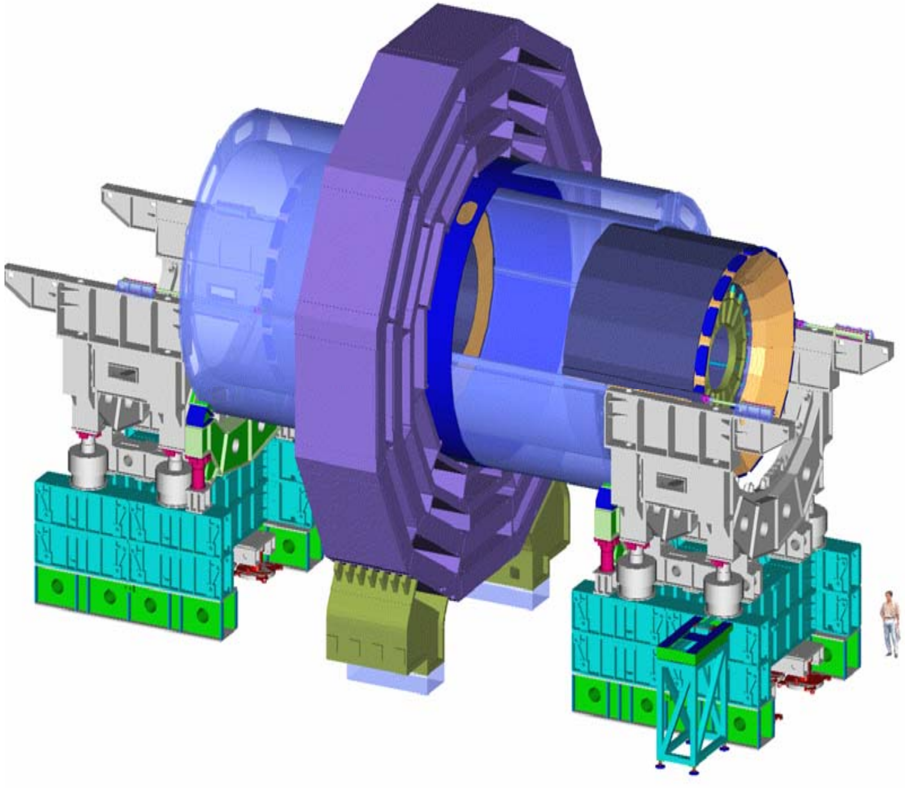
CMS HCAL and the Bronze Age

Jim Freeman

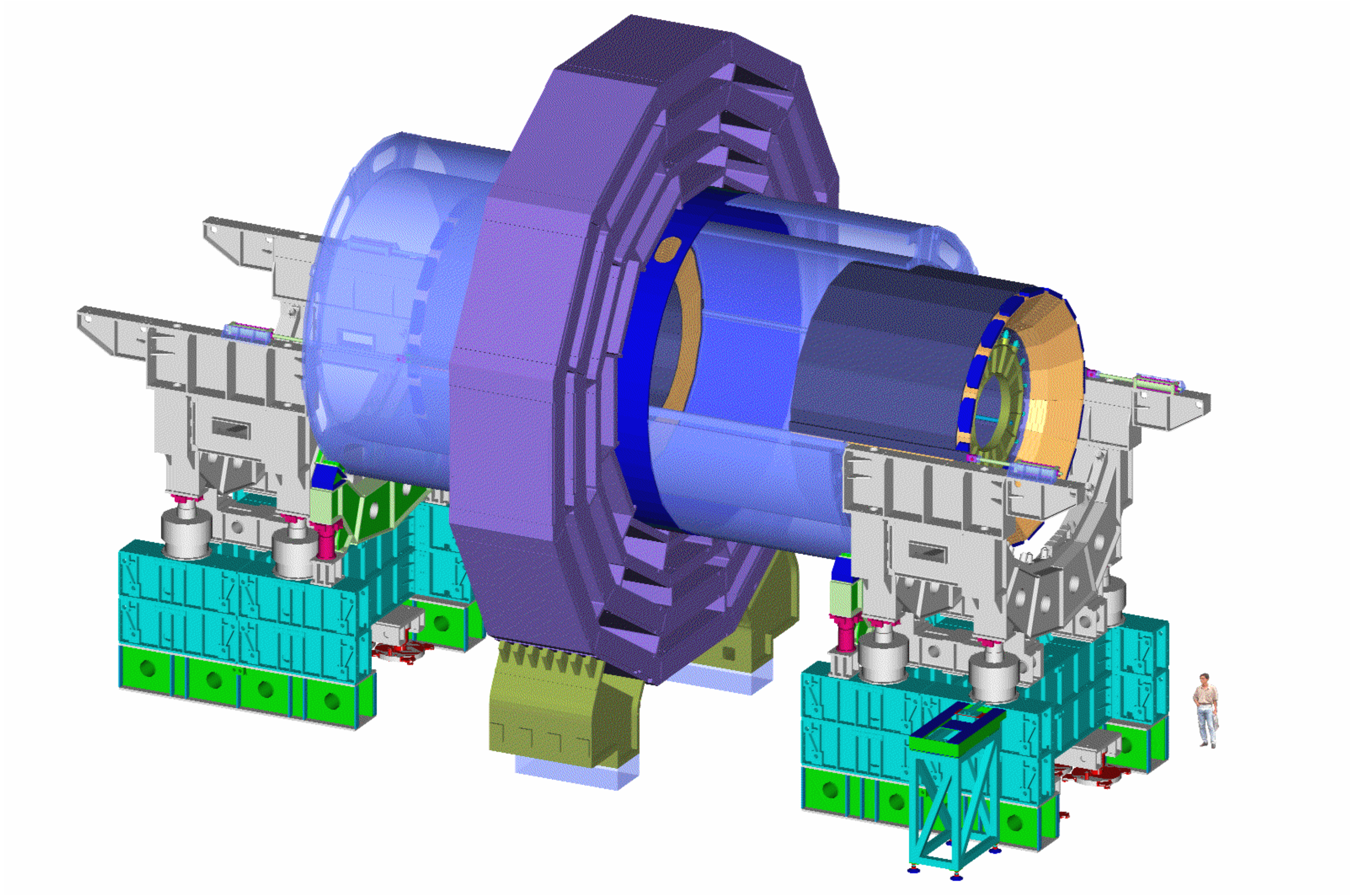
Fermilab



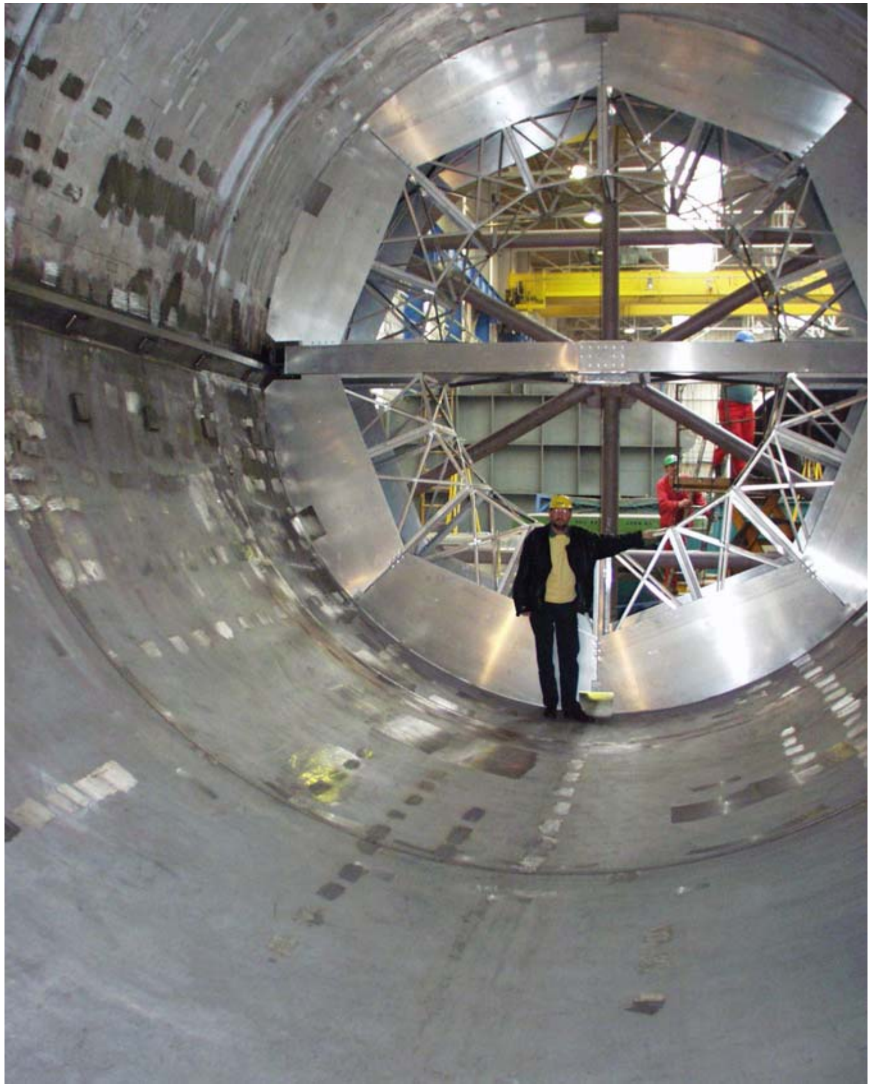
A Rambling Walk through CMS HCAL, where its copper came from, and its scale compared to other large copper works.

Jim Freeman
Fermilab

HCAL being installed into the CMS Superconducting Magnet



The inside of the CMS superconducting magnet



HCAL : HE and HB

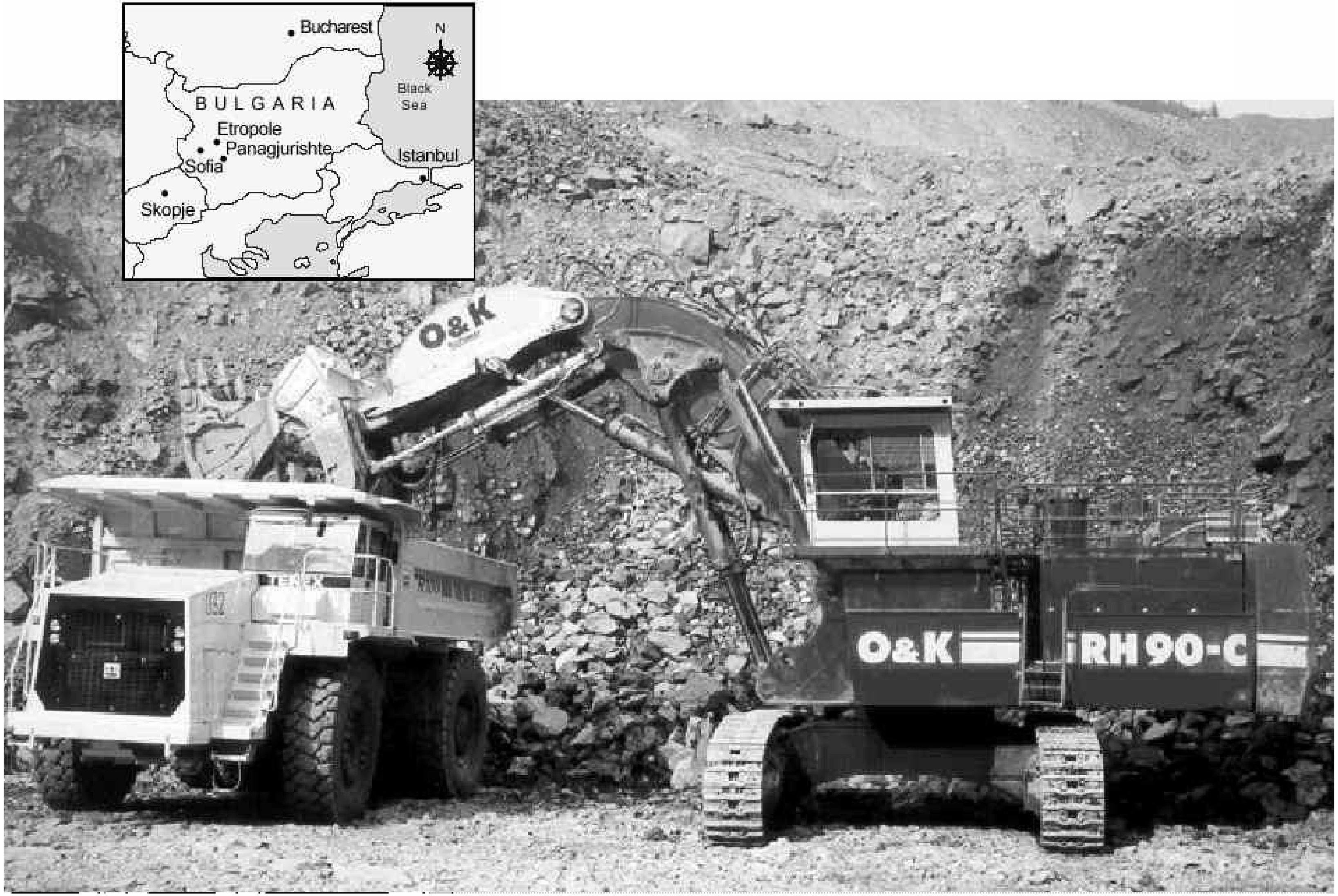
HB Wedges at machine shop

HCAL Copper

We bought the copper for HCAL in Bulgaria. This caused me to start thinking: Why Bulgaria? And thinking about the role and history copper has had in this region. Later, I also thought about the scale of HCAL compared to other things built out of copper. The answers to these questions are in this talk.

Southern Balkans

Open Pit Copper mine in Bulgaria

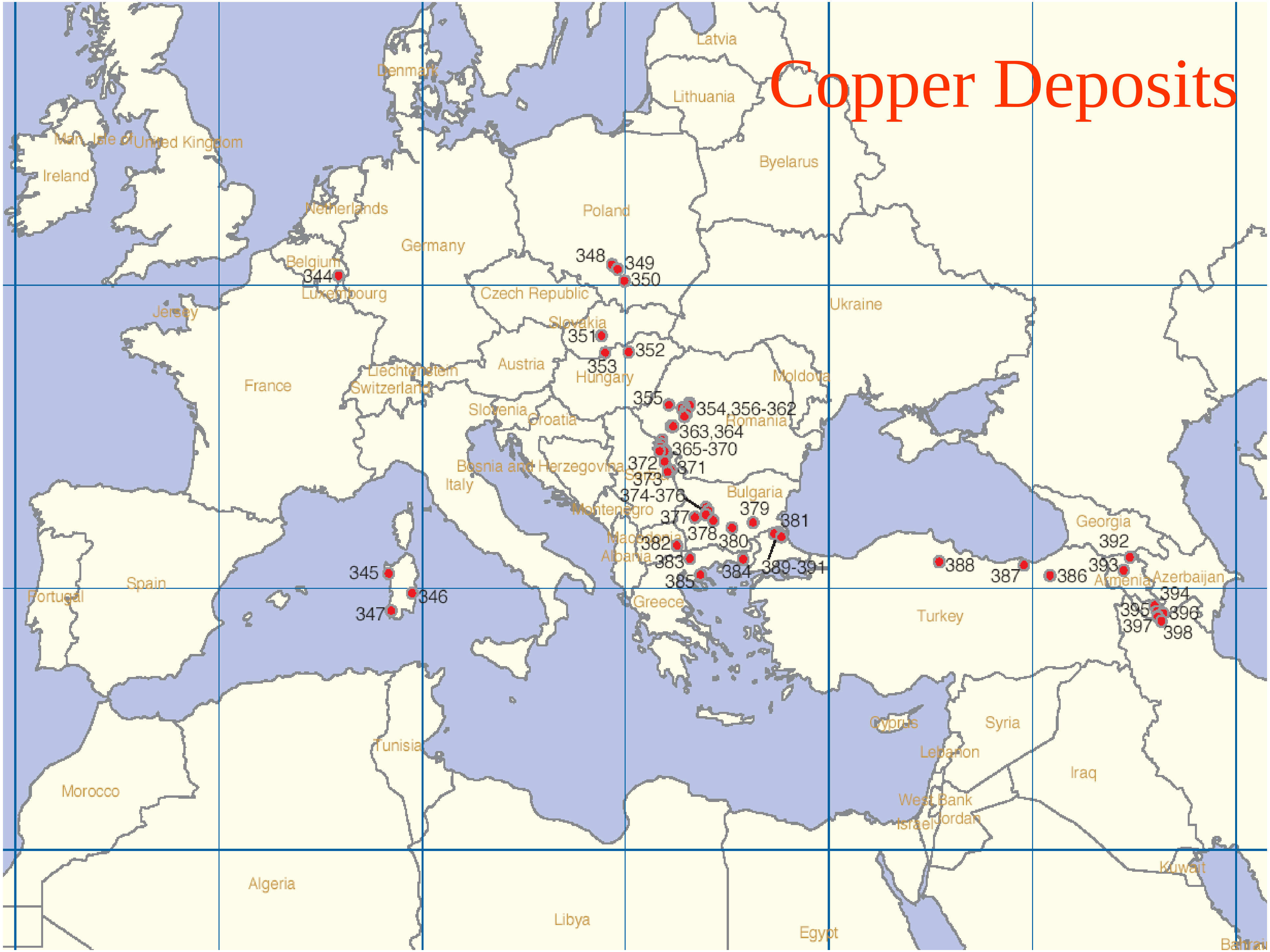


Copper in the Balkans

Copper is plentiful throughout the Balkans: Macedonia, Bulgaria, Albania. The Bronze age came into Europe through this region. Lots of copper ore is (or was) close to the surface, so mining is easy.

Question: Why is copper plentiful there?

Copper Deposits



World Copper Deposits

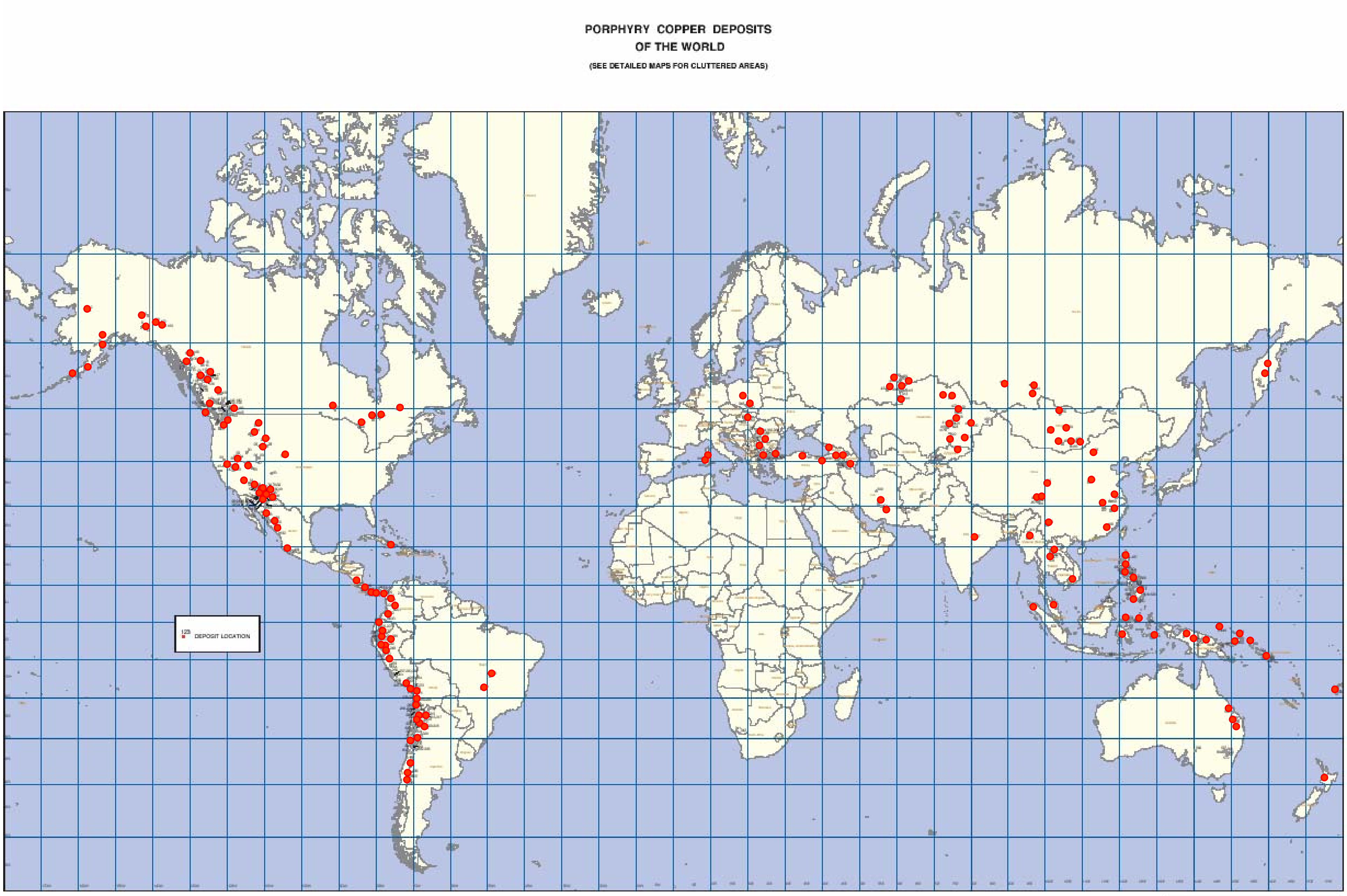
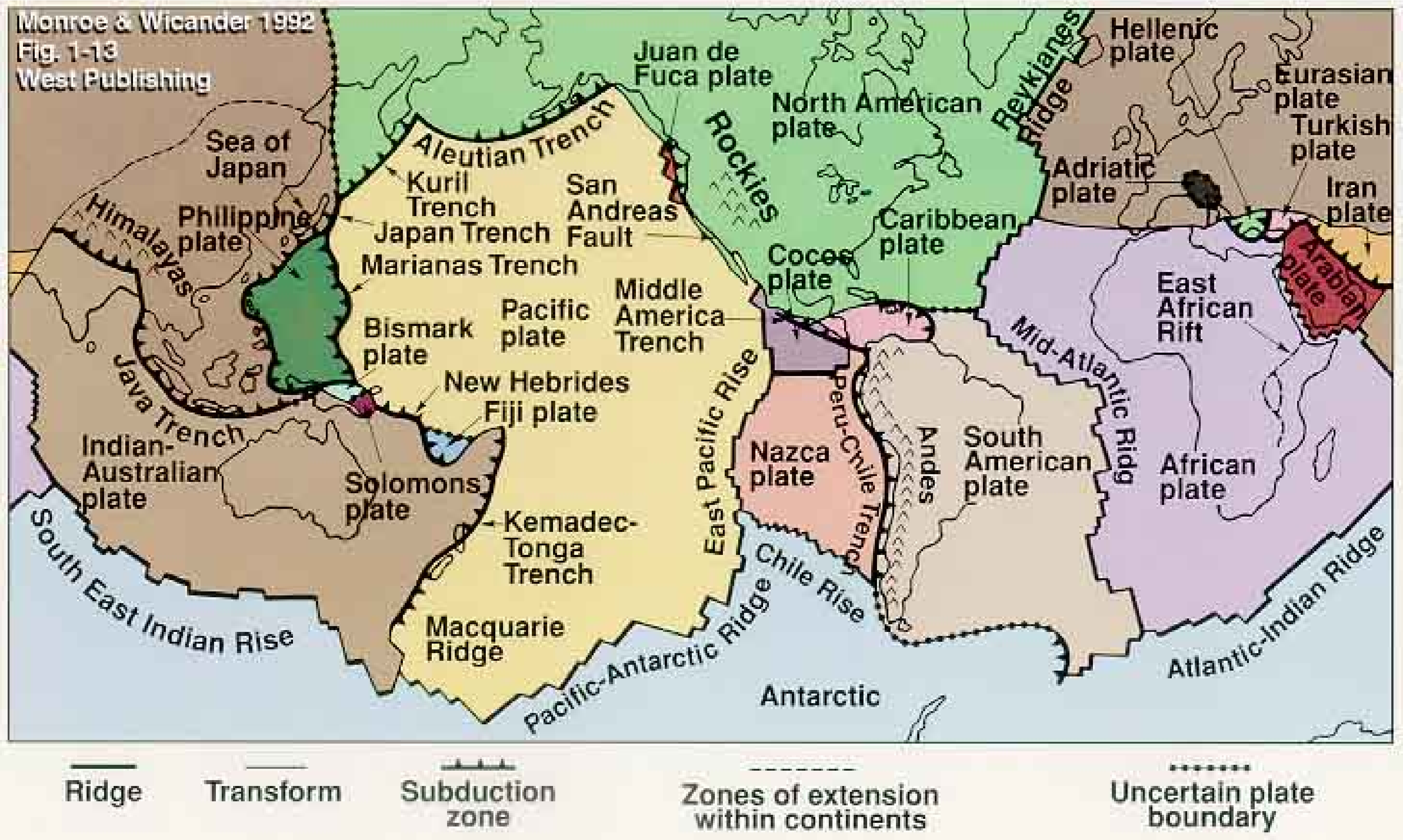
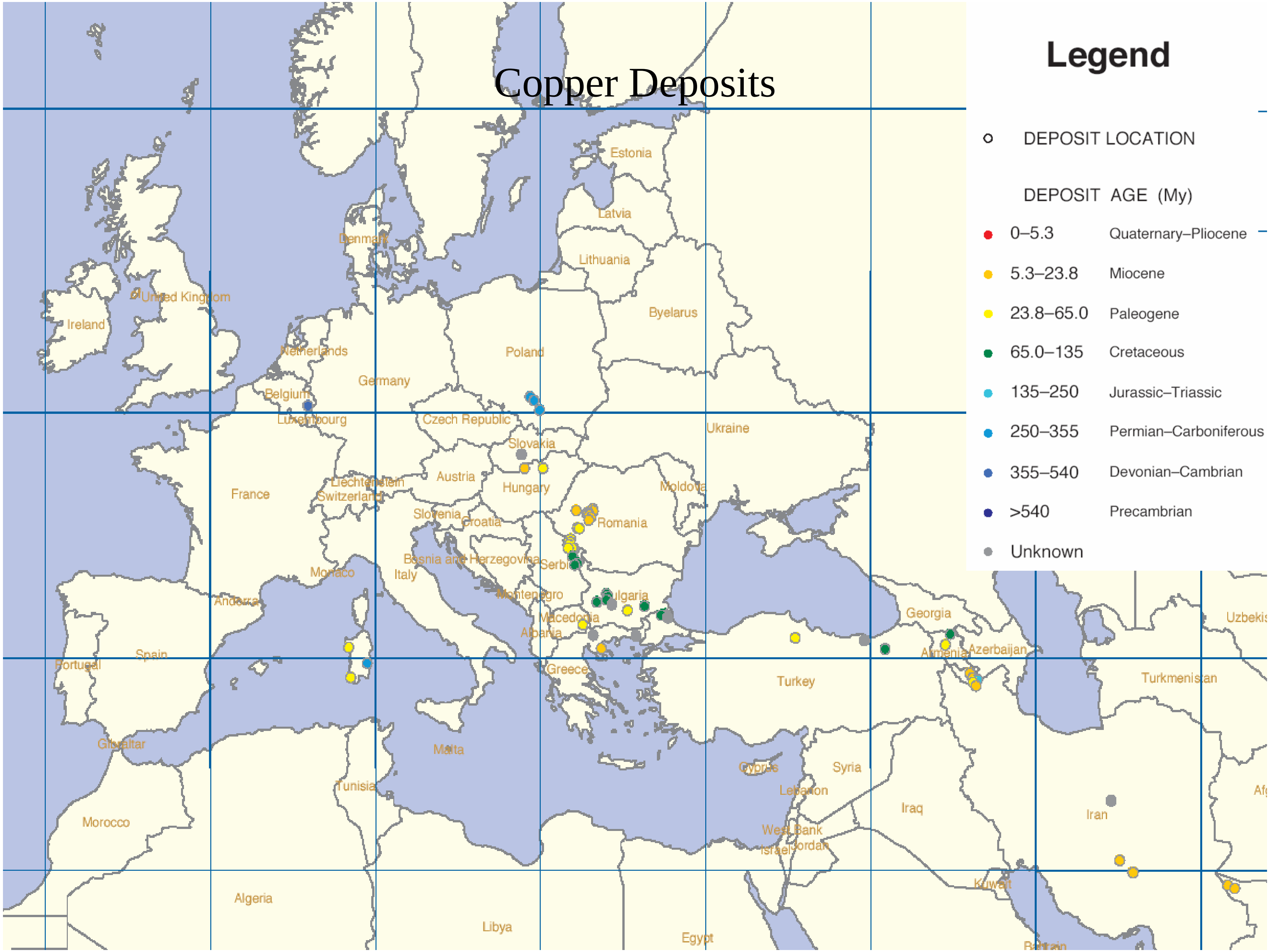
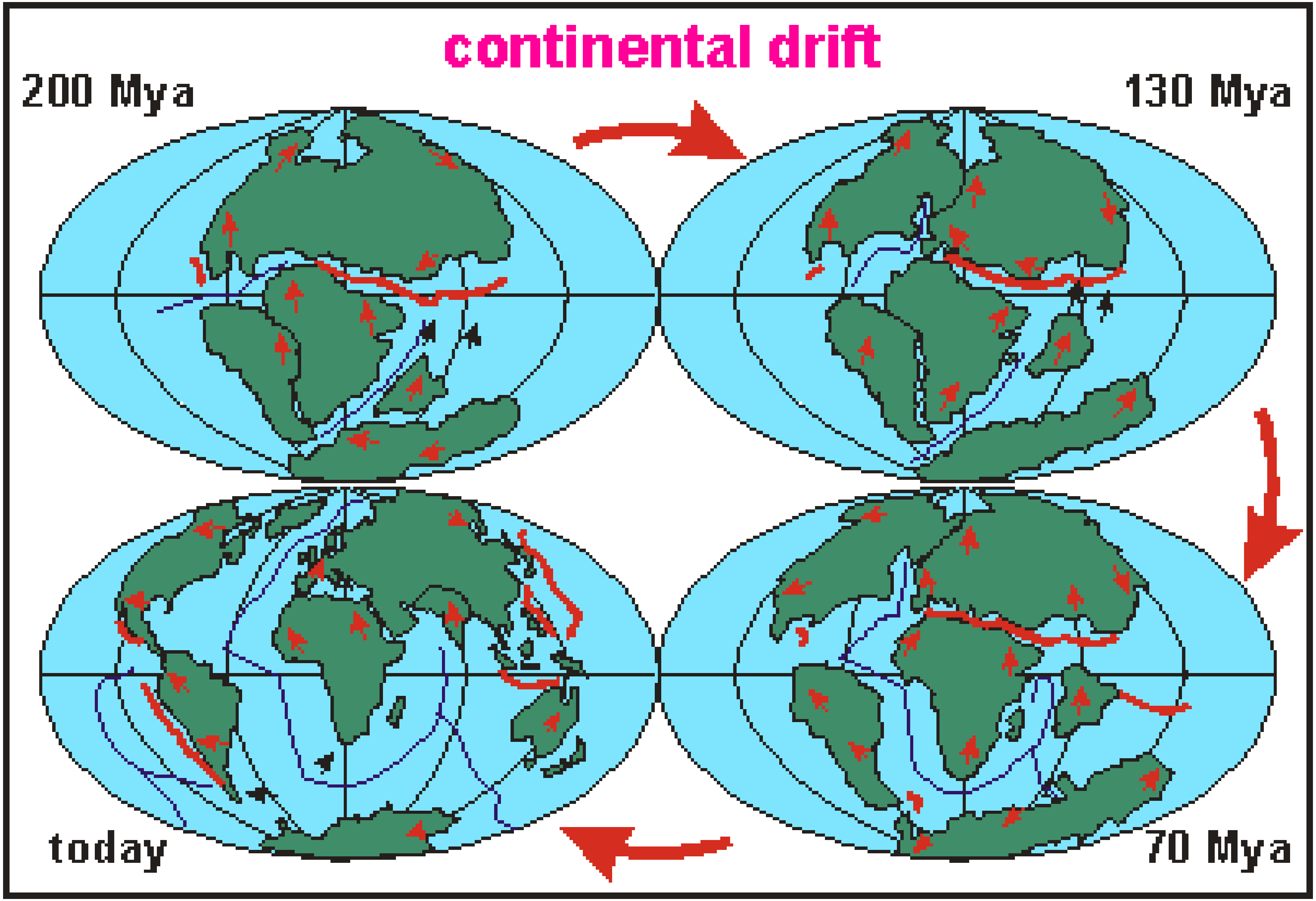


