Indian Institute of Technology, Kanpur

Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 14. Rocks

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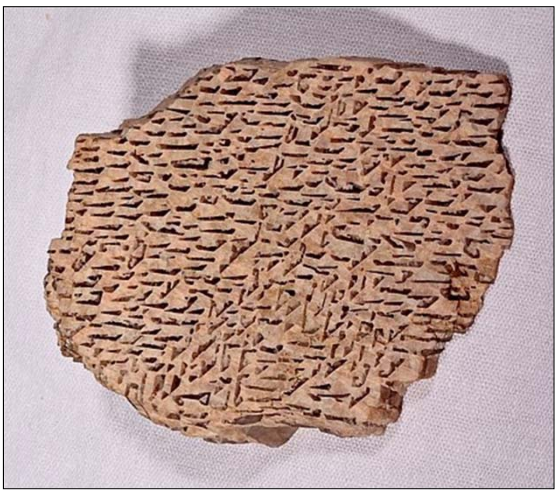
IITK Experimental Rock Deformation Laboratory

Aims of this lecture

- Definition and Characteristics
- Rock Cycle and Plate Tectonics
- Driving force(s) of Rock Cycles
- Major rock types, their genesis and involvement in Rock Cycles

Reference (selective reading):
Chapter 4-6, Grotzinger_Jordan's Book
Chapter 5-8, Marshak's Book

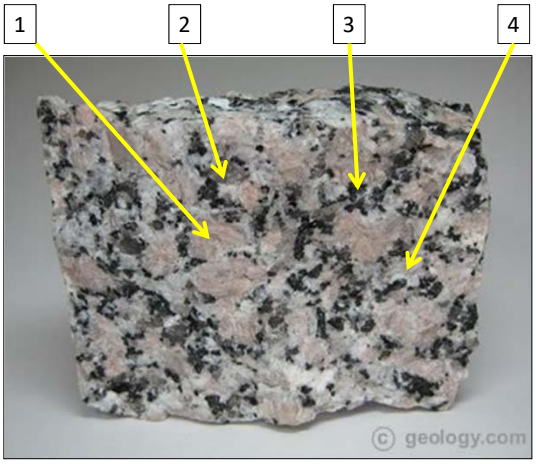
Basics



Basics

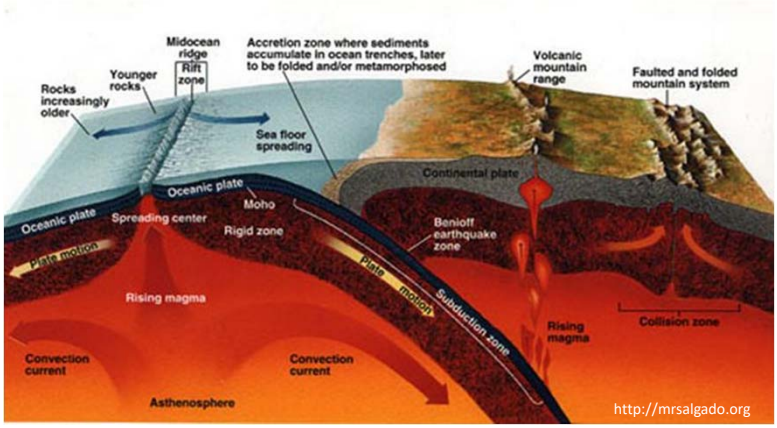
- Rock is a naturally occurring solid mixture of one or more minerals that may also include organic matter.
- Most of the rocks is made of crystalline minerals, but there are exceptions.
- Rocks are always changing through time.
- Natural processes make and destroy rocks. They change each type of rock into other types of rock and shape Earth's features.
- Different natural processes influence the type of rock that is found in each area of Earth's surface

Basics



Creation and destruction of lithosphere

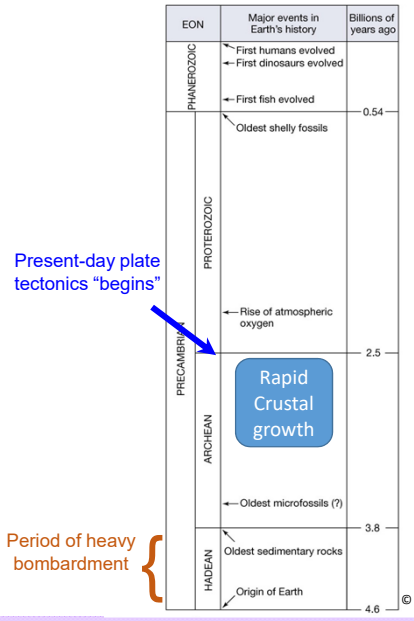
- Plate tectonics and continent building
  - Accretion through collisions
  - Recycling of material
  - Subduction
  - Segregation of melts



Evolution of modern plate tectonics

- Presence moderate temperatures
- Heat removal from mantle through subduction of cool oceanic lithosphere and upwelling of new crust
  - Drives convection cells
  - Allows basalt eclogite transition to be shallow
  - Subduction leads to fractional melting of oceanic crust and segregation to form continental crust
- Presence of water
  - Needed for granite formation
  - Catalyzes fractional melting in subducting sediments

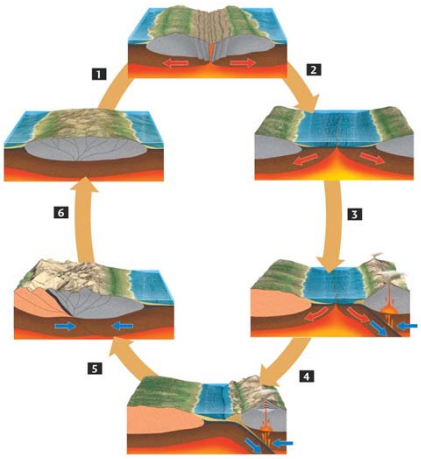
Modern plate tectonics



- Early plates became bigger and thicker
- Continued recycling of oceanic crust formed large amounts of buoyant continental crust
  - Continued partial melting/distillation
  - Separation of Si and other elements from Mg and Fe
- Decrease in heat production slowed mantle convection
  - Drove system to larger convection cells
  - Allowed larger plates to travel farther on the Earth's surface and cool more
  - Led to subduction rather than collision of plates
  - Modern plate tectonics

Since the Archaean

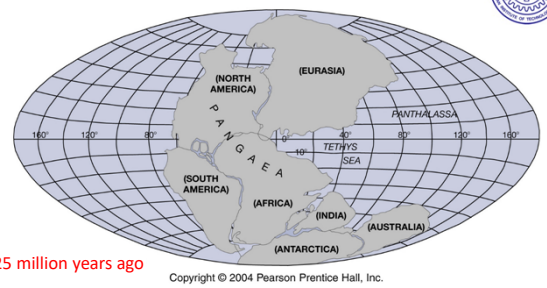
- Intensity of plate tectonics has varied over time
- Wilson cycles – 500 my cycles
  - Evidence of supercontinent 600-900 mybp
  - Pangea formed ~ 300 mybp
  - Causes not well understood



- Periods of rapid sea floor spreading (and vice versa)
  - Sea level rises because large amounts of shallow basalt form and don't cool (and subside) much
  - High CO_2 release – released at spreading centers when new crust forms and subducting crust has sediment on it including calcite which releases CO_2 when it melts

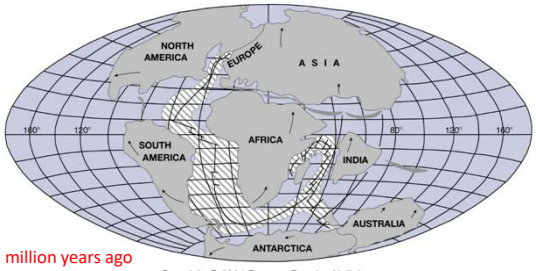
Age of crustal material

- Continental crust is older because it doesn't get subducted
  - Too buoyant
  - Becomes "core" for accretion
  - Collisions (closing of basins) mediate accretion
  - Losses only from weathering and subduction of sediment
  - Oldest rocks are 4.3 – 4.4 by old



225 million years ago

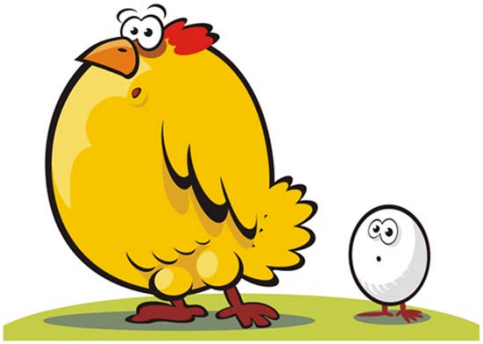
- Oceanic crust is young and constantly recycled (and fractionated)
  - Oldest oceanic crust is furthest from spreading centers near subduction zones



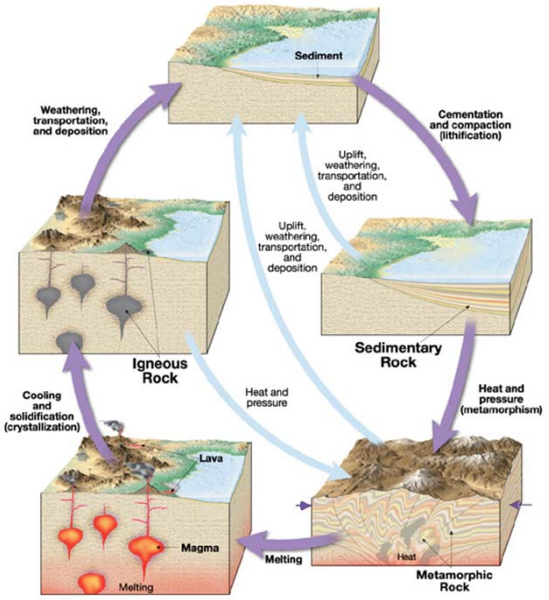
65 million years ago

Coming back to Rocks ….

- Plate tectonics certainly plays a major role in regulating the Rocks on the surface of the earth.
- And… we did not have rocks and plate tectonics since the beginning of the Earth..
- **The chicken egg problem**: which started first – rock cycle or plate tectonics?



The Rock Cycle



Igneous Rocks

Rocks that form by the freezing or solidification of melt

Sedimentary Rocks

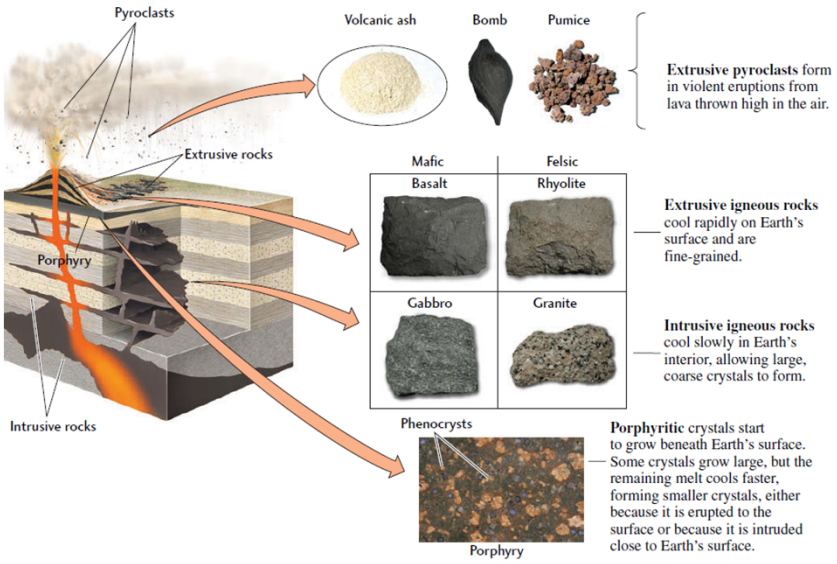
Rocks that form by the cementing of grains or fragments of pre-existing rocks, or by the precipitation of minerals out of a solution

Metamorphic Rocks

Rocks that form when pre-existing rocks change due to temperature or pressure, and/or as a result of squashing or shearing (deformation).

What was the first rock?

Igneous Rocks



MAGMA

Molten Rock

Usually with dissolved gasses

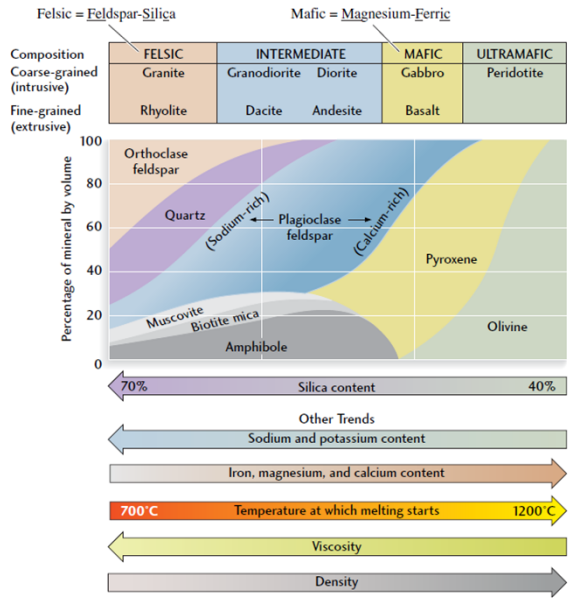
Generated at depth

Eruptions if magma (lava) reaches surface

If doesn't reach surface, Solidifies underground

- Intrudes *country or host rock*
- Intrusive *contact*
- *Xenolith- 'foreign body'*

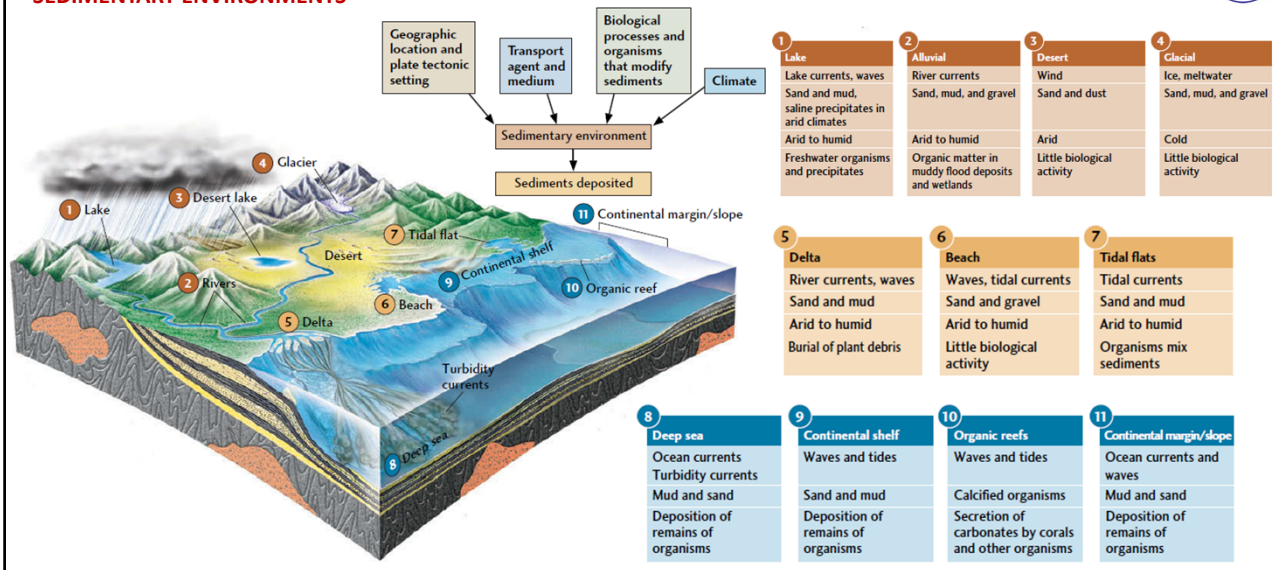
Igneous Rocks



Classification model for igneous rocks. The vertical axis shows the minerals contained in a given rock as a percentage of its volume. The horizontal axis shows the silica content of a given rock as a percentage of its weight. Thus, if you knew by chemical analysis that a coarsely textured rock sample was about 70% silica, you could deduce that its composition was about 6% amphibole, 3% biotite, 5% muscovite, 14% plagioclase feldspar, 22% quartz, and 50% orthoclase feldspar. Your rock would be granite. Although rhyolite has the same mineral composition, its fi ne texture would eliminate it from consideration.

