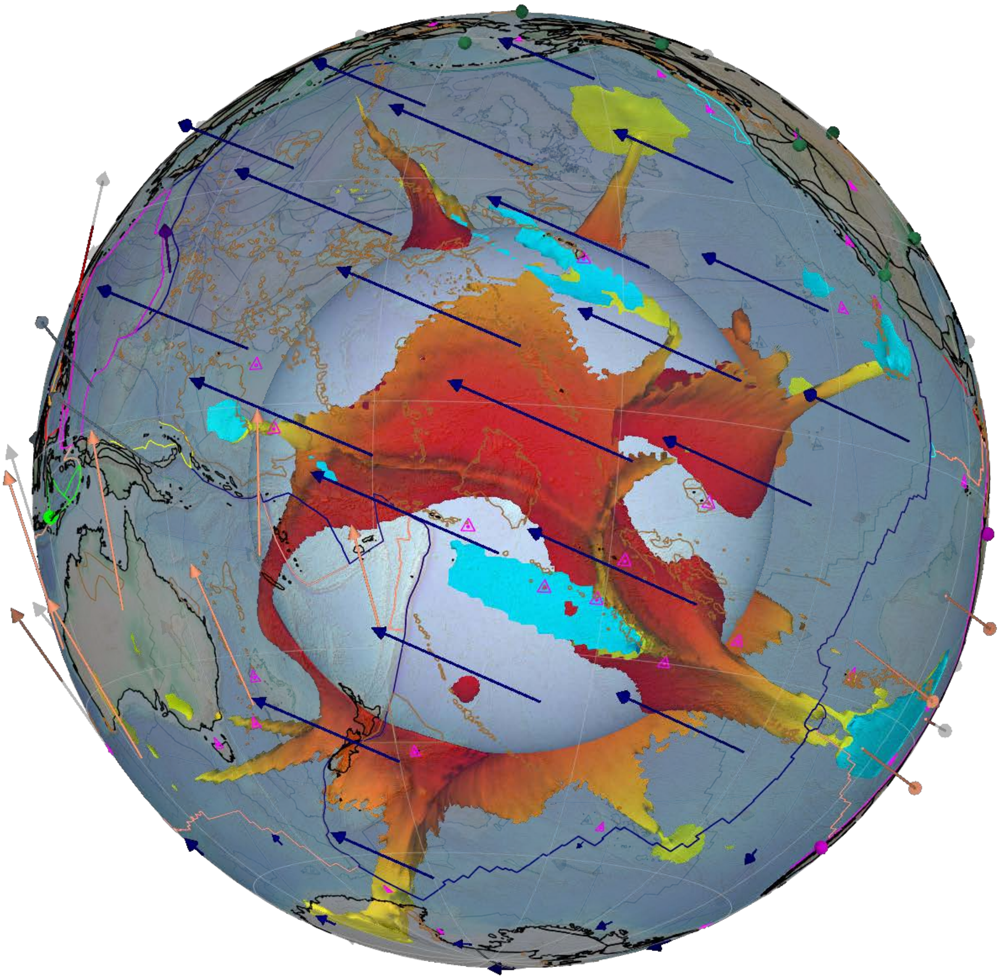
Deep-dive into our Dynamic Earth

STELR Program 2021



Dr Sabin Zahirovic

School of Geosciences
The University of Sydney

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Introduction

Earth formed 4.55 billion years ago in the circumstellar disk of an “average” star in the Milky Way. It is estimated that the Milky Way is comprised of 100 billion stars[1], with each star likely accompanied by one or many planets. However, there are two trillion (or more)[2] galaxies in the observable universe, which highlights the staggering number of planets that are likely to exist. As we continue to explore the solar system and beyond, we realise that Earth is simultaneously unique (say, in hosting life), and yet also quite ordinary (for example, the physical characteristics of the planet).