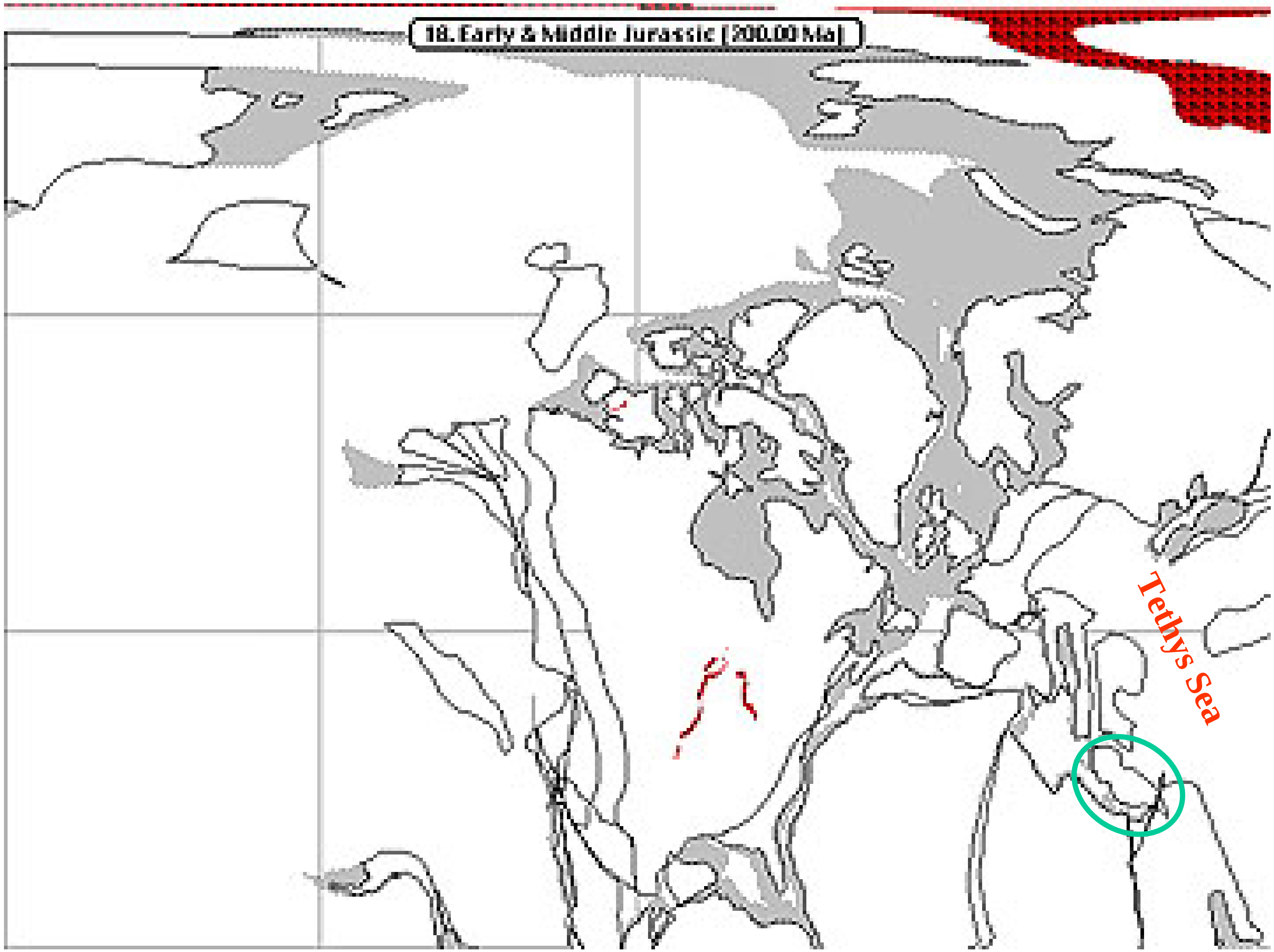
Plate Tectonics

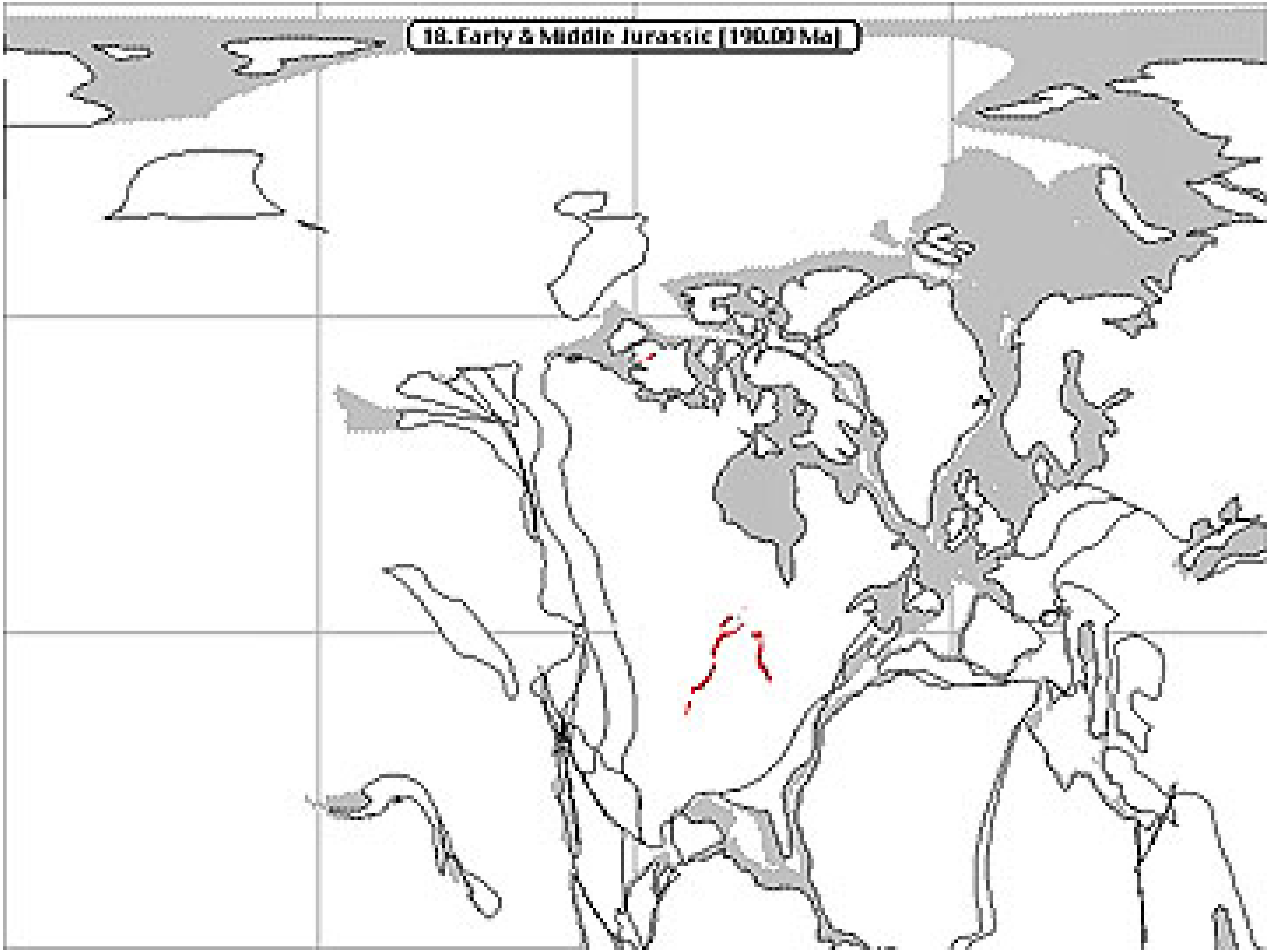

Monroe & Wicander 1992
Fig. 1-13
West Publishing

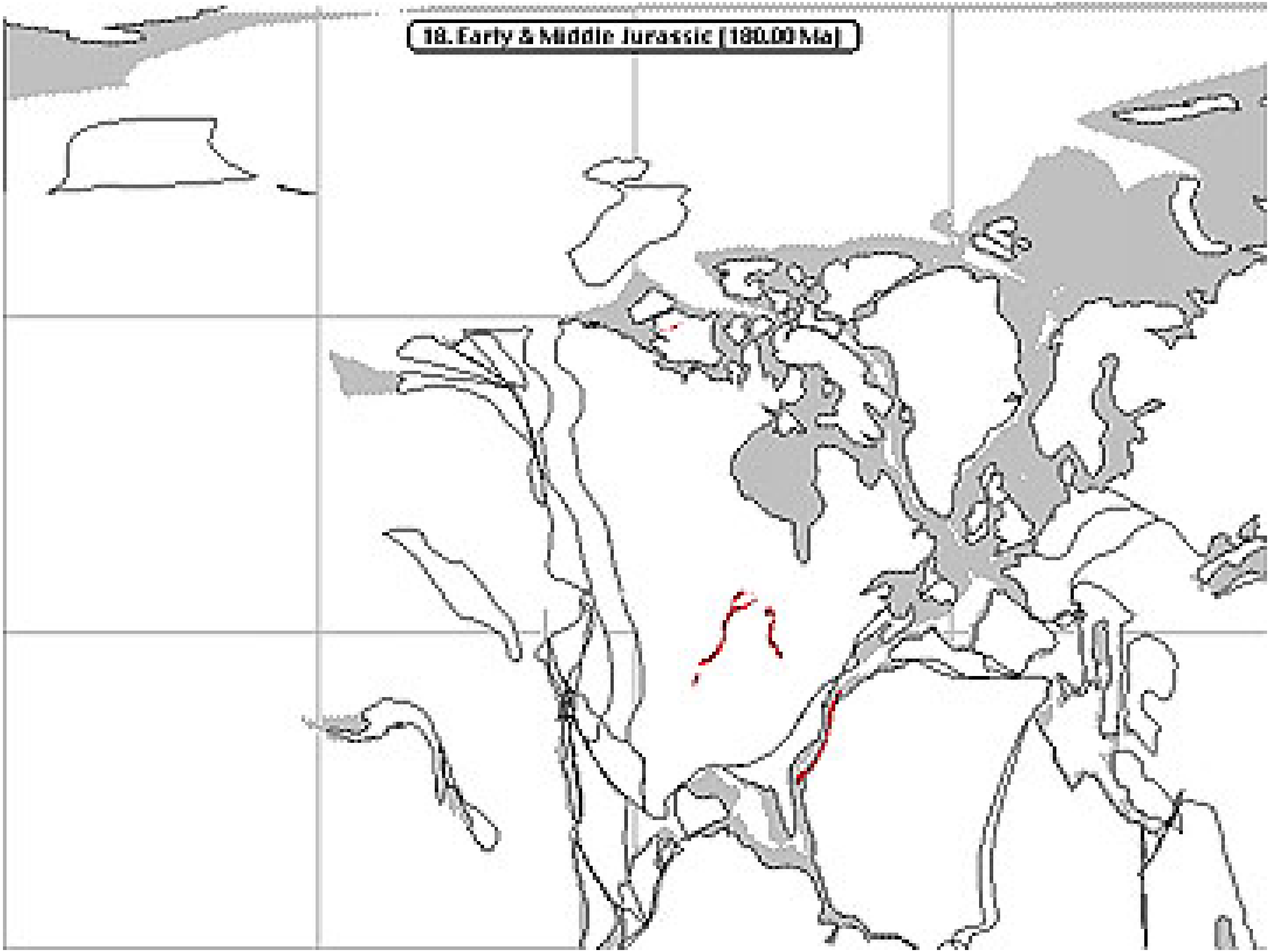
Copper Deposits



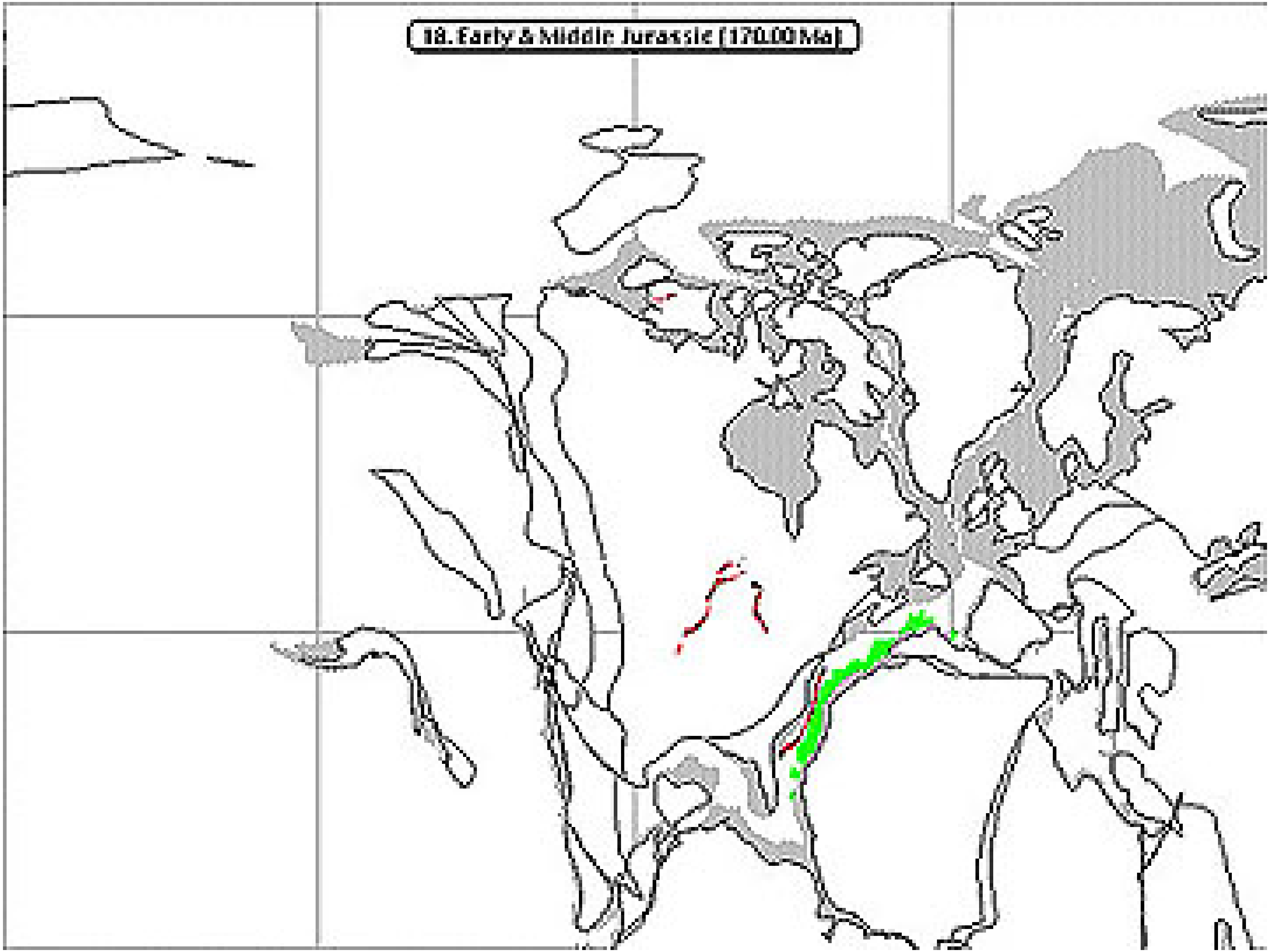

continental drift
200 Mya
130 Mya
70 Mya
today

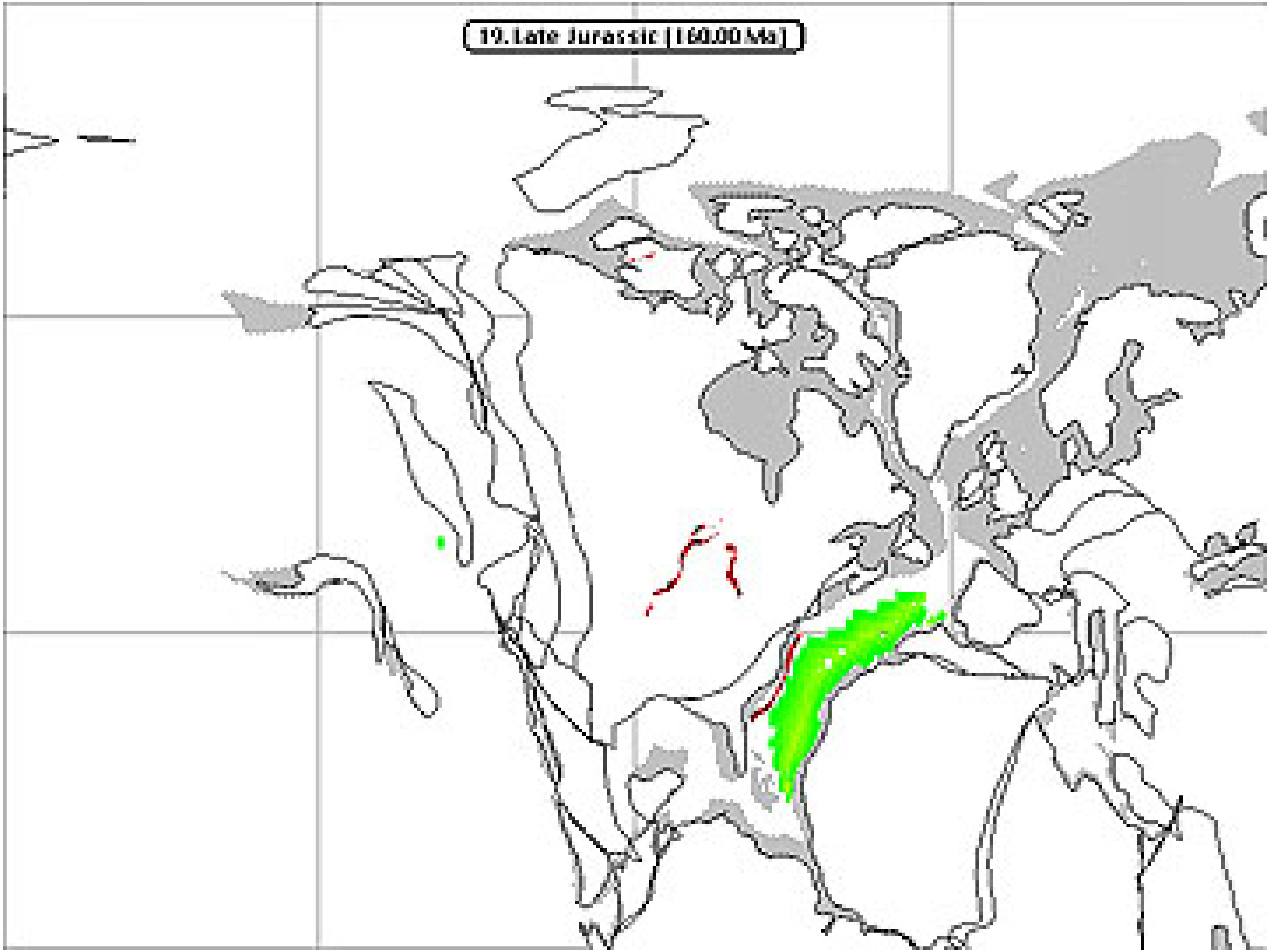

18. Early & Middle Jurassic [200.00 Ma]
Tethys Sea

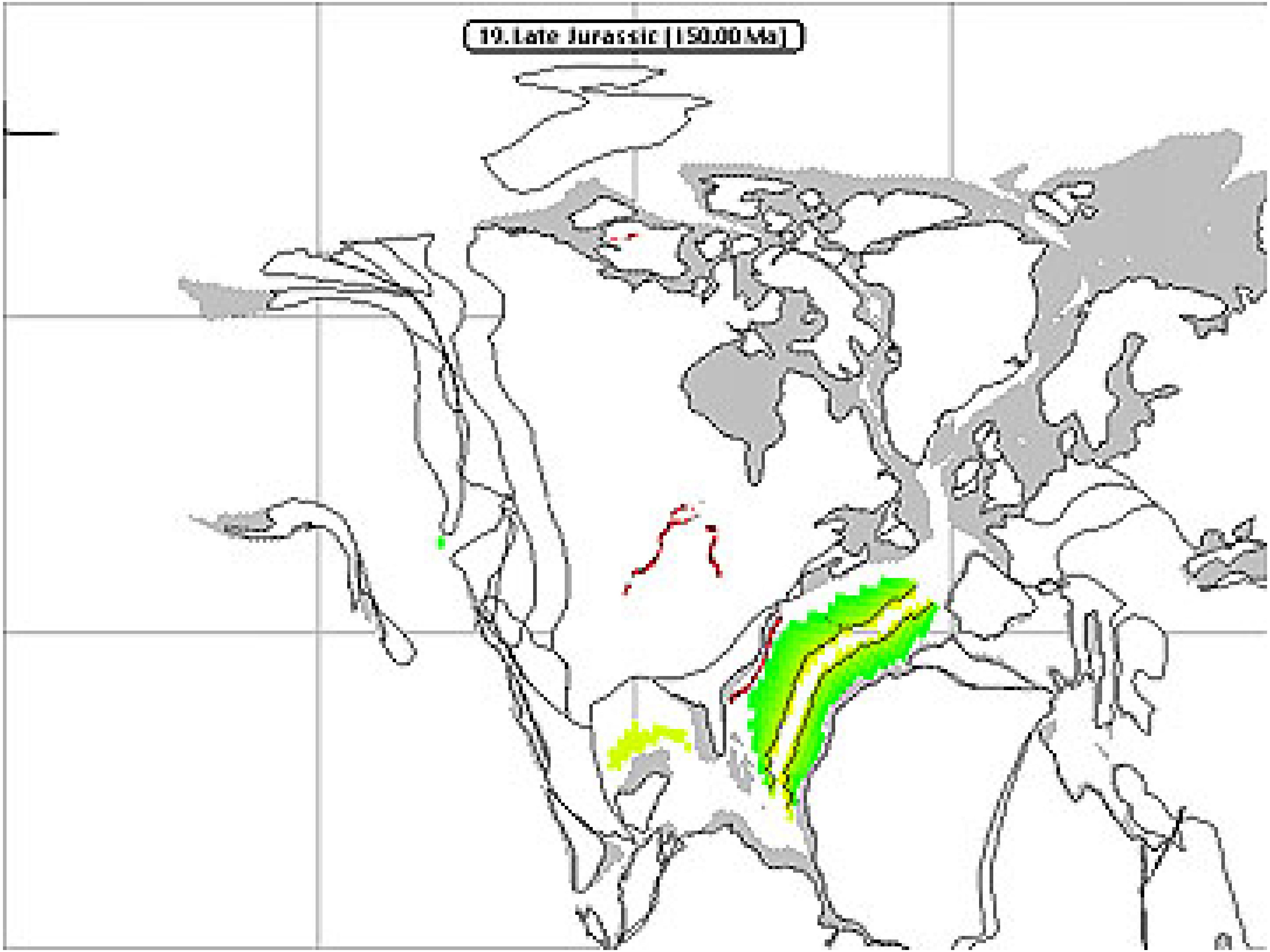

18. Early & Middle Jurassic (190.00 Ma)

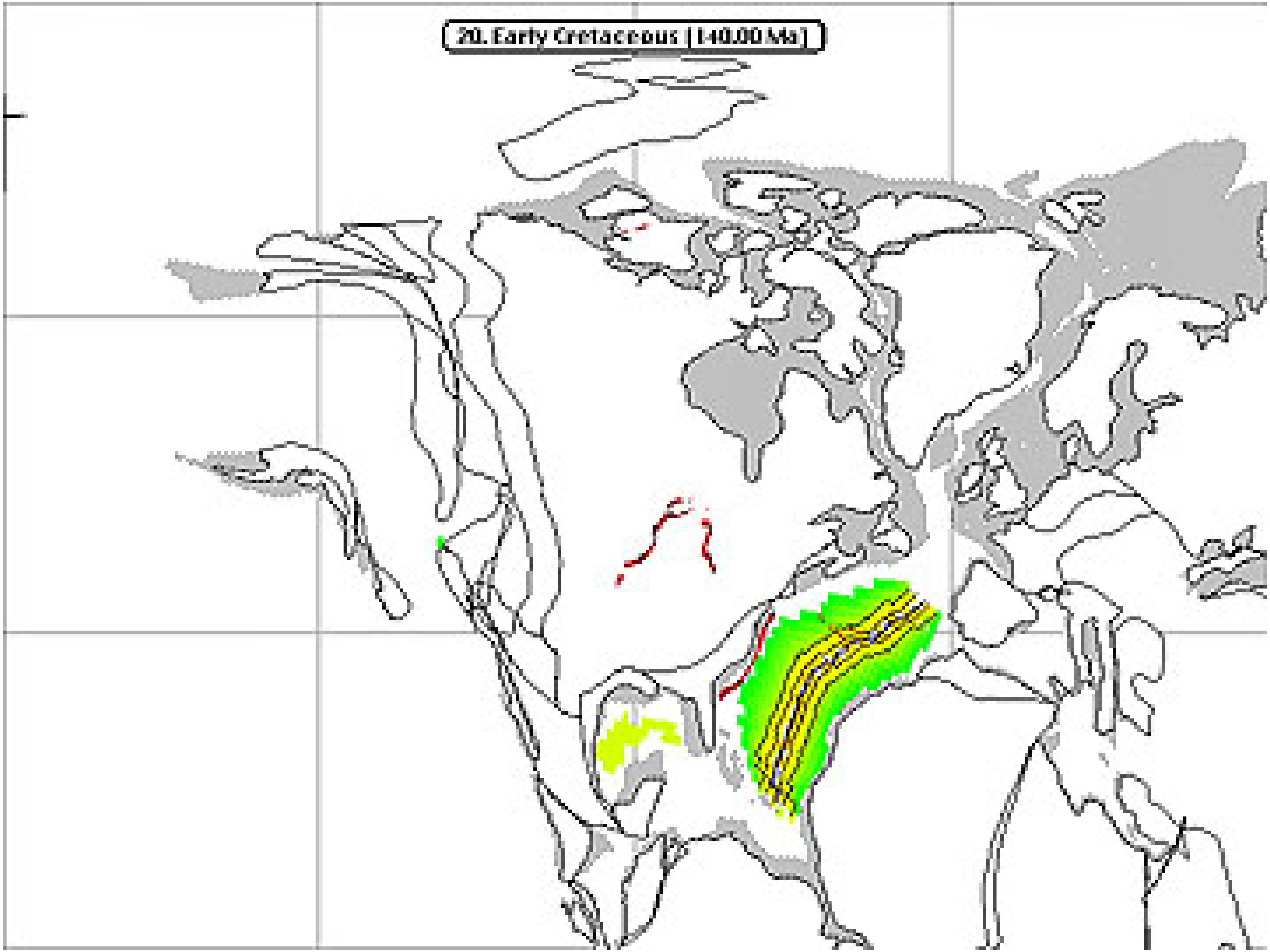


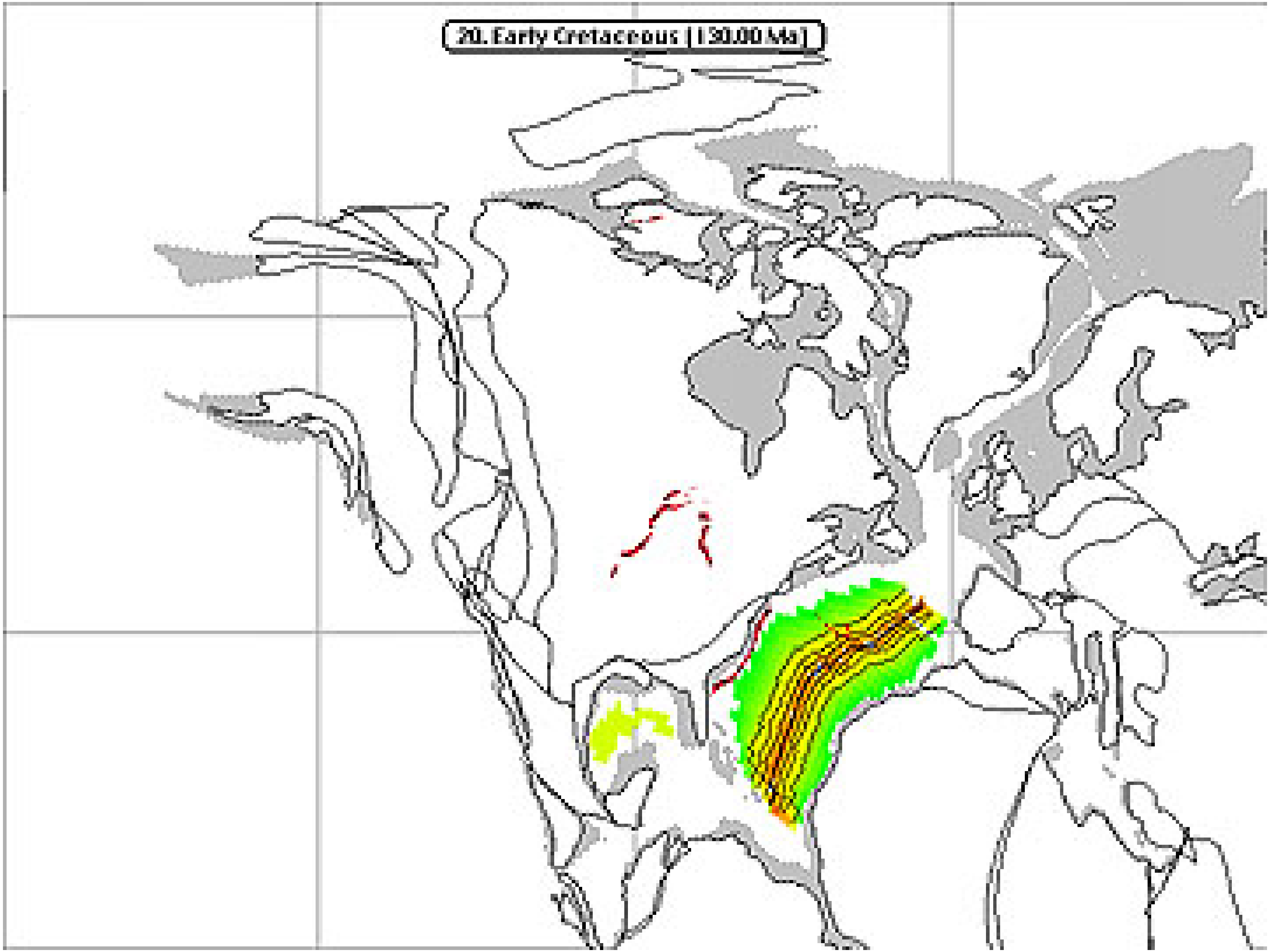
18. Early & Middle Jurassic (180.00 Ma)