Sedimentary Rocks

SEDIMENTARY ENVIRONMENTS



1 Lake	2 Alluvial	3 Desert	4 Glacial
Lake currents, waves	River currents	Wind	Ice, meltwater
Sand and mud, saline precipitates in arid climates	Sand, mud, and gravel	Sand and dust	Sand, mud, and gravel
Arid to humid	Arid to humid	Arid	Cold
Freshwater organisms and precipitates	Organic matter in muddy flood deposits and wetlands	Little biological activity	Little biological activity

5 Delta	6 Beach	7 Tidal flats
River currents, waves	Waves, tidal currents	Tidal currents
Sand and mud	Sand and gravel	Sand and mud
Arid to humid	Arid to humid	Arid to humid
Burial of plant debris	Little biological activity	Organisms mix sediments

8 Deep sea	9 Continental shelf	10 Organic reefs	11 Continental margin/slope
Ocean currents Turbidity currents	Waves and tides	Waves and tides	Ocean currents and waves
Mud and sand	Sand and mud	Calcified organisms	Mud and sand
Deposition of remains of organisms	Deposition of remains of organisms	Secretion of carbonates by corals and other organisms	Deposition of remains of organisms

Sedimentary Rocks

DETRITAL ROCKS

Texture	Sediment Name and Particle Size	Comments	Rock Name
Clastic	Gravel (>2 mm)	Rounded rock fragments	Conglomerate
		Angular rock fragments	Breccia
	Sand (1/16–2 mm)	Quartz predominates	Quartz sandstone
		Quartz with considerable feldspar	Arkose
		Dark color; quartz with considerable feldspar, clay, and rocky fragments	Graywacke
	Mud (<1/16 mm)	Splits into thin layers	Shale
		Breaks into clumps or blocks	Mudstone

CHEMICAL ROCKS

Group	Texture	Composition	Rock Name
Inorganic	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Dolomite, $CaMg(CO_3)_2$	Dolostone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Halite, NaCl	Rock salt
	Nonclastic	Gypsum, $CaSO_4 \cdot 2H_2O$	Rock gypsum
Biochemical	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Altered plant remains	Coal

Metamorphic Rocks

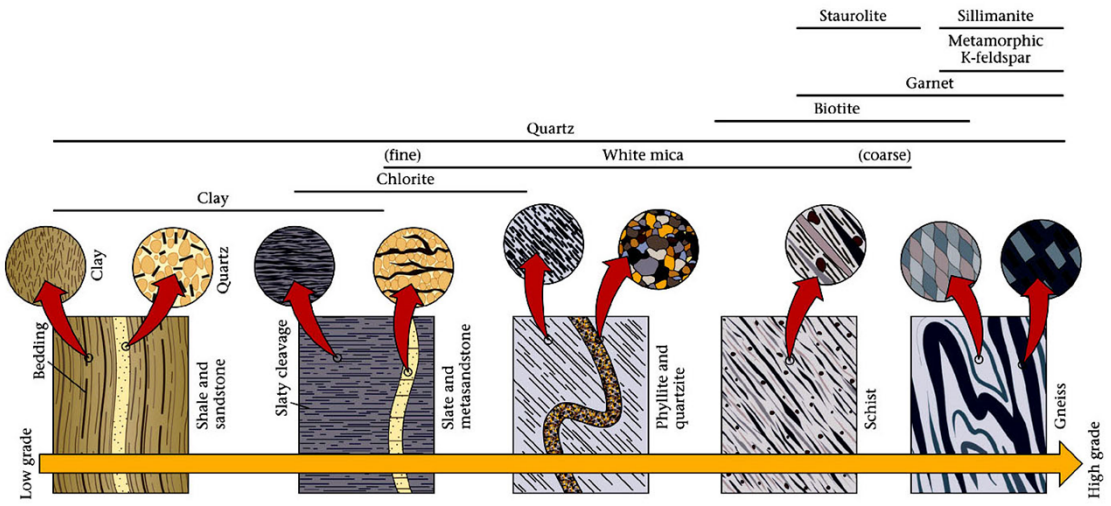
Metamorphic Textures – grains are interlocked and grew in place. Many different types of metamorphic textures.

Metamorphic Minerals – Certain minerals only grow under metamorphic temperatures and pressures. Called a **metamorphic mineral assemblage, or metamorphic facies.**

Foliation – The alignment of platy minerals or alternating layers of light (felsic) and dark (mafic) minerals.

Metamorphic Rocks

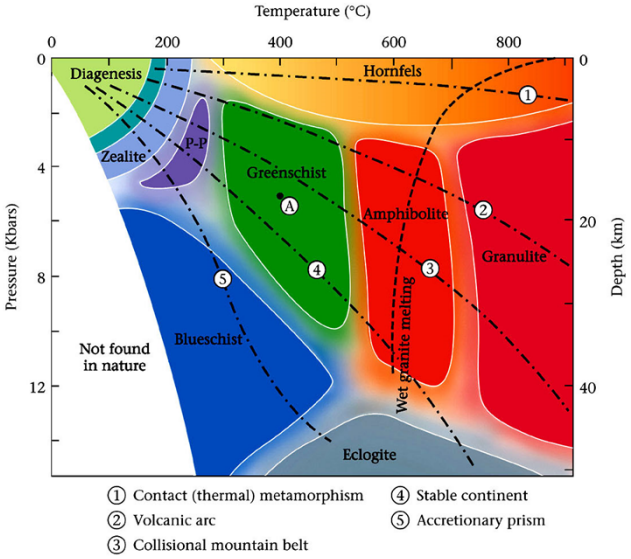
A single protolith (shale shown below) can form a variety of metamorphic rocks depending on the grade of metamorphism



Metamorphic Rocks

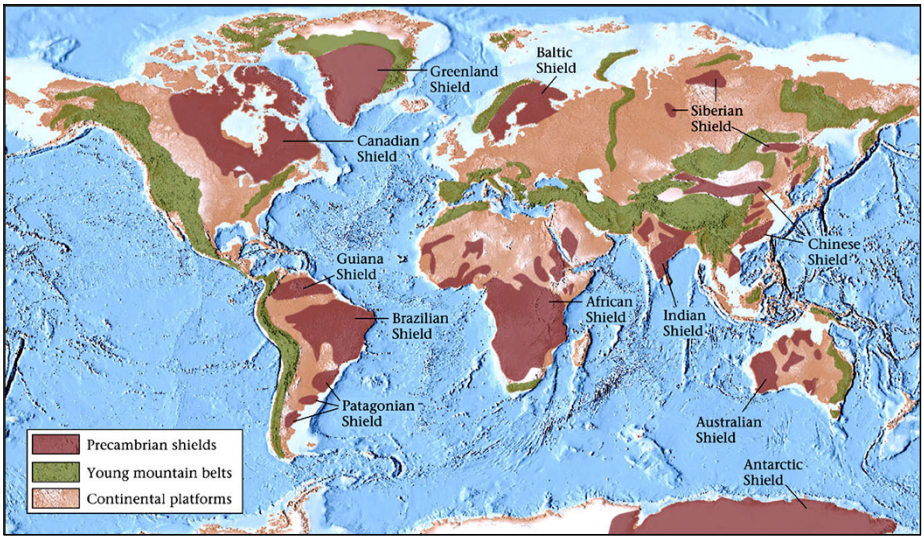
A given P-T horizon has a characteristic set of minerals that form. Which ones form depend on protolith composition

If you know the P-T conditions and the protolith composition, you can predict the mineralogy of the resultant metamorphic rock

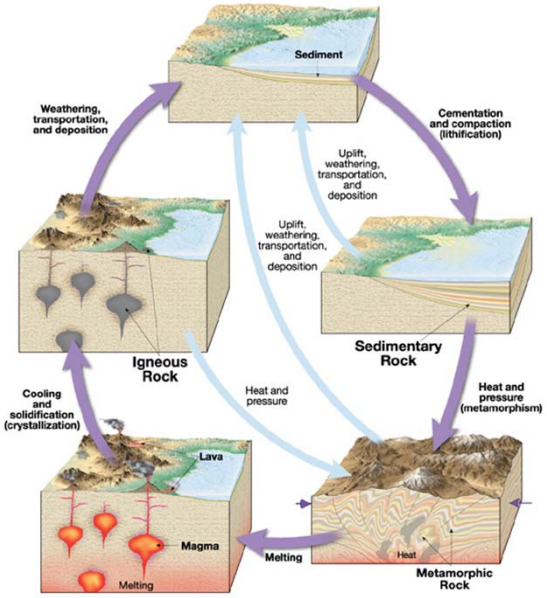


Metamorphic Rocks

- Where are the Metamorphic Rocks exposed today?



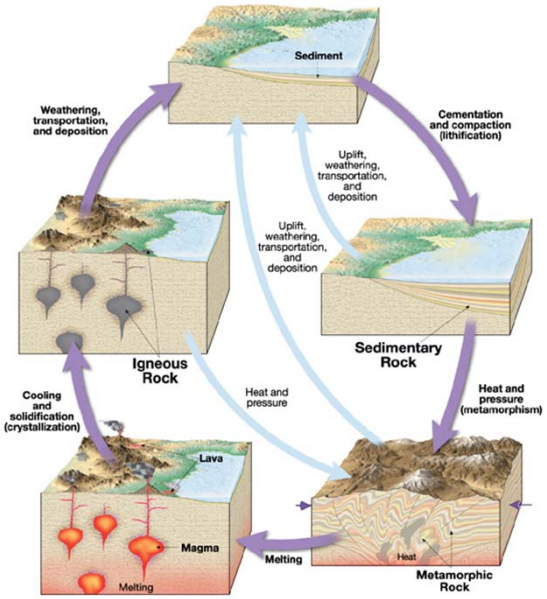
Let’s look this slide back again….



Processed involved in Rock Cycles

- ☐ Melting
- ☐ Cooling and solidification
- ☐ Weathering, transportation and deposition
- ☐ Cementation and compaction
- ☐ Heat and Pressure (subduction)
- ☐ Uplift

Let’s look this slide back again….



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Melting - I

MAGMA

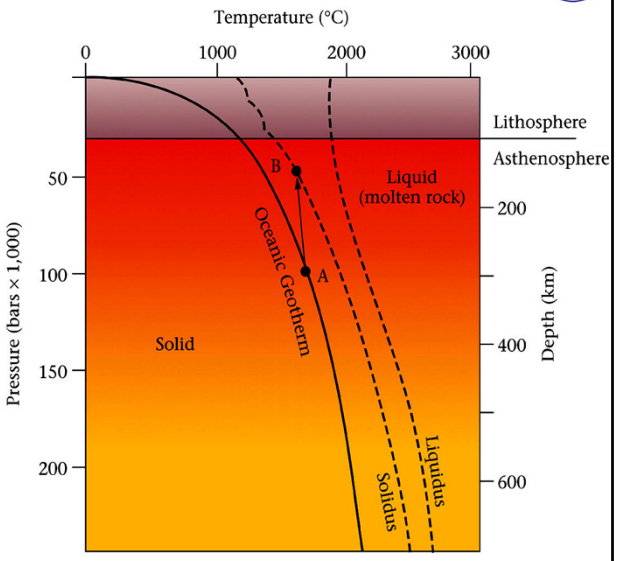
- The tectonic plates don't really float on a liquid asthenosphere, rather the asthenosphere is a ductile solid and is only melted in specific locations.
- Most magma/lava is not 100% liquid.
  - Magma/Lava is made of many compounds, all of which have different melting temperatures.
  - Only a few percent of liquid is required to make a melt.
- Other than a rise in temperature, melting can happen because of:
  - Decrease in pressure (decompression)
  - Addition of volatiles (H_2O, CO_2, etc…)
  - Heat transfer from rising magma

Decompression Melting

- The Earth gets hotter with increasing depth due to primordial heat and radioactive decay of elements near the core.
- The rate at which temperature increases with depth is called the ***geothermal gradient***, or ***geotherm***
- Liquids have no organized structure, so to melt a rock, the mineral bonds must be broken
- At depth, confining pressure prevents atoms from breaking free of crystals

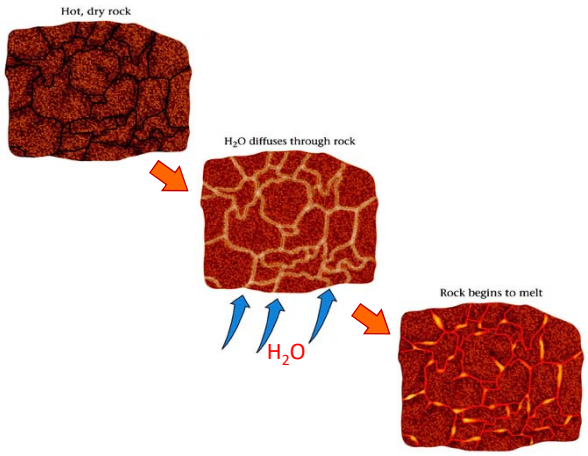
  Solidus: The temperature when a rock first begins to melt

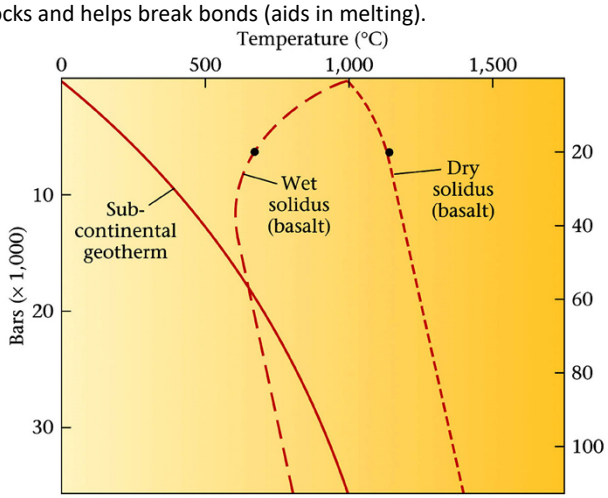
  Liquidus: The temperature where the last solid particle melts
- The asthenosphere cools only slightly as it rises (convection) because it is a good insulator (high specific heat)



Volatile induced melting

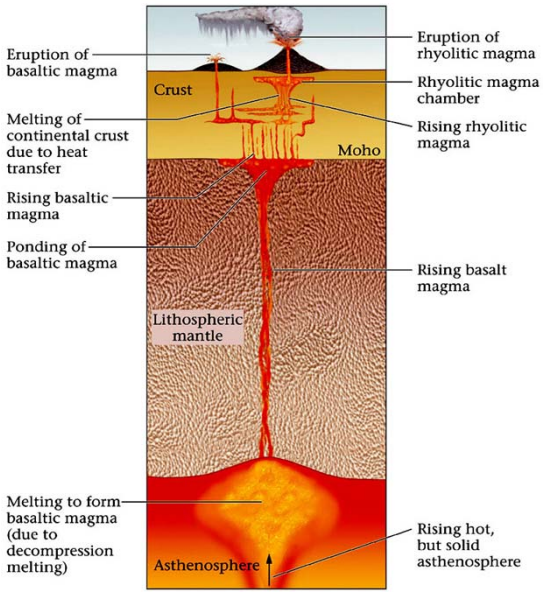
- Volatiles: A substance that can easily change into a gas at relatively low temperatures (H_2O, CO_2, etc…).
- The addition of volatiles at depth (mainly H_2O) seeps into rocks and helps break bonds (aids in melting).





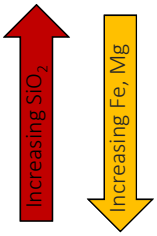
Melting due to Heat Transfer

- Melting can also occur when rising bodies of hot material essentially bake the nearby rock



Magma

- All magmas contain **Si** and **O**
  - Upon cooling, bond together into ***silicon-oxygen tetrahedrons;*** More silica (i.e. felsic), more viscous
  - Also contain varying amounts of other elements like Na, K, Al, Ca, Mg, Fe, etc…
- Dry magmas – no volatiles
- Wet Magmas – up to 15% volatiles
- Volatile content strongly effects the viscosity (ability to flow)
  - More volatiles, less viscous (easier to flow or more fluid)



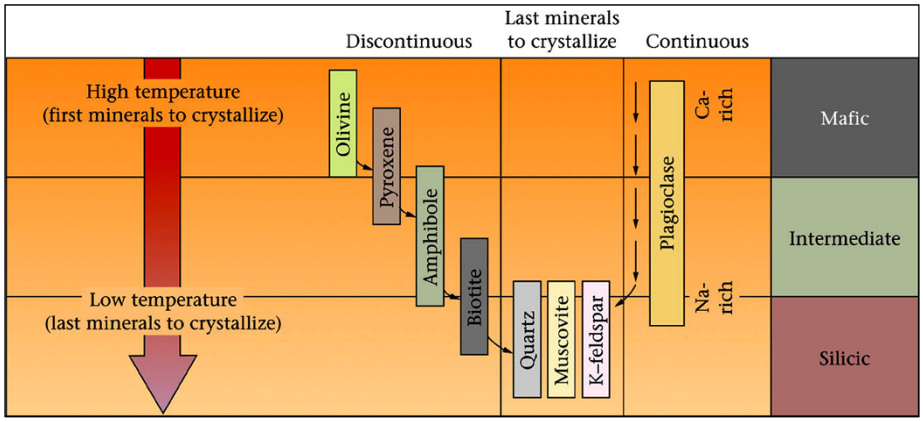
- Like rocks, not all magma is made of the same stuff
- We divide magmas into groups by their composition
  - **Felsic (Silicic):** 66-76% Silica (SiO_2)
    - Most viscous, Least dense (~2.5 gm/cm^3), melting point 650-800ºC
  - **Intermediate:** 52-66% SiO_2
  - **Mafic:** 45-52% SiO_2, lots of MgO, FeO, and Fe_2O_3
  - **Ultramafic:** 38-45% SiO_2, abundant MgO, FeO, and Fe_2O_3
    - Least viscous, Most dense (~3.5 gm/cm^3), melting point up to 1300ºC

Magma - volcanos

Type	Density	Temperature	Viscosity
Felsic	Very low	Very low (600 to 850°C)	Very High: Explosive eruptions.
Intermediate	Low	Low	High: Explosive eruptions.
Mafic	High	High	Low: Thin, hot runny eruptions.
Ultramafic	Very high	Very high (up to 1,300°C)	Very low

