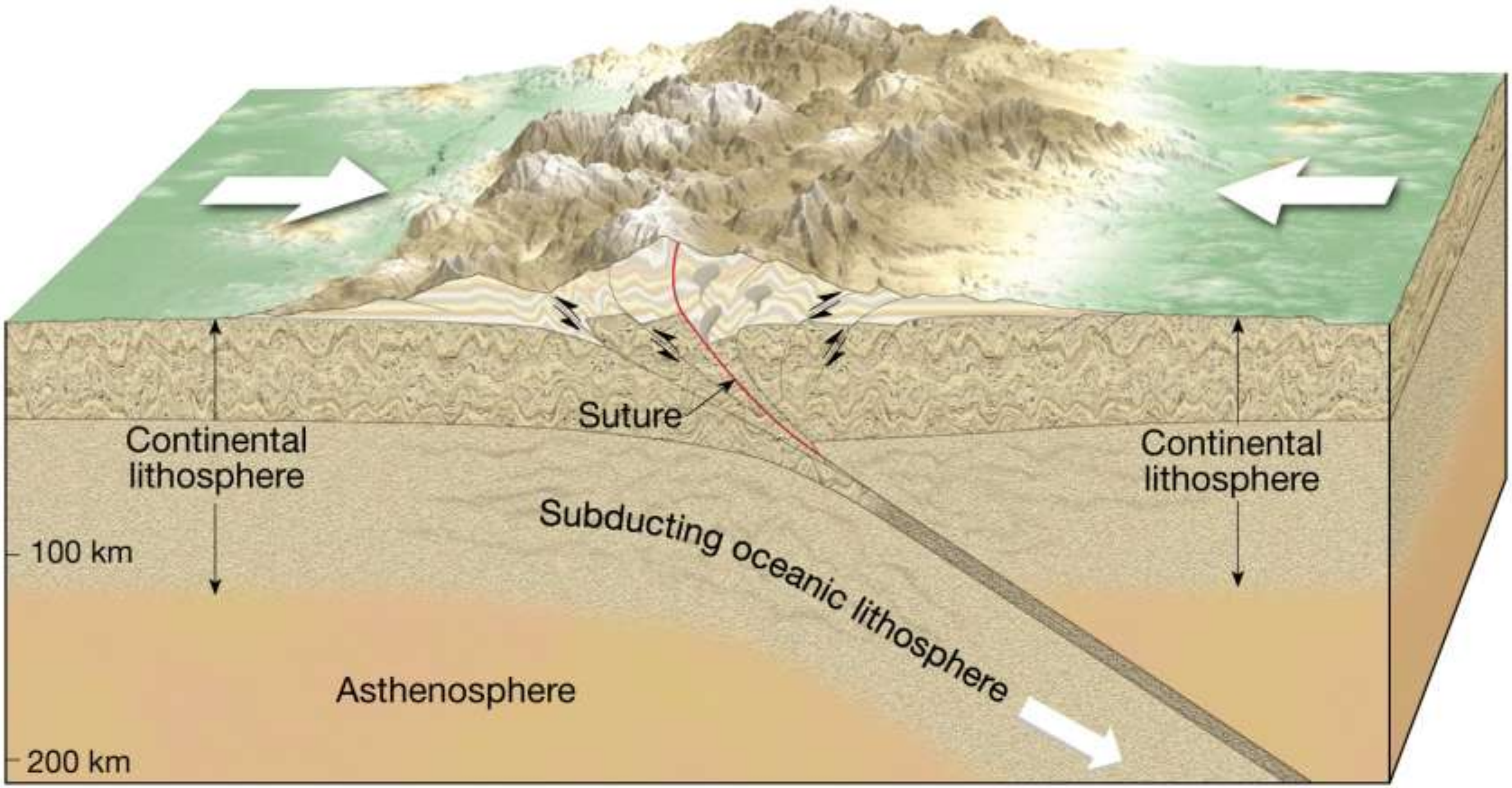
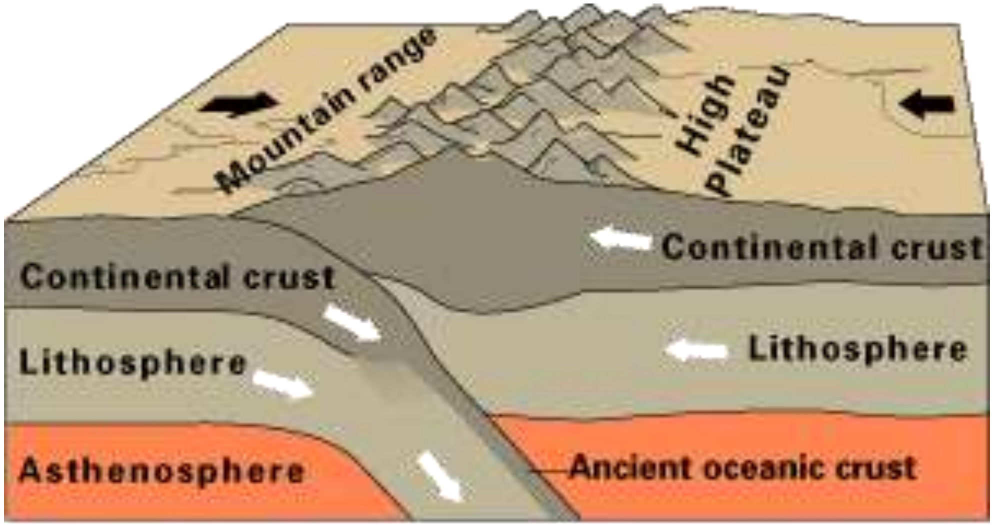
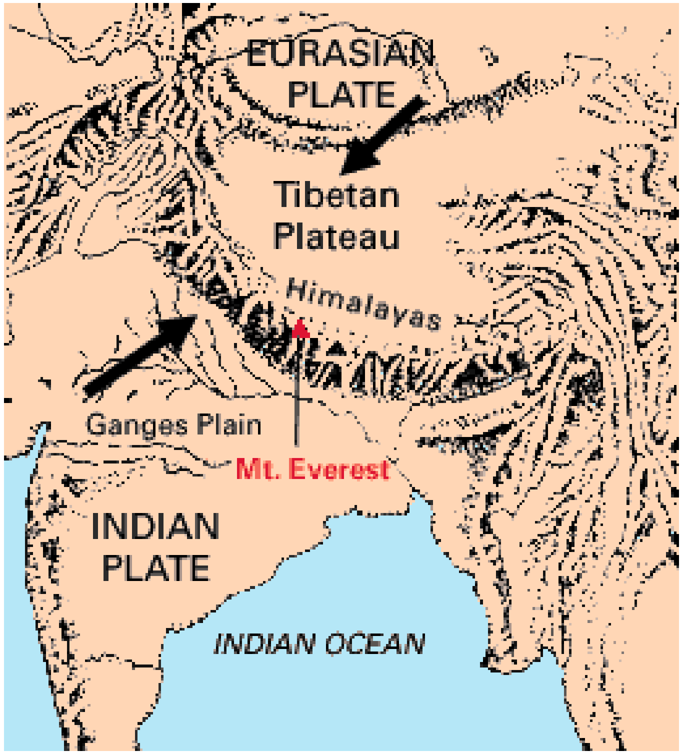


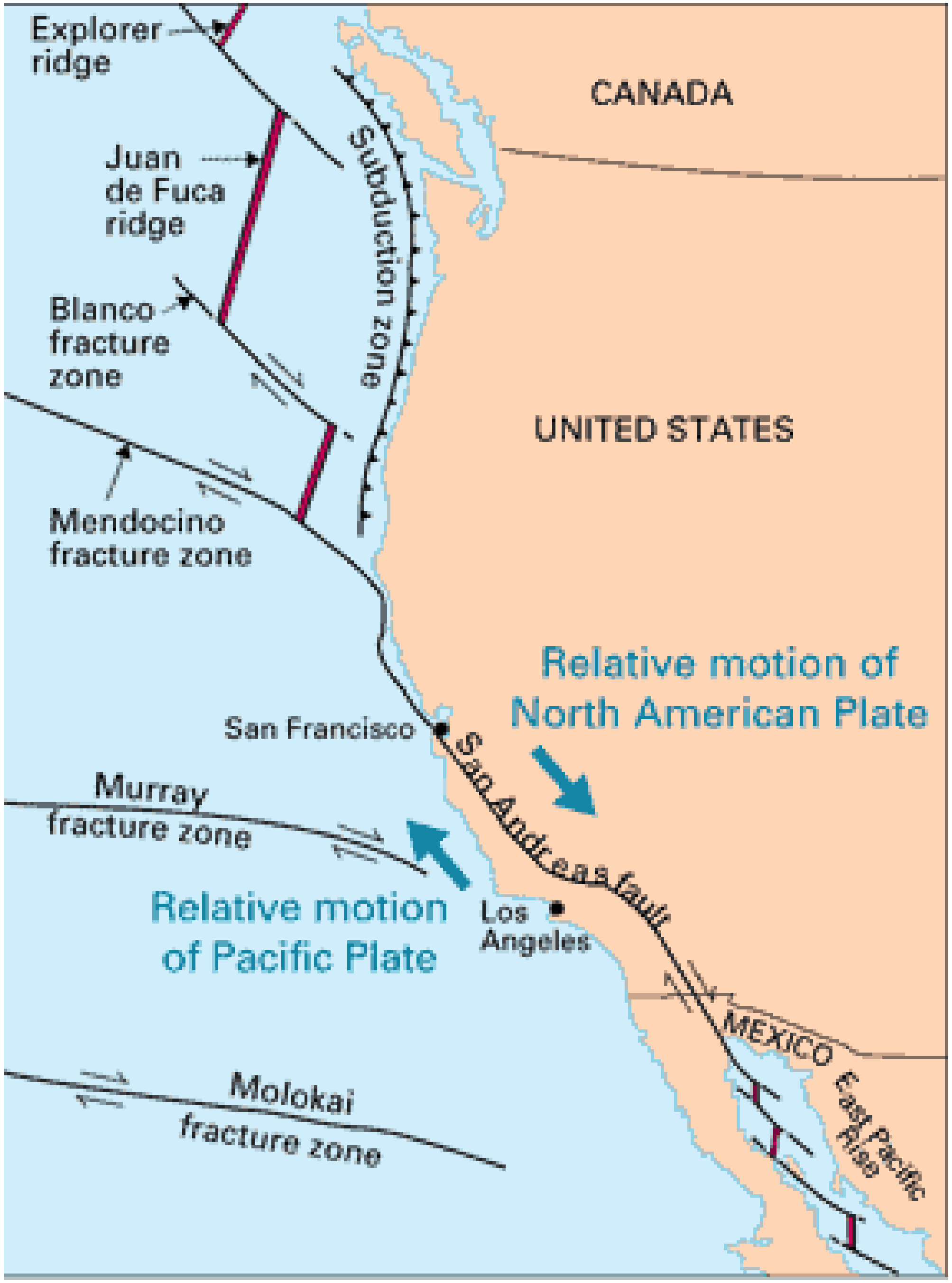
Figure 5.14 C



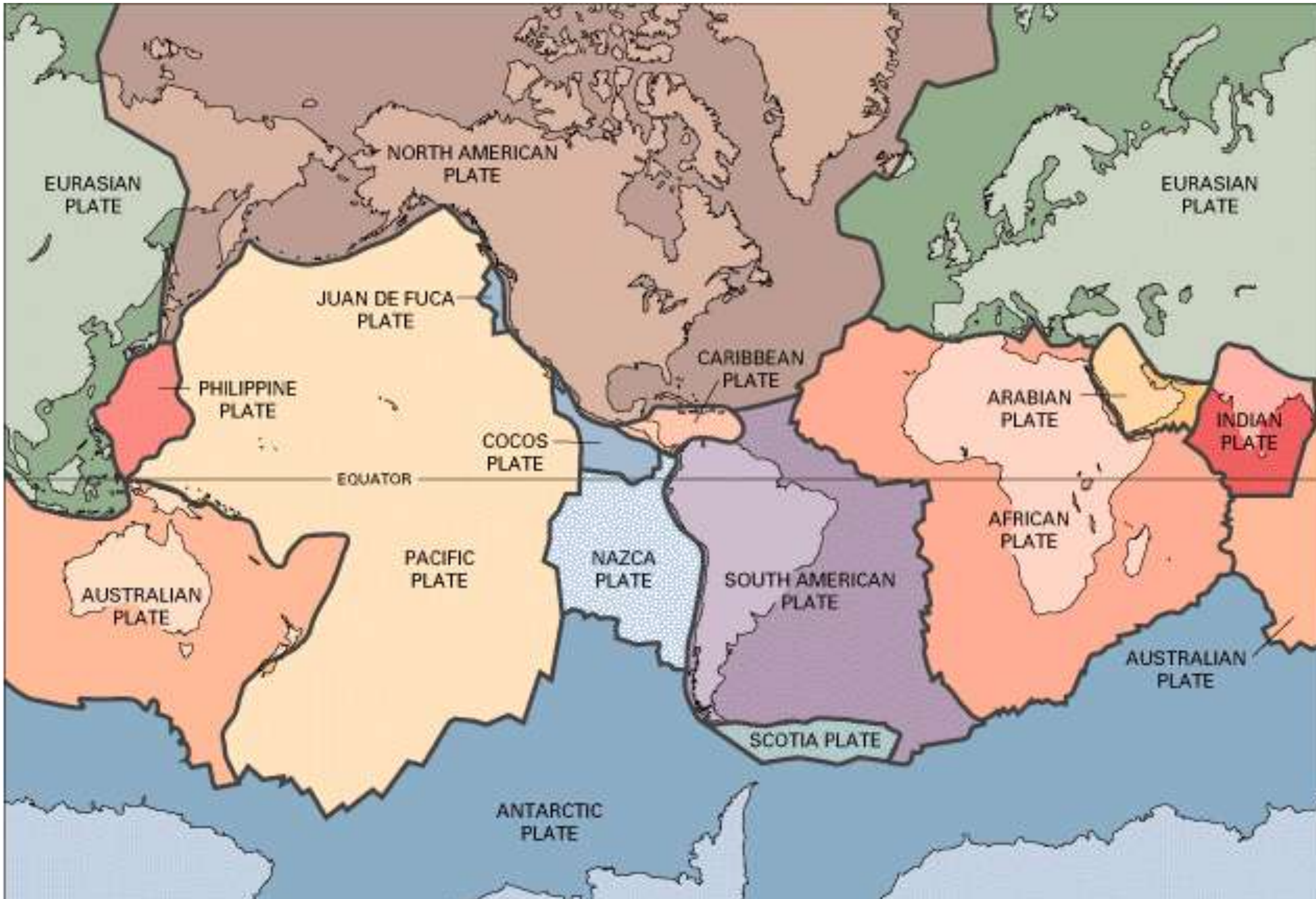
Continental-continental convergence

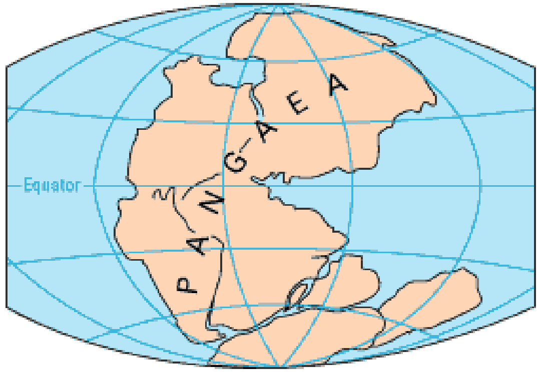


Transform Boundary

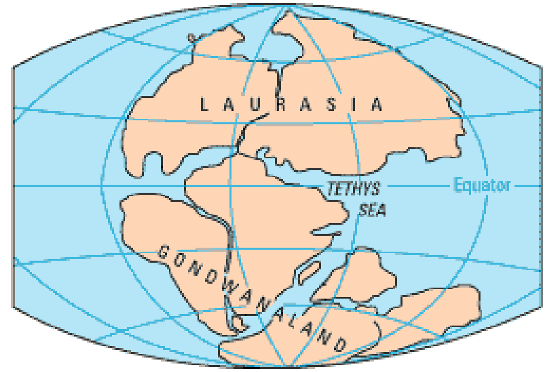


Present day distribution of lithospheric plates, but they are moving and changing size and shape. In the past the distribution of these plates was much different

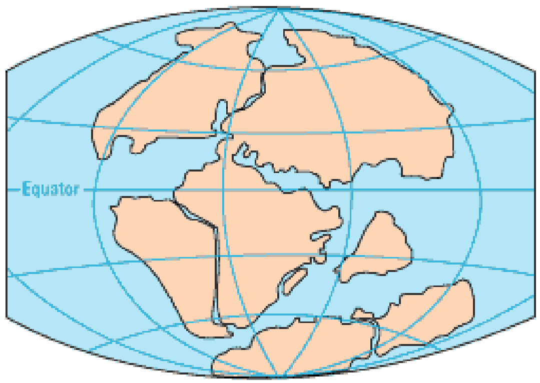




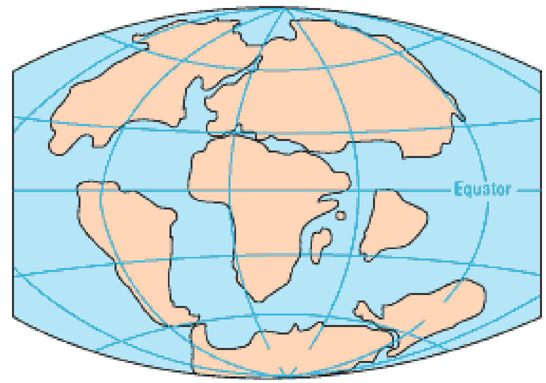
PERMIAN
225 million years ago



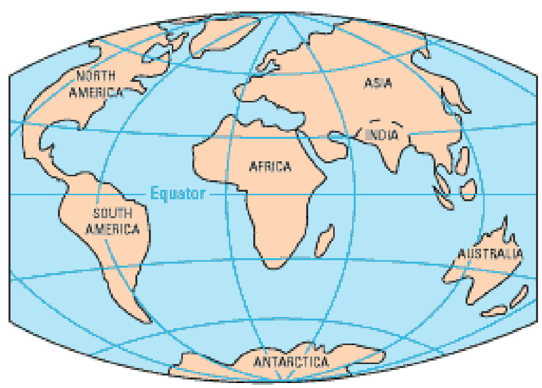
TRIASSIC
200 million years ago



JURASSIC
135 million years ago



CRETACEOUS
65 million years ago

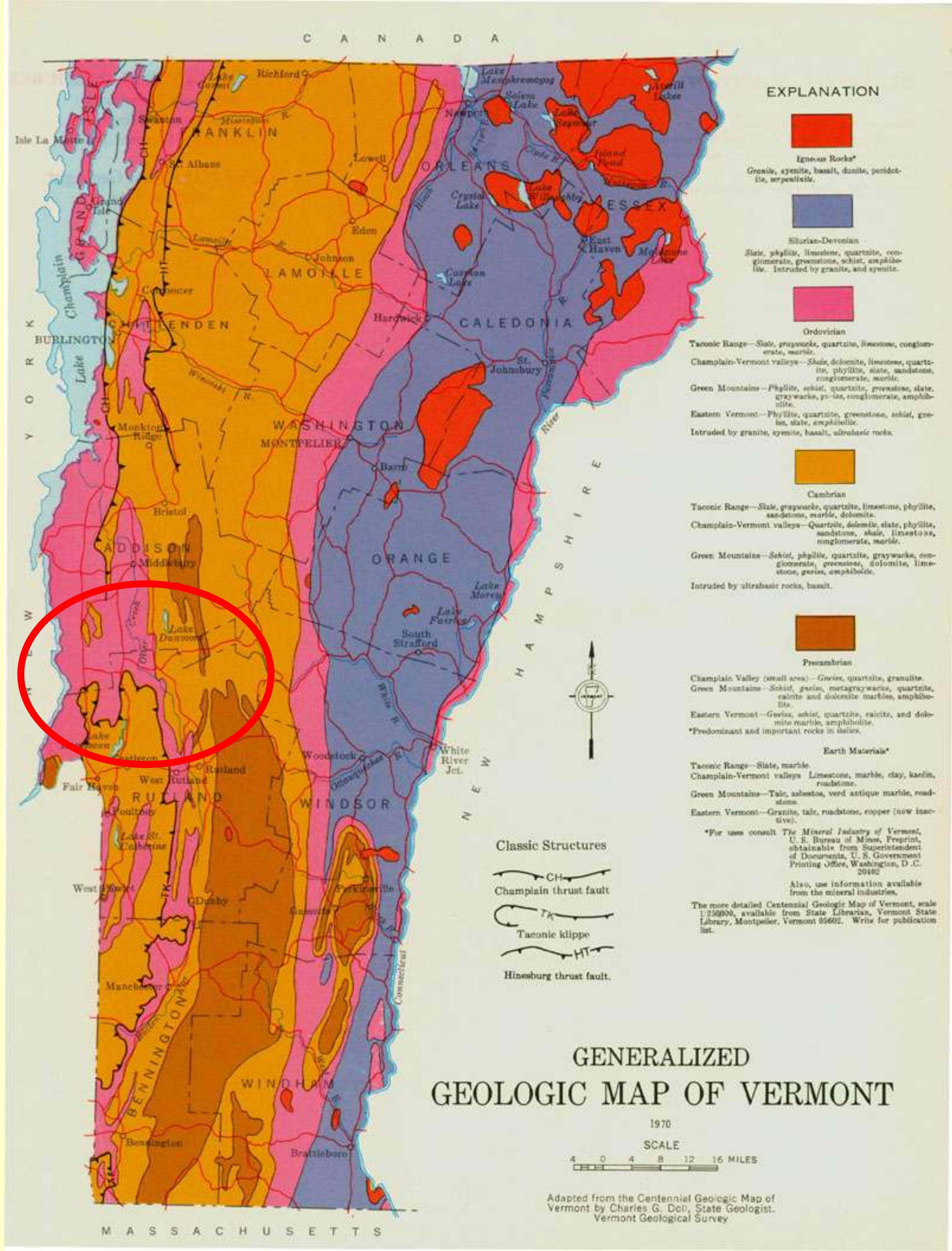


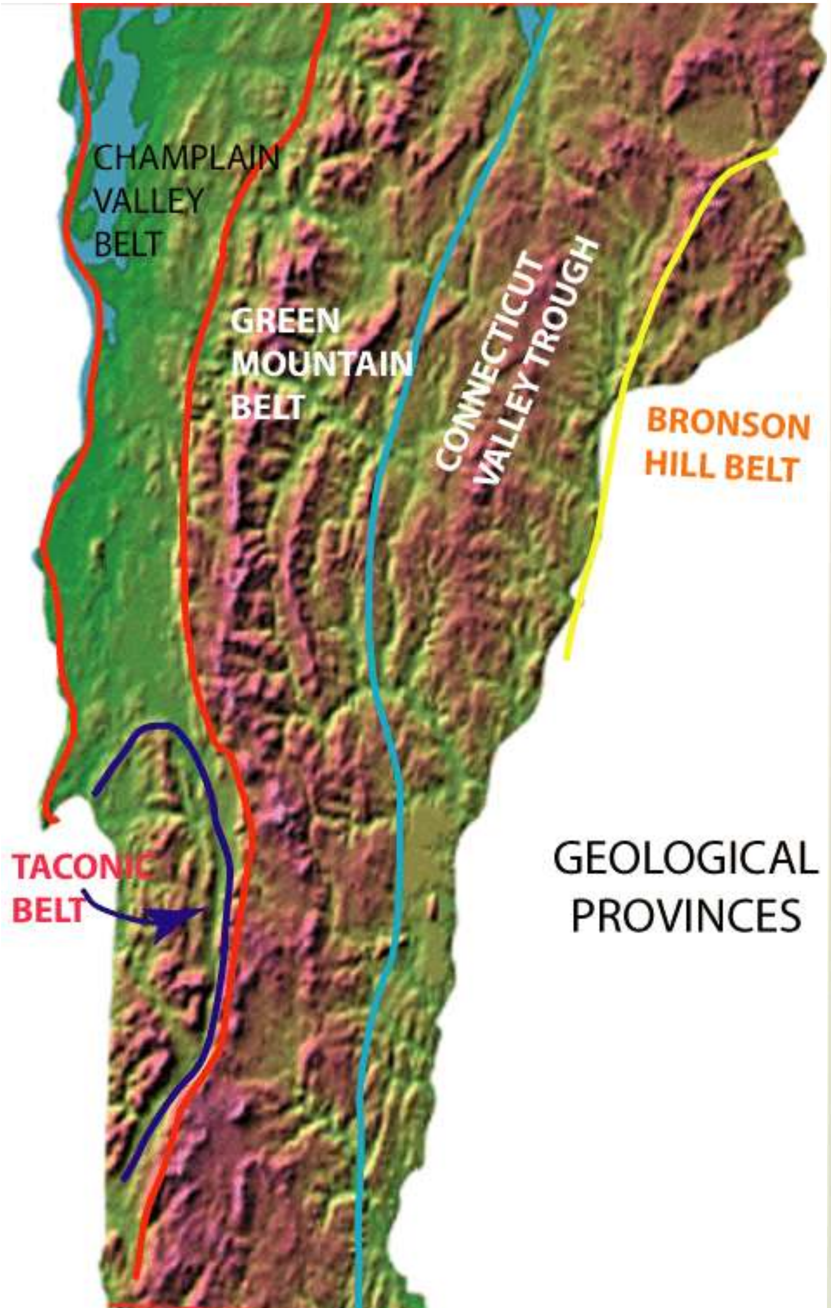
PRESENT DAY

<u>Principle of Uniformitarianism</u>

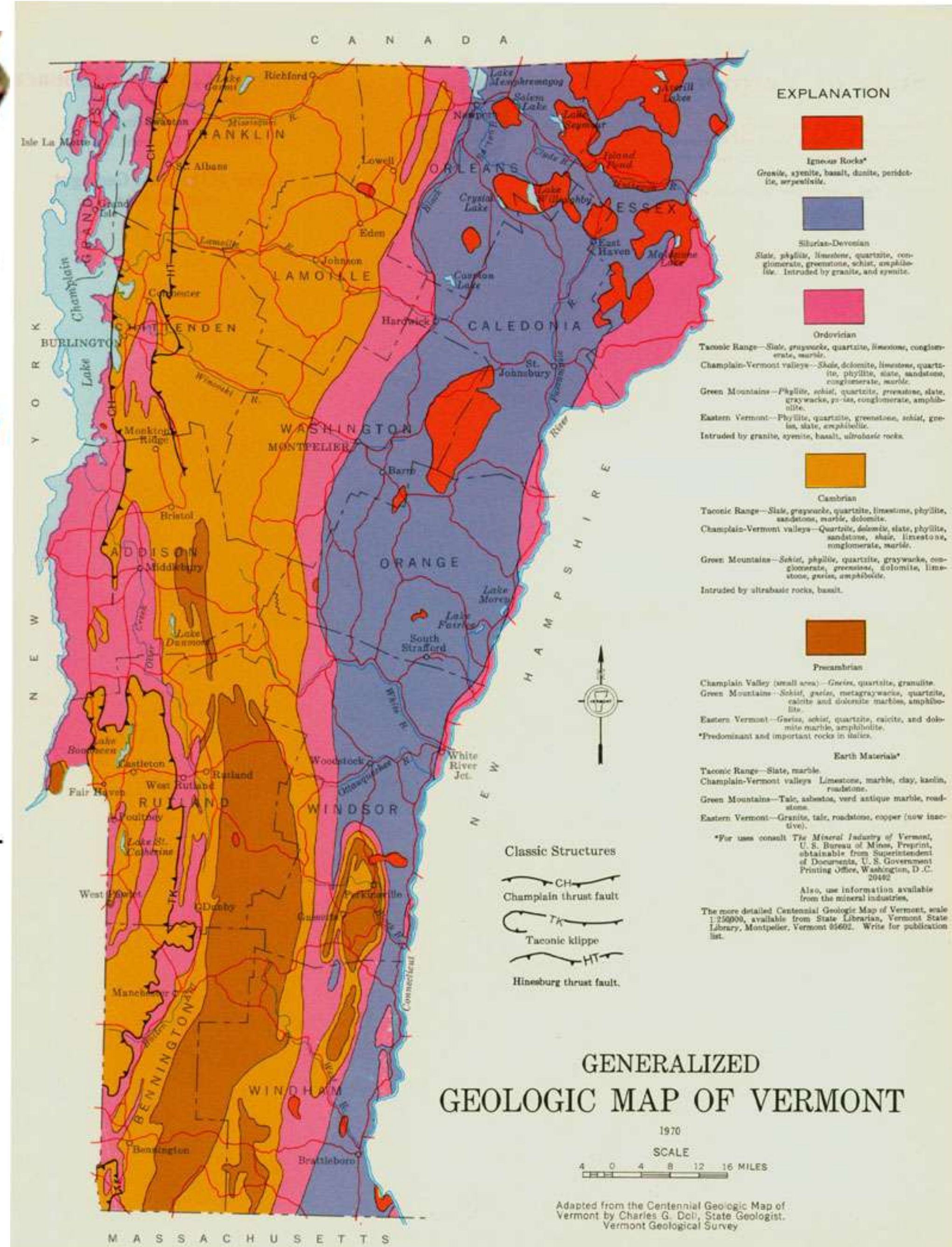
Laws of nature have always existed … so the study of rocks in modern tectonic environments enables reconstruction of past geological environments from the preserved rock record.

The present is the key to the past.





GEOLOGICAL PROVINCES



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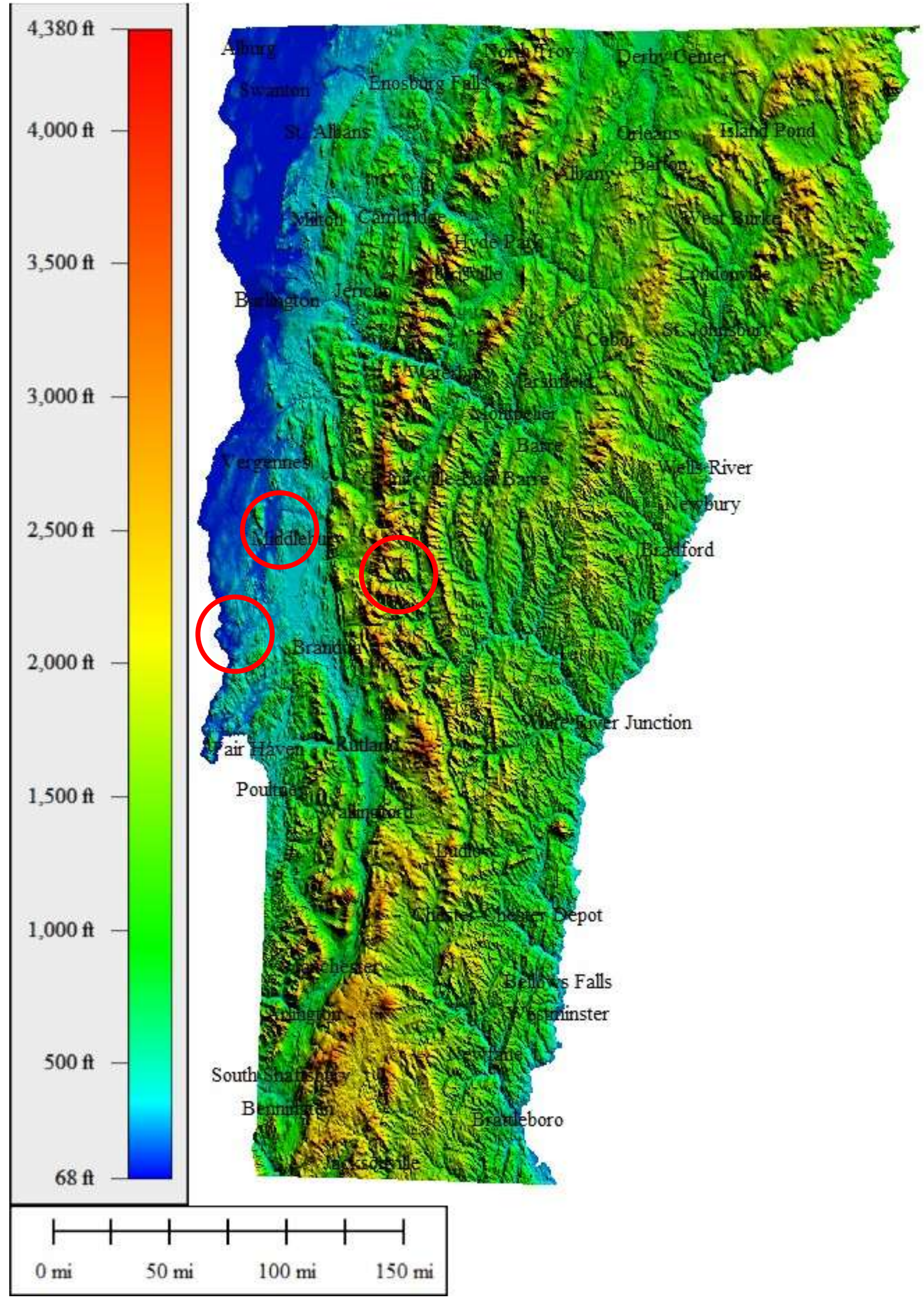
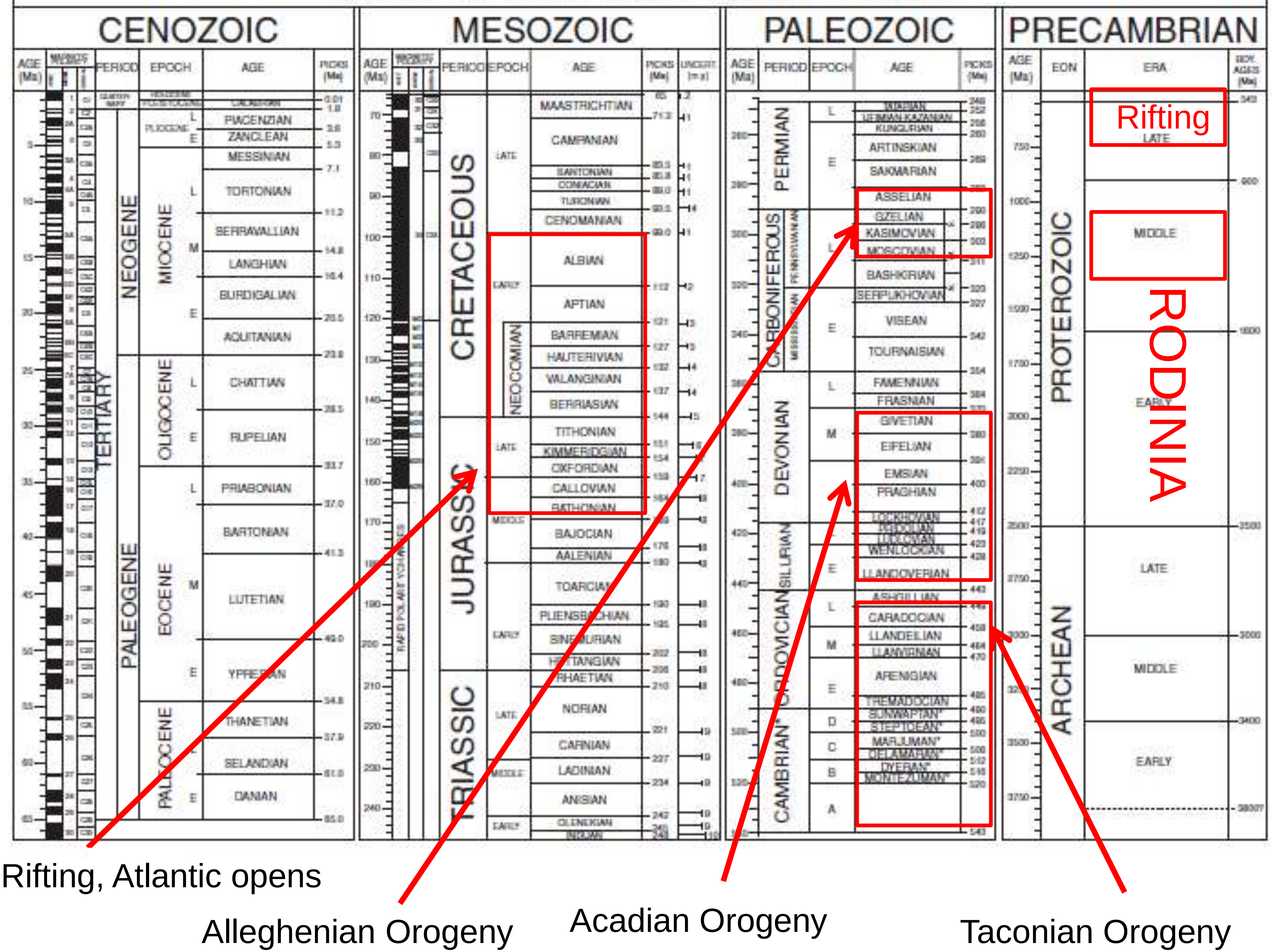
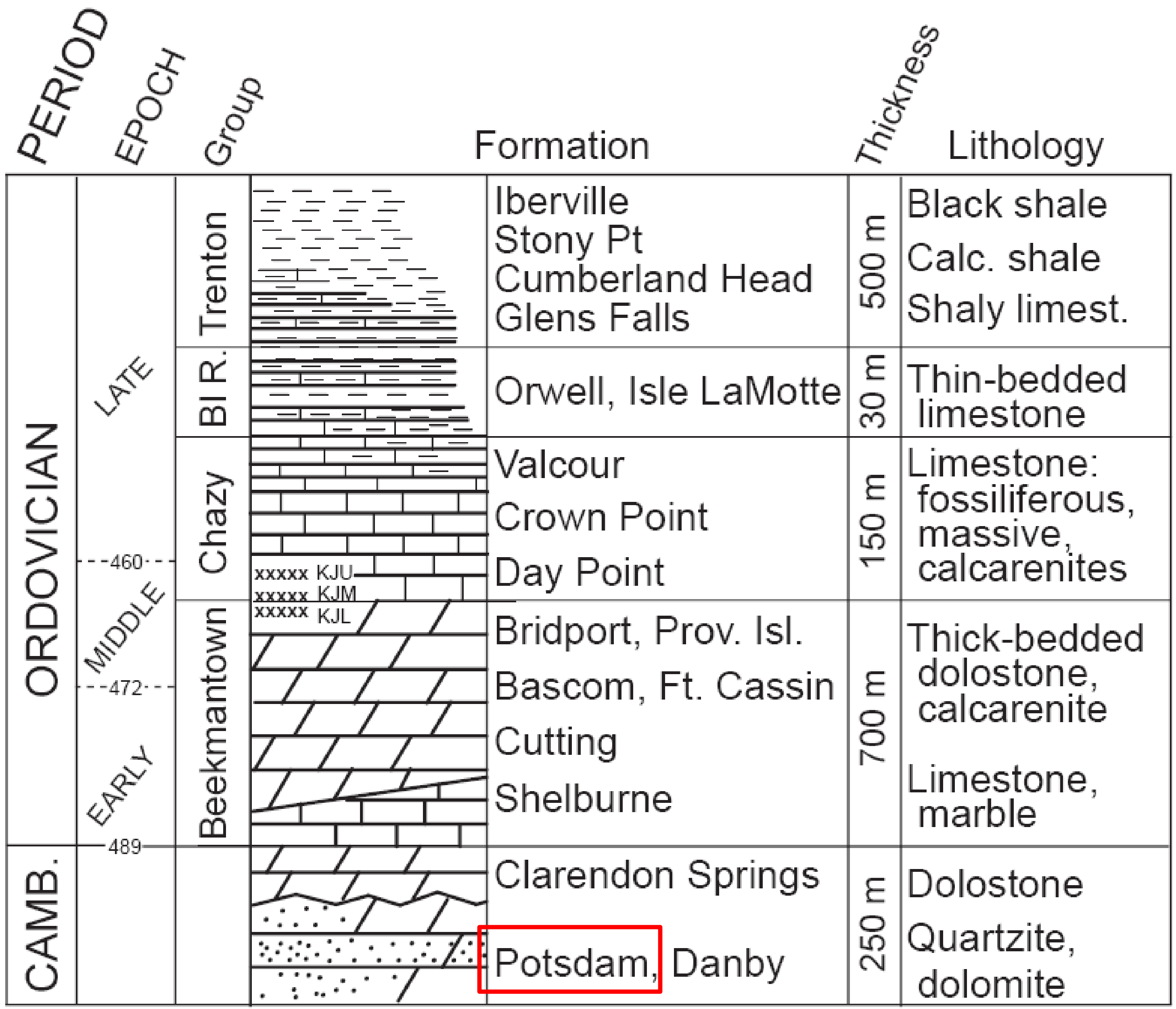