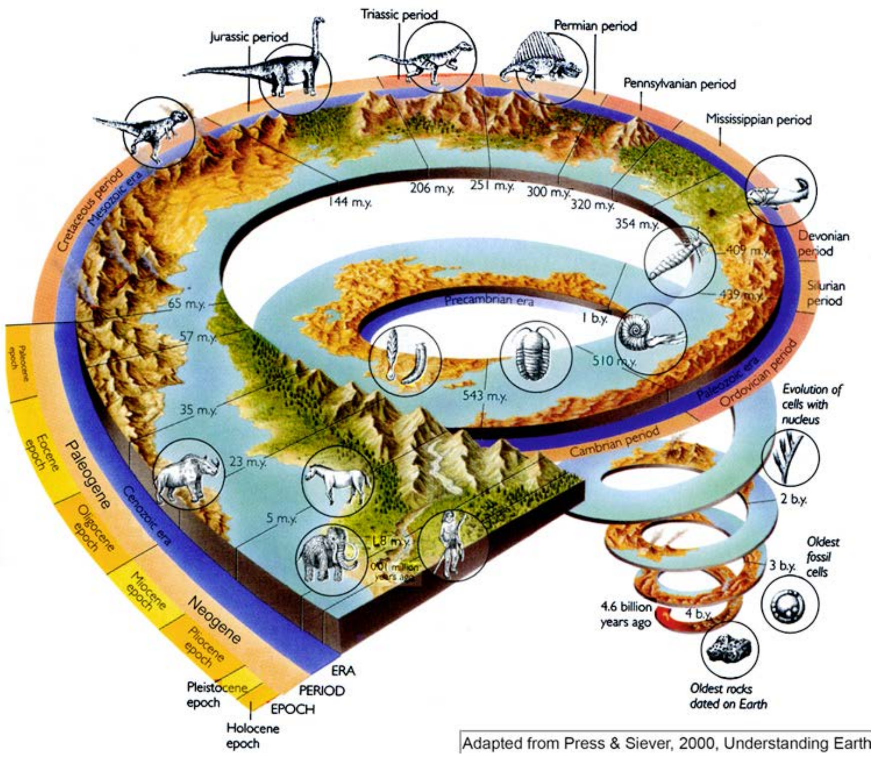

Figure 1. The vastness of geological time. If Earth’s history was condensed to one calendar year, humans arrive at 11:59:40 pm on December 31, which is a tiny fraction of planetary history.

Geosciences (also known as “Earth sciences” or “Geology”) enables us to explore the formation and evolution of bio-geo-chemical systems and their role in planetary habitability.

Geosciences provide the interdisciplinary, quantitiative and unifying framework for addressing major challenges faced by society – including energy, food and water security, as well as mitigating climate change, sea level rise, and a range of natural hazards.

[1] https://www.pbs.org/newshour/science/these-stunning-maps-of-the-milky-way-pinpoint-more-than-1-billion-stars
[2] https://www.nytimes.com/2016/10/18/science/two-trillion-galaxies-at-the-very-least.html

Your Geosciences Representative

Dr Sabin Zahirovic
Lecturer, ARC DECRA Fellow

Sabin is an Earth scientist (lecturer and researcher), working at the University of Sydney's School of Geosciences. Sabin completed a Bachelor of Science and Technology in Geology and Geophysics at the University of Sydney (Honours with a University Medal) in 2011, and received his PhD in 2015.

Sabin's research covers Earth habitability and climate change on geological timescales, optimisation and de-risking of resource exploration, and understanding the evolution of plate tectonics and mantle convection on our planet. Sabin's work in modelling the evolution of our planet has taken him on voyages across unexplored portions of our oceans, and field work to study the Iceland mantle plume and the Yellowstone supervolcano. Sabin is currently funded by the Australian Research Council to explore the rise and demise of massive reef systems (like the Great Barrier Reef).

Contact
sabin.zahirovic@sydney.edu.au

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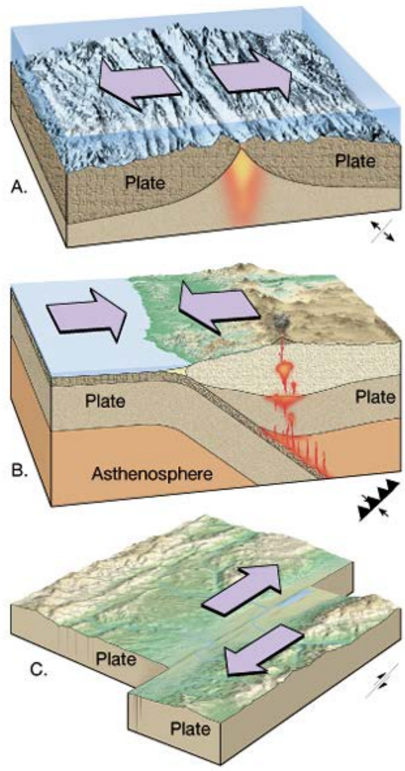
THE UNIVERSITY OF SYDNEY

Online Activity A
Tectonics and Topography

Earth's surface has been shaped by hundreds of millions of years of "plate tectonics". This process is driven by **convection** in the planetary interior, which drives the motion of **tectonic plates** on the surface. These tectonic plates can **converge** (resulting in destruction of Earth's crust, or in mountain-building), **diverge** (resulting in new crust being formed), or **slide past** one another (tearing the crust laterally). To give you an idea of the speed of this process, Australia is heading northward at about 7 cm/yr, which is approximately the same speed of fingernail growth. However, this process has shaped the **arrangement of continents and oceans over geological time,** which has influenced biological evolution (e.g., look up the "Wallace Line" in Southeast Asia), sea level, ocean circulation, climate, and even the formation of precious minerals. These tectonic processes are also responsible for most of the earthquakes, tsunamis, and volcanic eruptions on Earth.