Bowen's Reaction series – Cooling and Crystallization

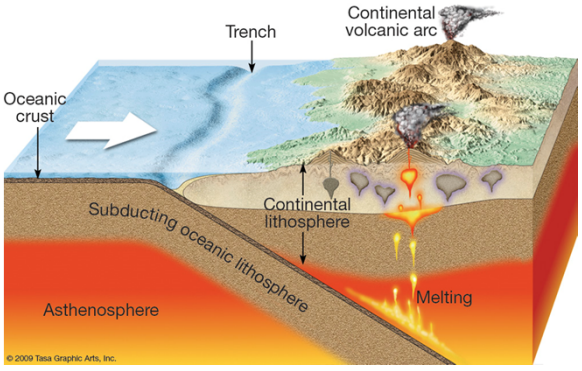
- In order to understand the melting and solidifying of magma we need to understand Bowen's reaction series. – *Bowen figured this out by melting rocks in an oven, letting them cool, and watching what minerals crystallized*
- This series outlines the order in which minerals form in a cooling melt
- Also applies in reverse order to rocks that are partially melted

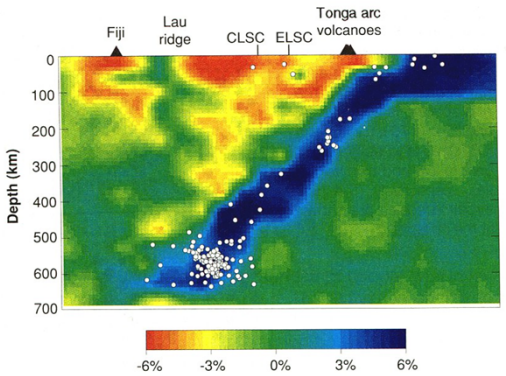


Discontinuous series (different minerals form) and Continuous series (Plagioclase only)

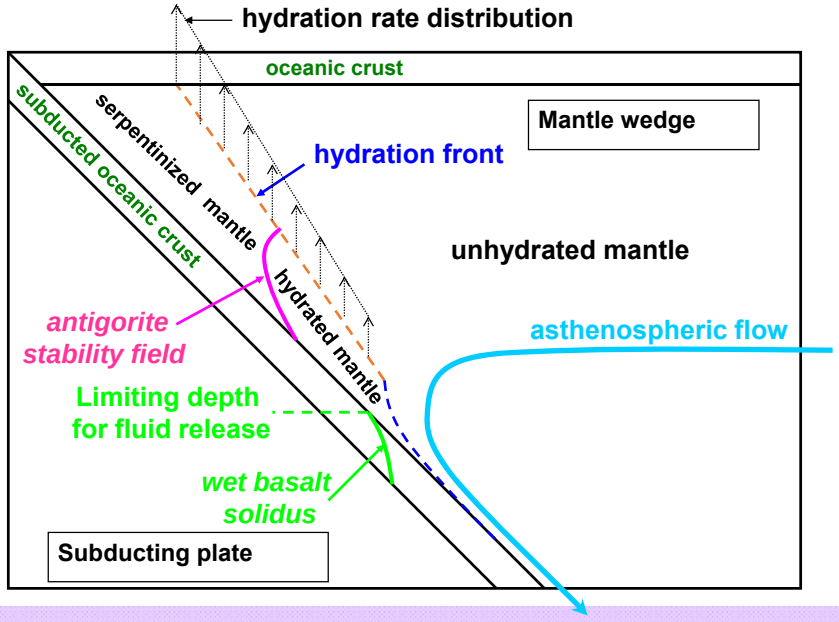
So, a melt gets less mafic as it cools; In heating, the first minerals to melt are felsic.

Subduction (heat and pressure)

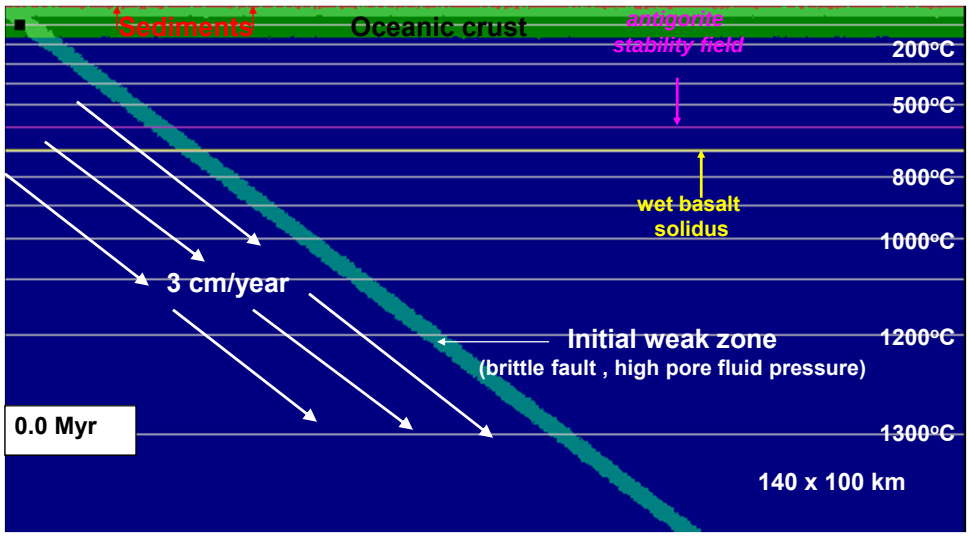




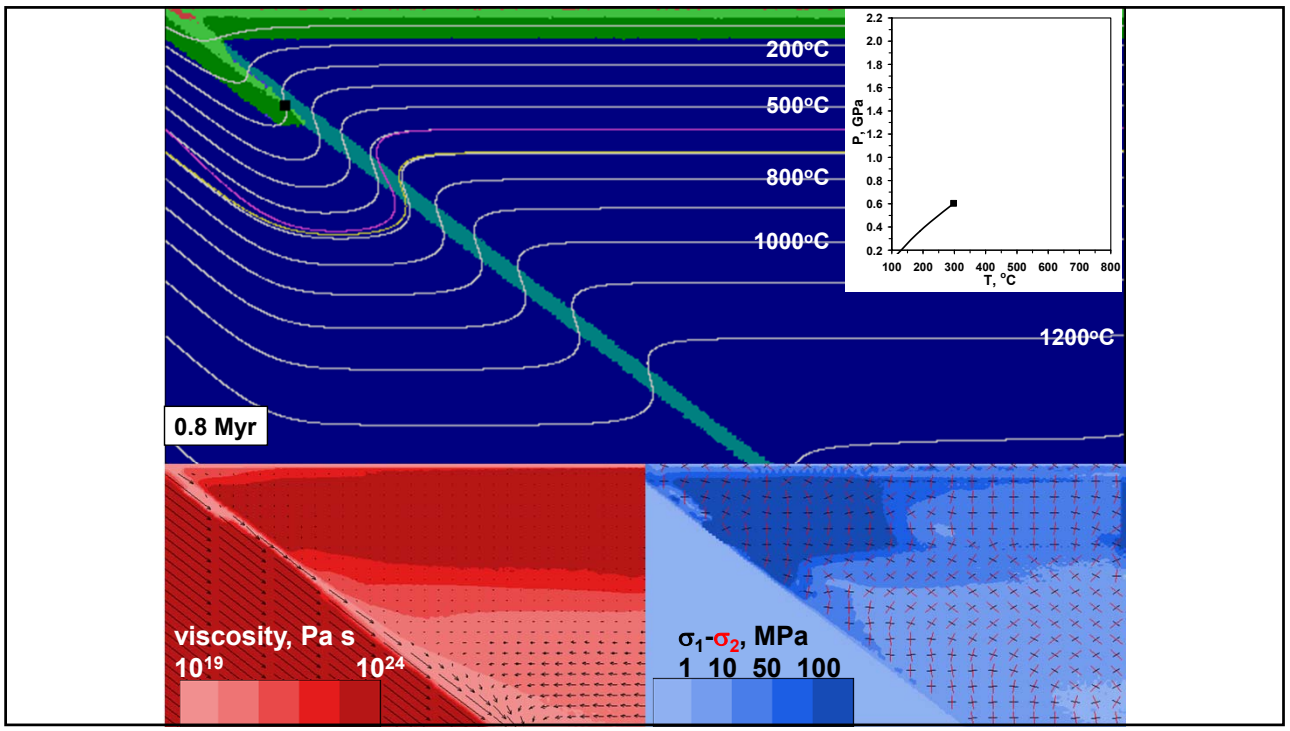
Subduction & Exhumation

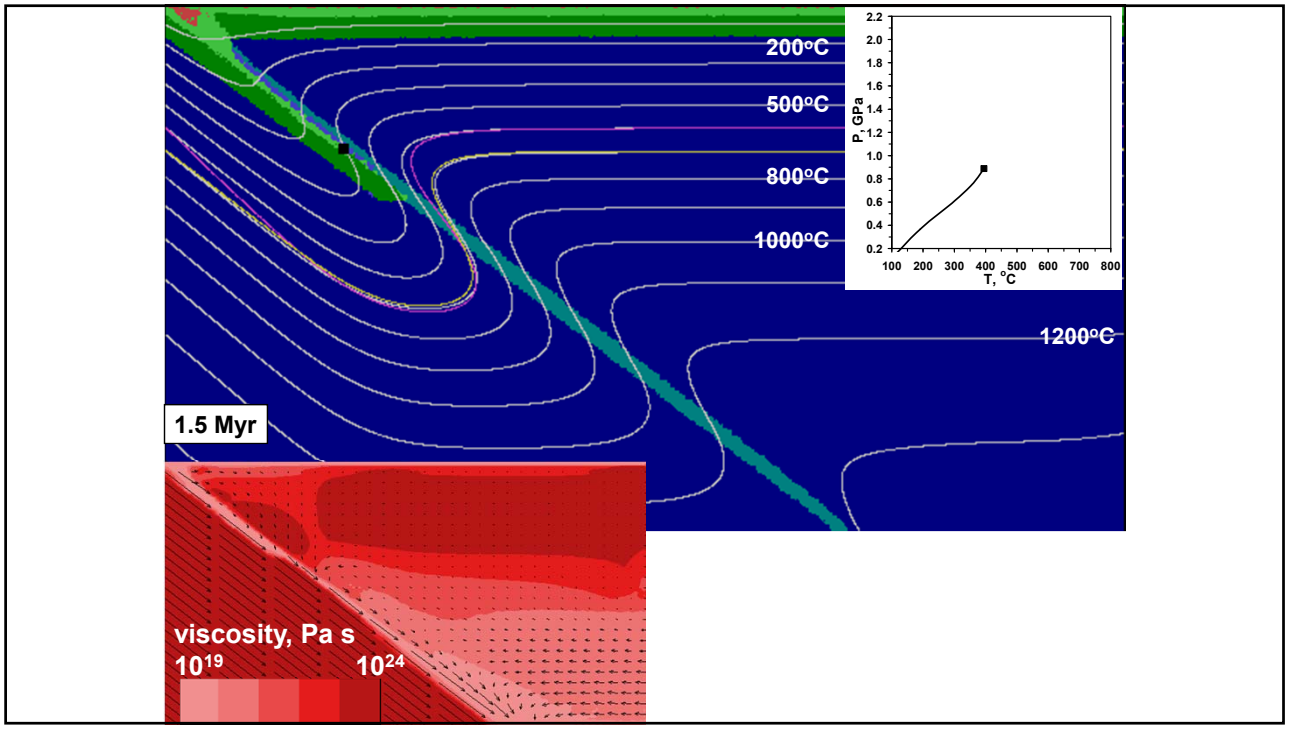


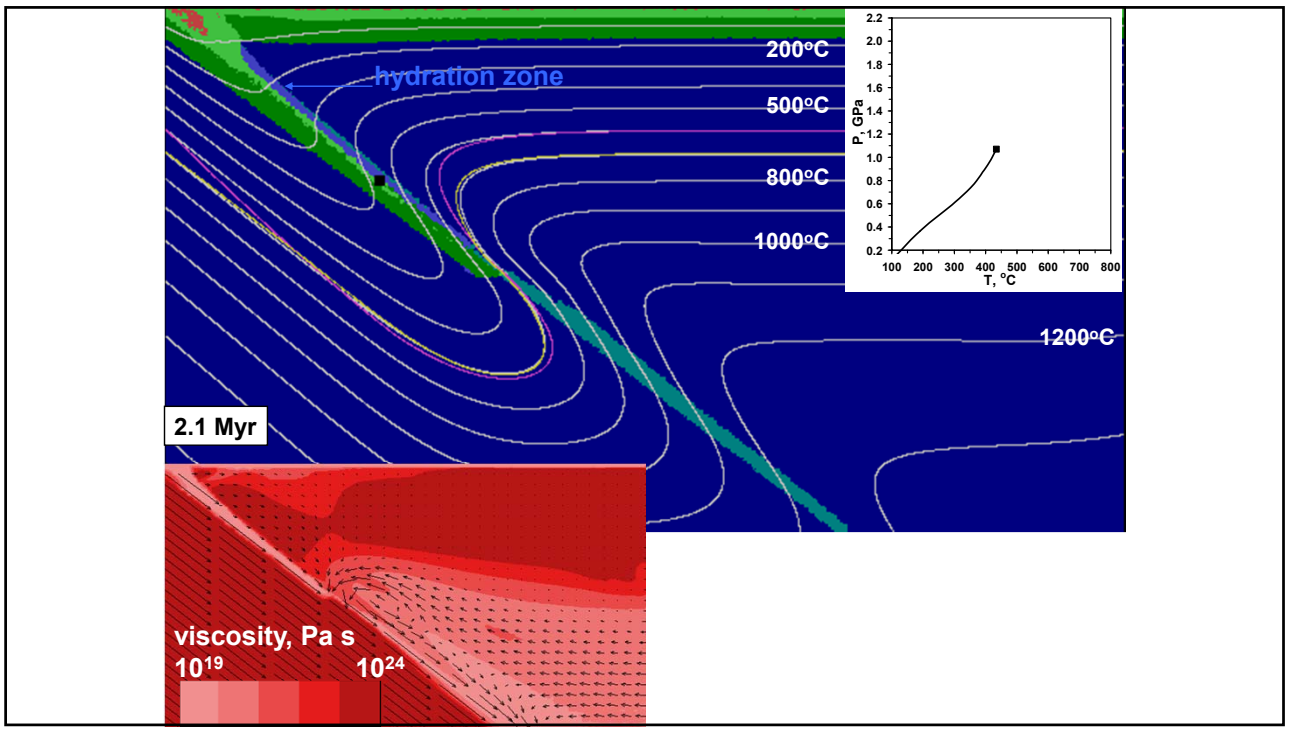
Subduction – Heat and pressure

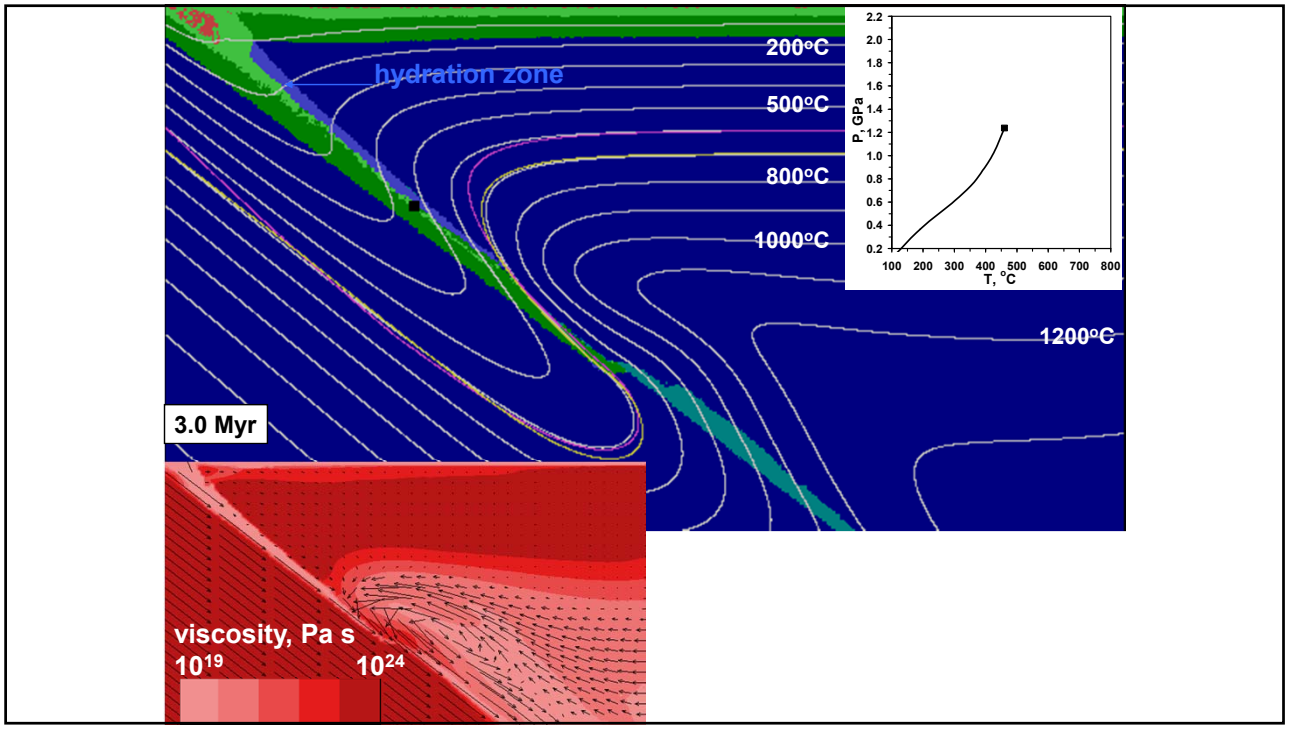


Litosphere: 40 Myr old; **Subduction:** rate 3 cm/year, angle 45°
Hydration of hanging wall: max rate 2 mm/year, max depth 90 km