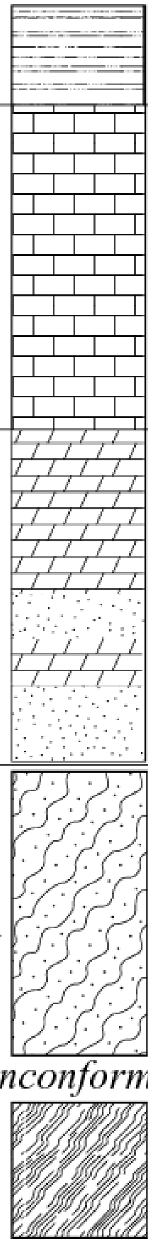


CENOZOIC
MESOZOIC
PALEOZOIC
PRECAMBRIAN
TERTIARY
NEOGENE
PALEOGENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC
NEOCOMIAN
PERMIAN
CARBONIFEROUS
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PROTEROZOIC
ARCHEAN
Rifting
RODINIA
Rifting, Atlantic opens
Alleghenian Orogeny
Acadian Orogeny
Taconian Orogeny

Central and western Champlain Valley

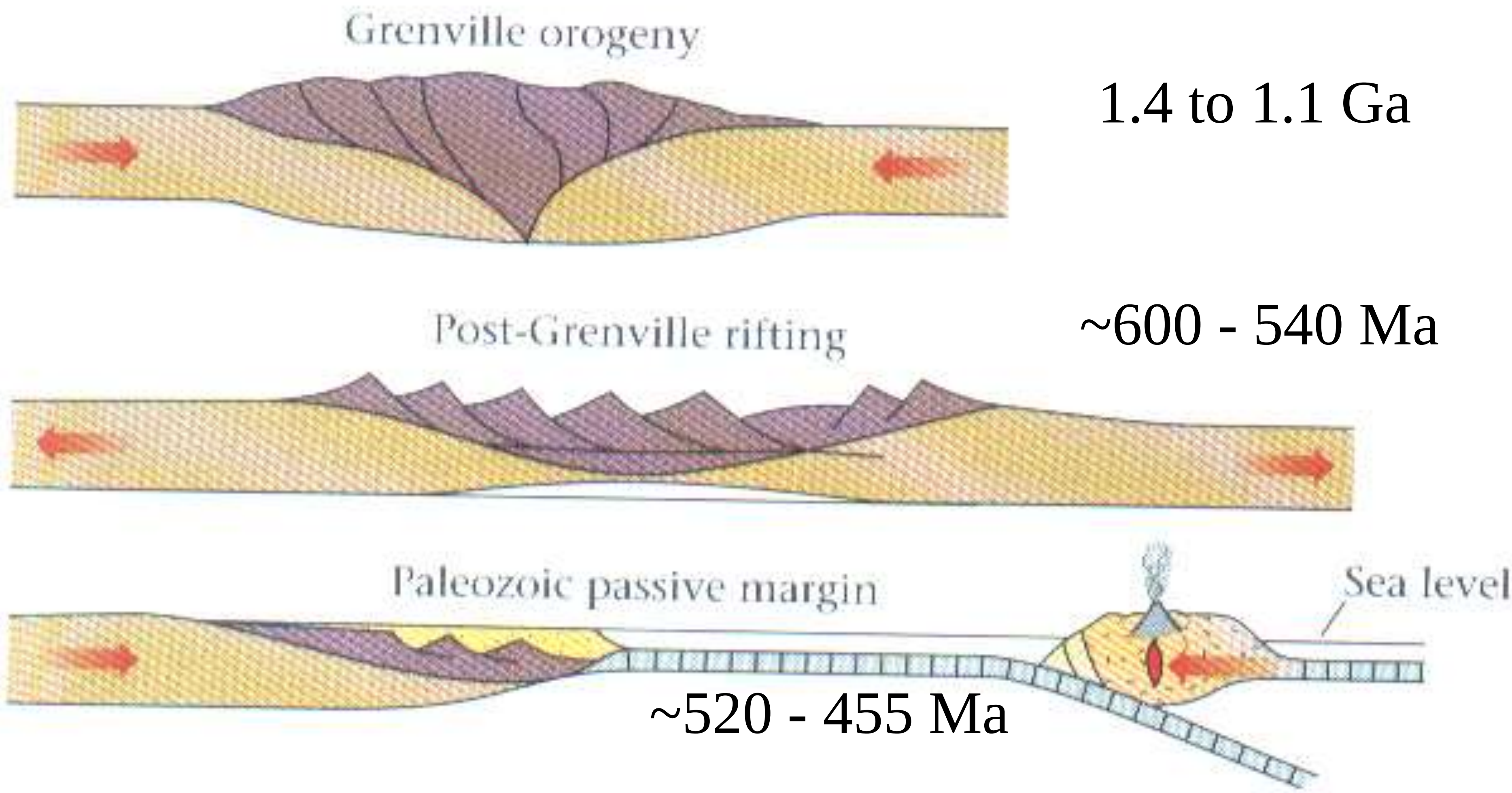


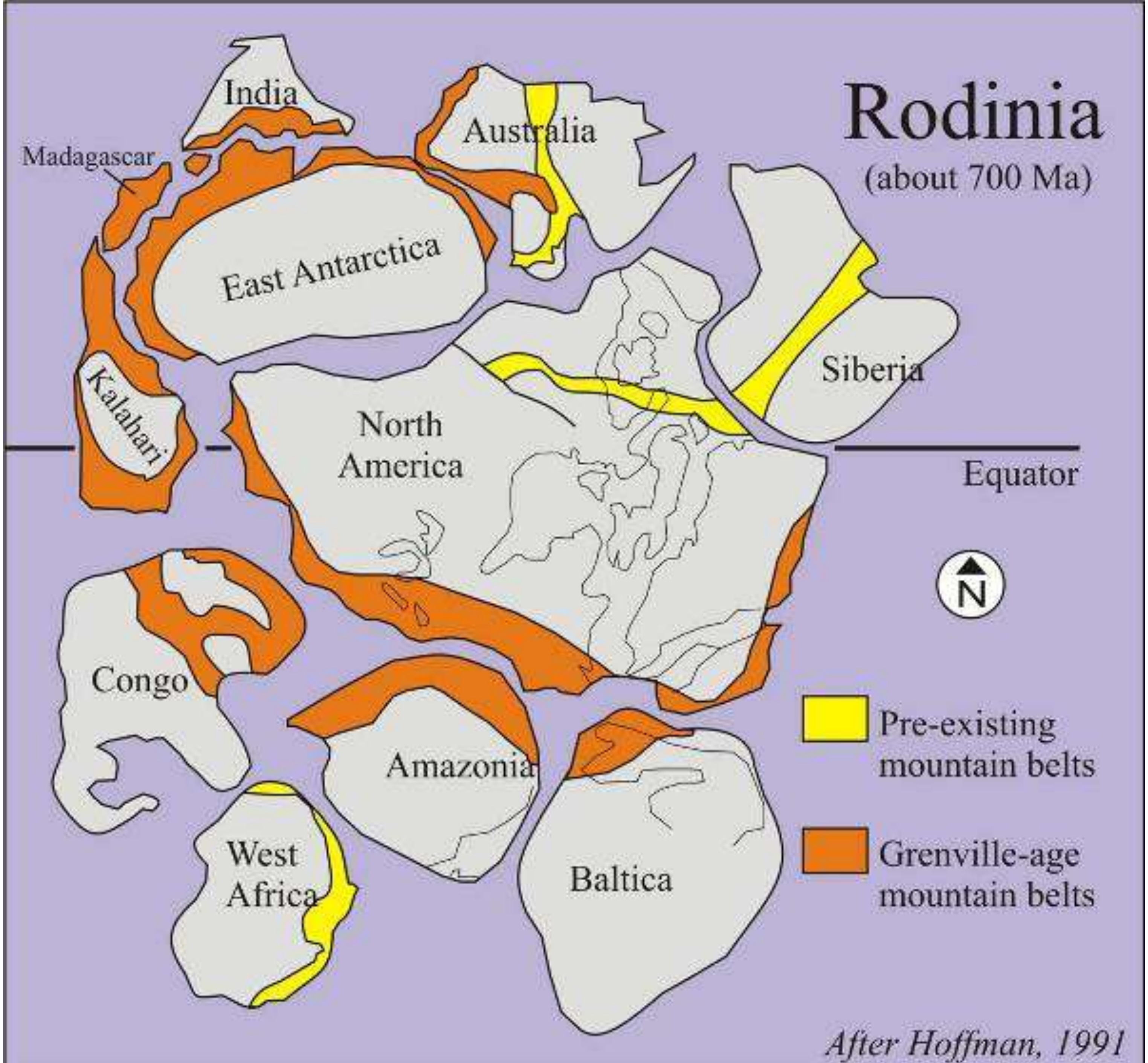
Green Mts, Flanks of Green Mts



Age	Formation Names	Rock Types	Tectonic Setting
Late Ordovician 455 Ma	* Iberville * Stony Point	Shales	Influx of Dirty Sediment from Approaching Arc
Early to Middle Ordovician 490 to 460 Ma	* Glens Falls * Orwell Middlebury * Chipman Bascom Cutting * Shelburne	Carbonate Rocks	Sequence of Very Stable, Passive Continental Margin Sediments (Carbonate Shelf)
Cambrian 540 to 490 million yrs.	Clarendon Springs Danby Winooski * Monkton Quartzite * Dunham * Cheshire Quartzite	Mixture of slightly metamorphosed sandstones & carbonates (dolostones)	Early Sequence of Stable, Passive Continental Margin Sediments
Late Precambrian to Early Cambrian 570 to 540 Ma	Underhill Hazens Notch * Pinney Hollow * Hoosac Pinnacle	Moderately deformed & weakly metamorphosed schists (meta-seds) and greenstones (meta-volc.)	Rodina Rifting & Early Iapetus Ocean Sedimentary and Volcanic Rocks
unconformity			
Precambrian 1.4 to 1.1 billion	Mt. Holly Complex * Grenville Basement Rocks	Intensely deformed & highly metamorphosed gneisses	Remnants of Rodina and the Grenville Orogeny

The Appalachians formed from the rifted remnants of an older mountain belt formed during the “Grenville Orogeny” (1.4 -1.1 Ga). The Grenville sequence formed within a super-continent called Rodinia.

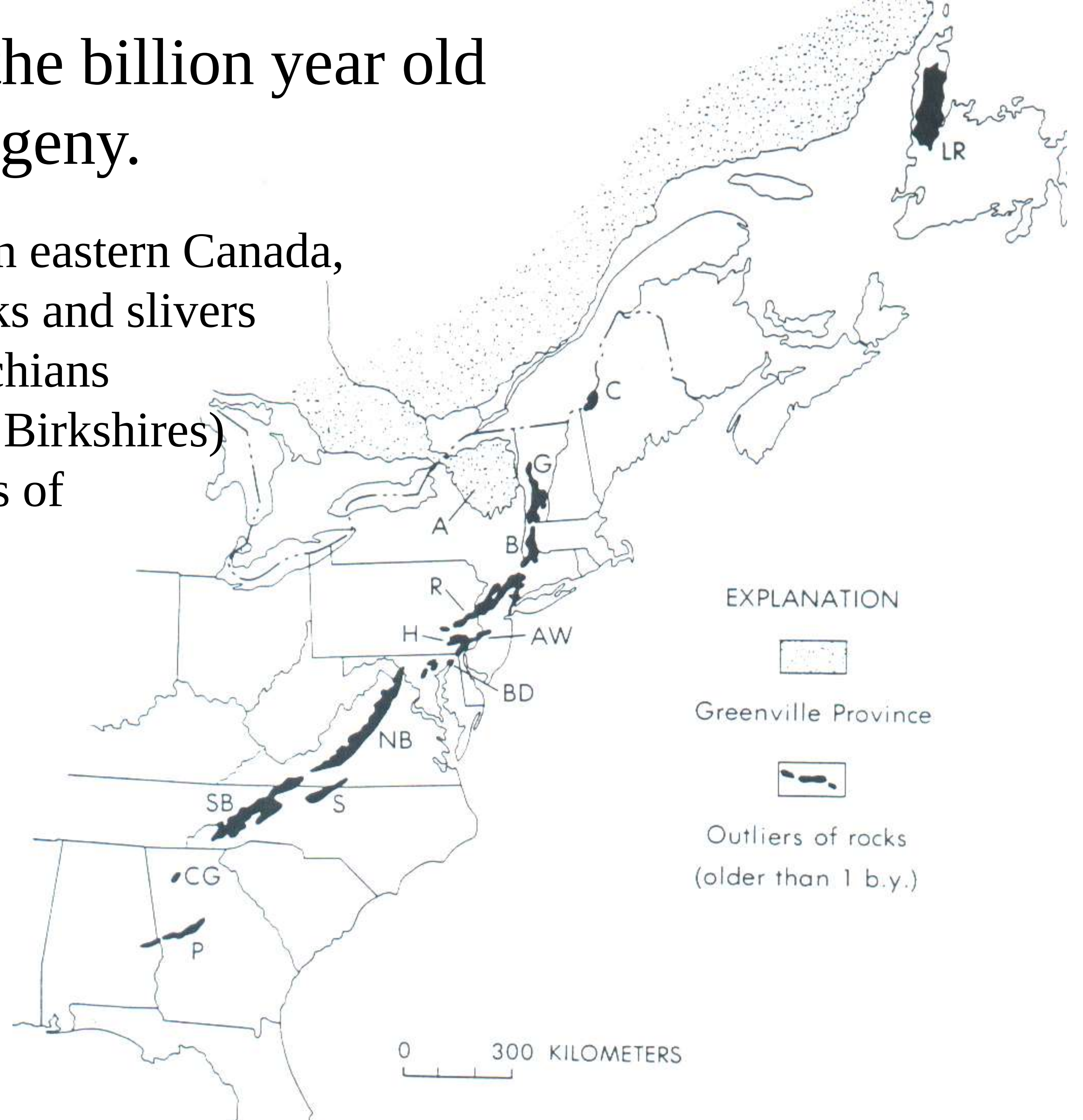




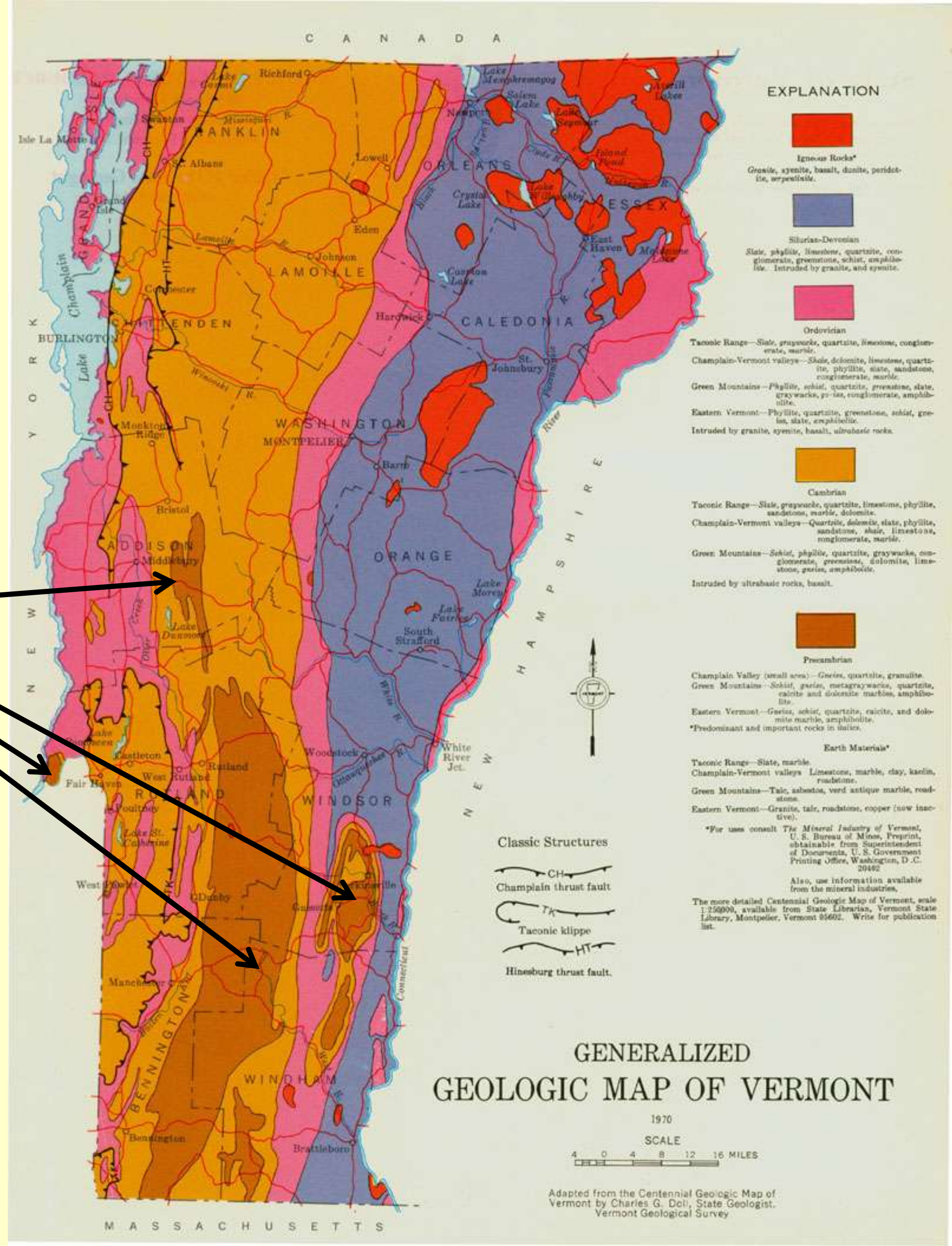
Rodinia
(about 700 Ma)
India
Australia
Madagascar
East Antarctica
Siberia
Kalahari
North America
Equator
Congo
Amazonia
West Africa
Baltica
Pre-existing mountain belts
Grenville-age mountain belts
N
After Hoffman, 1991

Remnants of the billion year old Grenville Orogeny.

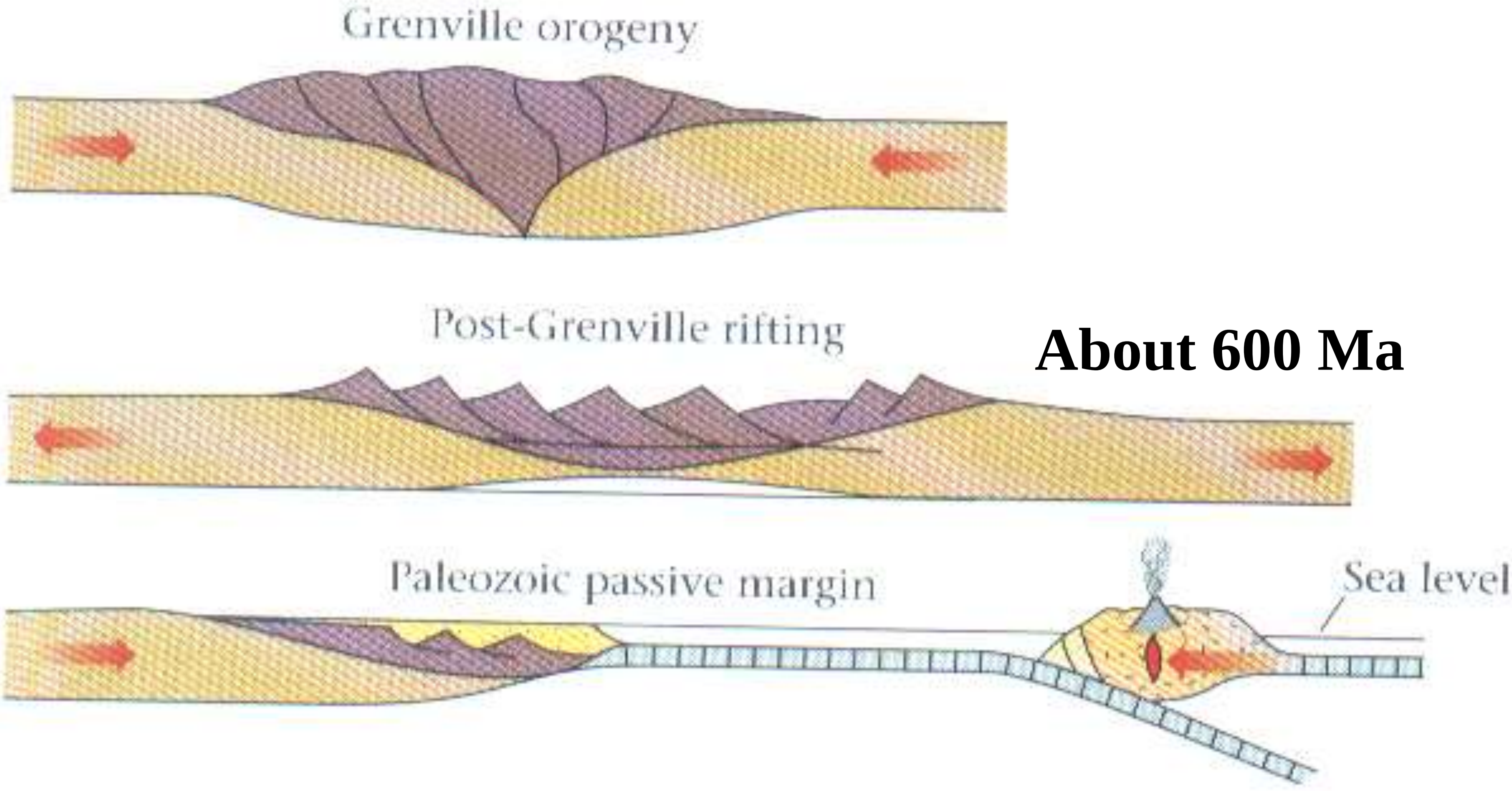
Most evidence is in eastern Canada, but the Adirondacks and slivers within the Appalachians (e.g., Green Mtns, Birkshires) also preserve rocks of this age.



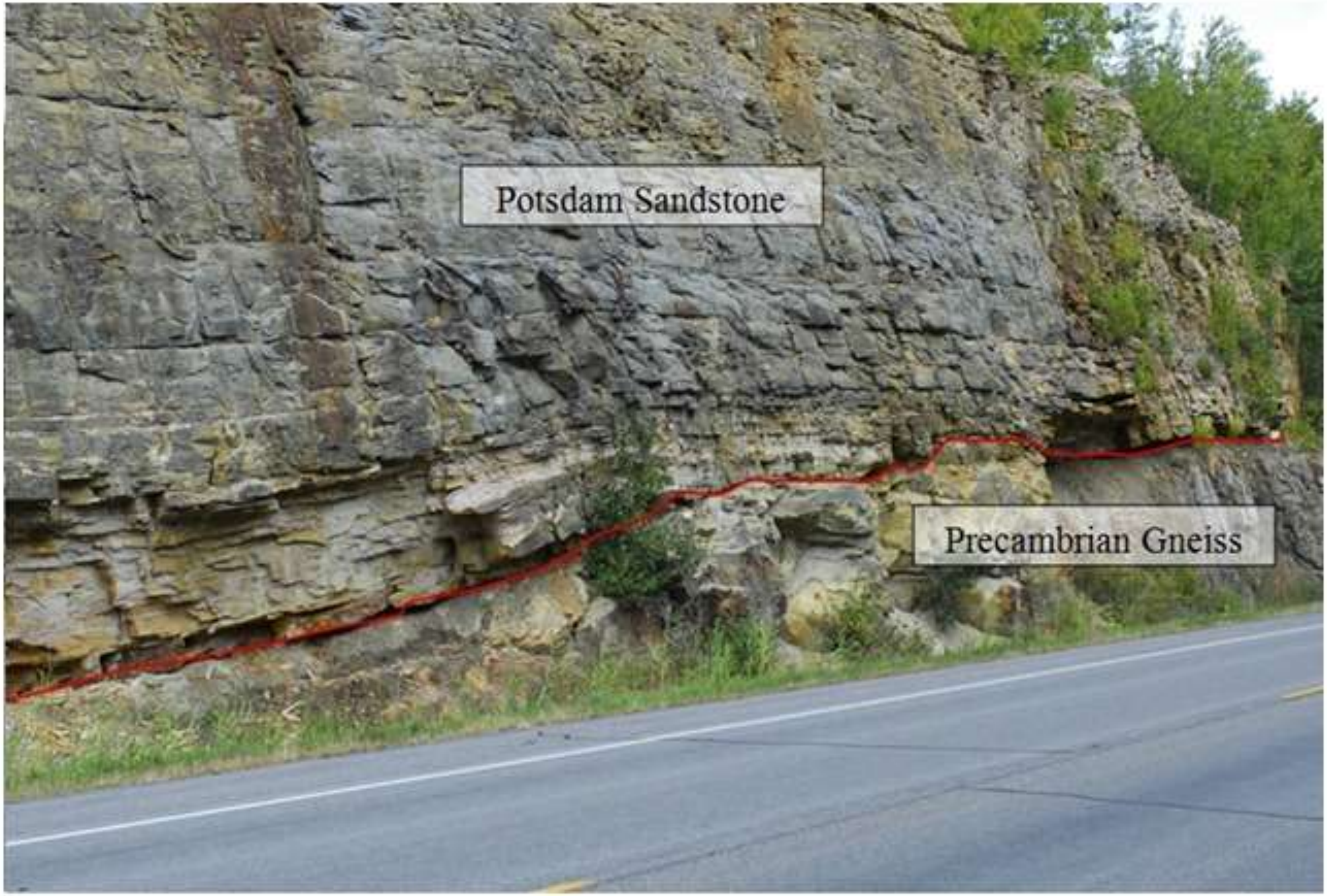
Precambrian Grenville-equivalent rocks in VT are light-brown.



Rodinia began to rift apart ~600 Ma …
sediments and volcanic rocks were deposited in
a narrow ocean basin between the two blocks, Laurentia
(paleo-N Am) and Baltica (paleo-NE Europe)

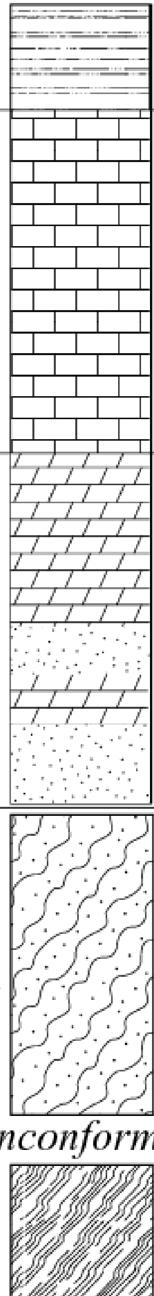


About 600 Ma


Potsdam Sandstone
Precambrian Gneiss

540
Ma

1100
Ma



Age	Formation Names	Rock Types	Tectonic Setting
Late Ordovician 455 Ma	* Iberville * Stony Point	Shales	Influx of Dirty Sediment from Approaching Arc
Early to Middle Ordovician 490 to 460 Ma	* Glens Falls * Orwell Middlebury * Chipman Bascom Cutting * Shelburne	Carbonate Rocks	Sequence of Very Stable, Passive Continental Margin Sediments (Carbonate Shelf)
Cambrian 540 to 490 million yrs.	Clarendon Springs Danby Winooski * Monkton Quartzite * Dunham * Cheshire Quartzite	Mixture of slightly metamorphosed sandstones & carbonates (dolostones)	Early Sequence of Stable, Passive Continental Margin Sediments
Late Precambrian to Early Cambrian 570 to 540 Ma	Underhill Hazens Notch * Pinney Hollow * Hoosac Pinnacle	Moderately deformed & weakly metamorphosed schists (meta-seds) and greenstones (meta-volc.)	Rodina Rifting & Early Iapetus Ocean Sedimentary and Volcanic Rocks
unconformity			
Precambrian 1.4 to 1.1 billion	Mt. Holly Complex * Grenville Basement Rocks	Intensely deformed & highly metamorphosed gneisses	Remnants of Rodina and the Grenville Orogeny

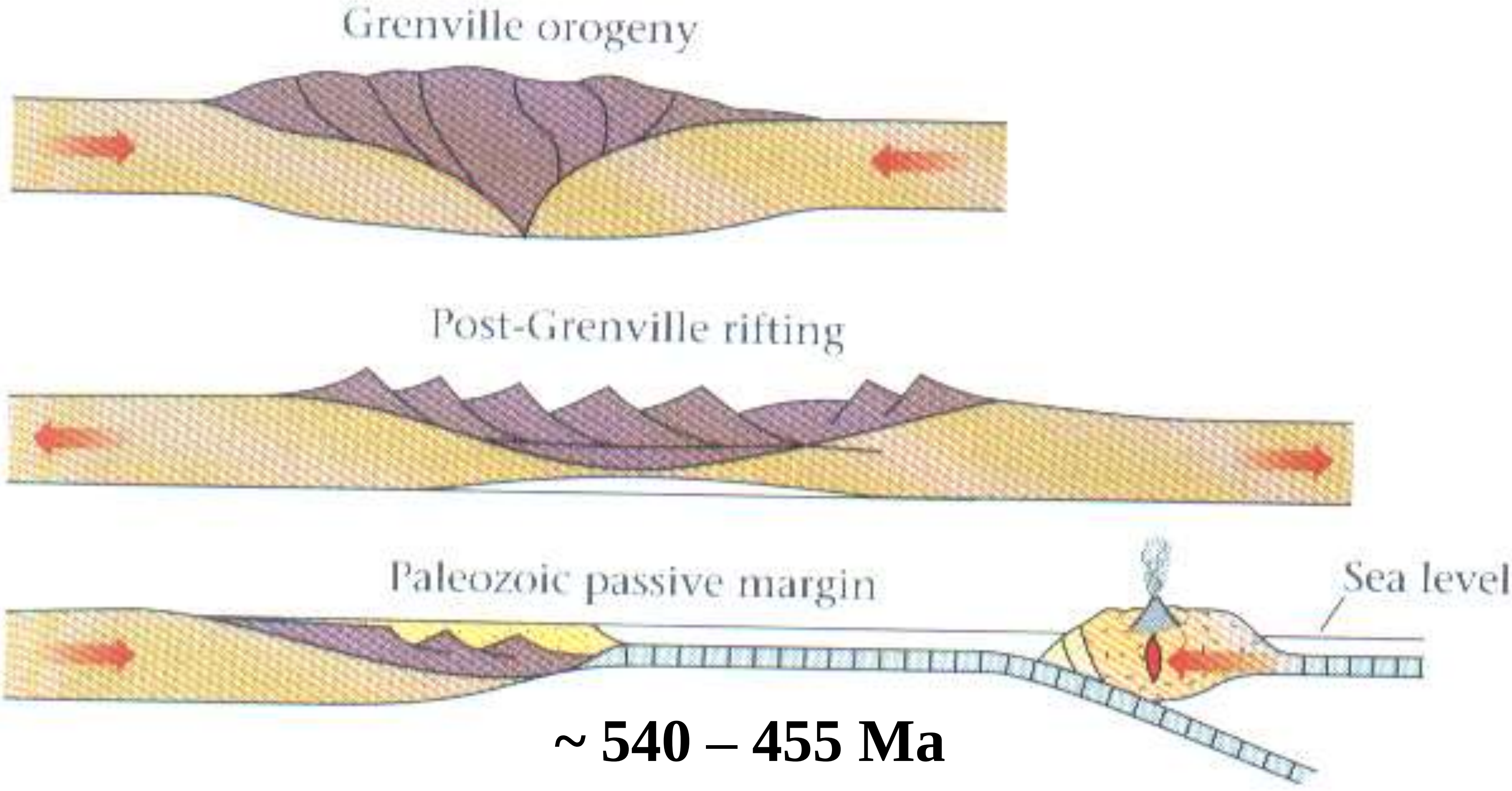
Monkton Formation – Passive Margin, Peritidal

The present is the key to interpreting the past

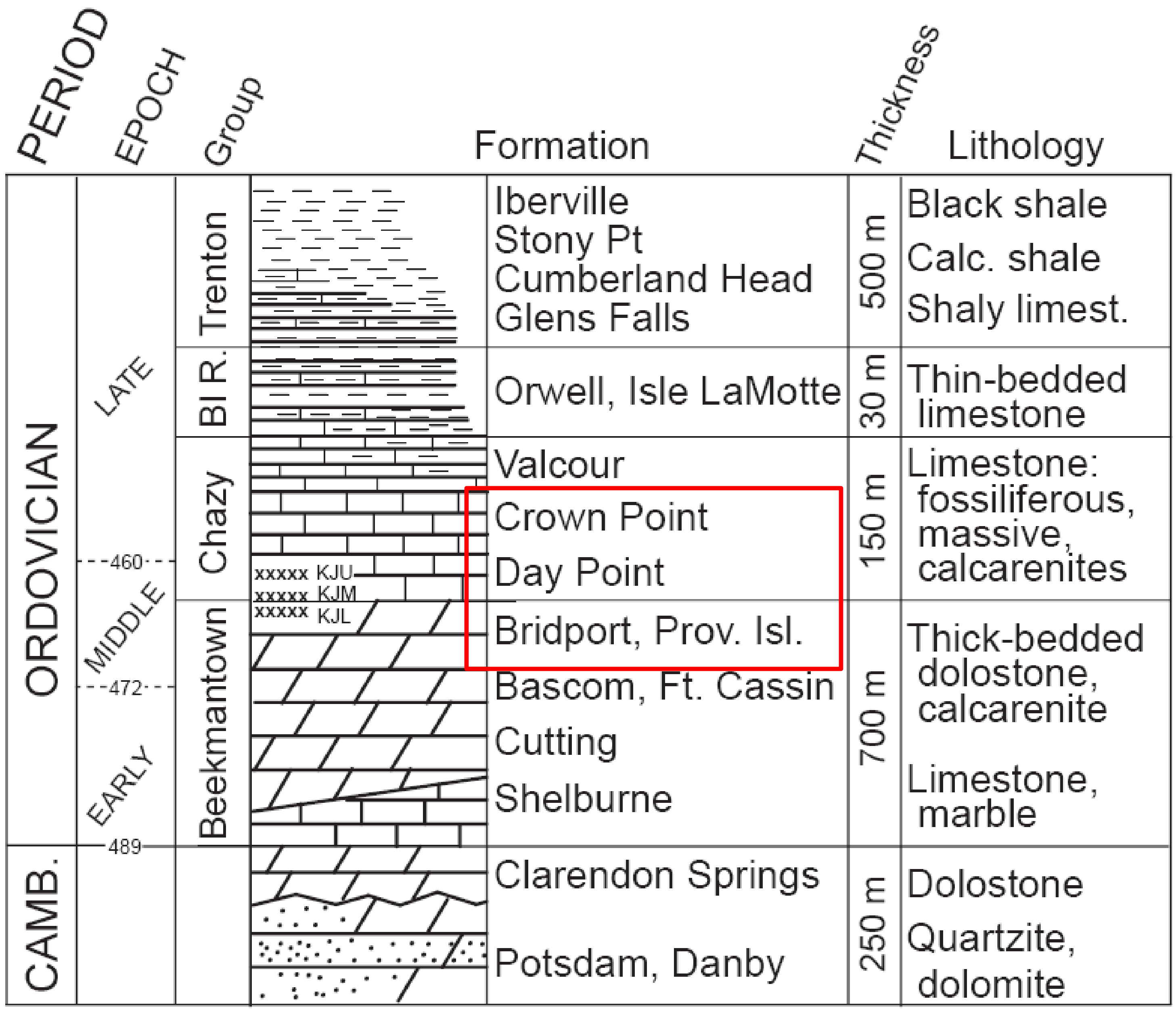
Modern Ripples (New Jersey)

Ancient Ripples (Pennsylvania)

This ocean basin is known as Iapetus, and by about 500 Ma it was quite wide (> 1000 km). The eastern margin of North America was parallel to the equator and at low latitudes. An extensive carbonate shelf (sandstones then limestones) like the Bahamas or Great Barrier Reef/N Australia existed.