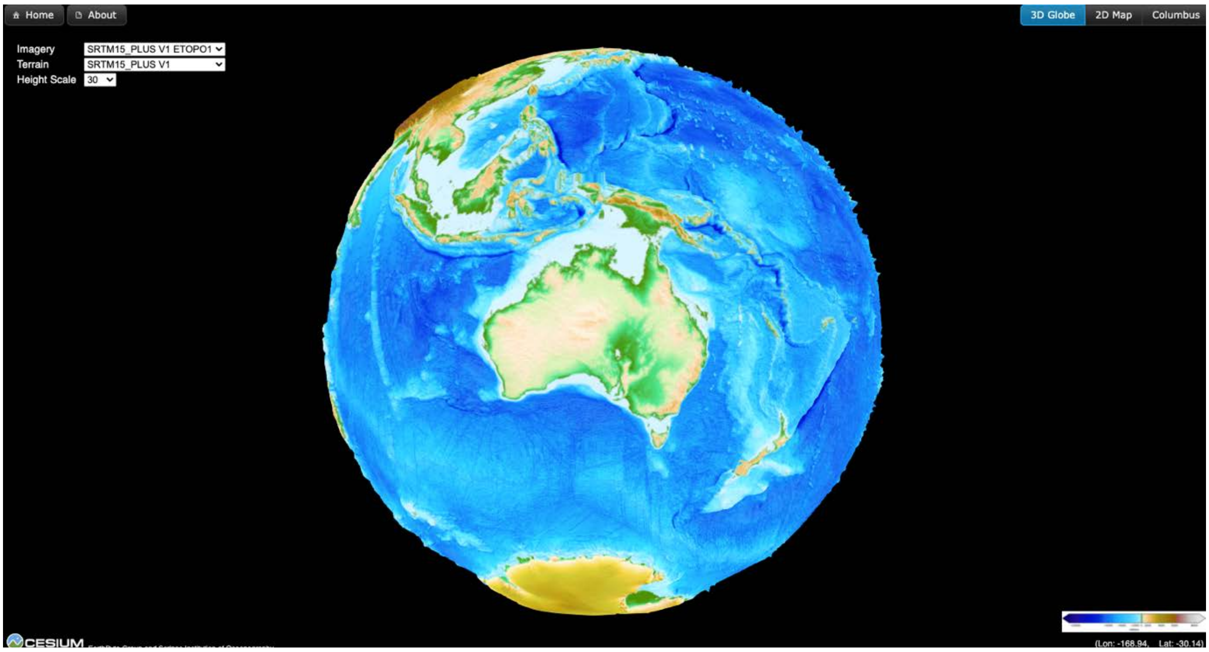
In this ~30 minute self-paced exercise, you will interpret Earth's surface topography and guess what kind of tectonic motion is responsible. During and after the STELR presentation, we will discuss your observations.

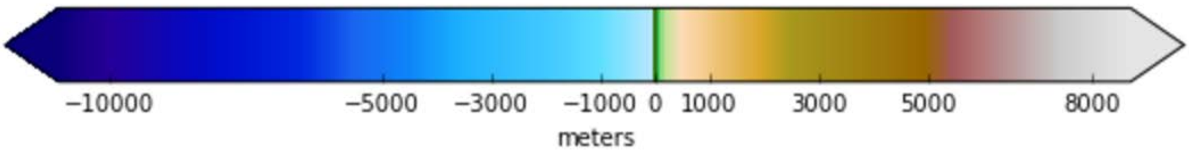
Figure 1 [right]: The three type of plate boundaries. A. Divergent, B. Convergent, C. Transform. (Source: BlendSpace)

On your browser, go to the GPlates Topography interactive globe: http://portal.gplates.org/cesium/?view=topo15

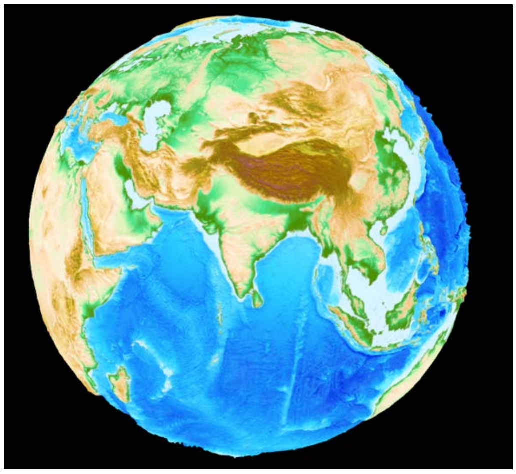
This interactive globe represents Earth's elevations, which are combined from sonar measurements under water and satellite (including space shuttle) measurements for emergent land.

Move the globe: Click and drag.
Tilt the view: Shift + Click and drag
Rotate the view: Control + Click and drag
Zoom in/out: Mouse scroll





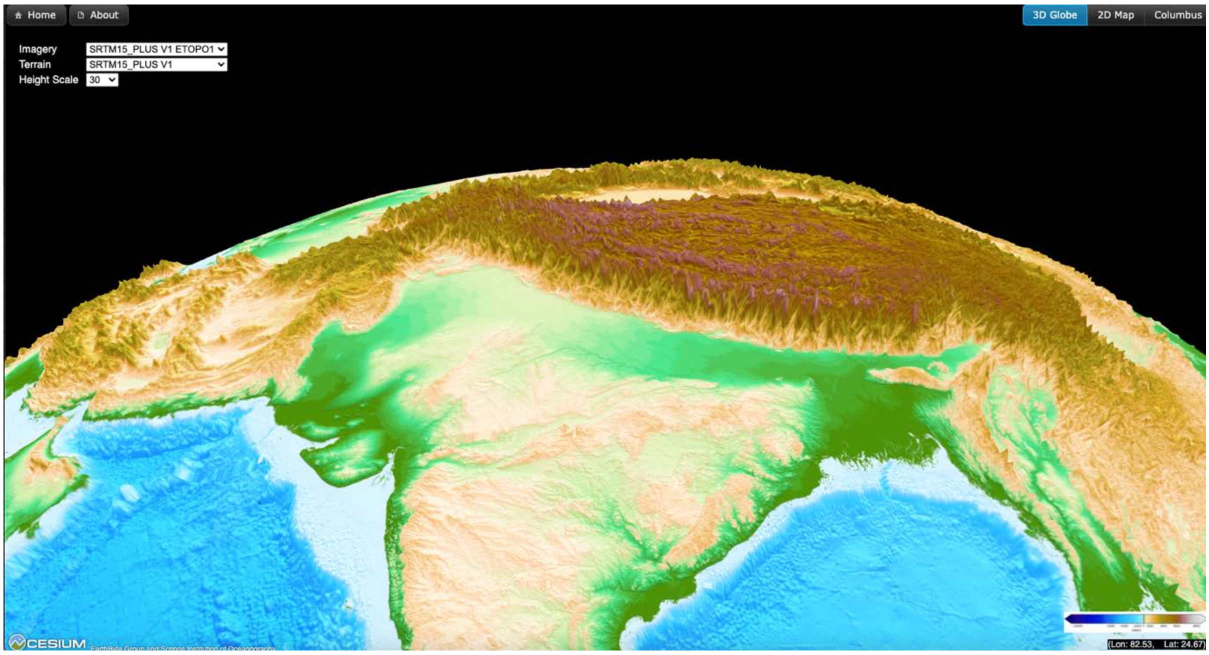
Use the instructions above to experiment with the view of the globe. Now focus the globe on India.