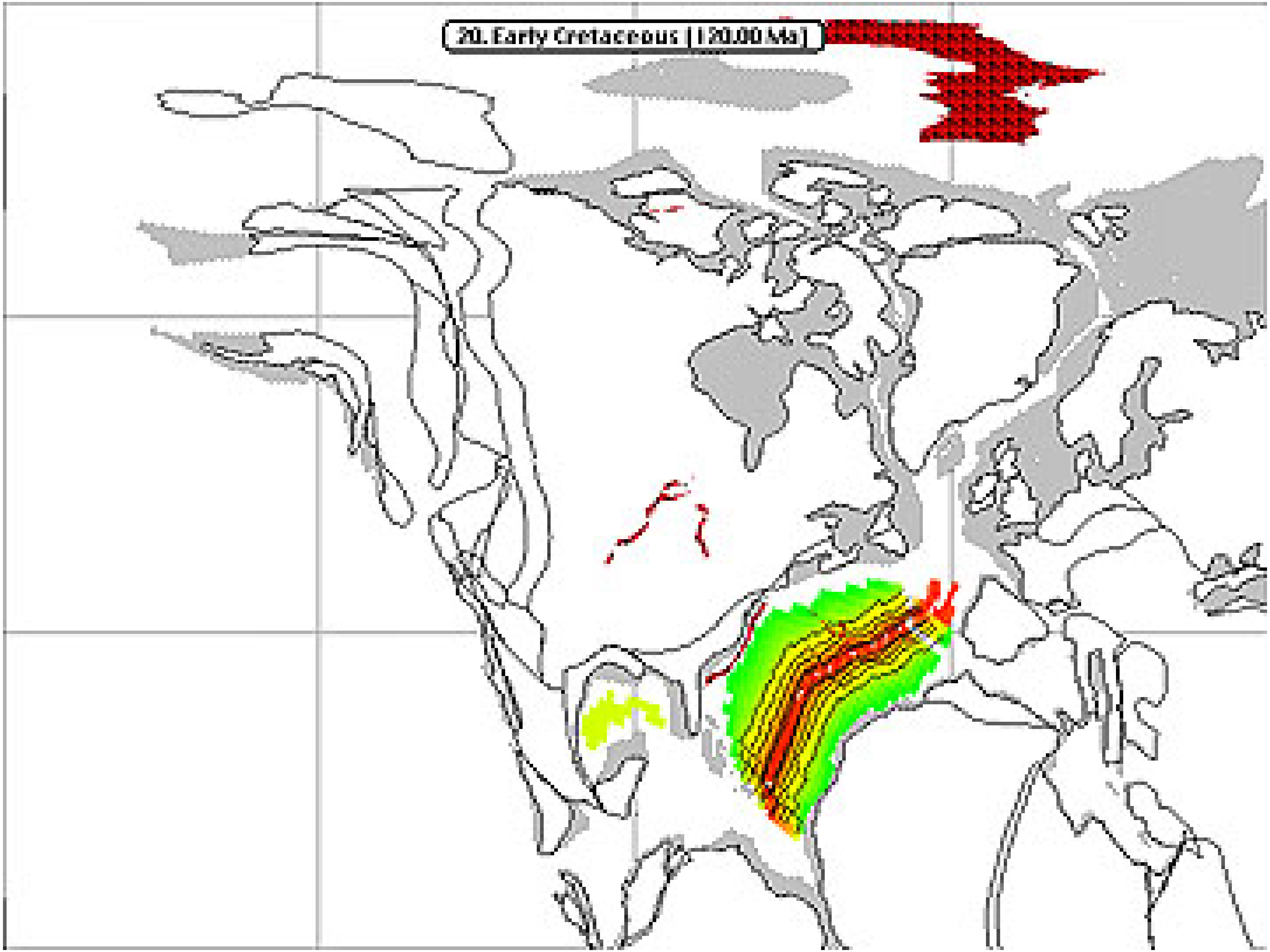

18. Early & Middle Jurassic (170.00Ma)

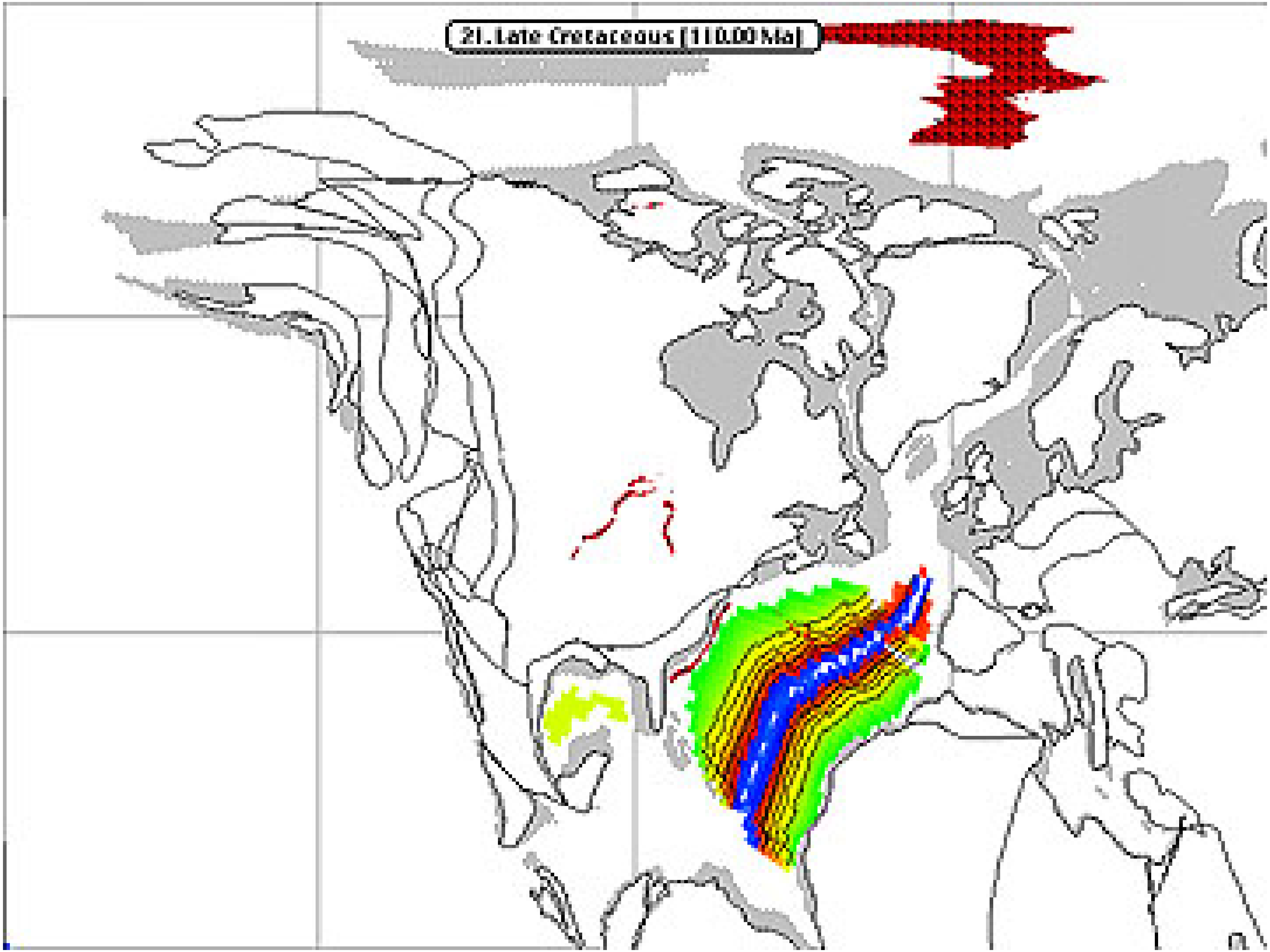

19. Late Jurassic (160.00 Ma)

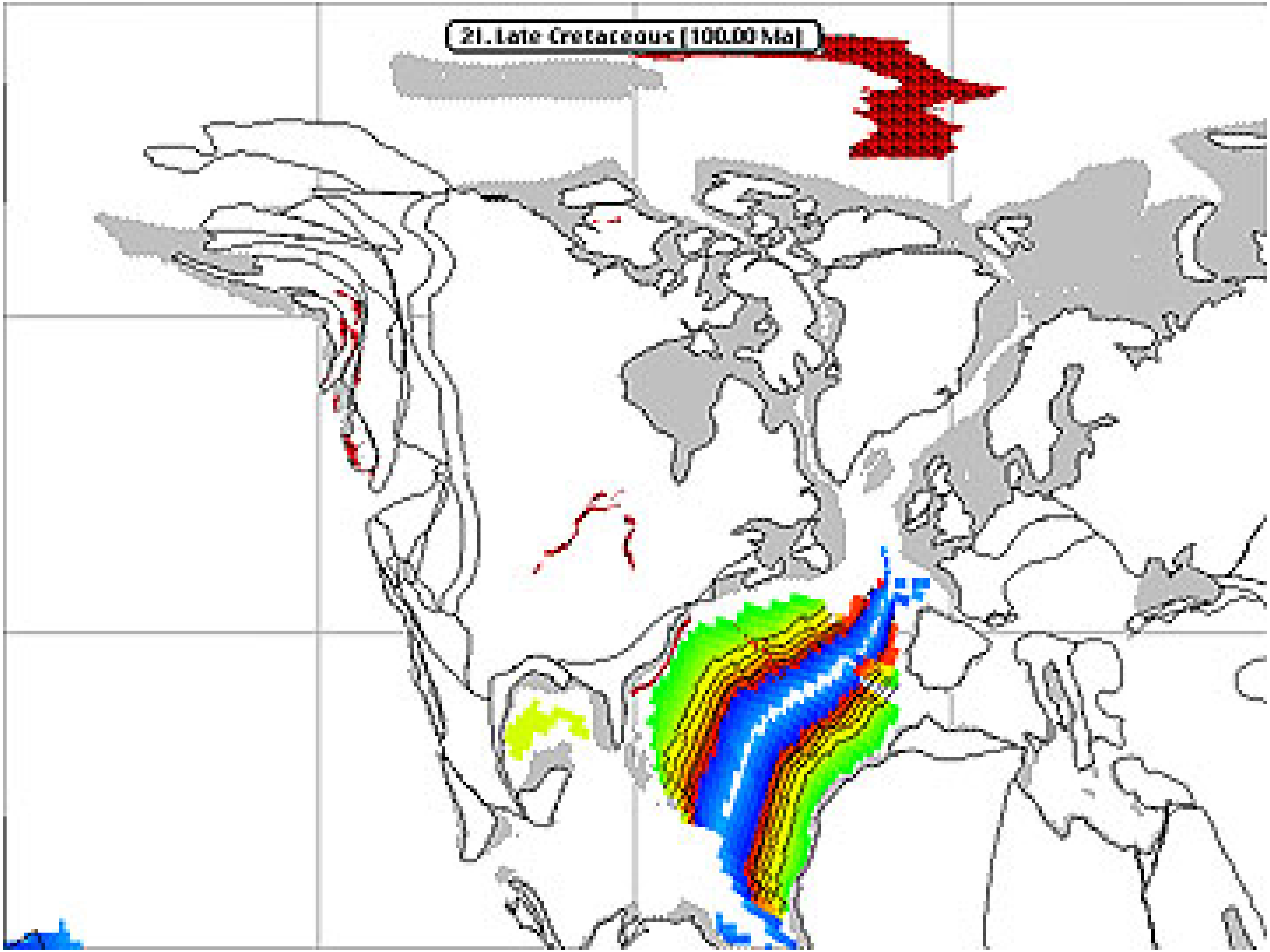

19. Late Jurassic [150.00 Ma]

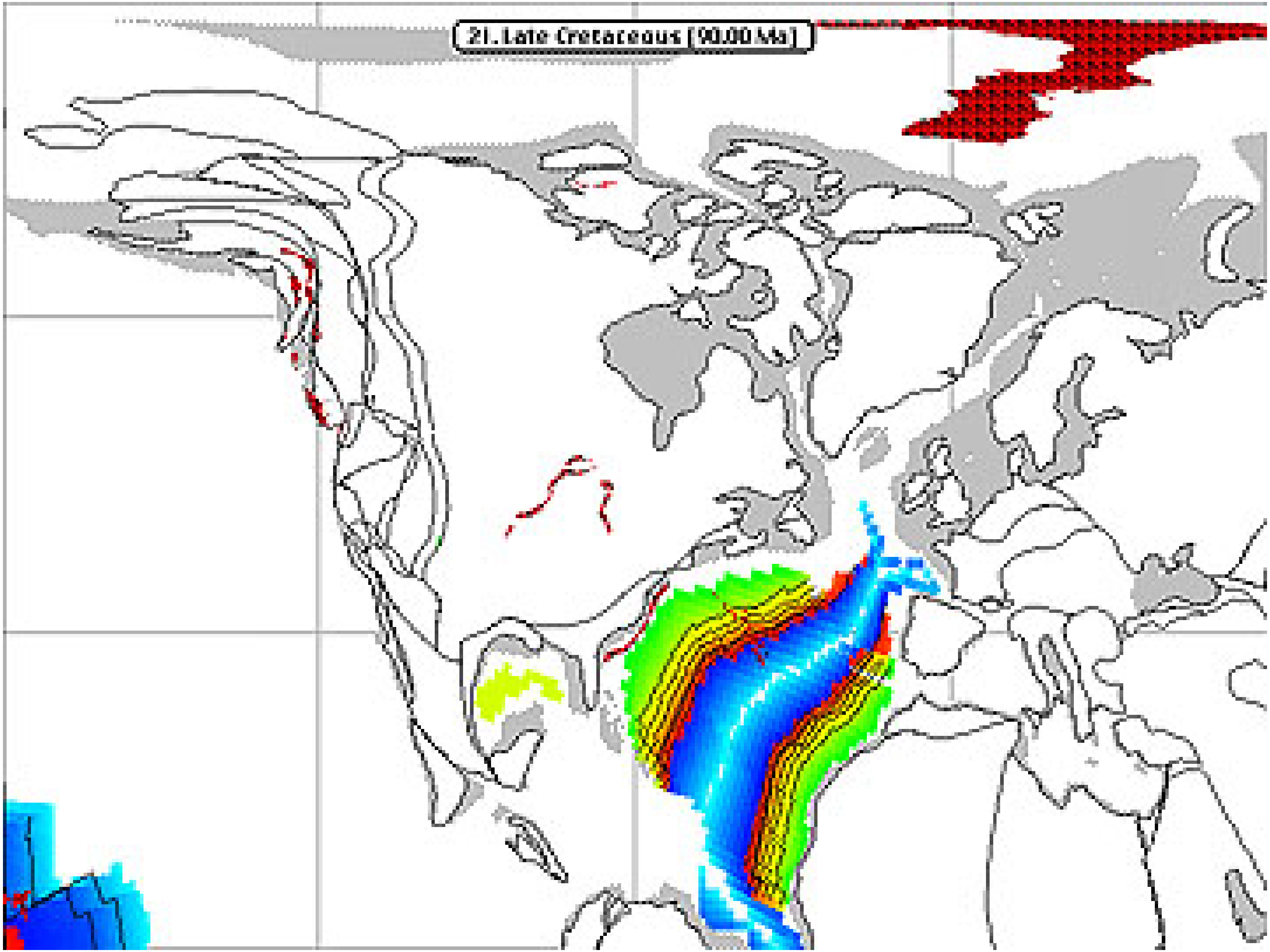

20. Early Cretaceous (140.00 Ma)

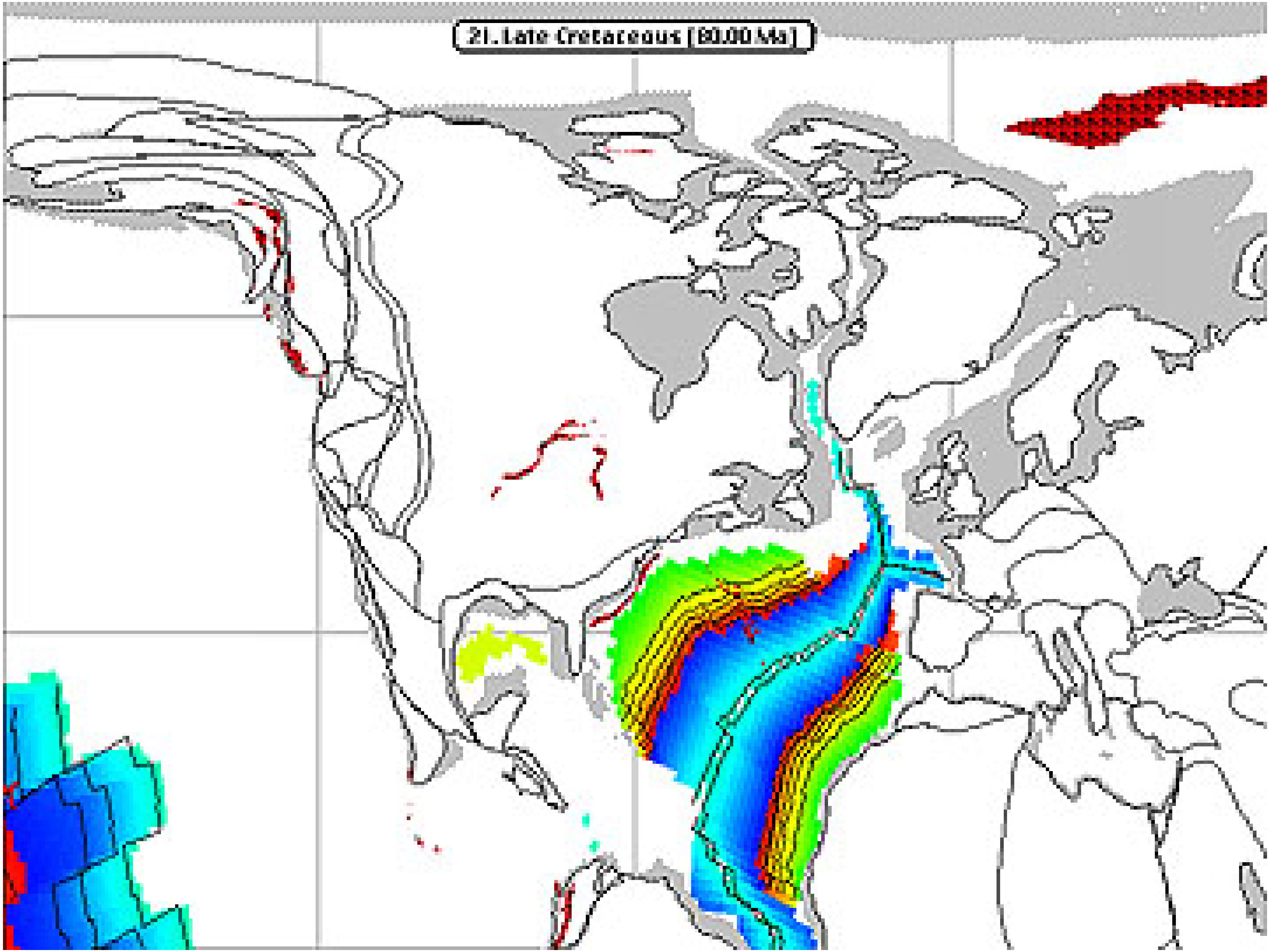

20. Early Cretaceous (130.00 Ma)

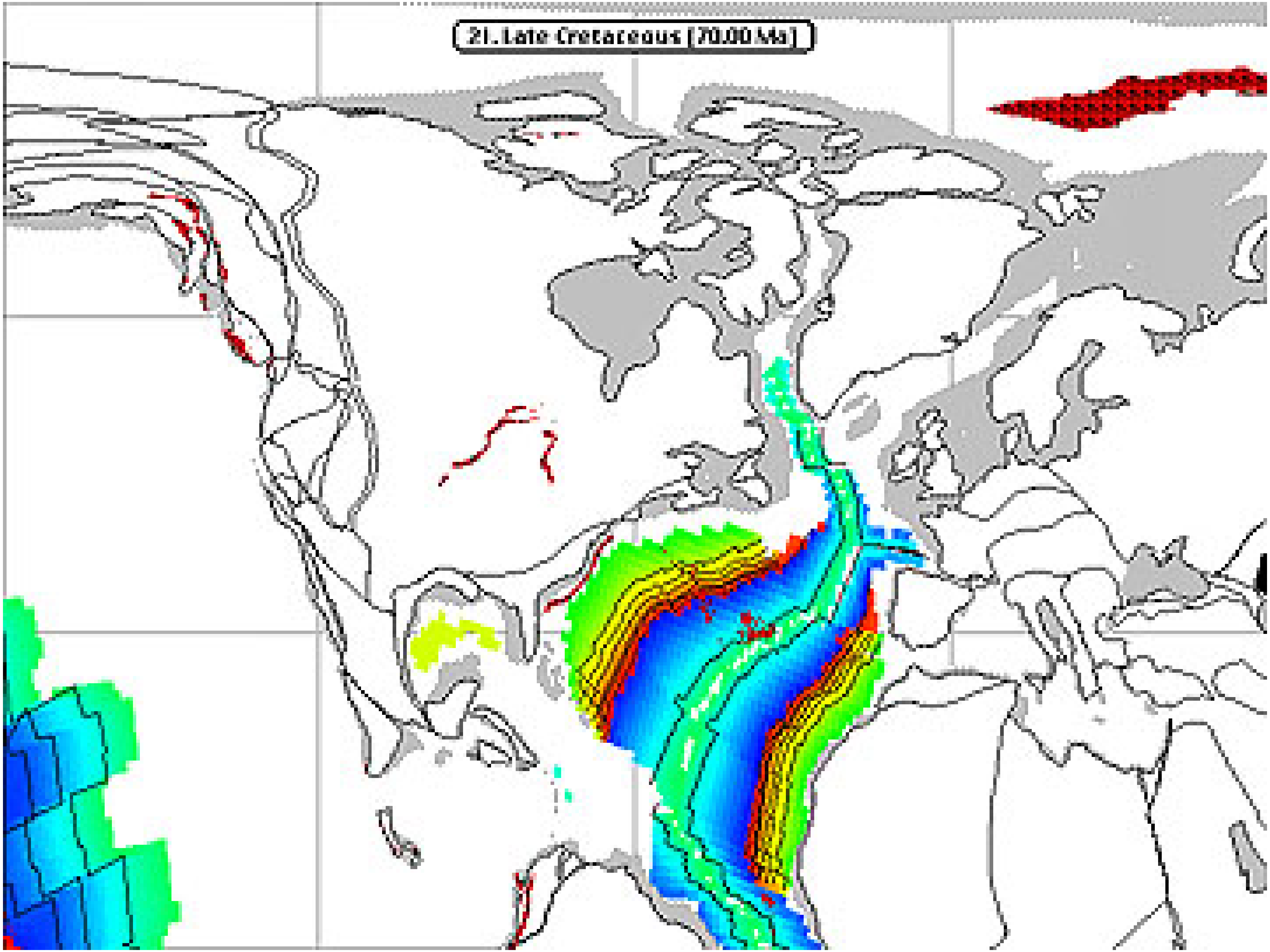

20. Early Cretaceous [120.00 Ma]

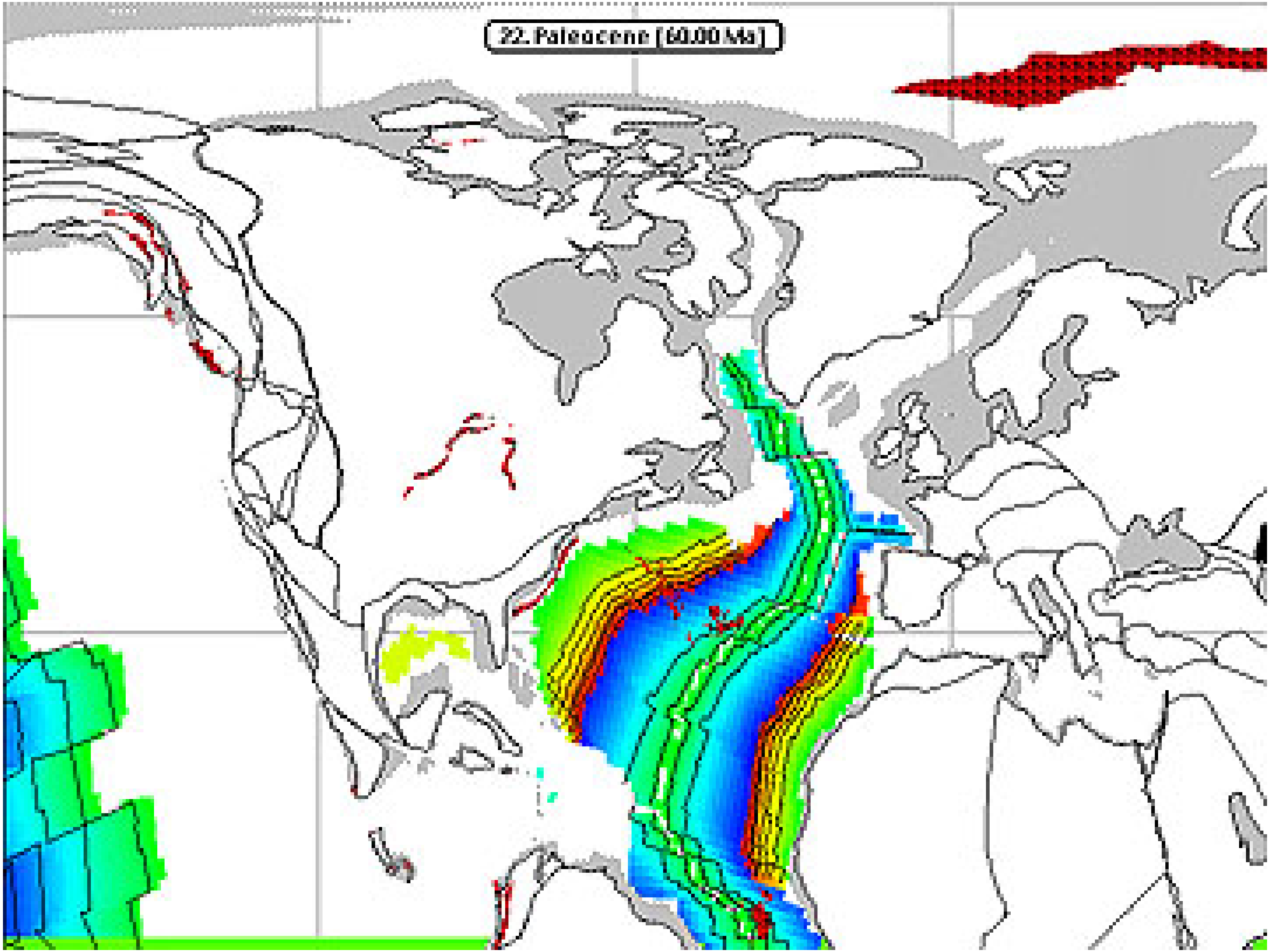

21. Late Cretaceous (110.00 Ma)

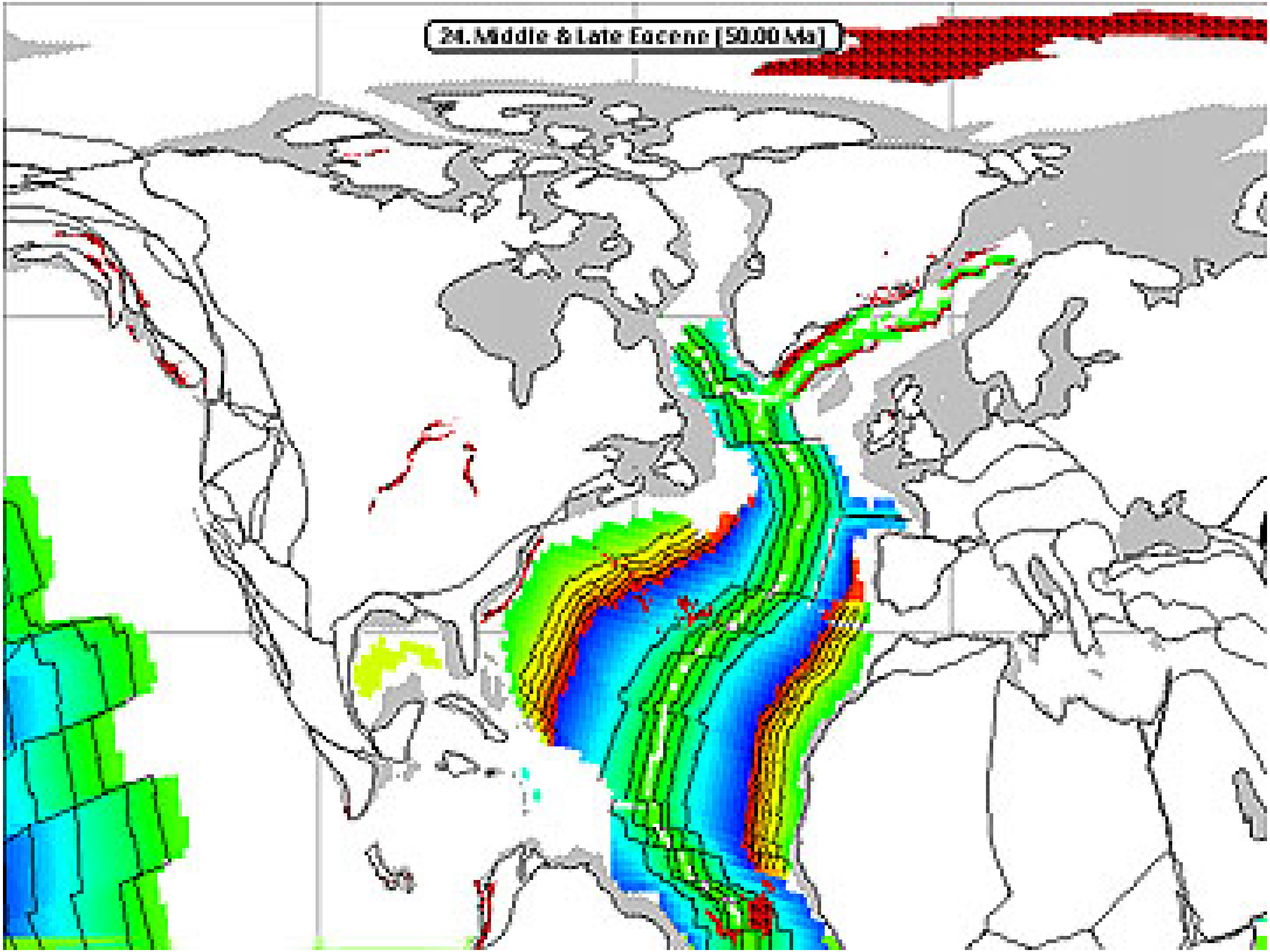

21. Late Cretaceous [100.00 Ma]

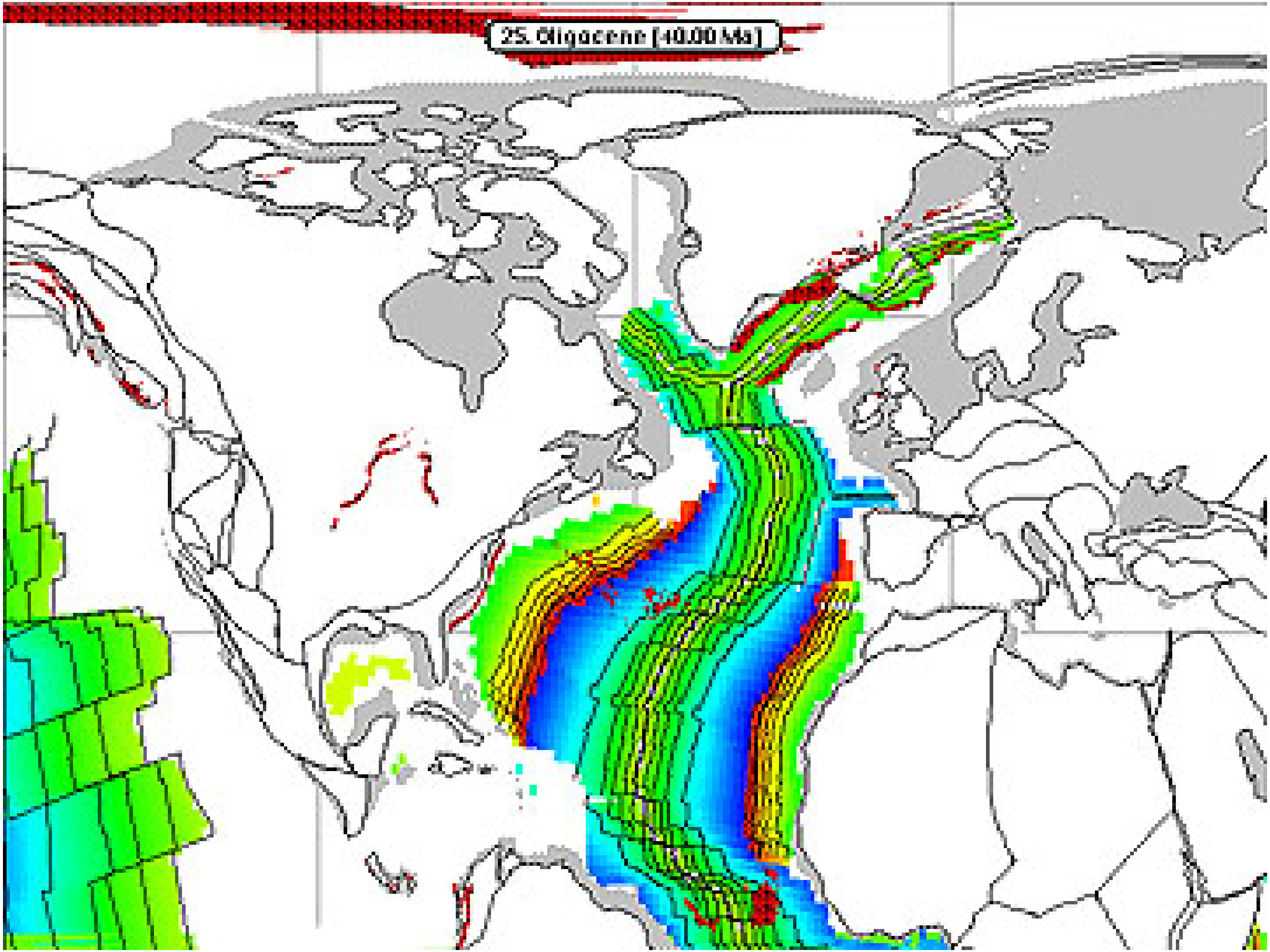

21. Late Cretaceous [90.00 Ma]

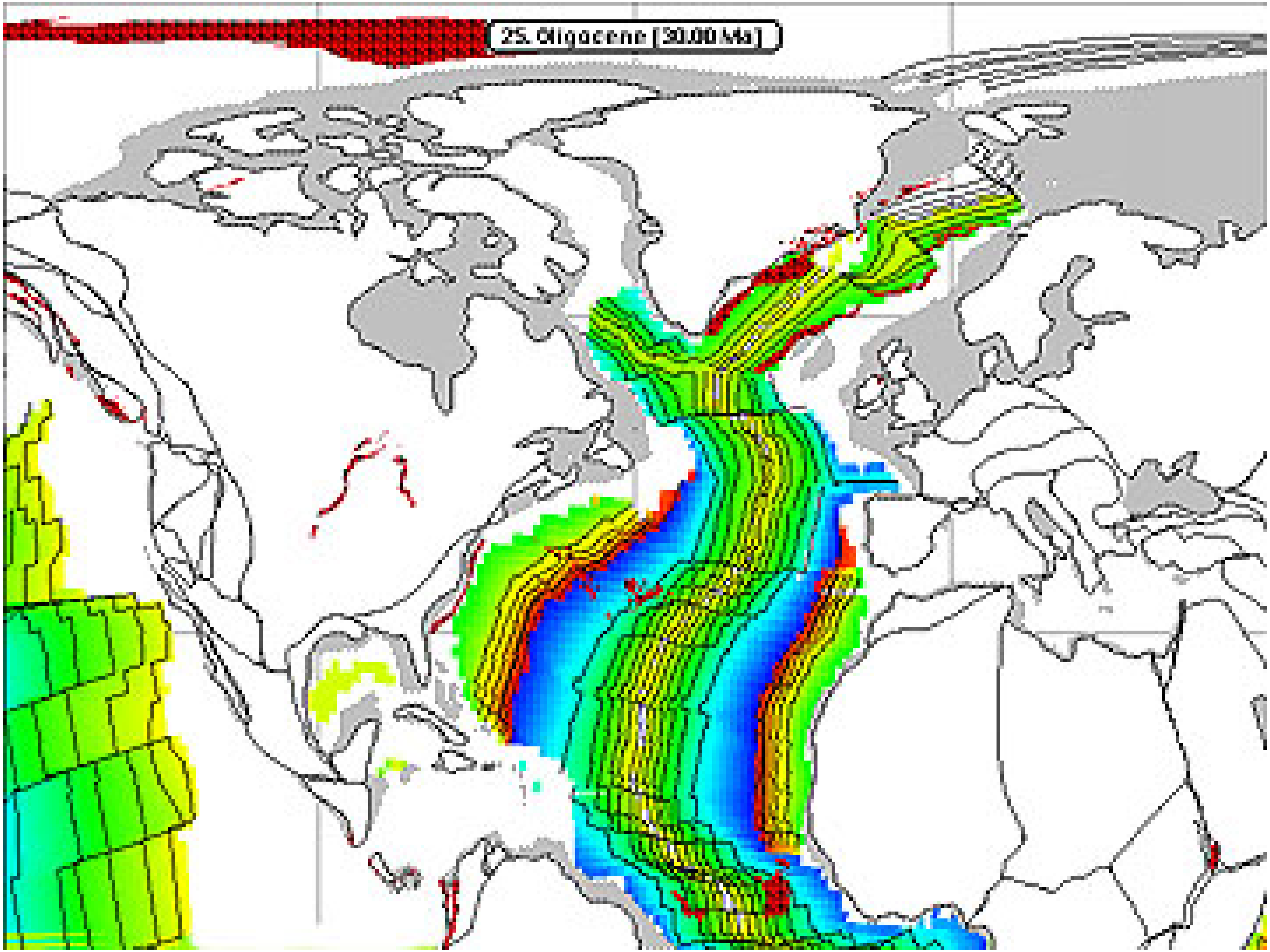

21. Late Cretaceous [80.00 Ma]

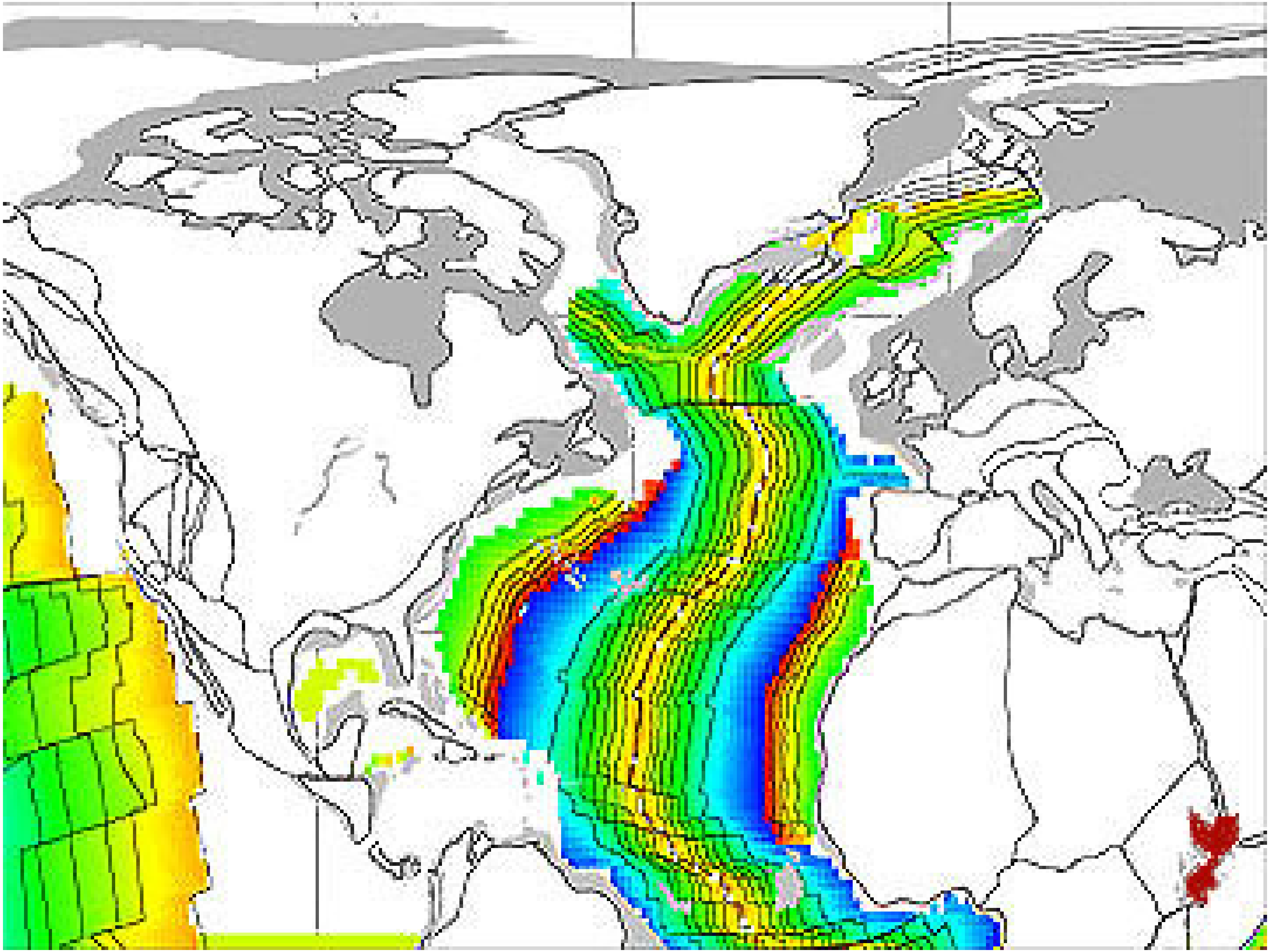

21. Late Cretaceous [70.00 Ma]