~ 540 – 455 Ma


PERIOD
EPOCH
Group
Formation
Thickness
Lithology
ORDOVICIAN
CAMB.
LATE
MIDDLE
EARLY
460
472
489
Trenton
Bl R.
Chazy
Beekmantown
xxxxx KJU
xxxxx KJM
xxxxx KJL
Iberville
Stony Pt
Cumberland Head
Glens Falls
Orwell, Isle LaMotte
Valcour
Crown Point
Day Point
Bridport, Prov. Isl.
Bascom, Ft. Cassin
Cutting
Shelburne
Clarendon Springs
Potsdam, Danby
500 m
30 m
150 m
700 m
250 m
Black shale
Calc. shale
Shaly limest.
Thin-bedded limestone
Limestone: fossiliferous, massive, calcarenites
Thick-bedded dolostone, calcarenite
Limestone, marble
Dolostone
Quartzite, dolomite

Beekmantown Group

Shelf carbonates (subtidal to peritidal)

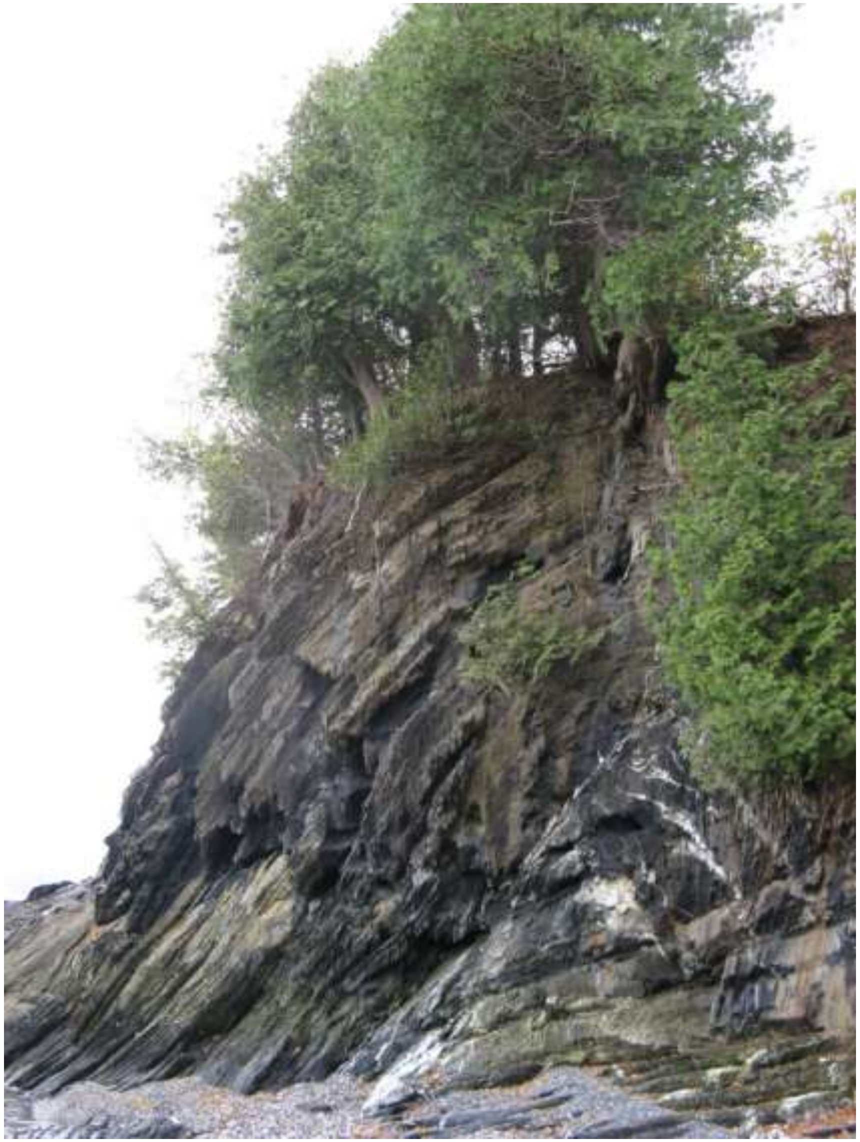
Chazy Group

Maclurites Magnus

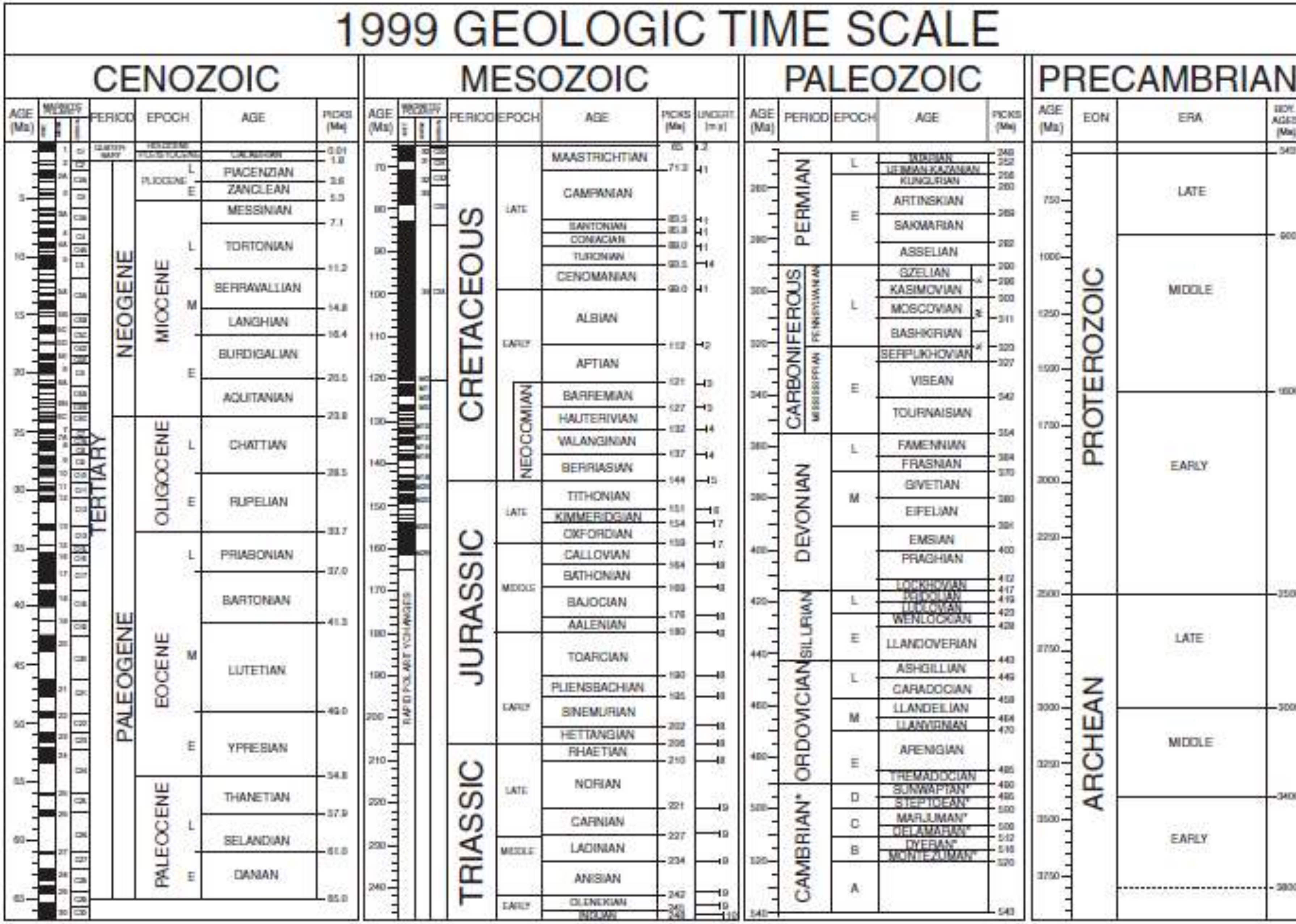
Cephalopods

Chazy Mound

Black River → Trenton groups (black shale, deep basin sedimentation)

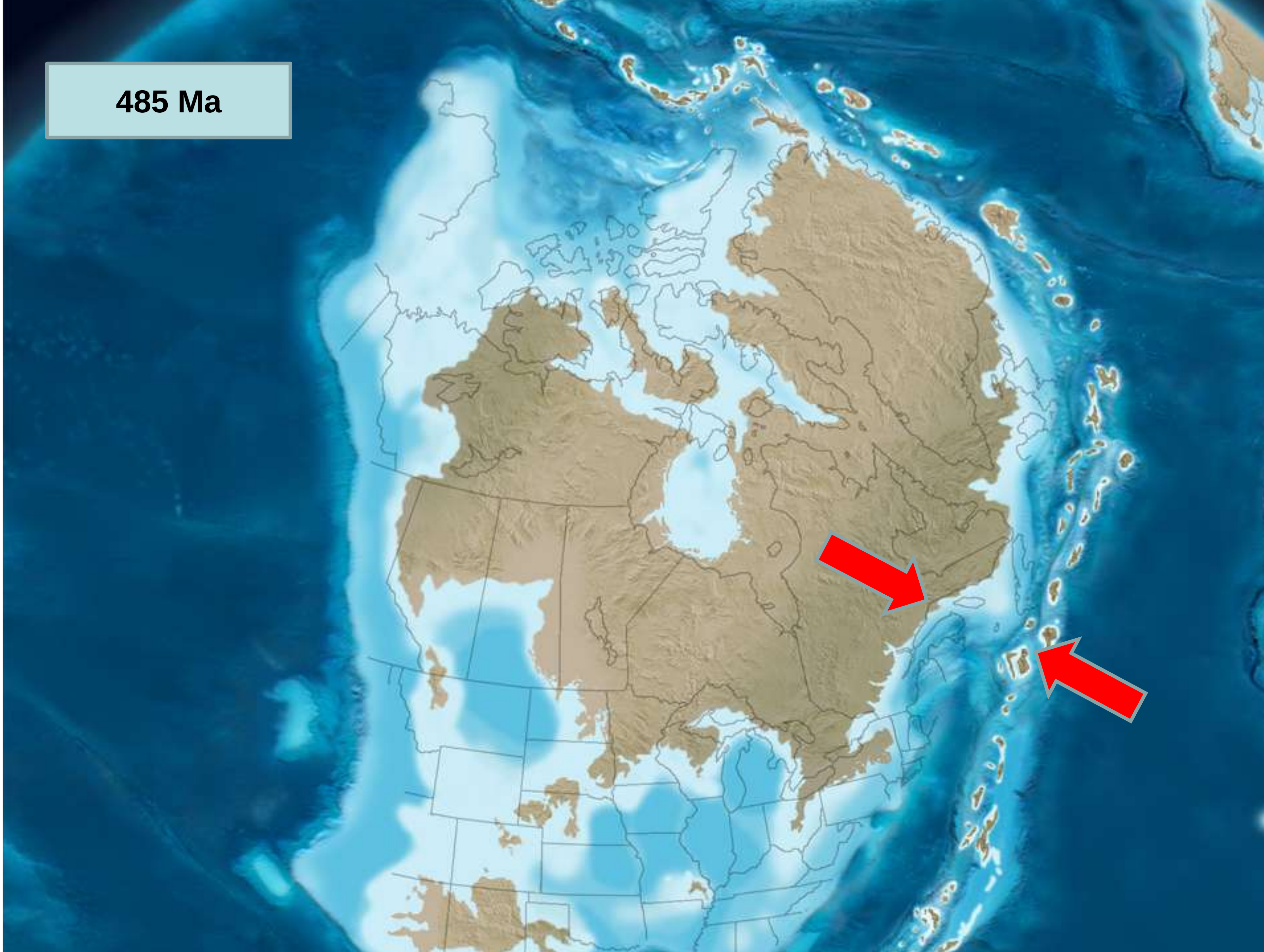


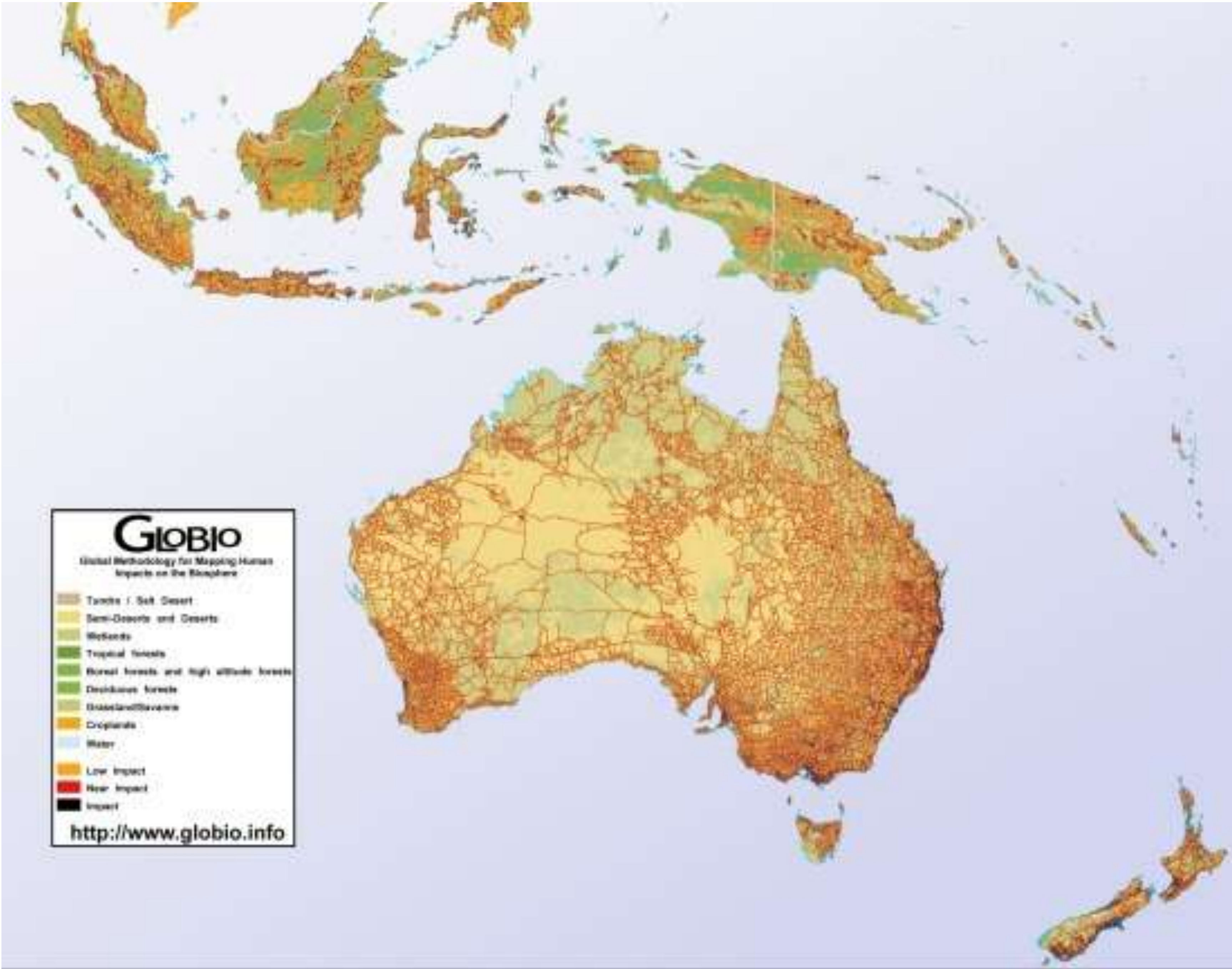
http://www.mcz.harvard.edu/Departments/InvertPaleo/Trenton/Intro/GeologyPage/Sedimentary%20Geology/BoonvilleNapanee7.gif


1999 GEOLOGIC TIME SCALE
CENOZOIC
AGE (Ma)
PERIOD
EPOCH
AGE
PICKS (Ma)
NEOGENE
PALEOGENE
TERTIARY
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
CALABRIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
SELANDIAN
DANIAN
0.01
1.8
3.6
5.3
7.1
11.2
14.8
16.4
20.5
23.8
28.5
33.7
37.0
41.3
49.0
54.8
57.9
61.0
65.0
MESOZOIC
UNCERT. (m.y.)
CRETACEOUS
JURASSIC
TRIASSIC
NEOCOMIAN
LATE
EARLY
MIDDLE
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
OLENEKIAN
INDUAN
RAPID POLARITY CHANGES
PALEOZOIC
PERMIAN
CARBONIFEROUS
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN*
TATARIAN
UFIMIAN-KAZANIAN
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSELIAN
GZELIAN
KASIMOVIAN
MOSCOVIAN
BASHKIRIAN
SERPUKHOVIAN
VISEAN
TOURNAISIAN
FAMENNIAN
FRASNIAN
GIVETIAN
EIFELIAN
EMSIAN
PRAGHIAN
LOCKHOVIAN
PRIDOLIAN
LUDLOVIAN
WENLOCKIAN
LLANDOVERIAN
ASHGILLIAN
CARADOCIAN
LLANDEILIAN
LLANVIRNIAN
ARENIGIAN
TREMADOCIAN
SUNWAPTAN*
STEPTOEAN*
MARJUMAN*
DELAMARAN*
DYERAN*
MONTEZUMAN*
PRECAMBRIAN
EON
ERA
BDY. AGES (Ma)
PROTEROZOIC
ARCHEAN
LATE
MIDDLE
EARLY
543
900
1600
2500
3000
3400
3800?

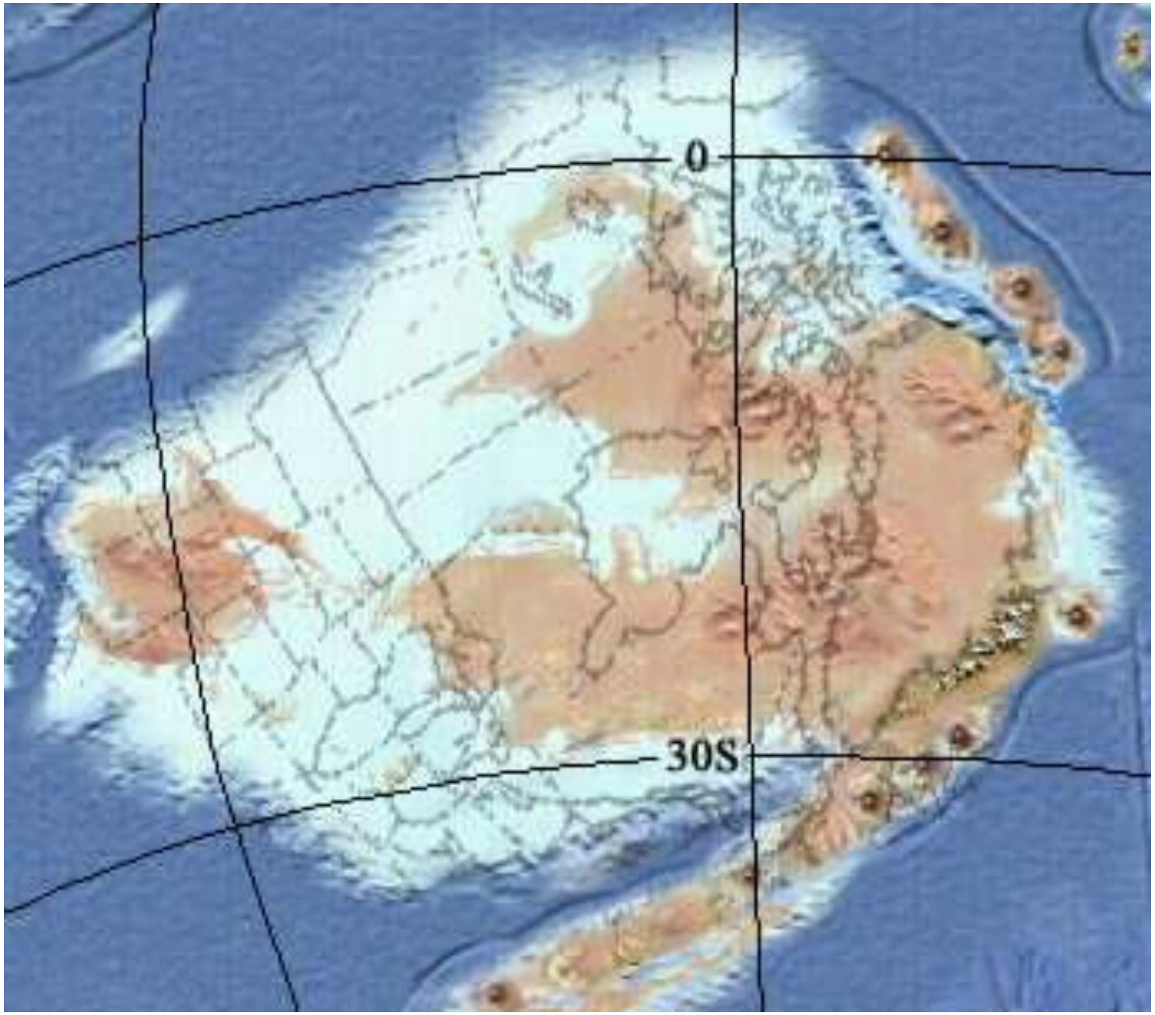

550 Ma
N

485 Ma

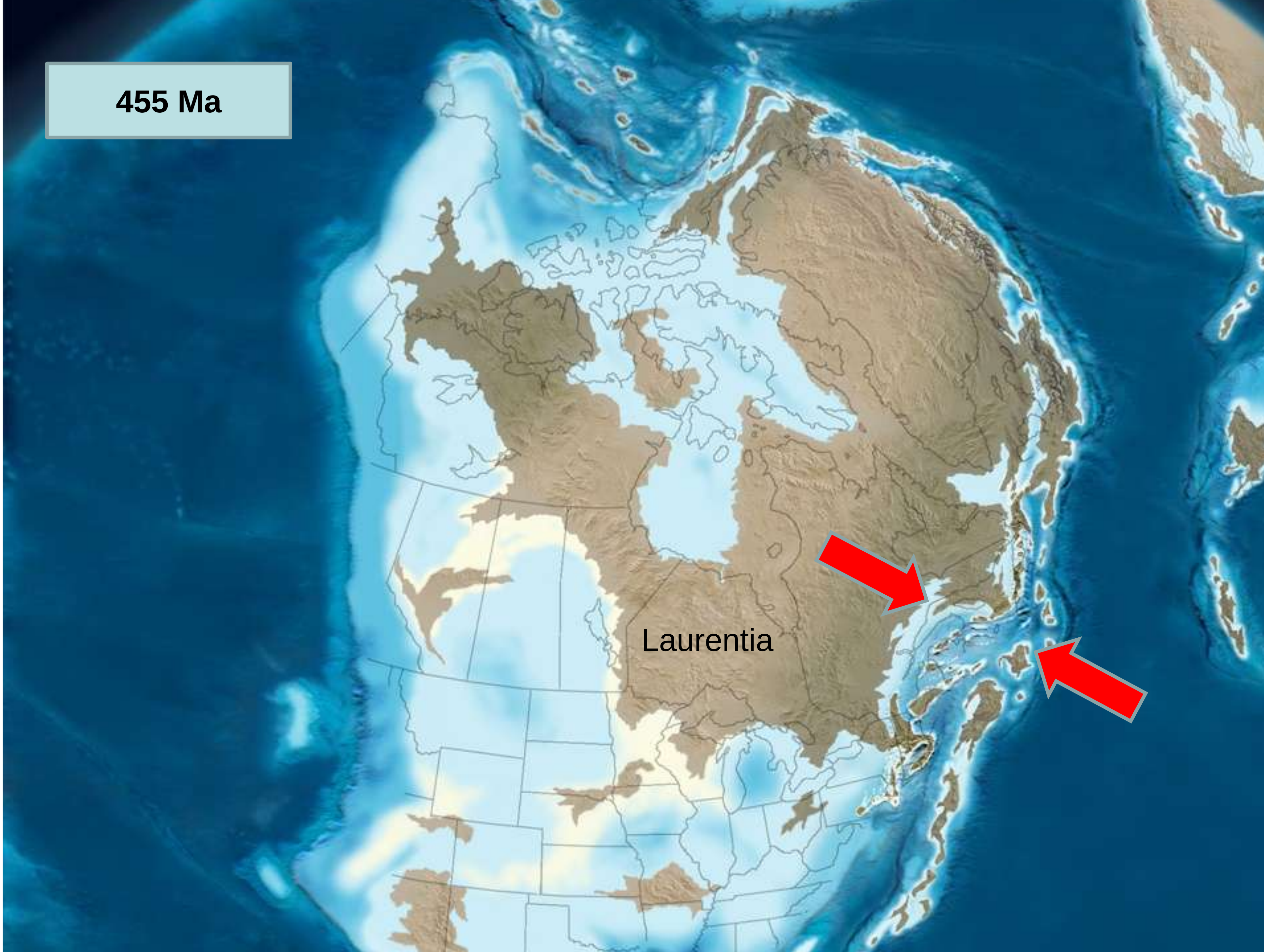



GLOBIO
Semi-Deserts and Deserts
Tropical forests
Deciduous forests
Croplands
Water
Low Impact
Impact
http://www.globio.info

Middle Ordovician Paleogeography (470 Ma)



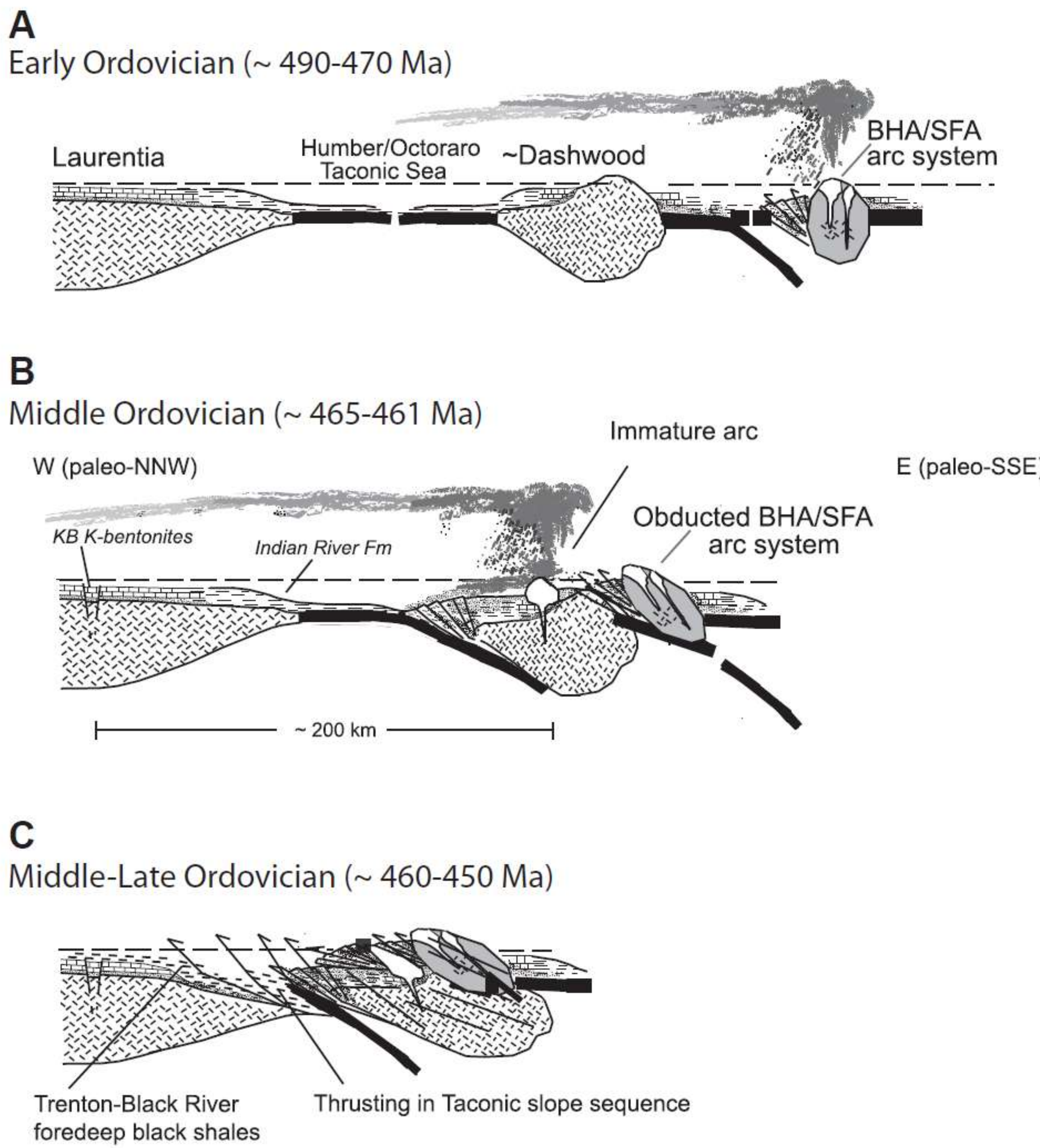
http://www.mcz.harvard.edu/Departments/InvertPaleo/Trenton/Intro/GeologyPage/Geologic%20Setting/paleoenvironmental.htm

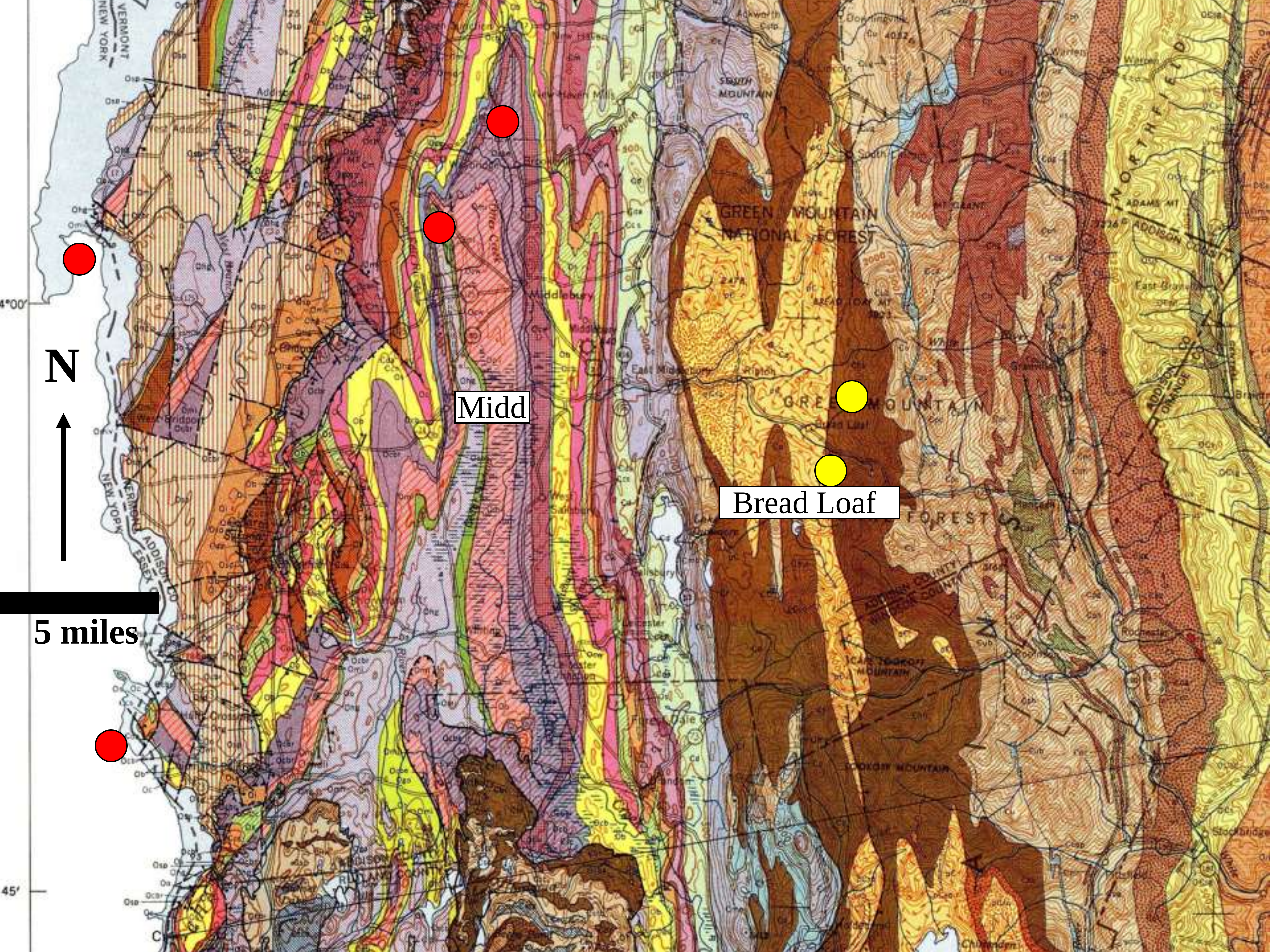

455 Ma
Laurentia

Beekmantown-Chazy Contact

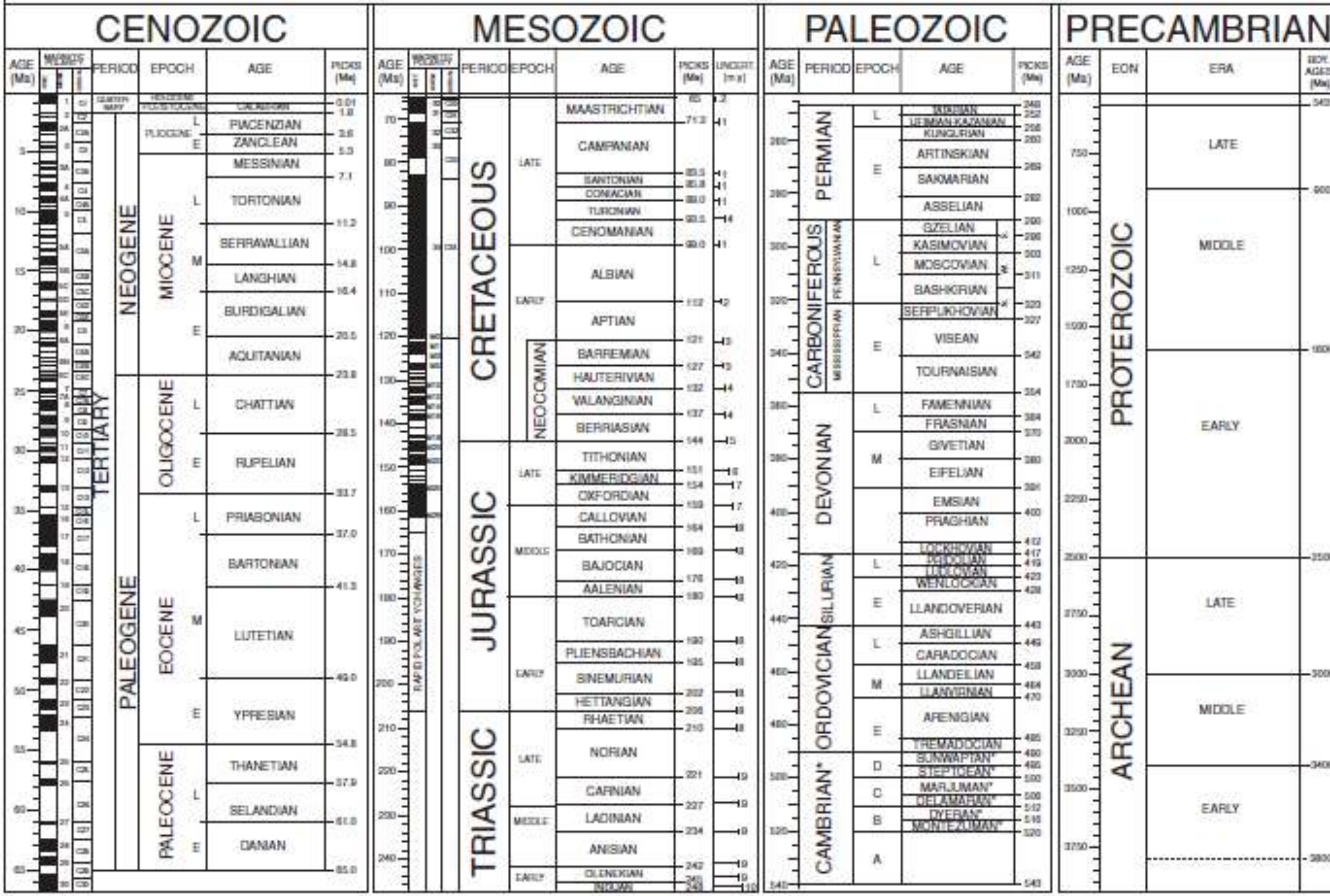
463 Ma

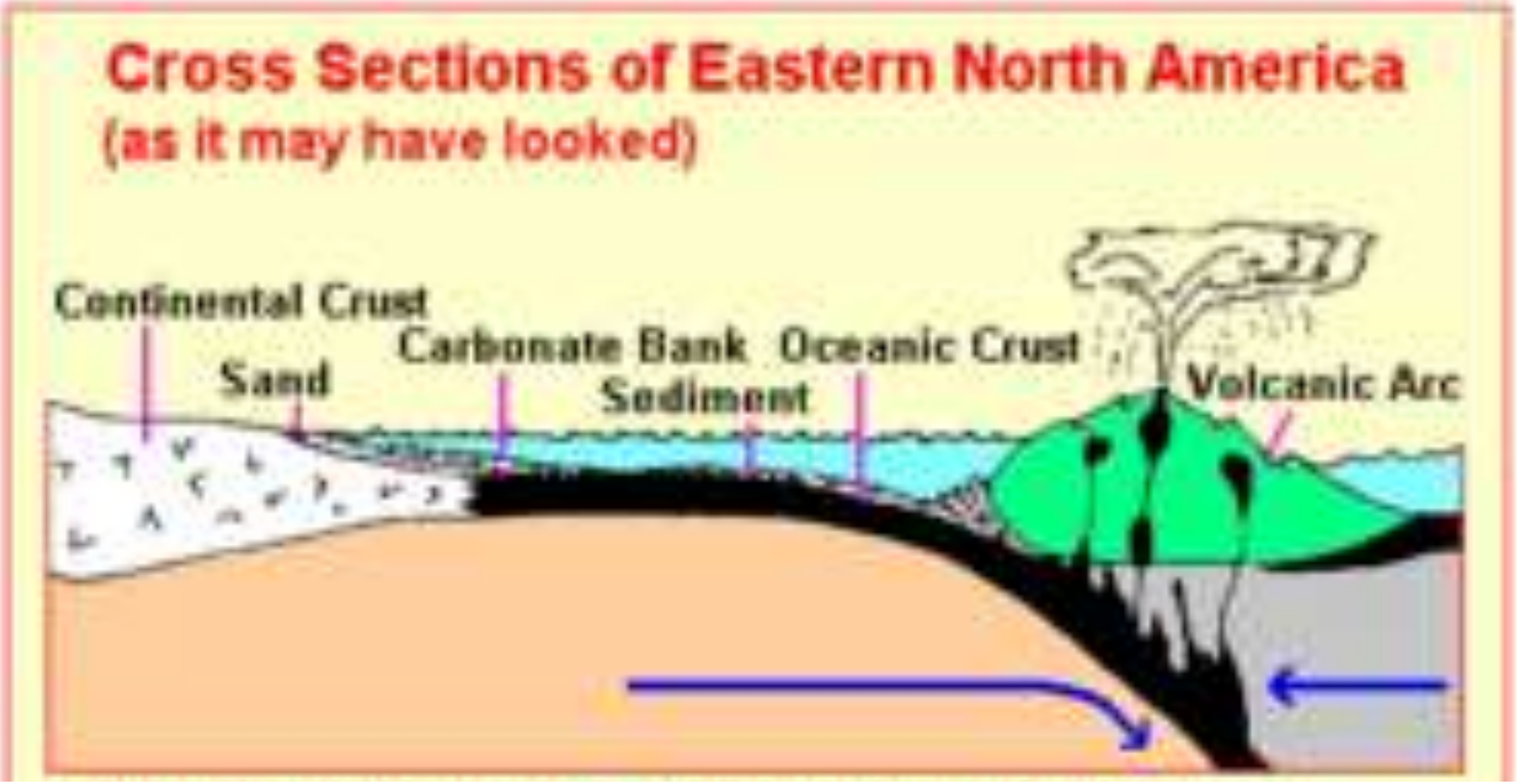
Beekmantown-Chazy Contact


A
Early Ordovician (~ 490-470 Ma)
Laurentia
Humber/Octoraro
Taconic Sea
~Dashwood
BHA/SFA
arc system
B
Middle Ordovician (~ 465-461 Ma)
Immature arc
W (paleo-NNW)
E (paleo-SSE)
Obducted BHA/SFA
arc system
KB K-bentonites
Indian River Fm
~ 200 km
C
Middle-Late Ordovician (~ 460-450 Ma)
Trenton-Black River
foredeep black shales
Thrusting in Taconic slope sequence

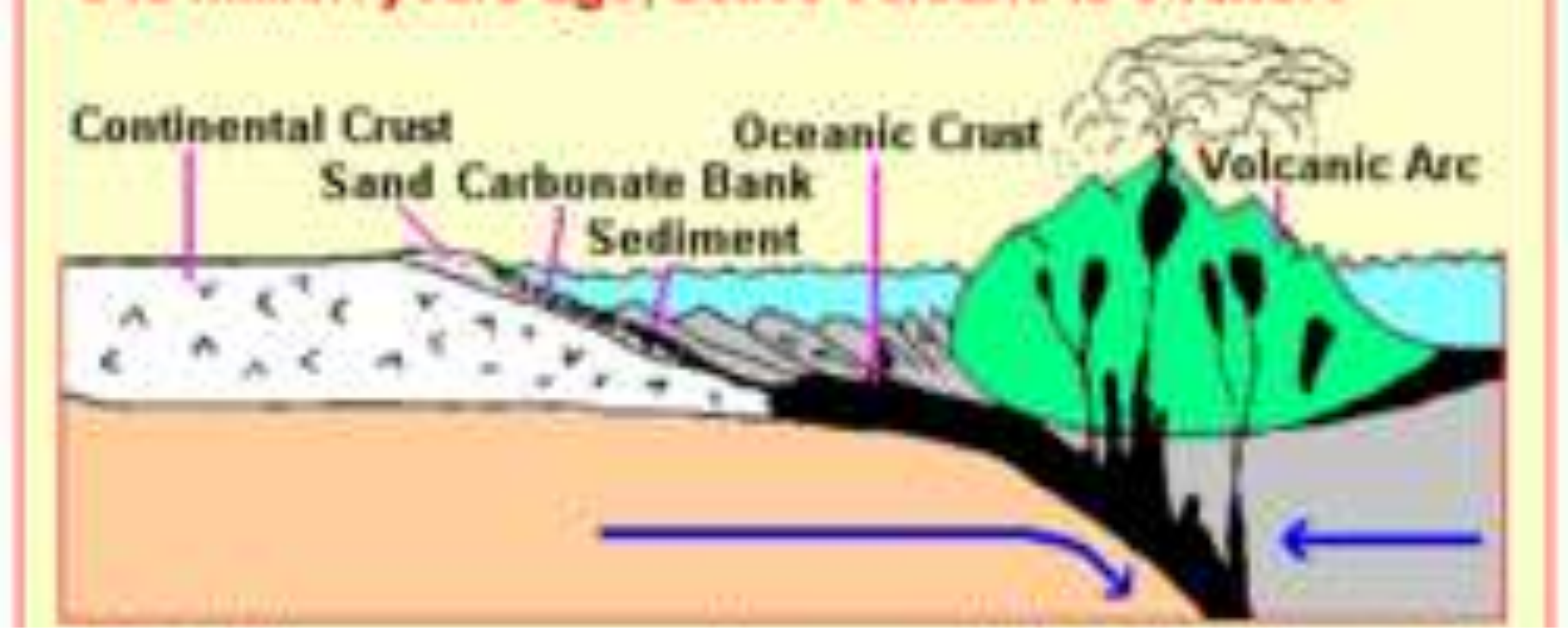

N
5 miles
Midd
Bread Loaf
GREEN MOUNTAIN
NATIONAL FOREST
VERMONT
NEW YORK
SOUTH MOUNTAIN
NORTHFIELD
ADAMS MT
ROCHESTER
STOCKBRIDGE
ADDISON COUNTY
WINDSOR COUNTY

1999 GEOLOGIC TIME SCALE



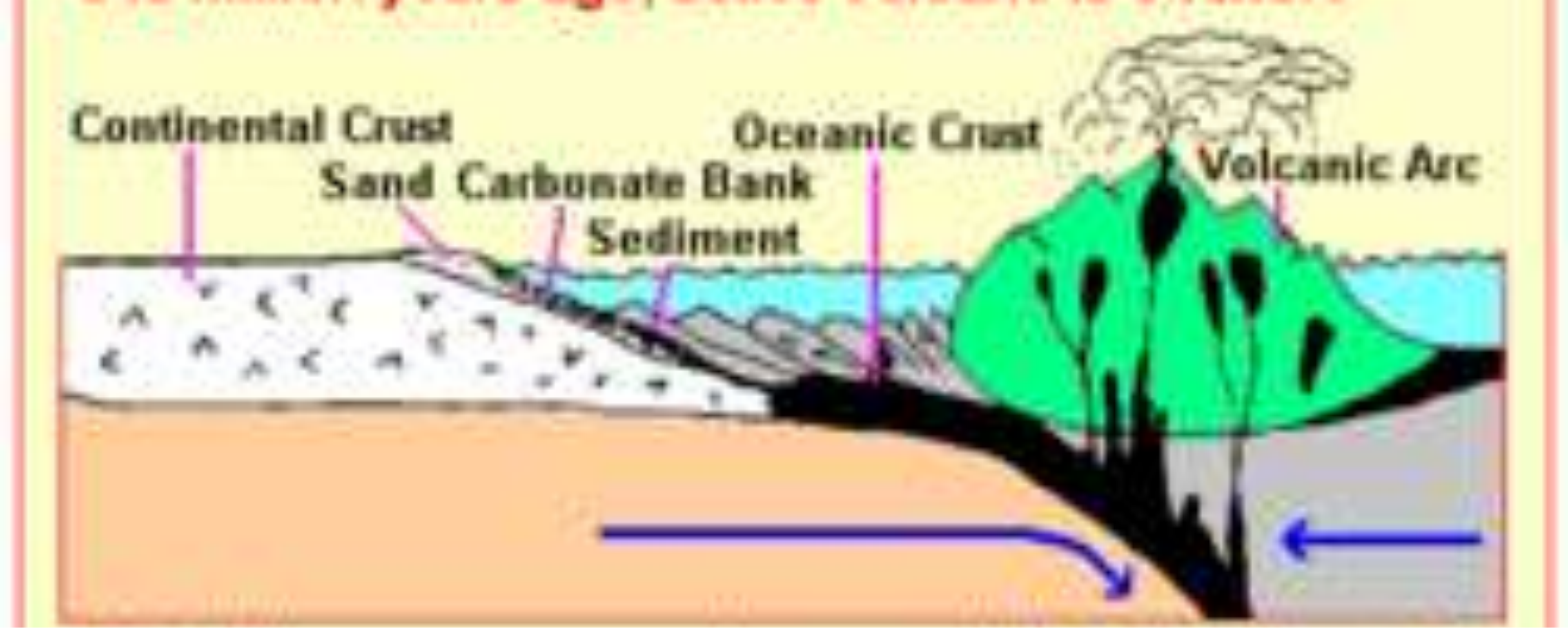


~ 475 Ma … Middlebury area = a warm shallow marine environment, much like the present day Bahamas. Offshore, an encroaching volcanic arc would eventually collide (~ 460 Ma).