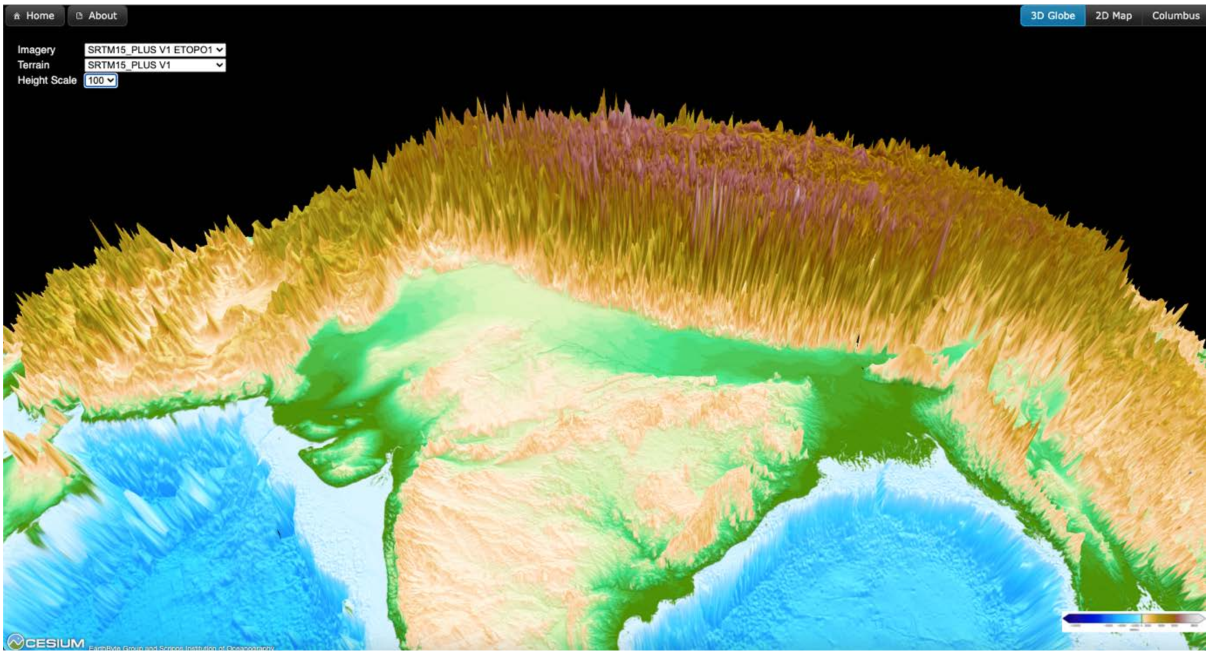


Tilt and rotate the view to focus on the mountain range north of India (the Himalayas and the Tibetan Plateau).

Use the “Height Scale” drop-down to experiment with the **vertical exaggeration**. Try the default value of 30, and also try a value of 100. What do you notice?

Himalayas and Tibet



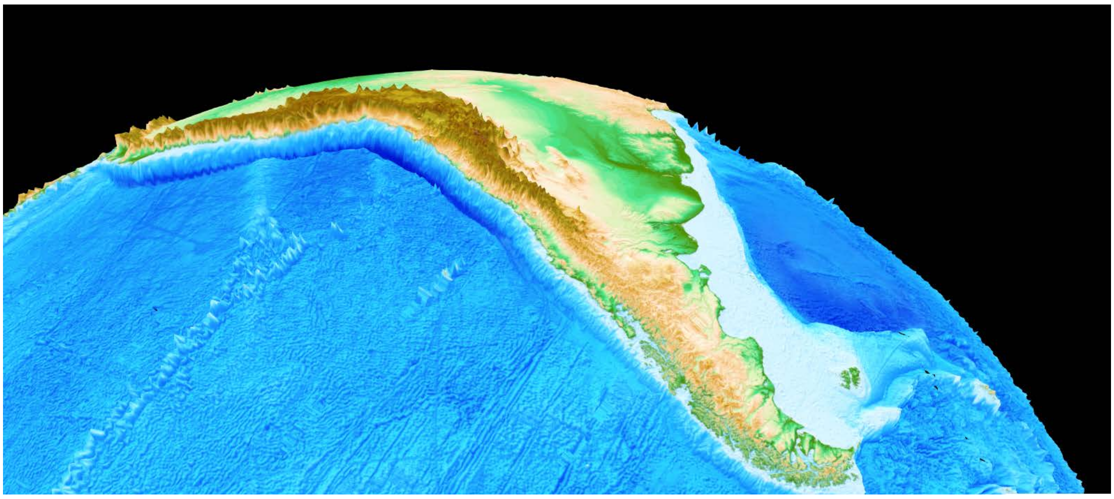


What kind of plate motions do you think were responsible in forming the Himalayas and Tibet (mountains)? (Circle or highlight the correct answer)

Divergent OR Transform OR Convergent

South America

Now, navigate to South America. Rotate, tilt, and zoom so that your view looks similar to below.