200°C
500°C
800°C
1000°C
1200°C
0.8 Myr
P, GPa
T, °C
viscosity, Pa s
10^19
10^24
σ1-σ2, MPa
1 10 50 100


200°C
500°C
800°C
1000°C
1200°C
1.5 Myr
P, GPa
T, °C
viscosity, Pa s
10^19
10^24


hydration zone
200°C
500°C
800°C
1000°C
1200°C
2.1 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C


hydration zone
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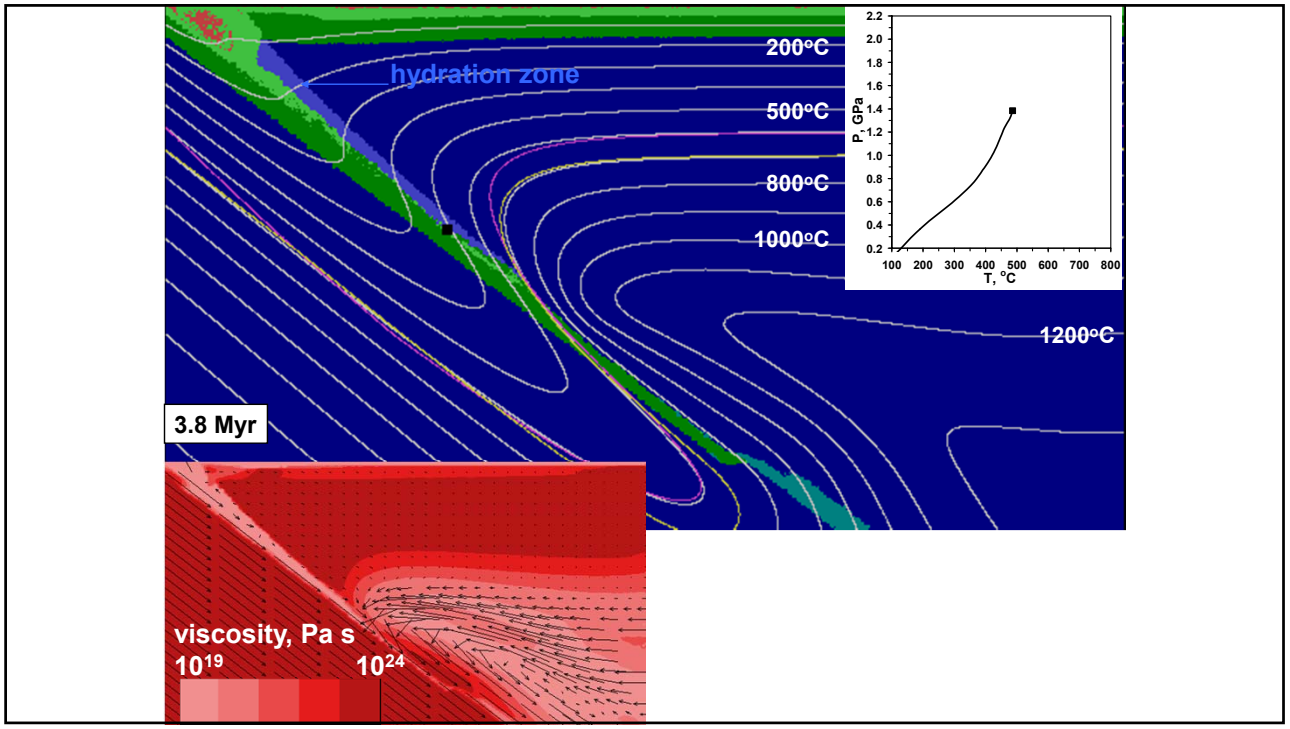
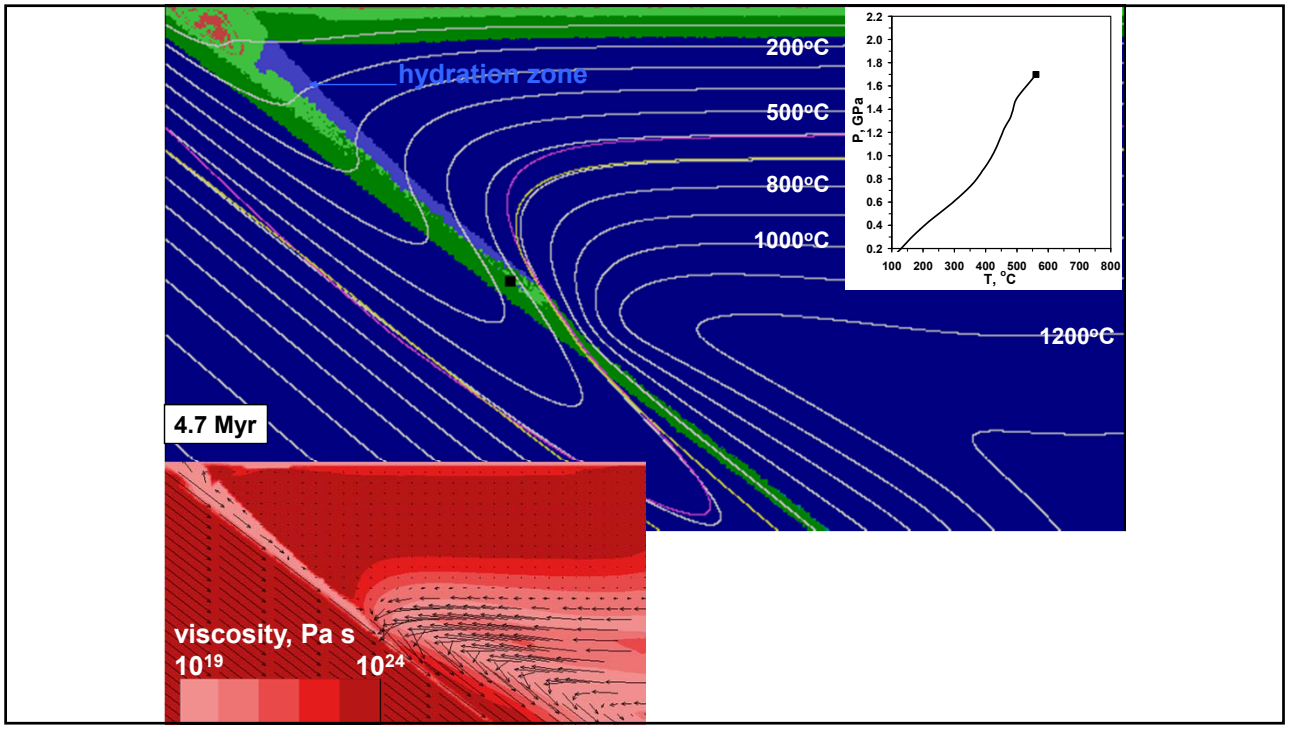
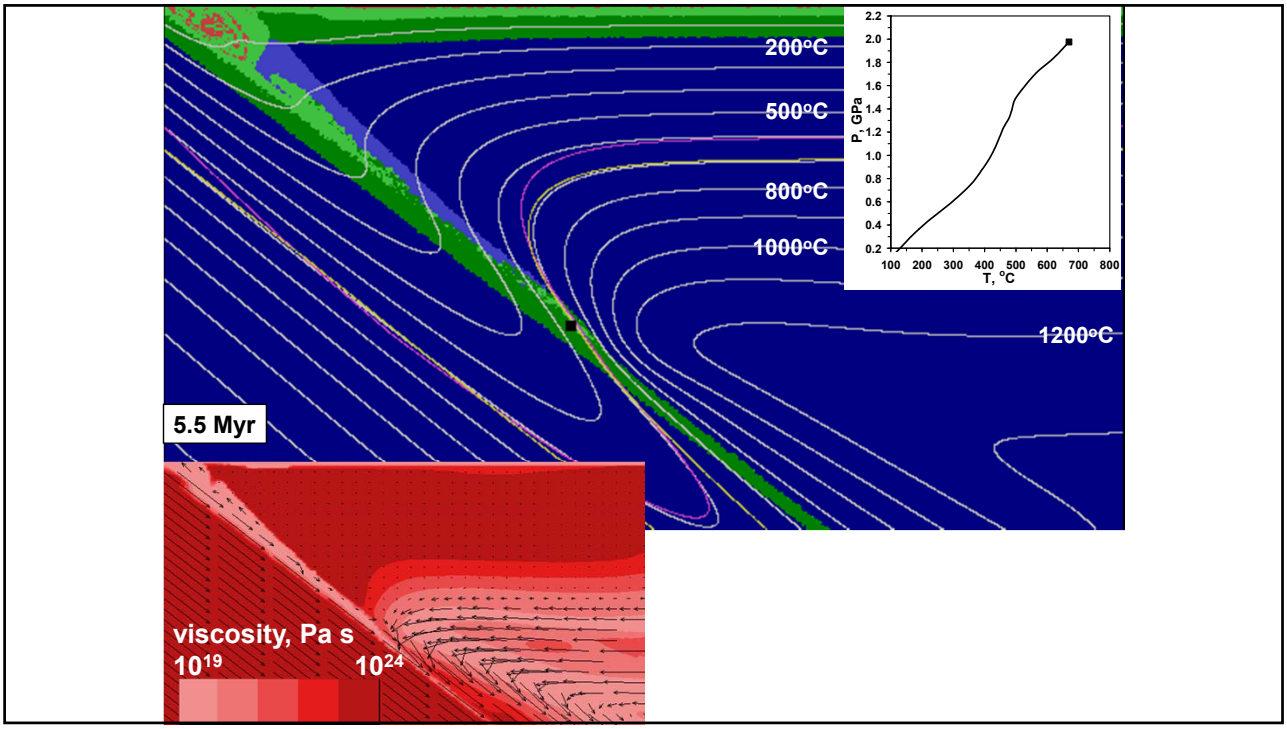
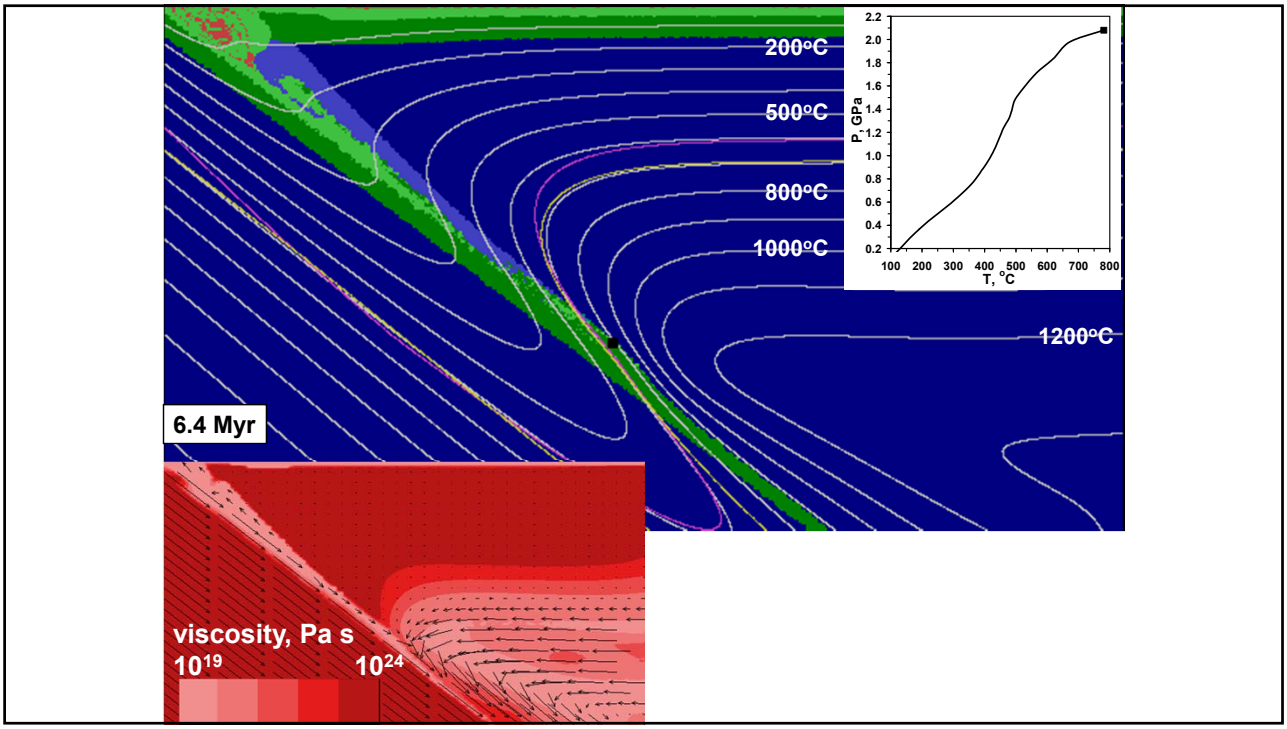
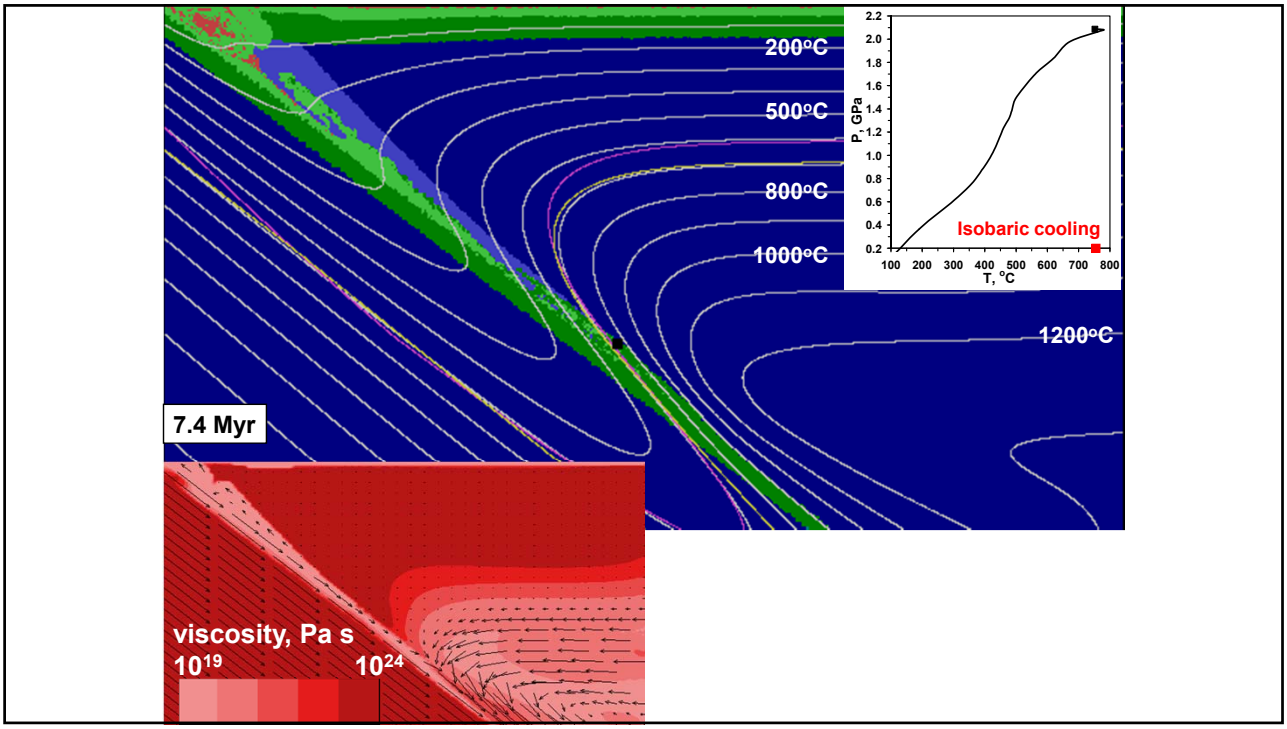
10^19
10^24
P, GPa
T, °C