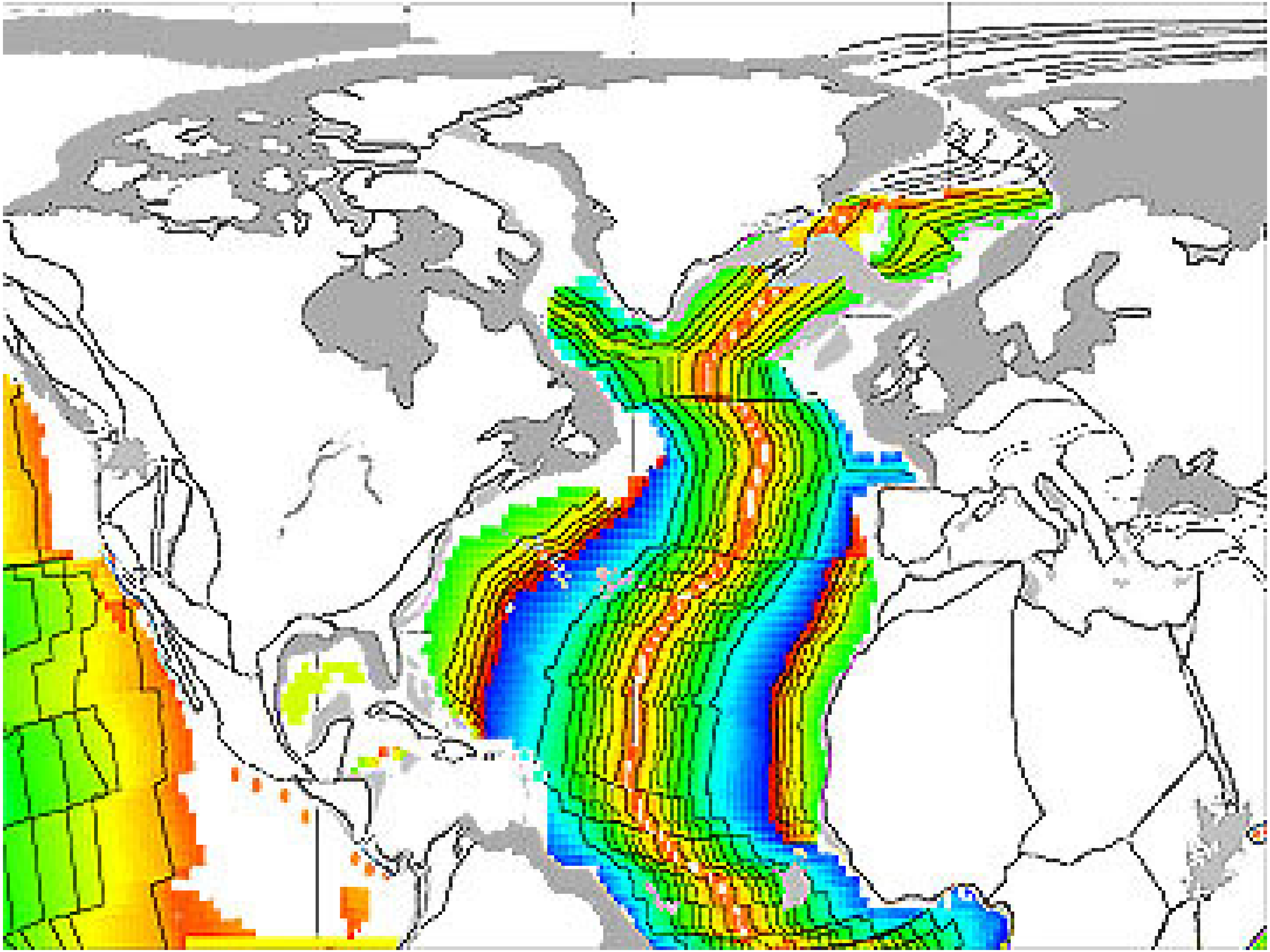

22. Paleocene [60.00 Ma]

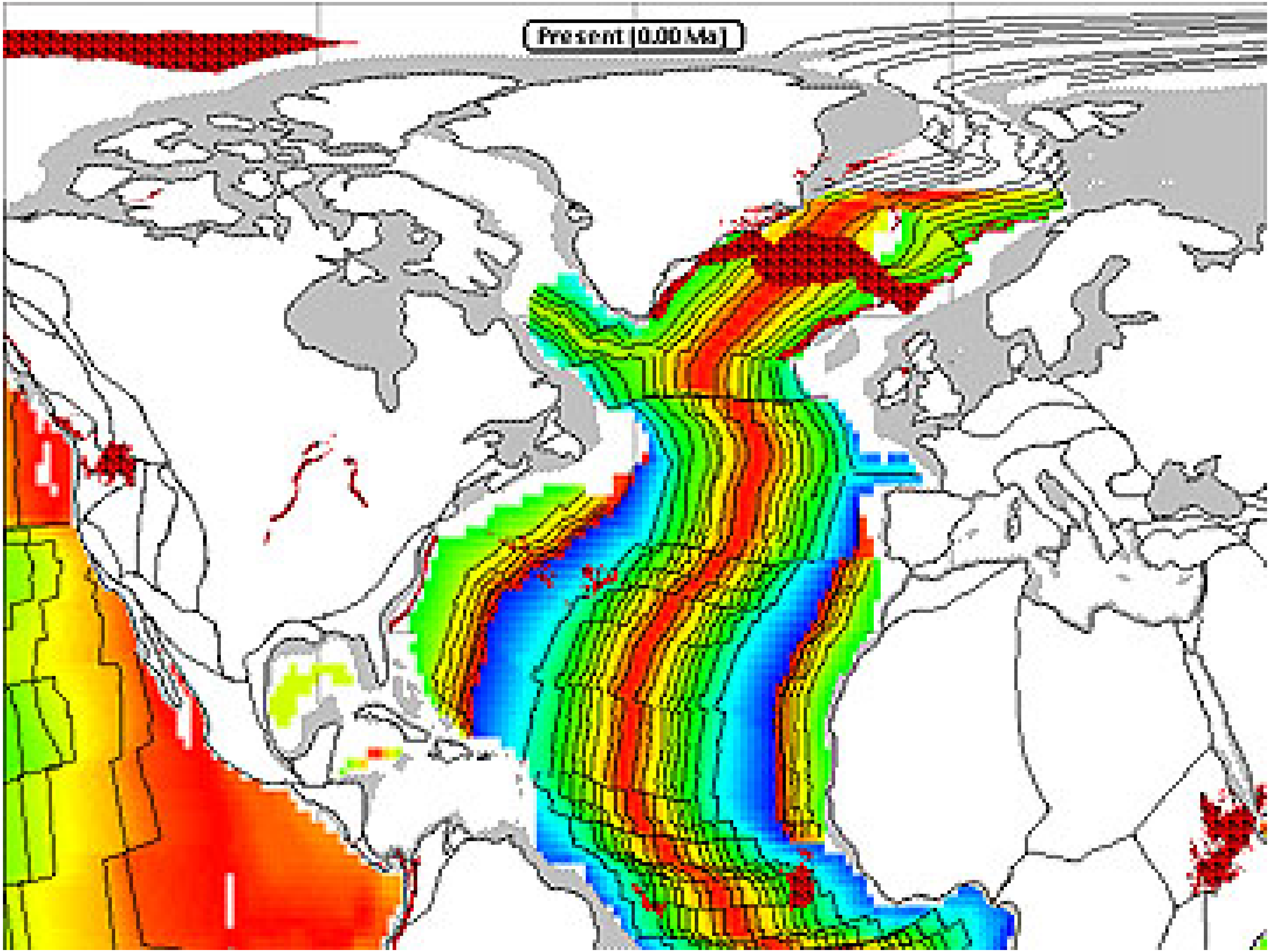

24. Middle & Late Eocene (50.00 Ma)


25. Oligocene [40.00 Ma]


25. Oligocene [30.00 Ma]






Present (0.00 Ma)

Plates in motion

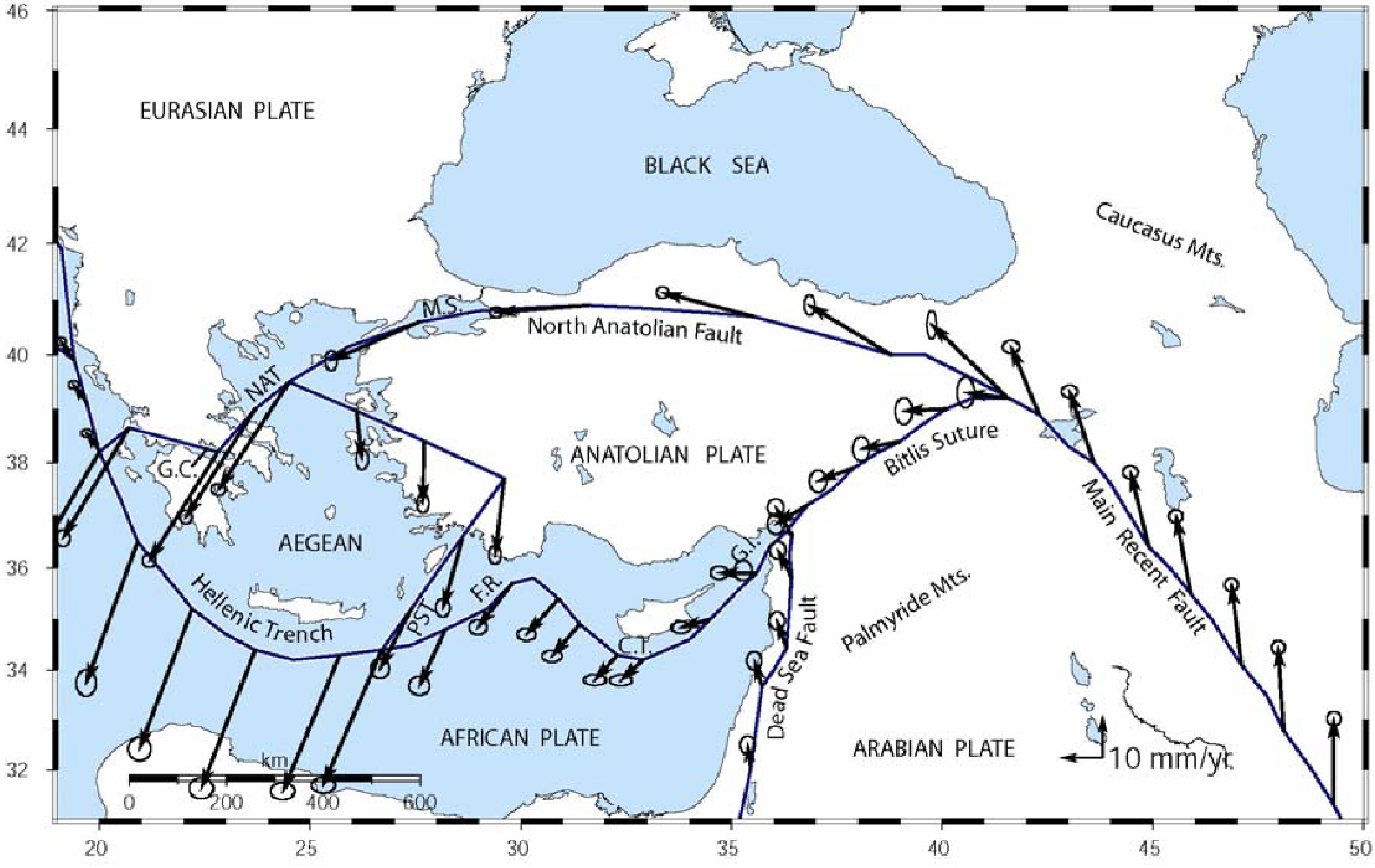
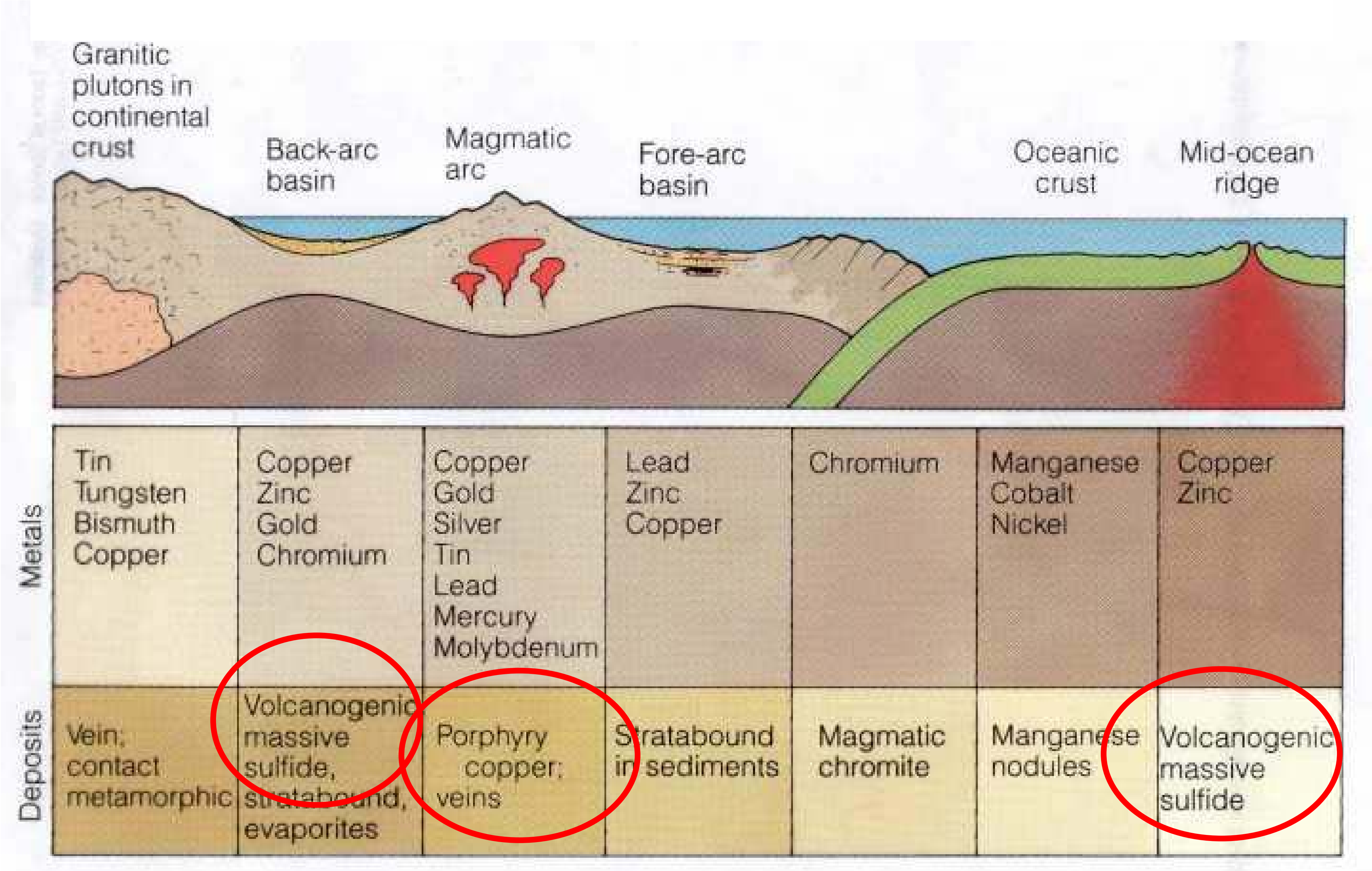
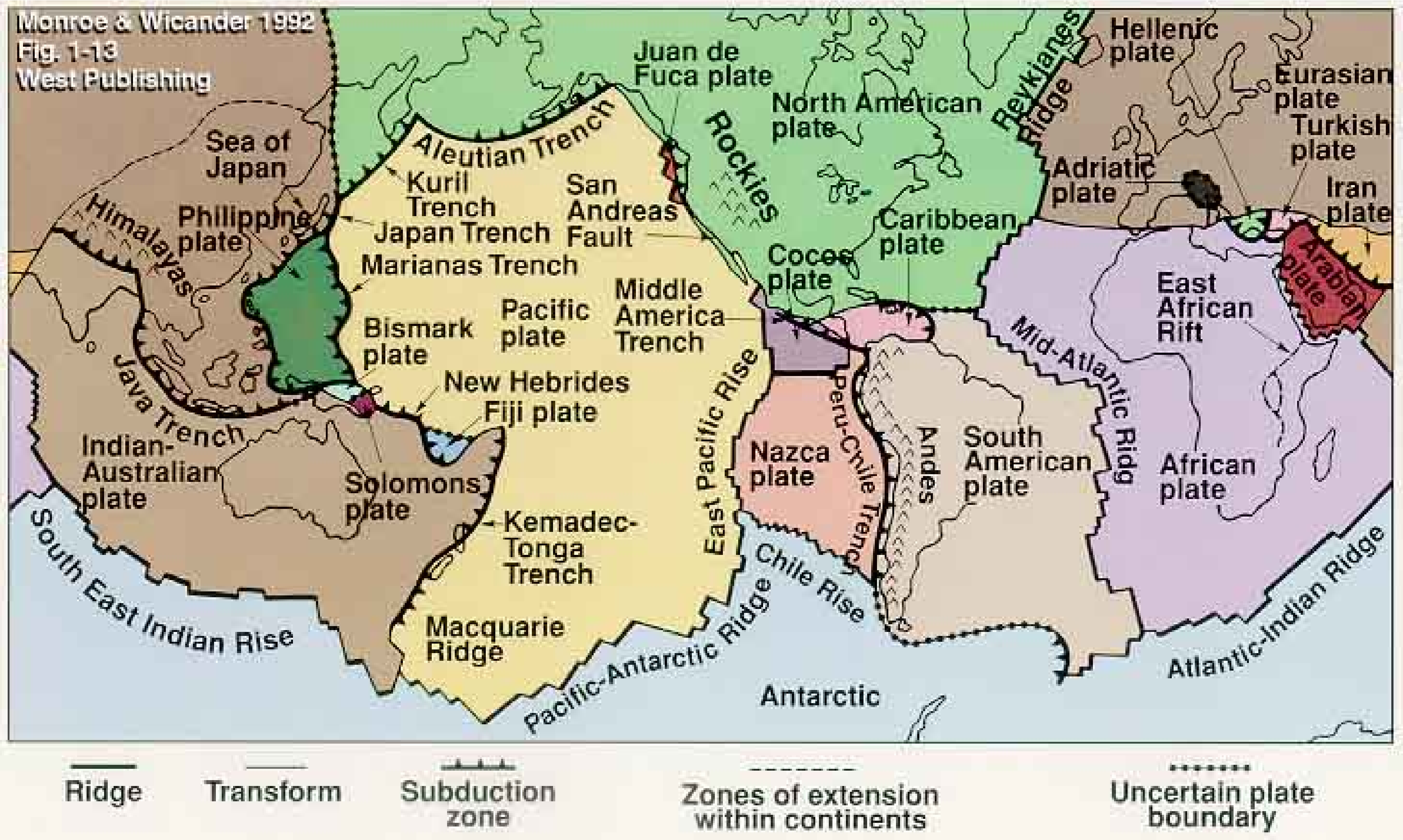


Plate Tectonic Ore Deposit Formation

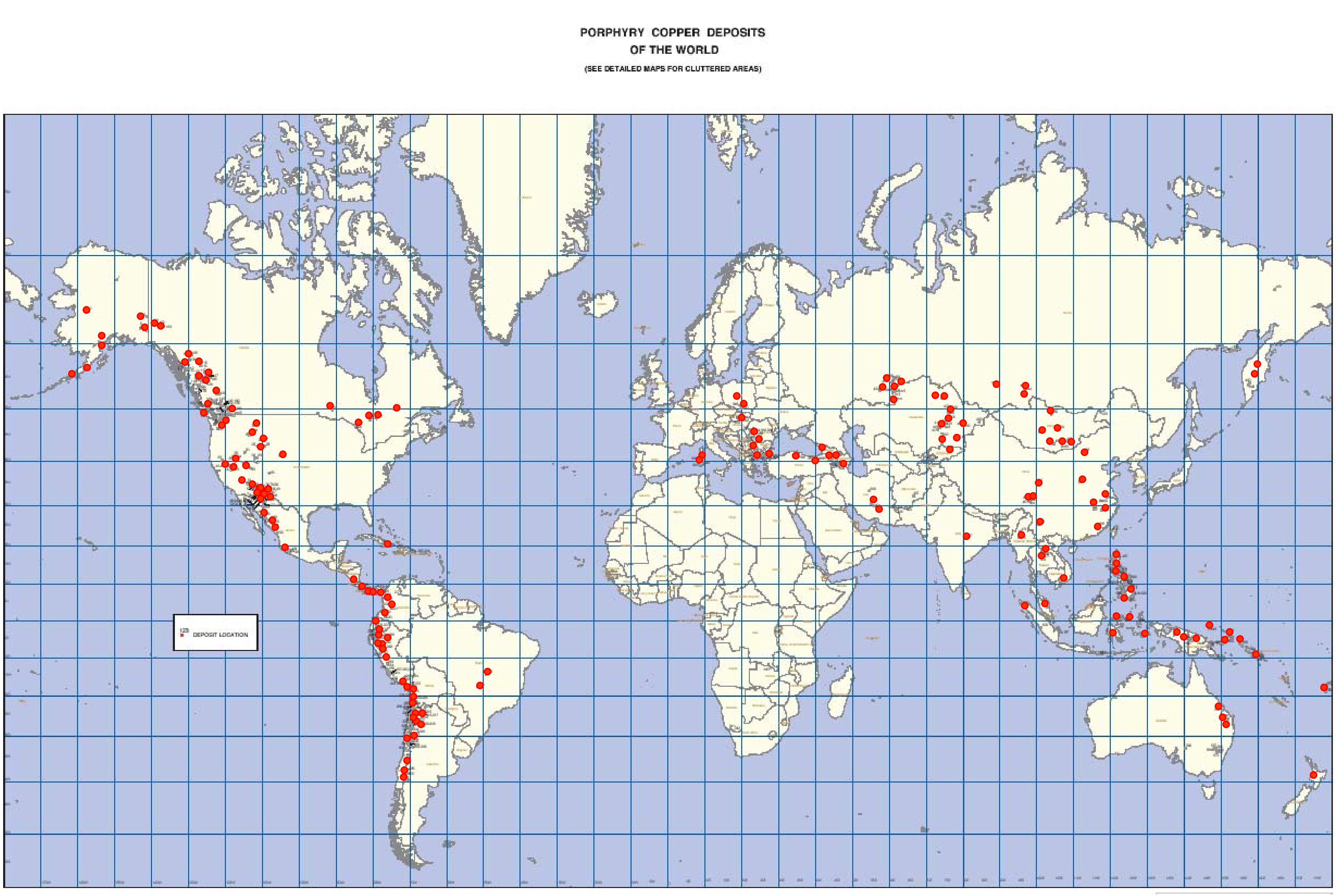


Metals	Tin Tungsten Bismuth Copper	Copper Zinc Gold Chromium	Copper Gold Silver Tin Lead Mercury Molybdenum	Lead Zinc Copper	Chromium	Manganese Cobalt Nickel	Copper Zinc
Deposits	Vein; contact metamorphic	Volcanogenic massive sulfide, stratabound, evaporites	Porphyry copper; veins	Stratabound in sediments	Magmatic chromite	Manganese nodules	Volcanogenic massive sulfide