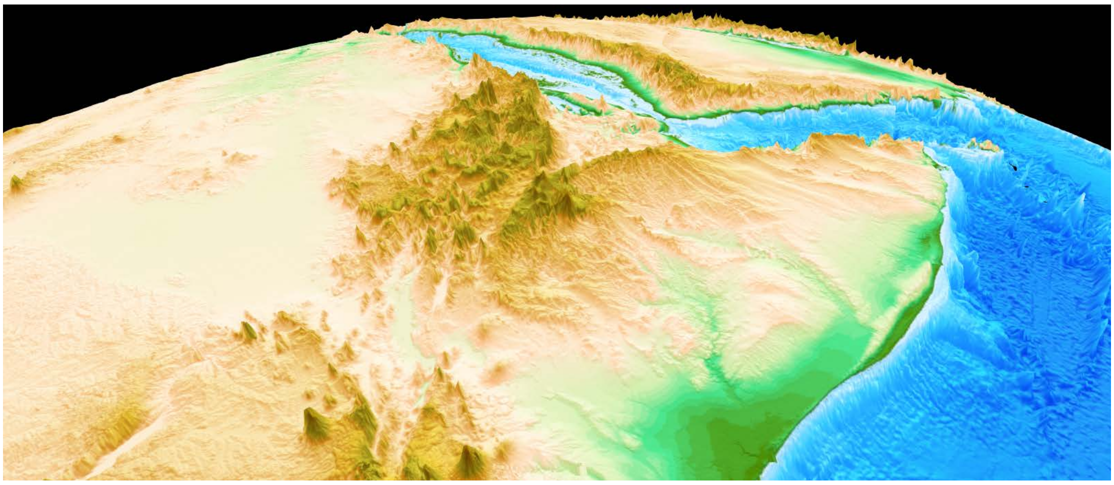


What tectonic motions might be responsible for the western margin of South America? This process has produced the Andean mountain range, and many of the volcanoes along the Andes. (Circle or highlight the correct answer)

Divergent OR Transform OR Convergent

East Africa and Arabia

For this view of East Africa and Arabia, what kind of plate boundaries might be responsible for breaking apart these continental fragments? (Circle or highlight the correct answer)

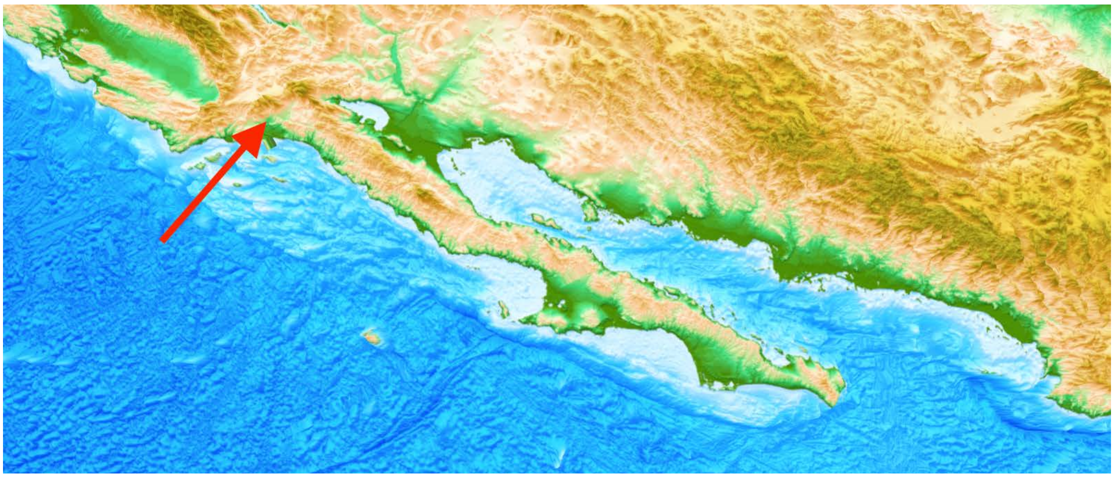


Divergent OR Transform OR Convergent

Western North America

The last example is trickier. What tectonic motion occurs on the plate boundary (along western North America) pointed out by the red arrow? (Circle or highlight the correct answer, Hint: Los Angeles is affected)

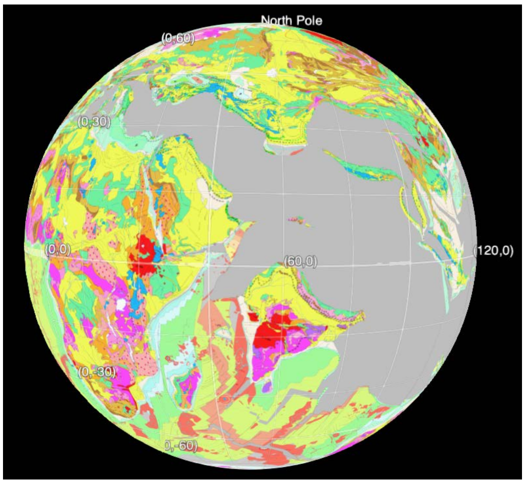
Divergent OR Transform OR Convergent



Online Activity B

Open the Tectonic Reconstruction globe on the GPlates portal:
http://portal.gplates.org/cesium/?view=GeologyR

This view allows you to change the time to any time in the last 200 million years (Ma, mega-annum). It will show the arrangement of continents, driven by plate tectonics. Play around with this globe, and watch the Pangea supercontinent break apart.