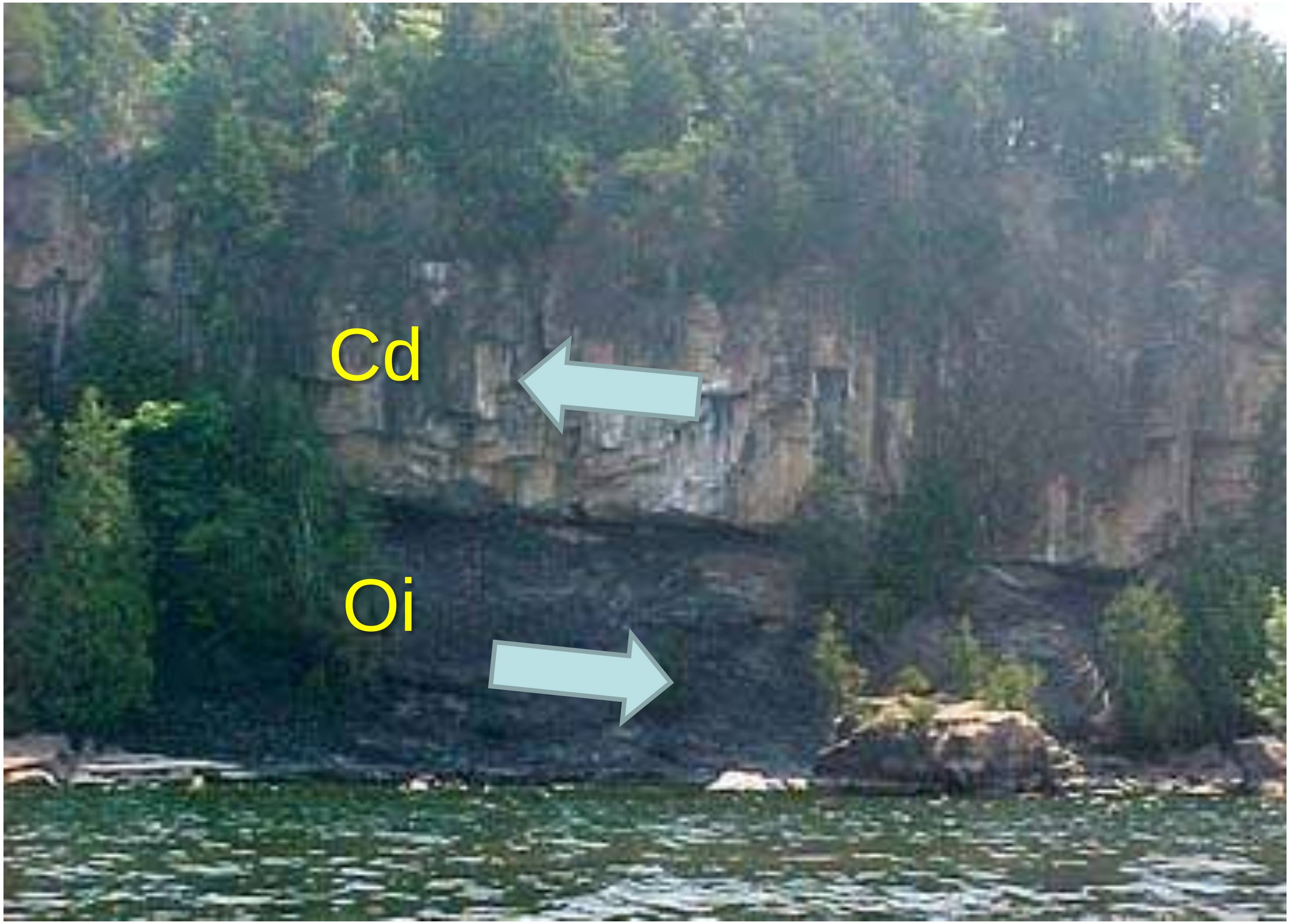
~460-450 Ma. Deposition and deformation of accretionary wedge.
Slivers of ocean crust and mantle often get obducted and
Preserved in continental crust. In VT, these mantle rocks

(1) Indicate suture zone
(2) Are elevated in arsenic (serpentinite, talc-carbonate) and impact rural water supplies.



The collision of this volcanic arc with eastern North America is known as the **Taconic Orogeny**. This collision resulted in folding, faulting and metamorphism of the previously deposited rocks. The volcanic arc itself is preserved in eastern Vermont and western New Hampshire.

Champlain Thrust fault (formed ~455 Ma)



We will see evidence of tectonic deformation associated with the Taconian Orogeny at nearly every stop.


Anticline
Syncline

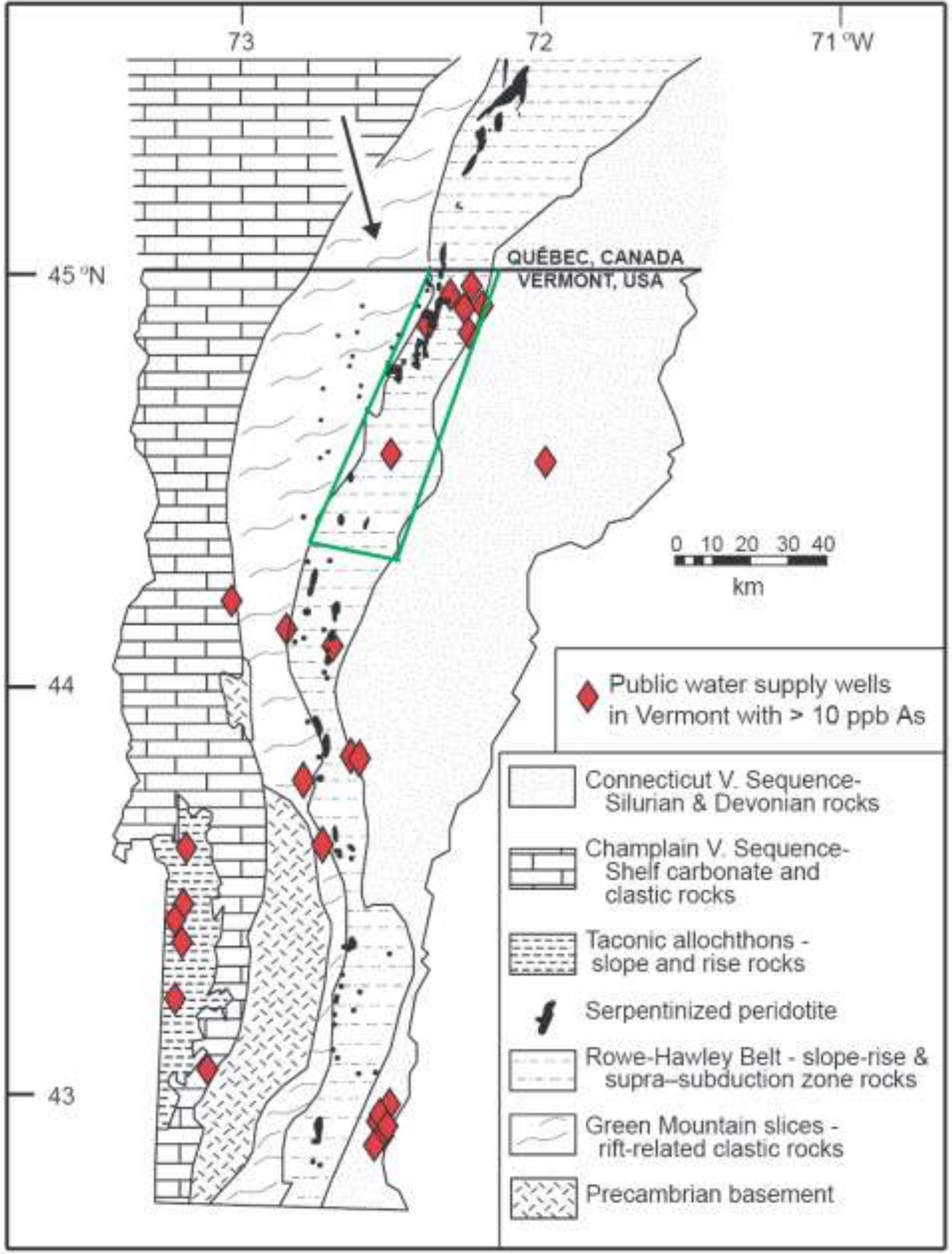
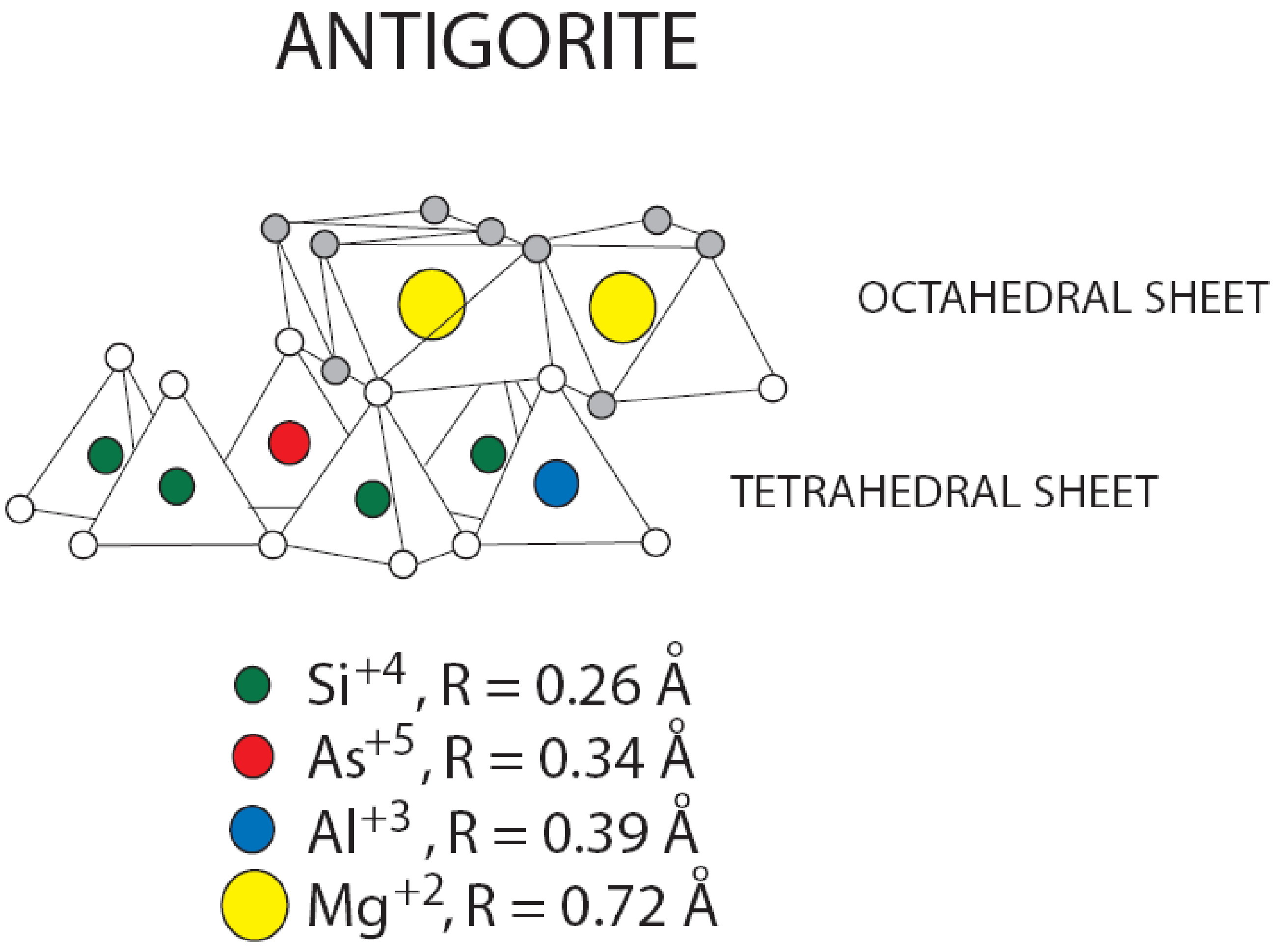


Fig. 1. Generalized geologic map of Vermont and adjacent southern Quēbec (after Doll et al., 1961; Shilts and Smith, 1981; Stanley and Ratcliffe, 1985; Van Baalen et al., 1999; Kim et al., 2003; Schroetter et al., 2006). Rock and water samples for this study were obtained from within the area outlined by the trapezoid in the north-central part of Vermont. Public water supplies in Vermont that exceed the USEPA maximum contaminant level of 10 ppb are also shown.

Tetrahedral As in Antigorite



Shannon (1976) Acta Cryst. A32, 751-767

Arsenic in talc-magnesite

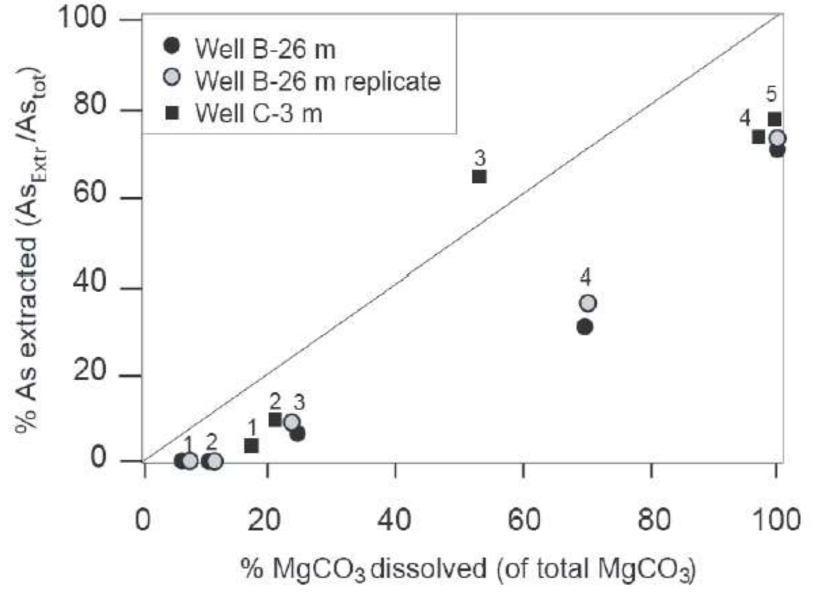


Fig 7. Bivariate diagram of arsenic extracted as a function of magnesite dissolution from two talc-magnesite rocks is consistent with occurrence of arsenic in magnesite. Extraction steps range from 1*M* NH_4NO_3 (ion exchange, step 1) to progressively stronger acids, culminating with aqua regia (step 5). The fact that not all As is released during these extractions implies that some As likely also occurs in magnetite or talc.

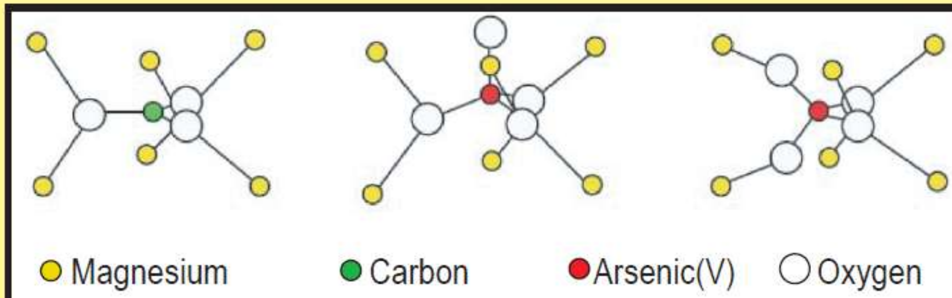
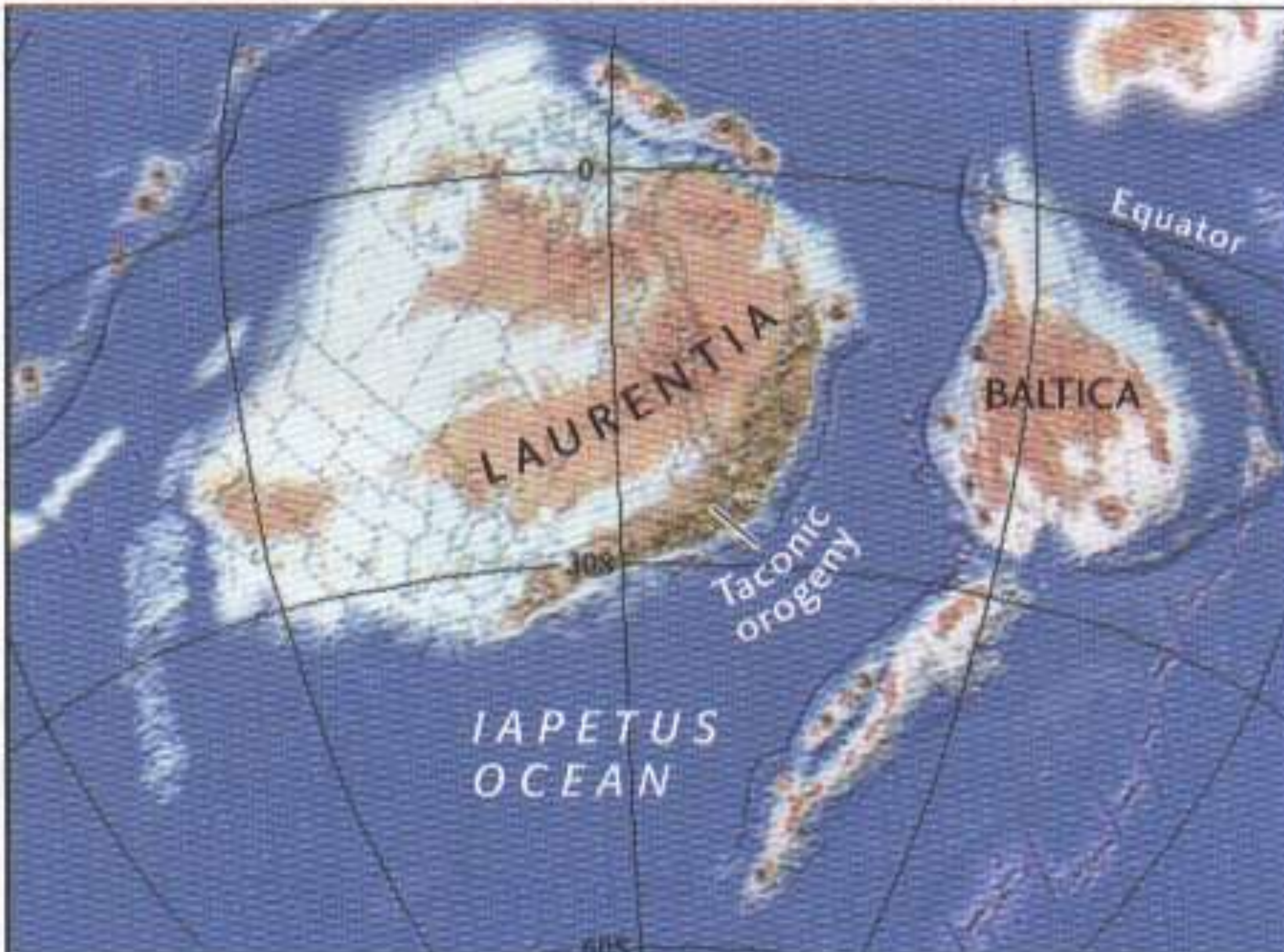
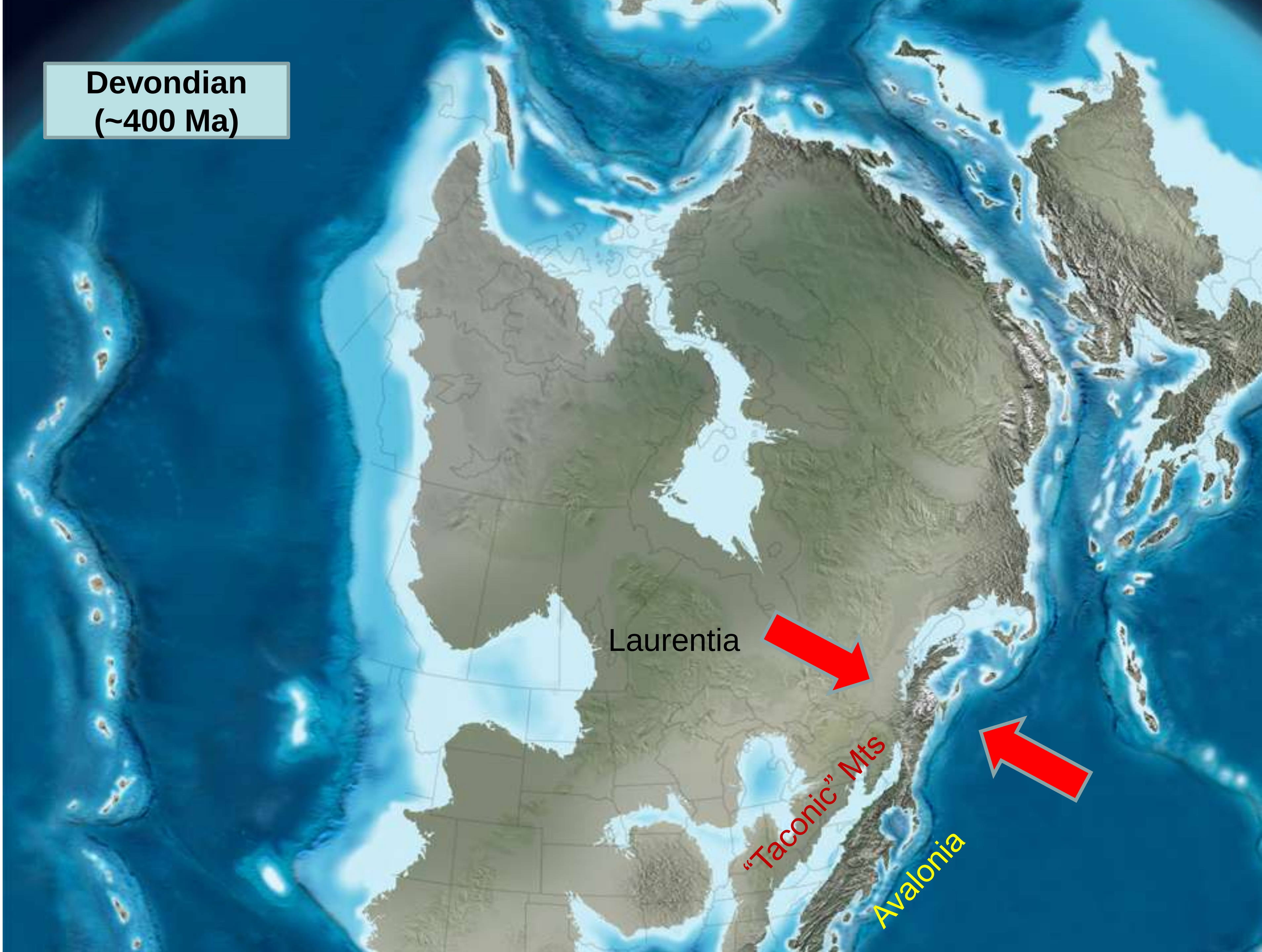


Fig 8. Schematic sketch depicting substitution of arsenate anion for carbonate anion in magnesite (after Alexandratos et al., 2007). As(V) in magnesite is suggested by preliminary XANES data (Fig. 5).

Late Ordovician (450 Ma)

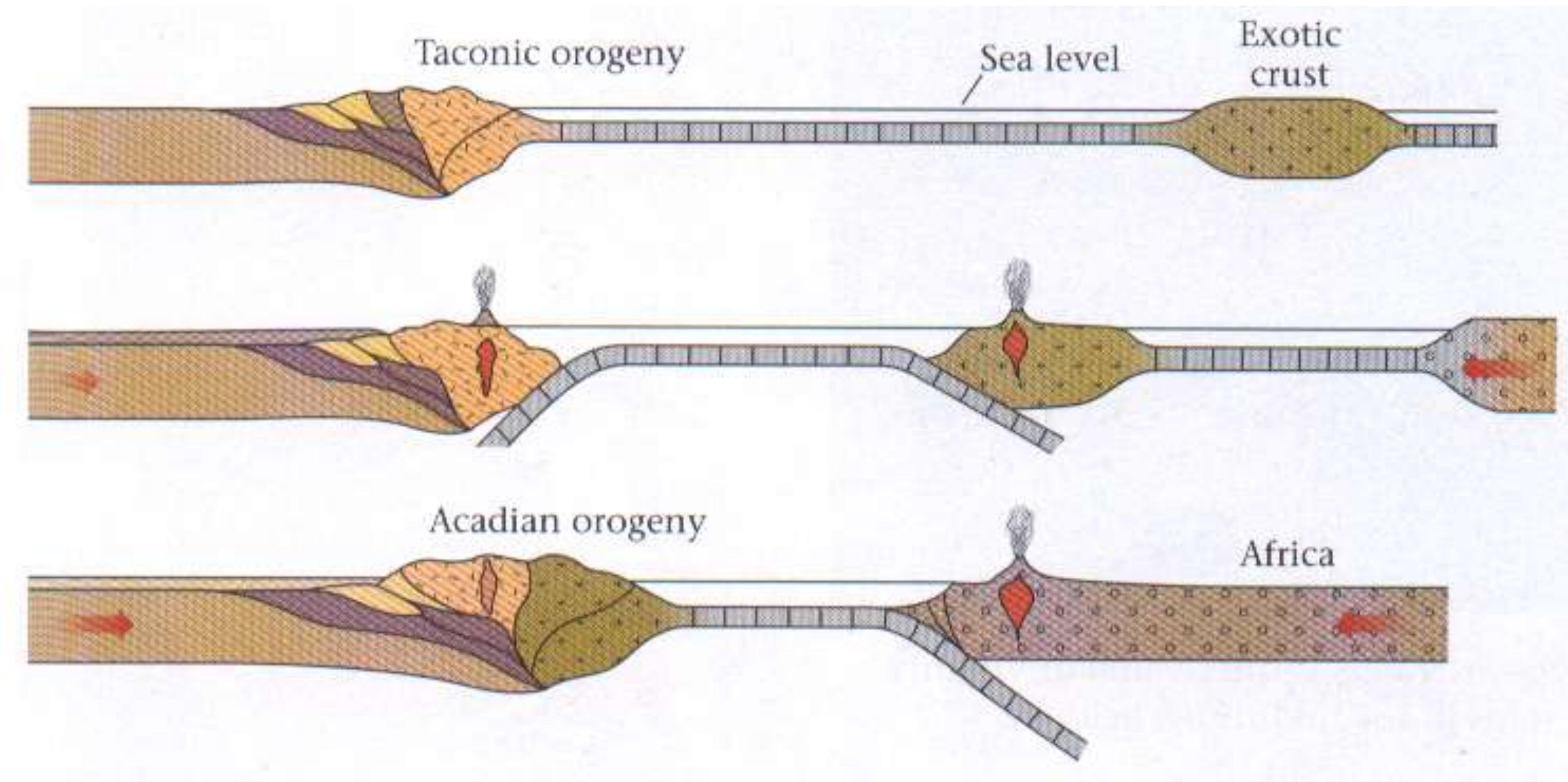
The island arc built up by the southward-directed subduction of Iapetus lithosphere collided with Laurentia in the middle to late Ordovician, causing the Taconic orogeny.





Devondian
(~400 Ma)
Laurentia
"Taconic" Mts
Avalonia

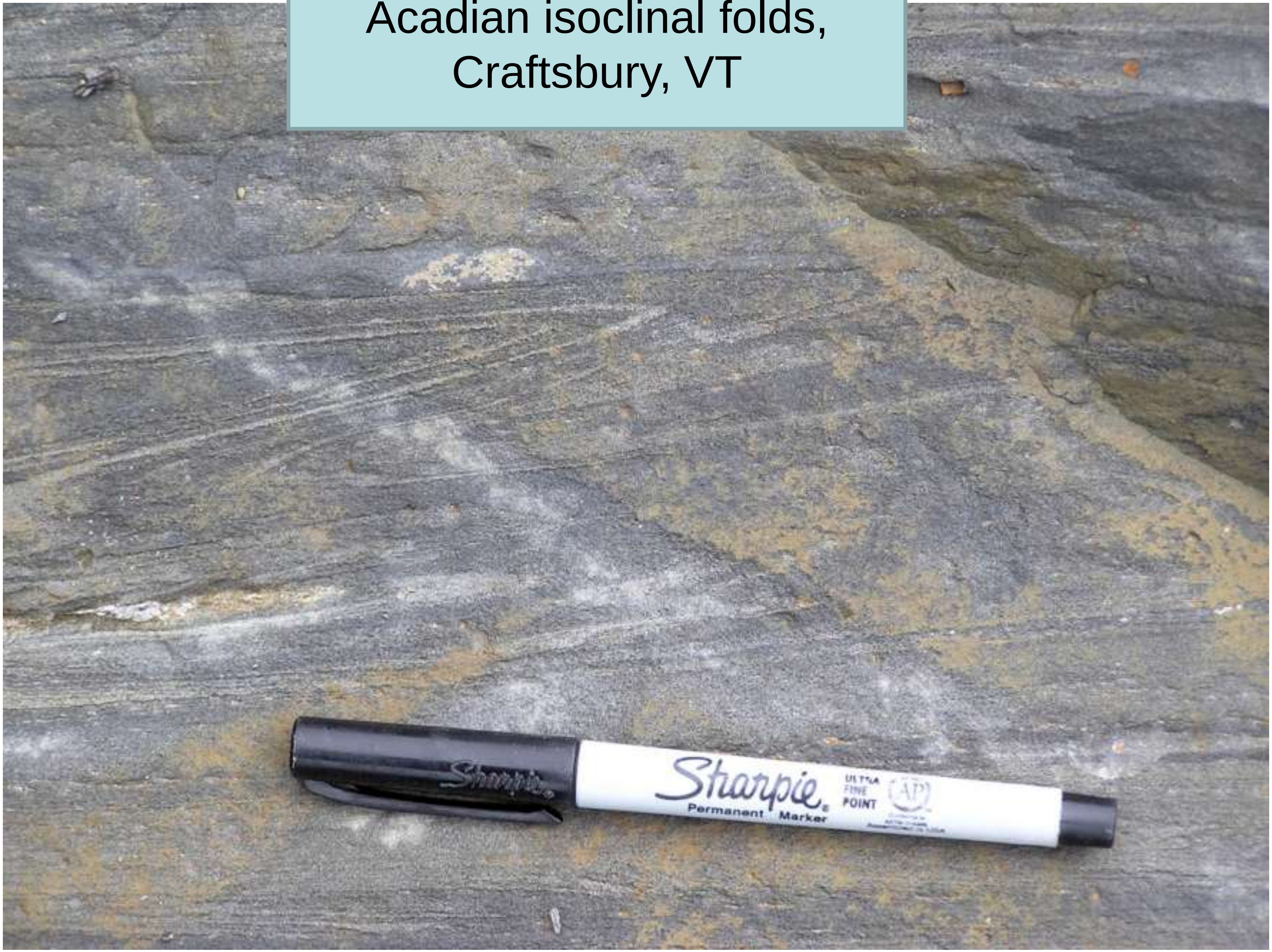
The Taconian Orogeny was responsible for many of the faults, folds and fractures preserved in west-central Vermont, but it was just the beginning for much of the Appalachians. At least two later collisions, the Acadian Orogeny (~ 400 – 350 Ma) and Alleghanian Orogeny (~320 – 270 Ma) resulted in more mountain building. Evidence of some of this later deformation is also preserved Vermont (more to E than W).



Early Devonian (400 Ma)

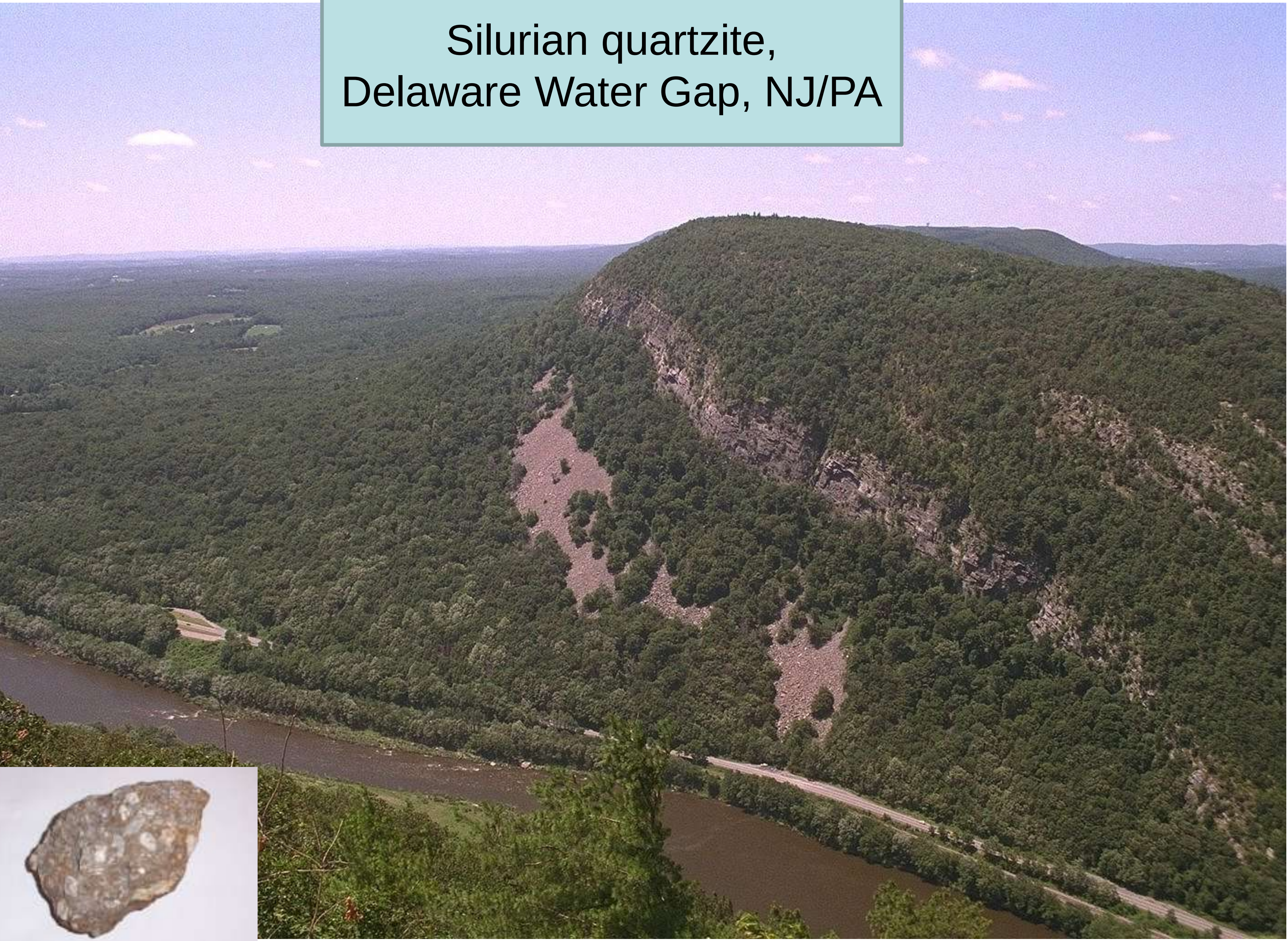
The collision of Laurentia with the continent of Baltica caused the Caledonian orogeny and formed Laurussia. The southward continuation of the convergence caused the Acadian orogeny.