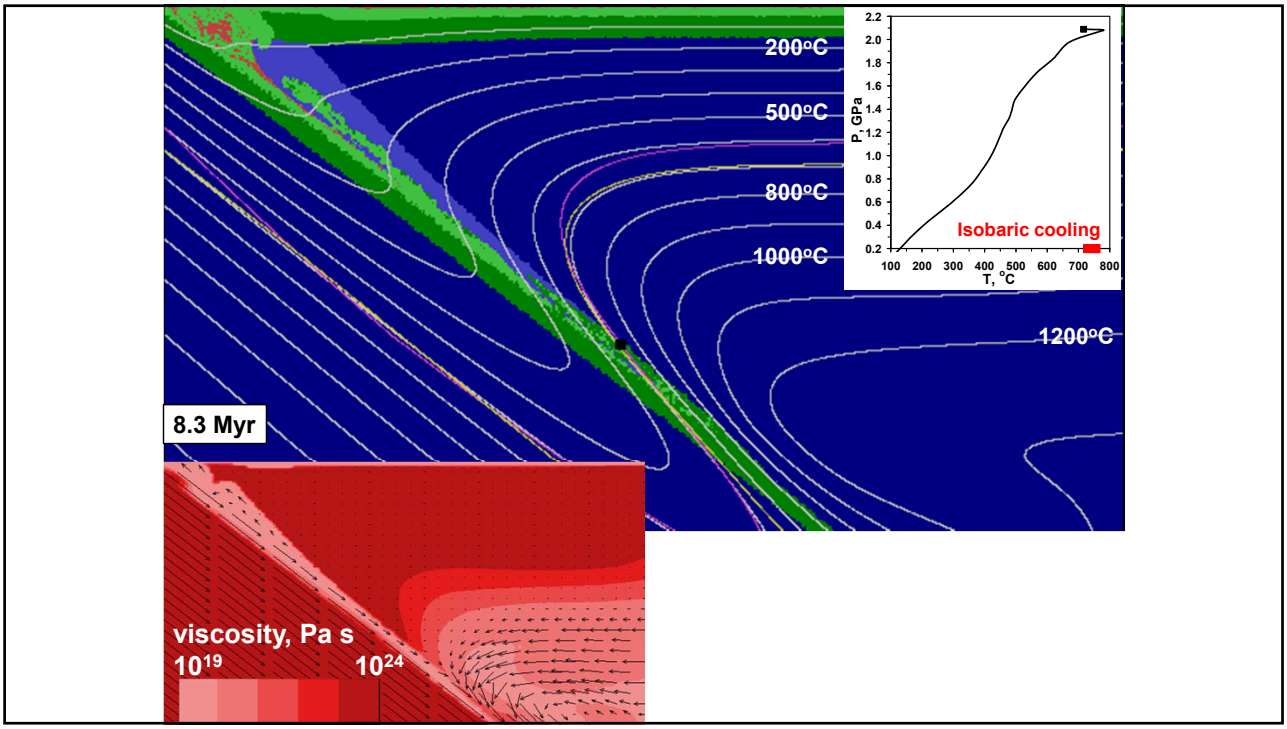

hydration zone
200°C
500°C
800°C
1000°C
1200°C
P, GPa
T, °C
3.8 Myr
viscosity, Pa s
10^19
10^24

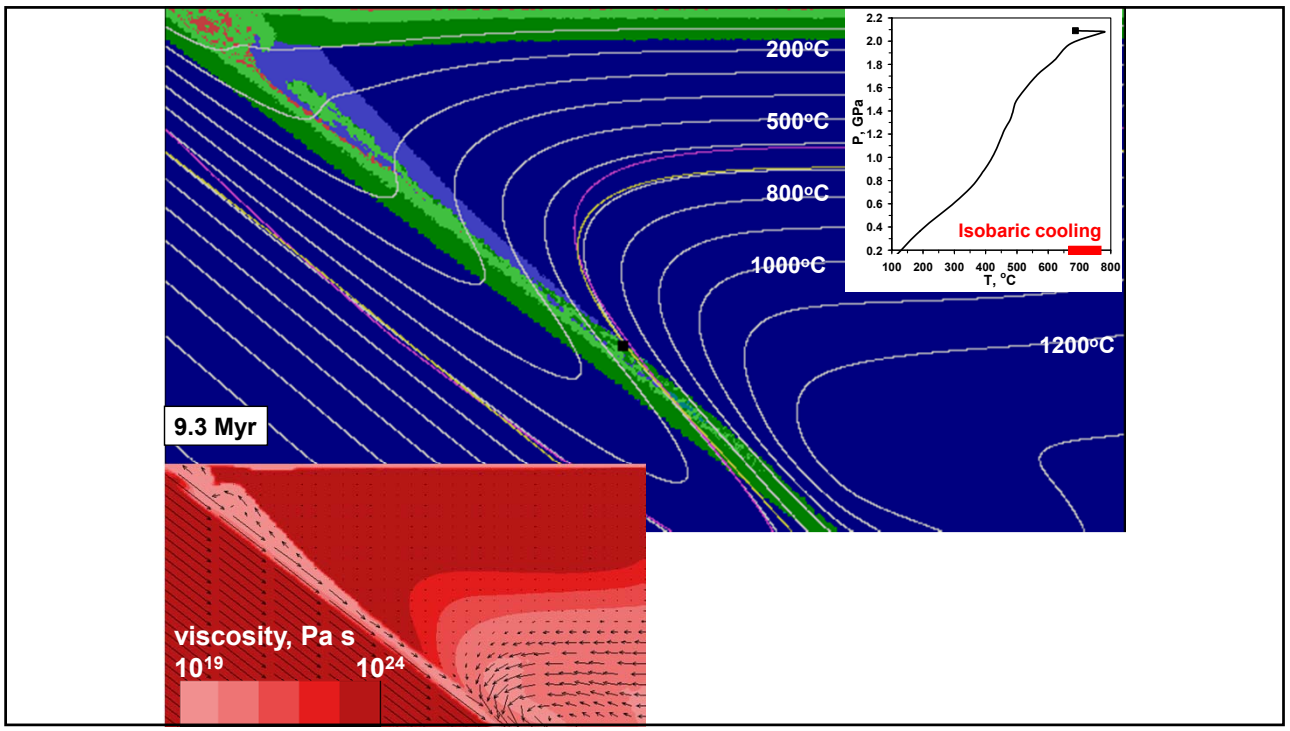

hydration zone
200°C
500°C
800°C
1000°C
1200°C
P, GPa
T, °C
4.7 Myr
viscosity, Pa s
10^19
10^24

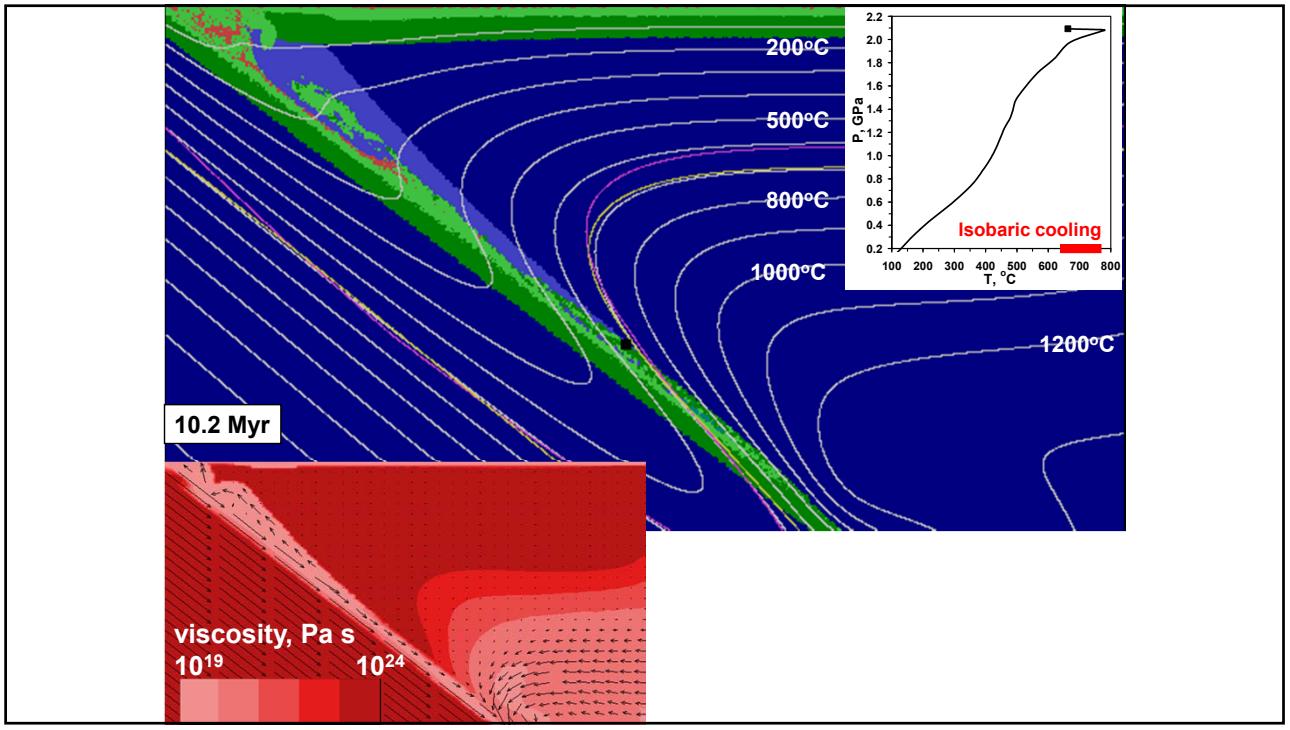

200°C
500°C
800°C
1000°C
1200°C
5.5 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C

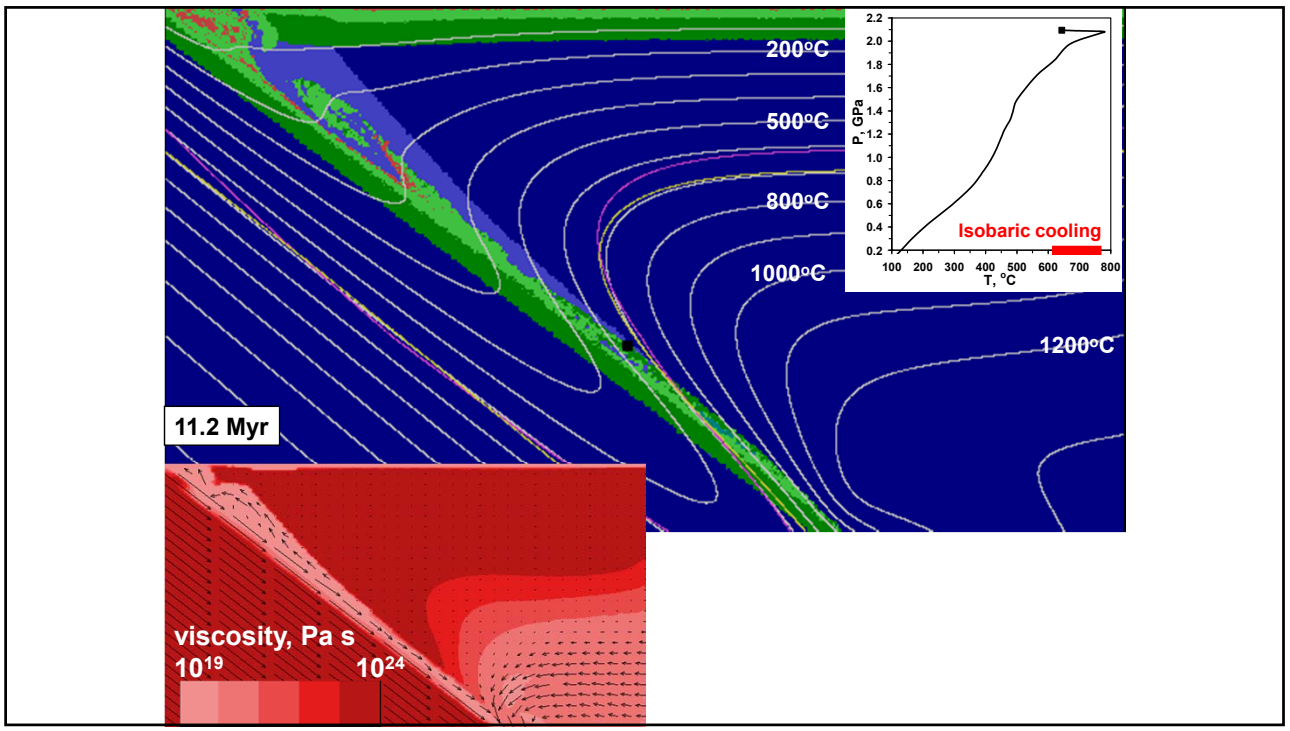

200°C
500°C
800°C
1000°C
1200°C
6.4 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C

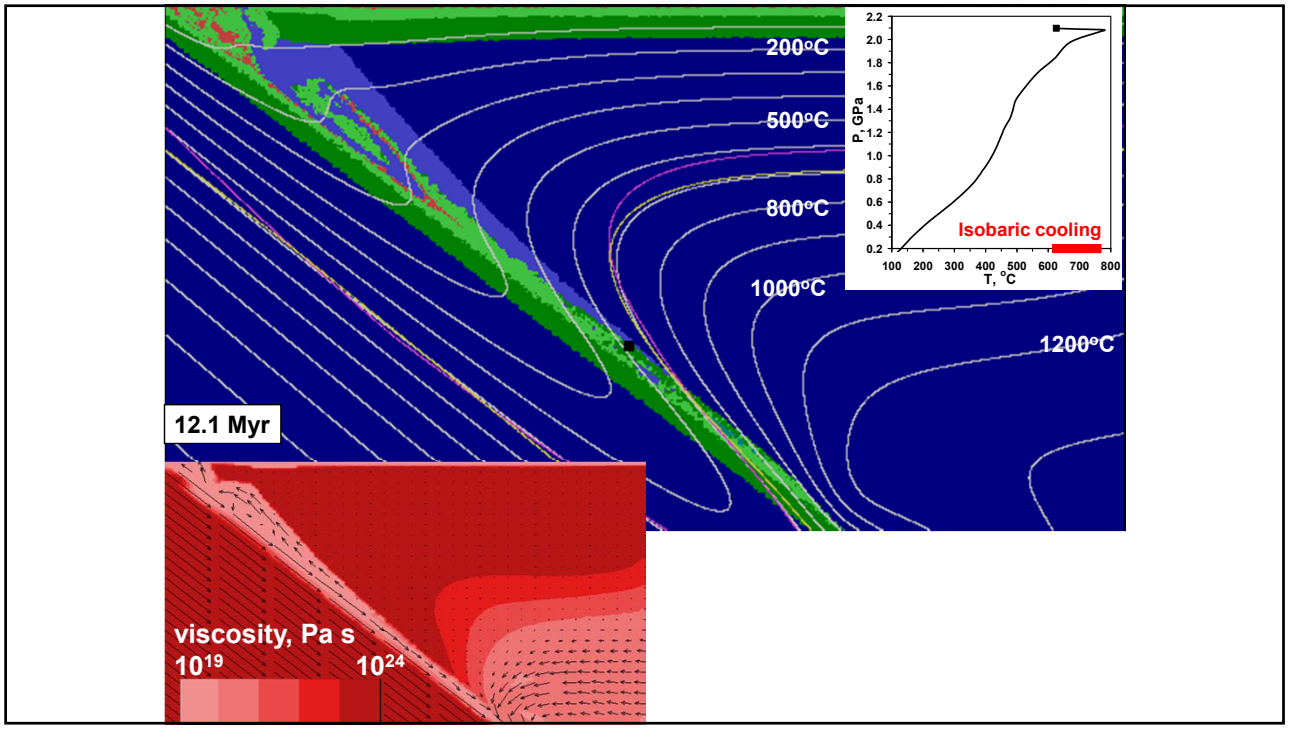

200°C
500°C
800°C
1000°C
1200°C
7.4 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

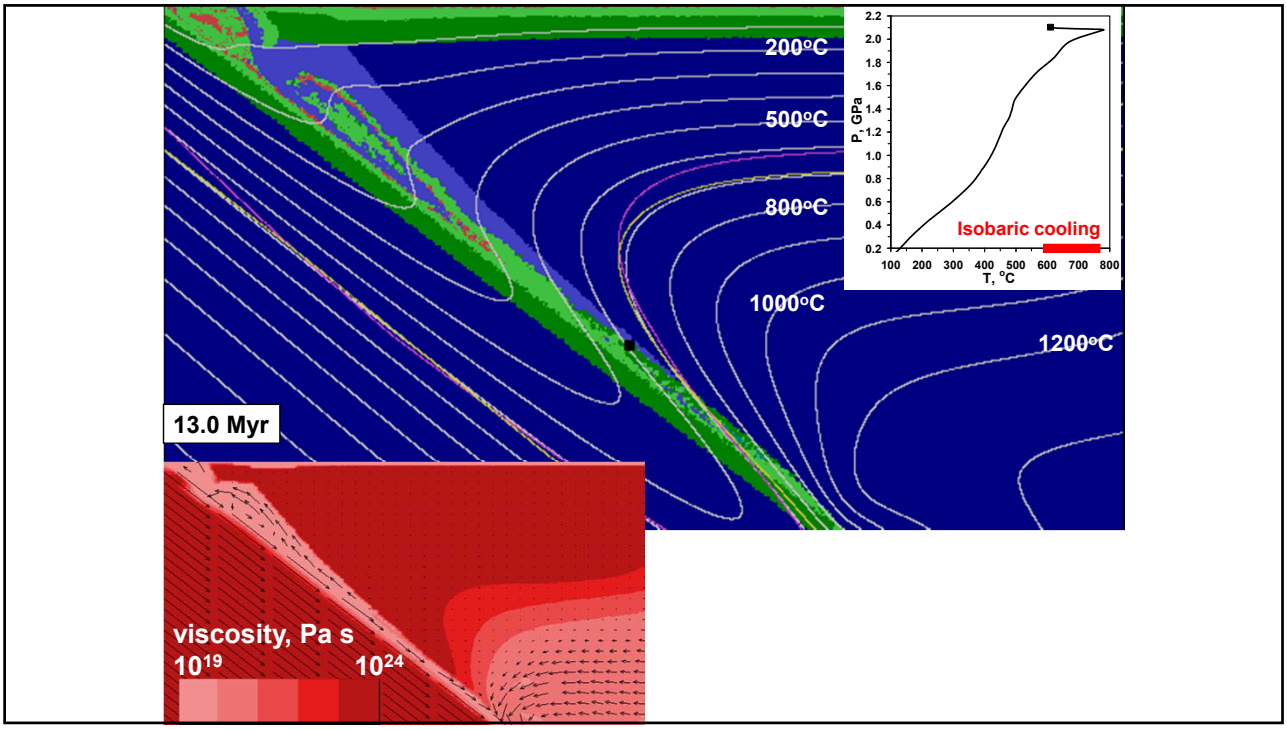

200°C
500°C
800°C
1000°C
1200°C
8.3 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