<u>Activity:</u> *Approximately, how fast was India moving in the last 62 million years?*

1. Click "Show Graticule", which will show the longitude and latitude lines.
2. "Reconstruct" to 62 Ma (million years ago). Note the approximate latitude of the northwestern tip of India.
3. "Reconstruct" to 0 Ma (present day). Note the approximate latitude of the northwestern tip of India.
4. How many degrees in latitude has the northwestern tip of India crossed in this time? What distance is this, assuming that 1° of latitude or longitude is approximately 110 km?

5. Based on that distance and duration of time, how fast was India moving (on average) in cm per year?

Hands-On Activity (Optional, Offline)

Safety is our number one priority. Please read the information below carefully.

Today we will be handling a number of items and materials that can be hazardous if used improperly. Please read the information below very carefully before beginning the activity.

You will be working with oil and water, so there is a potential for spill and slip hazards. To avoid this, please have an adult help you. Make sure you conduct your experiment on a tray to contain any spills. Have some towels ready in case there are any spills.

Some material used in the activity may be hazardous. Do not ingest any of the materials.

Please do not attempt this activity if you are allergic to:

- Aspirin
- Vegetable Oil
- Water
- Food Colouring
- Any other materials in the materials list

Mantle Convection and Plate Tectonics

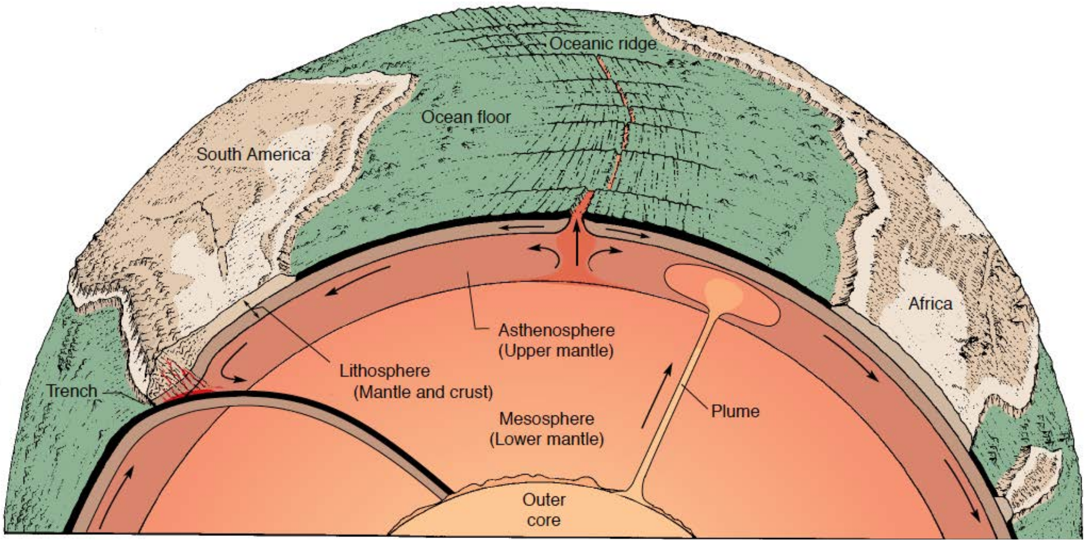


Figure 2. Cross-section of the planet between the surface and the core-mantle boundary (2900 km). Source: Earth's Dynamic Systems (Hamblin and Christiansen, 2004)

The Earth formed from cataclysmic collisions between **planetesimals** and **proto-planets** about 4.55 billion years ago. That **kinetic energy** was converted largely to **heat energy,** leading to an entirely molten state of the early Earth. The loss of heat to space has cooled the planet and allowed the crust and mantle to solidify, while the outer core remains a convecting liquid of primarily iron and nickel. The inner core is solid because the effect of pressure is greater than the effect of temperature at those depths.

The Earth's **mantle** (beneath the crust and lithosphere) to the **core-mantle boundary** at depths of 2900 km is a **solid at present-day** (with some regions containing 1-2% partial melt). However, the **mantle convects and behaves like a fluid on geological timescales** (i.e., over millions of years). This convection is driven by **primordial heat** from the planet's formation, but also from **radioactive decay** of unstable elements in Earth's interior. This process is largely controlled by **thermal gradients,** as well as **density** and **viscosity** contrasts. The convection in the mantle is inextricably linked to the motion of **tectonic plates** on the surface, with rates of motion typically 1-10 cm/yr.

One of the curious features of the mantle is that it also hosts **superheated** material, which rises usually from the core-mantle boundary. This rising material is called a **mantle plume,** and because it is so much hotter, it is usually a narrow rising conduit of rock. Closer to the surface, this rapidly rising hot rock begins to melt, piercing the lithosphere and crust to create **hot-spot volcanism.** These intra-plate (i.e., away from plate boundaries) eruptions produce enormous volumes of volcanic rocks, including the Hawaiian island chain, the Ontong-Java Plateau, and many other features on the continents and ocean floor.