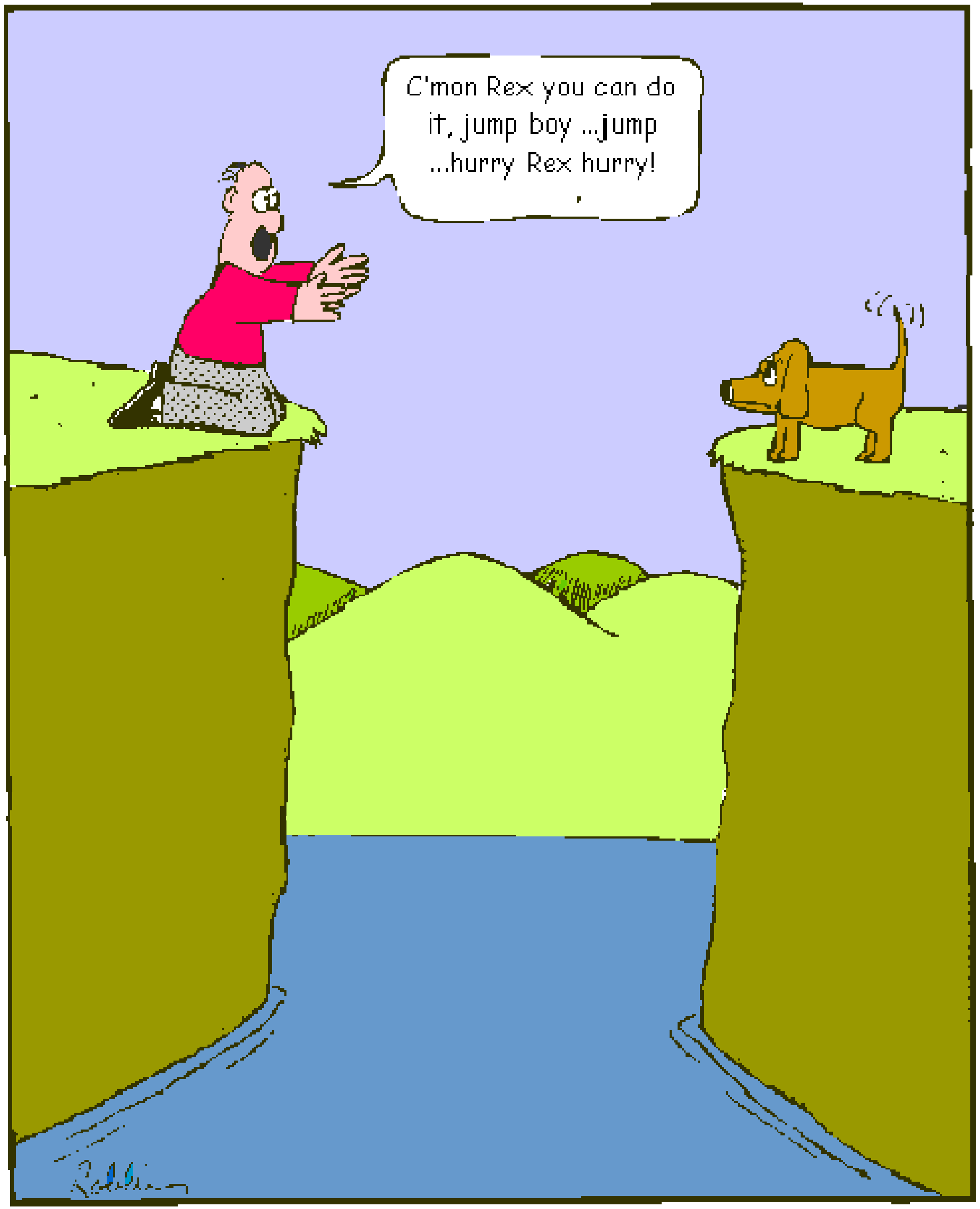
Plate Tectonics



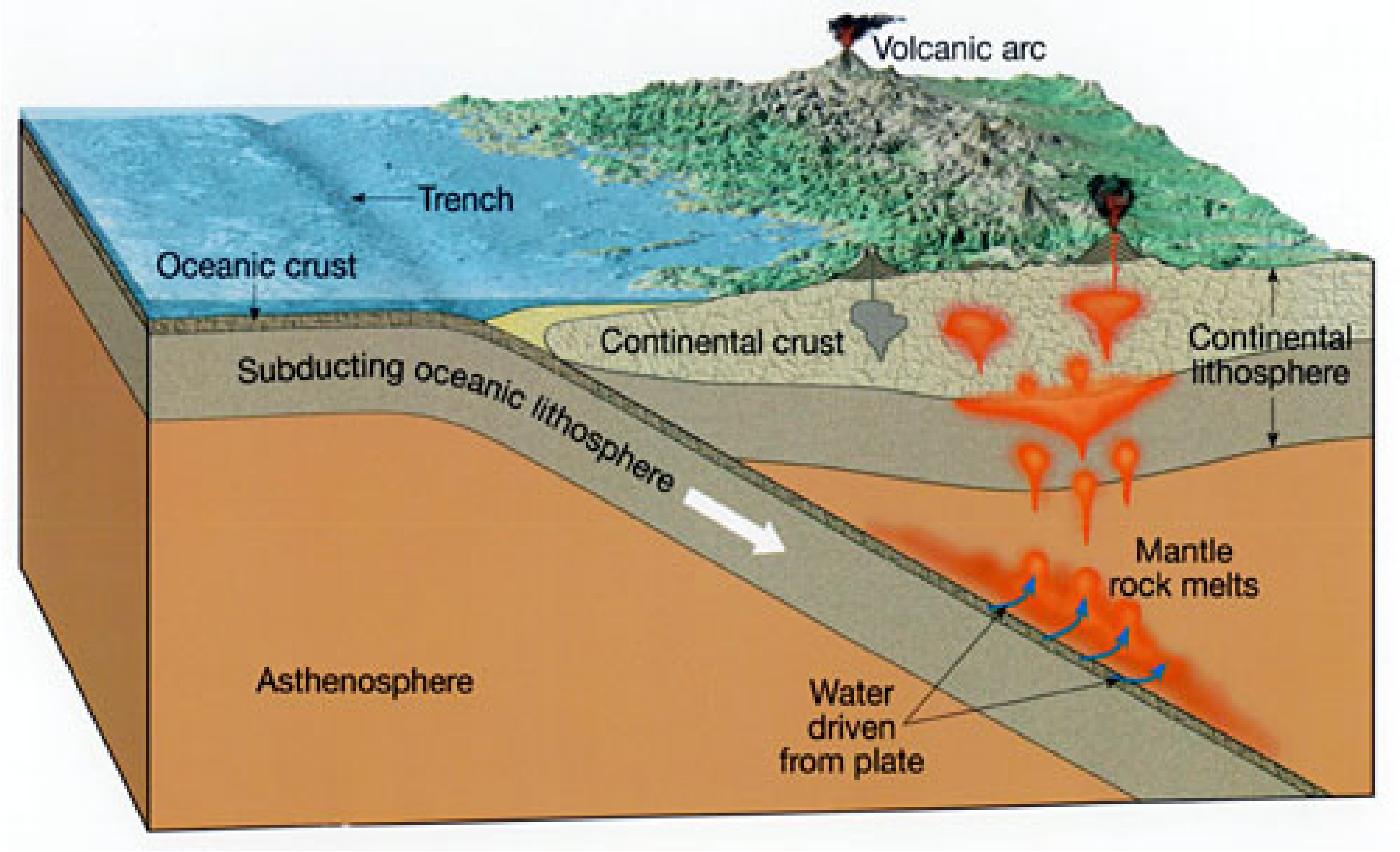
World Copper Deposits



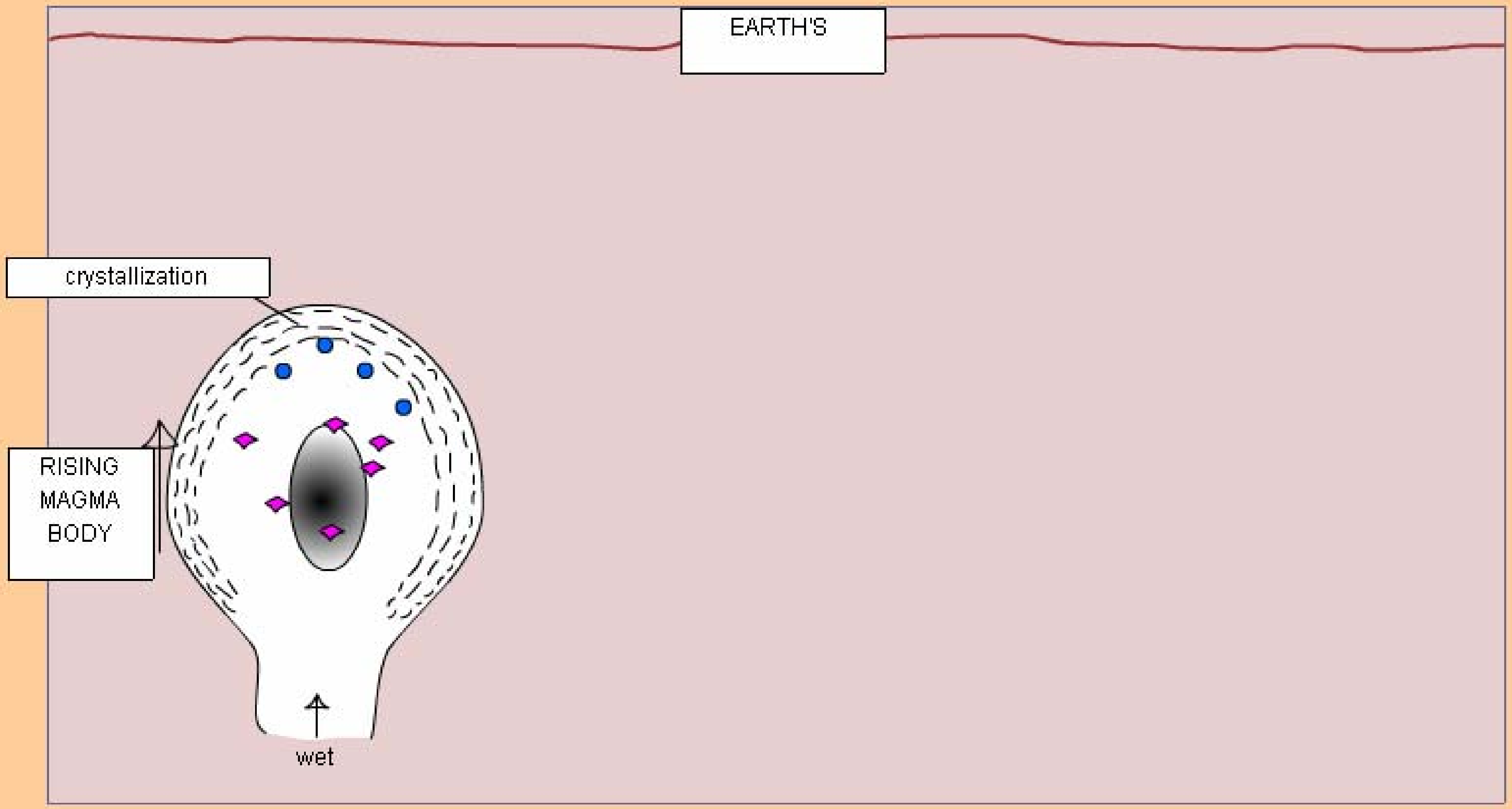
A down side of continental drift



Ocean-Continent Boundaries →Porphyry Deposits

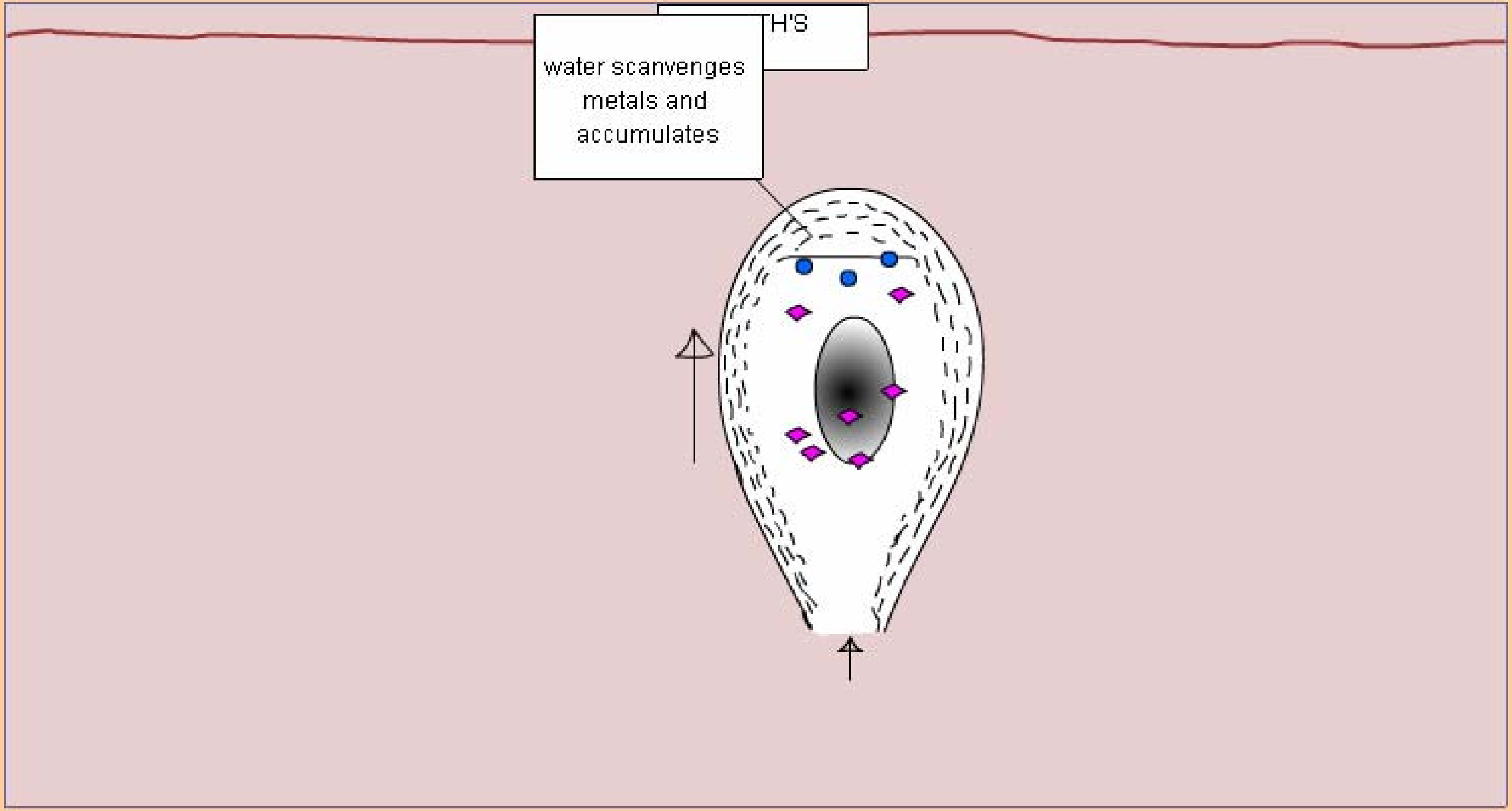


Development of Porphyry Ore Deposit



As wet magma cools, it starts to crystallize, and becomes saturated with water, which separates out as 'bubbles'

Development of Porphyry Ore Deposit



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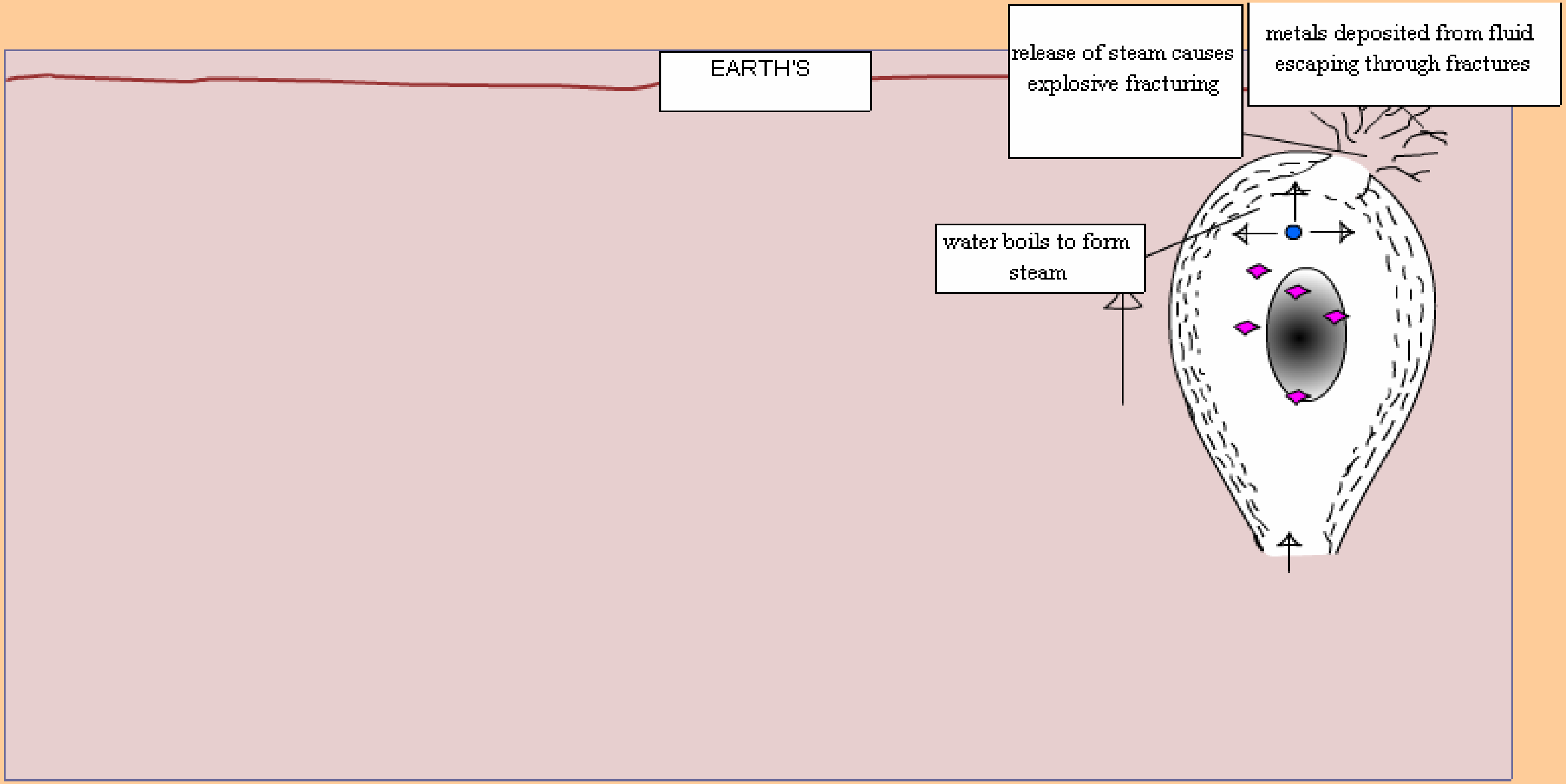
Water scavenges soluble metals, and accumulates near the top of the magma chamber

Development of Porphyry Ore Deposit



release of steam causes explosive fracturing

metals deposited from fluid escaping through fractures

water boils to form steam

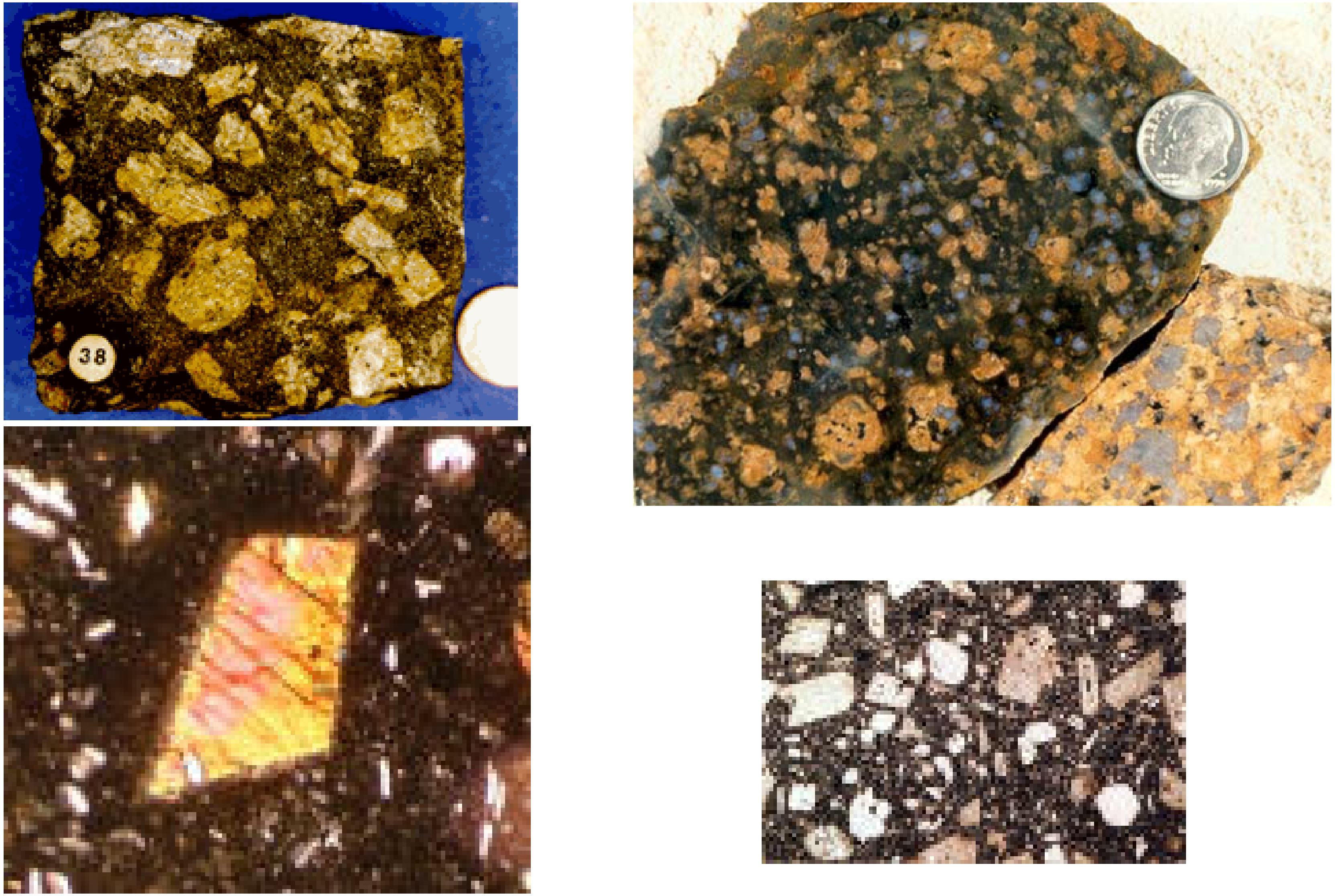
As wet magma cools, it starts to crystallize, and becomes saturated with water, which separates out as 'bubbles'

Water scavenges soluble metals, and accumulates near the top of the magma chamber

As the ascent through the crust continues, the reduction in pressure causes the water to boil, and formation of steam (occupying a much larger volume) causes explosive fracturing, forming pathways for the escaping metal-rich fluids

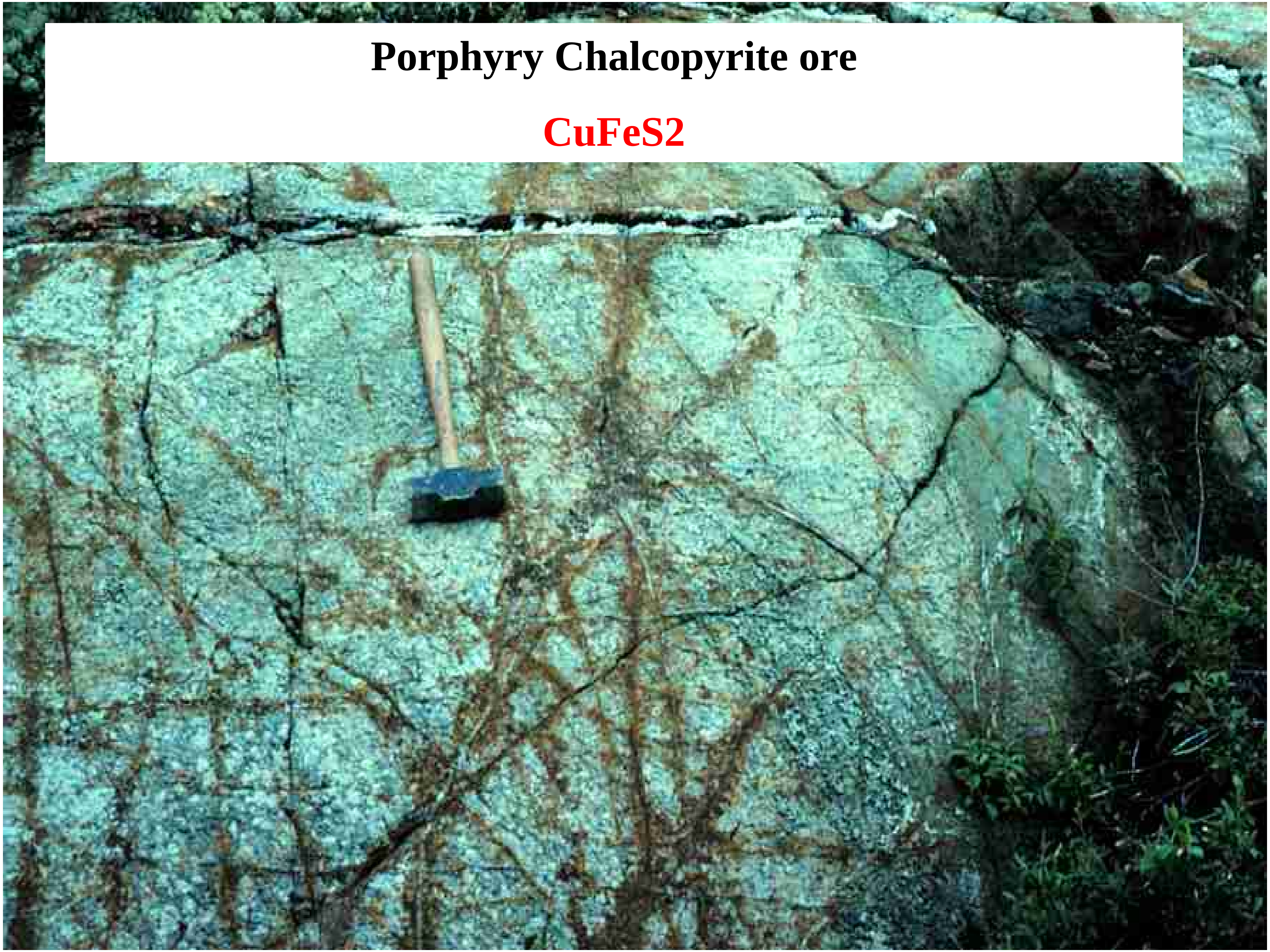
Characteristic of Porphyry Formation

Large mineral crystals in matrix of fine crystals. Slow cooling at high temperatures followed by rapid cooling at lower temperature.



Porphyry Chalcopyrite ore

$CuFeS_2$



Porphyry Copper Mining

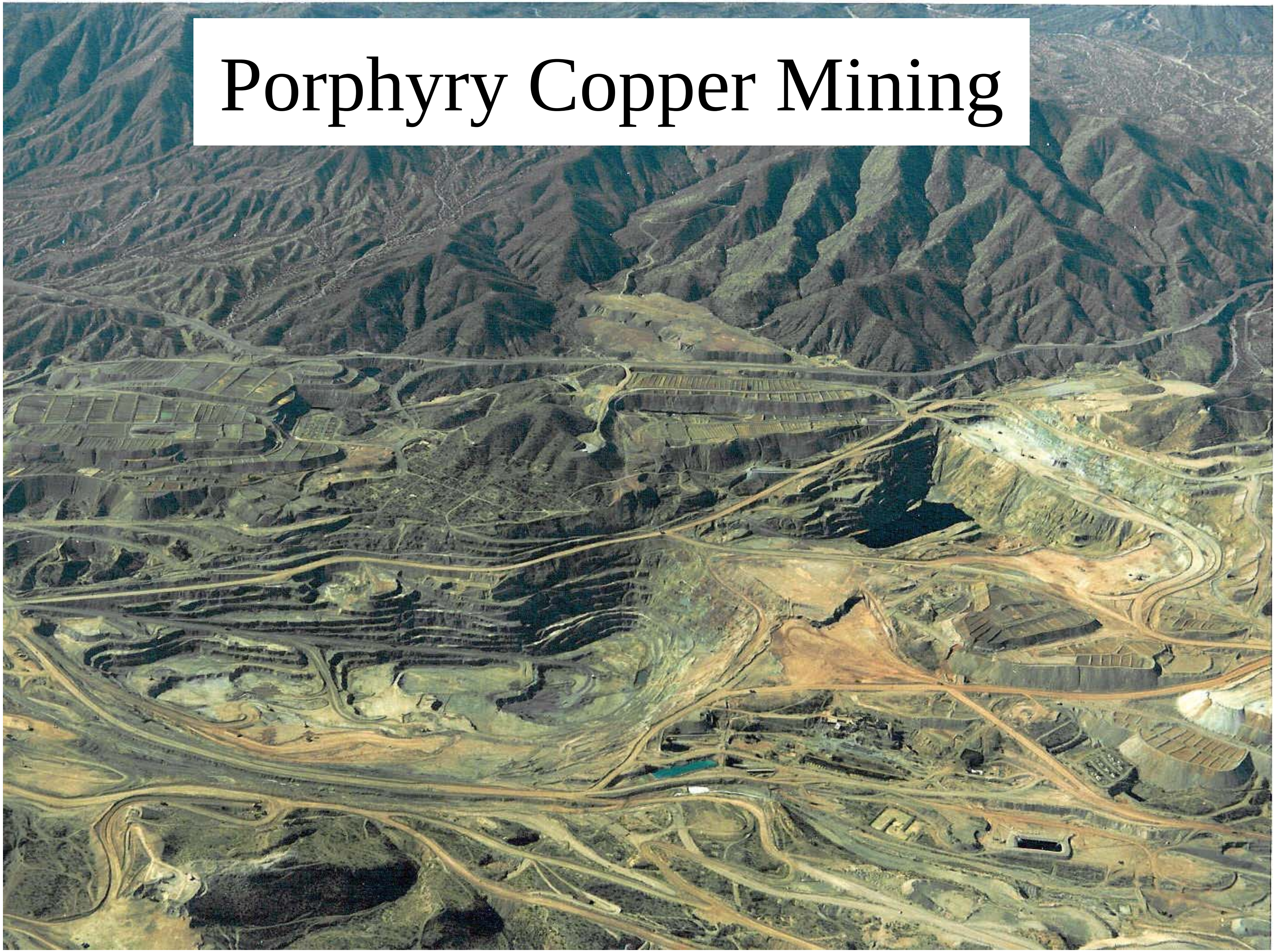
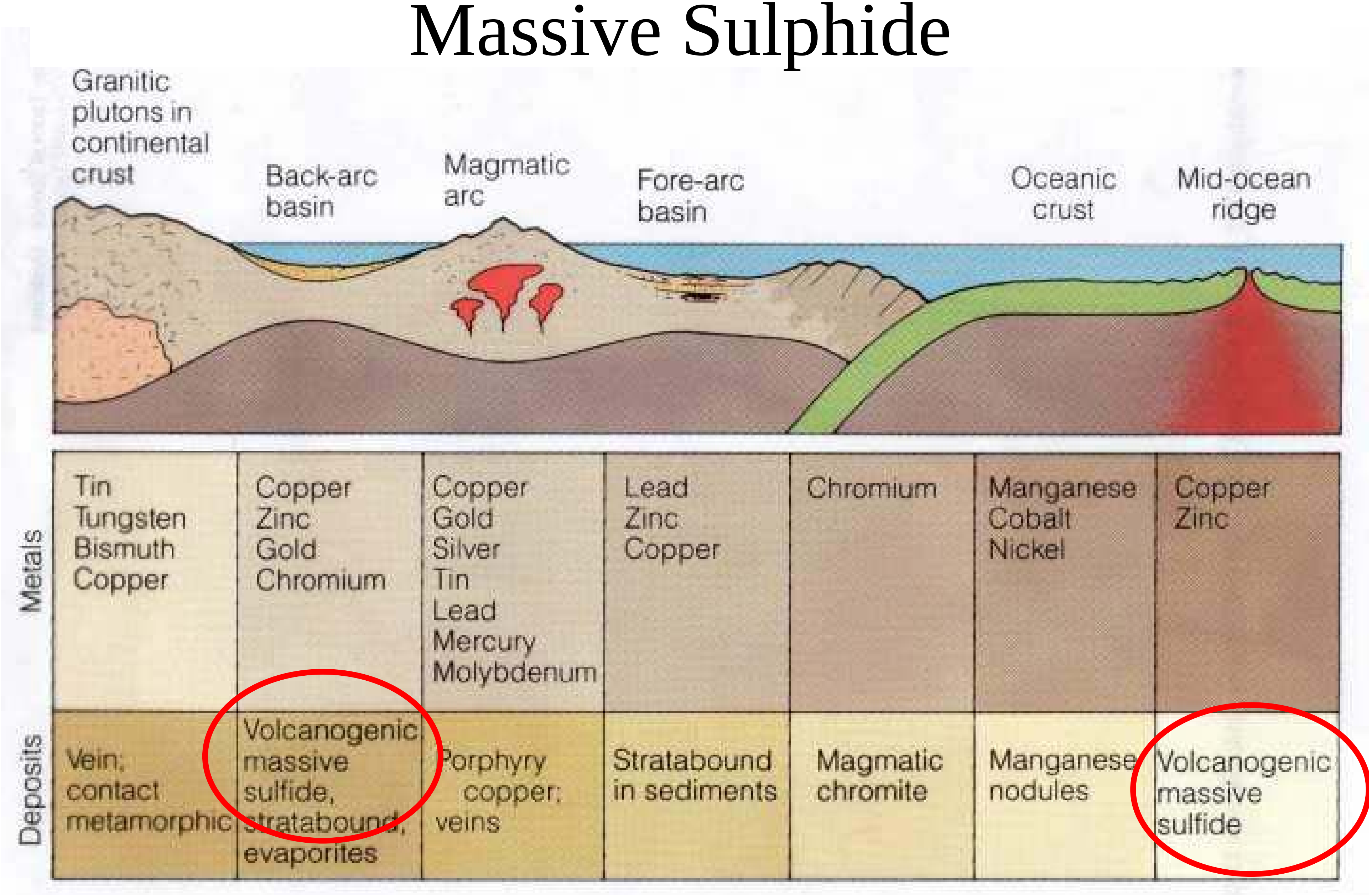
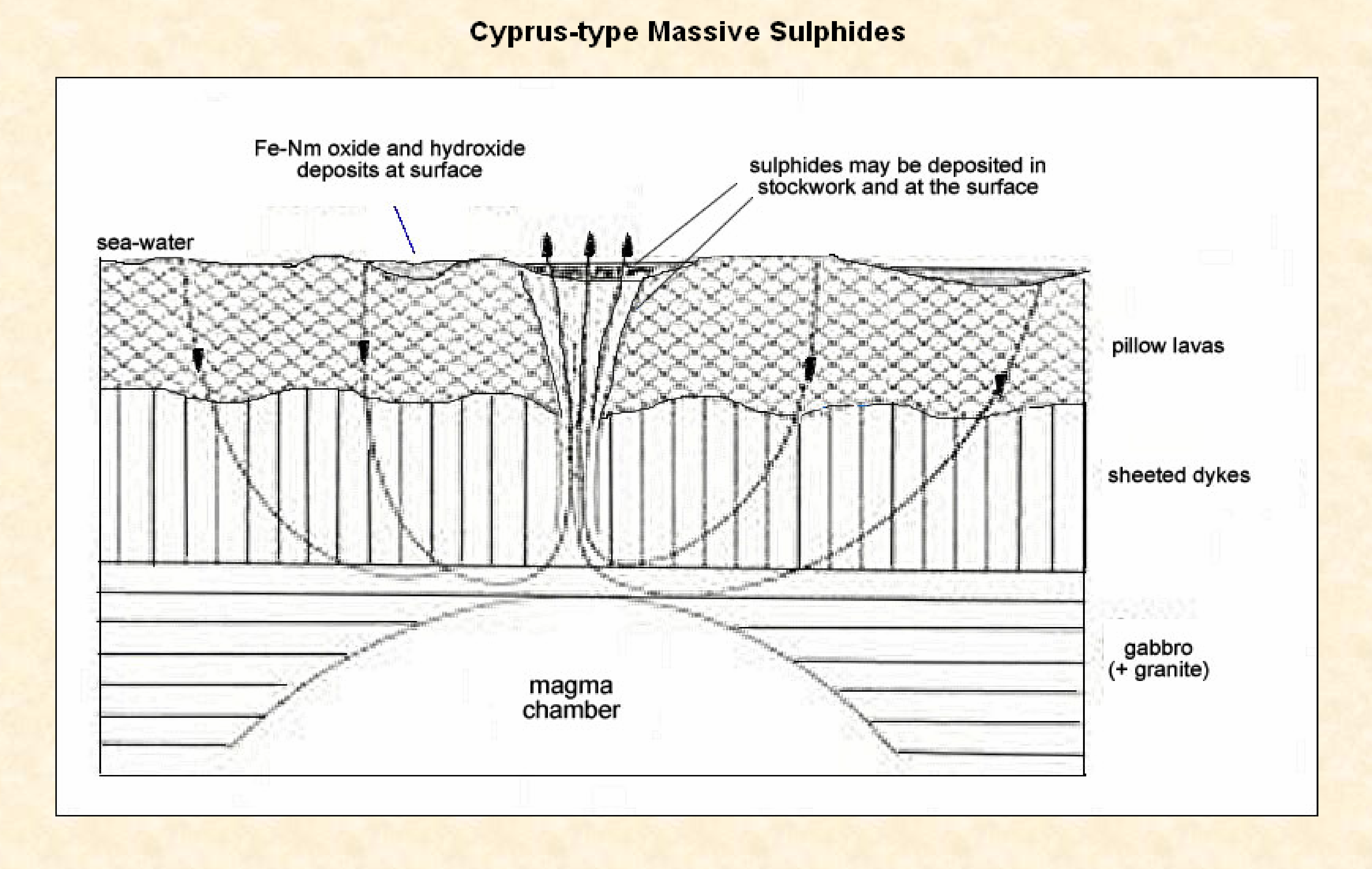