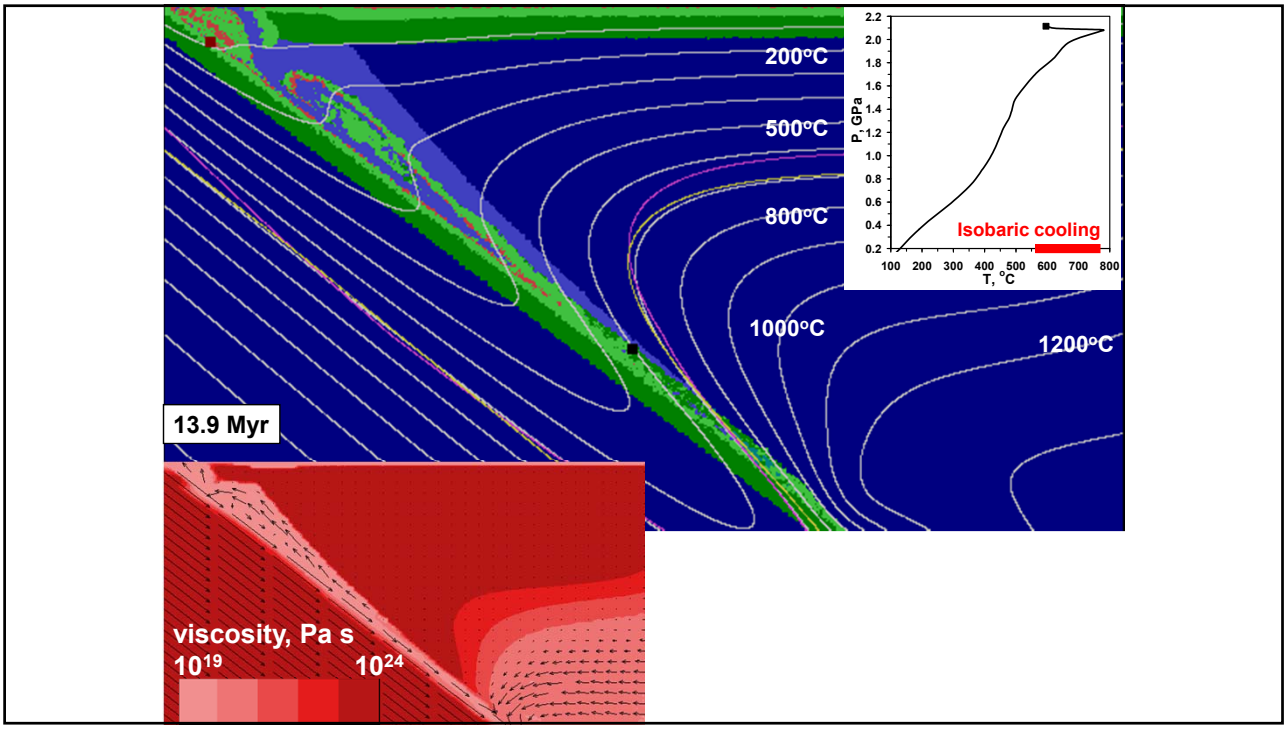

200°C
500°C
800°C
1000°C
1200°C
9.3 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

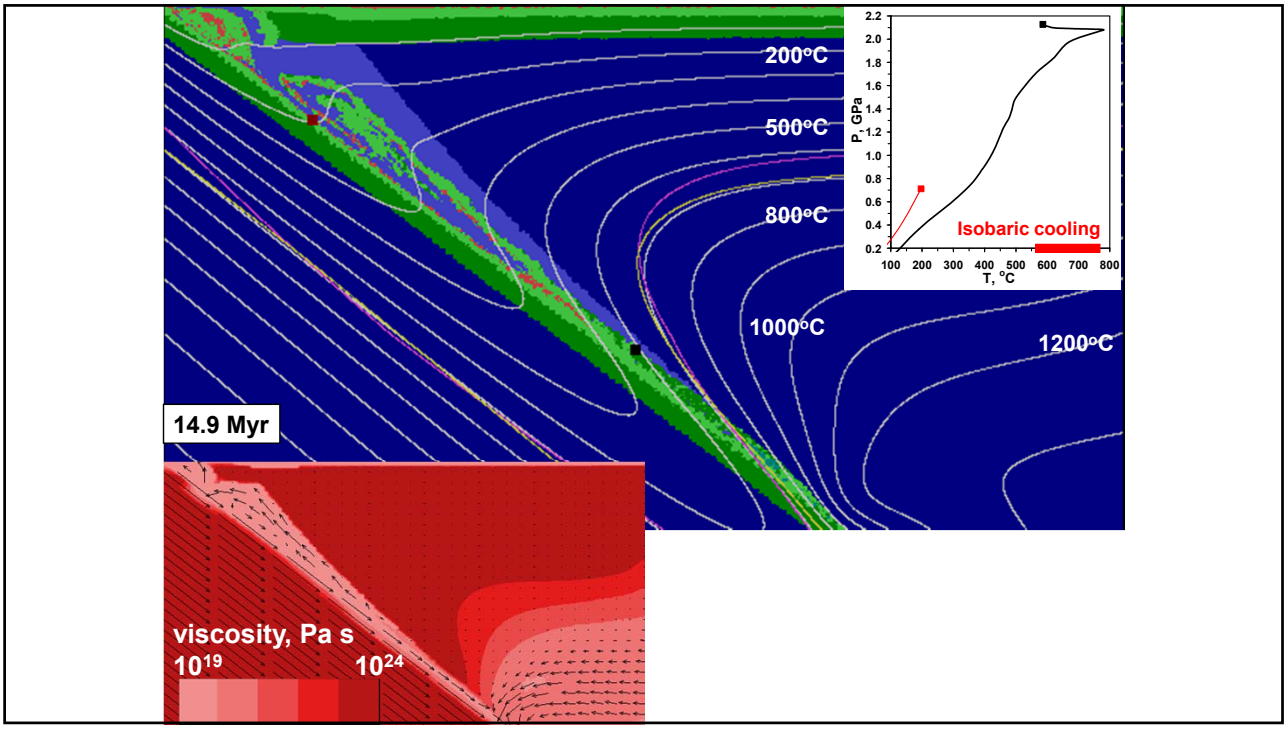

200°C
500°C
800°C
1000°C
1200°C
10.2 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

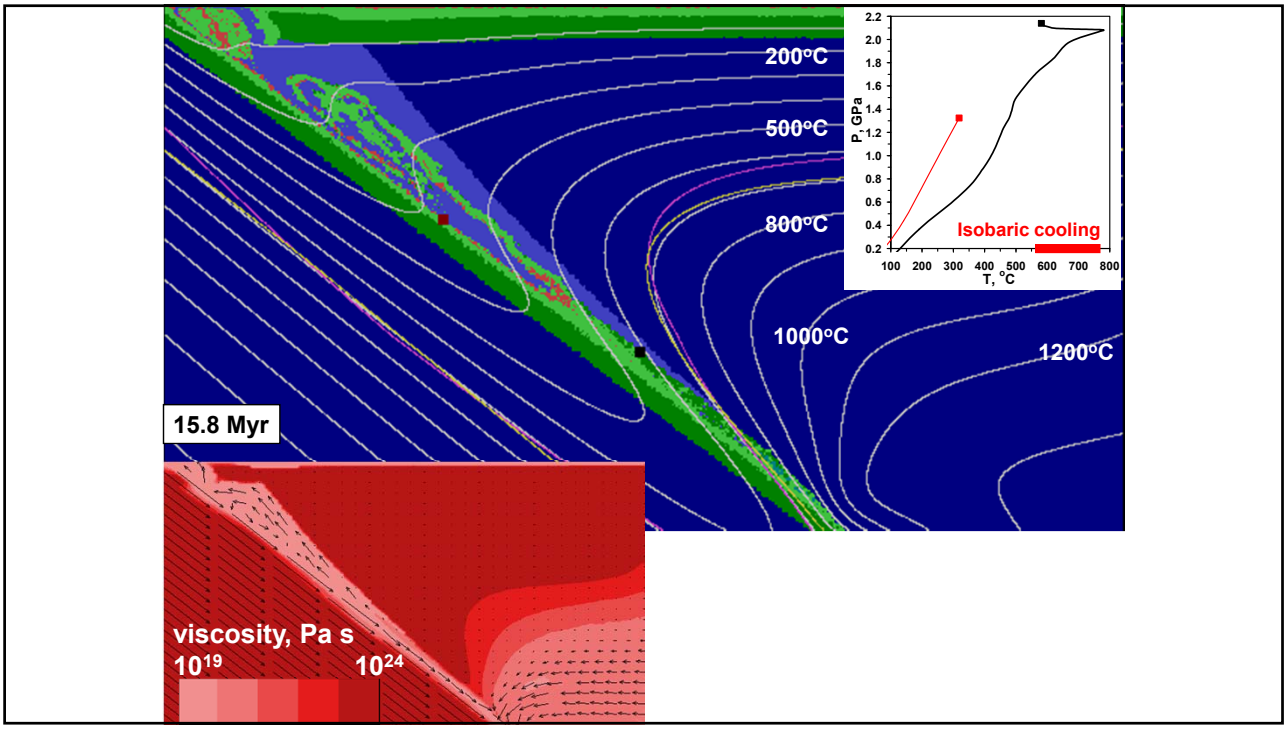

200°C
500°C
800°C
1000°C
1200°C
11.2 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

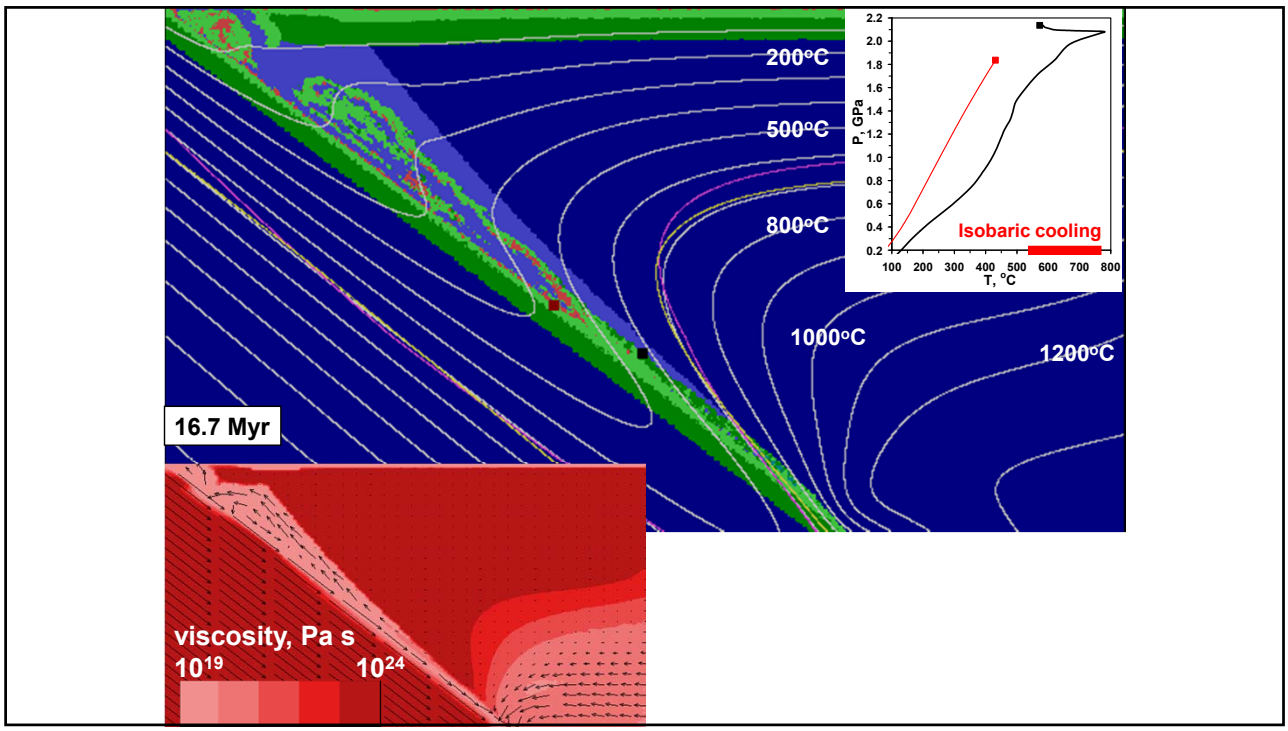

200°C
500°C
800°C
1000°C
1200°C
12.1 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

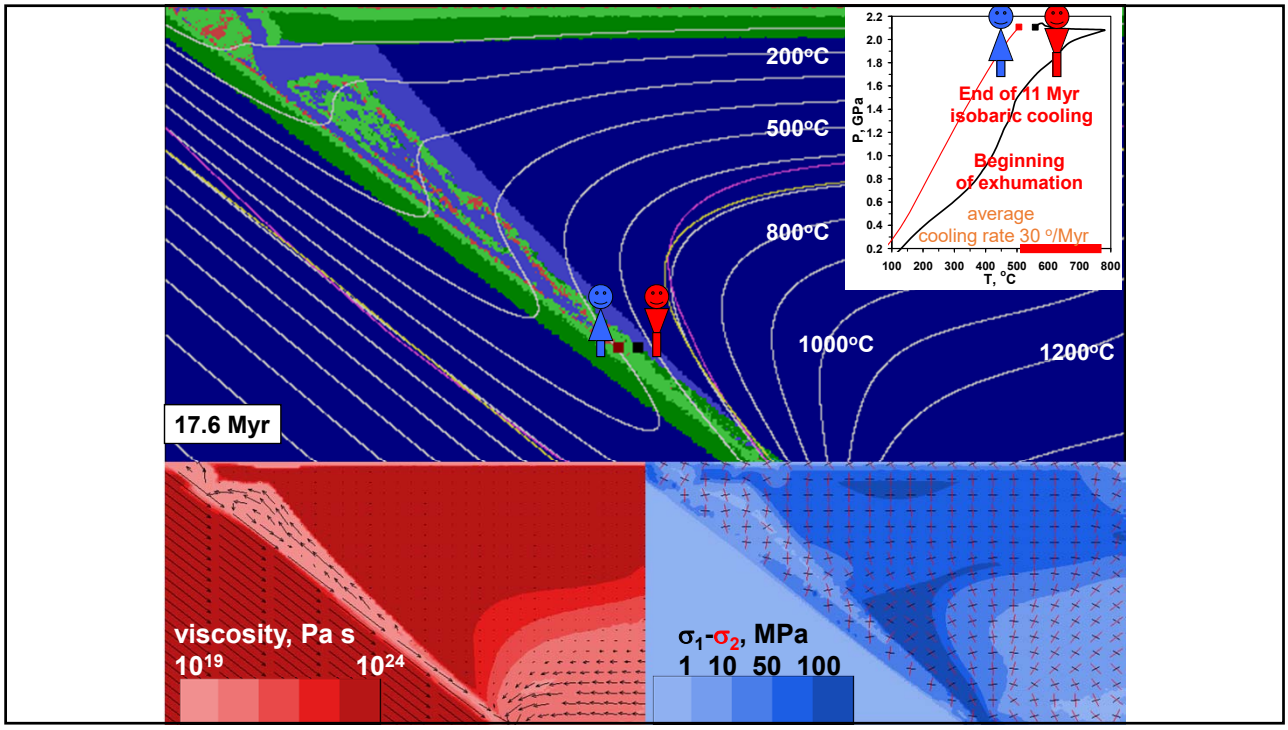

200°C
500°C
800°C
1000°C
1200°C
13.0 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