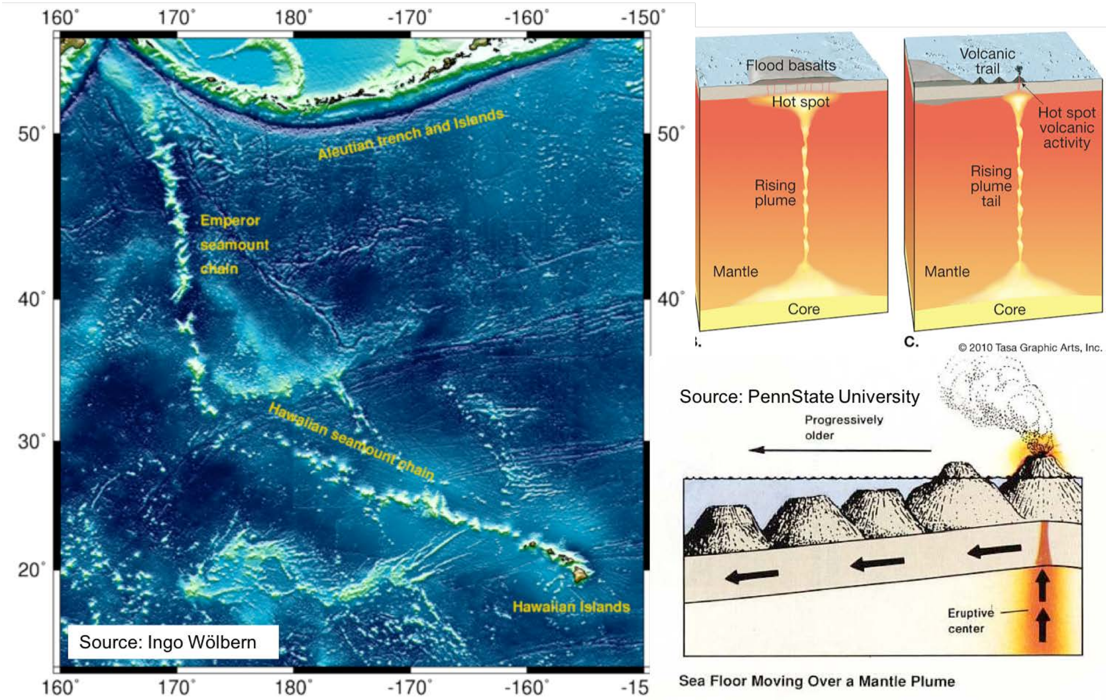


Figure 3. Mantle plume eruptions generate volcanic plateaus and island chains, like Hawaii.

The erupting mantle plumes also emit enormous volumes of **carbon dioxide** and **water vapour,** both of which are potent **greenhouse gases**. The mantle plume eruption of the **Siberian Traps** 251 million years ago led to the greatest **mass extinction** in Earth history. Almost all life was wiped out during this end-Permian mass extinction.

Figure 4. Side view of the analogue model of mantle plume formation and evolution.

The exercise today will get you to recreate mantle convection and mantle plume formation using common household materials.

Materials

- Ruler
- Transparent plastic cup (500 mL)
- Vegetable oil (60% of cup height, 6 cm if cup is 10 cm tall)
- Water (30% of cup height, 3 cm if cup is 10 cm tall)
- Red or pink food colouring (~ 5 drops)
- Whiteboard marker
- 4 Aspro Clear tablets

Instructions

1. Set up a large tray on a level working surface that can contain any spills.
2. Mark out the levels of water and oil that are required using a ruler and whiteboard marker.
3. Very carefully pour in the water to the required height.
4. Very carefully pour in the vegetable oil to the top line, making sure you leave enough clearance at the top of the cup to prevent spills. Spilling oil on the table and floor is a serious hazard, so please be very careful to avoid spills.
   Question: What happens to the water and oil?
5. Add four drops of the food colouring to the cup.
   Question: What happens to the food colouring?
6. Carefully drop ONE Aspro Clear tablet into the cup, and observe the reaction that is occurring. Write some notes in the space below.

7. Now carefully add TWO Aspro Clear tablets at the same time. Observe the formation and evolution of the "mantle plume", and write some notes in the space below.

8. Once the reaction has slowed, carefully add your LAST Aspro Clear tablet into the cup. This time also observe the surface of the oil. Write down your observations in the space below.

Figure 5. Top view of the cup after the experiment.

We call experiments like this "**analogue models**" as they use physical materials to mimic Earth behavior. We also use "**numerical models**" to simulate Earth processes on computers, and now more commonly on **supercomputers**. The numerical models below take about 30,000 hours to compute on a single **CPU** (central processing unit). However, supercomputers allow us to harness many hundreds of CPUs at the same time so that these simulations only take several days. More complex simulations can take weeks or months (and even years!) on the supercomputer.