Acadian isoclinal folds, Craftsbury, VT



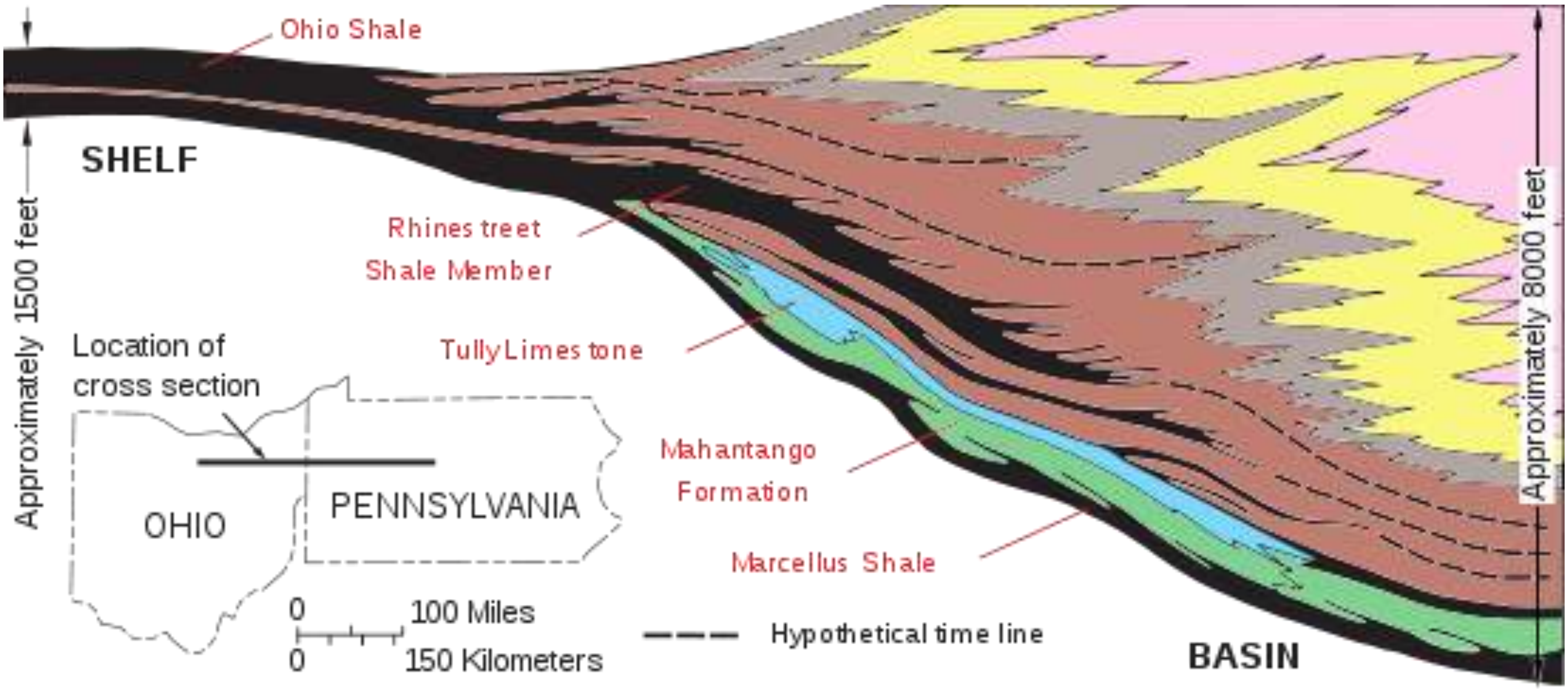
Acadian granite w/ xenolith, Marshfield, VT

Silurian quartzite,
Delaware Water Gap, NJ/PA



Catskill Delta

(sediments deposited W of Acadian Mtn range)



1999 GEOLOGIC TIME SCALE

CENOZOIC

Period		Epoch		Age	Picks (Ma)
QUATERNARY		HOLOCENE			0.01
		PLEISTOCENE		CALABRIAN	1.8
TERTIARY	NEOGENE	PLIOCENE	L	PIACENZIAN	3.6
			E	ZANCLEAN	5.3
		MIOCENE	L	MESSINIAN	7.1
				TORTONIAN	11.2
			M	SERRAVALLIAN	14.8
				LANGHIAN	16.4
			E	BURDIGALIAN	20.5
				AQUITANIAN	23.8
	PALEOGENE	OLIGOCENE	L	CHATTIAN	28.5
			E	RUPELIAN	33.7
		EOCENE	L	PRIABONIAN	37.0
			M	BARTONIAN	41.3
				LUTETIAN	49.0
			E	YPRESIAN	54.8
		PALEOCENE	L	THANETIAN	57.9
				SELANDIAN	61.0
			E	DANIAN	65.0

MESOZOIC

Period	Epoch	Age	Picks (Ma)	Uncert. (m.y.)
CRETACEOUS			65	.2
	LATE	MAASTRICHTIAN	71.3	1
		CAMPANIAN	83.5	1
		SANTONIAN	85.8	1
		CONIACIAN	89.0	1
		TURONIAN	93.5	4
		CENOMANIAN	99.0	1
	EARLY	ALBIAN	112	2
		APTIAN	121	3
	NEOCOMIAN	BARREMIAN	127	3
		HAUTERIVIAN	132	4
		VALANGINIAN	137	4
		BERRIASIAN	144	5
JURASSIC	LATE	TITHONIAN	151	6
		KIMMERIDGIAN	154	7
		OXFORDIAN	159	7
	MIDDLE	CALLOVIAN	164	8
		BATHONIAN	169	8
		BAJOCIAN	176	8
		AALENIAN	180	8
	EARLY	TOARCIAN	190	8
		PLIENSBACHIAN	195	8
		SINEMURIAN	202	8
		HETTANGIAN	206	8
TRIASSIC	LATE	RHAETIAN	210	8
		NORIAN	221	9
		CARNIAN	227	9
	MIDDLE	LADINIAN	234	9
		ANISIAN	242	9
	EARLY	OLENEKIAN	245	9
		INDUAN	248	10

RAPID POLAR WANDER

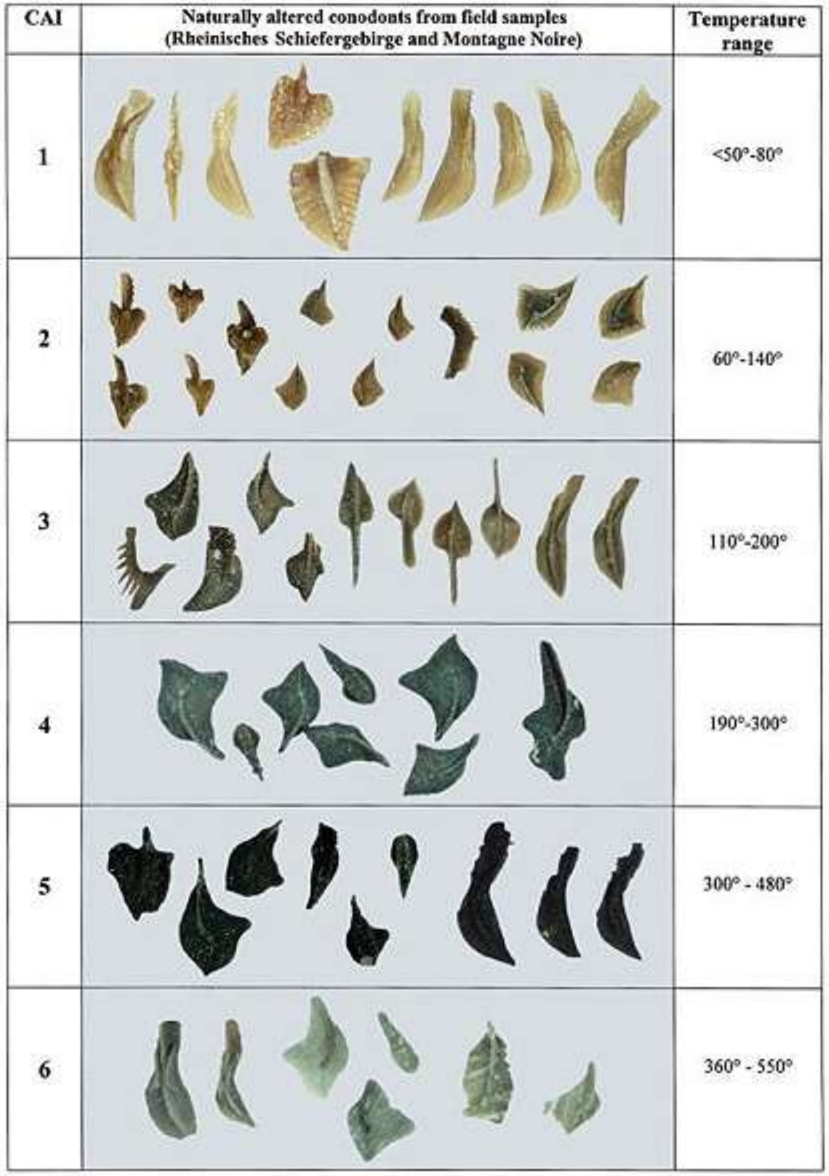
PALEOZOIC

Period	Epoch	Age	Picks (Ma)
PERMIAN			248
	L	TATARIAN	252
		UFIMIAN-KAZANIAN	256
		KUNGURIAN	260
	E	ARTINSKIAN	269
		SAKMARIAN	282
		ASSELIAN	290
CARBONIFEROUS – PENNSYLVANIAN	L	GZELIAN	296
		KASIMOVIAN	303
		MOSCOVIAN	311
		BASHKIRIAN	323
CARBONIFEROUS – MISSISSIPPIAN		SERPUKHOVIAN	327
	E	VISEAN	342
		TOURNAISIAN	354
DEVONIAN	L	FAMENNIAN	364
		FRASNIAN	370
	M	GIVETIAN	380
		EIFELIAN	391
	E	EMSIAN	400
		PRAGHIAN	412
		LOCKHOVIAN	417
SILURIAN	L	PRIDOLIAN	419
		LUDLOVIAN	423
		WENLOCKIAN	428
	E	LLANDOVERIAN	443
ORDOVICIAN	L	ASHGILLIAN	449
		CARADOCIAN	458
	M	LLANDEILIAN	464
		LLANVIRNIAN	470
	E	ARENIGIAN	485
		TREMADOCIAN	490
CAMBRIAN*	D	SUNWAPTAN*	495
		STEPTOEAN*	500
	C	MARJUMAN*	506
		DELAMARAN*	512
	B	DYERAN*	516
		MONTEZUMAN*	520
	A		543

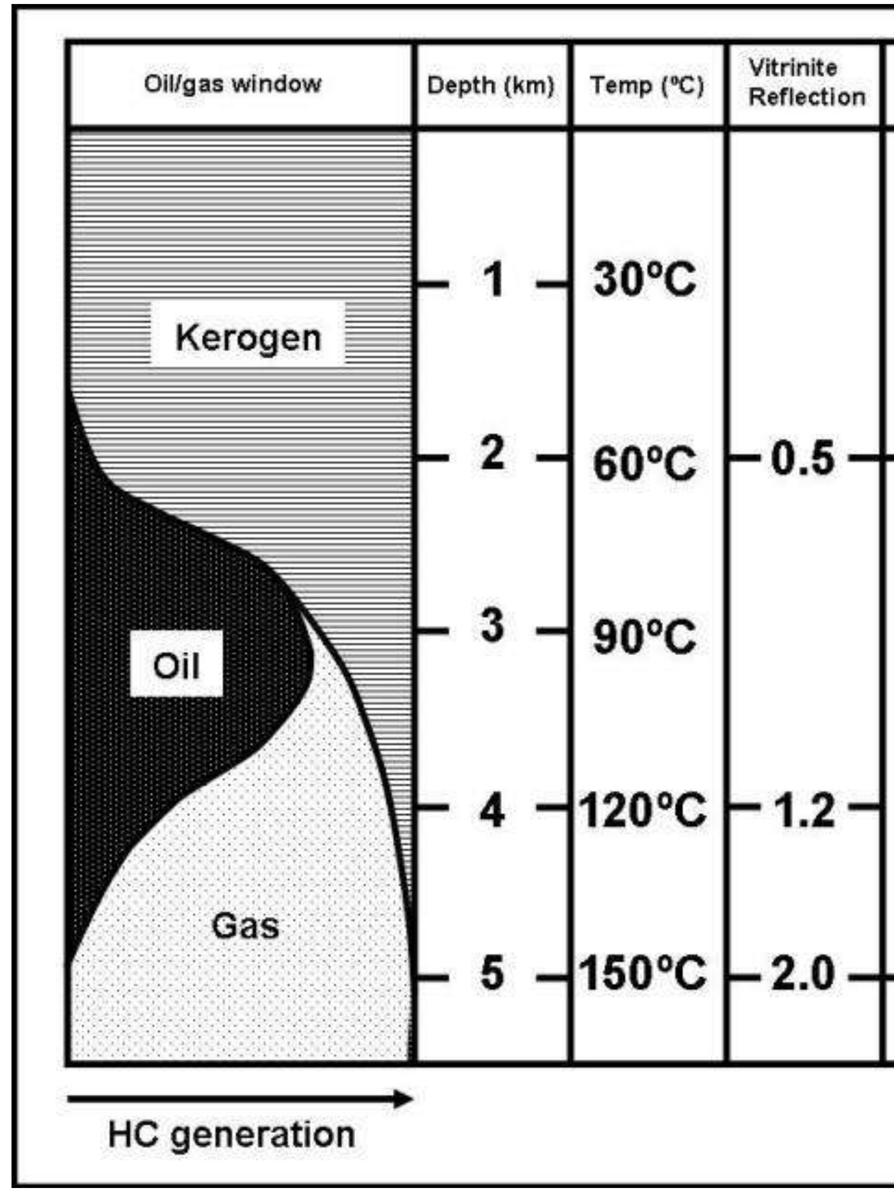
PRECAMBRIAN

Eon	Era	Bdy. Ages (Ma)
		543
PROTEROZOIC	LATE	900
	MIDDLE	1600
	EARLY	2500
ARCHEAN	LATE	3000
	MIDDLE	3400
	EARLY	3800?

Conodonts



Petroleum Maturation Window



Tectonic and regional metamorphic implications of the discovery of Middle Ordovician conodonts in cover rocks east of the Green Mountain massif, Vermont

Nicholas M. Ratcliffe, Anita G. Harris, and Gregory J. Walsh

Abstract: Middle Ordovician (late Arenigian – early Caradocian) conodonts were recovered from a dolostone lens in carbonaceous schist 30 m below the base of the Pinney Hollow Formation in the Eastern Cover sequence near West Bridgewater, Vermont. These are the first reported fossils from the metamorphic cover sequence rocks east of the Green Mountain, Berkshire, and Housatonic massifs of western New England. The conodonts are recrystallized, coated with graphitic matter, thermally altered to a color alteration index (CAI) of at least 5, and tectonically deformed. The faunule is nearly monospecific, consisting of abundant *Periodon aculeatus* Hadding? and rare *Protopanderodus*. The preponderance of *Periodon* and the absence of warm, shallow-water species characteristic of the North American Midcontinent Conodont Province suggest a slope or basin depositional setting. The conodont-bearing carbonaceous schist is traceable 3 km southeast to the Plymouth area, where it had been designated the uppermost member of the Plymouth Formation, previously regarded as Early Cambrian in age. The age and structural position of the carbonaceous schist above dolostones of the Plymouth Formation but below the Pinney Hollow Formation (upper Proterozoic and Lower Cambrian?) suggest that this unit may be correlative or time transgressive with the Ira Formation, which underlies the Taconic allochthons in the Vermont Valley. Such a correlation supports the concept of placing the western limit of the root zone of the Taconic allochthons beneath the Pinney Hollow Formation. An approximate absolute age assignment for the conodont-bearing rock is between 470 and 454 Ma. This suggests that dynamothermal metamorphism during the Taconian orogeny on the east flank of the Green Mountains was younger than early Caradocian, which is in accord with the middle Caradocian age of the Ira Formation west of the Green Mountain massif.

Résumé : Des conodontes datant de l'Ordovicien moyen (Arénigien tardif – Caradocien précoce) ont été collectés dans des lentilles de dolomie intercalées dans un schiste carboné, à 30 m sous la limite inférieure de la Formation de Pinney Hollow, dans la séquence d'Eastern Cover, près de West Bridgewater, Vermont. Ils représentent les premiers fossiles décrits provenant des roches de la séquence de couverture métamorphique à l'est des massifs des Green Mountains, Berkshire, et Housatonic de la partie ouest de la Nouvelle-Angleterre. Les conodontes sont recristallisés, enrobés de matière graphitique, altérés par échauffement à un «CAI» d'au moins 5, et déformés par les contraintes tectoniques. La faunule est formée presque entièrement d'une seule espèce, *Periodon aculeatus* Hadding?, accompagnée de rares *Protopanderodus*. La prépondérance de *Periodon* et l'absence des espèces d'eau peu profonde et chaude typiques de la Province de conodontes midcontinentale américaine, suggèrent un dépôt sur pente ou dans un bassin. On peut suivre le schiste carboné à conodontes à 3 km au sud-est de la région de Plymouth, où il est désigné comme le membre terminal de la Formation de Plymouth, qui était considéré auparavant d'âge du Cambrien précoce. L'âge et la position structurale du schiste carboné sus-jacent aux dolomies de la Formation de Plymouth, mais sous-jacent à la Formation de Pinney Hollow (Protérozoïque supérieur et Cambrien inférieur?), suggèrent que cette unité peut être corrélée ou est diachronique avec la Formation d'Ira qui est sous-jacente aux allochtones taconiques dans la Vallée du Vermont. Une telle corrélation plaide pour l'interprétation qui consiste à placer la limite occidentale de la zone de racines des allochtones taconiques sous la Formation de Pinney Hollow. L'âge absolu approximatif assigné aux roches contenant des conodontes se situe entre 470 et 454 Ma. Ces données suggèrent que le dynamométamorphisme durant l'orogénie taconienne sur le flanc des Green Mountains date d'une époque plus jeune que le Caradocien précoce, ce qui est en accord avec l'âge de Caradocien moyen attribué à la Formation d'Ira à l'ouest du massif des Green Mountains.

[Traduit par la Rédaction]

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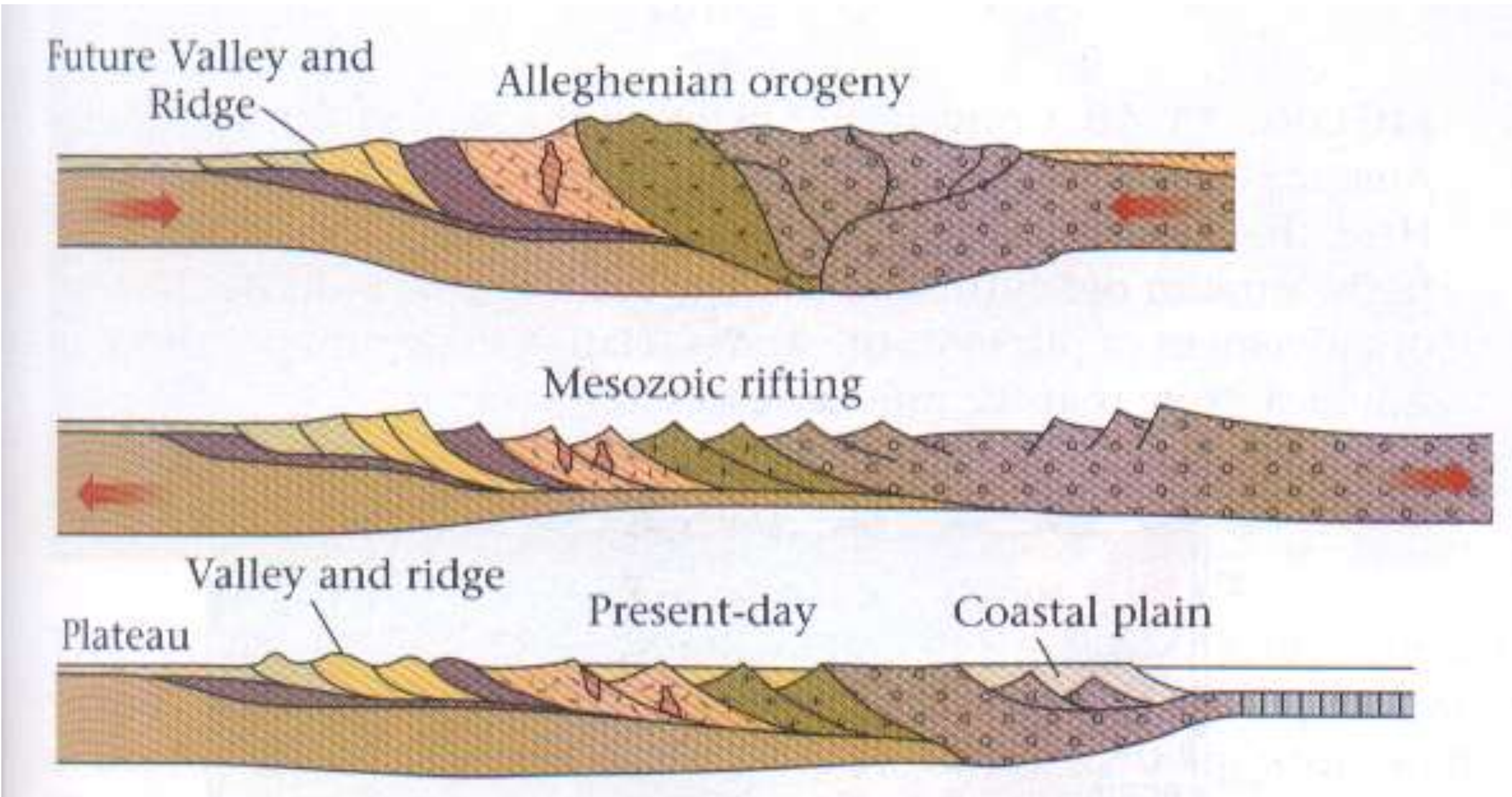
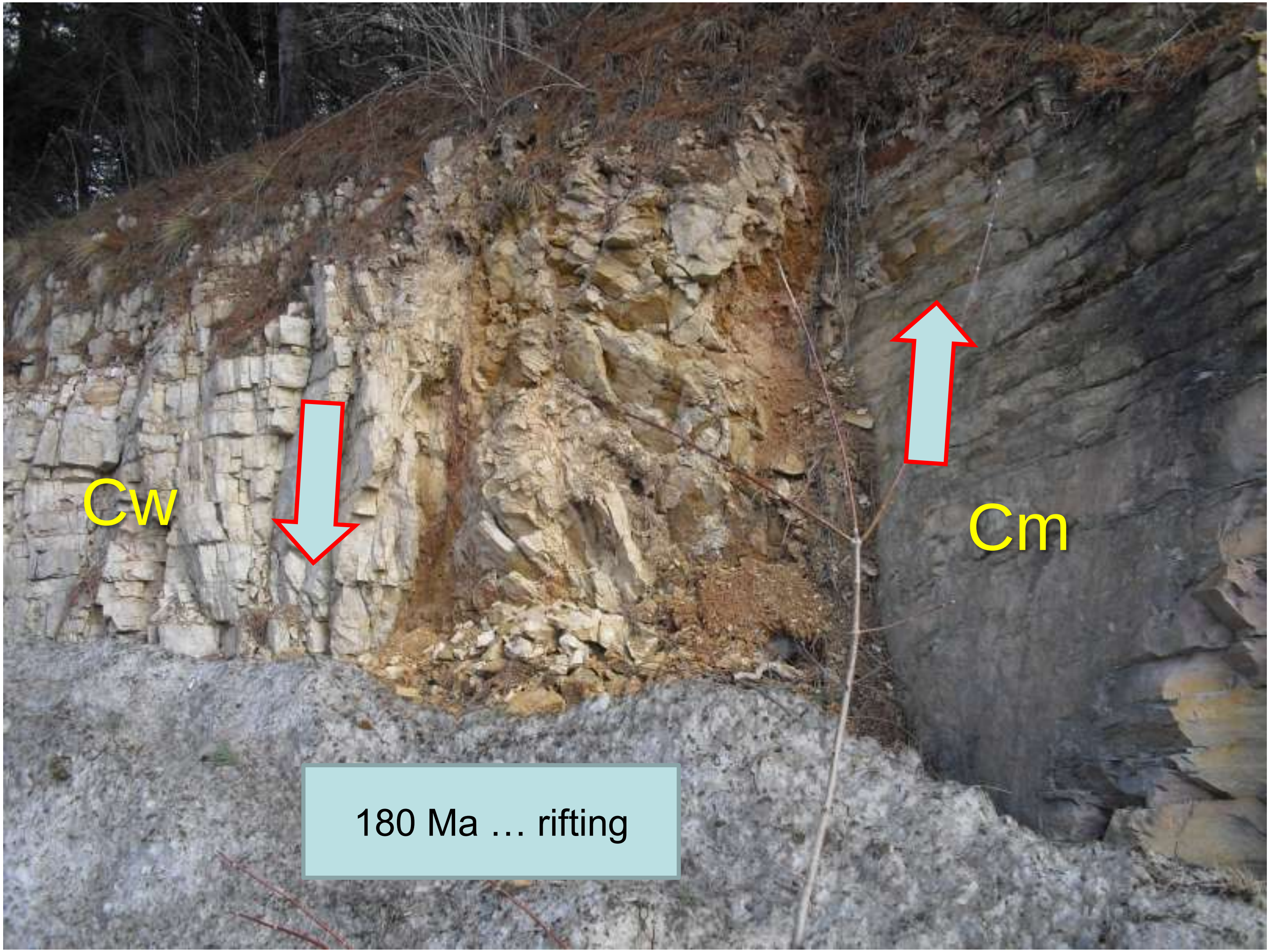
Introduction

Upper Proterozoic through Ordovician rocks of the Eastern Cover sequence form the depositional and tectonic cover of the Middle Proterozoic rocks of the Green Mountain mas-

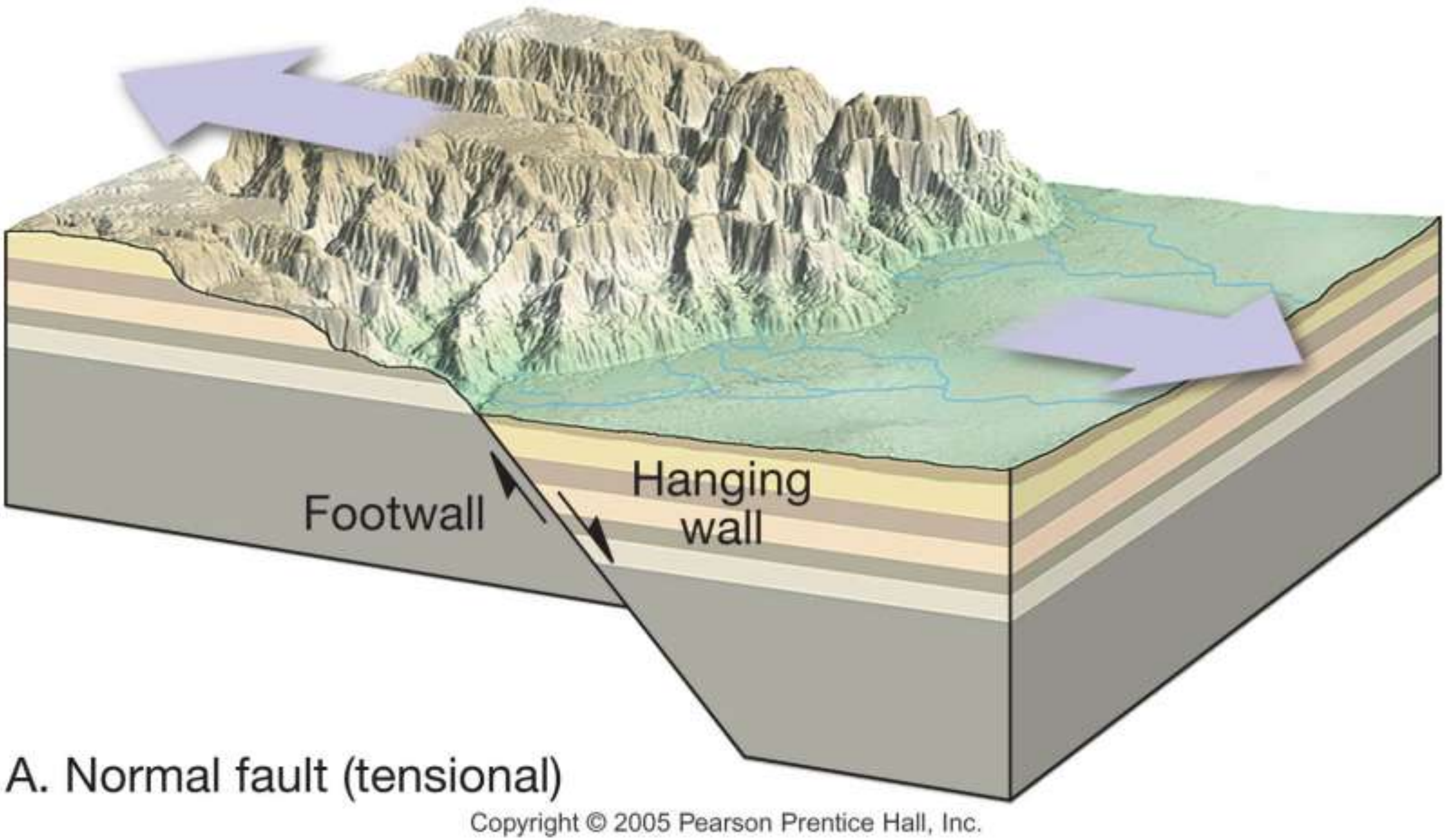
By about 250 Ma, Appalachian mountain building was complete and the result was the formation of another super continent called **Pangaea.** Beginning about 200 Ma, Pangaea began to rift apart much like Rodinia had 400 Ma earlier **(Mesozoic rifting)**. The result of this was the formation of the Atlantic Ocean. The Atlantic is currently growing at a rate of about 2.5 cm (1 inch) per year . . . .

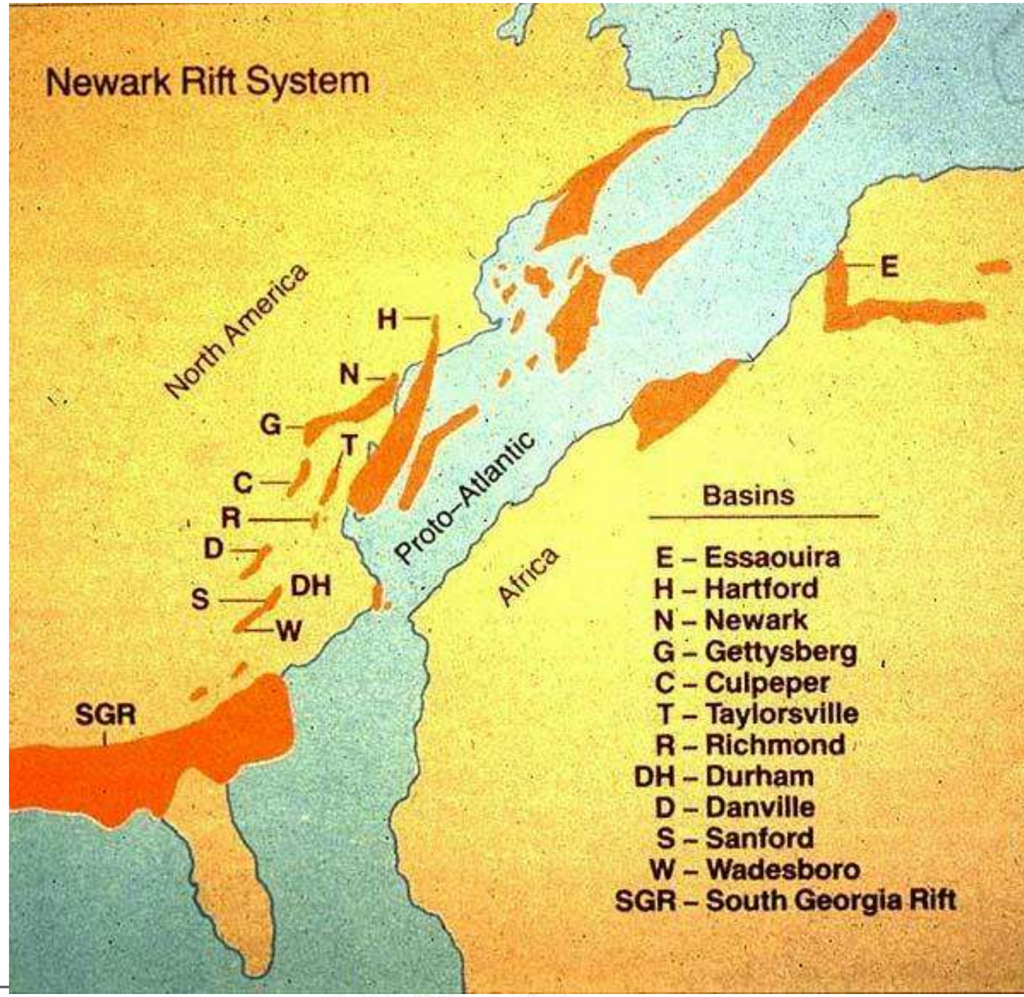


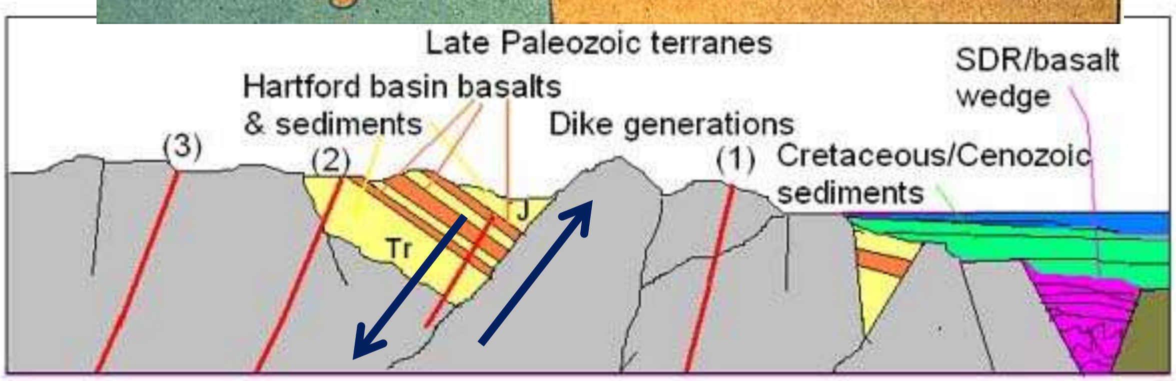

Cw
Cm
180 Ma … rifting

Normal fault

Hanging wall moves down relative to the footwall

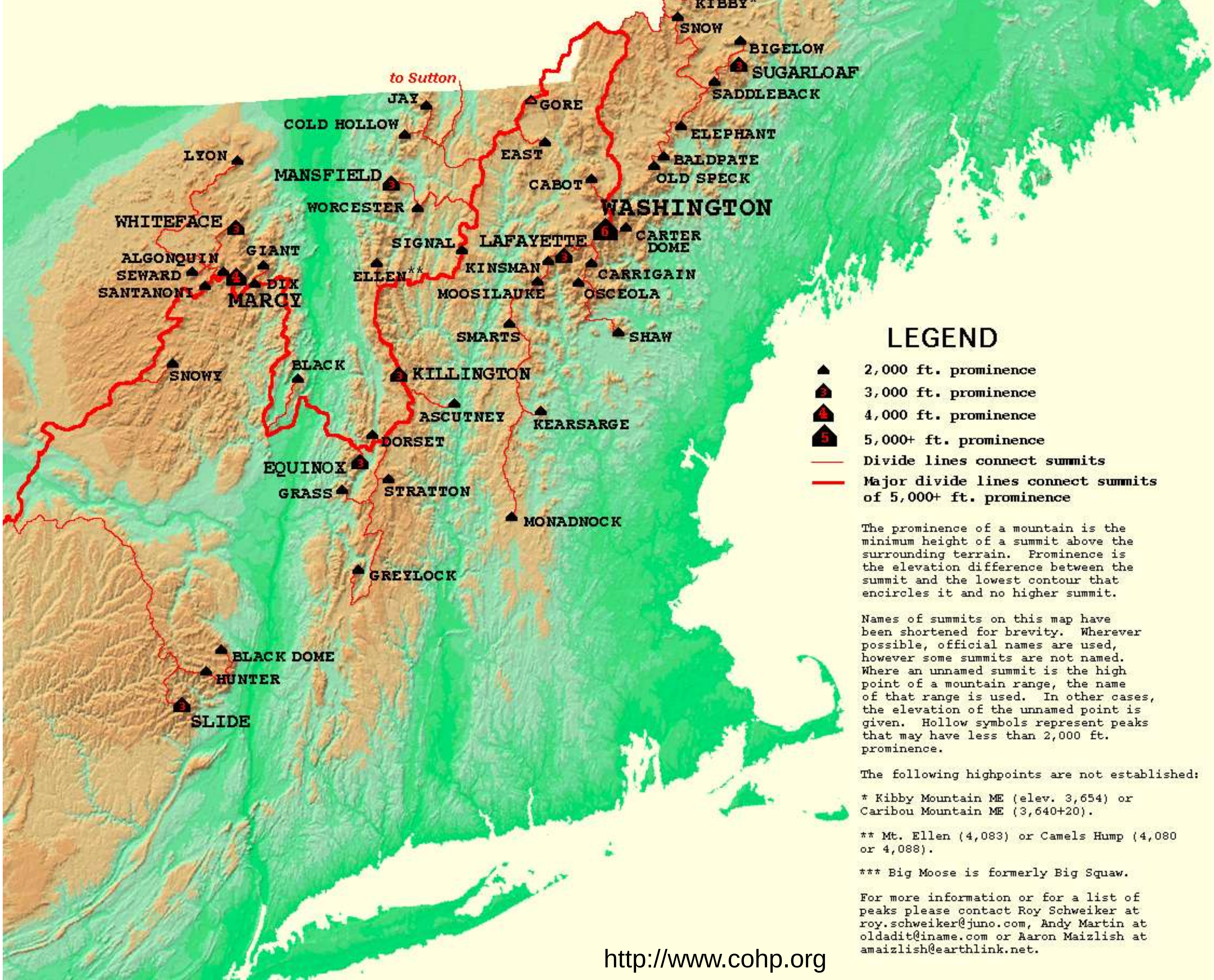






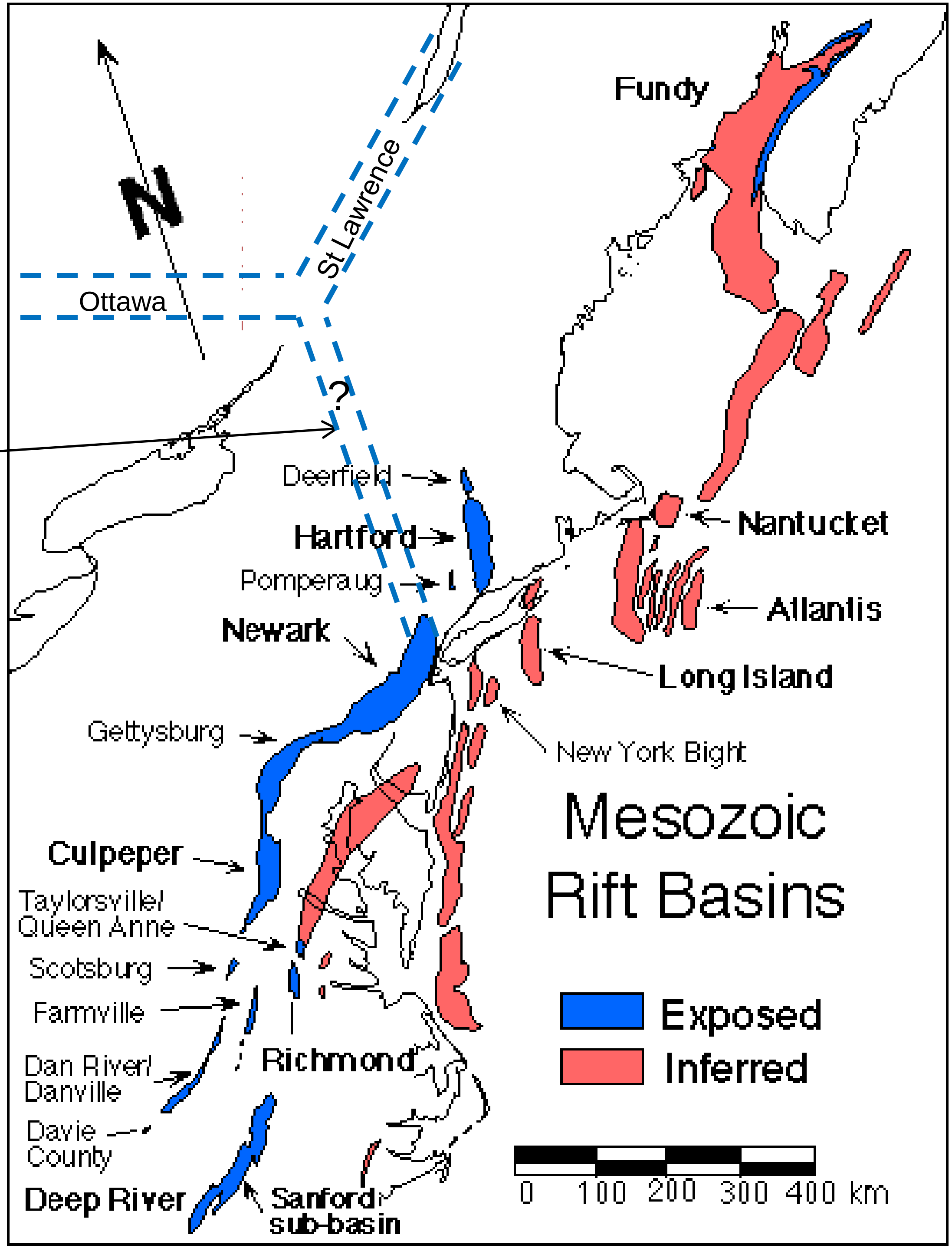
Cross section of the northeastern USA rift zone (southern New England)