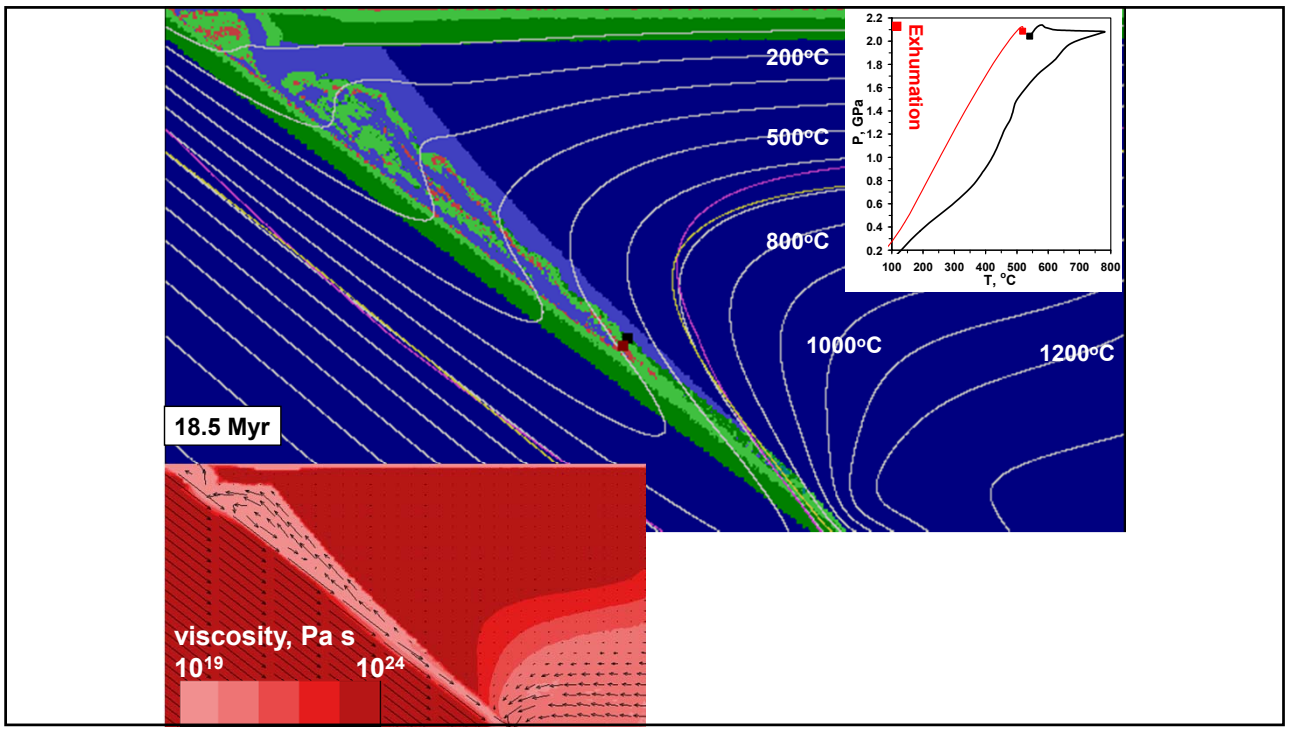

200°C
500°C
800°C
1000°C
1200°C
13.9 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

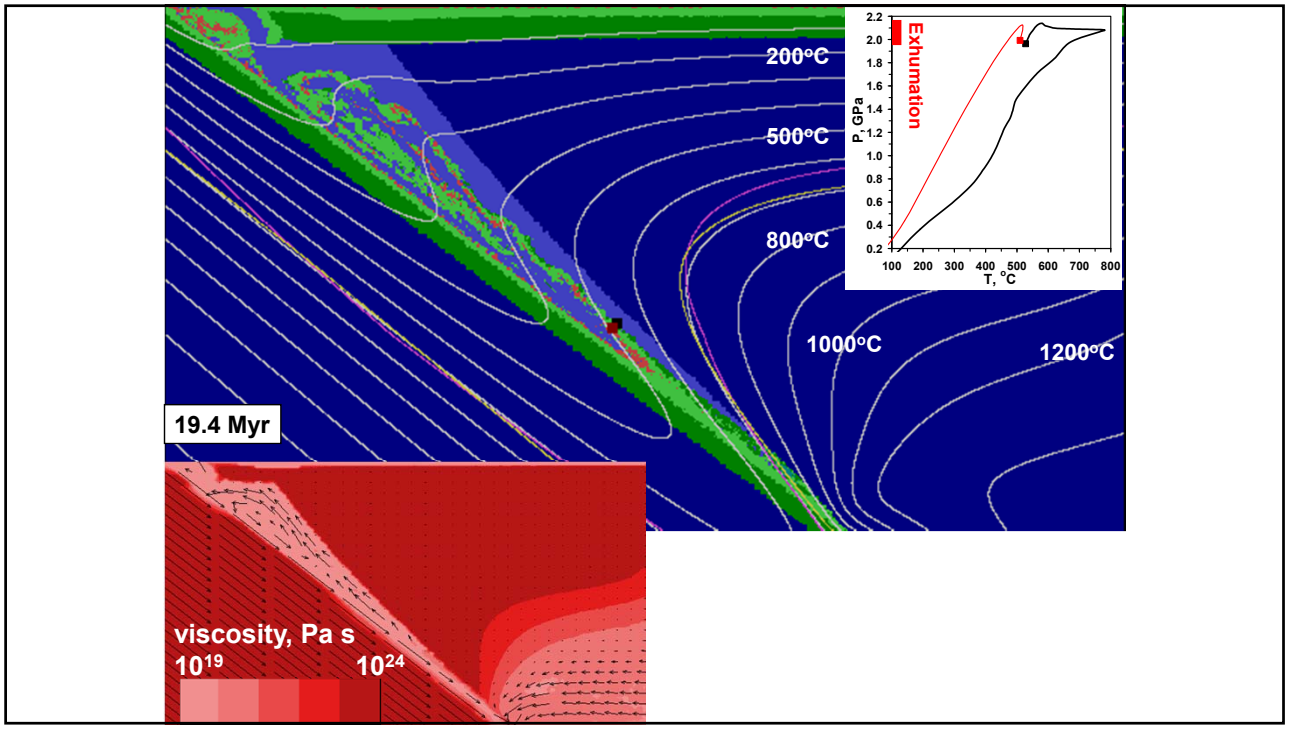

200°C
500°C
800°C
1000°C
1200°C
14.9 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

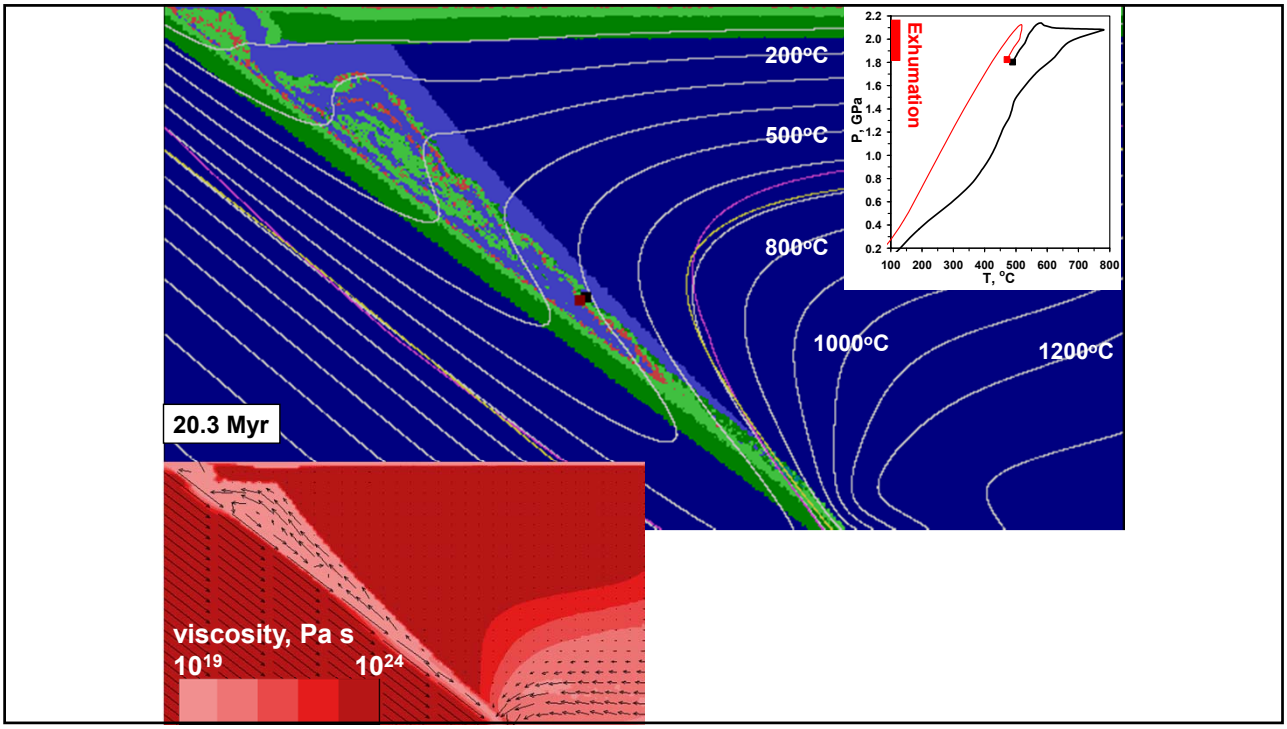

200°C
500°C
800°C
1000°C
1200°C
15.8 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

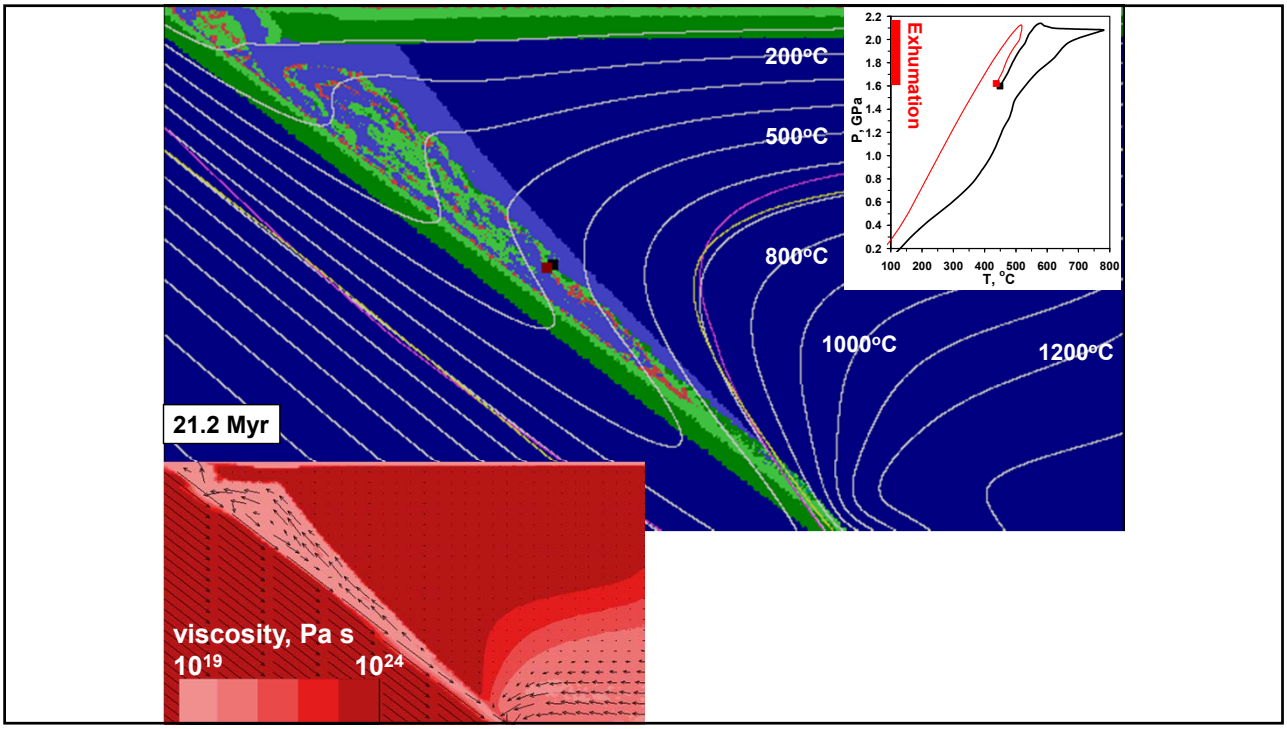

200°C
500°C
800°C
1000°C
1200°C
16.7 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C
Isobaric cooling

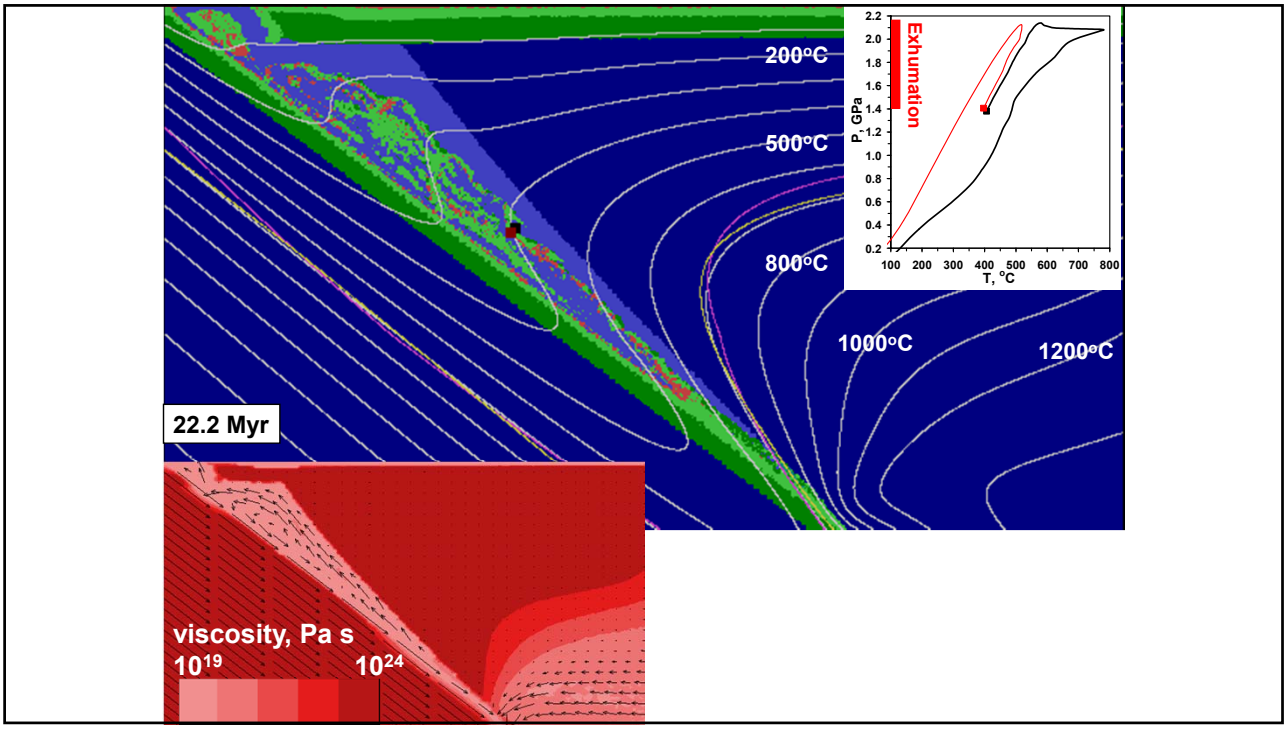

200°C
500°C
800°C
1000°C
1200°C
17.6 Myr
viscosity, Pa s
10^19
10^24
σ1-σ2, MPa
1 10 50 100
P, GPa
T, °C
End of 11 Myr
isobaric cooling
Beginning
of exhumation
average
cooling rate 30 °/Myr

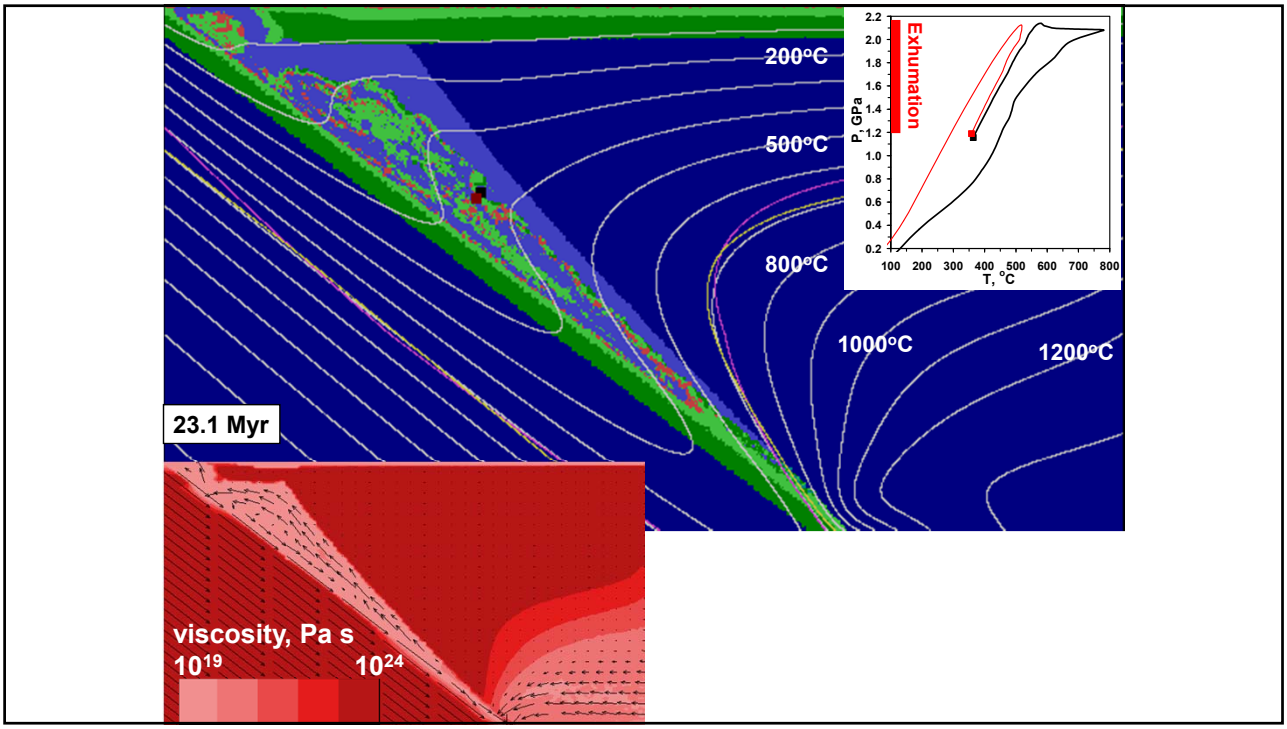

200°C
500°C
800°C
1000°C
1200°C
18.5 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C