Plate Tectonic Ore Deposit Formation
Massive Sulphide

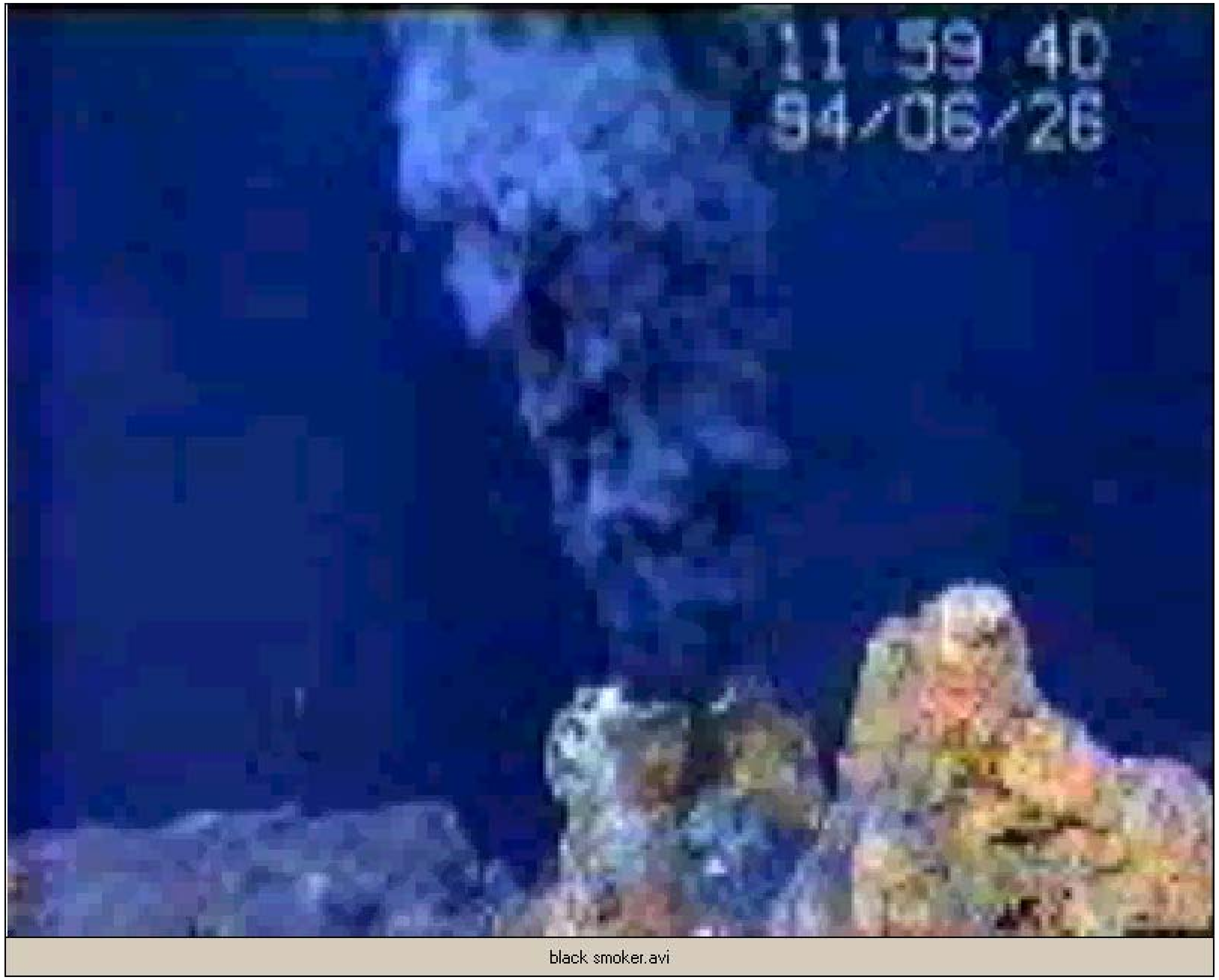


	Granitic plutons in continental crust	Back-arc basin	Magmatic arc	Fore-arc basin		Oceanic crust	Mid-ocean ridge
Metals	Tin Tungsten Bismuth Copper	Copper Zinc Gold Chromium	Copper Gold Silver Tin Lead Mercury Molybdenum	Lead Zinc Copper	Chromium	Manganese Cobalt Nickel	Copper Zinc
Deposits	Vein; contact metamorphic	Volcanogenic massive sulfide, stratabound, evaporites	Porphyry copper; veins	Stratabound in sediments	Magmatic chromite	Manganese nodules	Volcanogenic massive sulfide

Massive Sulphide Ore Deposit



Black Smokers → Create Volcanogenic massive Sulphides



Massive Sulphide Copper Mine

much smaller deposits, higher concentration of copper

Mine Head

Ore Vein

Bronze Age Mining

Bronze
age mine
entrance,
4000 BC

Burning wood to
heat/crack stone
copper ore

Basic tools were stone
hammers, wooden
shovels, and fire

Copper and why not Iron?

Copper was one of the first metals used, because it was comparatively easy to refine, and workable into objects. It was difficult to get hot fires to melt iron.

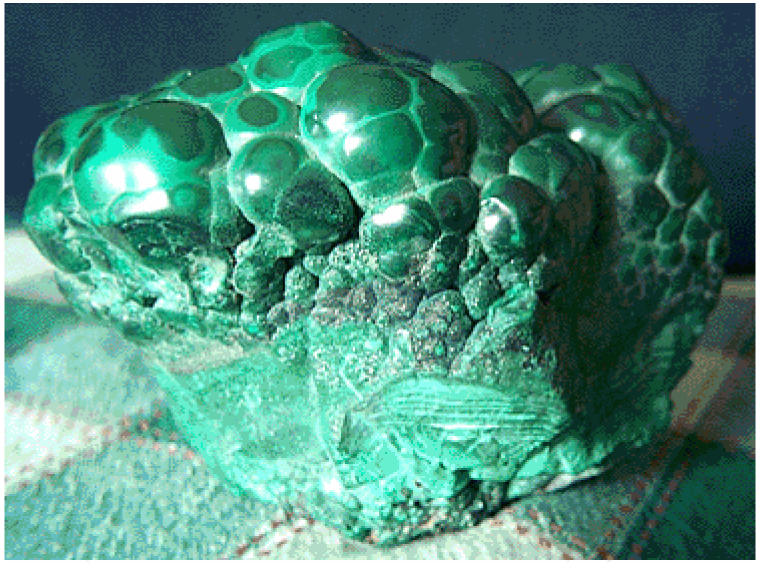
Material	Melting Point
Copper	1084.62 °C
Zinc	419.53 °C
Tin	231.93 °C
Iron	1538 °C

Timeline of Copper/Bronze/Iron Ages

- 7000 BC First evidence of copper production in eastern Turkey
- 4500 BC Copper working in Balkans, Aegean
- 3000 BC Bronze-making in Balkans/Greece/Turkey/Near East
- 2500 BC First iron objects, Turkey
- 1000 BC Widespread use of iron

Malachite copper ore

$Cu_2(CO_3)(OH)_2$



Early miners looked for Malachite, a copper ore that was easy to refine

The green color hints that it has copper inside

Making Copper I

Start with Copper ore, Malachite: $Cu_2(CO_3)(OH)_2$

Heat in kiln:

$Cu_2(CO_3)(OH)_2 = 2CuO + CO_2 + H_2O$

To get copper oxide, brownish powder

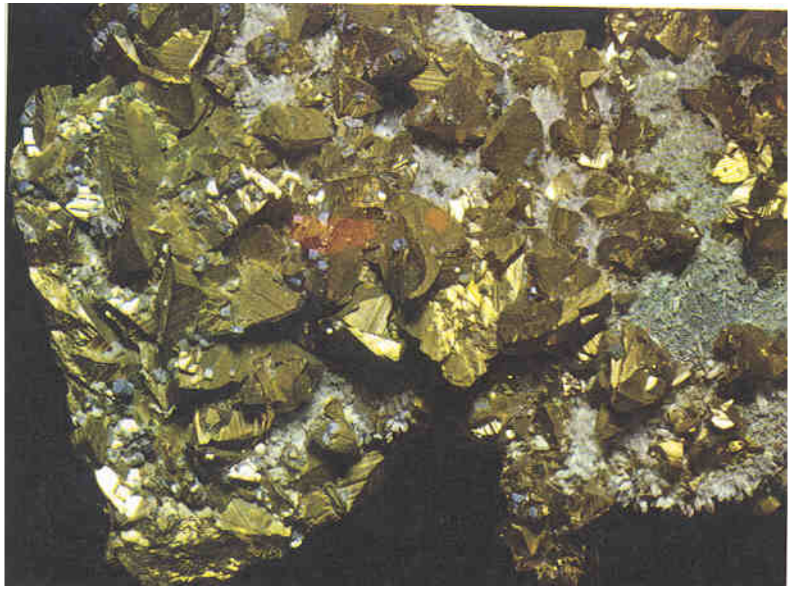
Then reducing fire, charcoal, oxygen-starved (rich in CO) to remove oxygen

At about 1100° C, copper oxide forms copper metal:

$$CuO + CO = Cu + CO_2$$

Bronze age pottery crucible for metal smelting

Making Copper II



Although Malachite was easier to smelt, Chalcopyrite, was more plentiful.

Start with Copper Sulfide ore, $CuFeS_2$

Heat in kiln while blowing air through

(roasting) :

$$4CuFeS_2 + 13O_2 \rightarrow 8SO_2 + 2Fe_2O_3 + 4CuO$$

Copper oxide was then reduced by stirring with green wood poles (effectively adding carbon to form CO_2)

Flux of $Si0_2$ was needed to dissolve the iron and float it to the surface. After cooling, it could be shattered and broken off, leaving copper.

Bronze

Bronze is an alloy of copper. Normally some Tin (10%) is added. Early bronze was Copper-arsenic, because Arsenic was easier to find. Bronze is a much stronger material than copper, so better for tools, weapons.

(Estimate for total bronze production in bronze age ~ 1 million tons. Cyprus – 200 kt; Rio Tinto – 100 kt)

Tin, Arsenic Ores

Casserite SnO_2

Not very distinctive

Adamite Cu_2AsO_4

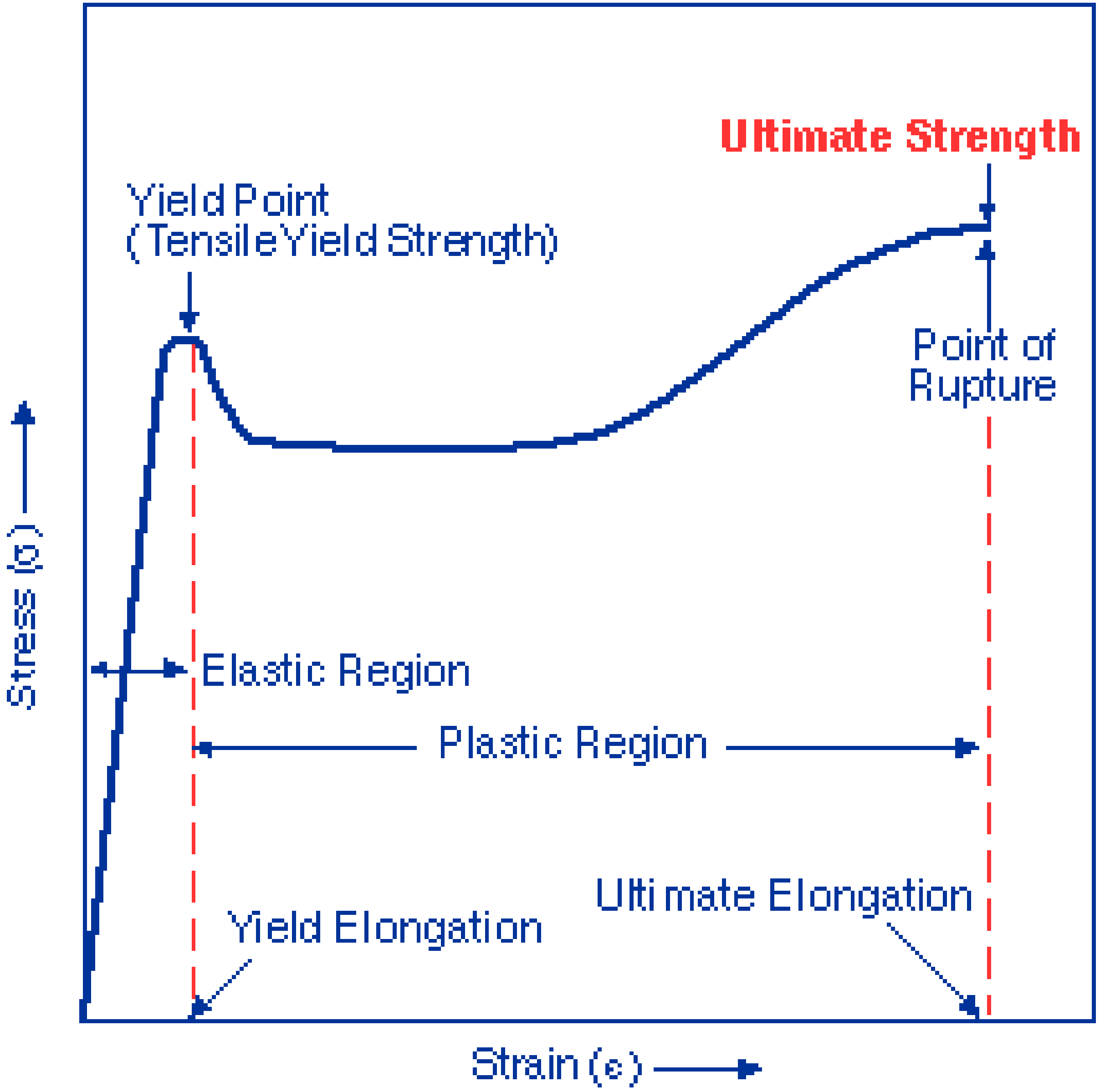
Arsenic Poisoning

Early Bronze was Cu-As. Arsenic is much more common that Tin and easier to identify. Smelters worked outside, no problem from the arsenic vapors. However the smiths worked inside, and would contract arsenic poisoning. First symptoms are nerve damage to limbs, crippling. Ultimately Bronze chemistry was switched to tin.

Vulcan, god of metalworking

Roman god Vulcan and analogous Greek god Hephaestus were always portrayed as lame, probably because many early metalworkers had arsenic poisoning and were crippled.

Strength of Materials



Change in length (Strain) is measured while pulling on test sample (Stress). Material acts spring-like for a while, then deforms (stretches), finally breaks.

Strength of Materials
The advantage of bronze

Material	Yield Strength	Ultimate Strength
Copper	10,000 psi (10 ksi)	30 ksi
Bronze	30 ksi	50 ksi
Wrought iron	18 ksi	25 ksi
Mild steel	35 ksi	50 ksi
Tool steel	100 ksi	150 ksi

Metal was of great economic importance

Athens became a great city state because it had a very large silver and lead mine under its control, Laurion Mines. 160 million ounces of silver was mined at Laurion. (A billion dollars worth today, even though silver is much more common now!)

Money was used to buy naval power, armies, as well as civil construction.

20,000 slaves worked the mines.

During Peloponnesian Wars (430 BC), Sparta laid siege to Laurion Mines before Athens.

Laurion Mines

Laurion Mines

Athenian silver coin from Laurion

Gallery. Height about 3 feet.

Ecological Impact of Mining

Early metal smelting needed enormous amounts of wood for fuel.

Copper smelting needs a great deal of fuel, especially if the ore supply is dominantly sulfide. About 300 kg of charcoal are needed to produce 1 kg of copper by smelting 30 kg of sulfide ore. A ton of charcoal needs somewhere between 12 and 20 cubic meters of wood, and for each cubic meter of wood a 100-year old tree has to be felled. So 3 large trees per pound of copper.

During life of Laurion Mines, about 300 years from 500 BC to 200 BC, 1 million tons of charcoal and 2.5 million acres of forest were consumed.

Over-foresting and the fall of Athens

Eventually, all forests around Athens were destroyed. Mine stopped producing, not because of lack of ore, but lack of wood.

Cutting the forests caused erosion.

Plato writes about environment of Athens:

a mere relic of the original country.... What remains is like the skeleton of a body emaciated by disease. All the rich soil has melted away, leaving a country of skin and bone. Originally the mountains of Attica were heavily forested. Fine trees produced timber suitable for roofing the largest buildings: the roofs hewn from this timber are still in existence.

Athens destroyed at end of Peloponnesian Wars. Although Laurion still had silver ore, no wood to use to refine.

With the end of silver production, Athens fell from power.

Over-foresting in the ancient world

- Cyprus produced 200,000 tons copper. Needed 40 million acres of forest!
- As a scale, recent California fires burned 600,000 acres.
- Current aridity and lack of trees in Cyprus, Greece, Lebanon and lack of trees thought to be aftermath of this deforestation. (Earlier thought due to introduction of goats and overgrazing.)

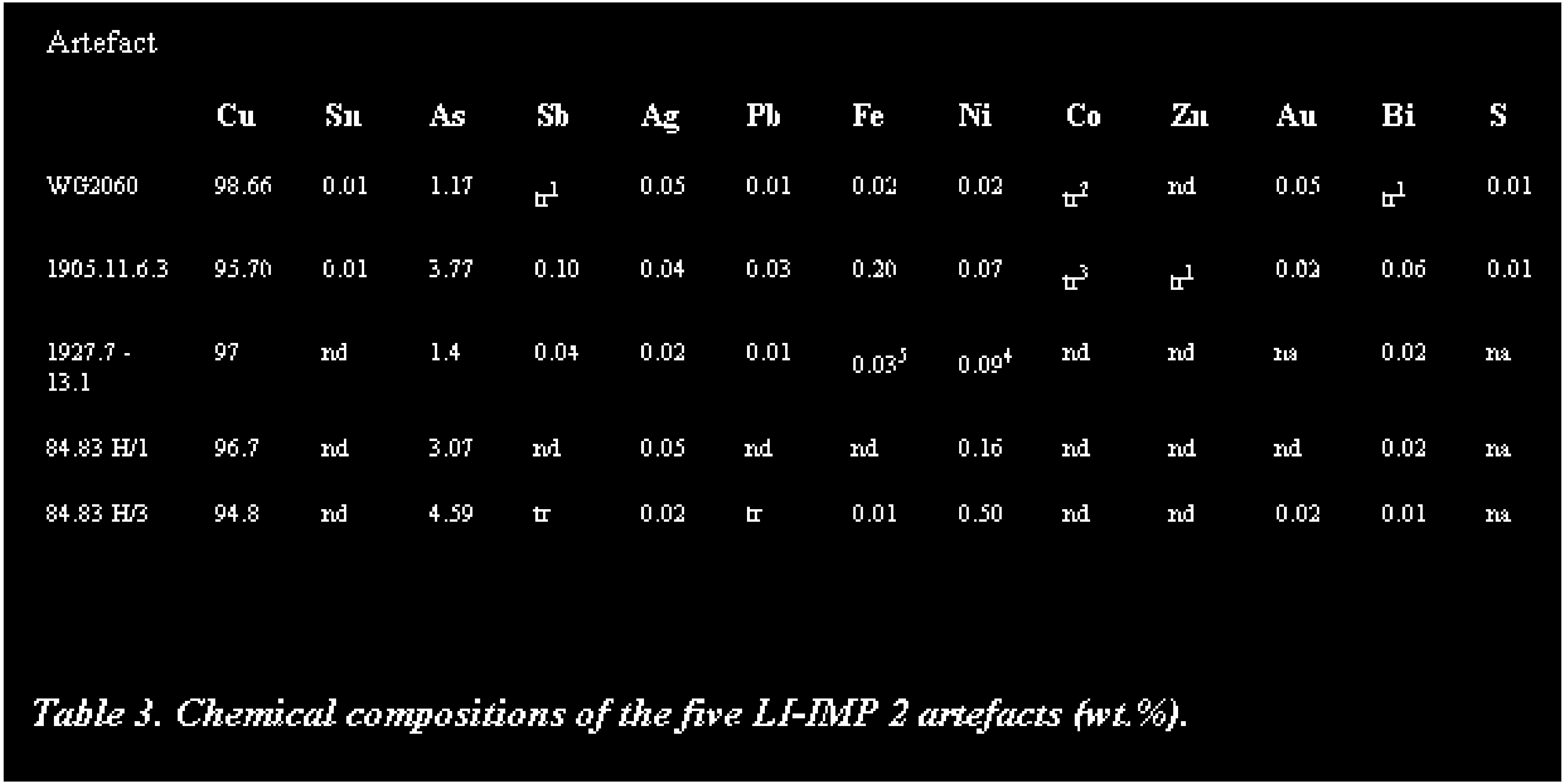
End of the Bronze Age

- Bronze Age “officially” ended around 1200BC in the Aegean region. Fall of Troy, end of Mycenaean civilization.
- Result was 400 years of “dark age” before rise of Greek civilization around 800BC. Loss of writing, …
- Cause(s) under debate:
  - Earthquakes
  - Invasions
  - Change in techniques of warfare (chariot vs infantry)
  - Deforestation
  - Cutoff of tin supply

Source of Tin for Bronze

Tin is pretty scarce. Where did the tin come from that was used for bronze? It is a question that interests archeologists today. The origin of the tin tells about the ancient trade routes and commerce. Science can be used to find out the source of the tin.

Chemical Assay used to compare 5 different copper artifacts



Artefact	Cu	Sn	As	Sb	Ag	Pb	Fe	Ni	Co	Zn	Au	Bi	S
WG2060	98.66	0.01	1.17	tr^{1}	0.05	0.01	0.02	0.02	tr^{2}	nd	0.05	tr^{1}	0.01
1905.11.6.3	95.70	0.01	3.77	0.10	0.04	0.03	0.20	0.07	tr^{3}	tr^{1}	0.02	0.06	0.01
1927.7 - 13.1	97	nd	1.4	0.04	0.02	0.01	0.03^{5}	0.09^{4}	nd	nd	na	0.02	na
84.83 H/1	96.7	nd	3.07	nd	0.05	nd	nd	0.16	nd	nd	nd	0.02	na
84.83 H/3	94.8	nd	4.59	tr	0.02	tr	0.01	0.50	nd	nd	0.02	0.01	na

Table 3. Chemical compositions of the five LI-IMP 2 artefacts (wt.%).

Radioactive decay chains into lead isotopes

^{238}U series		**^{232}Th series**		**^{235}U series**	
^{238}U	4.47×10^{9}yr	^{232}Th	1.40×10^{10}yr	^{235}U	7.04×10^{8}yr
^{234}Th	24.1 day	^{228}Ra	5.75 yr	^{231}Th	25.5 day
^{234}Pa	1.18 min	^{228}Ac	6.13 hr	^{231}Pa	3.25×10^{4}yr
^{234}U	2.48×10^{5}yr	^{228}Th	1.91 yr	^{227}Ac	21.8 yr
^{230}Th	7.52×10^{4}yr	^{224}Ra	3.66 day	^{227}Th	18.7 day
^{226}Ra	1.62×10^{3}yr	^{220}Rn	55.6 sec	^{223}Ra	11.4 day
^{222}Rn	3.82 day	^{216}Po	0.15 sec	^{219}Rn	3.96 sec
^{218}Po	3.05 min	^{212}Pb	10.6 hr	^{215}Po	1.78×10^{-3}sec
^{214}Pb	26.8 min	^{212}Bi	60.6 min	^{211}Pb	36.1 min
^{214}Bi	19.7 min	^{212}Po	3.0×10^{-7}sec	^{211}Bi	2.15 min
^{214}Po	1.64×10^{-4}sec	^{208}Pb	stable	^{207}Tl	4.77 min
^{210}Pb	22.3 yr			^{207}Pb	stable
^{210}Bi	5.01 day				
^{210}Po	138 day				
^{206}Pb	stable				

Radio-isotope comparison of 5 different samples

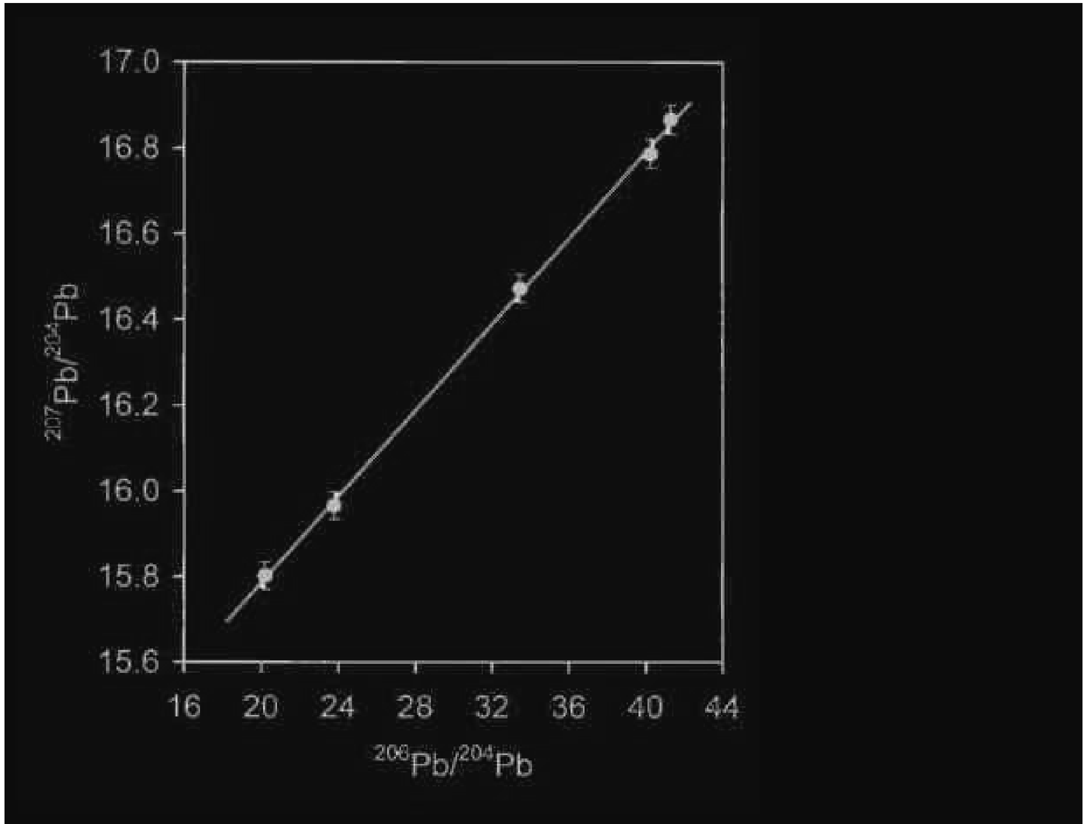
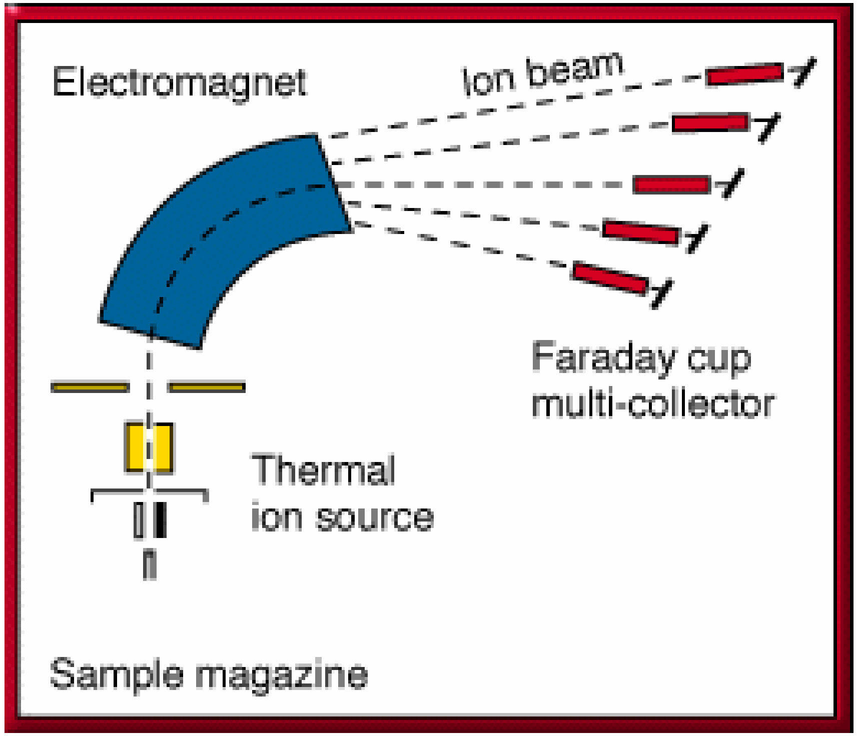


Figure 1. Lead isotope ratios of the five LI-IMP 2 artefacts (Rohl 1995, Rohl and Needham 1998). Data are plotted with 2 σ errors reflecting reproducibility of measurements of the NBS981 standard as given by Rohl (1995) (note that ^{206}Pb/^{204}Pb errors are smaller than the symbols on this scale). The linear regression (M.S.W.D. of 0.972) gives a Pb-Pb isochron yielding a model age of 205 ±72Ma (2 σ). The relatively large error is a consequence of the small sample size (n=5).

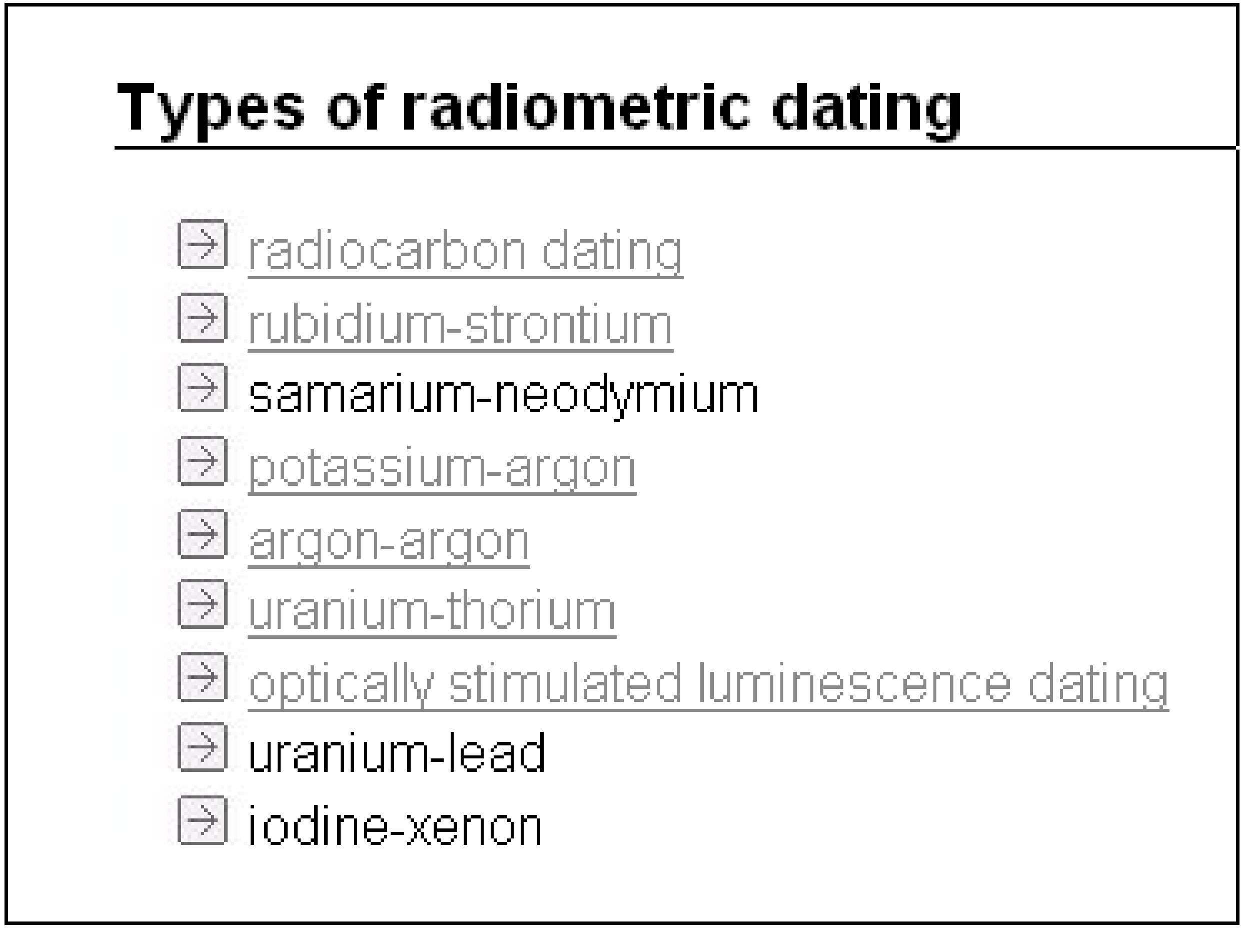
$$Pb^{207}/Pb^{206} = [U^{235}(e^{L235t}-1)]/[U^{238}(e^{L238t}-1)]$$

Mass Spectrometer for determining Isotope concentrations



Features of a mass spectrometer. A mass analysis is obtained by volatilizing the element placed in the *thermal ion source* of the machine, which is kept at high vacuum. The vapor is then ionized and accelerated through a magnetic field produced by an *electromagnet*. The ion beam travels through the analyzer tube and then goes to a *collector*, where it is measured.