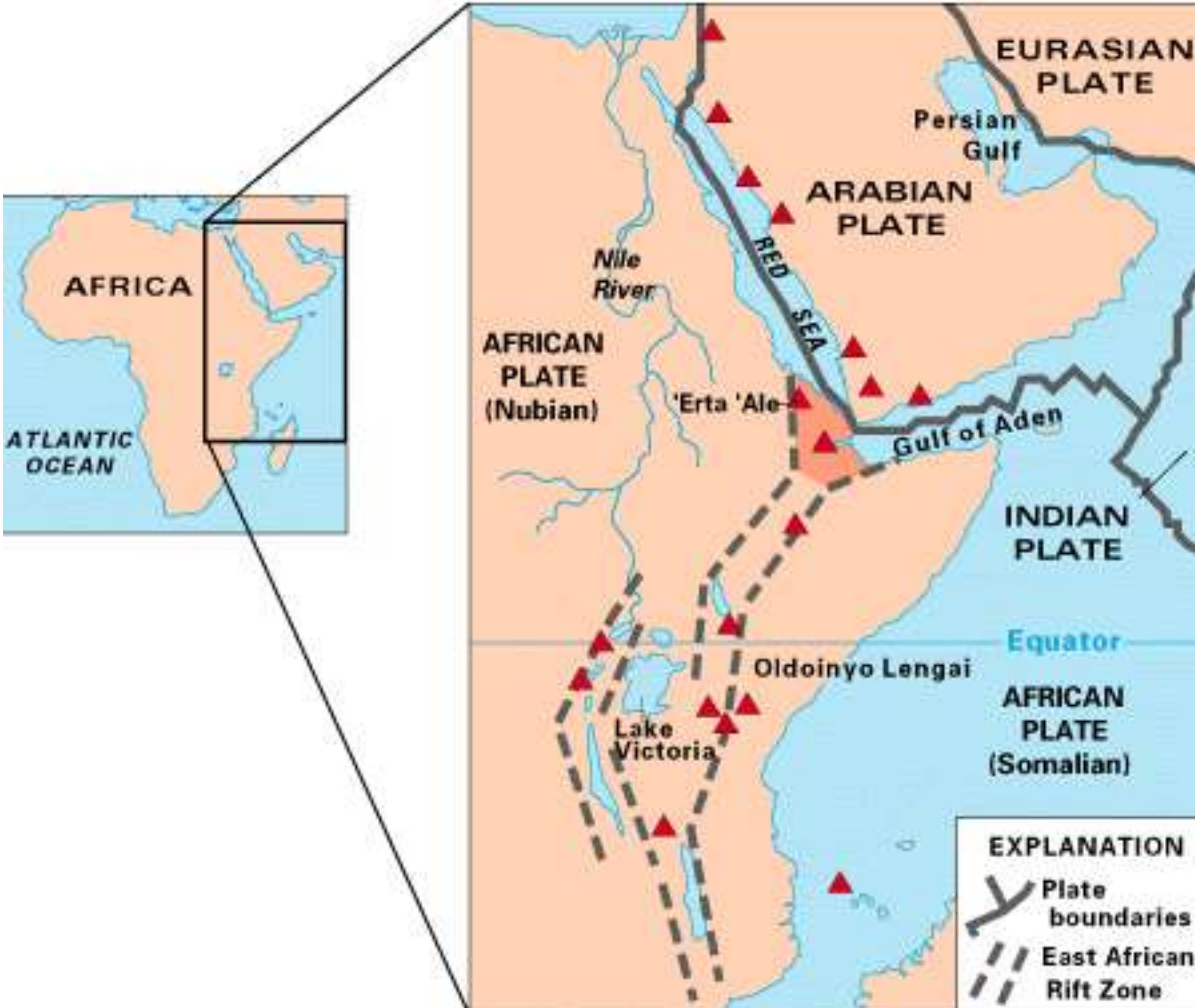
http://www.wesleyan.edu/ctgeology/CtLandscapes/CTlandscapes3.html



http://www.cohp.org

Champlain Valley

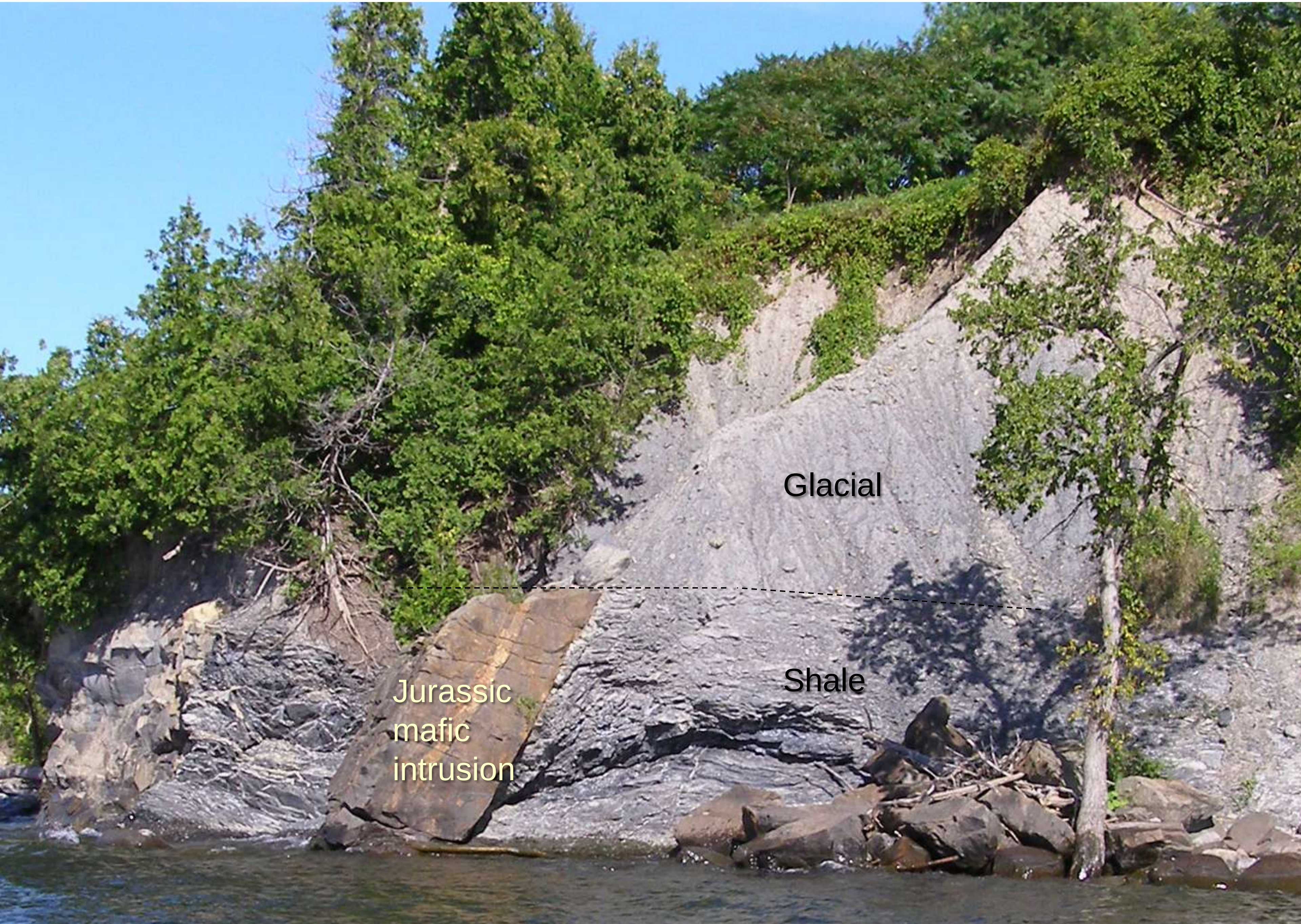


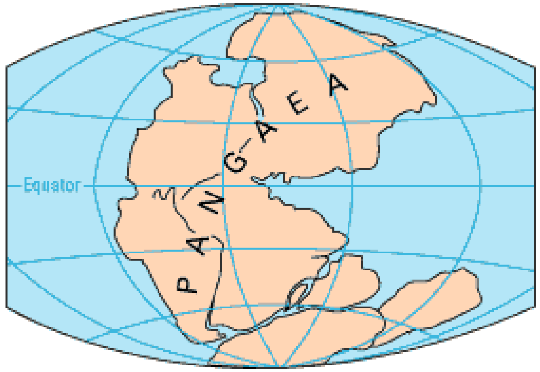


AFRICA
ATLANTIC OCEAN
EURASIAN PLATE
Persian Gulf
ARABIAN PLATE
RED SEA
Nile River
AFRICAN PLATE (Nubian)
'Erta 'Ale
Gulf of Aden
INDIAN PLATE
Equator
Oldoinyo Lengai
AFRICAN PLATE (Somalian)
Lake Victoria
EXPLANATION
Plate boundaries
East African Rift Zone

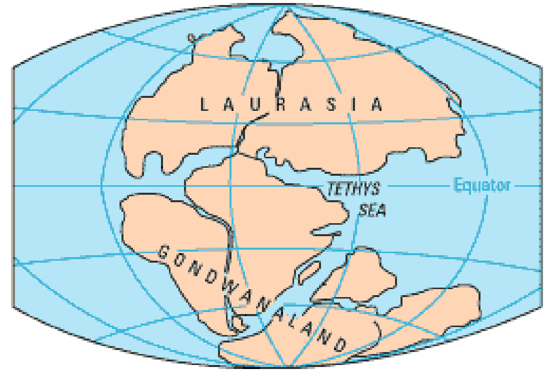
Barber Hill pluton, Charlotte, VT

http://www.darylstorrs.com/images/Barber_small.jpg

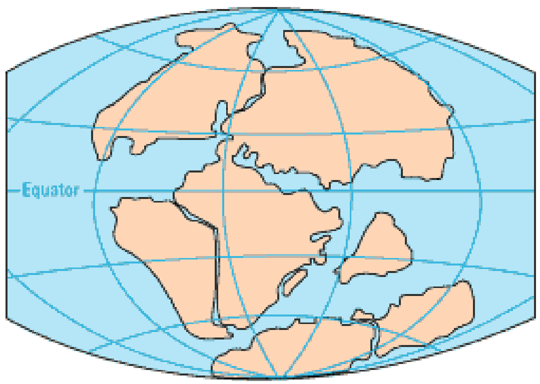

Glacial
Shale
Jurassic
mafic
intrusion



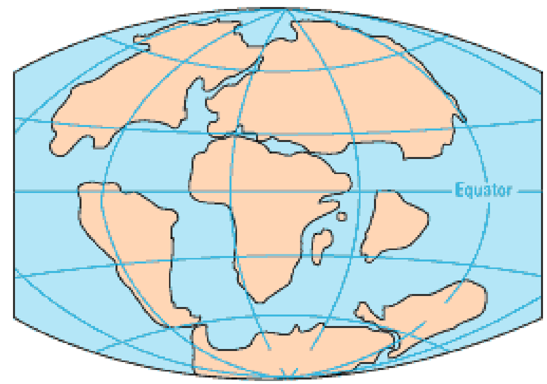
PERMIAN
225 million years ago



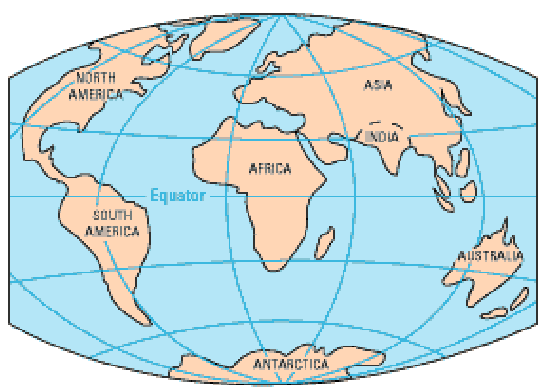
TRIASSIC
200 million years ago



JURASSIC
135 million years ago

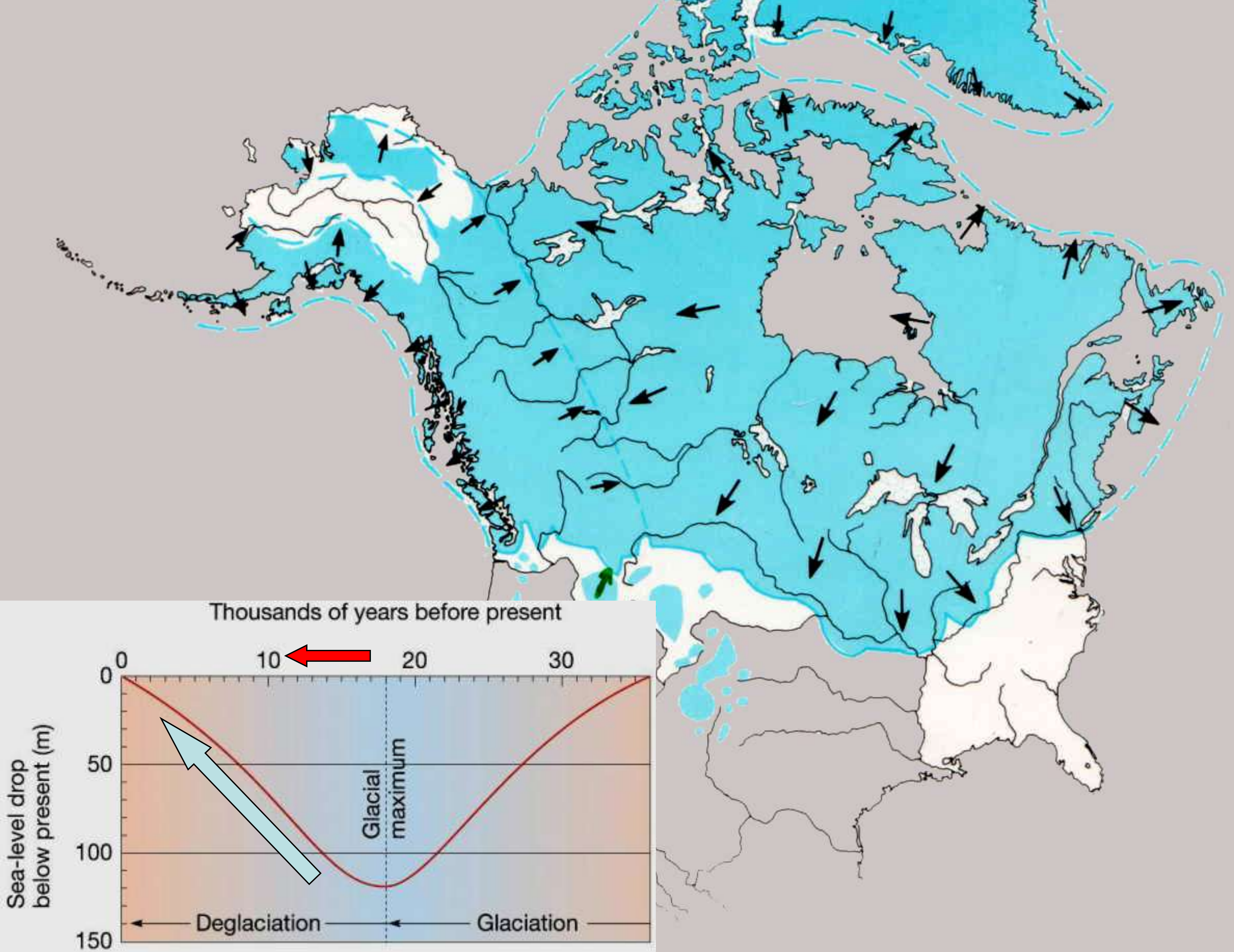


CRETACEOUS
65 million years ago



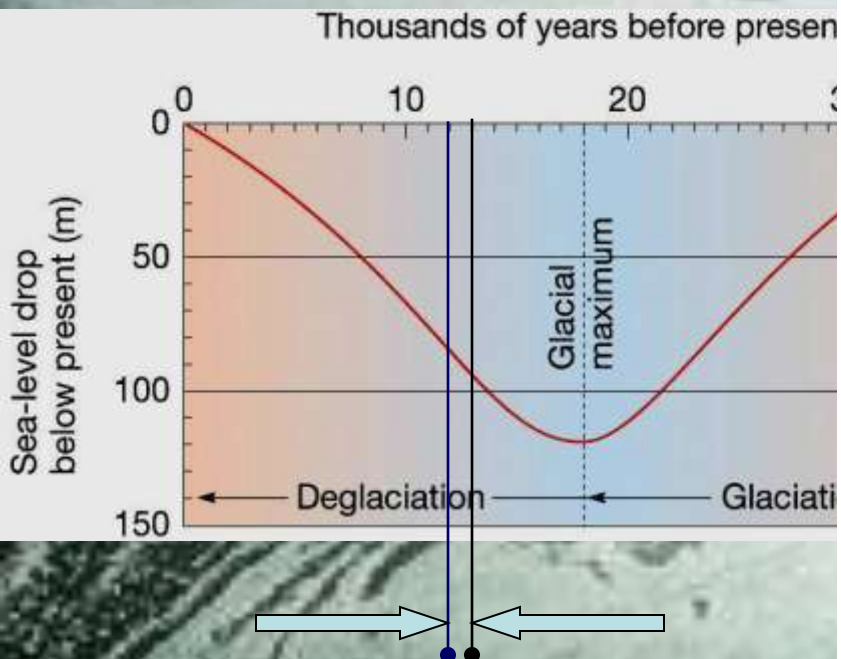
PRESENT DAY

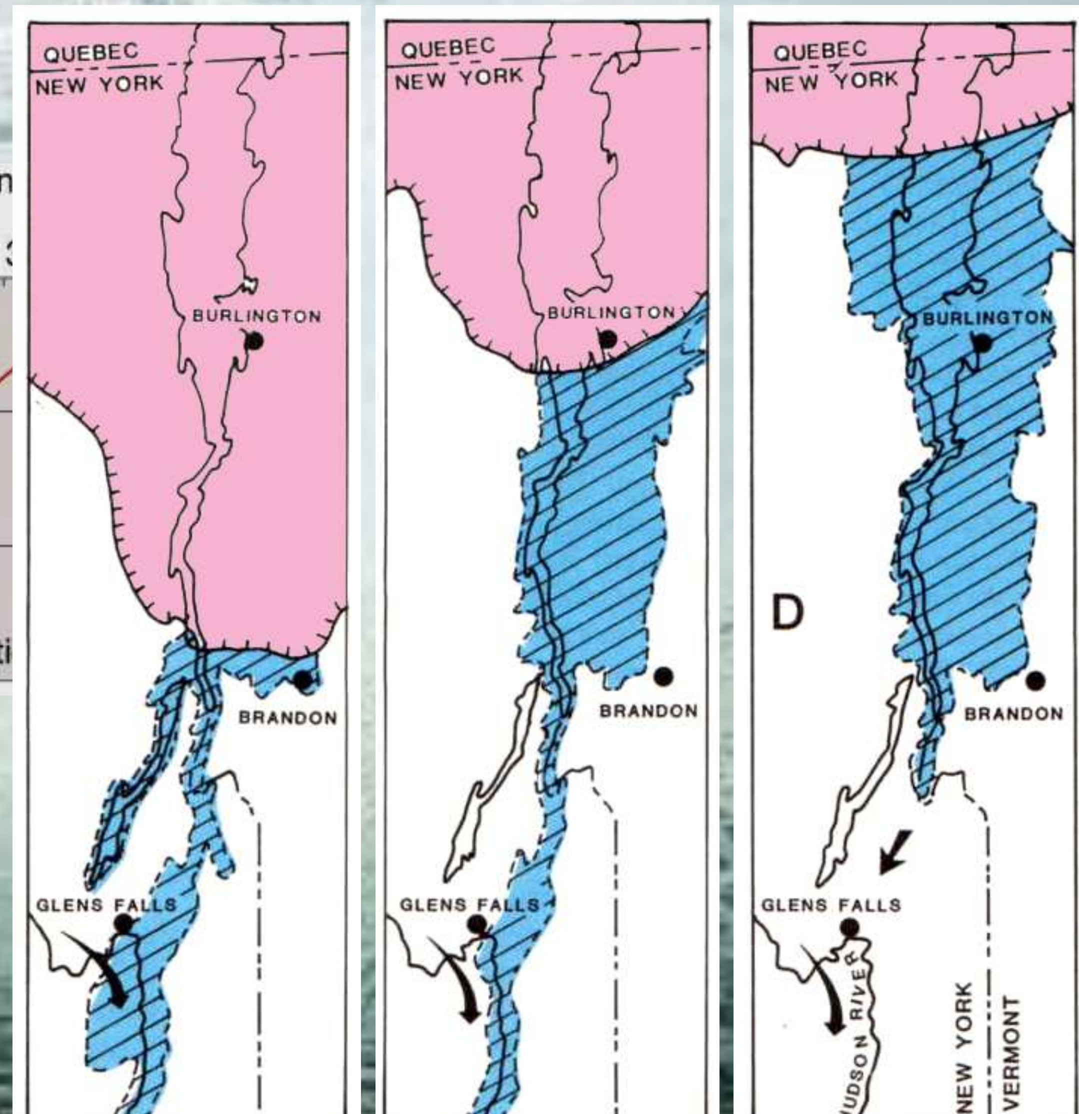
In addition to Paleozoic sediments, folds and faults, Vermont also possesses a well-preserved record of the much younger glacial history of the region (~20 - 10 ka).



Thousands of years before present
0
10
20
30
0
50
100
150
Sea-level drop below present (m)
Glacial maximum
Deglaciation
Glaciation

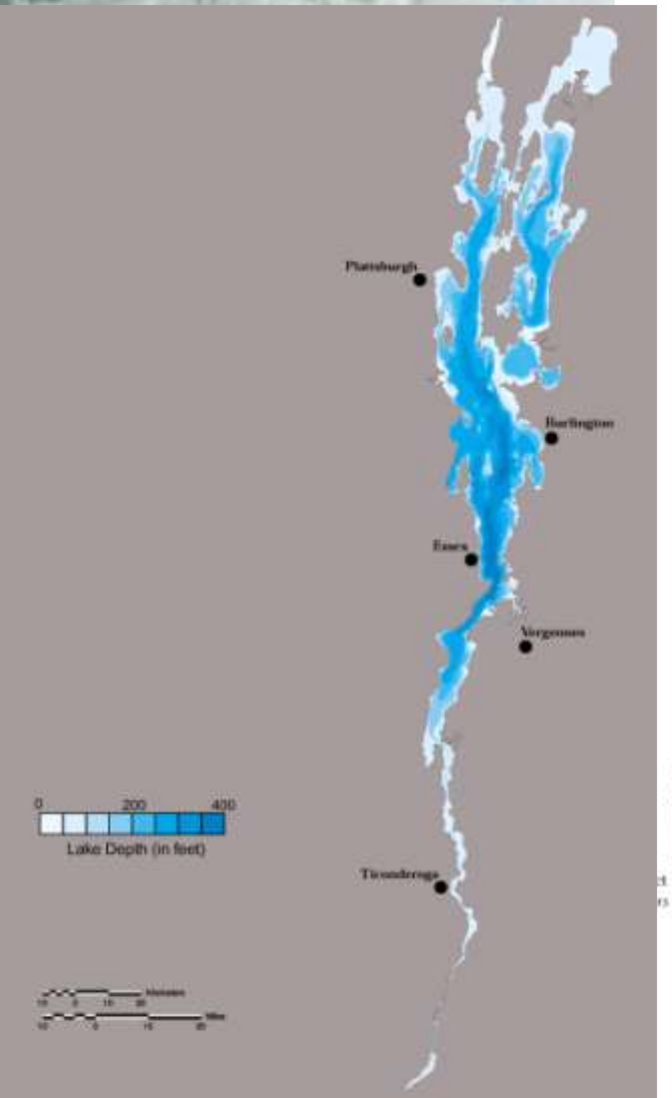
Time Step History

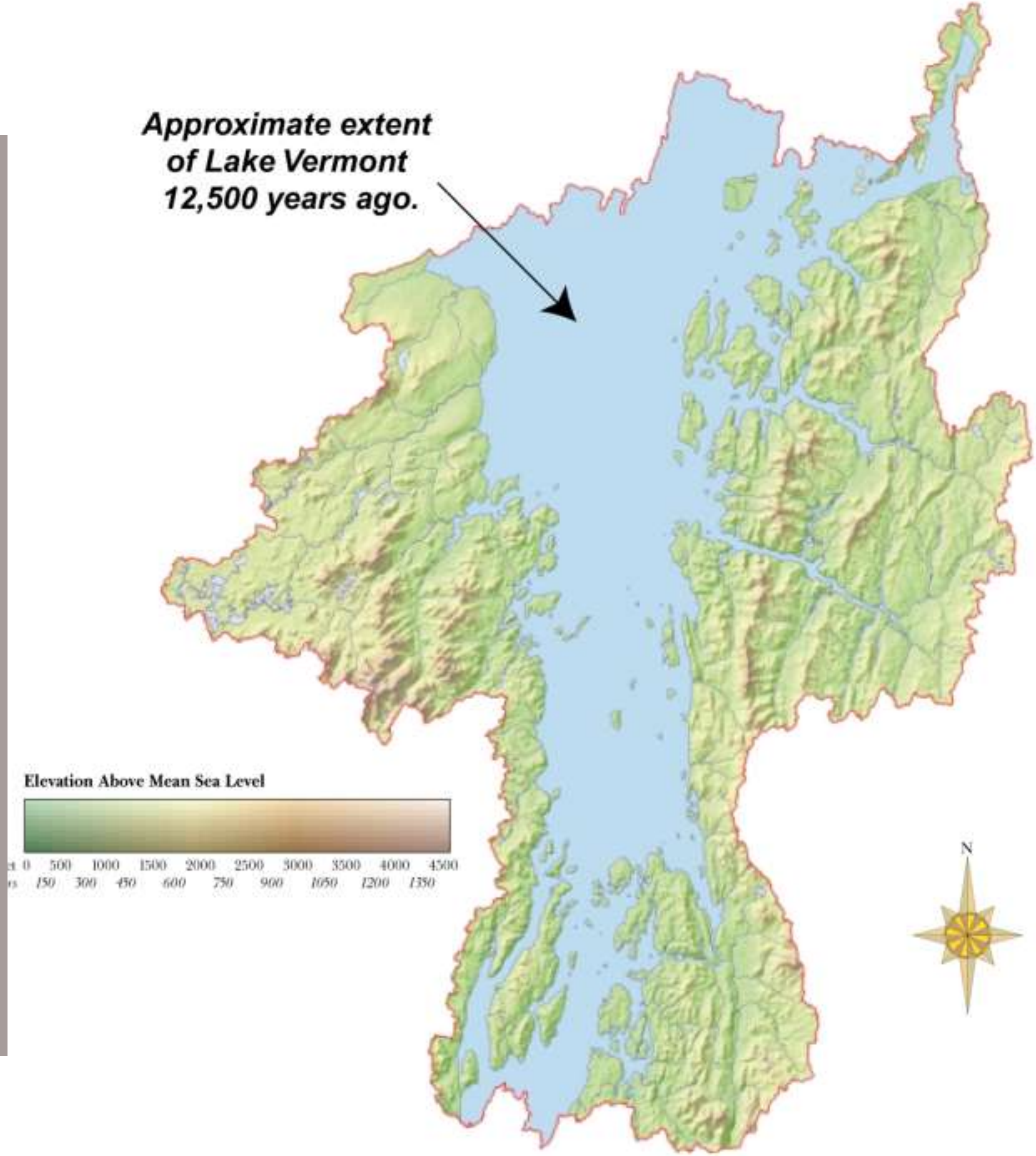




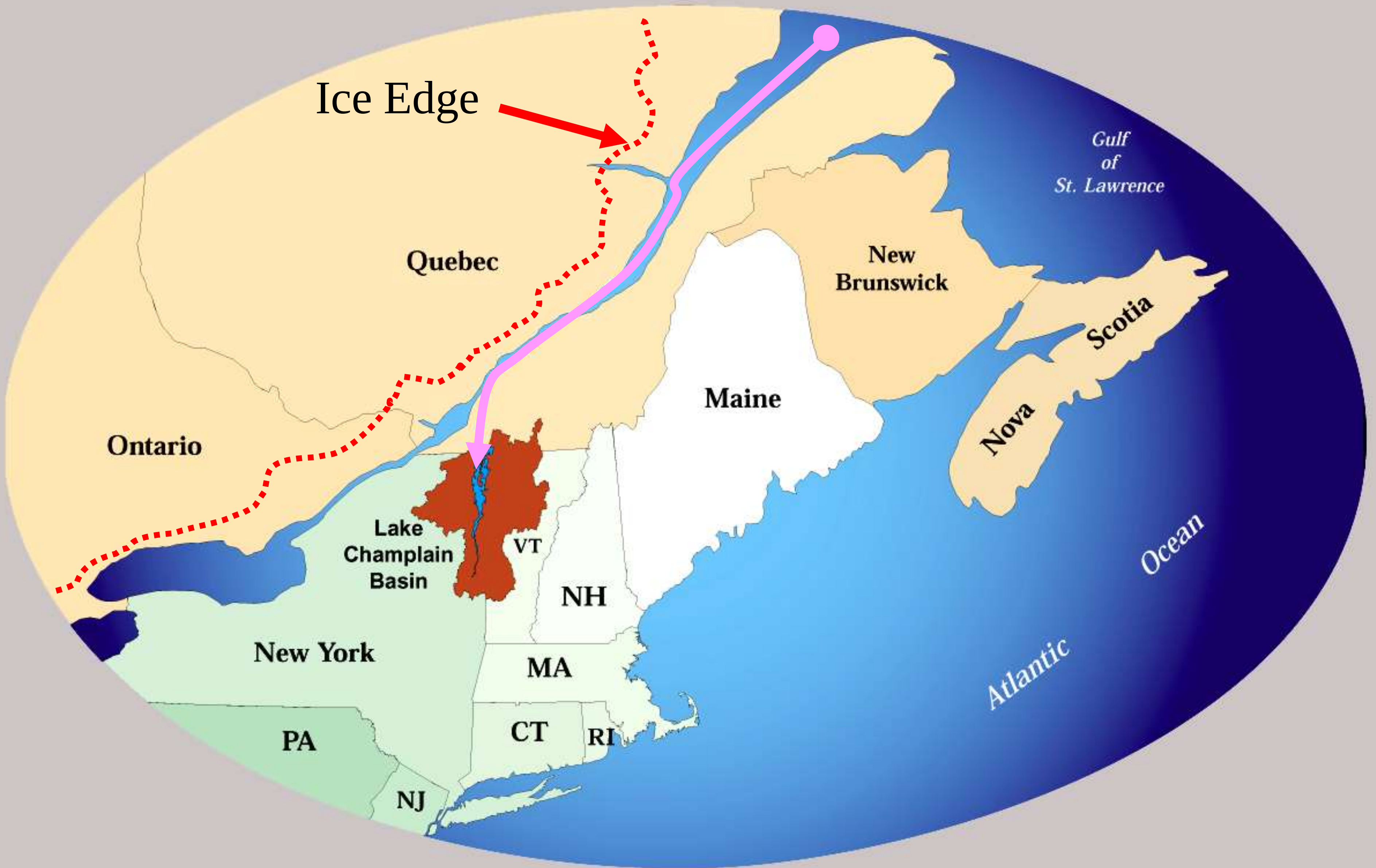
•~15 - 12 K …the Wisconsin Ice sheet retreated,creating successively lower-elevation proglacial lakes

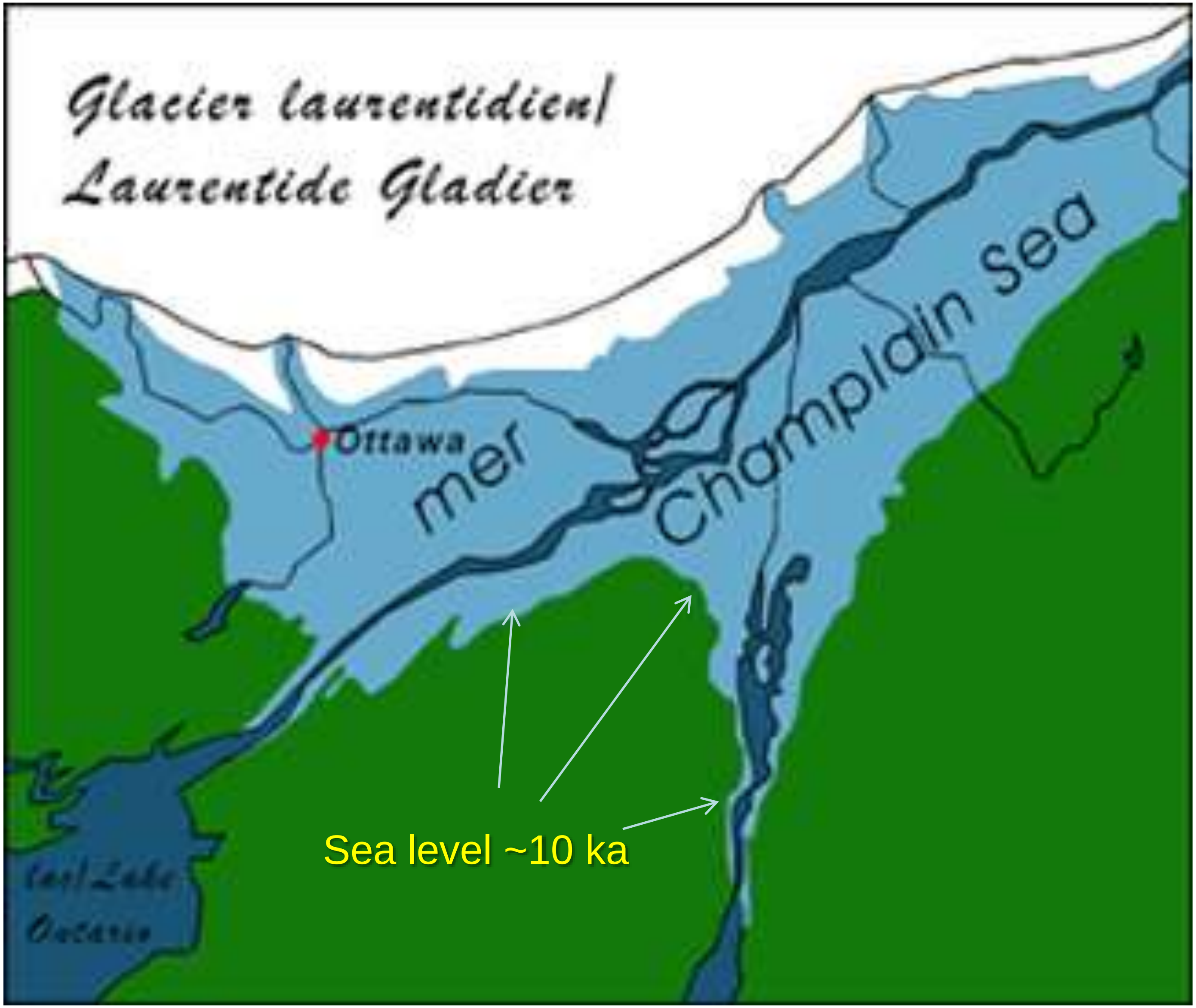
Collectively known as LAKE VERMONT

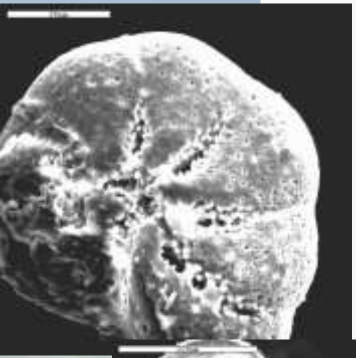

Plattsburgh
Burlington
Essex
Vergennes
Ticonderoga
0
200
400
Lake Depth (in feet)