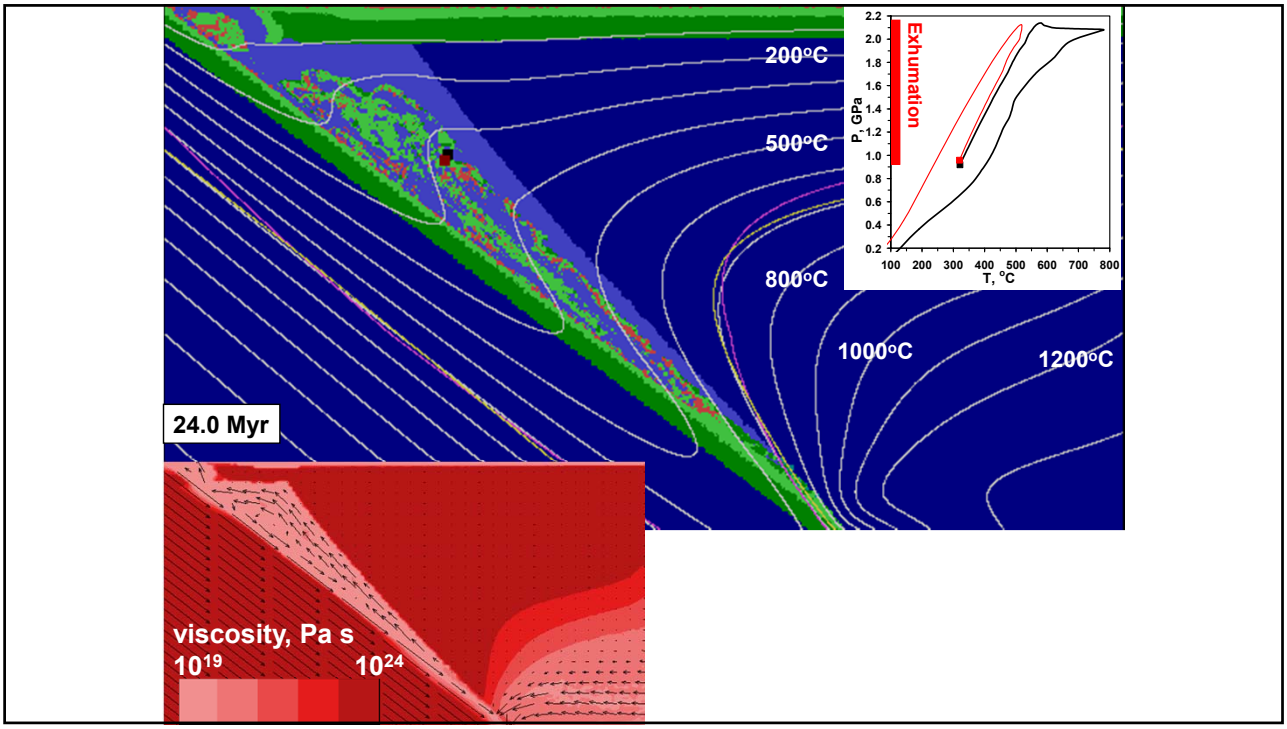

200°C
500°C
800°C
1000°C
1200°C
19.4 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C

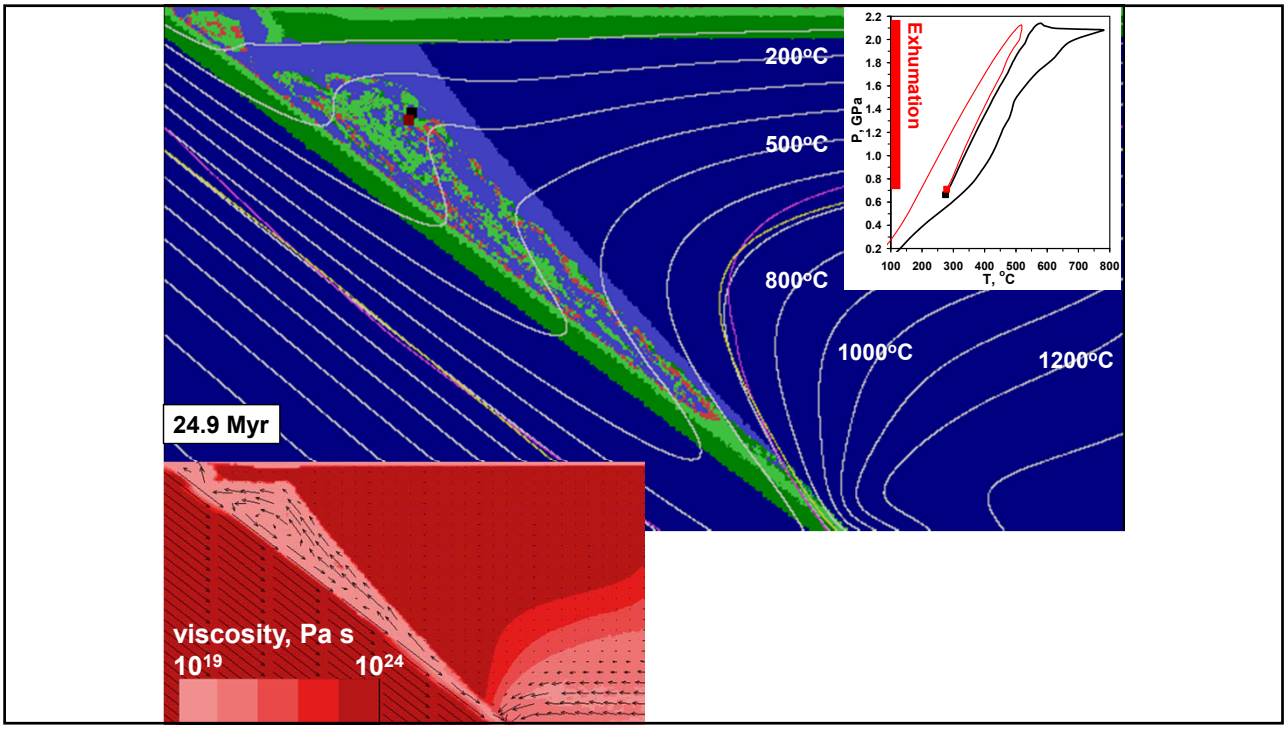

200°C
500°C
800°C
1000°C
1200°C
20.3 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C

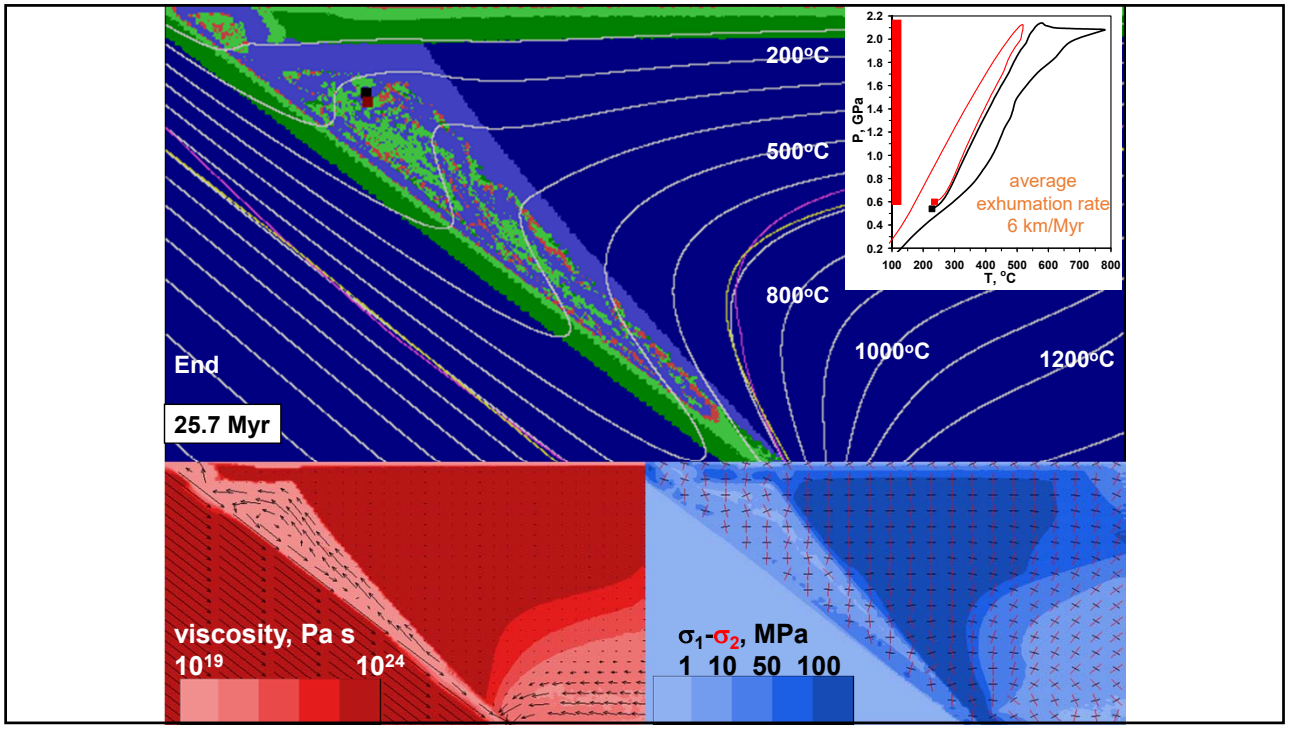

200°C
500°C
800°C
1000°C
1200°C
21.2 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C

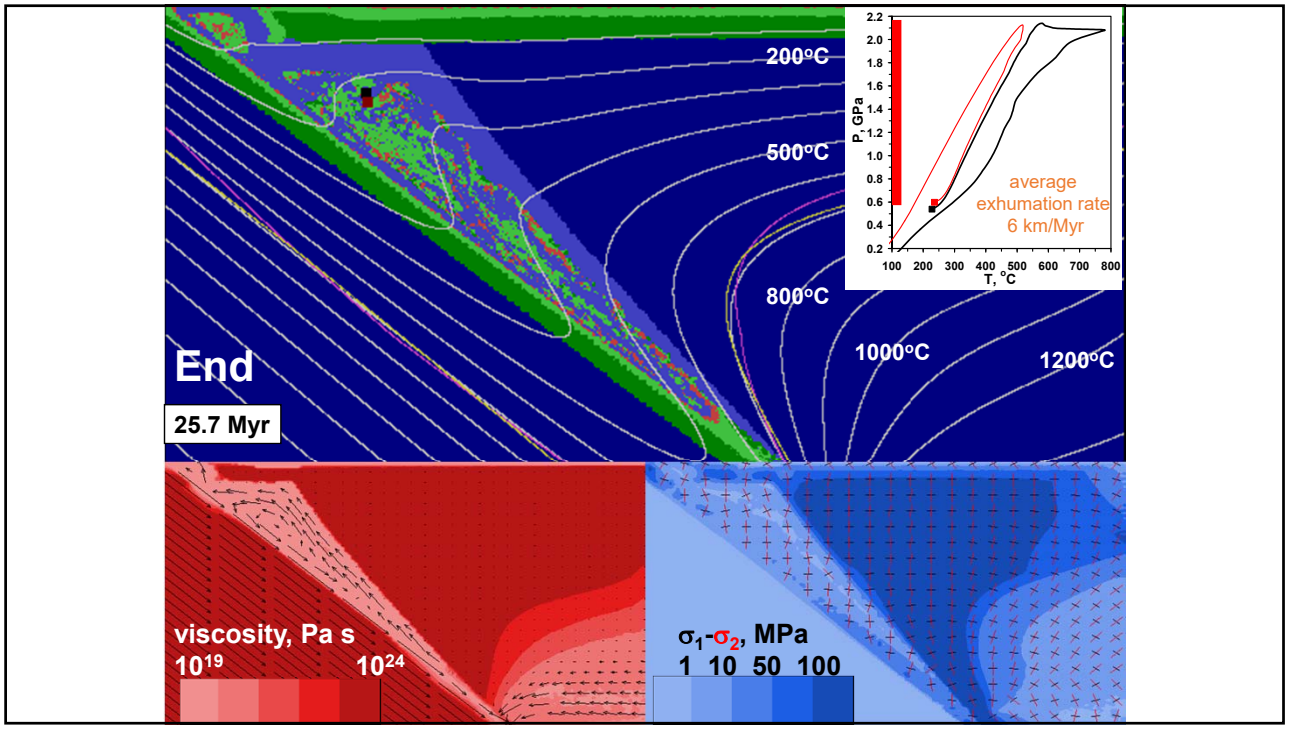

200°C
500°C
800°C
1000°C
1200°C
22.2 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C

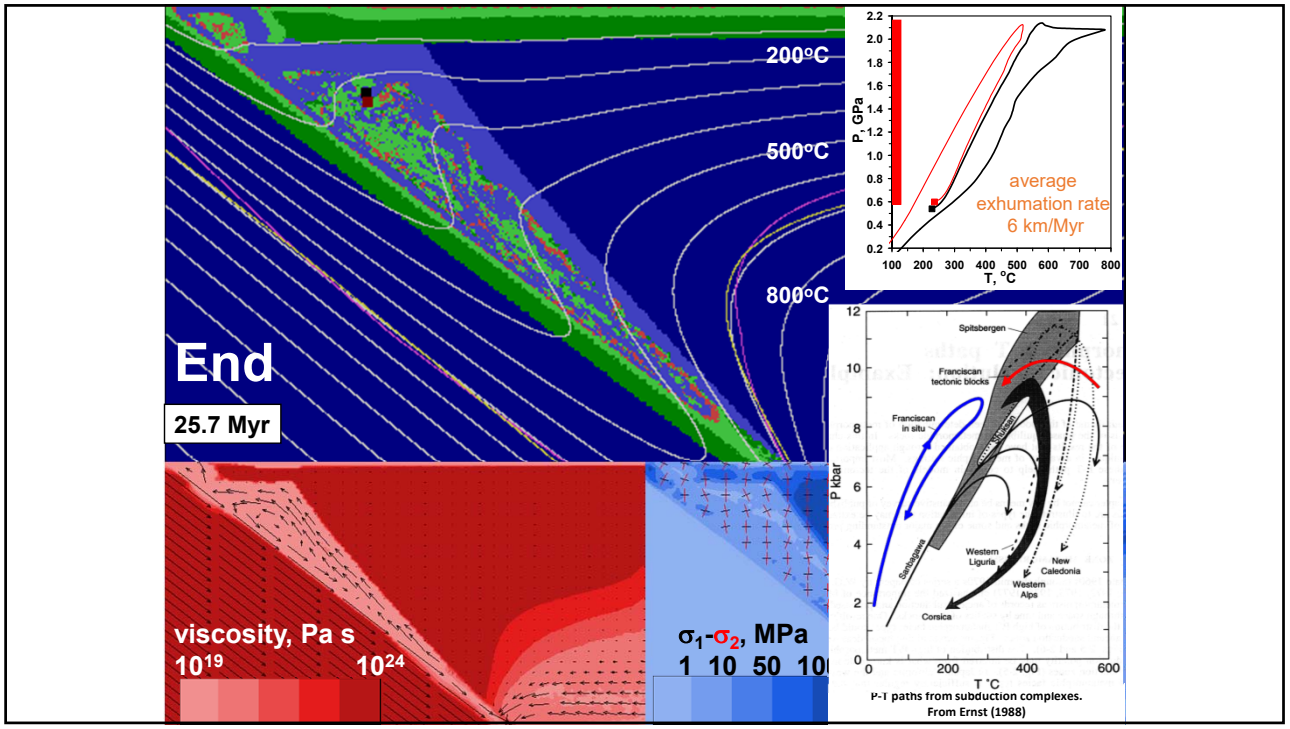

200°C
500°C
800°C
1000°C
1200°C
23.1 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C


200°C
500°C
800°C
1000°C
1200°C
24.0 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C


200°C
500°C
800°C
1000°C
1200°C
24.9 Myr
viscosity, Pa s
10^19
10^24
Exhumation
P, GPa
T, °C


200°C
500°C
800°C
1000°C
1200°C
End
25.7 Myr
P, GPa
T, °C
average
exhumation rate
6 km/Myr
viscosity, Pa s
10^19
10^24
σ1-σ2, MPa
1 10 50 100


200°C
500°C
800°C
1000°C
1200°C
End
25.7 Myr
P, GPa
T, °C
average
exhumation rate
6 km/Myr
viscosity, Pa s
10^19
10^24
σ1-σ2, MPa
1 10 50 100



Next Lecture

Deformation of Rocks