Other Radio-dating Techniques



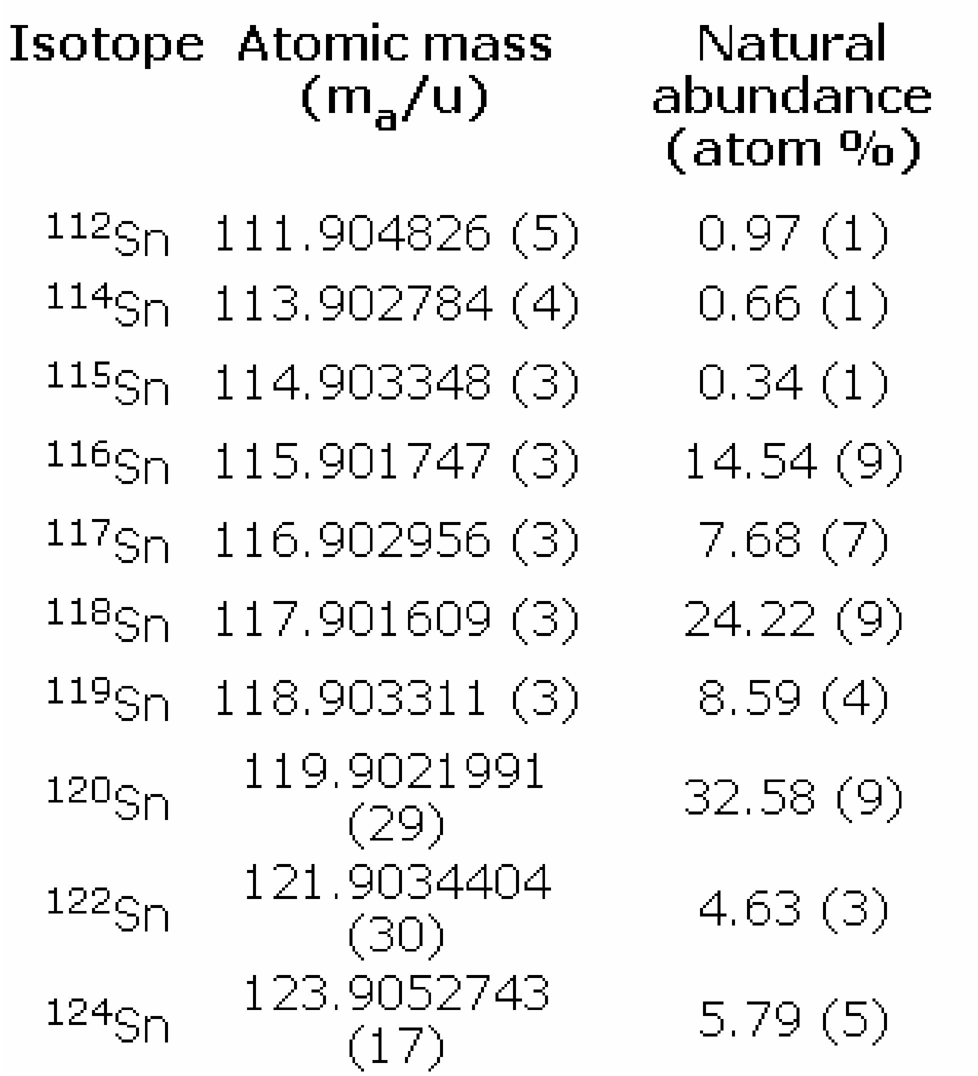
Types of radiometric dating

- radiocarbon dating
- rubidium-strontium
- samarium-neodymium
- potassium-argon
- argon-argon
- uranium-thorium
- optically stimulated luminescence dating
- uranium-lead
- iodine-xenon

Sn Isotope concentrations

Study is currently under way to see if tin ores can be determined by ratios of isotopes. All isotopes naturally occurring, not decay products.

Interesting fact: because there is so much difference in mass of the isotopes, heating and reheating bronze can change isotope ratios by up to 5%. Can tell if bronze was recycled.



Isotope	Atomic mass (m_a/u)	Natural abundance (atom %)
^{112}Sn	111.904826 (5)	0.97 (1)
^{114}Sn	113.902784 (4)	0.66 (1)
^{115}Sn	114.903348 (3)	0.34 (1)
^{116}Sn	115.901747 (3)	14.54 (9)
^{117}Sn	116.902956 (3)	7.68 (7)
^{118}Sn	117.901609 (3)	24.22 (9)
^{119}Sn	118.903311 (3)	8.59 (4)
^{120}Sn	119.9021991 (29)	32.58 (9)
^{122}Sn	121.9034404 (30)	4.63 (3)
^{124}Sn	123.9052743 (17)	5.79 (5)

Sources of Bronze Age Tin

Recently rediscovered Kestel mine was the source of near-Eastern Bronze age tin.

The Sumerian word for copper, "urudu", is the same word for the Euphrates, literally, the "copper river."

Compare HCAL to other large constructions

- HCAL is made of brass and stainless steel.
- 1600 tons total for barrel and endcap.
- About 1200 tons copper.
- What other large objects are made of copper alloy?

  → monumental statues
- Look into a little history of famous statues

Alexander the Great

356 –323 BC

- Phillip II of Macedonia
- Alexander the Great
- Aristotle
- Generals Antigous the one-eyed, Seleucus, Ptolemy
- Cleopatra

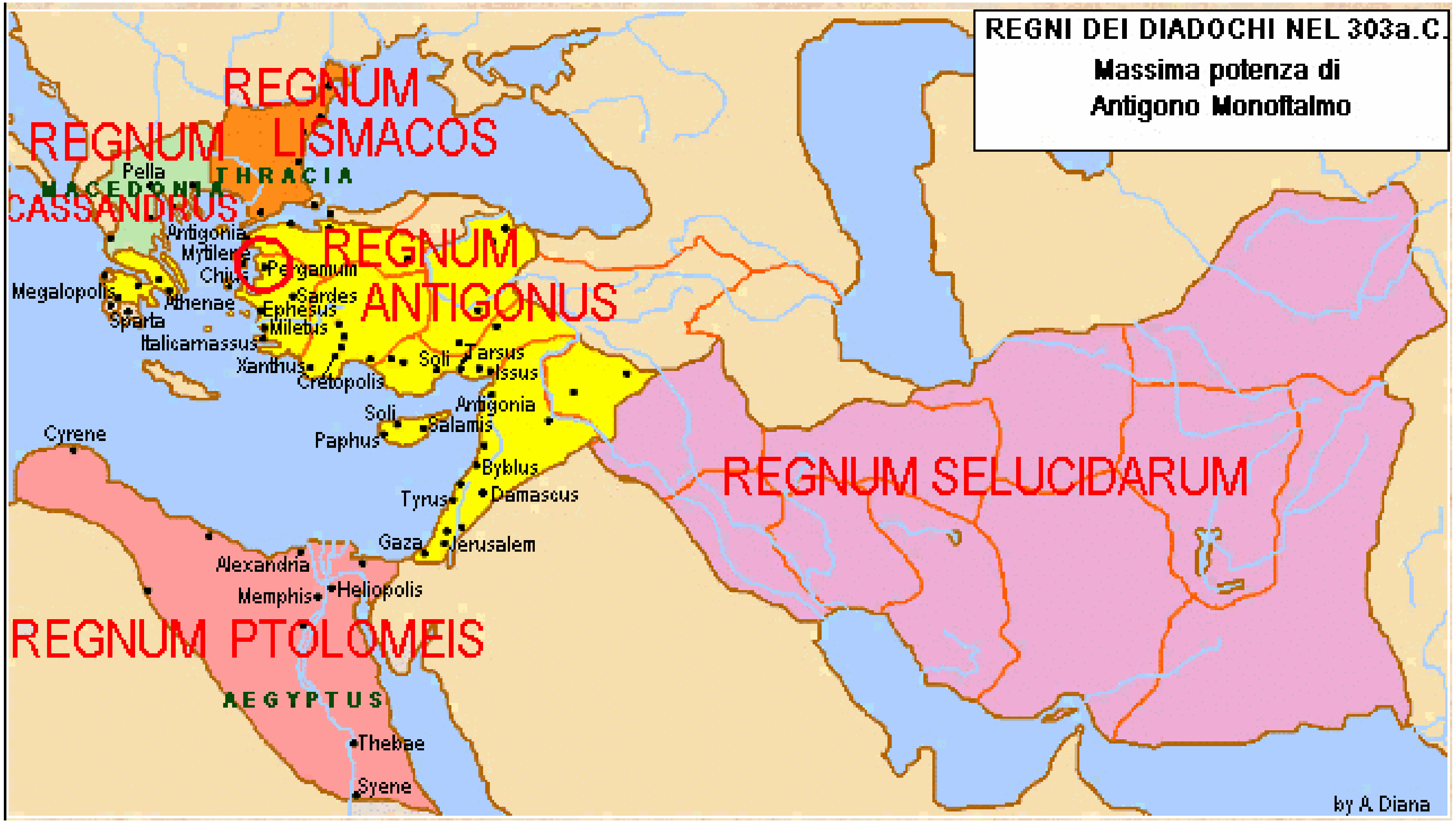
Alexander the Great bullets

Alexander the Great

PAR

- 356 –323 BC
- Took power after the assassination of his father, Philip II.
- Aristotle was his tutor.
- Considered very handsome. Short by modern standards, 5’3’’.
- Would bring in philosophers and scholars of conquered lands to discuss and learn from.
- Was a terrible drunk. He ordered the torching of Persepolis on a whim after a drinking binge.
- Lived to be 33 years old. Died from illness acquired during drinking bout.

Empire of Alexander the Great

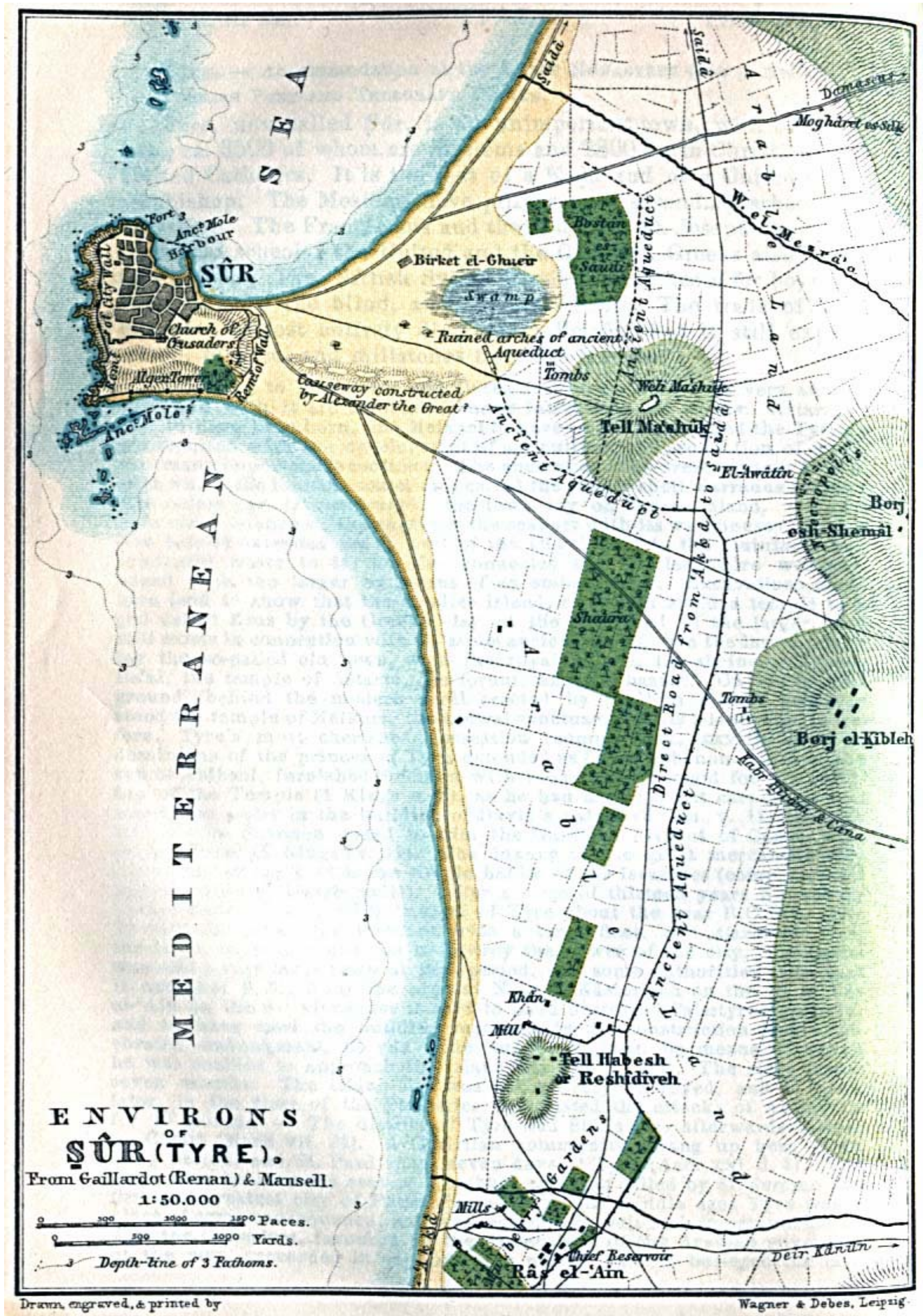


Diving at Tyre

Alexander tried to float siege engines to island city of Tyre. Citizens sank ships to block way. Alexander sent down divers (weighted wooden barrels over their heads) to clear wrecks. First record of underwater diving.

He ultimately built land bridge to island.

Map of Tyre from 1700’s still shows Alexander’s land bridge



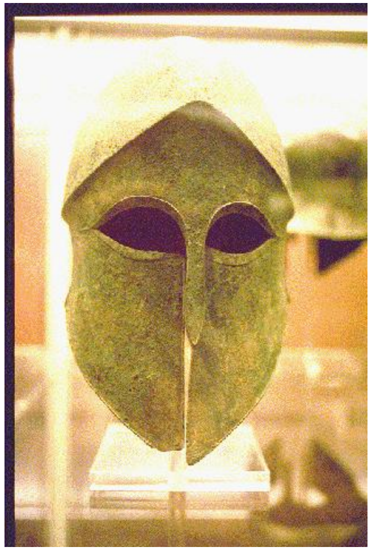
Colossus of Rhodes

After the death of Alexander (at 33), his empire divided between his three principal generals, Seleucus, Antigous, and Ptolemy. The Rhodians supported Ptolemy (who wound up ruling Egypt) in this struggle. This angered Antigous who sent his son Demetrius to capture and punish the city of Rhodes. Rhodes, off the coast of Turkey, seiged by Demetrius and army of 40,000. After one year, fleet of ships from Egypt, Ptolemy, came to the rescue.

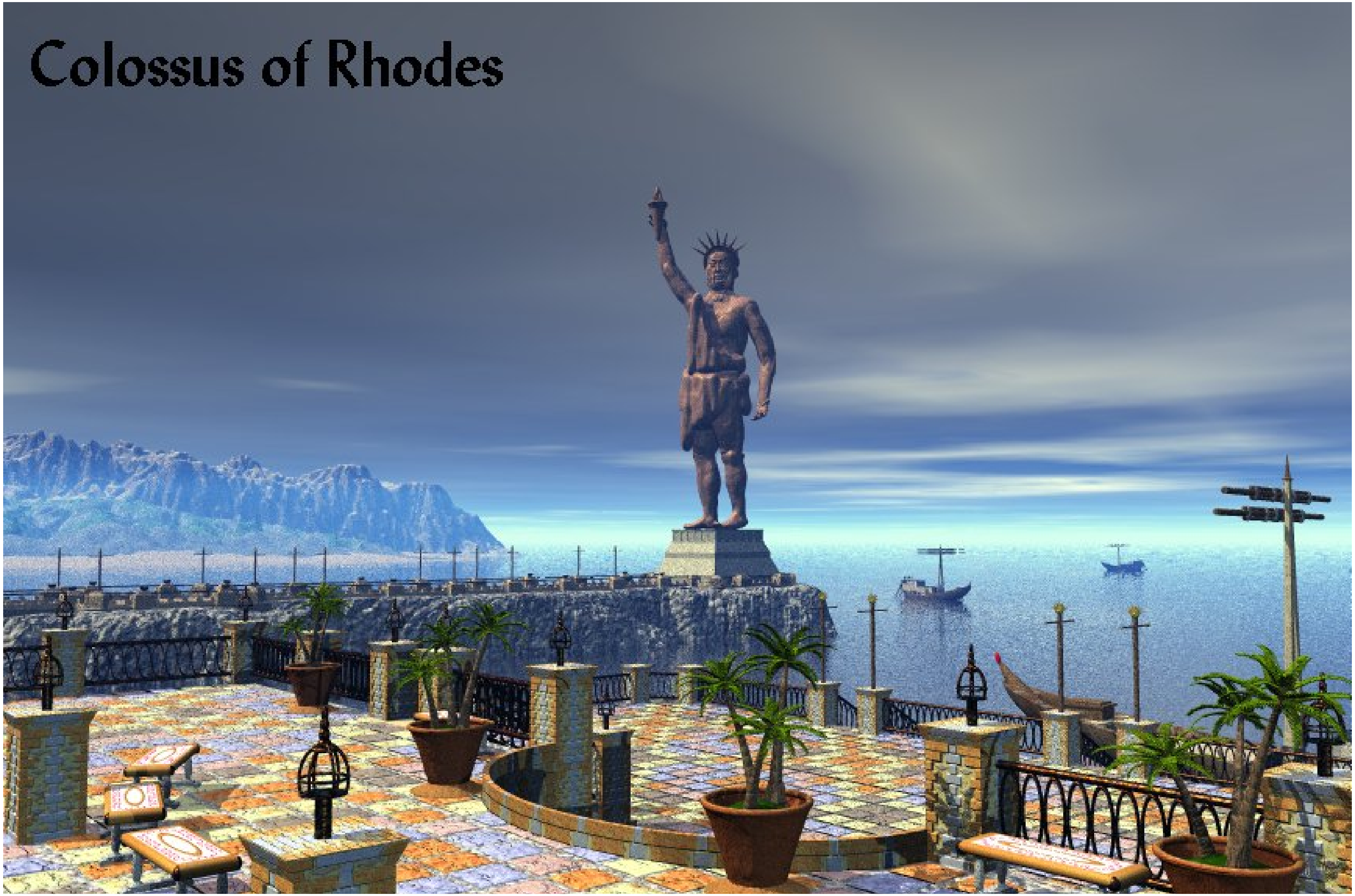
The siege was abandoned and departing soldiers left armor there. Citizens of Rhodes commissioned statue, had the bronze armor melted down and used in the statue, the Colossus of Rhodes. Started in 304 BC.

Statue stood for 54 years until earthquake broke it. Huge pieces lay on the ground for 1000 years. In 700 AD, sold for scrap, 700 camels carried the material away.

Armor

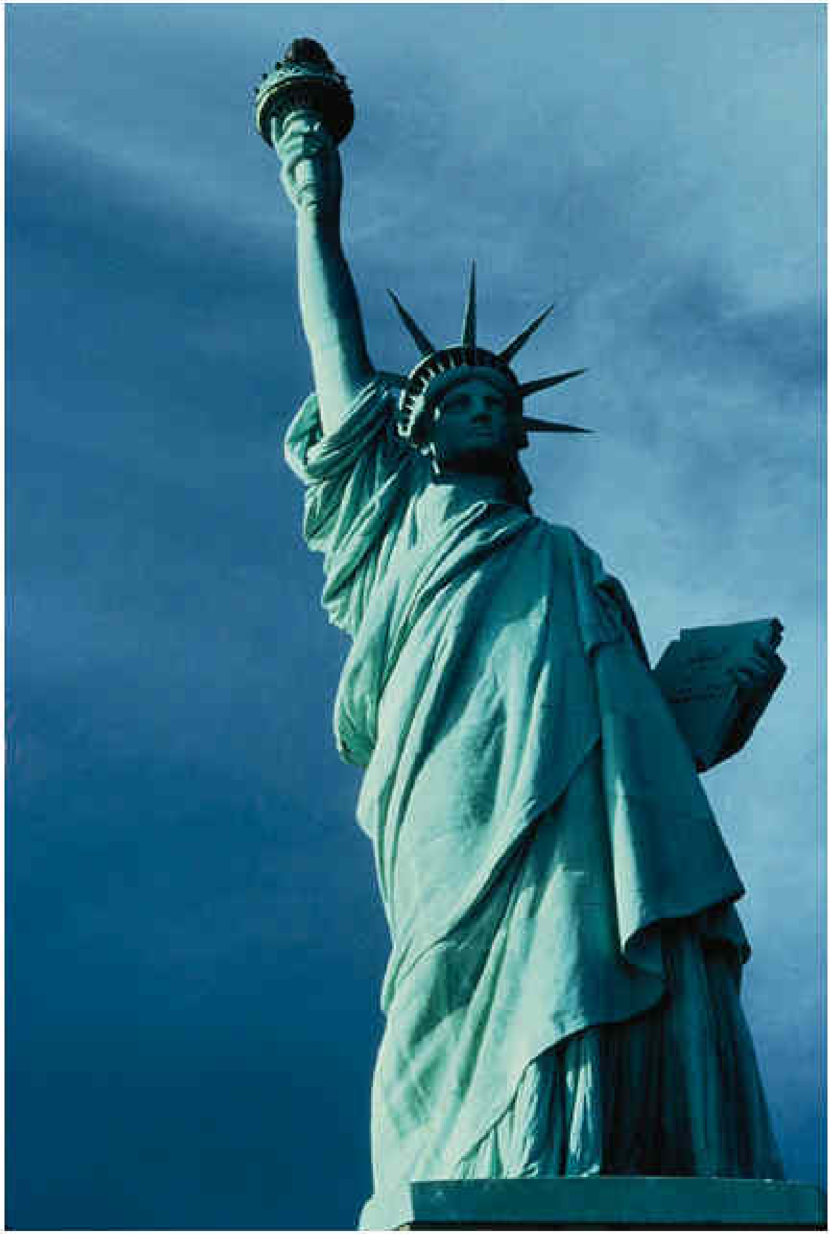


Full armor of soldier was about 80 pounds of bronze

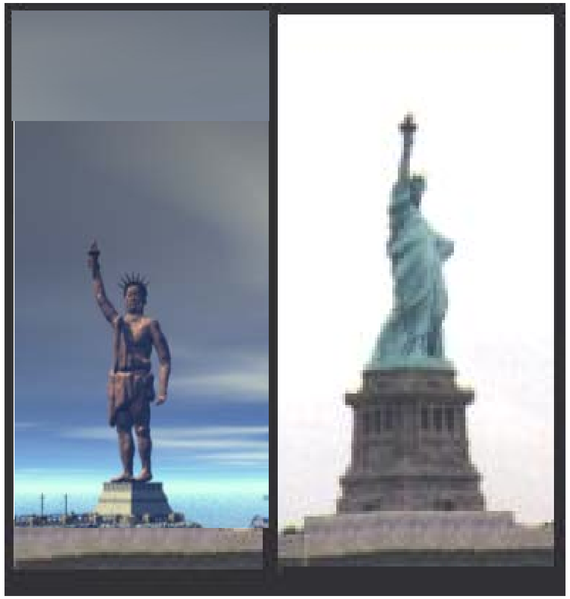


Colossus of Rhodes (40 meters) (200 tons Bronze)

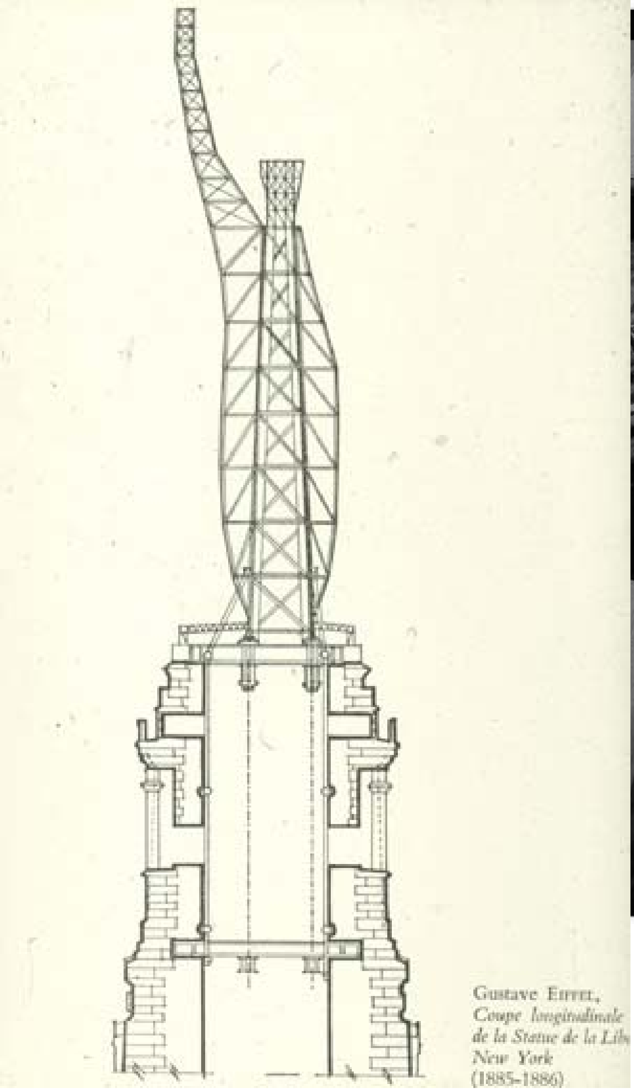
Statue of Liberty



Statue of Liberty designed by Frederic Auguste Bartholdi, inspired by Colossus of Rhodes. Designed to be the same size. It is 40 meters tall, uses 100 tons copper.



Structure of Monumental Statues

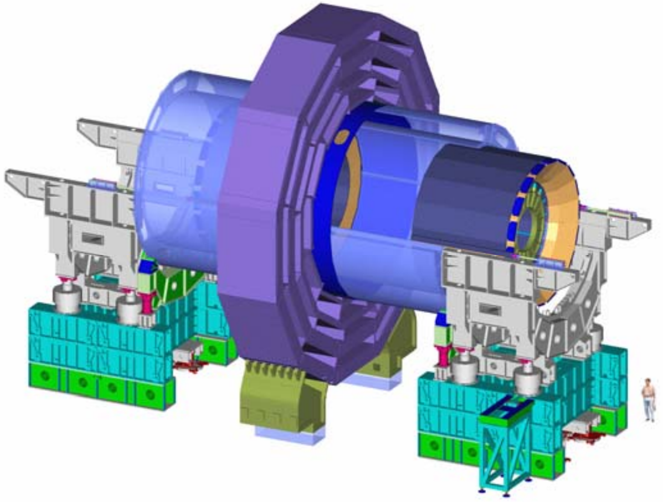


Interior view of Statue of Liberty. Structure is a cast iron framework with 2mm thick sheets of copper riveted to it. Same basic structure as Colossus of Rhodes. (By the way, Statue of Liberty iron frame designed by Gustave Eiffel, of Eiffel Tower fame.)

Science vs Religion

The world’s largest statue, Maitreya Buddha (150 meters tall) (2500 tons bronze) is being contemplated for Buddhgaya, India.

Until then, CMS HCAL, 1600 tons, will be the most massive copper structure ever built.



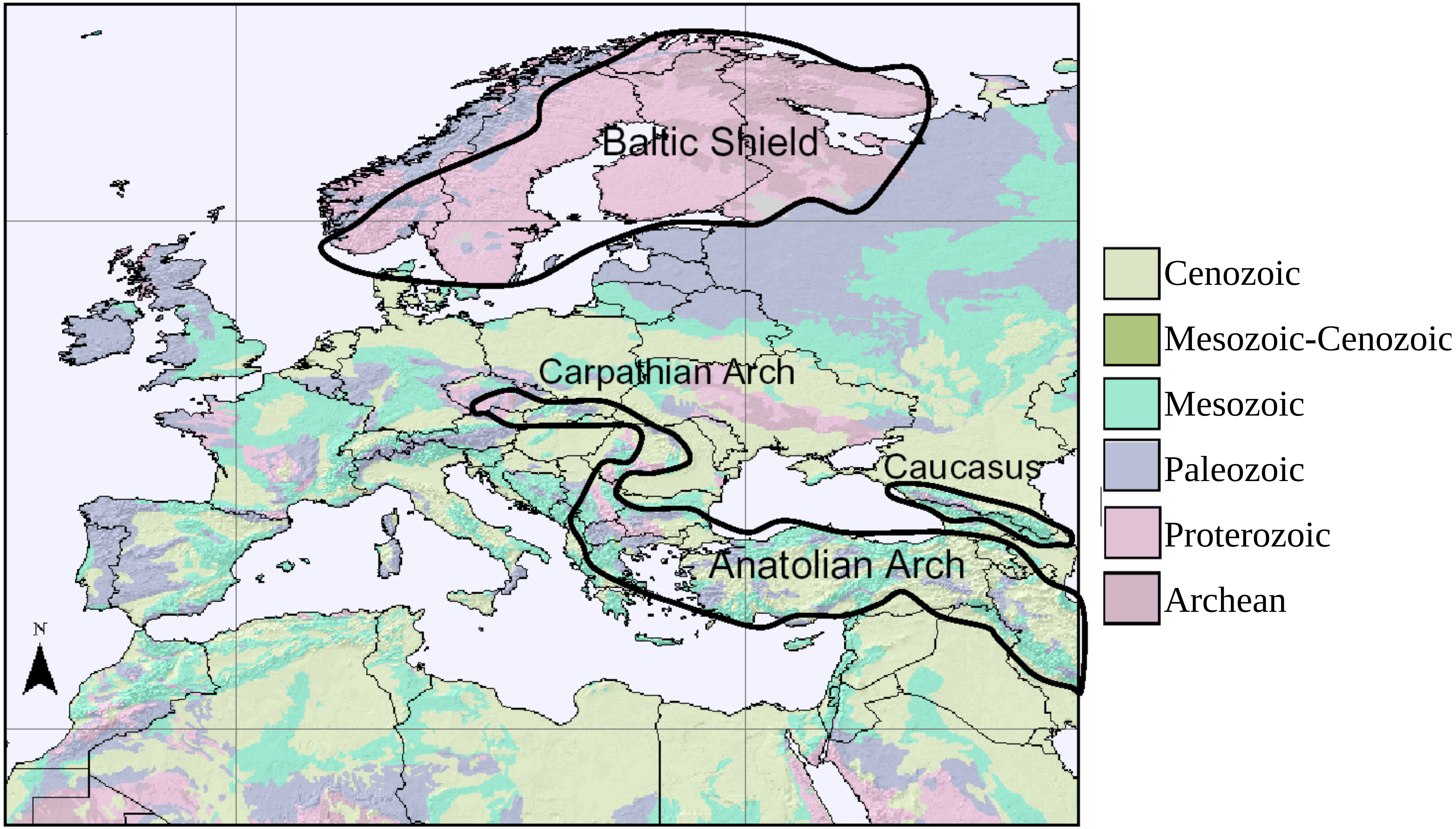
Backup

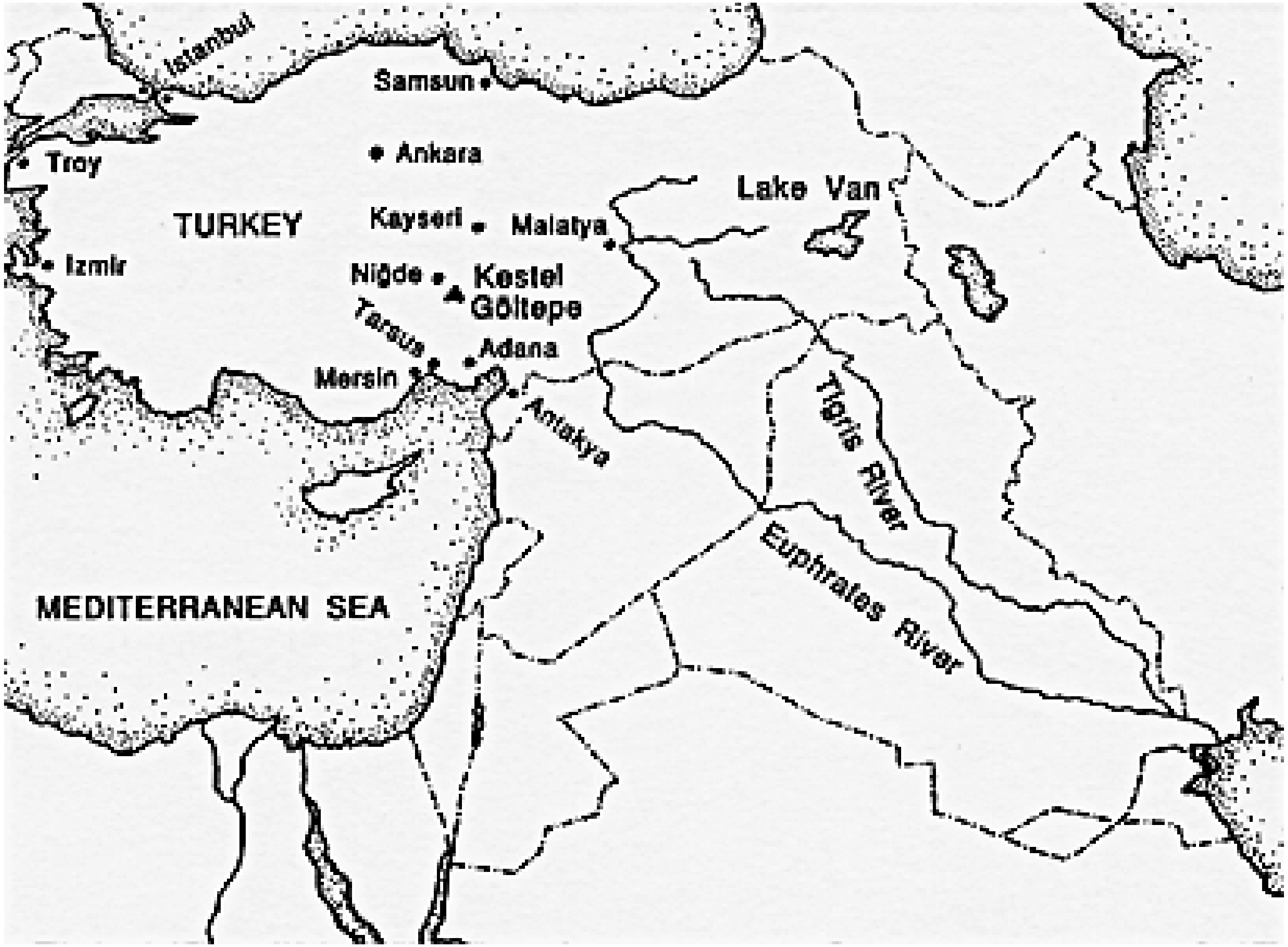
HCAL

The HCAL is a detector that will be used at the LHC at CERN. It sits inside a huge electromagnet with a very strong magnetic field. Because of this, it needs to be made from non-magnetic material, stainless steel or copper. We picked copper because it is cheaper and easier to machine.