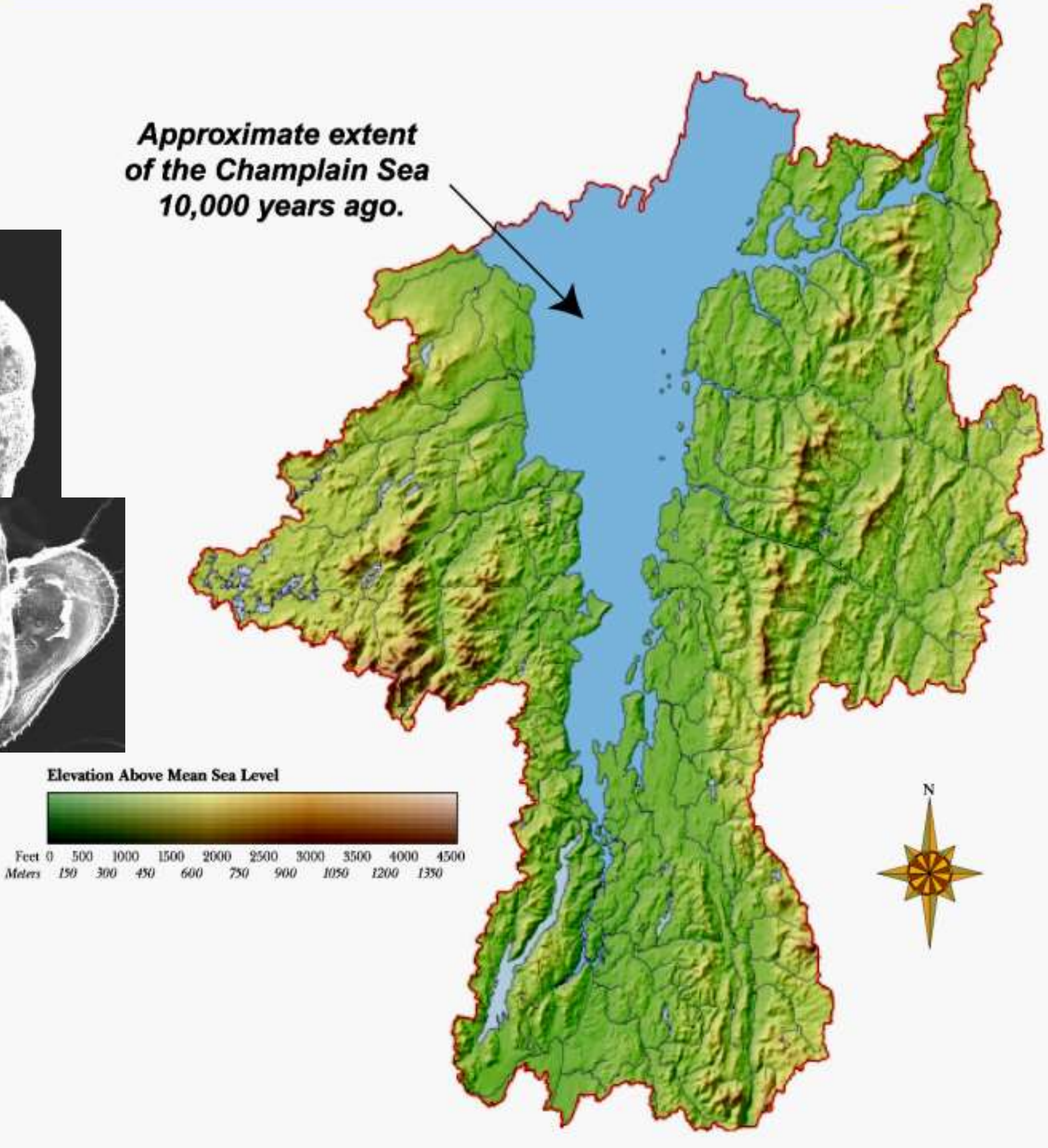

Approximate extent
of Lake Vermont
12,500 years ago.
Elevation Above Mean Sea Level
0 500 1000 1500 2000 2500 3000 3500 4000 4500
150 300 450 600 750 900 1050 1200 1350
N

Once glacier had retreated N of St Lawrence River valley, sea water rushed in → Champlain Sea




Glacier laurentidien/
Laurentide Glacier
Ottawa
mer Champlain Sea
Sea level ~10 ka




Approximate extent
of the Champlain Sea
10,000 years ago.
Elevation Above Mean Sea Level
Feet 0 500 1000 1500 2000 2500 3000 3500 4000 4500
Meters 150 300 450 600 750 900 1050 1200 1350
N

Beluga Whale (Charlotte)

Harbor Seal (Plattsburgh)


Newfoundland and Labrador
Strait of Belle Isle
Quebec
Sept-Îles
Gaspé
Newfounland
and
Labrador
Mont-Joli
Îles-de-la-
Madeleine
Cabot
Strait
Québec
New
Brunswick
P.E.I.
Atlantic
Ocean
U.S.A.
Nova Scotia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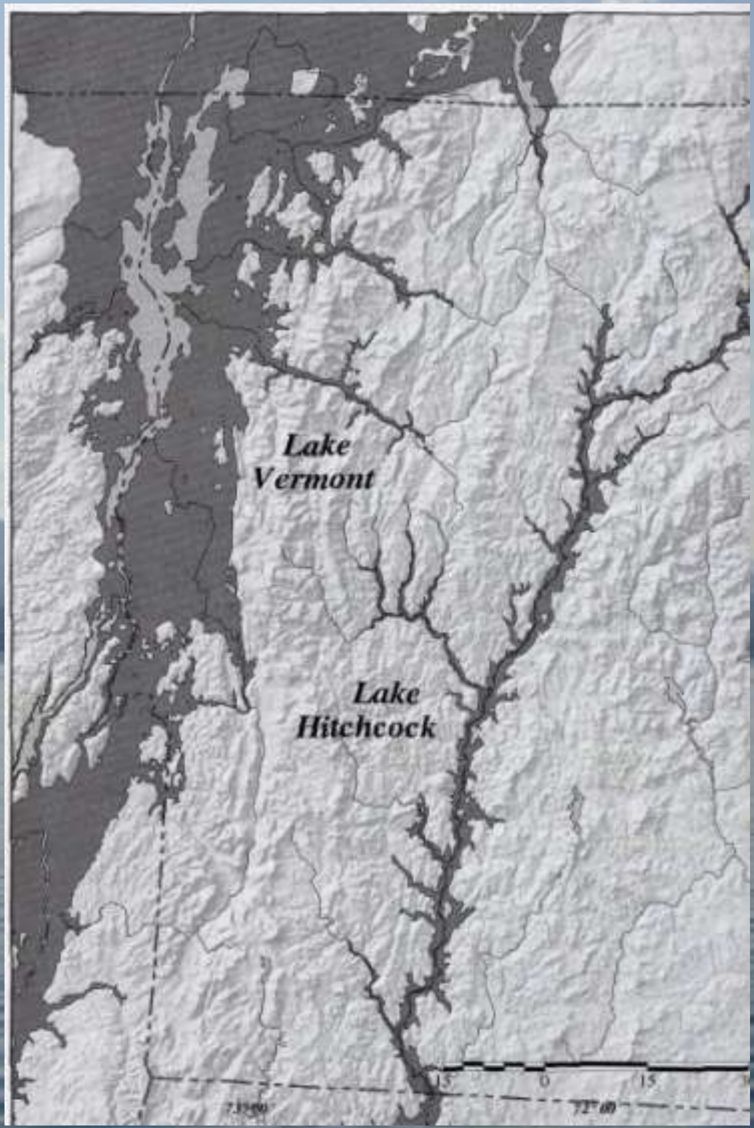
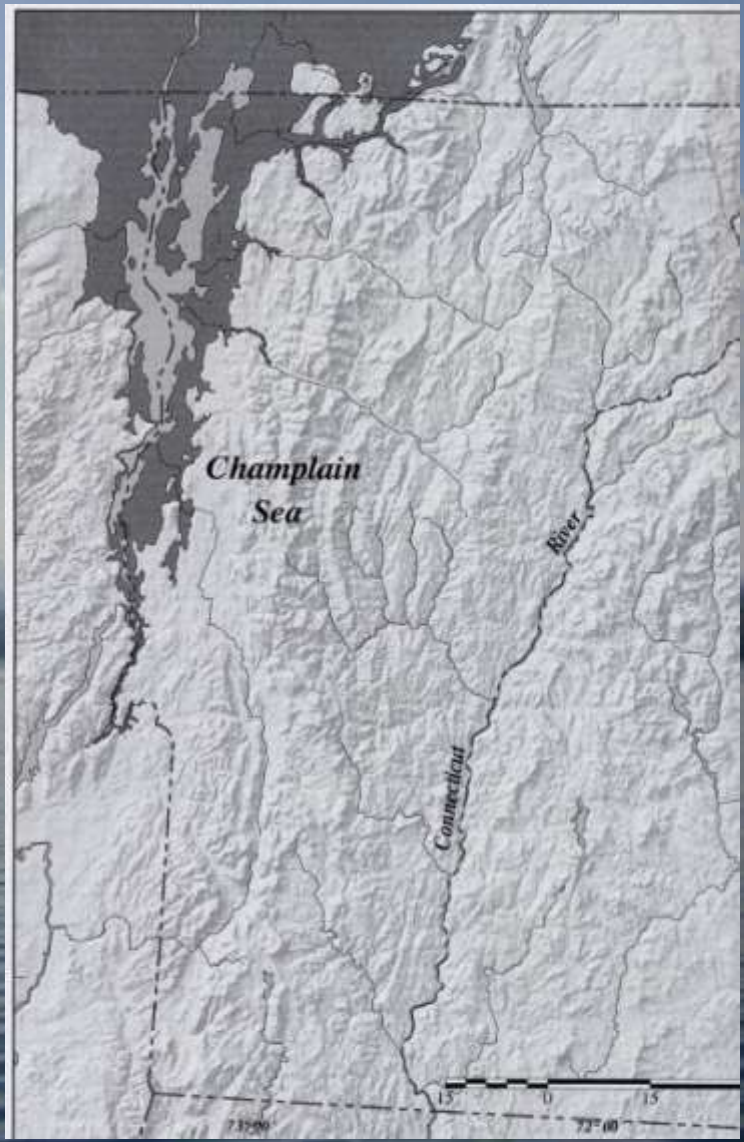
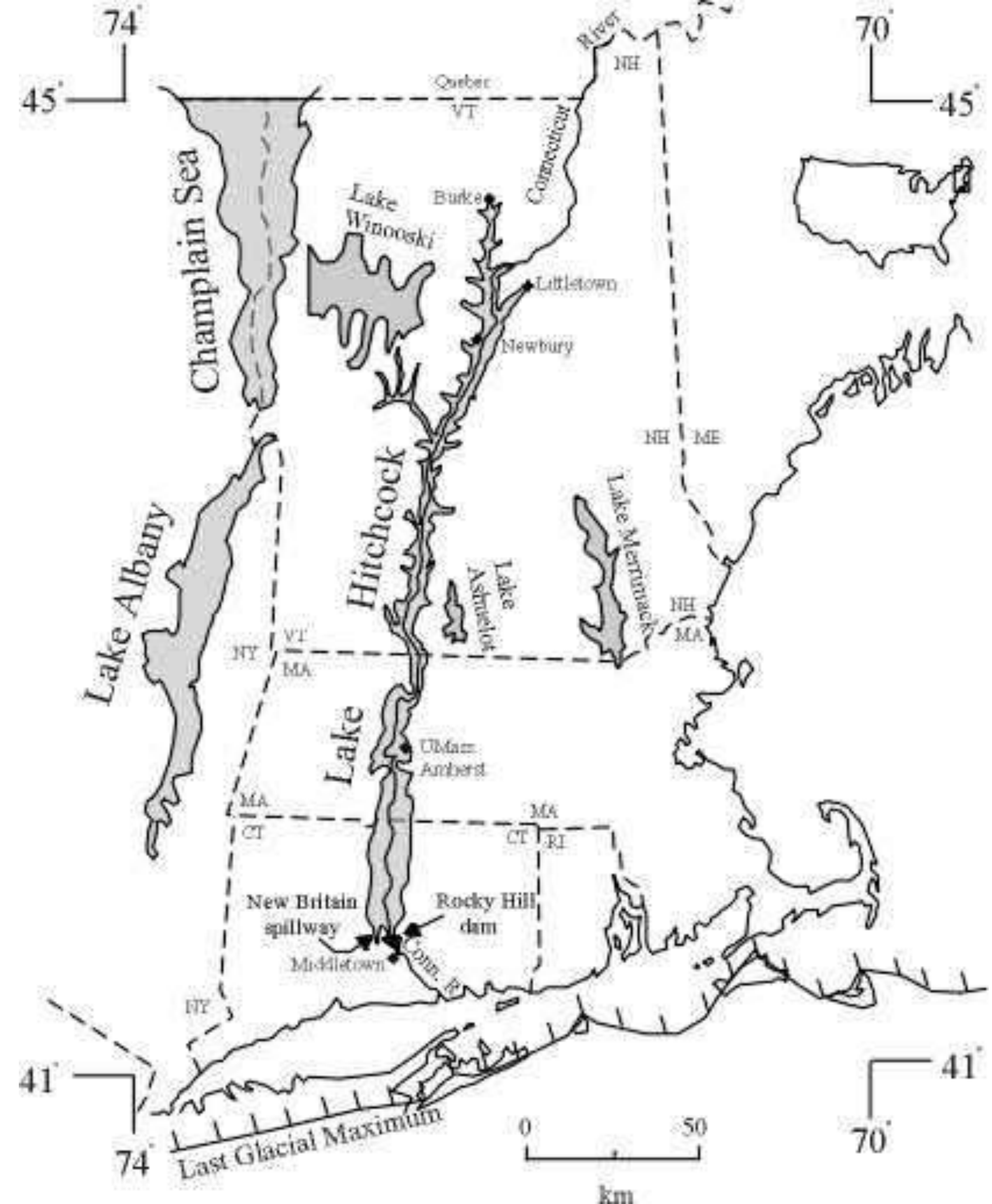
© Rolf Hicker

Lake Vermont



Champlain Sea

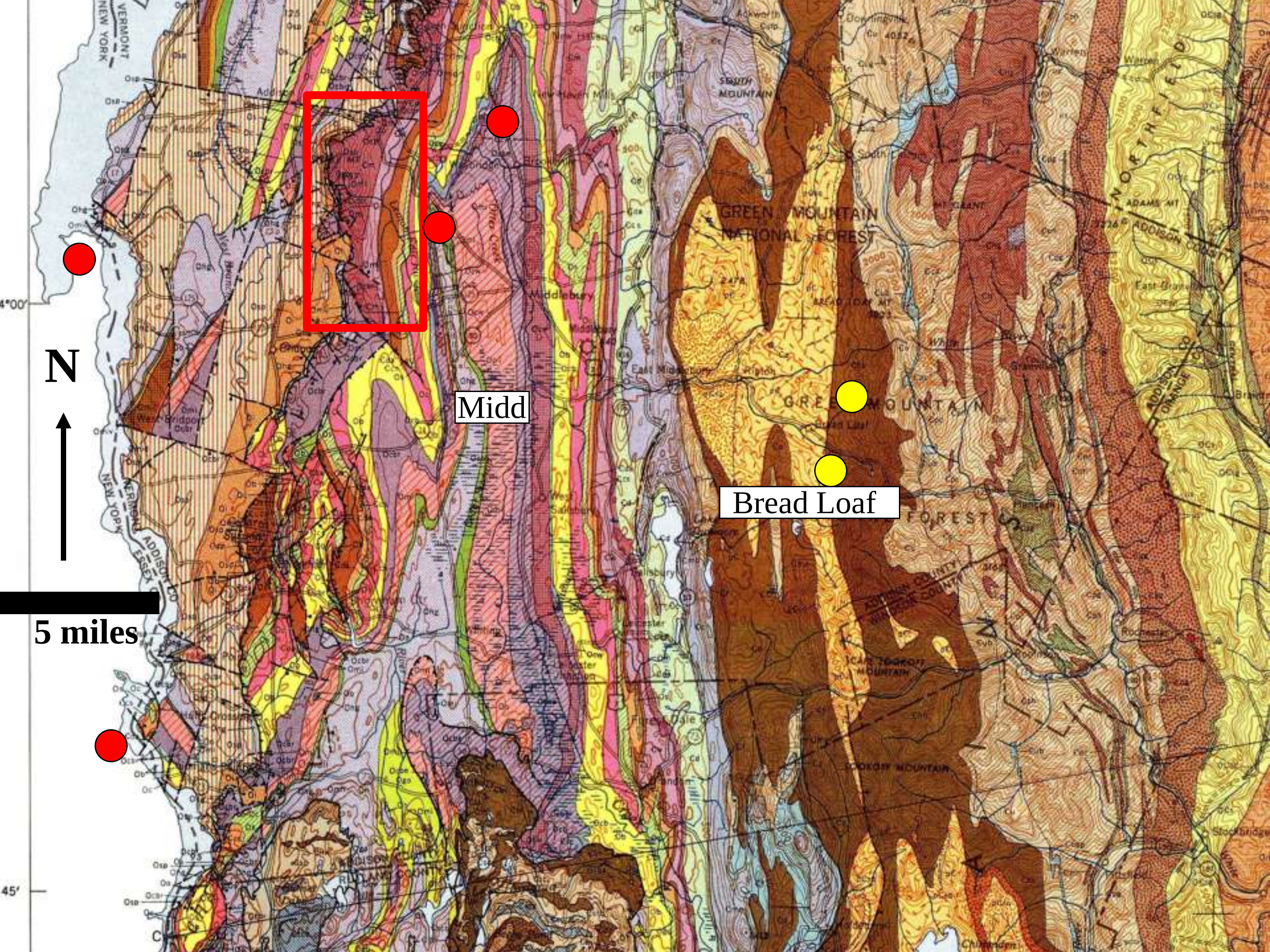



74°
45°
70°
45°
41°
74°
41°
70°
Quebec
VT
NH
River
Connecticut
Champlain Sea
Lake Winooski
Burke
Littletown
Newbury
NH
ME
Lake Hitchcock
Lake Albany
Lake Ashuelot
Lake Merrimack
NH
MA
NY
VT
MA
UMass Amherst
MA
CT
MA
CT
RI
New Britain spillway
Rocky Hill dam
Middletown
Conn. R.
NY
Last Glacial Maximum
0
50
km

Varves – annual layers
~ 11 years

History of Lake Champlain

- ~15-13 ka Wisconsian Ice Sheet retreated, blocked meltwaters, and proglacial lakes (e.g. Lk Vermont) formed
- At 12 ka valley was isostatically depressed
  – St. Lawrence seaway flooded valley with marine waters
- By ~9 ka differential rebound brought valley above sea level and formed present-day Lake Champlain



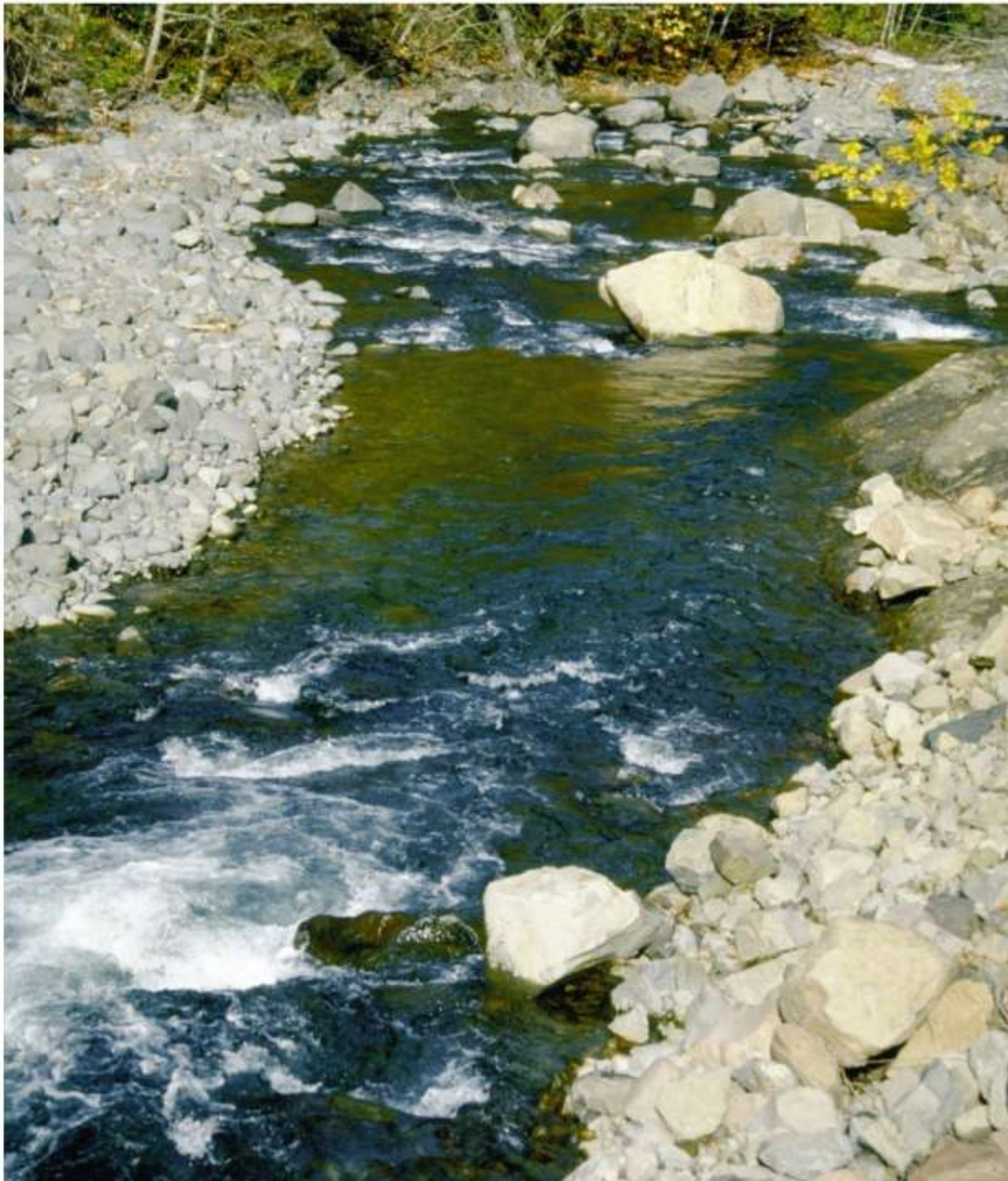
N
5 miles
Midd
Bread Loaf
VERMONT
NEW YORK
SOUTH MOUNTAIN
GREEN MOUNTAIN
NATIONAL FOREST
Middlebury
East Middlebury
NORTHFIELD
ADDISON CO.
ESSEX
FOREST

Although freshwater on the surface in the form of lakes, rivers and streams is quite small when compared to the total volume of water on the planet, it is important because of its accessibility and ~purity.

Green River, Wyoming

A stream is a body of water that flows downhill along a defined channel transporting solid particles and dissolved substances.

A river is simply a large stream.




Arctic Ocean
Hudson Bay
Pacific Ocean
Atlantic Ocean
Great Basin
Continental divide
Mississippi River
Gulf of Mexico
Drainage divide
Mississippi River basin limit

FIGURE 14.6

Vermont Watersheds

Longitudinal Profile

(similar to Middlebury River)

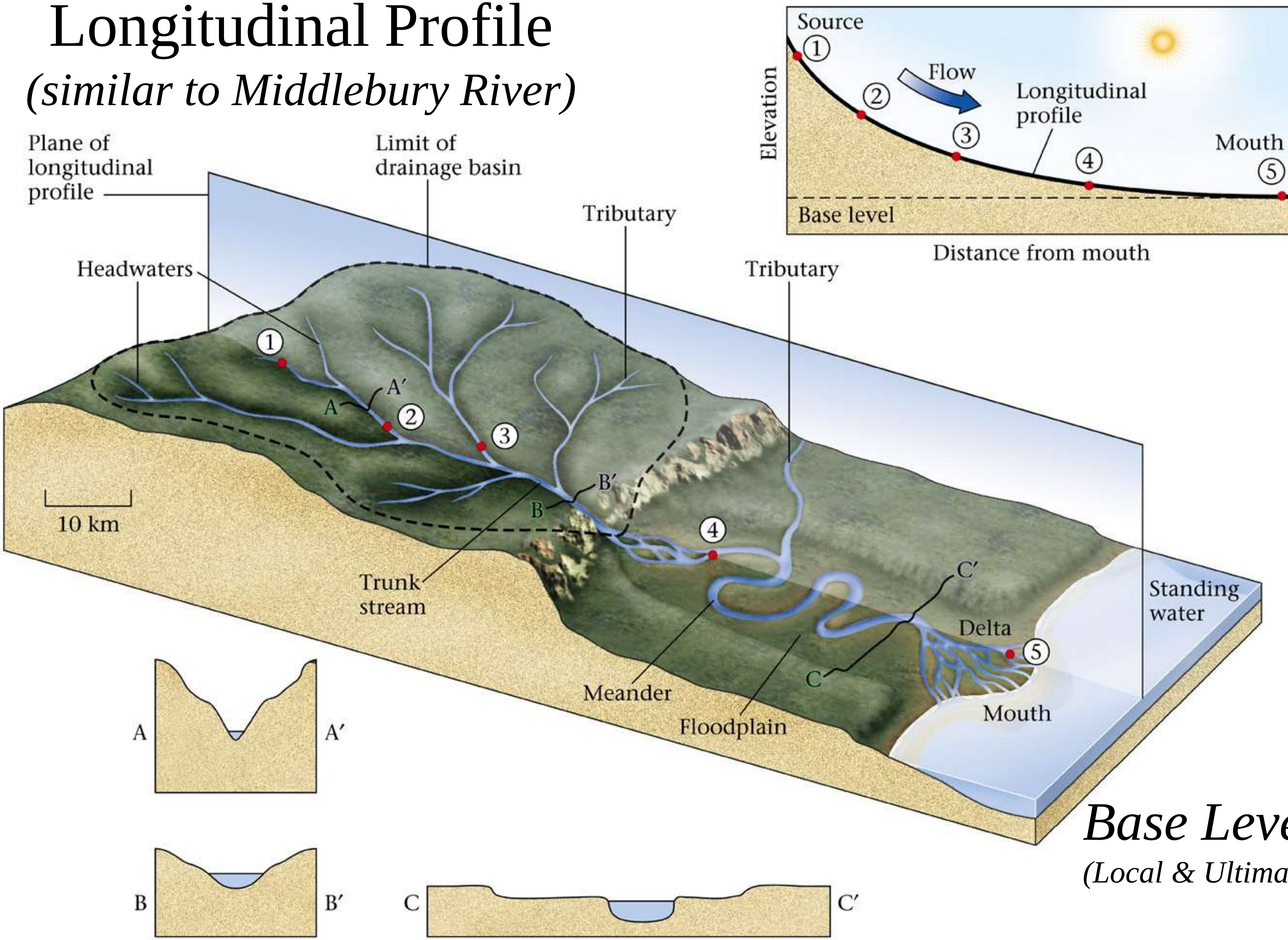
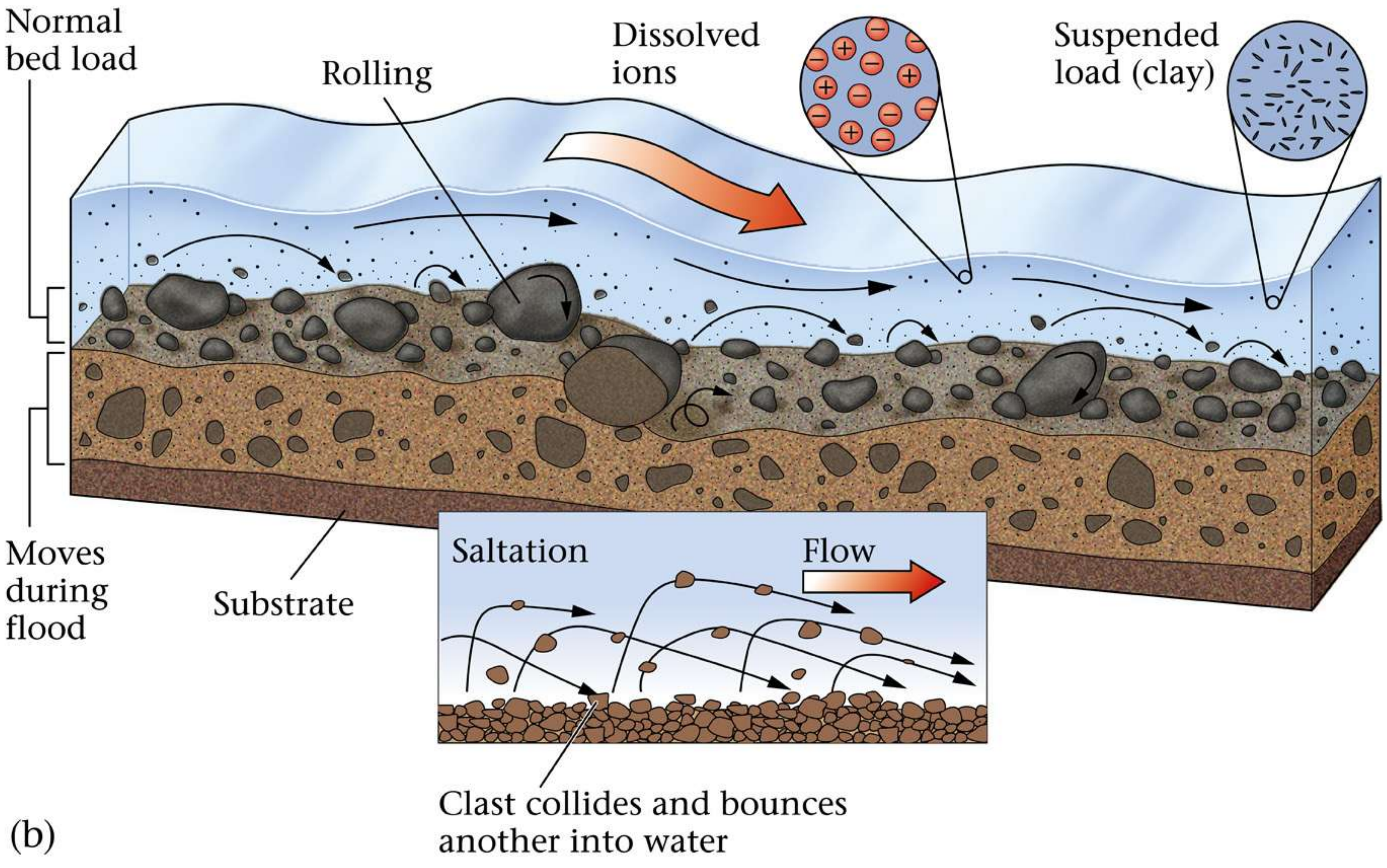


FIGURE 14.12 Cross-sectional profile

Base Level

(Local & Ultimate)

Sediment Transport in Streams



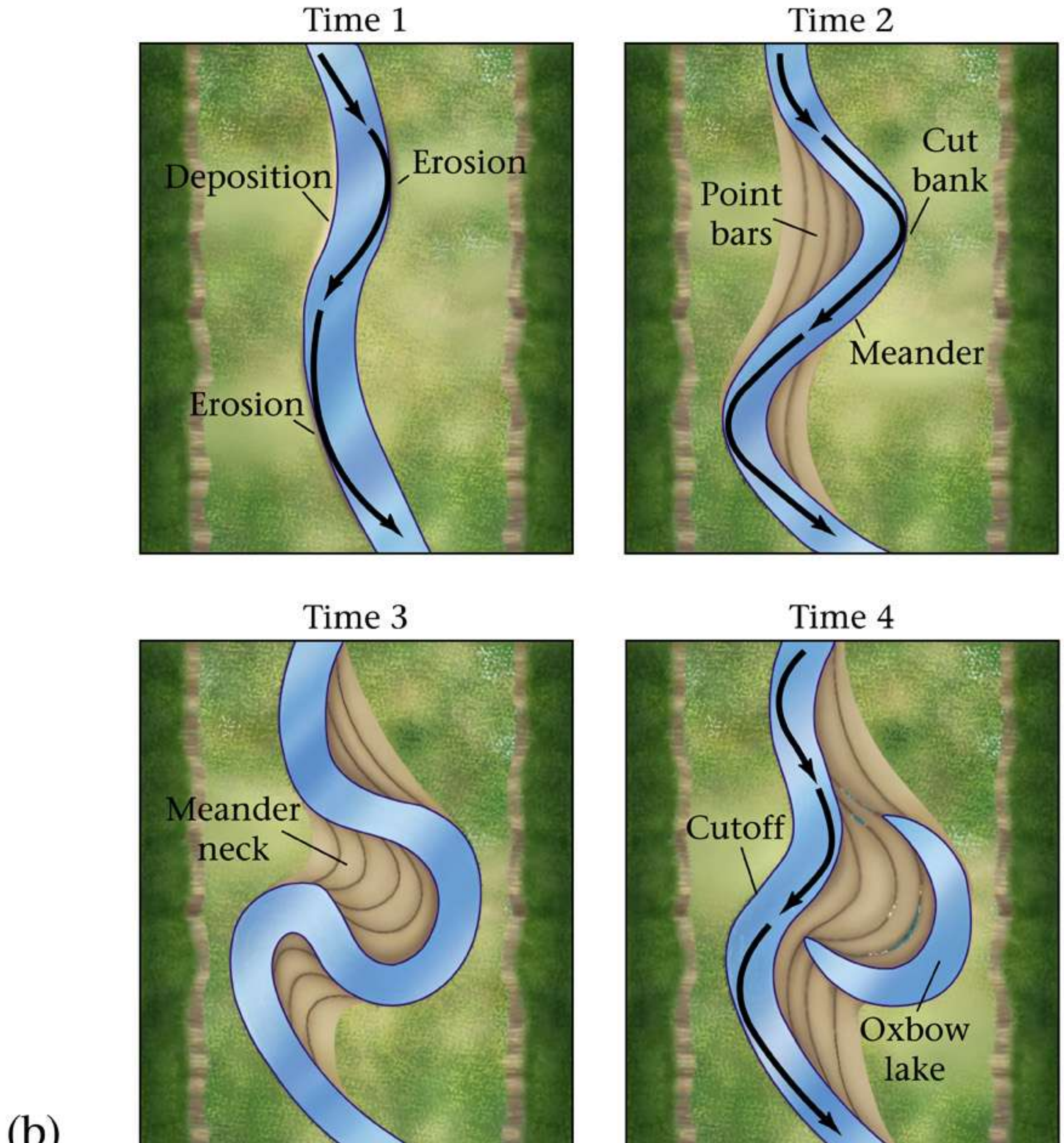
Stream Deposition (Alluvium)

Braided Stream

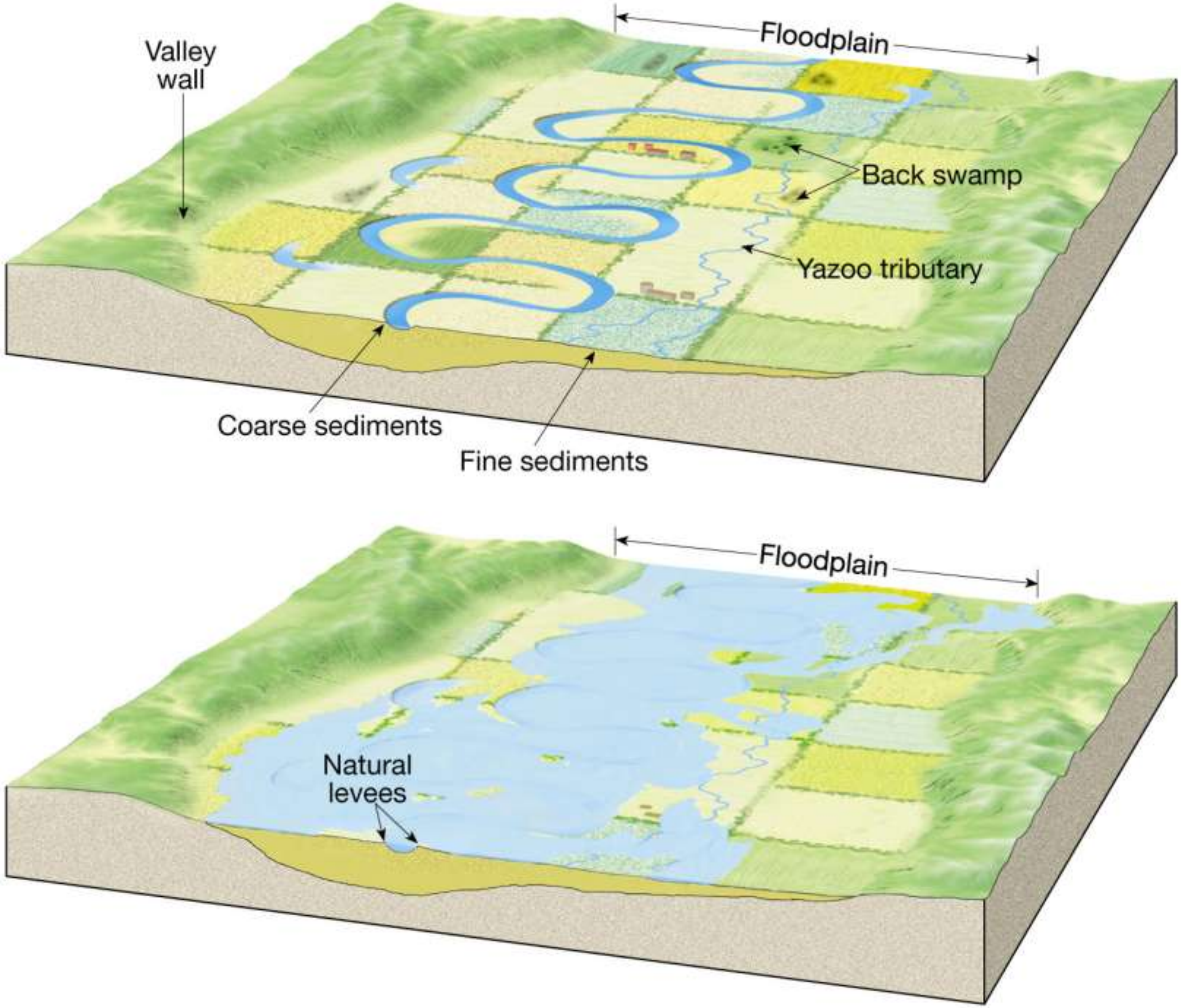

Meandering Stream

Point Bar

Cut Bank


Time 1
Deposition
Erosion
Erosion
Time 2
Point bars
Cut bank
Meander
Time 3
Meander neck
Time 4
Cutoff
Oxbow lake
(b)

Meandering Stream & Oxbow Lake


Floodplain
Valley wall
Back swamp
Yazoo tributary
Coarse sediments
Fine sediments
Floodplain
Natural levees

Fluvial Landscapes & Deposits

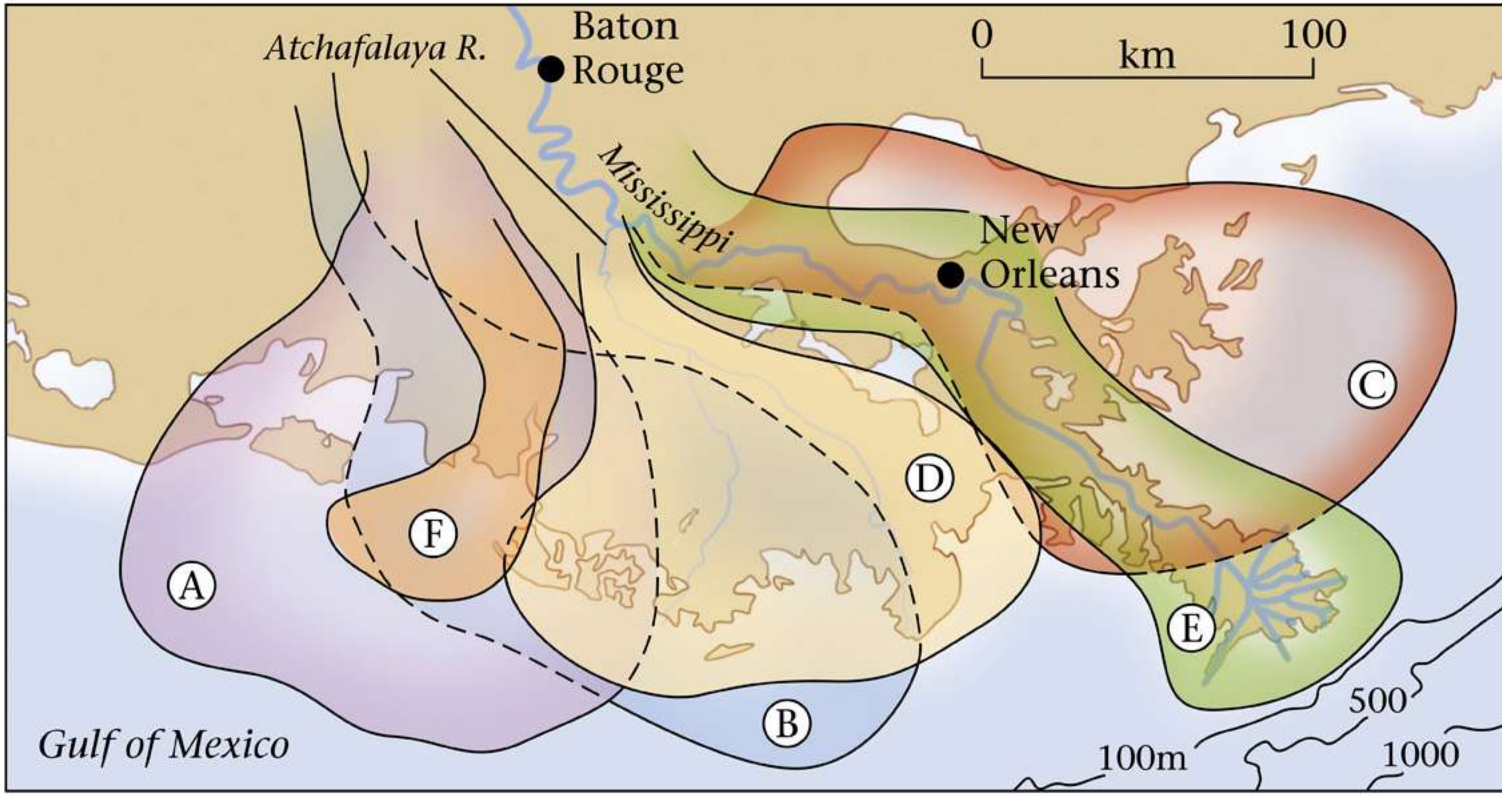
Canyons

Stream Deposition (Alluvium)

Sediment Deposition -- Deltas

Niger
River
Delta

Mississippi River Delta



Delta deposit	Age (years)
(F)	400 b.p. – present
(E)	1,000 b.p. – present
(D)	2,500 b.p. – 800 b.p.
(C)	4,000 b.p. – 2,000 b.p.
(B)	5,500 b.p. – 3,800 b.p.
(A)	7,500 b.p. – 5,000 b.p.