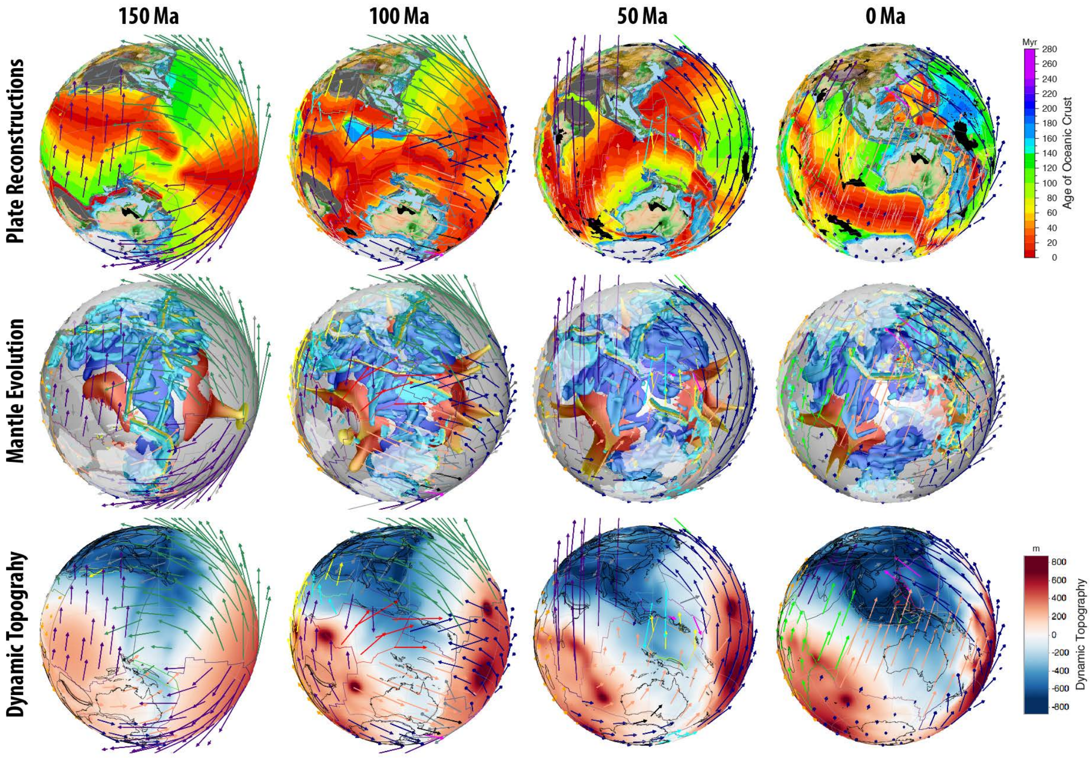


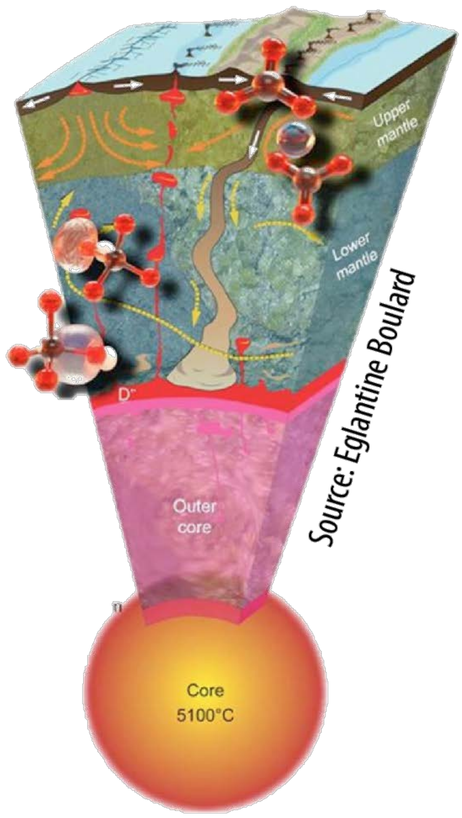
Figure 6. [TOP] Plate tectonic reconstructions using our open-source software GPlates (www.gplates.org) developed at the University of Sydney, with the post-Pangea evolution documented in Zahirovic et al. (2016). [MIDDLE] The evolution of the convecting mantle with hot (plume) material in red, and subducting (sinking) slabs in blue. [BOTTOM] The convecting mantle causes uplift (red) and subsidence (blue) on the surface, which we call "dynamic topography".

References

Hamblin, W. K., and Christiansen, E. H., 2004, Earth's Dynamic Systems, Prentice Hall.

Zahirovic, S., Matthews, K. J., Flament, N., Müller, R. D., Hill, K. C., Seton, M., and Gurnis, M., 2016, Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic: Earth Science Reviews, v. 162, p. 293-337.

Fun Facts



The Earth formed about 4,550,000,000 years ago (4.55 billion years). The universe is about 13.77 billion years old.

There are up to 1,000,000,000,000,000,000,000,000 stars in the universe, each is likely to host a planetary system.

A Harvard-Smithsonian Center for Astrophysics study estimated at least 17 billion Earth-sized planets in the Milky Way alone using Kepler data.

Only about 3,500 exoplanets have been confirmed by NASA (as of 2017), highlighting our lack of “sampling”. According to the Planetary Habitability Laboratory, 55 of these are potentially habitable.

Only Earth has active plate tectonics, while Venus is likely to have mantle convection (stagnant lid regime) and active volcanism. Io (moon of Jupiter), Enceladus (moon of Saturn), and Triton (moon of Neptune) have confirmed volcanic activity.

Research published by NASA in 2017 strongly suggests that Mars had a liquid ocean for one billion years of its early history. Liquid water has been confirmed on Mars.