HB sitting on its cradle in Spain

Geology of Europe /Asia Minor

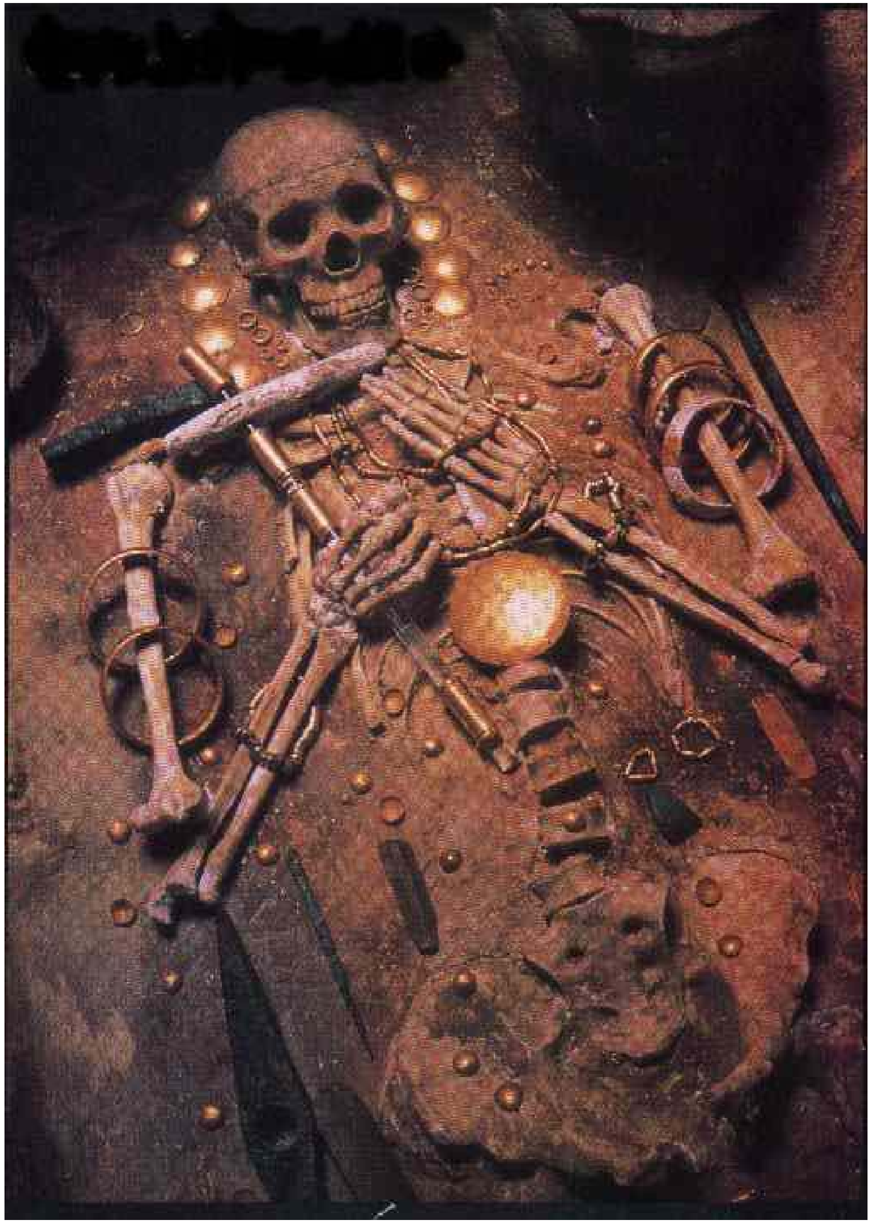



Istanbul
Samsun
Troy
Ankara
Lake Van
TURKEY
Kayseri
Malatya
Izmir
Niğde
Kestel
Göltepe
Tarsus
Adana
Mersin
Antakya
Tigris River
Euphrates River
MEDITERRANEAN SEA

Empire of Thrace

Part of present day Bulgaria. It was a powerful country 700 – 50 BC, with gold and copper riches. A pre-Grecian civilization. Kings were buried in mounds, many of which were forgotten about and not plundered.

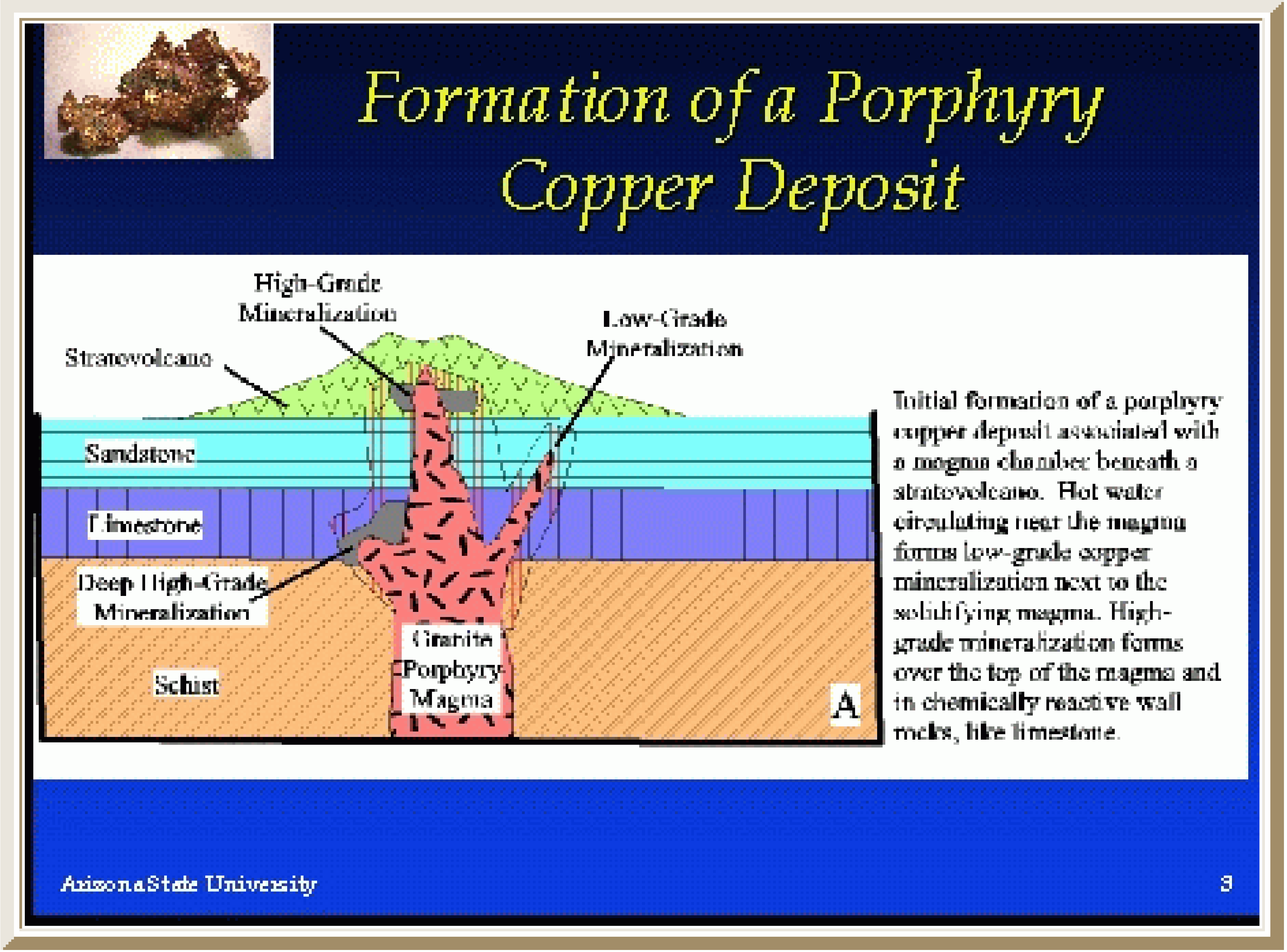
Grave of Pre-Thracian King, 4000BC



Wealth of Thrace

Massive Sulphide Ore

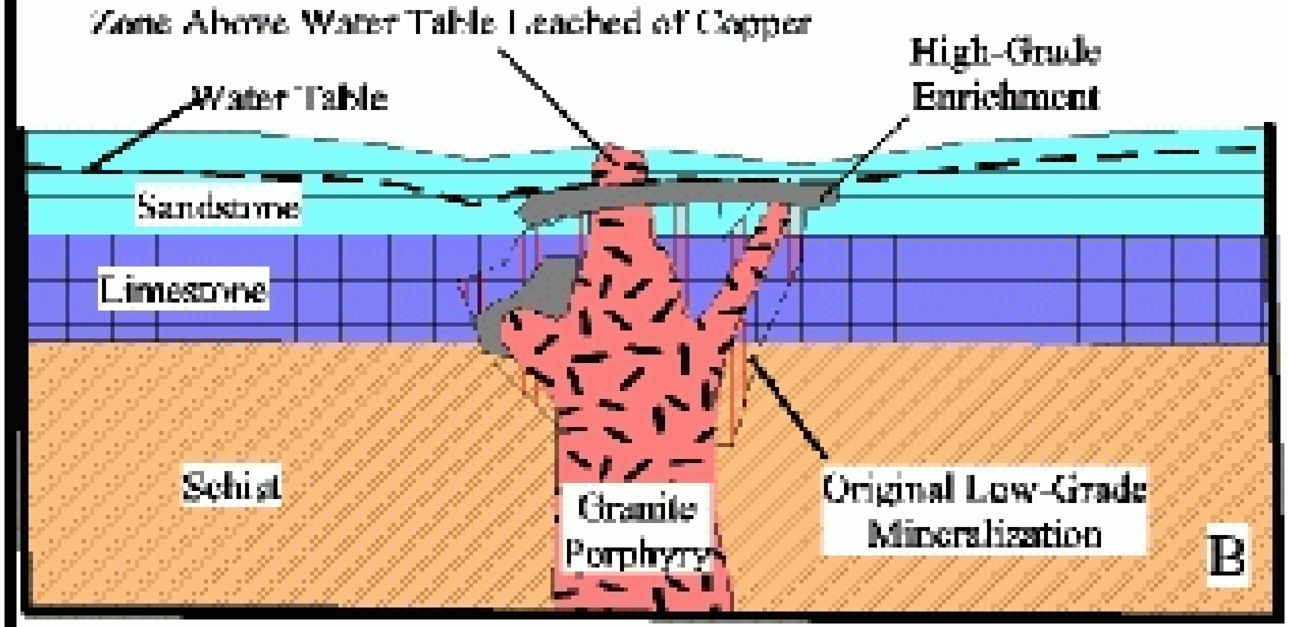
much smaller deposits,
higher concentration of copper



Formation of a Porphyry Copper Deposit

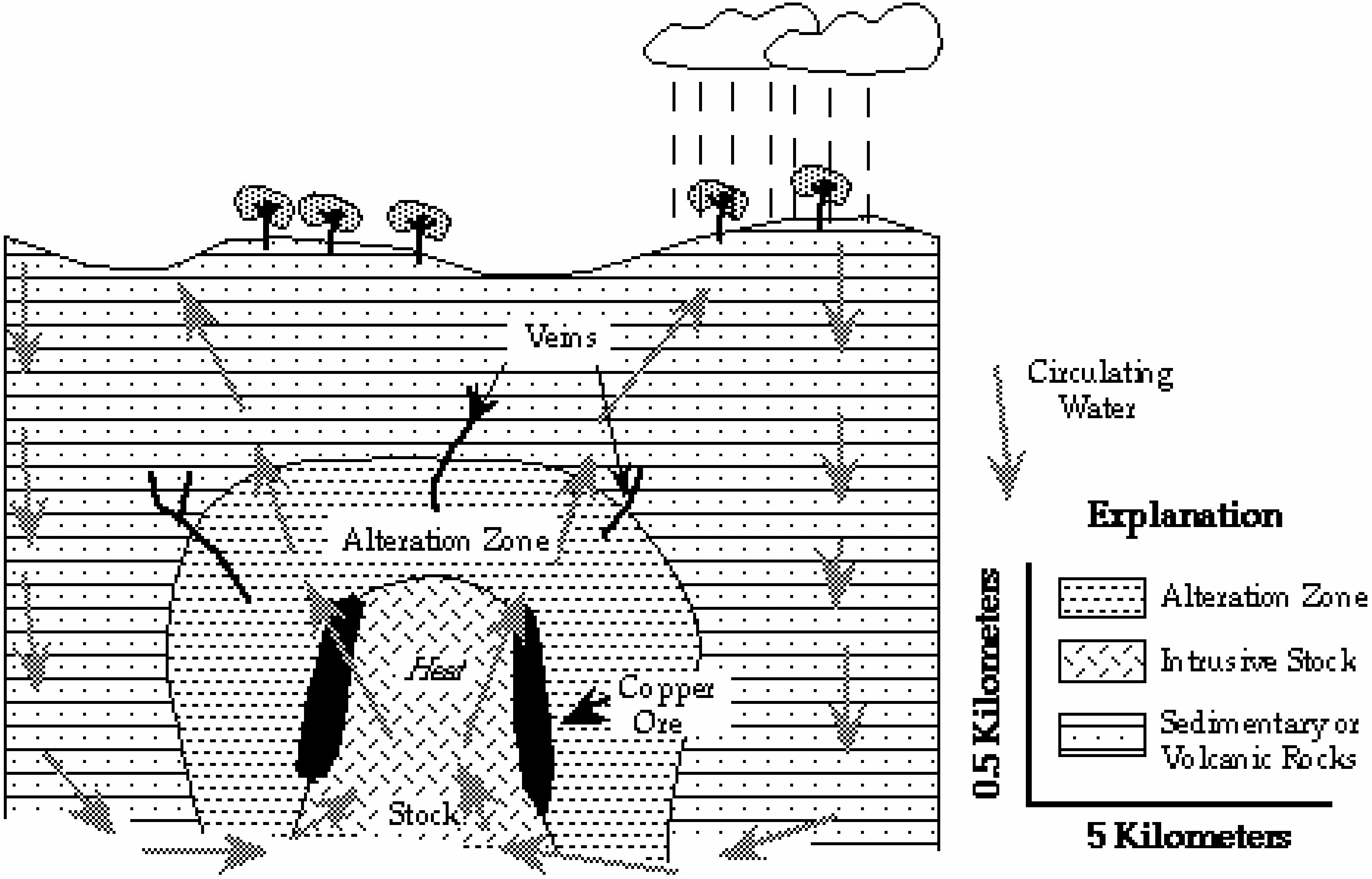
Initial formation of a porphyry copper deposit associated with a magma chamber beneath a stratovolcano. Hot water circulating near the magma forms low-grade copper mineralization next to the solidifying magma. High-grade mineralization forms over the top of the magma and in chemically reactive wall rocks, like limestone.

Formation of a Porphyry Copper Deposit



Erosion removes the stratovolcano and top of the original copper deposit. Rainwater and weathering cause copper to be leached from the top of the deposit and redeposited as the downward-moving groundwater reaches the water table. The resulting enriched zone is commonly high grade and fairly flat.

Massive Sulphide Formation



Balkan Metallogenesis and Plate Activity I

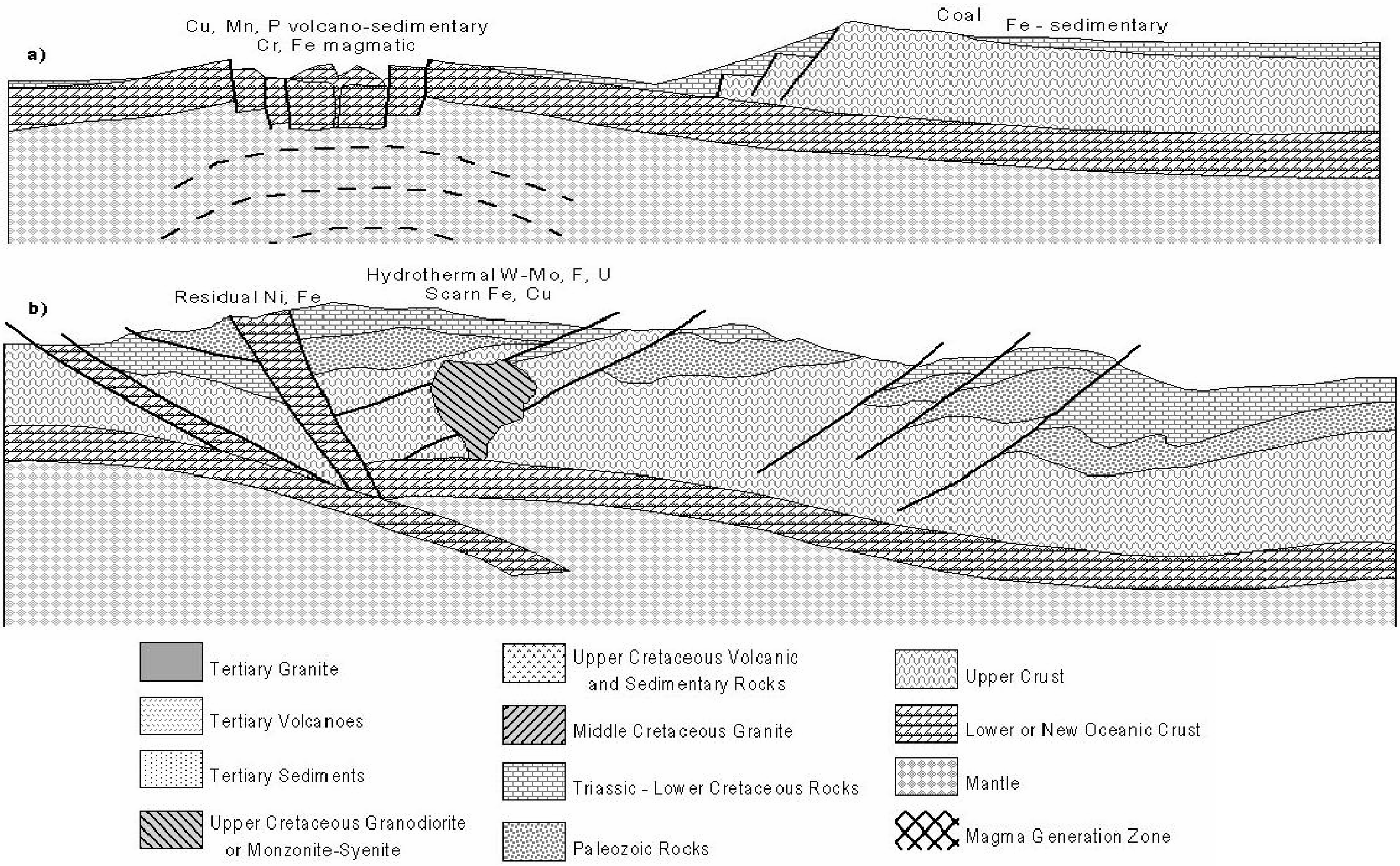


Figure 2. Models of the different tectonic settings and position of mineral deposits: a) spreading; b) early collision; c) intracollisional rifting; d) post-collisional orogen.

Balkan Metallogenesis and Plate Activity II

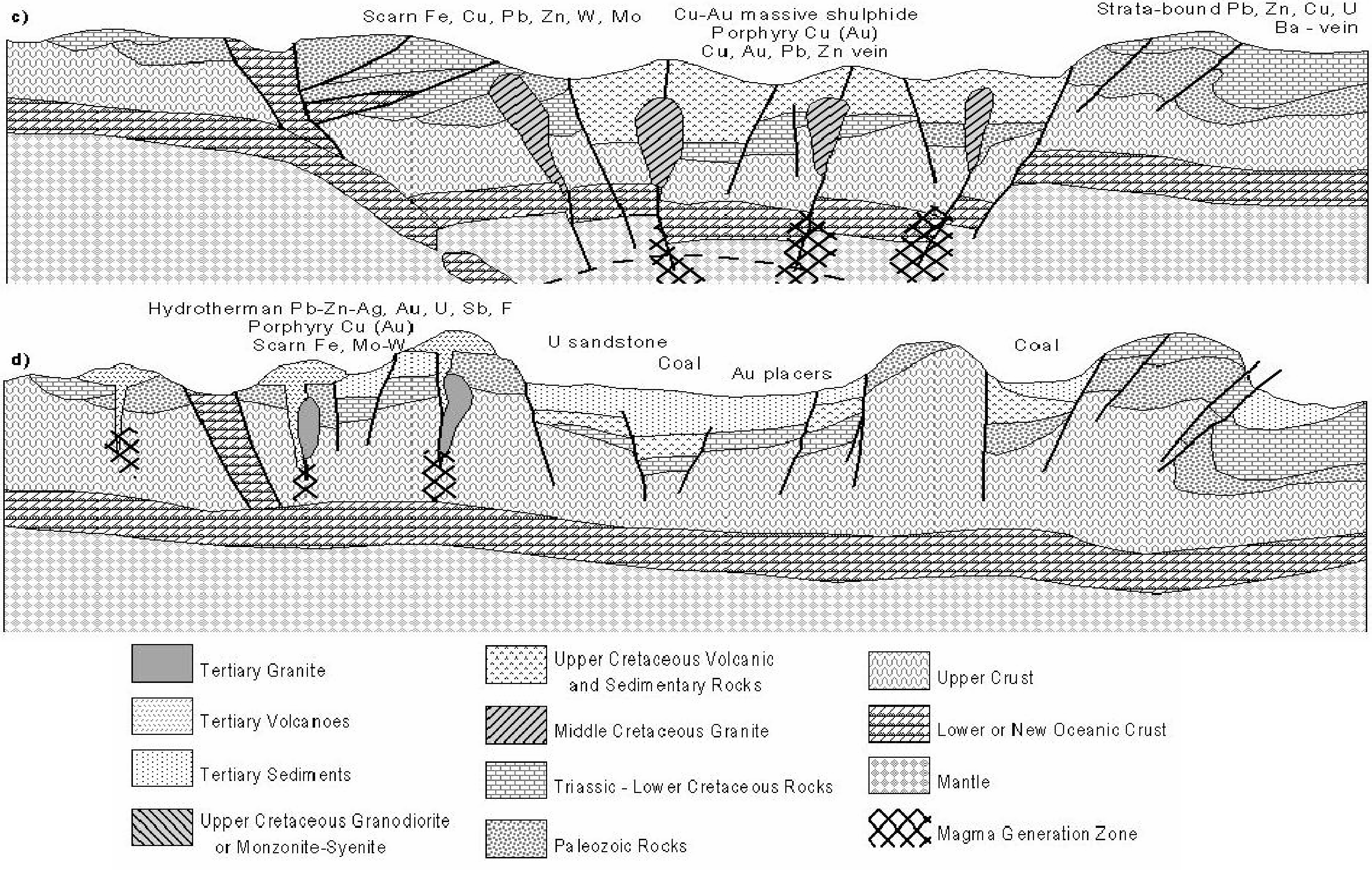
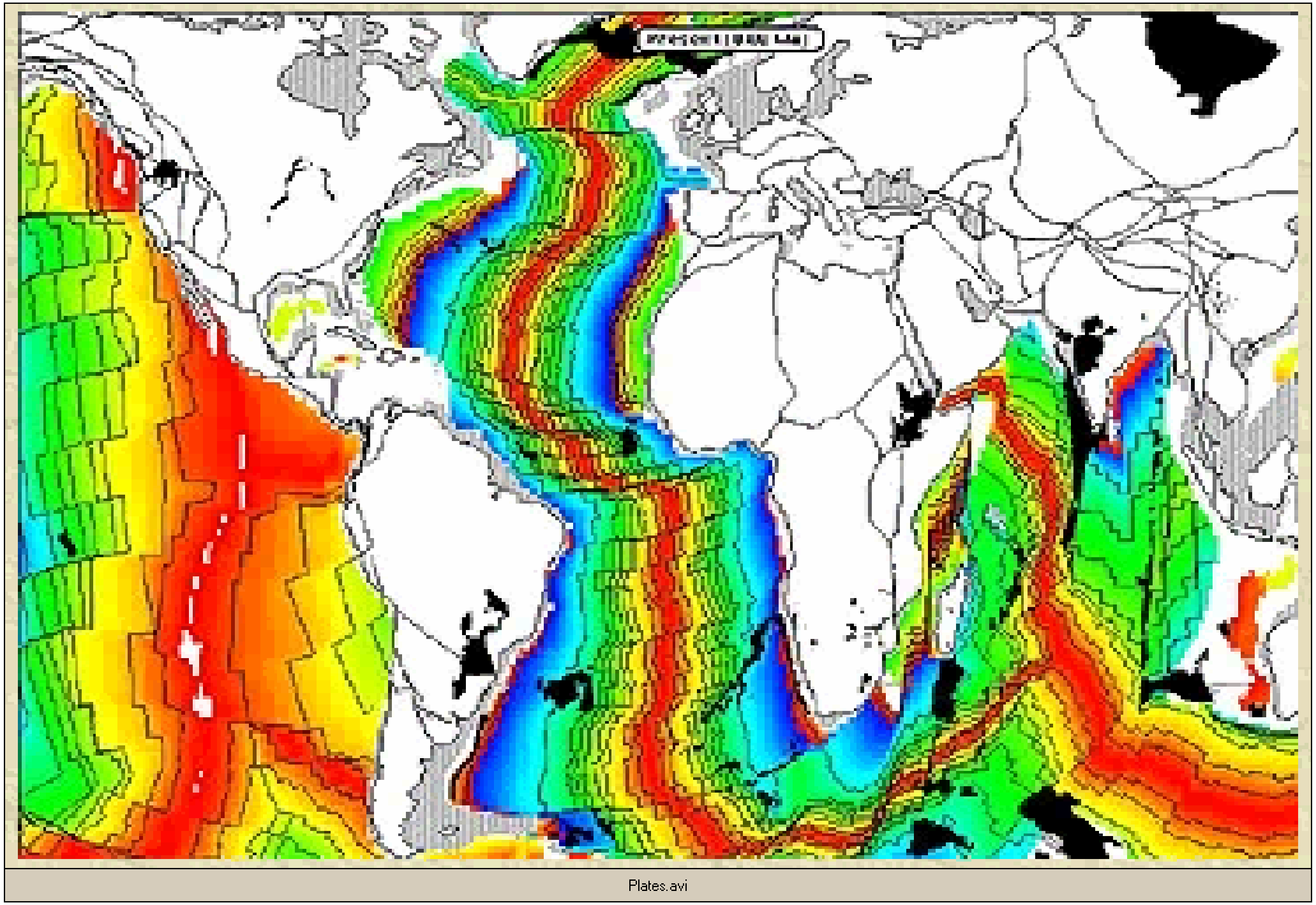
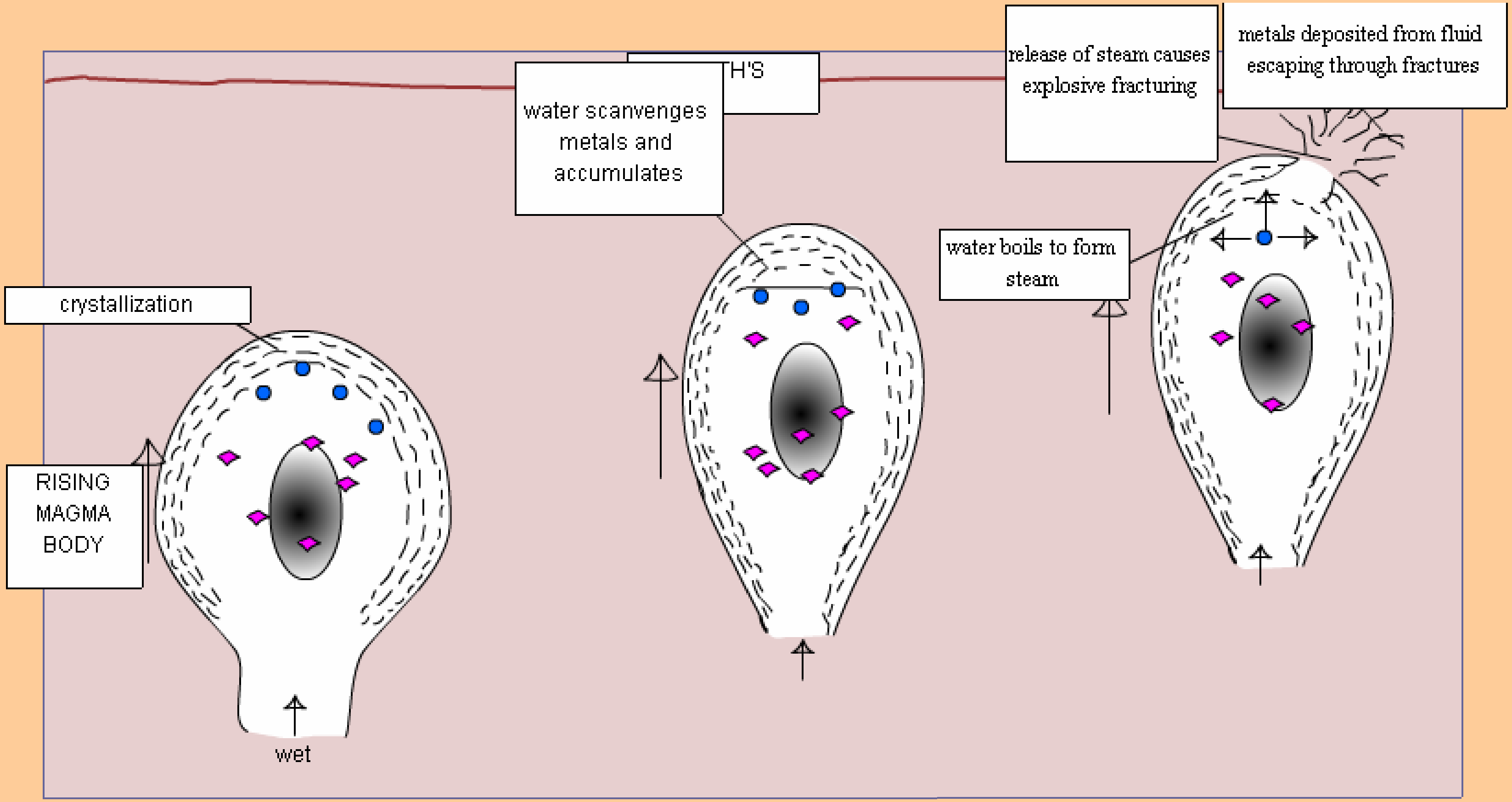


Figure 2. Models of the different tectonic settings and position of mineral deposits: a) spreading; b) early collision; c) intracollisional rifting; d) post-collisional orogen.


Plates.avi

Development of Porphyry Ore Deposit



crystallization

RISING MAGMA BODY

wet

water scanvenges metals and accumulates

H'S

water boils to form steam

release of steam causes explosive fracturing

metals deposited from fluid escaping through fractures

As wet magma cools, it starts to crystallize, and becomes saturated with water, which separates out as 'bubbles'

Water scavenges soluble metals, and accumulates near the top of the magma chamber

As the ascent through the crust continues, the reduction in pressure causes the water to boil, and formation of steam (occupying a much larger volume) causes explosive fracturing,