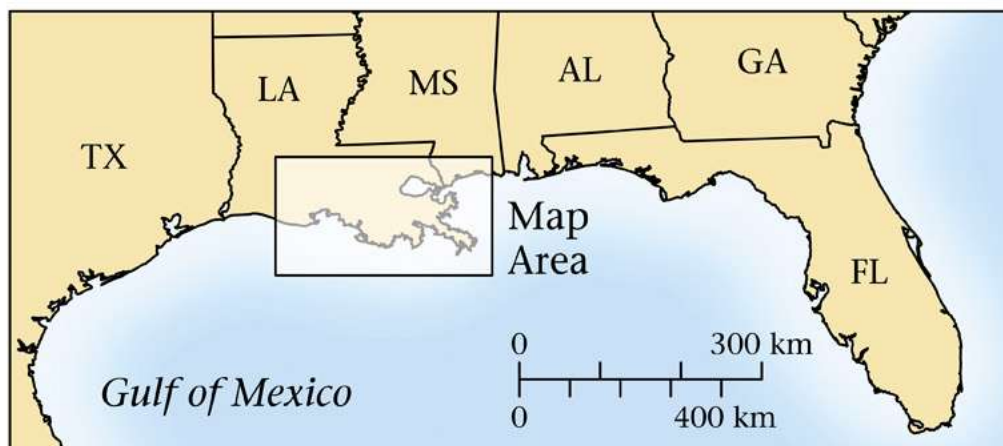
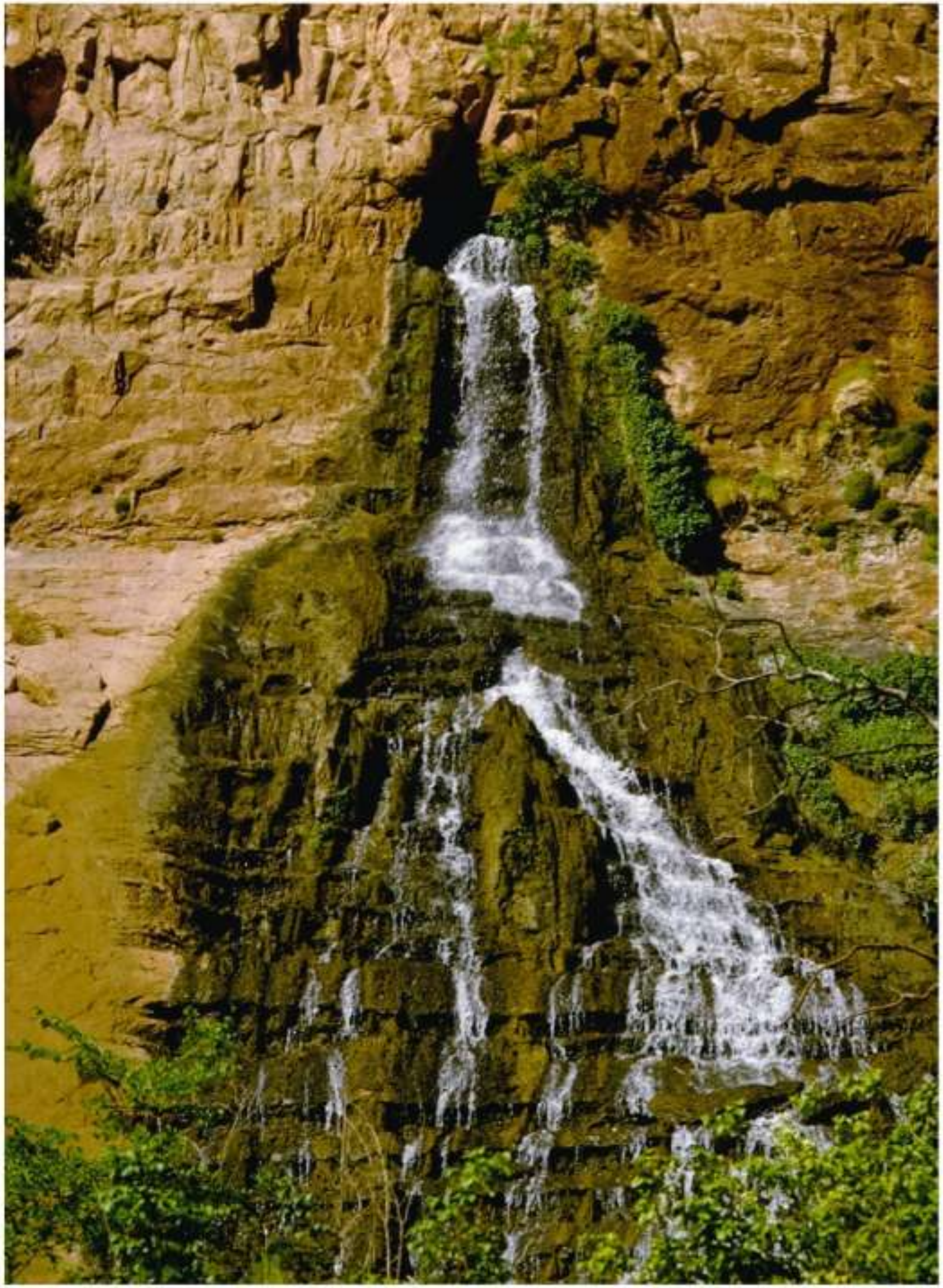


FIGURE 14.23

Delta in mountain lake, Maroon Bells, CO

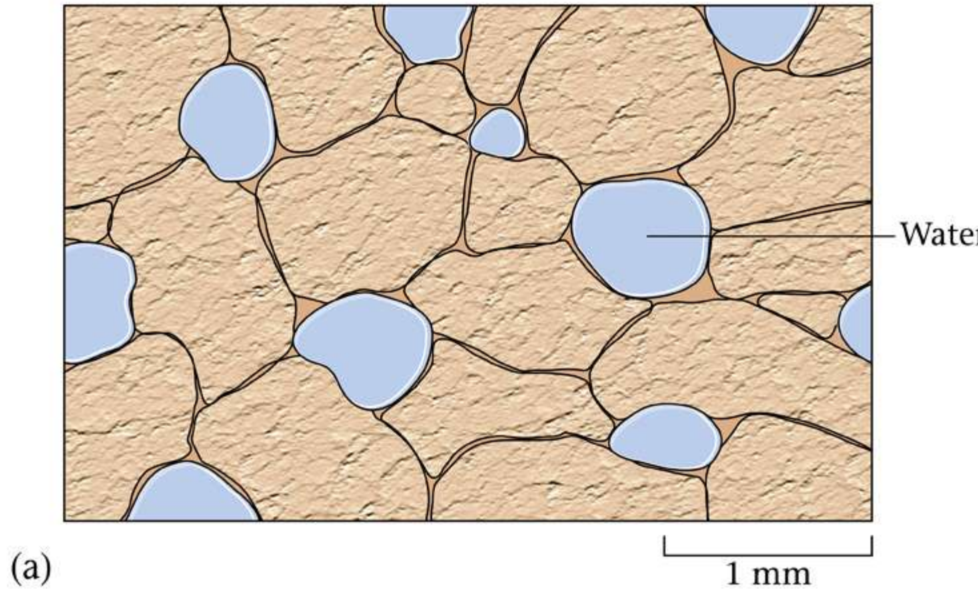
Groundwater

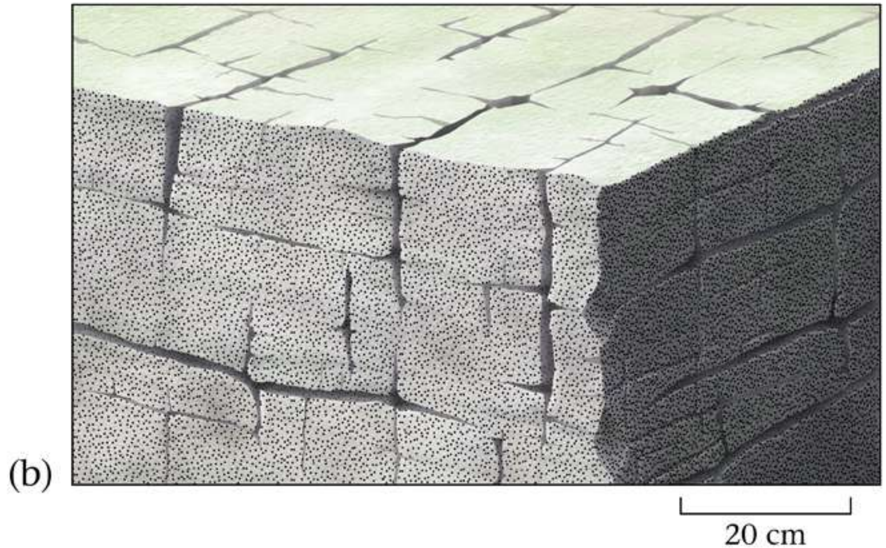
An extremely important hidden reserve of fresh clean water

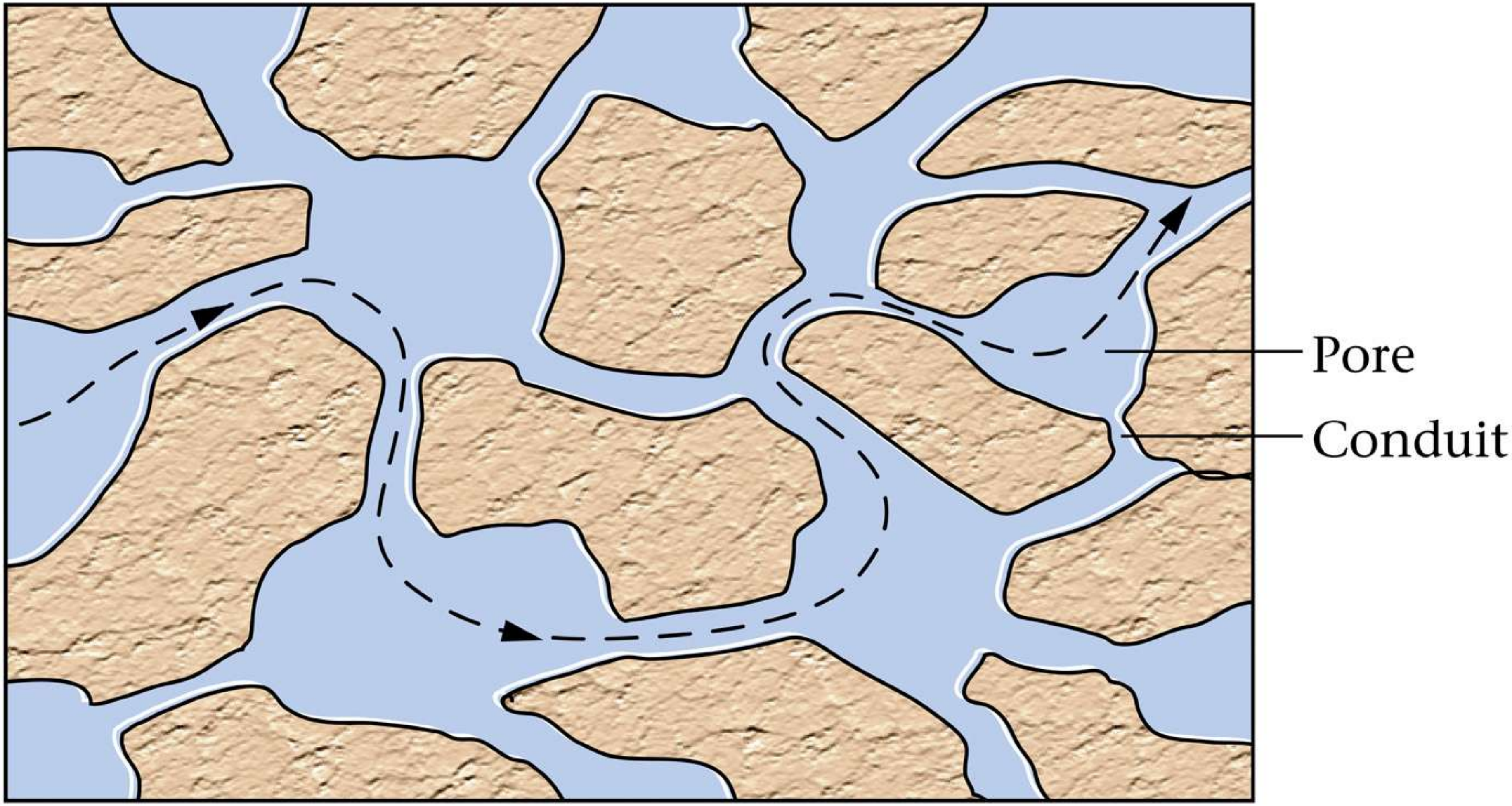


Porosity

% empty space in a material

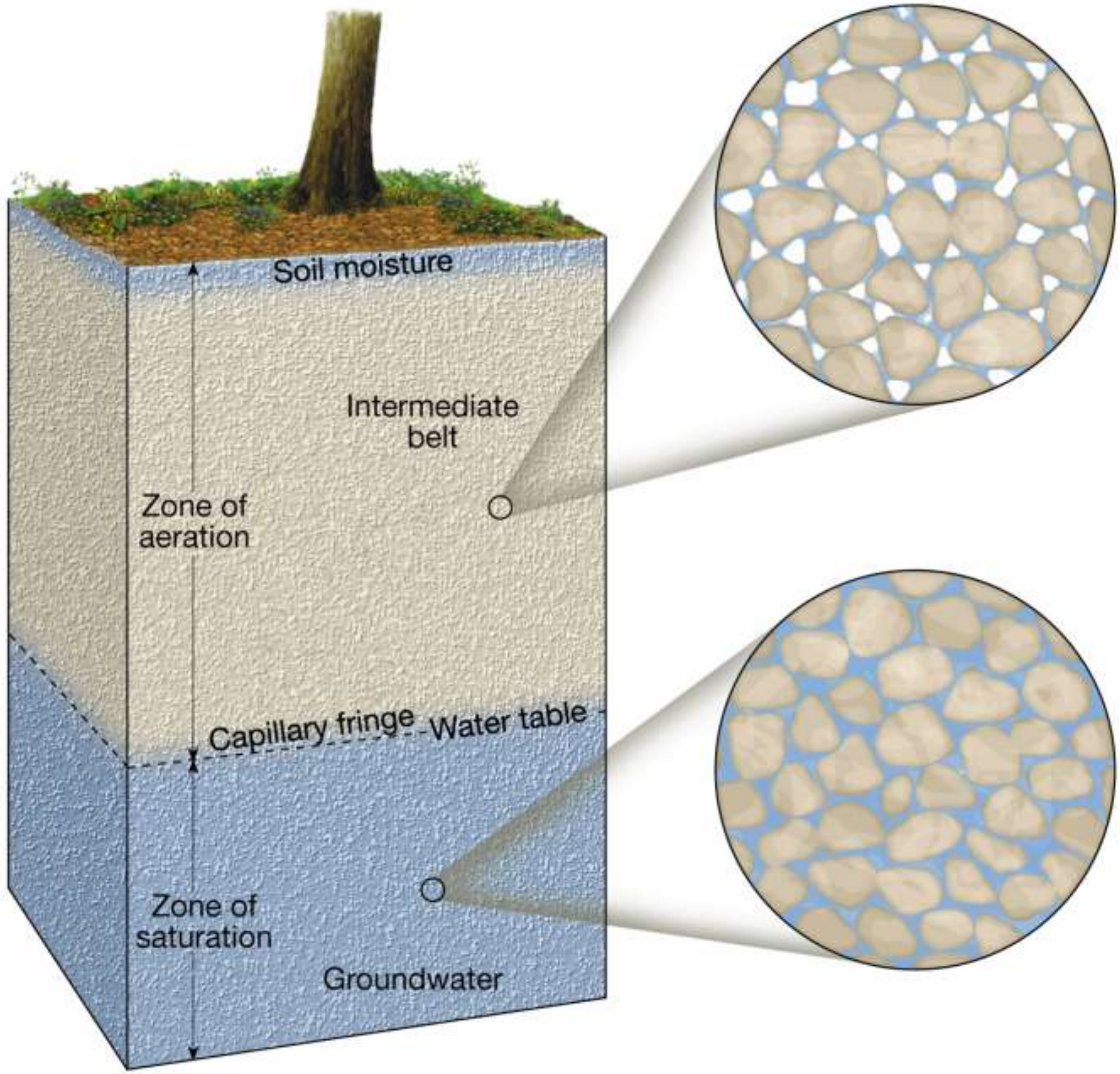




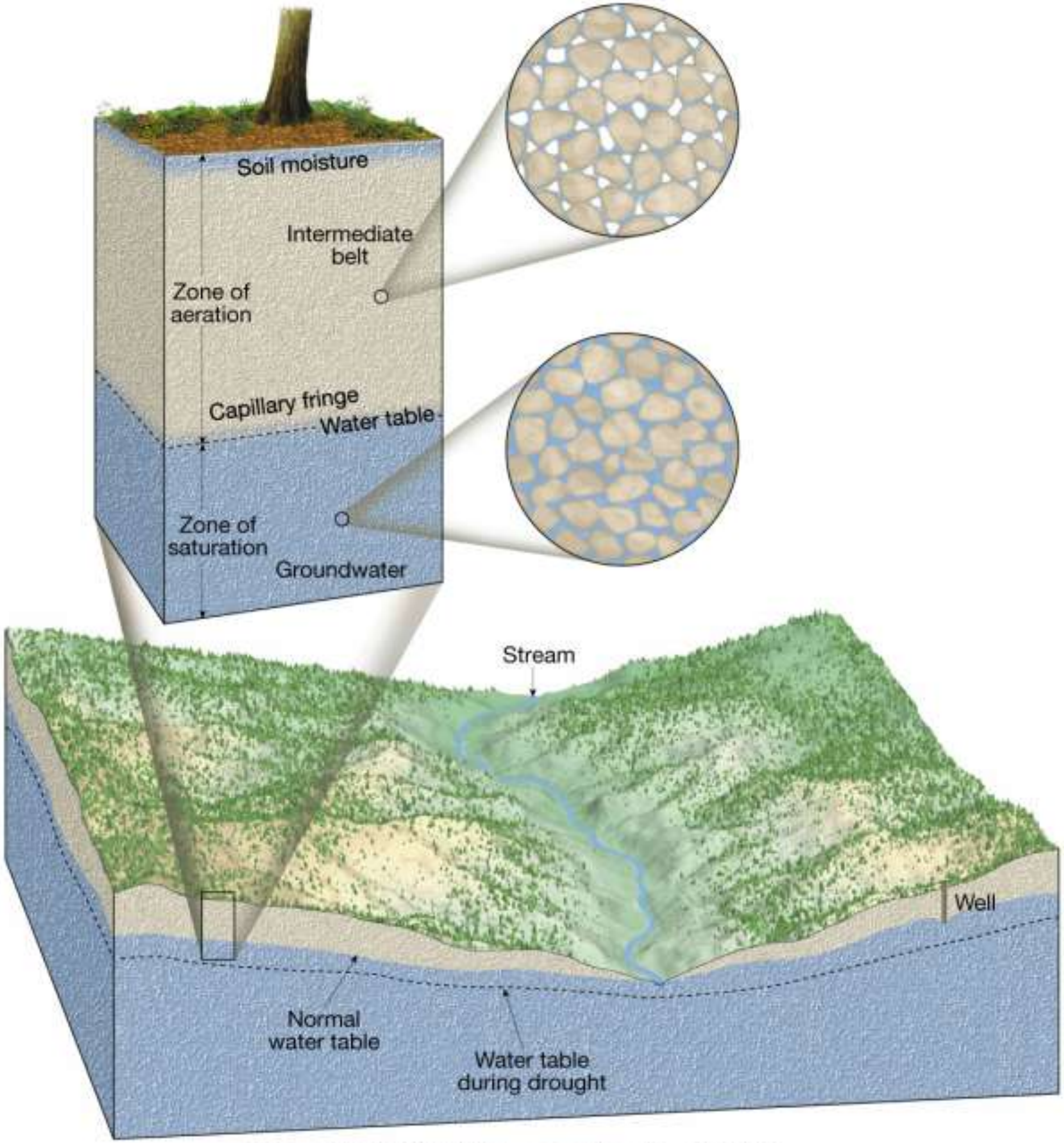


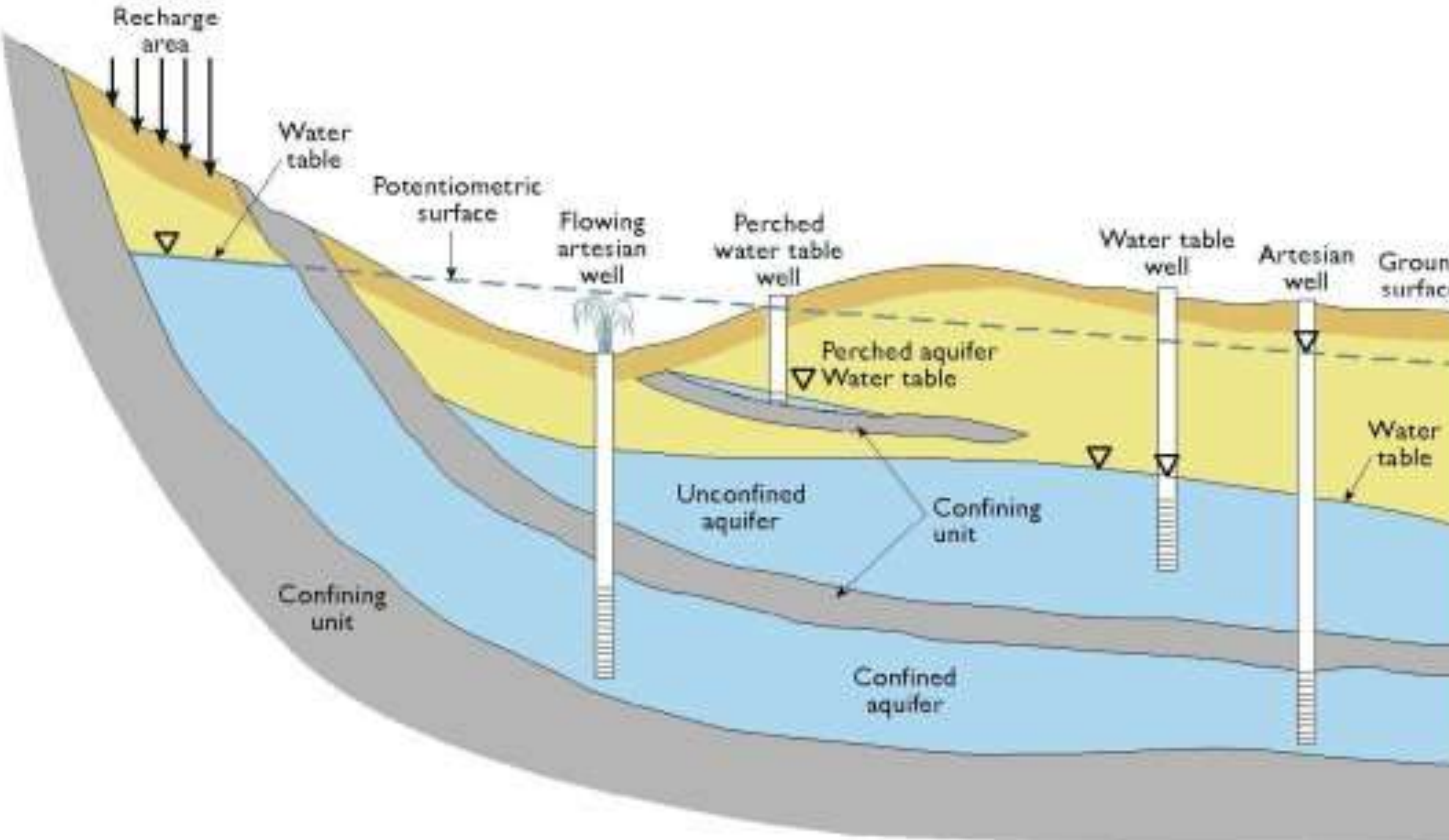
Permeability – measure of the ability of a material to **transmit** fluids. It depends on the connectivity of the pores

Water Table

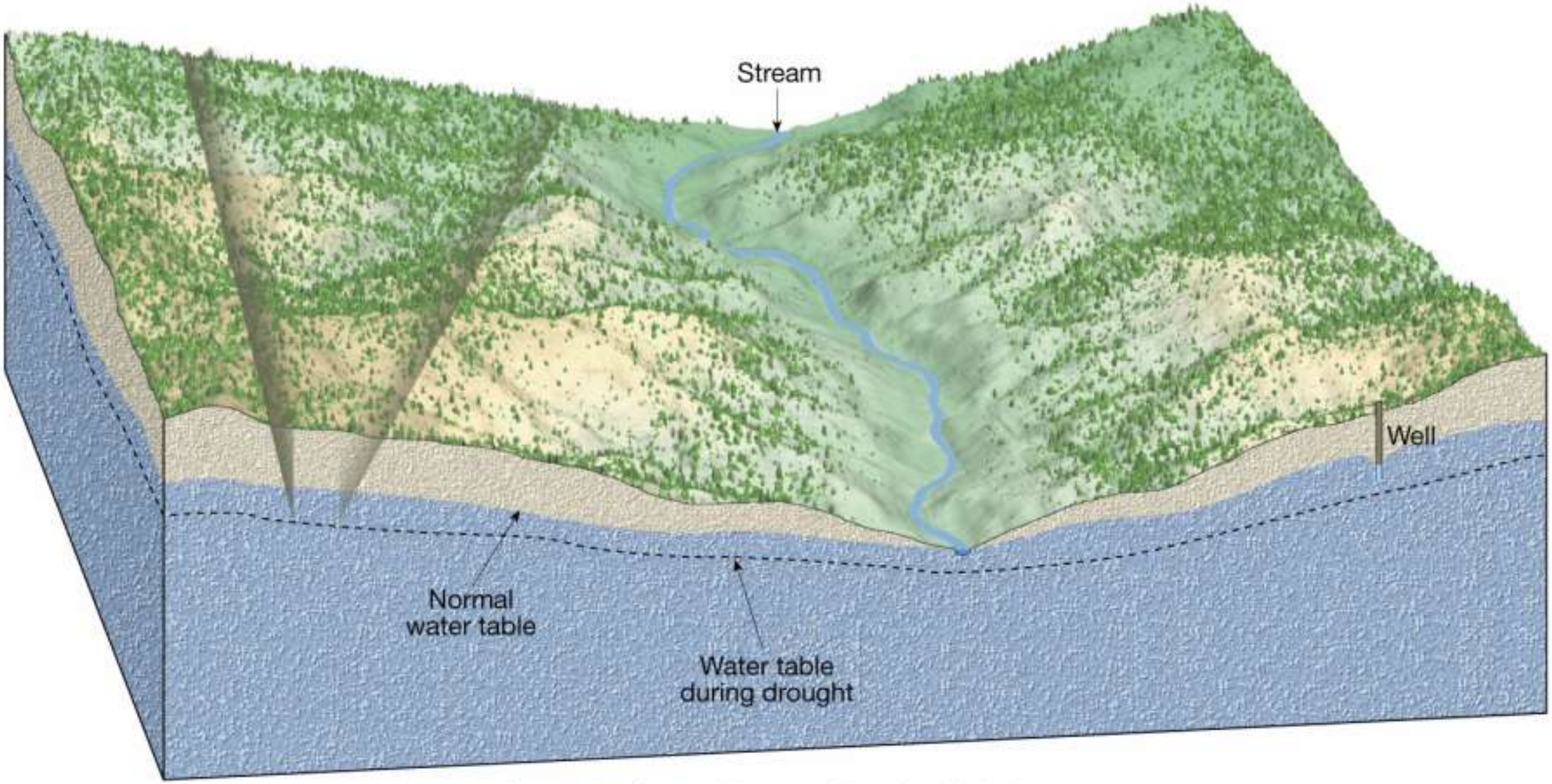


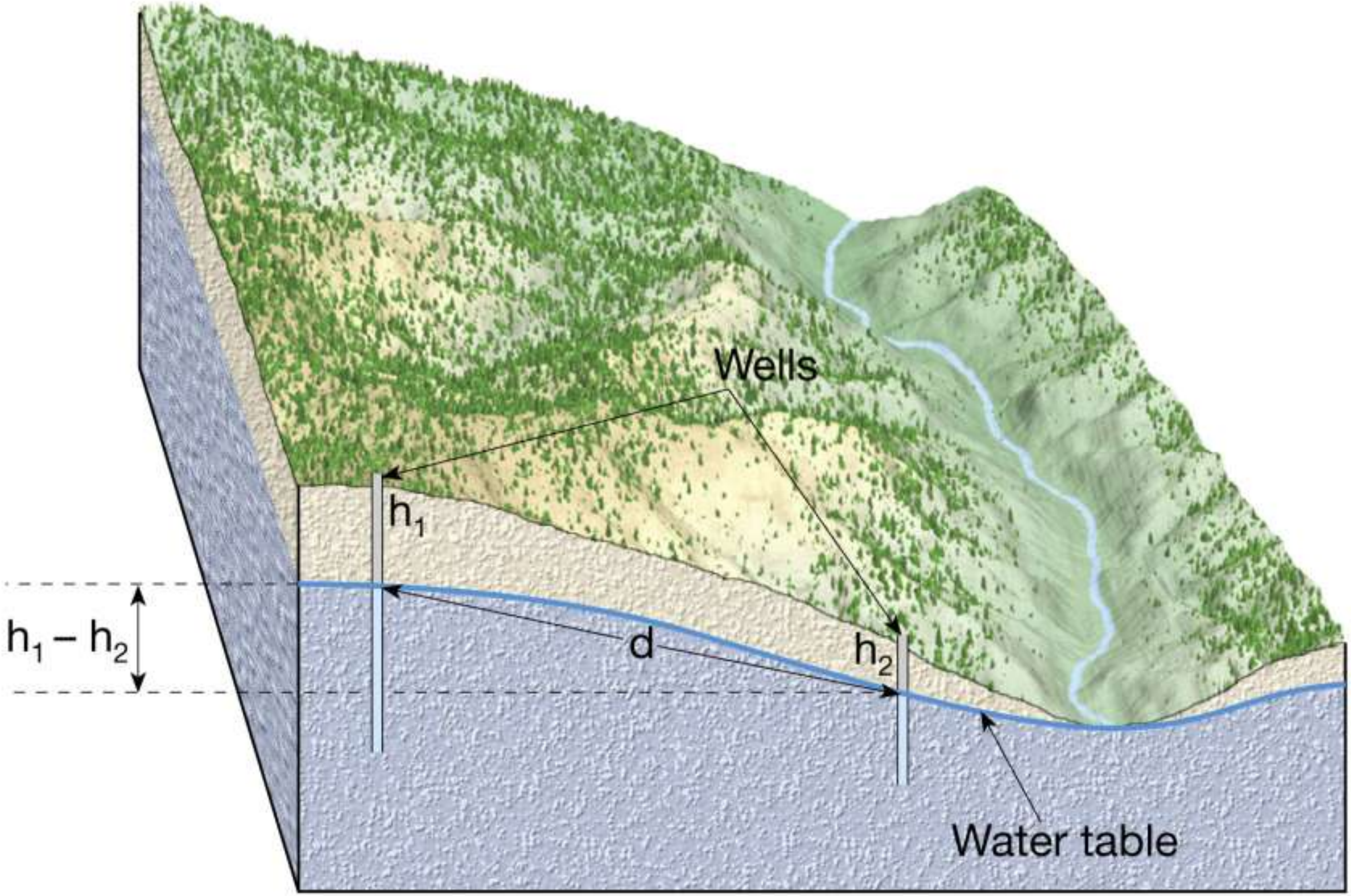
Soil moisture
Intermediate
belt
Zone of
aeration
Capillary fringe
Water table
Zone of
saturation
Groundwater


Soil moisture
Intermediate belt
Zone of aeration
Capillary fringe
Water table
Zone of saturation
Groundwater
Stream
Well
Normal water table
Water table during drought

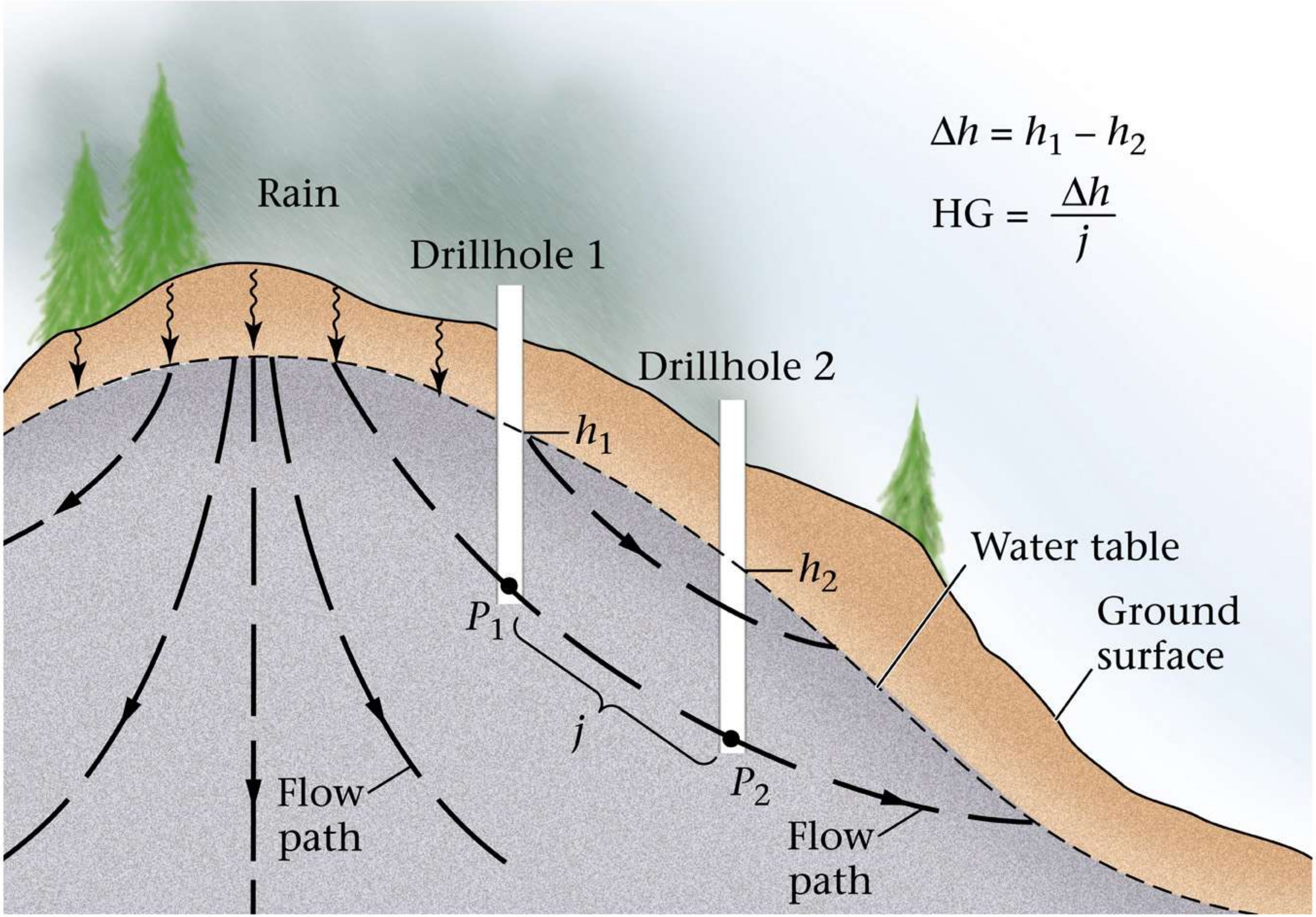


Modified after Harlan and others, 1989


Stream
Well
Normal
water table
Water table
during drought



$$\text{Hydraulic gradient} = \frac{h_1 - h_2}{d}$$



Essentials of Geology, 2nd Edition

FIGURE 16.9